CHARACTERISATION AND PROTECTION OF POTENTIAL DEEP AQUIFERS IN SOUTH AFRICA

Report to the
Water Research Commission

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EXECUTIVE SUMMARY

BACKGROUND

South Africa is a water-scarce country. Since the country's surface water resources cannot meet the increasing demand for water, groundwater has become an integral part of the water supply to many urban and rural communities. Many of South Africa's towns are completely dependent on the groundwater resource for their water supply. Furthermore, during periods of drought, when the surface water resources become more unreliable, the use of groundwater generally increases.

Groundwater abstraction from the shallow aquifer system has increased significantly in recent years. Where the rate of groundwater abstraction has exceeded the rate of groundwater recharge, this has resulted in the over-exploitation of some of the shallow aquifer systems. These aquifer systems have effectively been mined for their water reserves. The dewatering of aquifers has resulted in the lowering of the groundwater table, and possibly the closure of certain water-bearing fractures due to the reduction of water pressure in the fracture networks.

Boreholes used for groundwater supply are usually shallow (less than 100 m), although deeper abstraction boreholes occur. However, groundwater abstraction from aquifers that occur at depths greater than 300 m is very rare in South Africa. For this reason, not much is known about deep aquifer systems and their potential to provide water.

It is known that aquifers occur at depths much greater than 300 m. Many of these aquifers appear to be high yielding, although the salinity of the groundwater in the aquifers generally increases with depth. These deep aquifers may be considered as a potential groundwater resource to be used when the surface water and shallow groundwater sources are unable to meet the demands of the water users in an area. Deep aquifer systems may thus contribute to the water security of South Africa. The protection of this water resource for future generations is of prime importance.

RATIONALE

Since very limited information is available on deep aquifer systems in South Africa, the deep geohydrology is at present poorly understood. This research project aims to collate all the available information on the deep groundwater system and provide an overview of the current state of knowledge on the country's deep aquifers. From a study of the available information, a preliminary characterisation of deep aquifer systems may be done, while gaps in our understanding of deep geohydrology may be identified.

AIMS AND OBJECTIVES

The principal aim of this project is to characterise the deep groundwater systems of South Africa and describe policies and procedures that may be applied to ensure their protection for future generations. To realise this aim, the following objectives were identified:

- Provide a state-of-the-science overview of the deep geohydrology of South Africa
- Consolidate all available data on the deep aquifer systems
- Characterise the deep groundwater systems from a geohydrological perspective
- Assess the potential of deep groundwater resources to contribute to the water security of South Africa
- Discuss policies and procedures for the protection of the deep groundwater resources
- Create a publicly accessible database containing all the data relevant to deep aquifer systems

METHODOLOGY

The following actions were taken to achieve the aims and objectives identified for this project:

- A review was conducted of national and international literature on deep groundwater systems
- An assessment was done of the potential deep groundwater systems in South Afica by considering the known geology and geohydrology of the different rock formations that occur in the country
- Known and potential sources of data on the deep groundwater systems were identified
- The available data on the deep aquifers was collated and captured in a database
- The deep aquifer systems were described in terms of their geohydrological characteristics by making use of the collected data, as well as the available literature on these aquifer systems
- Approaches to protect the deep aquifer systems were identified by considering national and international technologies, best practices and legislation

RESULTS AND DISCUSSION

Assessment of potential deep aquifers in South Africa

To assess the potential for deep exploitable aquifer systems within the different geological formations of South Africa, a ranking system was used in which the formations were rated according to their likelihood of hosting, or being associated with, deep aquifers. Formations with Rank 1 were considered to show positive indications for the presence of deep aquifer systems, while formations with Rank 2 were considered to show some indications of deep groundwater. Rank 3 and Rank 4 were assigned to those formations that show neutral or negative indications for deep aquifers.

The geological formations most likely to be associated with deep aquifers (assigned Rank 1) were as follows:

- **The Limpopo Belt:** The occurrence of thermal springs within the Limpopo Belt serves as an indication of deeper groundwater flow systems.
- **The Witwatersrand Supergroup:** Fault zones within the Witwatersrand Supergroup play an important role in deep groundwater systems, where deep gold mines that intersect faults have had to deal with large inrushes of groundwater.
- **The Transvaal Supergroup:** The carbonate rocks of the Chuniespoort and Ghaap groups represent an important aquifer system in South Africa. Large volumes of groundwater are stored in the dissolution cavities that occur in these rocks.
- **The Waterberg and Soutpansberg groups:** Fractures are known to occur at large depths in these rock formations. These structures produce high-yielding boreholes when intersected.
- **The Natal Group:** High-yielding boreholes that are associated with water-bearing fractures or faults occur in these formations. The sandstones and quartzites of the Natal Group have a high quartz content and behave in a brittle manner when deformed, forming local zones of intense fracturing, which enhance recharge and permeability, and create preferential groundwater flow paths.
- **The Cape Supergroup:** The main groundwater intersections within the Table Mountain Group (TMG) occur at depths of greater than 100 m below ground level, and borehole yields have been found to increase with depth. Deep groundwater circulation has furthermore been confirmed within the TMG. For these reasons, the TMG is identified as having a high potential for deep aquifer systems.
- **The Main Karoo Basin:** The occurrence of groundwater in Karoo rocks is mainly associated with horizontal bedding planes and bedding plane fractures. Groundwater was struck in a borehole near East London at a depth of 3 700 m below ground level. Weathered and fractured zones, which are associated with faulting and folding, occur in the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines that are formed due to folding have characteristic open joints and fractures, which are seldom dry when drilled. The presence of a hot water spring in Aliwal North (Molteno Formation) indicates the presence of deep circulating groundwater systems.

- **The Tshipise and Tuli basins:** Deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with maximum water temperatures of 59 to 60 °C. These warm springs are associated with some of the major faults that occur in these basins.

Consolidation of data sources on deep groundwater systems

Various confirmed and potential sources of data on deep aquifers and groundwater conditions were identified. These are as follows:

- Boreholes of the International Heat Flow Commission (IHFC). The IHFC database indicates the location of 39 deep boreholes ranging in depth from 300 to 800 m, with an average depth of 535 m.
- The Pangea database of the International Council for Science (ICSU). The Pangea database has information on 119 boreholes in South Africa, of which 116 are deeper than 300 m.
- A database on deep boreholes at the Council for Geoscience (CGS). This database contains information on 5,221 boreholes with depths exceeding 300 m.
- The Southern Oil Exploration Corporation (Suidelike Olie-Eksplorasie Korporasie) (SOEKOR) reports, which contain information on at least 25 deep boreholes.
- Boreholes drilled as part of the Karoo Research Initiative (KARIN).
- Information on deep boreholes from the Petroleum Agency South Africa (PASA).
- The National Groundwater Archive (NGA) of the Department of Water and Sanitation (DWS).
- Information on the occurrence of thermal springs in South Africa
- Information on the location and depth of underground mines in South Africa. Information on the occurrence of deep groundwater could potentially be obtained from these mines.

Although information on a vast number of deep boreholes is listed in the various databases, the data relevant to the geohydrological conditions is very sparse for most boreholes. This implies that very limited data is available that could be used to characterise South Africa's deep aquifers.

Characterisation of the deep aquifer systems

The potential sources of information were interrogated to gain information on the deep aquifer systems and characterise the aquifer systems in terms of their physical and hydraulic properties, and in terms of the groundwater quality expected from these aquifers. Not all the potential sources yielded useful information. The databases of the IHFC and Pangea mostly contained information on temperature and heat production in deep boreholes. The database of the CGS also contained very little information relevant to deep aquifer systems, although the results of water content analyses performed on rock samples from deep boreholes are listed. The Petroleum Agency South Africa did not respond to requests for access to its reports on the deep exploration boreholes included in its database.

Apart from the databases, a literature review of publications relevant to potential deep aquifers in South Africa was done to allow further characterisation of these aquifer systems. This literature review focused on deep aquifers in the Karoo Supergroup, the basement and crystalline bedrock aquifers, the Table Mountain Group and the Bushveld Igneous Complex (BIC). The literature review also considered publications on geophysical surveys that could shed further light on the characteristics of the deep aquifer systems. Furthermore, four case studies were considered in which the geohydrological conditions at four deep mines were characterised.

The deep aquifer systems of South Africa are generally fractured hard-rock aquifers in which secondary porosity was developed through processes such as fracturing and dissolution. The primary porosity of most of the rocks that form the aquifers is very low. Apart from the dolomitic aquifers, most of the water storage occurs in the rock matrices. Groundwater predominantly flows along the fractures and dissolution cavities that act as preferential pathways for groundwater migration. The aquifers are generally highly heterogeneous and anisotropic.

The deep aquifers are generally confined and associated with positive hydraulic pressures. The groundwater quality generally decreases with depth as salinity increases. However, deep dolomitic aquifers may contain groundwater of good quality.

Due to the large depths of occurrence, the deep aquifer systems are generally not vulnerable to contamination from activities at the surface or in the shallow subsurface. The deep dolomitic aquifers are a notable exception since they may be hydraulically linked to the shallower systems through complex networks of dissolution cavities. The deep aquifers are, however, very vulnerable to over-exploitation since low recharge rates are expected.

Protection of the deep aquifer systems

For the protection of deep aquifer systems, activities that could potentially impact on South Africa's deep aquifers were identified. These are the following:

- Conventional deep mining
- Conventional deep oil and gas production
- Unconventional oil and gas production
- Carbon capture and storage
- Groundwater abstraction from deep aquifers for water provision
- Artificial recharge of deep aquifers

For each of the identified activities, different approaches for the protection of deep aquifers were considered, including the following:

- The establishment of baseline conditions prior to the commencement of activities
- The use of new technologies to prevent or minimise the potential impacts on the aquifers
- The use of national and international best practice guidelines for activities that could impact on the aquifers
- The application of regulatory tools to manage activities
- The development of monitoring programmes and adaptive management strategies

Deep groundwater database

A database was developed containing data relevant to South Africa's deep aquifer systems. The purpose of the database was to collate all the available information on deep aquifers in South Africa into a user-friendly format. This database should be continually updated as new information becomes available.

The database was compiled in an Excel file, accessed through the software package WISH (Windows Interpretation System for Hydrogeologists), developed by the Institute for Groundwater Study (IGS). The data captured in the database included all the data on deep aquifer systems gathered during the current research project. Unfortunately, the data is generally sparse and incomplete at most sites. There are also inconsistencies and contradictions in the data.

At present the database contains data on the following:

- 5,221 borehole sites from the database of the CGS
- 1,116 borehole sites from the NGA
- 123 borehole sites from the Pangaea database
- 71 thermal springs
- 49 borehole sites from the database of the IHFC
- 38 SOEKOR boreholes
- 13 borehole sites from the database of PASA
- Two KARIN boreholes

The results of 355 chemical analyses conducted on deep groundwater samples are included in the database, as well as data on 184 temperature measurements at some of the hot springs of South Africa. In addition, data on 38 measurements of the discharge rates from the hot springs are included.

The database compiled during this study should be managed as a work in progress and should be continually updated as more data becomes available and as inconsistencies are resolved.

CONCLUSIONS AND RECOMMENDATIONS

The results of the current research project show that only limited information is available on South Africa's deep aquifer systems. Our understanding of deep aquifer systems is therefore limited at present. There are, however, clear indications that deep groundwater systems could, in future, form part of South Africa's water supply, particularly during periods of water stress.

Considering that deep mining has been ongoing in South Africa for many decades, direct access to some of the country's deep aquifer systems has been available for many years. In addition, deep boreholes are routinely drilled as part of a mine's exploration programme. Regrettably, the mining industry has only been concerned about the deep geohydrological conditions as far as groundwater inrushes affect mining operations. The mines have recorded little to no data relevant to deep aquifer systems. The consequence of this is that valuable geohydrological data has been lost. Similar comments can be made about the deep boreholes drilled by SOEKOR and the oil and gas exploration boreholes. The deficiency in deep groundwater data is therefore not due to the absence of deep boreholes, but rather to the absence of geohydrological data collected from those boreholes.

Future cooperation between academic institutions, the groundwater industry, government departments and mining companies could ensure that geohydrological data is routinely recorded when mining activities allow access to deep aquifer systems. Although this will be a challenge in an industry driven by profit margins, a shift in thinking in this direction has already begun. A proposed drilling project in the Bushveld Igneous Complex by the International Continental Drilling Programme (ICDP) has invited geohydrologists to collaborate on the project to collect the relevant geohydrological data. Similarly, although the deep KARIN boreholes were drilled with the specific aim of studying the Karoo statigraphy, geohydrological data was also collected from these boreholes.

To allow the geohydrological characterisation of South Africa's deep aquifer systems, it is recommended that deep boreholes, designed by geohydrologists and dedicated to geohydrological investigations, be installed at selected locations. The construction of these boreholes should be such that geohydrologists will be able to collect comprehensive datasets on the aquifer parameters and groundwater conditions. These boreholes could potentially allow the development of new technologies to characterise deep aquifer systems.

The database developed during the current project should be continually updated as new data becomes available. It is recommended that an organisation be appointed to manage the database and to capture any new data. This will avoid the creation of several dissimilar versions of the database. Keeping the database updated will again require cooperation between various stakeholders and actors.

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LIST OF ACRONYMS AND ABBREVIATIONS

εUCG	Exergy Underground Coal Gasification
AKGT	Agulhas-Karoo Geophysical Transect
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BEDD	Blikhuis Experimental Deep Drilling
BIC	Bushveld Igneous Complex
BICDP	Bushveld Igneous Complex Drilling Project
BIF	Banded Iron Formation
BPG	Best Practice Guideline
CAPP	Canadian Association of Petroleum Producers
CBM	Coalbed Methane
CCP	CO_2 Capture Project
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CFB	Cape Fold Belt
CGS	Council for Geoscience
CGWB	Central Ground Water Board
CIMERA	NRF-DST Centre of Excellence for Integrated Mineral and Energy Resource Analysis
COC	Chain of Custody
CRIP	Continuous Retraction Injection Point
CSIR	Council for Scientific and Industrial Research
CTL	Coal-to-Liquid
DACC	Drilling and Completions Committee
DAGEOS	Deep Artesian Groundwater Exploration for Oudtshoorn Supply
DBG	Deep Biogenic Gas
DMR	Department of Mineral Resources
DST	Department of Science and Technology
DWA	Department of Water Affairs

DWAF	Department of Water Affairs and Forestry
DwC	Drilling-with-casing
DWS	Department of Water and Sanitation
Eh	Oxidation-reduction Potential
EIA	Environmental Impact Assessment
EMP	Environmental Management Plan
ERT	Electrical Resistivity Tomography
FDEM	Frequency-Domain Electromagnetic
GIPIP	Good International Petroleum Industry Practices
GTL	Gas-to-Liquid
GUI	Graphical User Interface
ICDP	International Continental Drilling Programme
ICSU	International Council for Science
IEAGHG	International Energy Agency Greenhouse Gase R&D Programme
IGC	International Geothermal Center
IGS	Institute for Groundwater Studies
IHFC	International Heat Flow Commission
IPCC	Intergovernmental Panel on Climate Change
IRP	Industry Recommended Practice
ISO	International Organization for Standardization
IWRM	Integrated Water Resource Management
KARIN	Karoo Research Initiative
KGEG	Karoo Groundwater Expert Group
MFL	Magnetic Flux Leakage
ℓ/min	Litres per minute
ℓ/s	Litres per second
MRPDA	Mineral Resources and Petroleum Development Act
m/s	Metres per second
m/d	Metres per day
m^3	Cubic metres
Mm^3	Million cubic metres

m^3/h	Cubic metres per hour
mg/ℓ	Milligrams per liter
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NGS	National Groundwater Strategy
NOGA	Norwegian Oil and Gas Association
NORM	Naturally Occurring Radioactive Material
NNMB	Namaqua-Natal Metamorphic Belt
NRC	National Research Council (USA)
NRF	National Research Foundation
NWRS	National Water Resource Strategy
OES	One Environmental System
OGP	Oil and Gas Producers
PAH	Polycyclic Aromatic Hydrocarbons
PASA	Petroleum Agency South Africa
PGE	Platinum Group Elements
PGM	Platinum Group Metals
PSAC	Petroleum Services Association of Canada
PWV	Pretoria-Witwatersrand-Vereeniging
RDM	Resource Directed Measures
RGS	Rashoop Granophyre Suite
RLS	Rustenburg Layered Suite
SACCCS	South Africa Centre for Carbon Capture and Storage
SABS	South African Bureau of Standards
SANAS	South African National Accreditation System
SANS	South African National Standard
SAR	Sodium Adsorption Ratio
SDC	Source Directed Control
SOEKOR	Southern Oil Exploration Corporation (Suidelike Olie-Eksploraise Korporasie)
TDS	Total Dissolved Solids
TMG	Table Mountain Group

TMGA	Table Mountain Group Aquifer
TNF	Tritium Zero Limit (Tritium Null Flache)
UAA	Uitenhage Artesian Aquifer
UKOOG	United Kingdom Onshore Operators Group
UCG	Underground Coal Gasification
USEPA	United States Environmental Protection Agency
UT	Ultrasonic Testing
VLF	Very Low Frequency
WISH	Windows Interpretation System for Hydrogeologists
WRC	Water Research Commission
WRI	World Resources Institute

CHAPTER 1: INTRODUCTION AND OBJECTIVES

Water is an essential component of life in all spheres and a basic right for all people. Groundwater forms an important freshwater component of this resource. In recent times, the importance of groundwater has increased in South Africa, as well as the world, due to the pressure on surface water resources in response to increasing water supply demands. As research progresses on the shallow groundwater resources that are conventionally used for water supply, deeper groundwater resources have become a focus point as a future water source. This focus on deep groundwater aquifers is driven by new developments such as shale gas development, the injection of brines into deep aquifers, carbon sequestration and geothermal energy that all require deep groundwater information. However, there is limited data available to characterise the deep groundwater systems. Consequently, the understanding of the geohydrology of these deep groundwater resources is limited due to the high cost and technical challenges associated with investigations at these depths. If deep groundwater aquifers are to be protected to ensure future water sources, these systems will need to be better understood and defined.

The first step towards the goal of characterising deep groundwater aquifers in South Africa to facilitate the protection of this resource is to study the current information on these systems that is available. It is important to note that investigations at depths within the earth's subsurface have been taking place for decades. Regrettably, these investigations were not focused on characterising the aquifer systems, but rather on studying the deep geological formations, oil exploration and gathering data for climate reconstructions. The consequence of this is that valuable geohydrological data was lost as this component of the system was often not considered. It follows that the reason behind the deficiency of deep groundwater data is usually not due to the absence of deep boreholes, but rather the absence of geohydrological data collected from those boreholes. For example, the large mining industry in South Africa has created numerous deep boreholes for geological investigations and reserve estimations, but geohydrological data such as hydraulic conductivities is either not measured, or the data is not made available. Another aspect of this unfortunate situation is that there has been little or no communication between the different disciplines, which has resulted in perceived divides when characterising the same natural system.

The main aim of this project will be to characterise deep groundwater systems and use these characterisations to assist in suggesting policies and procedure to ensure their protection for future generations. To achieve this aim, the project will attempt to bring an end to the unfortunate situation where geohydrological data is omitted from investigations into the earth's subsurface, by breaking down the perceived divides between disciplines through edification. By facilitating the collection of groundwater data from deep boreholes drilled for alternate objectives by different disciplines, the current state of deep groundwater data will be improved. A shift in thinking in this direction has already began, where a proposed drilling project by the ICDP in the Bushveld Igneous Complex, initially designed only for geological characterisation, has invited hydrogeologists to collaborate on the project to collect the relevant hydrogeological data.

Additionally, the data that is already available should be used to its optimal capacity to characterise deep groundwater systems in South Africa to ensure that this potential water resource is properly regulated and protected from activities that could potentially have a negative impact in the future. Thus, methods and techniques to both directly and indirectly define the deep groundwater flow systems will be determined to ensure the optimal use of the currently available data at these depths, while efforts to improve the level of data are piloted.

In light of changing circumstances, where climate change and ever-increasing water demands are threatening traditional water resources, increasing research efforts into the geohydrology of deep aquifers are warranted as these aquifers contain a possible future water resource.

The main objectives set for the project are as follows:

- Conduct a literature review on deep aquifer systems
- Consolidate the available deep groundwater data
- Assess the potential deep groundwater resources of South Africa
- Characterise deep aquifers
- Investigate technologies, procedures and legislation to protect deep aquifer systems

Six reports on the various components of the investigations formed the deliverables for the current WRC project. These reports have been combined into a single report (this document), forming the seventh deliverable.

The deliverables of the project were as follows:

1. A report on a literature review of national and international case studies describing the characteristics and use of deep aquifer systems
2. A report on the potential deep groundwater resources of South Africa
3. A report on the potential sources of data on South Africa's deep aquifer systems
4. A report describing the characteristics of deep groundwater systems
5. A report describing technologies and legislation available for the protection of deep aquifer systems
6. A report on a database in which all the available data on deep groundwater systems has been captured
7. A final report combining the findings of all the preceding deliverables

CHAPTER 2: LITERATURE REVIEW

In this chapter, a review of literature is given to investigate deep groundwater fundamentals and define the depth below which groundwater may be considered "deep". Deep groundwater in the current South African context is explored, followed by both international and national case studies. The protection of potential deep groundwater is considered, before a final summary of the literature is given.

2.1 DEEP GROUNDWATER FUNDAMENTALS

As a starting point, the fundamental concepts of groundwater and groundwater at depth are revised, including regional groundwater flow patterns, generic deep groundwater quality and circulation depths, secondary porosity and permeability, and an introductory view of currently available groundwater data is given.

2.1.1 General groundwater flow patterns

2.1.1.1 Aquifers and confining layers

Fitts (2002) reiterated that the terms "aquifer" and "confining layer" are relative descriptors of water-bearing zones or layers in the subsurface. An aquifer can be considered to be geological layers with higher hydraulic conductivity in a specific flow system, while confining layers can be considered to be geological layers with lower hydraulic conductivity in that system. Confining layers retard flow and typically transmit relatively little water when compared to the layers above and below (Fitts, 2002).

Aquifers (relative water-bearing zones) are further classified into unconfined and confined aquifers (Figure 2-1). Unconfined aquifers are defined as aquifers where the water table occurs within the aquifer layer. Confined aquifers are defined as aquifers where the whole thickness of the aquifer layer is saturated, and a confining layer is found above the aquifer. The groundwater within a confined aquifer is under pressure, and the potentiometric surface demarcates the level to which groundwater will rise in a confined aquifer. The water level in a borehole in a confined aquifer can rise above the level of the ground surface and can flow freely without pumping in certain circumstances. The aquifer in such a case is then called a free-flowing artesian aquifer and the borehole is called an artesian borehole (Fitts, 2002).

2.1.1.2 Recharge and discharge

Characteristically, groundwater is on the move, originating as recharge in upland areas and discharging to the surface in low-lying areas (Fitts, 2002). The pathlines along which an individual water molecule will travel are often irregular due to the heterogeneous distribution of hydraulic conductivities in the subsurface. However, the average flow direction in a high conductivity layer will be parallel to the layer boundaries (Figure 2-2). Conversely, in a low conductivity layer, the general groundwater flow direction will be perpendicular to the layer boundaries, so as to follow the shortest path across this layer (Fitts, 2002).

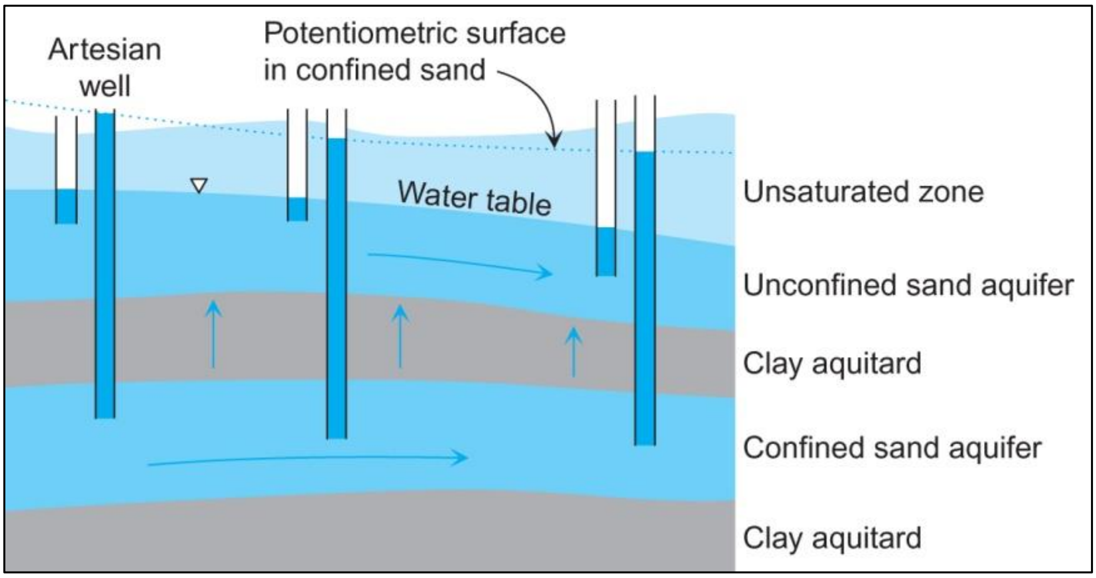


Figure 2-1: Vertical cross-section through an unconfined aquifer and a confined aquifer, with a confining layer separating the two (Fitts, 2002)

From Figure 2-2, it can be seen that there are many small, localised flow patterns at shallow depths. Below a certain depth, groundwater tends to flow in larger regional patterns that reflect the larger geology and topography, instead of the local conditions (Fitts, 2002). Residence times for groundwater can range from days to hundreds of thousands of years, with longer residence times found in large groundwater basins and deeper parts of the flow system. In the deeper aquifers, there are longer flow paths between recharge and discharge areas, and slower groundwater velocities (Figure 2-2). Figure 2-2 also shows how groundwater tends to move faster in aquifers than in confining layers, as represented by the residence times.

Fitts (2002) described investigations into the effect of the water table configuration and heterogeneity on regional groundwater flow patterns by using mathematical models to simulate different scenarios. The results of these investigations confirmed that localised flow systems occur at shallow depths and that heterogeneity can have a dominating influence on flow patterns (Fitts, 2002). The results of two of the mathematical models are shown in Figure 2-3.

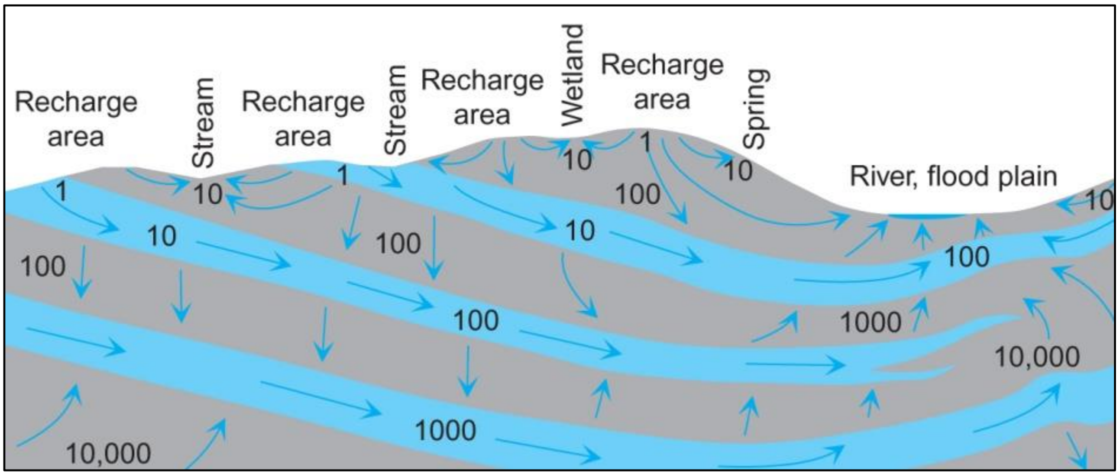


Figure 2-2: Vertical cross-section showing groundwater recharge and discharge areas in a hypothetical setting. Arrows show the direction of flow, and numbers indicate the residence time of groundwater in years. Lighter shading indicates aquifers and darker shading indicates aquitards (Fitts, 2002).

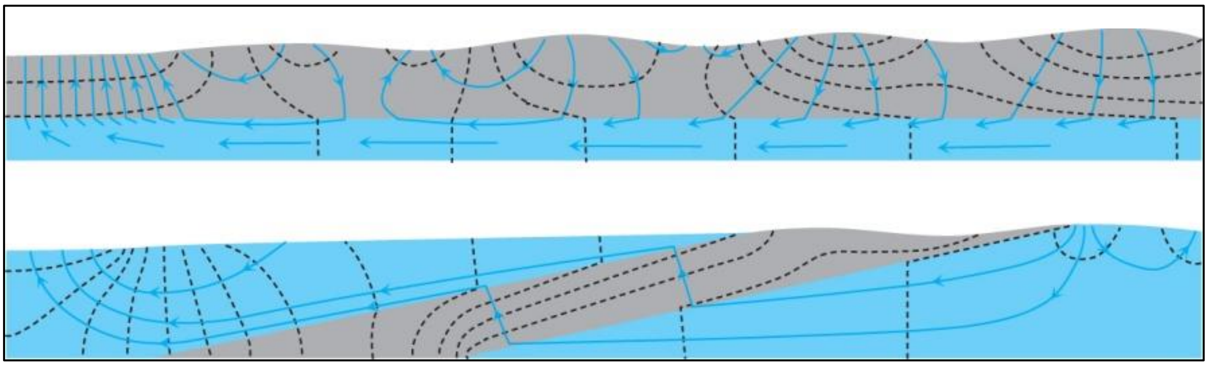


Figure 2-3: Mathematical models of steady-state flow in the vertical plane. The subsurface is heterogeneous with the light-shaded areas being 100 times more permeable than the dark-shaded areas (Fitts, 2002).

2.1.1.3 Crustal-scale pore fluid flow

Although most studies on groundwater systems focus on shallow depths within the first hundred metres of the surface, fluid flows deeper in the crust (Fitts, 2002). Deeper groundwater is relevant to oil and gas exploration, mineral exploration and crustal-scale geological processes. However, the porosity and permeability of geological layers tend to decease with increasing depth, while fluid’s temperature and the concentration of dissolved minerals increase with depth (Fitts, 2002). At depths below 10 km, the crust has an intrinsic permeability of less than 10^{-20} m^2 due to high confining pressures and the ductile deformation of rock. Rock permeabilities are significantly higher at depths above 6 km, where pore fluids can traverse flow paths on continental scales (Fitts, 2002). These flows are mainly driven by four mechanisms: the regional water table topography, compaction under sediment load, tectonic compaction and thermal convention (Figure 2-4).

2.1.1.3.1 Regional water table topography

Groundwater flow at shallow depths is predominantly driven by local variations in the elevation of the water table surface. This flow mechanism is called topography-driven flow because the water table usually mimics the surface elevation in shallow, unconfined aquifers (Fitts, 2002). This mechanism can also cause large-scale flow patterns, where there are continental-scale topography trends (Figure 2-4). For example, sandstone aquifers in Australia convey groundwater great distances from the Great Dividing Range across the Great Artesian Basin (Fitts, 2002).

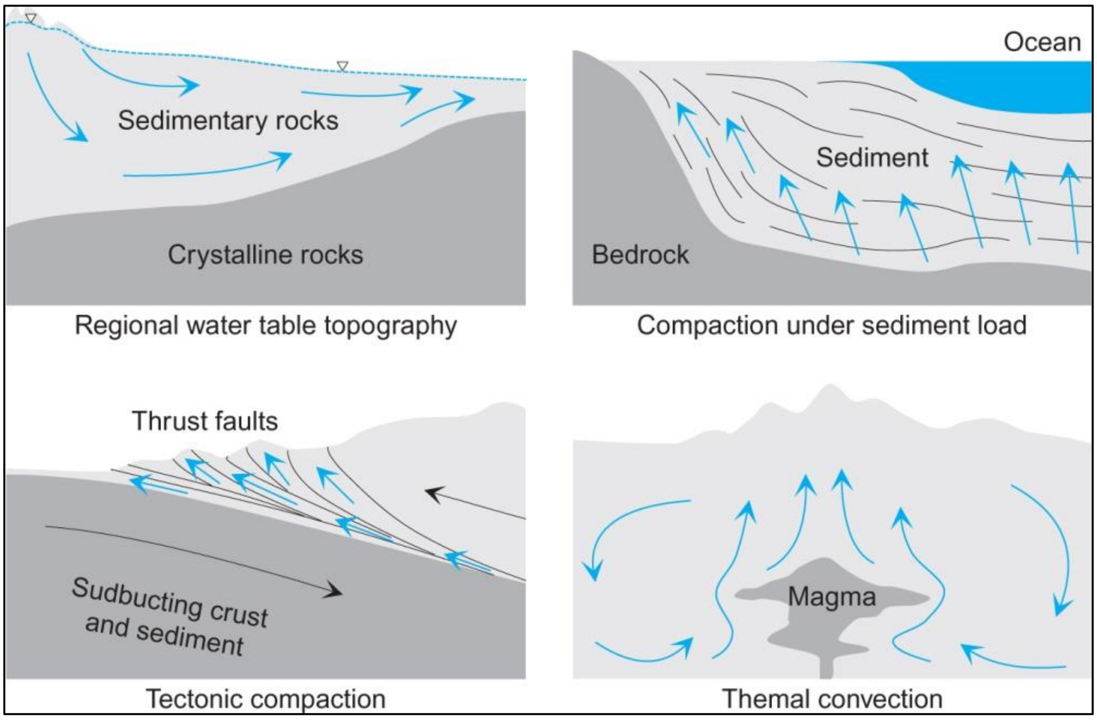


Figure 2-4: Causes of large-scale pore fluid flow patterns in the upper crust (Fitts, 2002)

2.1.1.3.2 Compaction under sediment load

Compaction of sediments can also drive groundwater flow in active and subsiding sedimentary basins (Fitts, 2002). Pressure exerted on deep sediment layers increases as more sediment accumulates at the surface, and this pressure load can drive fluid flow out of the deeper sediment layers as compaction takes place (Figure 2-4). Compaction-driven flow tends to be more important in basins with fast sedimentation rates (Fitts, 2002).

2.1.1.3.3 Tectonic compaction

Compaction can also be driven by tectonic forces. For example, at convergent plate boundaries, sedimentary basins can be subject to tectonic deformation (Figure 2-4). Fluid will respond in the same manner as described for compaction under a sediment load, because fluid is driven away from the zone of compaction regardless of the cause, i.e. sediment load or tectonic forces (Fitts, 2002).

2.1.1.3.4 Thermal convention

Fluid flow is induced by magma rising into the shallow crust for two main reasons. Firstly, convection flow is caused by the lower density of heated pore fluids in the immediate vicinity of the magma compared to cooler adjacent pore fluid (Figure 2-4). Secondly, the magma itself can be a source of fluids. Accelerated chemical reactions near the magma can generate fluids, change fluid pressures and induce flow (Fitts, 2002).

2.1.2 Deep groundwater quality and circulation depths

Deep groundwaters contain high dissolved solids for several reasons (Fitts, 2002). Deep groundwater typically has longer residence times, which allow mineral dissolution reactions to approach equilibrium, which is not usually reached in shallow groundwater systems due to the shorter residence times. Additionally, temperature and pressure increase with depth, which causes the solubility of many common minerals to also increase with depth. The flow paths of deep groundwater are long, thus increasing the probability of intersecting highly soluble minerals (Fitts, 2002).

Evidence of the high concentration of dissolved minerals in deep groundwater can be seen in the formation of veins and ore deposits (Fitts, 2002). These features are formed by mineral-rich deep groundwater being driven upwards due to the driving mechanisms discussed. As these fluids rise, they encounter lower pressures and temperatures, which cause some of the dissolved minerals to precipitate (Fitts, 2002).

Laaksoharju et al. (1995) investigated the Laxemar deep borehole in Stockholm, Sweden, and analysed the groundwater chemistry. After the investigation, the authors formed the hypothesis that the upper 800 m of the bedrock at Laxemar lies within a groundwater recharge area. This hypothesis was based on the groundwater quality in which the upper 800 m was found to be low-saline, brackish water, but below 1,000 m, highly saline groundwater was observed. Based on this hypothesis, the quality of deep groundwater and the related degree of use as a potential water supply source was directly related to circulation depths.

2.1.3 Secondary porosity and permeability and circulation depths

The rocks in most of South Africa's sedimentary basins are metamorphosed and have little or no primary porosity, only secondary porosity where they have been faulted and fractured (Viljoen et al., 2010). As discussed, the porosity and permeability of geological layers tend to decease with increasing depth. This is the conventional geological/structural theory that joint or fracture openings will close up with increasing depth due to the pressure of the overlying rock mass (Rosewarne, 2002a).

However, there are special cases where this conventional theory does not apply. Circulation depths of up to 2,000 m have been found in the Table Mountain Group aquifers (Rosewarne, 2002a). The Table Mountain Group aquifers form a special case due to a number of factors. The main lithology consists of fairly uniform, brittle quarzitic sandstone, which fractures readily under pressure. The continental-scale orogeny that formed the Cape Fold Belt provided sufficient levels of stress to produce widespread and deep fracturing. Additionally, the groundwater quality is usually acidic and low in dissolved solids, which lessen the likelihood of the deposition of minerals that could block fractures. The sandstones are predominantly composed of silica, which lessens the likelihood of weathering products that could also block fractures (Rosewarne, 2002a).

Lin et al. (2007) analysed a deep borehole in the Graafwater area in the Western Cape to determine fracture network characteristics of the Table Mountain Group. The analysed borehole was 800 m deep, and was characterised into four zones based on the degree to which fractures were hydraulically active. These zones were the following: high (0-150 m below ground level), medium (150-400 m below ground level), low (400-570 m below ground level) and hydraulically inactive (570-800 m below ground level or deeper). Lin et al. (2007) stated that the top of the hydraulically inactive fracture zone clearly indicated that groundwater flow could not take place below a depth of approximately 570 m. However, this analysis was based on a single borehole and Lin et al. (2007) added that the depth model of groundwater circulation developed was not necessarily applicable to all areas of the Table Mountain Groupaquifers.

2.1.4 Deep groundwater data

Alley et al. (2013) discussed deep groundwater in terms of deep sedimentary basins, where aquifers can occur at depths greater than 10,000 ft (approximately 3,000 m). Hydraulic data for deep flow systems is expensive and requires different field-testing strategies and methods than the traditional techniques used to characterise shallow groundwater for water supply (Alley et al., 2013). The high cost of drilling to depth should encourage the exploitation of alternative means of data collection, such as deep mineral exploration, geothermal exploration, deep oil and gas exploration. The different methods to be implemented for deep groundwater systems will require hydrogeologists to acquire new skill sets.

The characterisation of deep groundwater flow requires the use of pressure data instead of the traditional water level data, intrinsic permeability instead of the conventional hydraulic conductivity, and single-well drill-stem tests instead of multiple well aquifer tests (Alley et al., 2013).

In essence, hydrogeologists will need to acquire some of the concepts and skills that petroleum engineers use to characterise deep oil reserves to characterise deep groundwater flow. For example, Horner plots (similar to the Cooper-Jacob semi-log versus drawdown plot) are used to compute initial formation pressures and intrinsic permeabilities (Alley et al., 2013).

Tsang and Niemi (2013) also listed the typical data to be obtained in a deep borehole in a discussion of the issues and research needs for deep geohydrology. In addition to geophysical logs and core samples, data to be collected includes pore pressure, temperature, fluid chemistry, rock mechanical stress, local permeability, storativity, thermal conductivity and porosity. Tsang and Niemi (2013) also suggested the use of tracer testing methods, including single-well injection-withdrawal tests. These measurements involve different techniques and approaches, which require a carefully planned testing strategy to ensure the optimal sequence of testing so as not to interfere with each other or influence the drilling procedure (Tsang and Niemi, 2013).

2.2 HOW DEEP IS DEEP?

The definition of deep groundwater is typically subjective and ambiguous, with the dividing depth between shallow and deep being a moving target. There is no commonly agreed upon or standardised depth distinction between shallow and deep groundwater (Alley et al., 2013).

2.2.1 Definition catalogue for deep groundwater

Various depths have been suggested for the divide between shallow and deep groundwater, ranging from 100 to 1,000 m. Some of these depth divides are discussed along with the relevant studies on which they are based.

Lippmann-Pipke et al. (2011), Tsang and Niemi (2013), Pimentel and Hamza (2014) and Laaksoharju et al. (1995) considered deep groundwater to be at depths greater than 1,000 m. Tsang and Niemi (2013) stated this choice arbitrarily in a paper that discussed the issues and research needs of deep geohydrology. Their divide of shallow and deep was based on the reasoning that, at this depth, with the associated high stress, the effect of residual permeability becomes evident. Pimentel and Hamza (2014) indirectly gave this distinction while discussing the use of geothermal methods to outline deep groundwater flow systems in the Paleozoic basins of Brazil. Lippmann-Pipke et al. (2011) considered “shallower fluids” or groundwater in the gold mines of the Witwatersrand Basin to a depth of 1 km, while analysing deep fracture water in search of microbial communities. Laaksoharju et al. (1995) made this depth distinction while analysing the groundwater chemistry of the Laxemar deep borehole in Stockholm, Sweden.

Another divide between shallow and deep groundwater has been set at 300 m, as seen in work by Van Wyk (2013), González-Ramón et al. (2013), Mejías et al. (2008) and Umvoto (2005). Mejías et al. (2008) made a distinction between shallow and deep groundwater in their methodology of the geohydrological characterisation of deep carbonate aquifers as potential reservoirs of groundwater and applied to an aquifer in Spain. Mejías et al. (2008) explained that the definition of a deep aquifer included different types of aquifers: unconfined aquifers with water tables deeper than 300 m, confined aquifers whose top lies below 300 m, and those aquifers that, due to their hydraulic properties, require deep boreholes and the application of specific techniques for study. Van Wyk (2013) and Umvoto (2005) characterised deep groundwater as below 300 m from a South African perspective.

Reddy and Nagabhushanam (2012), Zektser and Everett (2004), Pietersen and Parsons (2002), Seiler and Lindner (1995) and Castany (1981) established a boundary between shallow and deep groundwater at a depth of 100 m. Reddy and Nagabhushanam (2012) considered boreholes with depths from 100 to 250 m, while investigating chemical and isotopic seismic precursory signatures in deep groundwater. Zektser and Everett (2004) evaluated the groundwater resources from a global perspective. The commonly reported average depths of boreholes was 100 m.

Pietersen and Parsons (2002) included a prologue where the mission was to move groundwater exploration an order of magnitude deeper, from 100 to 1,000 m. Castany (1981) considered the vertical zoning of groundwater and described three zones based on flow systems: local, regional and global. Castany (1981) defined the upper zone as the zone of the subsurface aquifers where local flow systems reach depths of 50 to 100 m, followed by the zone of intermediate aquifers where regional flow systems in confined aquifers reach depths of 200 to 300 m. Lastly, the zone of deep aquifers was defined to occur below 300 m with large-scale flow systems, where vertical mixing predominates. Castany (1981) stated that the depth of development of groundwater for human consumption is limited by the increase in mineralisation. Two case studies were considered and the limiting depths for groundwater production was given: 1,000 m in the Paris Basina and 2,000 m in the northern Sahara Basin (Castany, 1981).

Drake et al. (2015), Murray et al. (2015), González-Ramón et al. (2013) and Bouri et al. (2008) referred to a divide of shallow and deep groundwater at 400 to 500 m below ground level. Drake et al. (2015) investigated boreholes that were deeper than 400 m to investigate sulphur-isotope fractionation in groundwater in fractured crystalline rock. Murray et al. (2015) referred to shallow groundwater above 500 m in the Karoo groundwater systems, while discussing preferential flow paths that potentially link deep and shallow systems. González-Ramón et al. (2013) investigated intensively exploited aquifers in southern Spain, where the lower aquifer is between 300 and 700 m. Bouri et al. (2008) made a distinction between shallow and deep groundwater at 500 m, with shallow groundwater considered to occur at depths from 50 to 500 m, and deep groundwater to occur at depths from 500 to 3,500 m.

2.2.2 Related-disciplines' perspectives on deep groundwater

2.2.2.1 Geothermal energy

Geothermal energy is the heat energy contained within the earth, but geothermal energy is most commonly used to define that part of the earth's heat that can potentially be recovered and exploited (Dickson and Fanelli, 2003). Water is required as the medium to transport this heat from deep hot zones to or near the surface, and currently forms a limiting factor on the conditions at which geothermal energy can be harvested. Geothermal energy is divided into shallow and deep geothermal systems.

The International Geothermal Center (IGC) makes a clear distinction between shallow and deep geothermal energy (IGC, 2015). The depth threshold for shallow geothermal energy is taken as 400 m, and geothermal systems below this depth are considered deep. Stober et al. (2014) define shallow geothermal energy as the geothermal heat extracted from shallow depths, normally down to a depth of 150 m and at a maximum depth of 400 m. Deep geothermal energy differs from shallow geothermal systems in that deep boreholes are required to extract geothermal energy and the energy can usually be used without additional heat pumps (Stober et al., 2014). Stober et al. (2014) define deep geothermal energy as geothermal energy extracted from depths of more than 400 m and temperatures exceeding 20 °C. Furthermore, Stober et al. (2014) state that it was becoming common practice to reserve the term "deep geothermal" for energy extracted from depths greater than 1,000 m with temperatures higher than 60 °C.

2.2.2.2 Petroleum industry

The production of oil and gas requires high temperature and pressure, which occur at depths. Oil and gas produced at great depths can move to the surface through porous media or get trapped by impermeable geological layers.

However, oil and gas reservoirs are usually found deep in the earth's subsurface. According to Vermeulen (2012), oil is generated at temperatures and pressures found at depths between 1.5 and 5 km, while gas is generated between depths of 3 and 6 km. In a summary of the deep wells and reservoirs in the USA, "deep" oil production wells were defined as wells drilled to 15,000 ft. (4,572 m) or more (Dyman and Cook, 2001). Figure 2-5 is a representation of the depths of some boreholes drilled in search of oil.

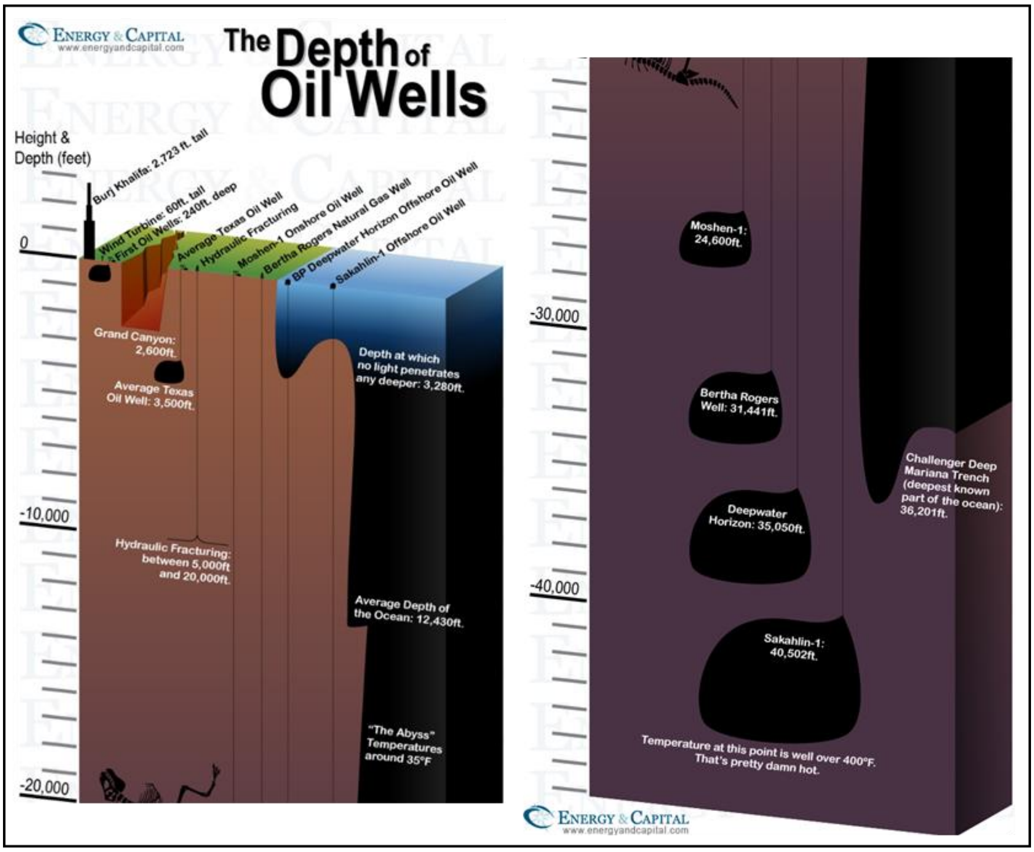


Figure 2-5: A relative representation of the depth of oil wells in feet (Energy and Capital, 2015)

Recent developments in technology have directed petroleum production to offshore resources, i.e. deepwater oil and gas. There is no agreed upon industry definition of what constitutes deepwater for oil and gas production, according to the CEO of Oil and Gas UK (Dragani and Kotenev, 2013). A general definition of deepwater drilling depth is 400 m and greater, while ultra-deepwater is defined at depths greater than 1,500 m (Dragani and Kotenev, 2013).

Vermeulen (2012) gave the depths of the target geological formations for hydraulic fracturing in South Africa between 3,000 and 5,000 m. Unconventional gas can be defined as gas resources that were not always accessible, but that, with recent advancements in technology and understanding, can now be exploited. By this definition, all unconventional gas could be classed as "deep".

2.2.2.3 Carbon storage

Viljoen et al. (2010) describe the geological storage of CO_2 as the injection of anthropogenic (or man-made) CO_2 into underground formations, so that it becomes trapped in the pore spaces of the sedimentary rock. It has been determined that a burial depth of at least 800 m is needed to achieve a high enough temperature and pressure for CO_2 to occur in the supercritical phase (IPCC, 2005; Viljoen et al., 2010). Thus, when considering deep saline aquifers for carbon storage, the divide between deep and shallow is 800 m.

2.2.3 Revision of the term "deep" with technological advancements

The depth at which groundwater is considered deep will inevitably increase as technology improves and allows for more accessible methods for deep drilling. A similar trend is seen in deepwater drilling, where Dragani and Kotenev (2013) reported that when deepwater drilling started 30 to 40 years ago in the North Sea, depths of 150 m would have been considered as deepwater. Now deepwater is defined as depths greater than 400 m, with the drilling of ultra-deepwater becoming common at depths greater than 1,500 m. A similar trend is seen in groundwater development, with geothermal resources, geosequestration, and hydrocarbon migration and production driving the development of these technologies (Commander, 2010).

There are also technology advances in fields other than drilling that will advance deep groundwater development in the future. Hartnady et al. (2008) discussed emerging science and technology for deep groundwater resource assessment, with an emphasis on the application of modern earth observation and space-geodetic methods. These new technologies will serve to improve the exploration, development and management of groundwater within deep artesian basins (Hartnady et al., 2008).

2.2.4 Definitions of deep groundwater without depth

Commander (2010) restated that the term deep groundwater is relative, with some referring to deep groundwater as groundwater below alluvial systems, or groundwater below the depth to which groundwater is currently allocated and licenced. Commander (2010) offered an alternative definition of deep groundwater as groundwater that is unknown or unexplored. An example of where deep groundwater equates to unknown groundwater is in the arid-zone Canning and Officer basins in Australia, which are largely unexplored for groundwater. Groundwater conditions in these areas are largely inferred from petroleum exploration well data, particularly stratigraphic and electric logs. Conversely, in the Perth and Great Artesian basins, groundwater from depths of over 1,000 m is exploited and is certainly not unknown, yet is considered deep groundwater (Commander, 2010). Commander (2010) concluded that the knowledge of deep groundwater is uneven over specific areas. In these areas, the realisation of deep groundwater will diverge from the norm due to the lack of knowledge. Thus, in these areas, the depth of deep groundwater will be controlled by the data and understanding of these systems.

Alternatively, groundwater quality can also be used to define the depth of deep groundwater. Laaksoharju et al. (1995) investigated the Laxemar deep borehole in Stockholm, Sweden, by means of chemical analysis. The investigation indicated that the groundwater compositions consisted of two distinct groupings: one a shallow to intermediate sodium-bicarbonate type to a depth of 1,000 m, and the other a calcium-chloride type of deep origin (Laaksoharju et al., 1995). Based on the results from this study, the divide between shallow and deep groundwater could be based on groundwater quality that reflected the divide between different flow systems.

Murray et al. (2015) recently investigated the use of chemistry, isotopes and gases as indicators of deeper circulating groundwater in the main Karoo basin. The use of chemical constituents was considered as an alternative indicator due to the lack of suitable boreholes for sampling the deep formations targeted for shale gas development in South Africa (Murray et al., 2015). Determinands, including temperature, were analysed, and their ability to differentiate between deep and shallow groundwater was assessed.

Table 2-1 provides a summary of the results.

Table 2-1: Success rate and prioritisation of different determinands for identifying deep groundwater. A 100% success rate means that all the determinands listed meet the criteria set (Murray et al., 2015).

Group	Success Rate	Determinands
Group 1	100% success rate	^{14}C, $\delta^{18}O$, fluoride, %sodium, magnesium, uranium, alkalinity
Group 2	>75% success rate	Boron, vanadium, lithium, $\delta^{11}B$, $^{36}Cl/Cl$, ^{222}Radon, H_2S
Group 3	50-75% success rate	Sodium, pH, tritium, nitrate, temperature, ^{4}He, $^{3}He/^{4}He$, CH_4
Group 4	< 50% success rate	$^{87}Sr/^{86}Sr$, $\delta^{13}C$, rare earth elements, other trace elements

Tritium concentrations have historically also been used to define deep groundwater based on residence times. Goldbrunner (1999) defined deep groundwater as groundwater that has a residence time of greater than 50 years, as indicated by the absence of anthropogenic tritium.

The depth at which tritium concentrations become unmeasurable is called the Tritium Zero Limit (TNF). At this depth, water ages exceed 50 years and quickly increase in age over short depth ranges to ages of several thousands of years (Seiler and Lindner, 1995). This TNF is met at an average groundwater depth of between 40 and 100 m in Germany where the groundwater resources are not overexploited (Seiler and Lindner, 1995).

Additionally, the classification of unconfined and confined aquifers can be used to help define deep groundwater. Netili (2007) quoted a groundwater specialist, stating that shallow and deep groundwater systems are commonly referred to as unconfined aquifers and confined aquifers, respectively. The unconfined aquifer is often considered to be the shallow aquifer as it forms the uppermost system in a multiple aquifer system, while confined aquifers are typically considered deep aquifers (Netili, 2007).

2.2.5 Definition of deep groundwater for South Africa

As stated previously, the definition of deep groundwater is typically subjective and ambiguous, with the dividing depth between shallow and deep a moving target. There is no commonly agreed upon or standardised depth distinction between shallow and deep groundwater (Alley et al., 2013). South Africa is no exception, but the definition that should be applied to South Africa should take into account the specific environments and conditions in the country. The discussion on the various means to define the divide between shallow and deep groundwater may include definitions based on depth to current groundwater exploitation, groundwater quality (chemical determinands), unconfined versus confined, unknown areas or depths, and the groundwater below alluvial aquifers. These components will be investigated for South Africa to aid in the generation of a representative definition of deep groundwater.

2.2.5.1 Depth to current groundwater exploitation

Vermeulen (2012) noted that geohydrological investigations performed on Karoo aquifers were traditionally restricted to the upper 100 m of the subsurface. Advances in drilling equipment have increased the average depth of drilling to 150 m, but boreholes deeper than 300 m are still uncommon in the Karoo.

Information on the depths of boreholes was extracted from the NGA in 2008 and analysed. The analyses indicated that only 4% of the 2,323 boreholes were drilled deeper than 100 m (Vermeulen, 2012). In the vicinity of Victoria West, Woodford and Chevallier (2002) analysed 67 boreholes. Their analyses found that the average depth of these boreholes was 206 m, but that 73% of all the water strikes occurred within the top 80 m of the subsurface. If a definition of deep groundwater is used that is based on the current depth of groundwater exploitation (Commander, 2010), then these values become important. An up-to-date account of the average depth of groundwater boreholes in South Africa would serve as a sound foundation to define deep groundwater in South Africa. The current project aims to further investigate the depth of boreholes in the country to assist in the definition of deep aquifer systems.

2.2.5.2 Groundwater quality (chemical determinands)

Murray et al. (2015) recently investigated the use of chemistry, isotopes and gases as indicators of deeper circulating groundwater in the main Karoo basin. The use of chemical constituents was considered as an alternative indicator due to the lack of suitable boreholes for sampling the deep formations targeted for shale gas development in South Africa (Murray et al., 2015). According to Diamond and Harris (2000), there are over 87 thermal springs in South Africa, ranging in temperature from 25 to 64 °C. Groundwater quality from these thermal springs should be considered in defining the depth of deep groundwater in South Africa, especially due to the present scarcity of suitable deep boreholes for groundwater testing.

2.2.5.3 Unconfined vs confined

As stated previously, the classification of unconfined and confined aquifers can be used to support the definition of deep groundwater. Van Wyk (2013) discussed southern African pre-cretaceous deep groundwater flow regimes from a geological perspective of deep artesian (confined) systems, and evaluated a number of potential deep flow systems in terms of their geohydrological characteristics obtained from deep drilling results. A list of potential deep flow systems was identified: the Table Mountain Group sandstones, the Karoo Supergroup in southern Africa and the hot springs in southern Africa’s Karoo environments (Van Wyk, 2013). These confined systems will be investigated in the current project to assist in the definition of deep groundwater in South Africa.

Van Wyk (2013) and others have highlighted the importance of understanding the underlying geology for identifying deep groundwater systems. Consequently, an emphasis on understanding the deep basin geology for South Africa will be incorporated into this study. Scheiber-Enslin et al. (2015) developed a new depth map of the Main Karoo Basin using geophysics. This map, along with supplementary geological mapping for other areas, will be used to better define the deep geology of South Africa to allow insight into the deep aquifer systems. According to Viljoen et al. (2010), South Africa has a number of sedimentary basins covering most of the land surface. These basins range in age from the Archaean to the present. Viljoen et al. (2010) investigated them to determine their carbon storage potential. The delineation of these basins will be used in the current project to assist in the evaluation of the potential of deep aquifers.

2.2.5.4 Unknown groundwater areas or depths

Commander (2010) offered an alternative definition of deep groundwater, where deep groundwater is groundwater that is unknown or unexplored. This perspective on deep groundwater has not been applied to South Africa before, but will be considered in this project. Where there is no current groundwater information below a certain depth for a specific area, the definition of deep groundwater will be restricted to the depth below the current understanding of deep groundwater.

2.2.5.5 Deep groundwater as groundwater below alluvial or weathered aquifers

Some consider depth to alluvial or weathered aquifers to be the divide between shallow and deep groundwater, especially in Australia (Commander, 2010). However, South Africa is mainly underlain by hard rock (Shahin, 2003) and the main Karoo Basin aquifers are secondary in nature. Their storage and transmissivity values are mainly related to fracturing, faulting and the intrusion of dolerite bodies (Vermeulen, 2012). In light of this, the definition based on the thickness of alluvial aquifers will not be considered as an option for South Africa.

2.3 DEEP GROUNDWATER OF SOUTH AFRICA

2.3.1 Introductory geology and geohydrology

According to the 1:1000 000 geological map of the Republic of South Africa, published by the CGS, the country is predominantly covered by sedimentary rocks with abundant igneous intrusions and extrusions, and metamorphic rocks. Two major sedimentary basins have been identified: the Karoo and Cape sedimentary basins. These basins formed roughly 510 to 160 million years ago (McCarthy and Rubidge, 2005) and primarily form the stratigraphic sequences known as the Karoo Supergroup and the Cape Supergroup (Thamm and Johnson, 2006; Johnson et al., 2006).

The majority of groundwater in South Africa is stored within these sedimentary basins. The depth to actual groundwater varies across South Africa, depending on the area. The majority of the country encounters groundwater at an average depth of approximately 35 m below ground level, whereas the northwestern part of the country encounters groundwater at depths greater than 35 m below ground level (refer to Figure 2-6). For the most part, this evidence suggests a predominance of shallow aquifers in South Africa.

In the early 1990s, the Department of Water and Forestry (DWAF) published a series of geohydrological maps to a scale of 1:500 000. The maps depict classifications of aquifers according to expected yields, which have been designated groups a to d, as shown in Table 2-2.

Table 2-2 is the extracted legend of the 1:500 000 geohydrological map series and the classifications assigned to shallow aquifers in South Africa. On the assumption that deep aquifers exhibit similar properties as shallow aquifers, the yield of deeper aquifers can be predicted. However, the validity of these assumptions would need to be investigated in detail.

According to Table 2-2, aquifers are differentiated into the following four categories:

a) Intergranular acquifers
b) Fractured acquifers
c) Karst acquifers
d) Intergranular and fractured acquifers

Group a (intergranular aquifers) comprises unconsolidated sedimentary deposits, such as sediments along the coastal areas, i.e. the Richards Bay area. These aquifers generally have yields in the range of 0.5 to 2.0 ℓ/s. According to Nel et al. (2014), these aquifers have transmissivity values in the range of 4 to 70 m^2/day and storage coefficients in the range of 7 to 25%.

Group b (fractured aquifers) has secondary porosity features, i.e. faults, fractures and joints in hard bedrock. These form the primary pathways along which groundwater will move. According to Nel et al. (2014), these aquifers have transmissivity values in the range of 7 to 1,320 m^2/day and storage coefficients in the range of 0.0002 to 2%.

Group c (karst aquifers) refers to aquifers characterised by the presence of cavities (in dolomite areas). These aquifers are considered to be high-yielding aquifers. According to Nel et al. (2014), intrusive dykes form impermeable or low permeable barriers that restrict the flow of groundwater and create different compartments within these cavities. In addition, these aquifers have transmissivity values in the range of 800 to 8,000 m^2/day and storage coefficients in the range of 1 to 25%.

Group d (intergranular and fractured aquifers) displays properties of a multi-porous aquifer system. According to Nel et al. (2014), these are commonly found in granite, dolerite and sandstone areas. Geohydrologists often target the contact zones between the dolerite and the host rock as these areas are known to have a high degree of fracturing. According to Nel et al. (2014), these aquifers have transmissivity values in the range of 0.5 to 150 m^2/day and storage coefficients in the range of 0.003 to 7%.

2.3.2 Evidence of deep groundwater flow regimes

Van Wyk (2013) described the evidence of deep groundwater flow regimes in South Africa. The exploration for gold and diamonds in South Africa increased substantially in the 19th century, and large volumes of water were required for steam-powered locomotives. Hence, the Cape Government Railways initiated investigations for potential groundwater supply sources. Twenty-seven boreholes were drilled to depths in the range of 183 to 1 103 m below ground level. However, data is available for only four boreholes (refer to Table 2-3). Only minor water strikes were encountered at depths greater than 100 m (Van Wyk, 2013).

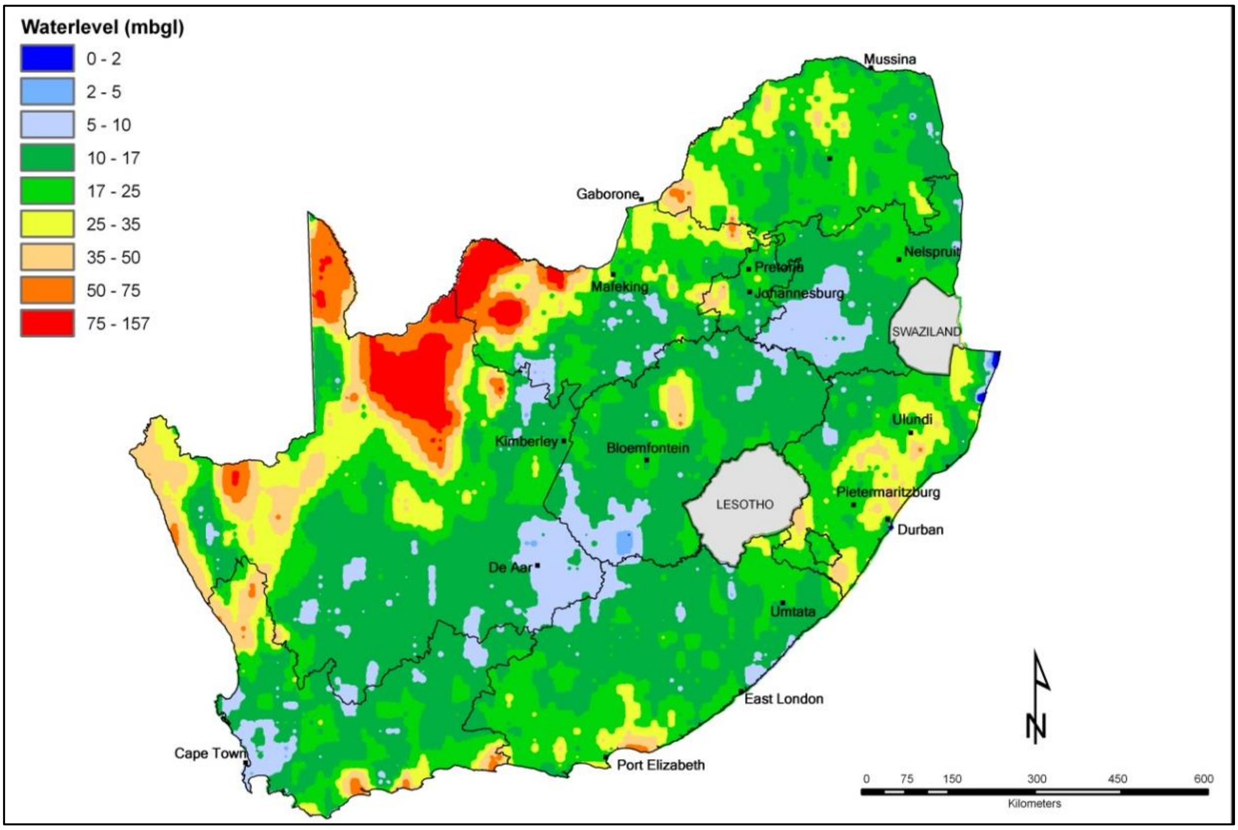


Figure 2-6: Indicative groundwater levels for shallow aquifers in South Africa (DWA, 2010c)

Table 2-2: Aquifer classification based on groundwater yields (DWA, 2001)

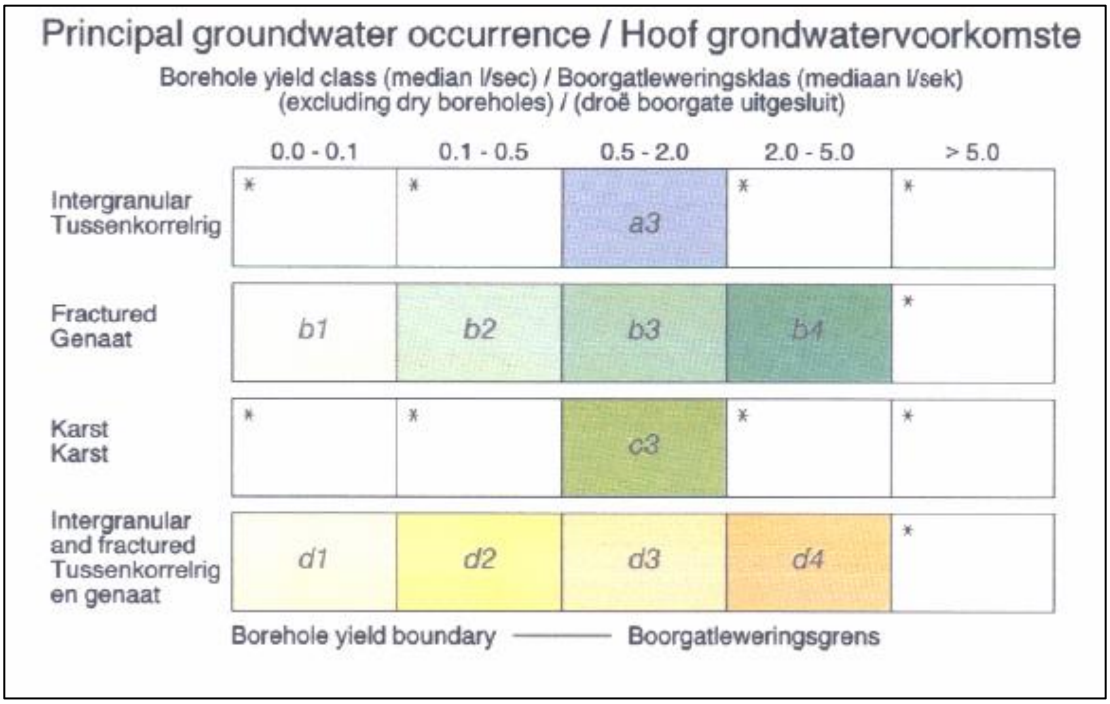


Table 2-3: Borehole names, depths to water strikes and groundwater yields of boreholes drilled by the Cape Government Railways (Van Wyk, 2013)

BOREHOLES (ID)	DEPTH TO WATERSTRIKE (mbgl)	YIELD (L/s)
Leeu-Gamka	366	4
Camdeboo	> 244	0 (no water)
De Aar	> 497	0 (no water)
Matjesfontein	458	1.2

Between 1893 and 1913, numerous projects were carried out to explore the potential for deep artesian wells (Van Wyk, 2013). A borehole drilled within the Swartkops River Valley to a depth of 1,085 m below ground level encountered various water strikes with a total yield of 13 ℓ/s and a temperature of 54 ºC.

According to Van Wyk (2013), hot springs in South Africa and Namibia mainly occur along faults and/or dykes, and geothermal heated water is brought to the surface. This provides evidence of deep groundwater flow circulation. Kent (1949) suggested that the thermal water within the Karoo is sourced at significant depths beneath ground surface. The water temperatures of hot springs in South Africa vary from 26 to 57.2 ºC (Kent, 1949). Considering that the hydrothermal gradient is approximately 3 ºC per 100 m, these temperatures suggest circulation depths of approximately 200 to 1,200 m.

In the 1960s, the Department of Mines funded exploration projects to depths greater than 300 m below ground level for groundwater sources within the Kalahari Basin (Smith, 1964). During drilling, these boreholes encountered saline groundwater to depths in the range of 137 to 426 m below ground level with final borehole depths in the range of 441 to 652 m below ground level. The geological formations encountered within these boreholes were the Dwyka Group, the Nama Group and the basement granites (Van Wyk, 2013).

During the 1960s, SOEKOR drilled numerous boreholes for hydrocarbon exploration. The drilling results showed that the Karoo Supergroup was between 2,035 and 5,288 m thick at the various drill sites (Van Wyk, 2013). Saline groundwater was encountered at depths greater than 1,500 m below ground level in some of these boreholes. Some of the deep boreholes were artesian, showing that the deep aquifer systems were pressurised.

Two prominent examples of deep confined aquifer systems in South Africa are the Table Mountain Group sandstones and the Karoo Supergroup. The Table Mountain Group was subject to ductile deformation approximately 230 million years ago, which resulted in the folding of the sedimentary layers. Two drilling projects at Blikhuis and Blossoms, where boreholes were drilled to depths of 860 and 650 m below ground level respectively, intersected pressure aquifers. Pressure heads of 8 and 76 m were recorded in the Blikhuis and Blossoms boreholes, respectively (Van Wyk, 2013).

The Karoo Supergroup extends across South Africa, Botswana and Namibia, with the northwestern part of South Africa forming the Aranos Basin (Figure 2-7). The Aranos Basin can be considered a typical artesian flow model (Van Wyk, 2013). The basin covers an area of approximately 500 km^2 and comprises mainly Dwyka Group and Ecca Group sediments with the Nossob Formation (sandstone) at the base. The Nossob Formation (with a thickness of ~20 m) represents the base and the stratigraphically lower pressurised formation of the two main artesian to semiartesian sandstone formations in the Aranos Basin. Figure 2-8 shows the depths of the different geological formations within the Aranos Basin as derived from borehole data (Van Wyk, 2013).

From the above examples, it appears that deep aquifers are most likely to occur in sedimentary basins, primarily within sandstone formations. Deep aquifer systems are likely to be associated with folded geological formations in which the water will occur in the host rock and fractures. Natural springs may provide insight into the quality and type of water facies within the deeper aquifer systems.

2.4 INTERNATIONAL CASE STUDIES FOR DEEP GROUNDWATER

Alley et al. (2013) considered the distinction between shallow and deep groundwater to be poorly defined. However, there is growing interest in understanding groundwater beneath the depths of traditional water supply (Alley et al., 2013). The concept of deep aquifer systems will be discussed on an international scale, with cases studies from Germany and India (Figure 2-9).

2.4.1 Deep carbonate aquifers, Germany

Two deep carbonate aquifers, occurring in the upper Jurassic and middle Triassic layers, are a key source of hydrothermal energy in Germany (Stober, 2014). The names given to these aquifers are the Malm Limestone (upper Jurassic) and the Muschelkalk Limestone (middle Triassic). According to Stober (2014), wells drilled into these aquifers are known to occur down to depths of at least 3.5 km. These aquifers are situated within the Molasse Basin that formed during the Cenozoic period. Stober (2014) states that the water quality within the Malm Limestone varies considerably. This is attributed to the dolomitisation, karstification and tectonic situation. The Muschelkalk aquifer is the deeper of the two aquifers and comprises a fractured and karst system. Figure 2-10 shows the occurrence of the Molasse Basin in Germany.

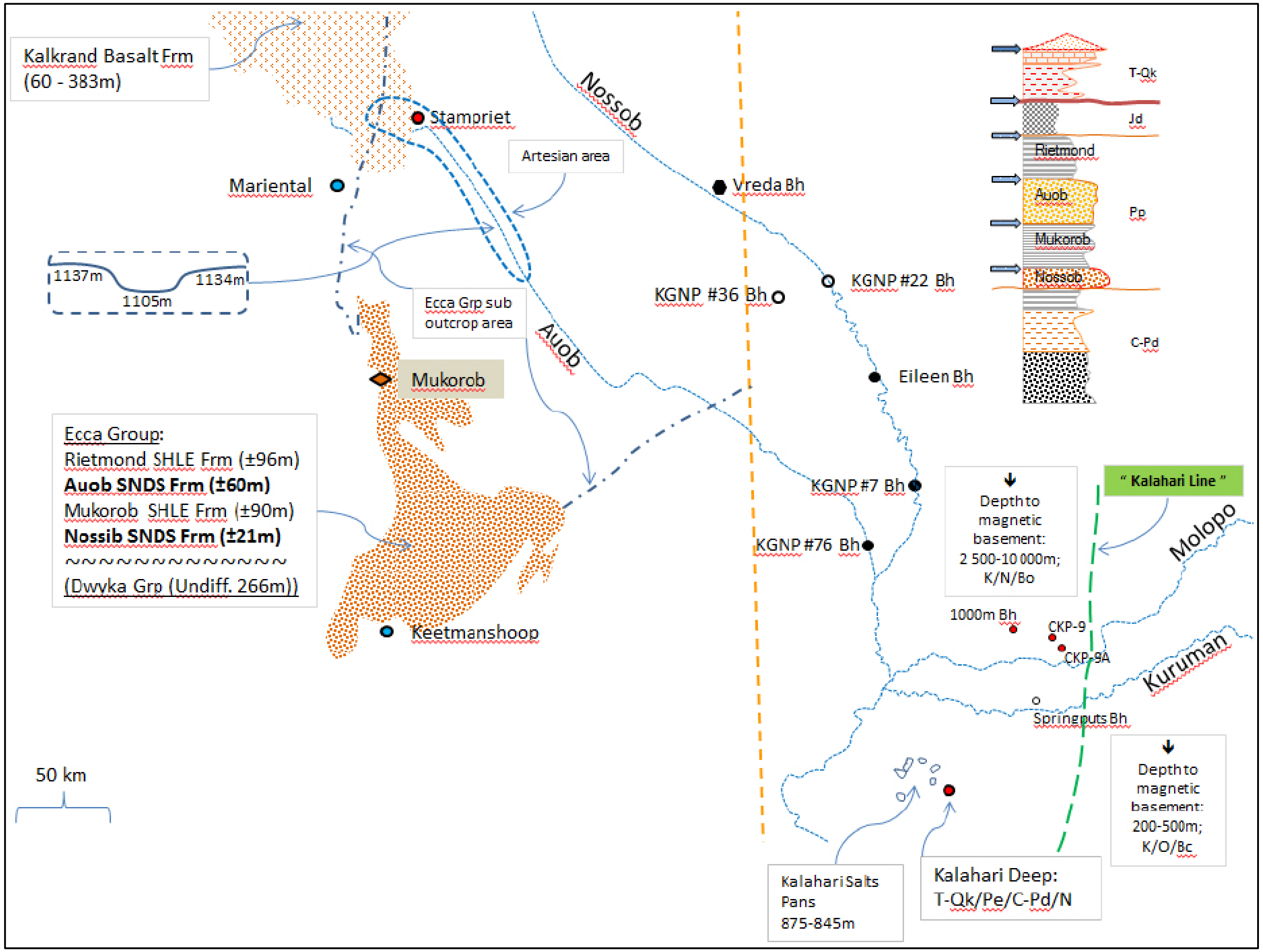


Figure 2-7: Diagram illustrating the extent of the Aranos Basin (Van Wyk, 2013)

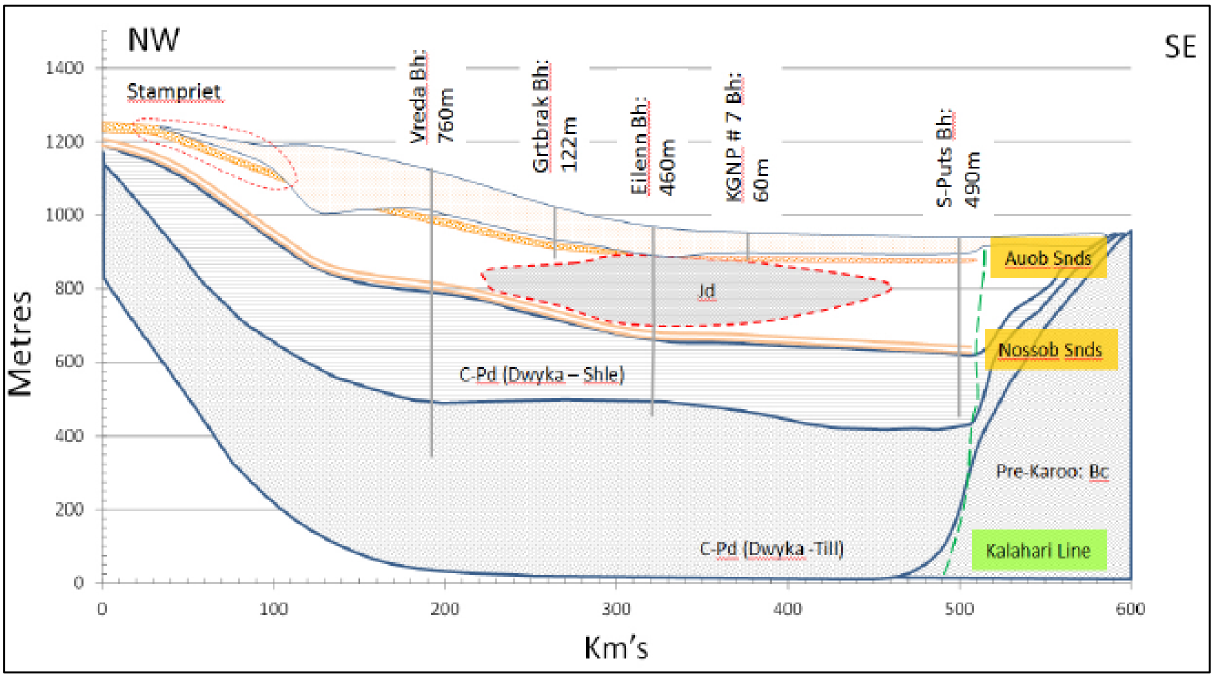


Figure 2-8: Longitudinal profile of the Aranos Basin showing the intersected lithologies (Van Wyk, 2013)

Figure 2-9: International case studies on deep groundwater: Molasse Basin, Germany, and Nizamabad, Andhra Pradesh, India

Figure 2-10: Location of the Molasse Basin (Stober, 2014). The green line indicates the trace of a cross-section through the basin.

Geochemical tests carried out on water samples from both aquifers indicated that the upper 1,200 m, i.e. the upper Jurassic aquifer, is associated with lower concentrations of total dissolved solids (TDS) at depths below 1,200 m than in the lower-middle Triassic aquifer. An increase in TDS usually results in more saline water, which is unhealthy for human consumption. Figure 2-11 is a typical cross-section through the Molasse Basin showing the depths of the aquifers. According to Stober (2014), the upper Jurassic aquifer contains Ca-HCO_3-rich waters, while the middle Triassic aquifer contains Ca-SO_4-HCO_3-rich water. This increase in TDS and sulphate in rocks of the middle Triassic aquifer supports the view that sulphate-rich rocks underlie the Jurassic aquifer (Stober, 2014).

The study carried out by Stober (2014) identified that an increase in temperature will result in an increase in the Ca/Mg ratio in water. Similarly, an increase in temperature and sodium chloride concentration will cause an increase in the Ca/C ratio and a decrease in the HCO_3 concentration.

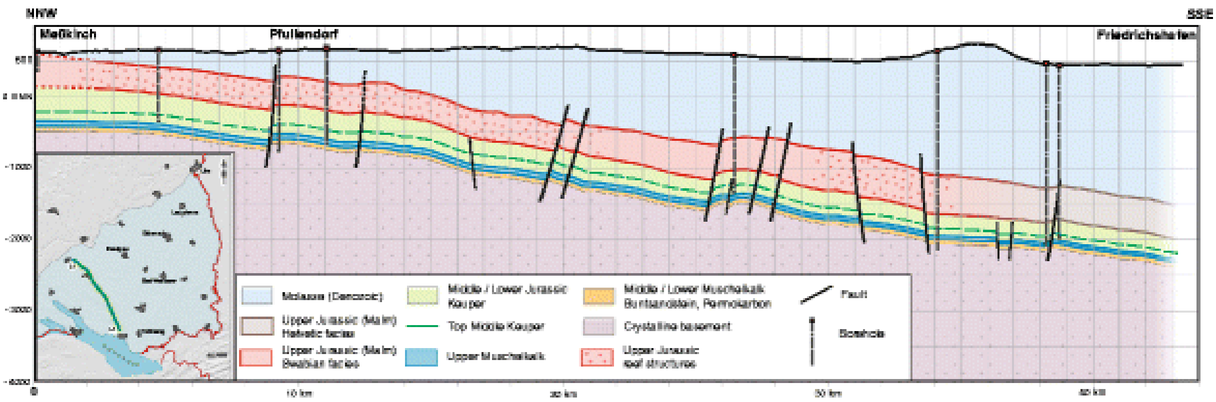


Figure 2-11: Geological cross-section through the Molasse Basin (Stober, 2014)

2.4.2 Potential aquifers in granitic rocks in Nizamabad, Andhra Pradesh, India

India has been suject to water scarcity problems and the over-exploitation of its groundwater aquifers has led to a drastic lowering of the groundwater level in the country (Chandra et al., 2012). At the current rate of abstraction, the groundwater reservoirs are expected to dry up by 2025. Large areas of India are underlain by granites. Chandra et al. (2012) indicate that these granites have the characteristics of good aquifers down to a depth of 60 m below ground level. However, due to the water scarcity problem, they investigated the possibility of exploiting the deeper aquifers within the granites.

The geology of the study area comprises the Peninsular Gneissic Complex with several dolerite dyke intrusions and quartz veins (Chandra et al., 2012). Generally, it is understood that crystalline rock mostly stores groundwater in fractures, but at low volumes. Contact zones between dykes and granite bedrock are provisionally good target zones for encountering groundwater. The geophysical method used during the exploration phase of the project was the electrical resistivity technique. Chandra et al. (2012) carried out four resistivity profiles to identify fractured zones in the subsurface.

A suitable drilling target was identified and an exploratory borehole drilled to a depth of 270 m below ground level. Chandra et al. (2012) did not provide a detailed description of the geological profile of the borehole. Three water strikes occurred at depths of 31, 110 and 180 m below ground level, with a total yield of 15 m^3/h. Resistivity profiling was carried out within the borehole and it was found that the fractures displayed low resistivity readings. Figure 2-12 shows the resistivity profile of the borehole.

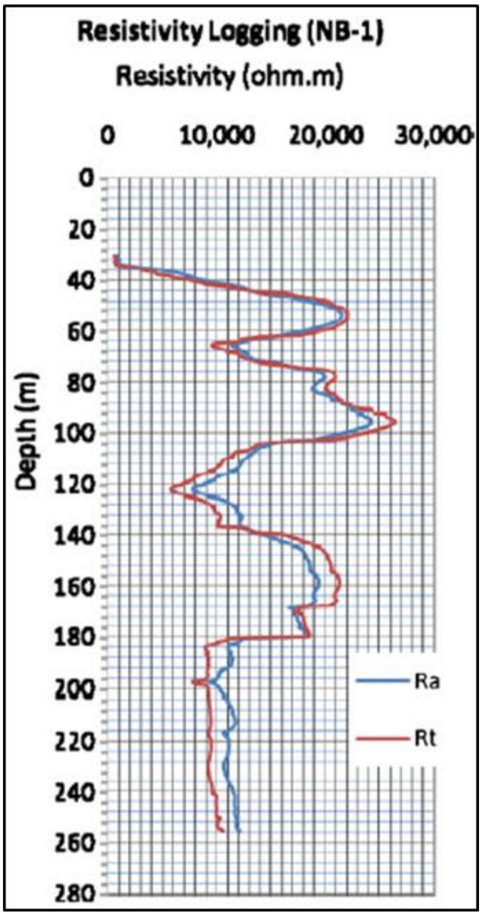


Figure 2-12: Resistivity profile of the borehole (Chandra et al. 2012)

Water samples collected from the boreholes provided a good indication of the water type and quality for both the shallow and the deep aquifers. Chandra et al. (2012) drew the following conclusions:

- The TDS concentrations were lower in the shallow aquifer.
- Sodium was more concentrated in the deeper aquifer.
- The calcium and magnesium concentrations in the two aquifers were similar.
- The chloride concentration was higher in the deeper aquifer.
- High nitrate concentrations were anticipated in the deeper aquifer.

Carbon 14 analyses indicated that the age of the water was in the order of 50 years, which was considered relatively young for groundwater (Chandra et al., 2012).

Based on the results of Chandra et al. (2012), it can be concluded that aquifers in crystalline rock environments have the potential to yield sufficient quantities of groundwater for adequate water supply. The yield will depend on the fracture density in the bedrock, with highly fractured zones forming good targets for grpundwater exploration (refer to Figure 2-13).

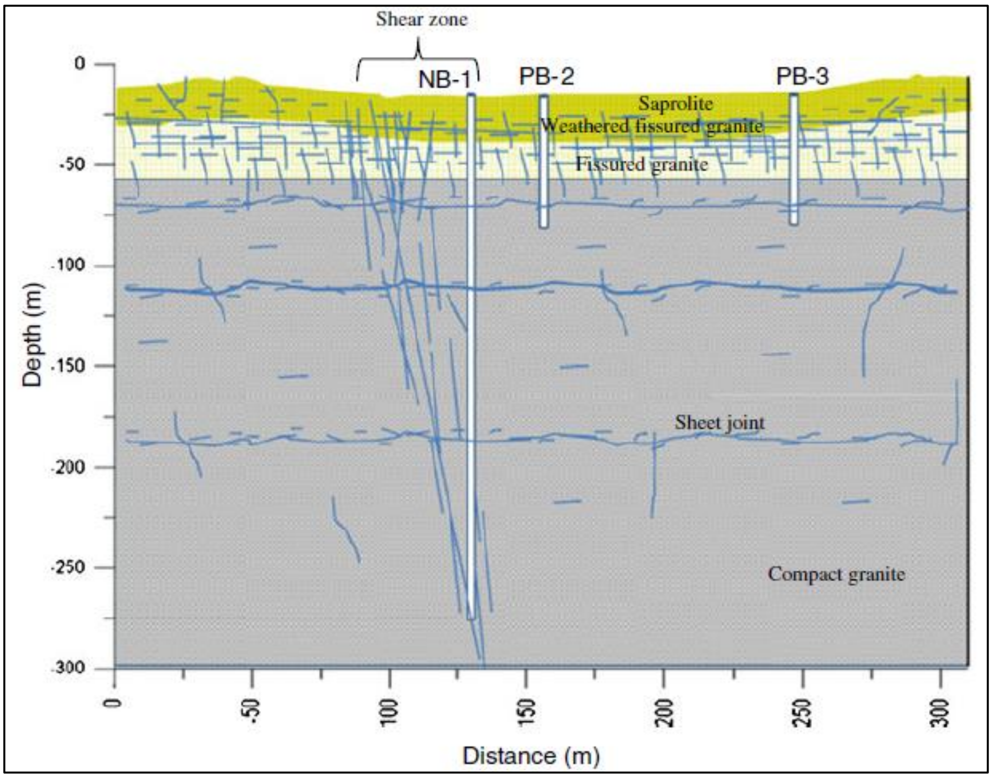


Figure 2-13: Geological cross-section through the site (Chandra et al., 2012)

2.5 NATIONAL CASE STUDIES FOR DEEP GROUNDWATER

The case studies from South Africa discussed below primarily concentrate on the Witwatersrand area as this is where the deepest gold mines in South Africa are situated. Figure 2-14 shows the locality of the five case studies in Johannesburg, the West Rand, Rustenburg, Oudtshoorn and Blikhuis.

2.5.1 Surface and groundwater interaction within Johannesburg: shallow and deep aquifers

Johannesburg is a city that has been developed primarily around mining activities. The city has some of the deepest gold mines in the country with depths reaching 3.2 km below the ground surface. Johannesburg is colloquially known as "the city of gold". According to Barnard (2000), the city has a semi-arid climate and receives an annual rainfall of approximately 650 mm. Groundwater quality in the Johannesburg area is influenced by acid mine drainage (Barnard, 2000).

Johannesburg is underlain by rocks of the Witwatersrand Supergroup. According to McCarthy (2010), the rocks that occur below and in the vicinity of the city consist of shale, quartzite, conglomerate, dolomite and igneous intrusions and extrusions. Figure 2-15 shows a north-south cross-section of the geology in the vicinity of the city. The general dip of the geologic strata is towards the south with dip angles in the range 20 and 80^{o} (McCarthy, 2010).

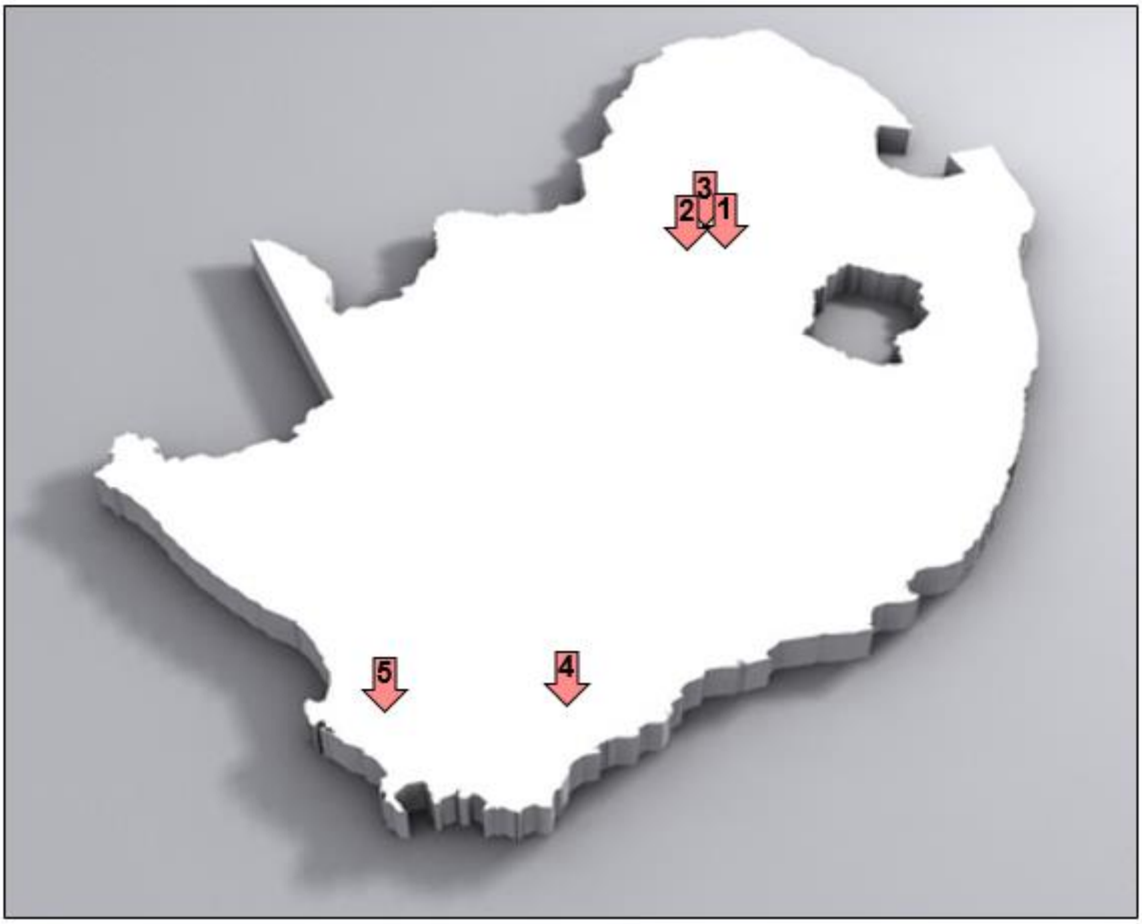


Figure 2-14: Location of five national case studies on deep groundwater: Johannesburg, the West Rand, Rustenburg, Oudtshoorn and Blikhuis, Olifants River Valley

Abiye et al. (2011) differentiated between the following three types of groundwater occurrences in the area:

- Near-surface occurrence within the weathered profile
- Fractures, dykes and shear zones
- Dolomite cavities

An illustration of a fractured rock aquifer system similar to that encountered near Johannesburg prior to mining is shown in Figure 2-16. McCarthy (2010) based his conceptualisation of the Witwatersrand Goldfields on a model of a fractured rock aquifer system. Fractures within the bedrocks were caused by various geological processes. These fractures form the pathways along which water and/or other fluids generally move or get transported. Water from the surface can infiltrate into the subsurface and then percolate down to the saturated zone along these fractures. The depth extents of these fractures can be several hundred metres to kilometres (McCarthy, 2010). Pollution at the surface can therefore potentially migrate to the deeper aquifer systems along these fratures.

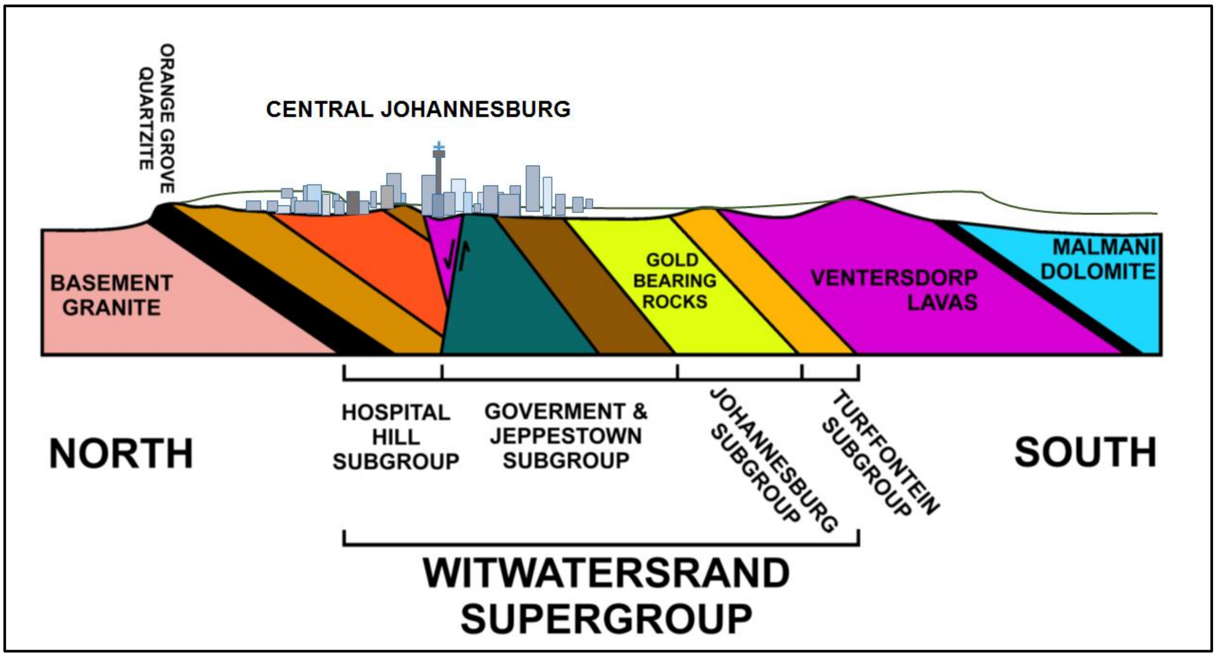


Figure 2-15: Simplified cross-section of the Johannesburg area in a north-south direction (Wikipedia, 2016)

Abiye et al. (2011) developed a conceptual geohydrological model of the Johannesburg area. This model is shown schematically in Figure 2-17. Abiye et al. (2011) stated that the shallow groundwater is stored within the weathered bedrock, but infiltrates into the intergranular and fractured quartzite aquifers and then finally into dolomite cavities. In this way, contaminated acid main drainage water has reached the dolomitic aquifer, causing contamination of the deep groundwater resource.

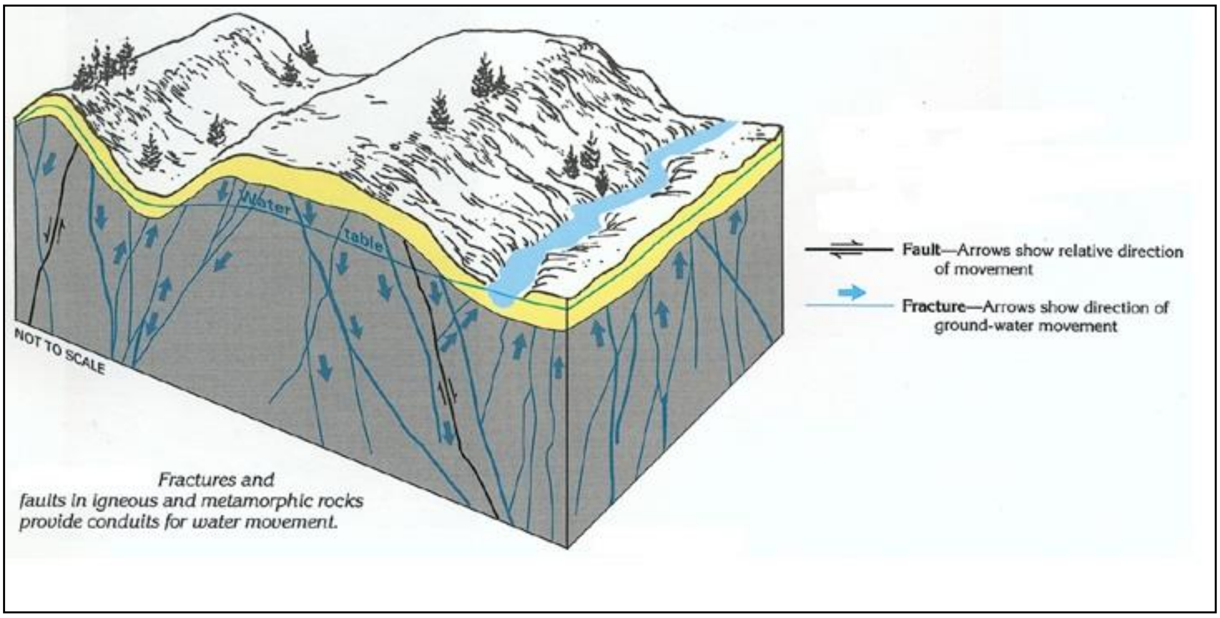


Figure 2-16: Flow of groundwater prior to mining (USGS, 2015)

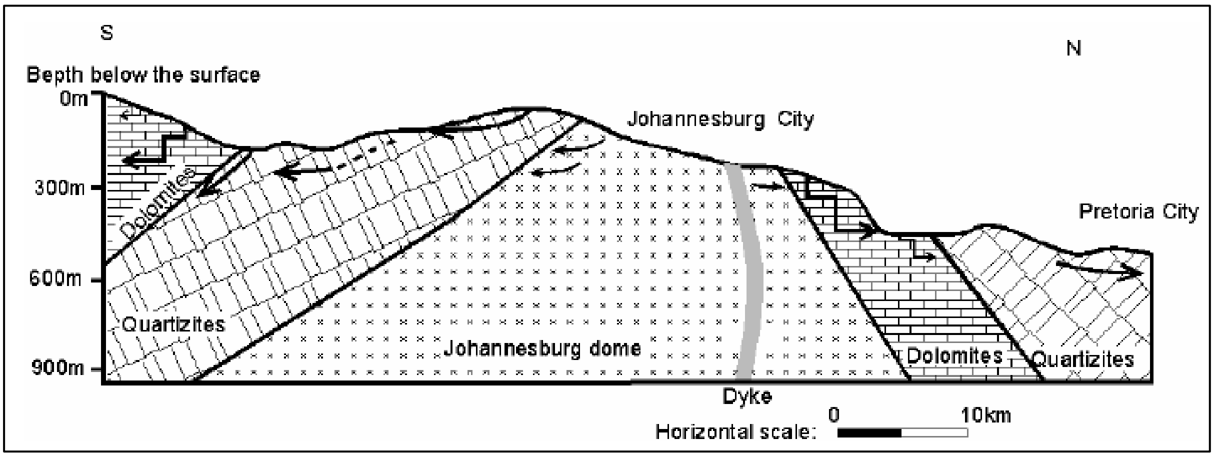


Figure 2-17: Conceptual geohydrological model of Johannesburg (Abiye et al., 2011)

2.5.2 Deep karst aquifers of the West Rand

The deep gold mines of the West Rand reach depths in excess of 1,200 m below ground level. These mines are overlain by highly fractured dolomite rock and karst aquifers. Schrader et al. (2014a) gathered over four decades of dewatering data from the mining industry to investigate the geohydrological parameters of these aquifers. The karst aquifers of the Malmani Subgroup are said to comprise some of the largest aquifers in South Africa (Schrader et al., 2014a).

Mining has occurred in this region since the early 1900s. It was initially assumed that the karst aquifers would not pose a threat since mining activity occurs at such a great depth. However, at the beginning of the summer of 1968, a large volume of water flooded the West Driefontein Mine from these aquifers. According to Winde et al. (2006), this was a result of mining activity encountering the Big Boy Fault that extends to a depth 100 m below ground level (Figure 2-18). Following this incident, it was recommended that dewatering of the karst aquifer should begin to limit any future problems. Due to dewatering, many of the karst springs have dried up (Schrader et al., 2014a).

Figure 2-18 shows that there are highly fractured and weathered dolomite rocks to a depth of approximately 90 m below ground level. The storativity at these depths is relatively high (10%) because of the weathering and fine grain size in this unit, which results in a higher porosity (Schrader et al., 2014a). The cavernous dolomite occurs beneath this layer, which extends to a depth of approximately 200 m below ground level and has a relatively low storativity of 2%. The total volume of water stored within this dolomite is estimated to be in the range of 663 to 2 200 million m^3.

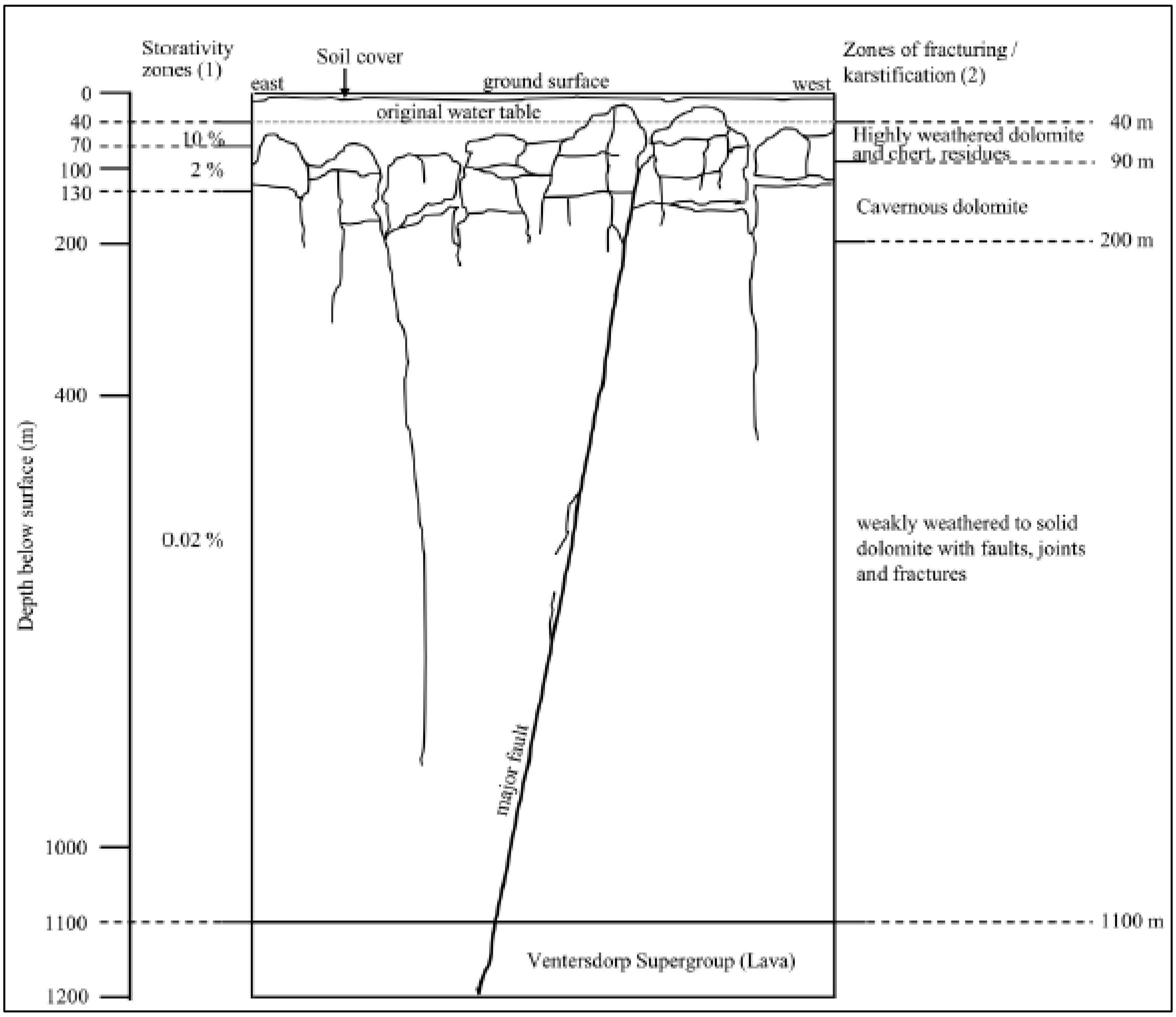


Figure 2-18: Schematic cross-section through the deep karst aquifers of the West Rand showing the dolomite zones and the major fault running through them (Winde et al., 2006)

The transmissivity in these dolomite rocks differs widely and has been estimated to be in the range of 1,000 to 25,000 m^3/d. Schrader et al. (2014a) estimated the hydraulic conductivity in boreholes to be in the range of 7x 10^{-5} m/s, 3.1 x 10^{-4} m/s for the upper 200 m, and 2.9 x 10^{-6} m/s and 1.0 x 10^{-5} m/s for the deeper aquifers (Figure 2-19). The storativity and transmissivity of the aquifer generally decrease with depth.

2.5.3 Groundwater and mining in the Bushveld Igneous Complex

The mines associated with the Bushveld Igneous Complex are situated within the Rustenburg area in North West. The geology of the area comprises felsic to ultramafic rocks (i.e. norite to gabbro). According to Cawthorn et al. (2006), the mineral deposits associated with the Bushveld Igneous Complex are the platinum group elements (PGE). Both open-cast and deep underground mining activities occur within the Bushveld Igneous Complex.

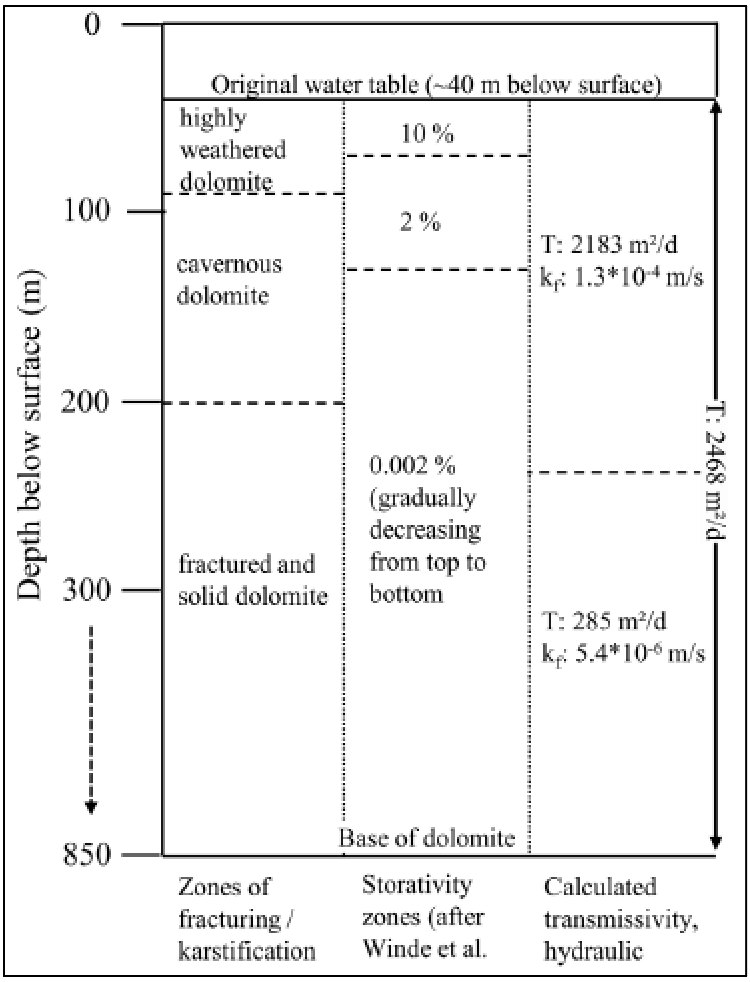


Figure 2-19: Calculated values for transmissivity and storativity in relation to the zones of fracturing (Schrader et al., 2014a)

According to Titus et al. (2009b), the hydraulic activity within the weathered and unweathered bedrock is dominated by interlinked fracture networks. Titus et al. (2009b) divided the aquifers into two distinct aquifer groups: a shallow intergranular aquifer and a deeper fractured aquifer system. The domestic boreholes and irrigation boreholes are sourced from the shallow weathered profile. The shallow aquifer is associated with weathered rock profiles to an approximate depth of 50 m below ground level. These aquifers are primarily associated with saprolitic rocks (i.e. highly weathered igneous rocks of low density). Titus et al. (2009b) found that the deeper aquifer is associated with highly fractured norites, anorthosites and pyroxenites that have a hydraulic conductivity (generally low), dependent on the fracture network within the host rock and/or mine voids.

The chemical tests that were carried out on water samples (Titus et al., 2009b) differentiated the water into three facies:

- Mg-Ca-HCO_3 for the shallow aquifer
- Mg-Ca-HCO_3-CL for alluvial aquifers
- Na-Cl for deeper aquifers

According to Titus et al. (2009b), the results showed that the surface water and groundwater samples had a similar chemistry, which could possibly indicate surface-groundwater interaction. In addition, the groundwater within the deep mines was classified as Na-Ca-Cl water with TDS values in the range of 350 to 1,000 mg/ℓ. The increase in TDS was attributed to the increase in residence time within the subsurface.

Titus et al. (2009b) suggested that the shallow aquifer possesses variations in chemical content as opposed to the uniform chemistry of the deeper aquifers. The results of the chemical analyses are presented in the form of a piper diagram in Figure 2-20. The shallow and deep groundwaters are seen to plot in different areas of the diagram.

The shallow aquifer is associated with low to moderate transmissivity (3 to 8 m^2/d) and high storativity (10^{-3} to 10^{-4}). Abstraction rates for boreholes in the area are typically 0.5 to 1 ℓ/s. However, there are isolated areas with increased rates of 2 ℓ/s (Titus et al., 2009b).

The deeper aquifer system is associated with low porosity and higher hydraulic conductivity along fractures (Titus et al., 2009b). Gustafson and Krásný (1994) found that the aquifers within the Bushveld Igneous Complex are associated with severe heterogeneity, and hydraulic properties are subject to variations.

As examples, two mining operations within the Bushveld Igneous Complex are discussed: those within the Brits Graben area and those within the Thabazimbi area.

2.5.3.1 Mining in the Brits Graben area

The Brits Graben was created as a result of structural activity within the area. The area is associated with shallow mining activities to a depth of approximately 25 m below ground level. Groundwater poses a major threat to mining activity as large volumes of groundwater rush into the mine from the occasional high transmissivity zones (Titus et al., 2009b). Pump tests carried out on various boreholes indicate that transmissivity values as high as 285 m^2/d are found in the area. Hydraulic conductivity values up to 5.7 m/d and storativity values up to 10^{-1} have been recorded.

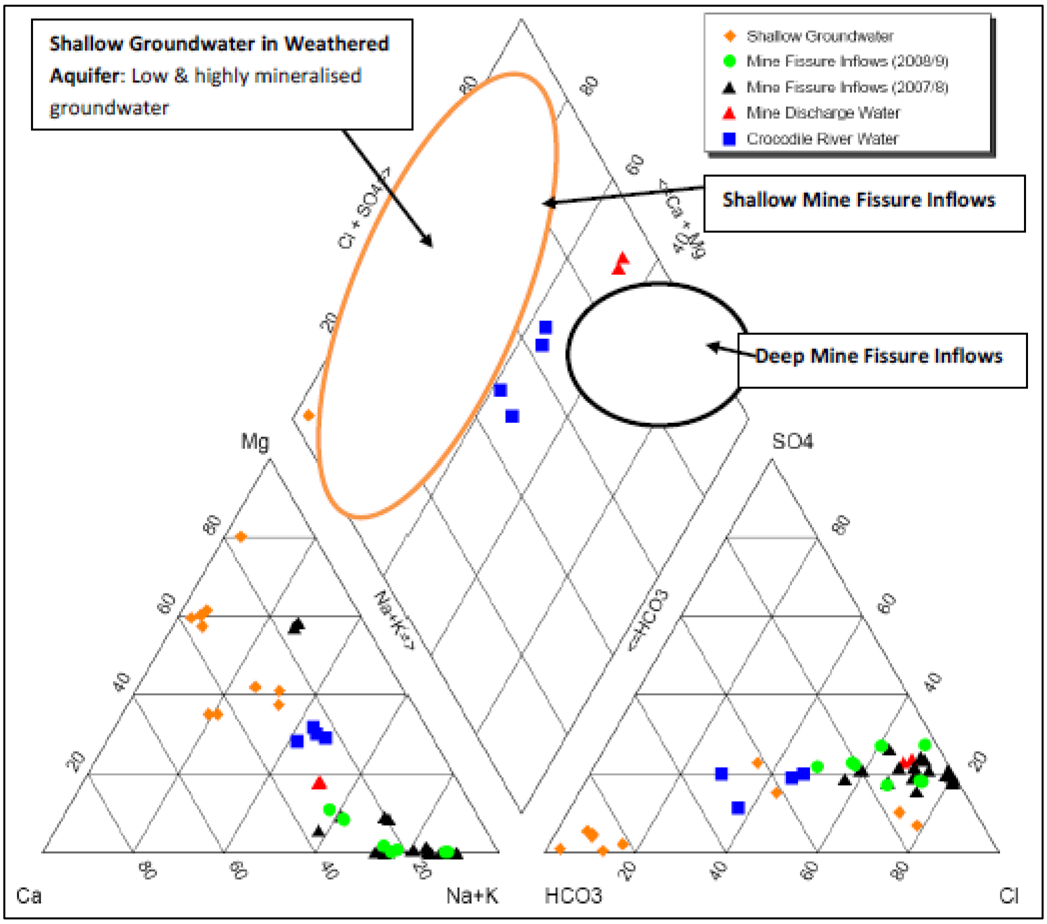


Figure 2-20: Piper diagram depicting shallow groundwater, as well as deep mine fissure inflows (from Titus et al., 2009)

2.5.3.2 Deep mining in the Thabazimbi area

Groundwater flow into deeper mines varies spatially. This is related to the recharge and precipitation in the area, as well as mine discharges (Titus et al., 2009b). The groundwater that is recharged at great distances from the mine often makes its way into the mining areas, which results in fluctuations in the mine water inflow. The dominant sodium-chloride facies of groundwater indicate relatively old groundwater associated with longer residence times. Due to mine dewatering, the flow direction of groundwater in the vicinities of the mines is towards the mines (Titus et al., 2009b).

2.5.4 Deep artesian groundwater for Oudtshoorn municipal water supply

The Deep Artesian Groundwater Exploration for Oudtshoorn Supply (DAGEOS) project was launched in 2000 and culminated in the development of the Blossoms Wellfield (Hartnady et al., 2013). The aim of the DAGEOS project was to secure deep groundwater as a long-term option to augment the water supply to the greater Oudtshoorn Municipality, and/or to contribute to a conjunctive surface and groundwater augmentation scheme (Umvoto, 2005). Figure 2-21 shows the location of the DAGEOS study area. Key objectives of the DAGEOS project included the following (Umvoto, 2005):

- Explore and quantify the deep artesian groundwater resource potential in the confined fractured rock aquifers of the Table Mountain Group within a water-stressed catchment through the integrated application and further enhancement of structural-geological, remote-sensing and geophysical methods.
- Develop the technical capacity for drilling deep (>300 m) wells at selected sites of potentially high water resource yield (>35 ℓ/s or >1 million m^3 per year).

- Complete and pump-test at optimum yield an experimental deep groundwater well at one or more target sites for the purpose of constraining the aquifer parameters and proving a sustainable and environmentally acceptable augmentation of the Oudtshoorn municipal water supply.

2.5.4.1 Stratigraphy and hydrostratigraphic units

Umvoto (2005) analysed the structural geology and geometry of the large-scale fracturing in the study area, using satellite images and aerial photographs to define target sites for deep drilling. According to Umvoto (2005), the formations of the Cape Supergroup dominate the DAGEOS study area. The Cape Supergroup consists of the Table Mountain Group, the Bokkeveld Group and the Witteberg Group.

The Peninsula Formation constitutes the lower aquifer in the Table Mountain Group of the Swartberg-Outeniqua region (Umvoto, 2005). The Peninsula Formation is topographically dominant and is geohydrologically the most important due to its wide areal extent in the areas of maximum precipitation and recharge potential, and its great subsurface volume of permeable fractured rock (Umvoto, 2005).

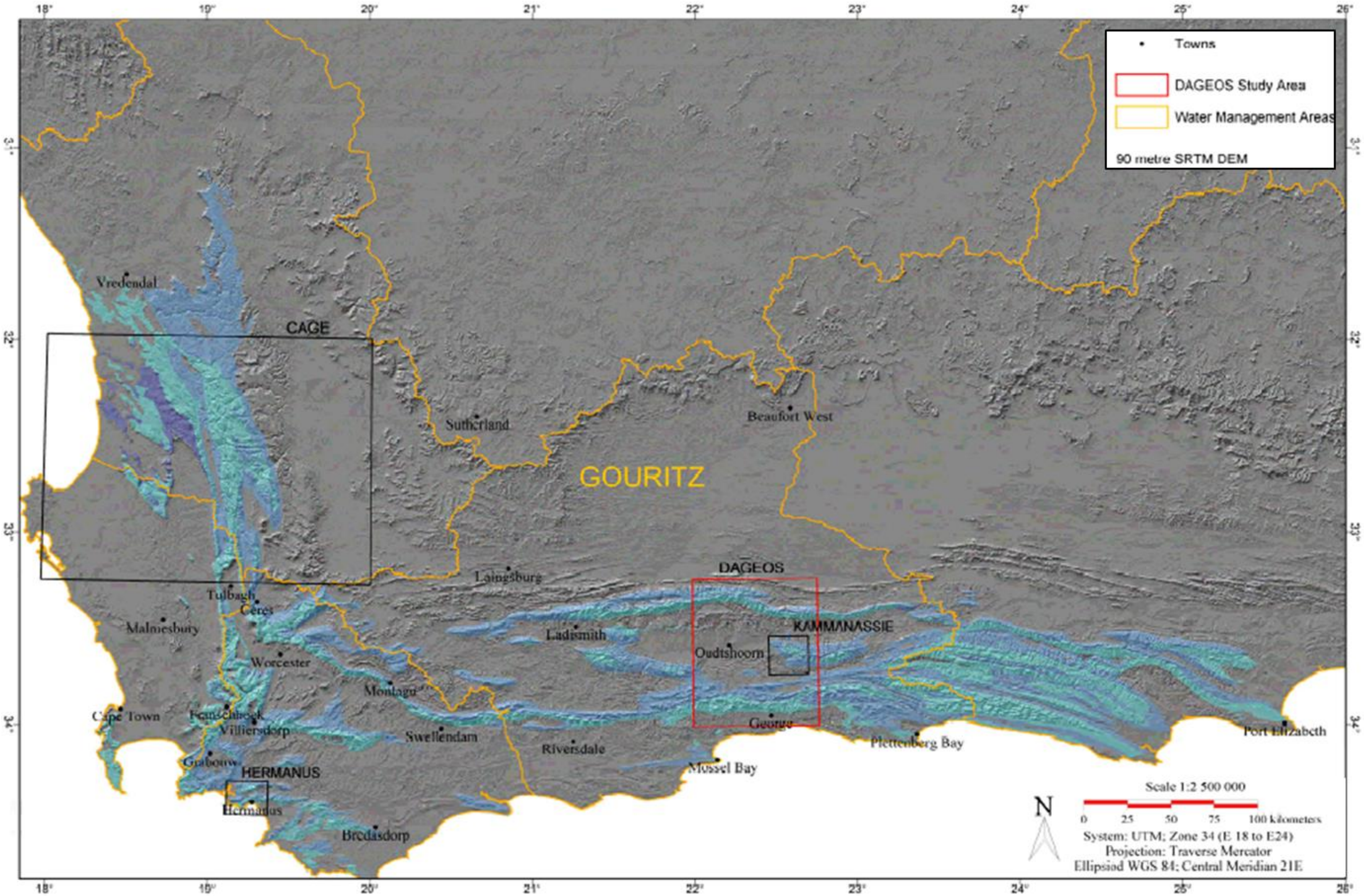


Figure 2-21: Locality map for the DAGEOS project (Umvoto, 2005)

The Peninsula Formation forms a thick aquifer, with an approximate thickness of 550 m in the Cape Peninsula, reaching up to 1,300 m in thickness in the Citrusdal region (Umvoto, 2005). The Peninsula Formation can be up to 1,500 m thick within the Cape Fold Belt, and it is speculated to be greater than 2,000 m thick in the Oudtshoorn area (Umvoto, 2005). The Skurweberg Formation within the Nardouw Subgroup of the Table Mountain Group is also considered to be a potentially important fractured rock aquifer. The Skurweberg Formation consists of thick, cross-bedded quarzitic sandstones, and can reach thicknesses of up to 400 m in some areas. The Bokkeveld Group forms an overlying, confining layer to the Table Mountain Group, with the major unit in this area being shaley strata. The Bokkeveld Group does not form a significant aquifer, except where the intercalated sandstone formations have become fractured and relatively porous. However, this is usually only up to 50 m below the ground surface (Umvoto, 2005).

The hydrostratigraphic units defined by Umvoto (2005) are summarised in Table 2-4. From Table 2-4, it can be seen that Umvoto (2005) conceptualised two main aquifers in the study area: the Skurweberg and Peninsula formations within the Table Mountain Group. A number of aquitards, forming confining layers, are also conceptualised (Umvoto, 2005).

Table 2-4: Hydrostratigraphic units of the eastern Table Mountain Group in the DAGEOS study area. Grey indicates aquitards and white indicates aquifers (Umvoto, 2005).

<table>
<tr><th>Superunits</th><th>Units</th><th>Subunits</th></tr>
<tr><td></td><td>Gydo Mega-aquitard</td><td></td></tr>
<tr><td rowspan="8">Table Mountain Superaquifer</td><td rowspan="3">Nardouw Aquifer</td><td>Kareedouw Subaquifer</td></tr>
<tr><td>Baviaanskloof Mini-aquitard</td></tr>
<tr><td>Skurweberg (Kouga) Subaquifer</td></tr>
<tr><td rowspan="3">Winterhoek Mega-aquitard</td><td>Goudini (Tchando) Meso-aquitard</td></tr>
<tr><td>Cedarberg Meso-aquitard</td></tr>
<tr><td>Pakhuis Mini-aquitard</td></tr>
<tr><td rowspan="2">Peninsula Aquifer</td><td>Platteklip Subaquifer ?
(not yet separately mapped in this area)</td></tr>
<tr><td>Leeukop Subaquifer ?
(not yet separately mapped in this area)</td></tr>
<tr><td></td><td colspan="2">Saldanian Aquicludes [Kansa Subgroup]
[Cape Granite Suite]
[Kango & Kaaimans Groups]</td></tr>
</table>

A geological cross-section was produced by Umvoto (2005) from a north-south section line through the Outeniqua Synlinorium (see Figure 2-22).

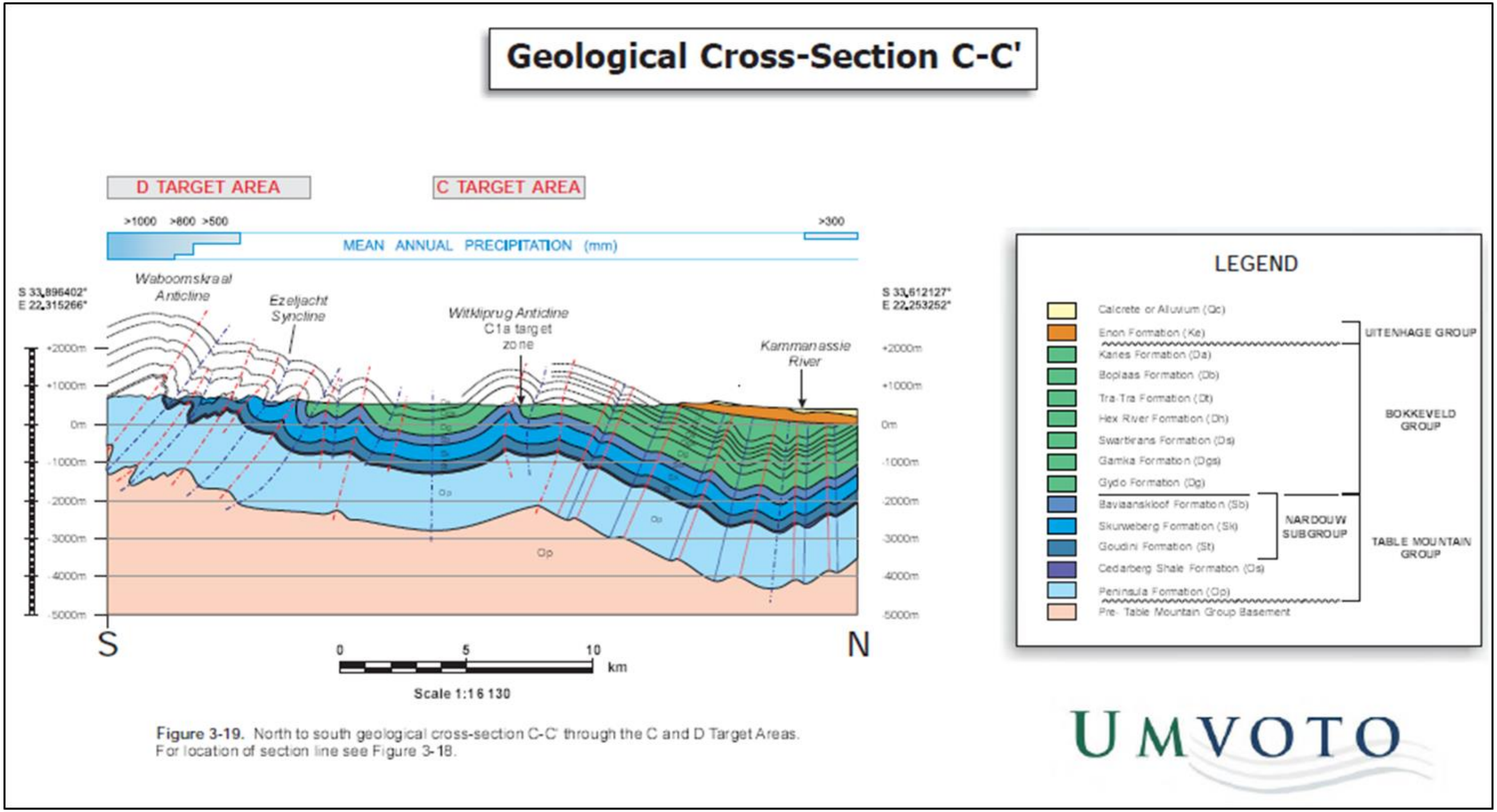


Figure 2-22: North-south geological cross-section through target areas identified within the DAGEOS study area (Umvoto, 2005)

The cross-section shown in Figure 2-22 highlights the complex structural architecture of the Table Mountain Group stratigraphy, and the variable depths of the Peninsula and Skurweberg aquifers (Umvoto, 2005). It can be seen that targeting the Peninsula or Skurweberg formations as deep groundwater aquifers will require a thorough understanding of the structural geology as the depth of this formation is highly variable.

2.5.4.2 Deep drilling for production wells

The deep, confined, thermal-artesian system within the thick Peninsula Formation of the Table Mountain Group was the target for the deep drilling done on the DAGEOS project (Hartnady et al., 2013). An exploratory percussion borehole (C1b1) was drilled at the C1b target site area, but could not be drilled deeper than 180 m below ground level due to high hydraulic heads and resistant quartzite rock conditions (Hartnady et al., 2013). However, a deep diamond-core exploration borehole (C1b2) was successfully drilled to a depth of 715 m below ground level. The exploration borehole C1b2 confirmed the artesian nature of the Peninsula Aquifer, formed a monitoring well, and allowed for the drilling of the C1b3 production well. The C1b3 production borehole that intersected the Peninsula Aquifer showed an initial artesian flow rate of 60 ℓ/s during a free-slow test in 2009 (Hartnady et al., 2013).

The production borehole C1b3 proves that the deep Peninsula Aquifer can be viable for water supply. The Peninsula Aquifer is considered deep because drilling to depths greater than 300 m below ground level is required to intersect this artesian aquifer.

2.5.4.3 Protection of deep confined aquifer

Hartnady et al. (2013) stated that there is a difference between the Blossoms deep artesian groundwater scheme and other conventional groundwater supply schemes. Hartnady et al. (2013) divided the potential adverse influences of high abstractions from the Peninsula Aquifer into two general categories: depletion or degradation of the groundwater resource, and environmental or ecological consequences.

Hartnady et al. (2013) consider unconfined aquifers to be “water-limiting” because the available groundwater storage space remains unchanged, as long as there is enough water to replace what has been removed. Conversely, confined aquifers are not “water-limited” because water does not drain under gravity. It is rather released in response to pressure changes. As the water pressure in a confined aquifer decreases, the porosity decreases by a small amount and an equivalent volume of water is released from storage (Hartnady et al., 2013).

Figure 2-23 shows a microscopic view of the contact between an aquifer and the overlying confining bed. The total load on top of the aquifer is partly supported by the solid skeleton of the aquifer and partly by the hydraulic pressure exerted by the water in the aquifer. When the water pressure declines, more of the load must be supported by the solid skeleton. As a result, the rock particles are distorted, and the pore space is reduced. The water forced from the pores when their volume is reduced represents part of the storage coefficient due to compression of the aquifer (Heath, 1983).

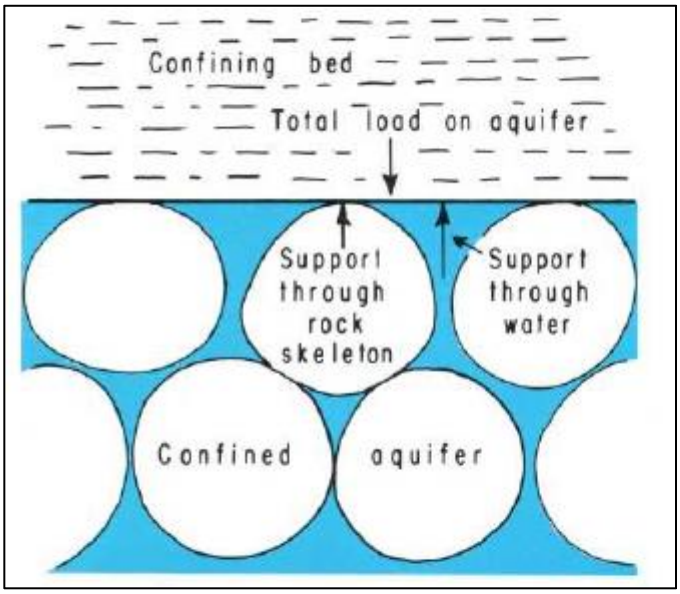


Figure 2-23: Illustration of a compressed, confined aquifer and the forces acting therein (Heath, 1983)

The danger then of over-abstracting water from a confined aquifer is that it can induce non-elastic deformation (subsidence), where a certain amount of porosity will be permanently reduced (Hartnady et al., 2013).

In the case of a deep, confined aquifer, where the abstraction location is distant from the recharge and discharge boundaries, the environmental or ecological impacts of groundwater extraction occur only when the radius of influence reaches these boundaries (Hartnady et al., 2013). According to Hartnady et al. (2013), once this state is reached, the groundwater extraction may capture significant amounts of recharge or discharge, where the surface water flow regime around these boundaries can be affected. For the Peninsula Aquifer in the eastern Klein Karoo, the recharge boundary along the Peninsula-Goudini contact in the Waboomskraal area and on the adjacent northern slopes of the Outeniqua range represents the area that is most vulnerable to the adverse effects of capture. Similarly, these areas will form areas from which the aquifer could also potentially be contaminated.

2.5.5 Blikhuis Experimental Deep Drilling

The Blikhuis Experimental Deep Drilling (BEDD) project study site is located approximately 25 km from Citrusdal. The drilling at the site comprises a combination of percussion drilling (down to 300 m below ground level) and diamond-bit drilling (down to 600 m below ground level). The target of the drilling was the confined section of the Peninsula Aquifer along the faulted hinge zone of a major synclinal fold (Hartnady and Hay, 2002a). Reaching the main deep aquifer in the Peninsula Formation requires drilling through the lower part of the Nardouw Subgroup (Goudini Formation) and the underlying Cedarberg and Pakhuis formations (Figure 2-24).

Four experimental boreholes were drilled as part of the BEDD project, but one was abandoned due to technical problems (Hartnady and Hay, 2002a). The BH2 borehole intersected the Nardouw Aquifer and indicated that the potentiometric surface in this confined layer is 165 m below ground level. The deepest of the boreholes started flowing when water strikes in the Peninsula Aquifer were encountered below a depth of 145 m below ground level. Analyses performed on groundwater samples also indicated that there are physical and chemical differences between the shallower Nardouw groundwater and the deeper artesian Peninsula groundwater. The Nardouw groundwater is distinctive as it contains a higher iron content (Hartnady and Hay, 2002a).

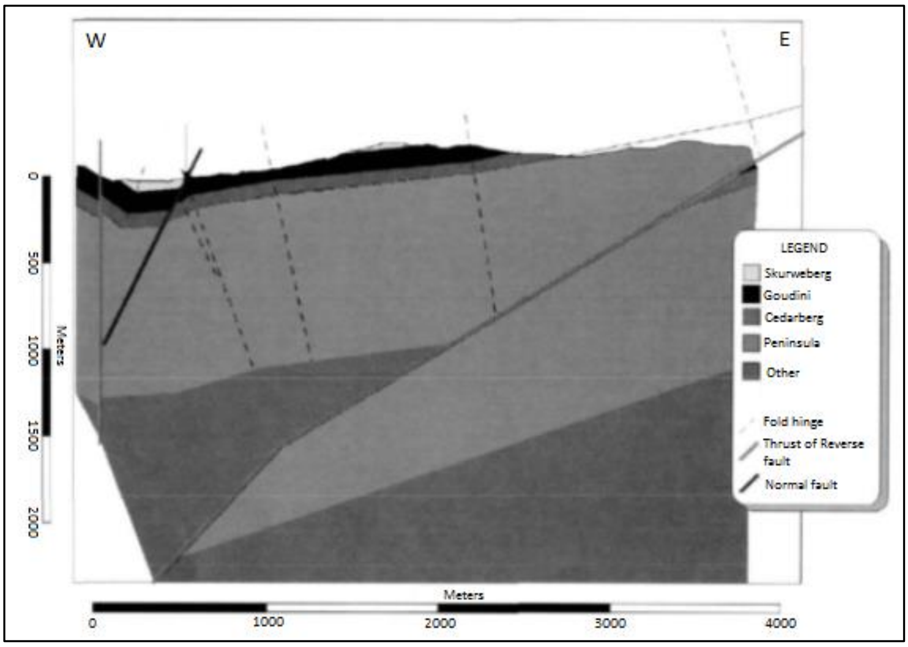


Figure 2-24: Preliminary geological cross-section through the BEDD project study area (Hartnady and Hay, 2002)

The BH2 borehole at the Blikhuis deep drilling site was drilled to a depth of 160 m below ground level when the Cedarberg-Goudini contact was intersected. At a depth of 304 m below ground level, the borehole was terminated in black carbonaceous shale. The BH2 borehole showed that the Cedarberg Formation was considerably deeper at the drilling site than the regional thickness of 90 m. The borehole was later deepened using diamond-bit rotary core drilling, where the borehole intersected the Cedarberg-Pakhuis contact in just a few decimetres. The Pakhuis-Peninsula contact was intersected at 324 m below ground level and a highly fractured Peninsula quartzite was found at a depth of 349 m below ground level. A few smaller water strikes followed between 349 and 352 m below ground level, until a main water strike at a depth of 360 m below ground level was intersected. Afterwards, the rest water level in the borehole rose and BH2 become artesian (Hartnady and Hay, 2002a).

According to Hartnady and Hay (2002a), after casing off all water strikes, drilling below 381 m below ground level proceeded at a diameter of 76 mm using the wire-line method of core retrieval. Further fracture intersections were observed at depths of between 434 and 444 m below ground level. Water strikes associated with these fractured zones resulted in an artesian flow of 1 to 3 ℓ/min. Another porous zone of sandstone at a depth of 475 to 485 m below ground level was reported (Hartnady and Hay, 2002a). When the borehole reached a depth of 490 m below ground level, the artesian flow had recovered further to 0.31 ℓ/s. At a depth of between 528 and 544 m below ground level, a complex fault zone was found where the bedding dips were steepened to become sub-parallel to the borehole core axis. Hartnady and Hay (2002a) reported that there was no notable increase in the artesian flow rate below 500 m below ground level.

The information gathered from the deep BH2 borehole of the Blikhuis deep drilling project serves to indicate that sufficient amounts of water could potentially be extracted at depths greater than 300 m below ground level in the Table Mountain Group. Additionally, there is the potential for artesian flow from the Peninsula Aquifer. However, the information from BH2, which indicates that no substantial flow occurred below 500 m below ground level, agrees with the conclusions drawn by Lin et al. (2007). Lin et al. (2007) analysed an 800 m deep borehole and characterised the fractures into four zones, based on the degree to which fractures are hydraulically active. These zones are: high (0-150 m below ground level), medium (150-400 m below ground level), low (400-570 m below ground level) and hydraulically inactive (570-800 m below ground level or deeper).

2.5.6 Application of carbon storage in deep saline aquifers in South Africa

Coal-fired power stations produce tonnes of CO_2 every year. New methods are required to dispose of this waste by-product. According to Birkholzer et al. (2009), the CO_2 may be stored within the deep saline aquifers as a potential means of minimising climate change.

2.5.6.1 Introduction to carbon storage

Holloway (1996) first identified the potential to store CO_2 in geological formations, specifically saline aquifers, oil and gas reservoirs, and coalbeds. Birkholzer et al. (2009) identified that the best possible storage source of CO_2 was deep saline aquifers in sedimentary basins. However, the effects of this potential storage on the aquifers are not yet clearly understood. According to Birkholzer et al. (2009), a possible effect is the alteration of the pressures within the strata, which may cause an increase in hydraulic head and result in saline waters entering drinking water aquifers. The rate at which water will move through the geological formations will depend on the conductivity of the confining unit (aquitard or aquiclude). Figure 2-25 is an illustration of CO_2 being pumped into the deep aquifer under pressure, causing the migration of saline water into the upper aquifer systems.

To further investigate this theory, a numerical model was set up with eight aquifers (approximately 60 m thick) and seven aquitards (approximately 100 m thick) (Birkholzer et al., 2009). A 50 km radius was established, and effects were simulated for a 100-year period, i.e. 30 years of pumping CO_2 and 70 years after pumping. The initial pressures, temperatures, saline density and salt mass fraction are shown in Figure 2-26. It can clearly be seen that the pressure and temperature increase with depth, while the salt mass fraction and saline density are constant up to a depth of 540 m below ground level (freshwater aquifers were assumed to occur to a depth of 540 m below ground level) (Birkholzer et al., 2009).

Figure 2-27 and Figure 2-28 show the modelled effects of CO_2 storage 30 and 100 years after storage commenced. The hydraulic conductivity of the confining aquifer was a significant factor in the migration of saline waters into the upper aquifers. Birkholzer et al. (2009) identified that the higher the permeability of the confining layer, the higher the migration rate of saline waters into the upper aquifers. Moreover, the lower the permeability of the confining layer, the higher the migration of saline water laterally.

Although it may be relatively environmentally safe to store CO_2 at great depth, the zones in which storage will take place need to be studied in great detail since the confining layers play a significant role in the possible contamination of the upper freshwater aquifer systems. Geological structures such as faults and shear zones are features typically associated with zones of increased permeability. Such zones could hydraulically link the deeper and shallower aquifer systems. Since groundwater generally decreases with depth (as salinity increases), groundwater from the deeper aquifers could have adverse impacts on the quality of the shallow water resource (Birkholzer et al., 2009).

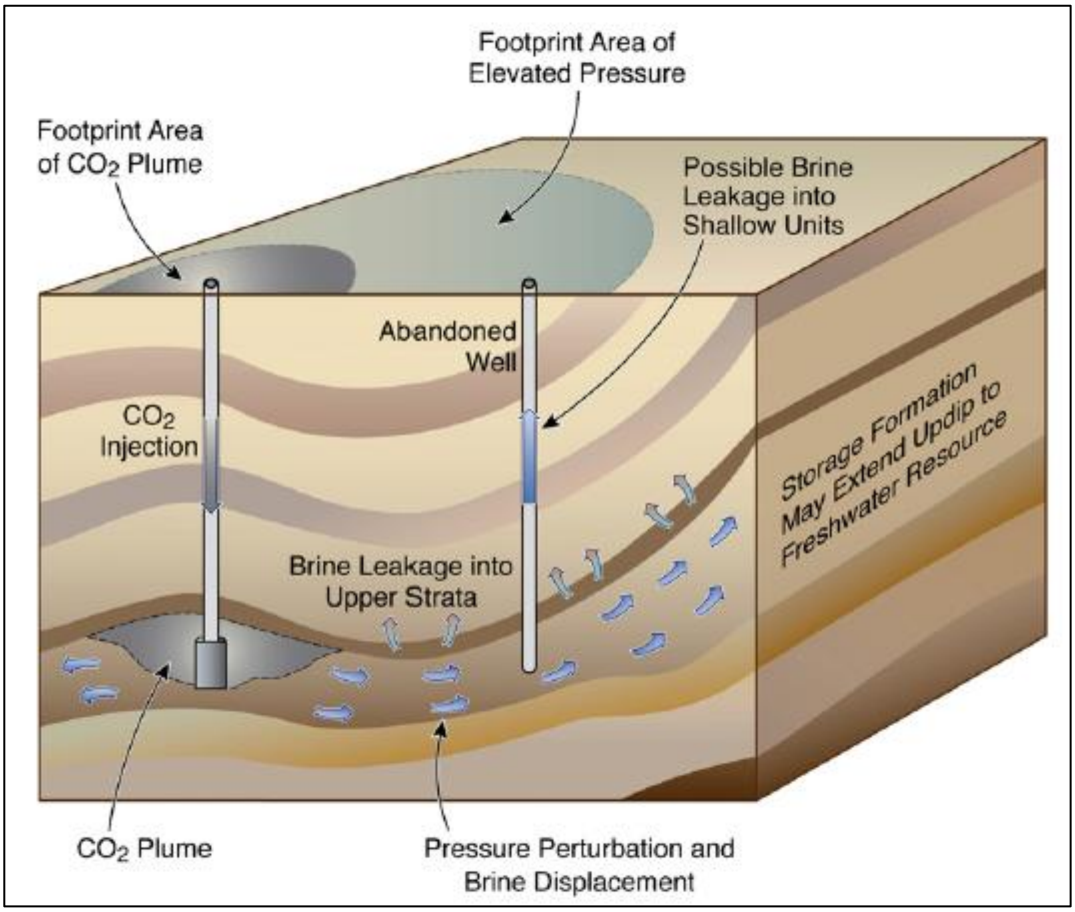


Figure 2-25: Schematic showing the different regions of influence related to CO_2 storage (Birkholzer et al., 2009)

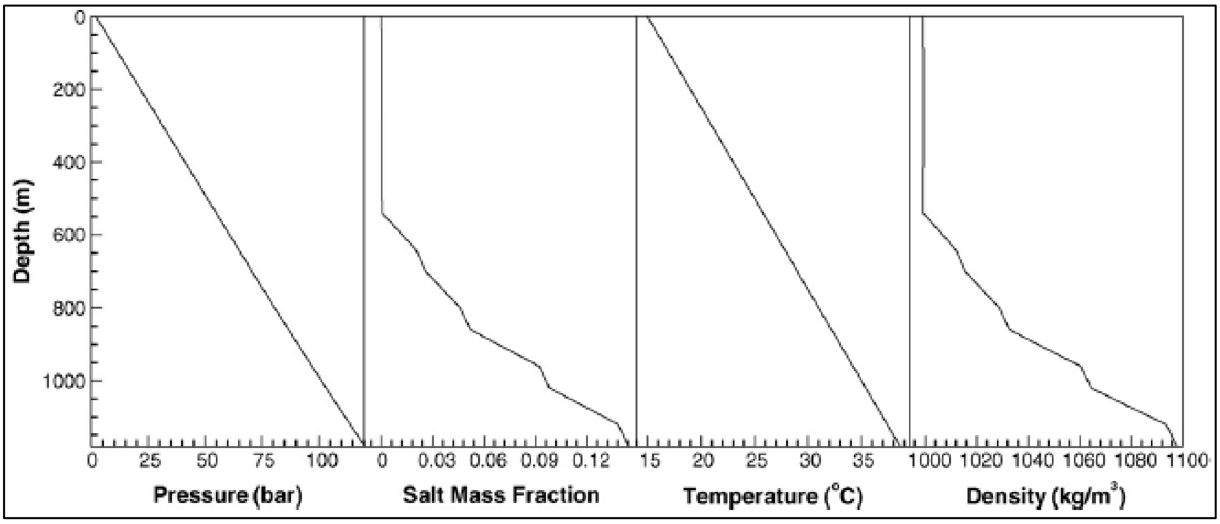


Figure 2-26: Vertical profiles of pressure, salt mass fraction, temperature and saline density from the top of the aquifer to the storage formation (Birkholzer et al., 2009)

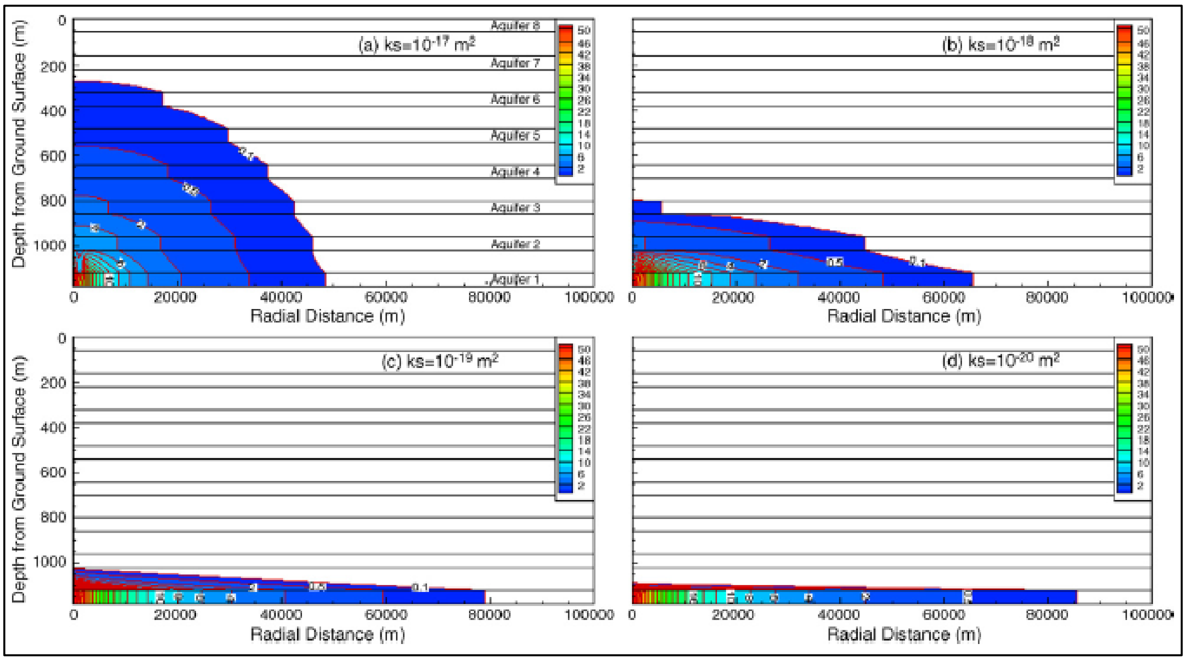


Figure 2-27: Contours of pressure build-up at 30 years of CO_2 pumping for different values of permeability (Birkholzer et al., 2009)

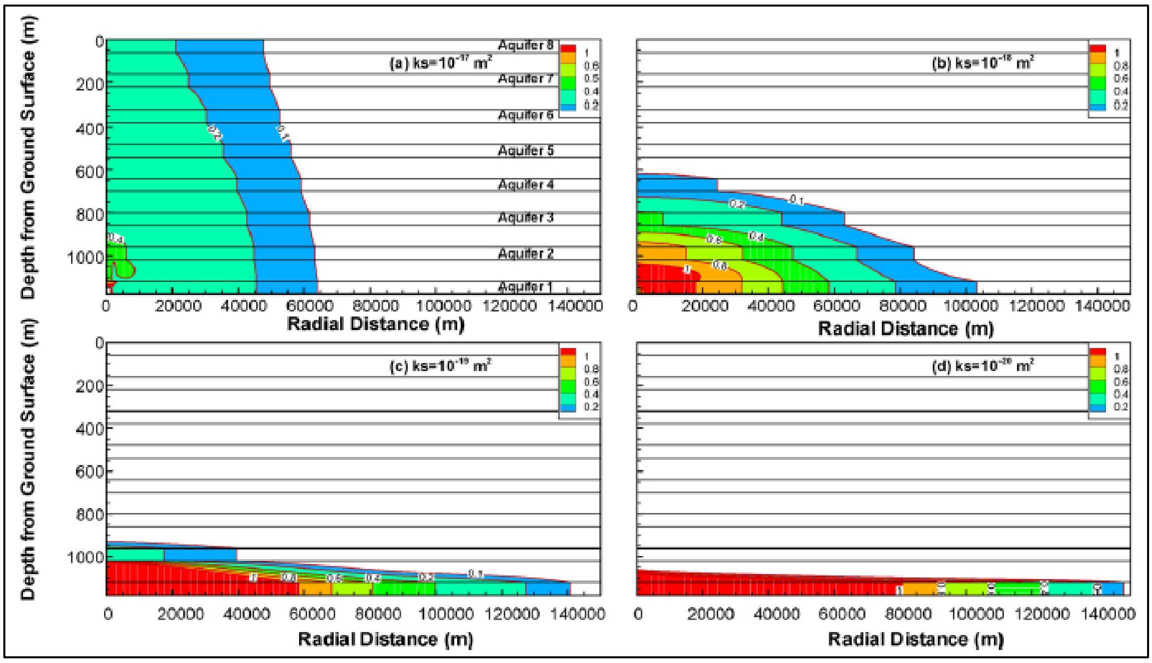


Figure 2-28: Contours of pressure build-up 70 years after CO_2 pumping for different values of permeability (Birkholzer et al., 2009)

2.5.6.2 Carbon storage in South Africa

Viljoen et al. (2010) produced a technical report on the geological storage of CO_2 in South Africa. The report aimed to assemble information on the various large-scale emission point sources of CO_2 in South Africa, the physical properties of CO_2 that affect its storage, the range of possible geological storage types, and previous work done on CO_2 storage in South Africa (Viljoen et al., 2010). The authors examined the geological criteria that affect CO_2 storage, and how basins could be ranked and assessed to identify the best storage potential.

Viljoen et al. (2010) listed the screening criteria used to determine the potential for carbon storage:

- Tectonic setting of the basin
- Size of the basin
- Thickness
- Lithology of the basin (potential of the reservoir)
- Fault intensity
- Dolerite dykes and sills
- Geothermal regime
- Presence, potential and size of oil or gas deposits
- Maturity
- Presence of coal or organic-rich shale or sandstone
- Coal rank
- Onshore/offshore sites
- Economic mineral commodities (other than oil, gas and coal)
- Infrastructure
- Distance from major CO_2 sources
- Other criteria

Thickness is included in the list of Viljoen et al. (2010) because a minimum depth for storage in saline aquifers is anticipated to be approximately 800 m below ground level, and for storage in coalbeds it has been taken as 300 m below ground level. Viljoen et al. (2010) thus excluded any shallower basin. On the other hand, if the selected reservoir rocks are too deep, it can impact negatively on the economic feasibility of the basin, as the greater the depth to the injection target, the larger the associated costs of drilling (Viljoen et al., 2010). The evaluation of potential storage sites could assist in the identification of aquifers below depths of 300 to 800 m below ground level in South Africa.

Viljoen et al. (2010) evaluated the lithology and associated potential for a CO_2 storage reservoir. A large, deep, simple, undeformed, layered sedimentary basin with alternating porous sandstone and impervious mudstone is the ideal basin for CO_2 storage (Viljoen et al., 2010). In standard oil exploration, the reservoir potential of sandstone is classified from poor to very good, as shown in Table 2-5. This screening criteria could also be useful in identifying deep aquifers that have parameters that would allow for groundwater flow at depths.

Table 2-5: Porosity and permeability classification for determining reservoir potential for oil exploration (from Viljoen et al., 2010)

	Poor	Fair	Good	Very good
Porosity (percent)	10	10–15	15–20	>20
Permeability (mD)	1	1–10	10–100	>100

Fault intensity and the presence of dolerite dykes and sills are used to gauge the appropriateness for carbon storage because these features will enhance the movement of CO_2 back to the surface. However, these features are desirable for groundwater flow at depth. The fractures and dolerite dykes identified as possible problems for carbon storage can thus be used to identify potential deep fractured aquifers (Viljoen et al., 2010).

Some of the parameters listed under other criteria are geohydrology, the salinity of the groundwater and the availability of data. Geohydrology, as a criterion, relates to the preference of basins with deep, relatively slow, regional, long-range flow systems for carbon storage. Shallow, short flow systems or compacted flow negatively influence the CO_2 storage potential of a basin. Again, the identification of deep, regional flow systems will assist in identifying deep aquifers (Viljoen et al., 2010). Similarly, information on the salinity of groundwater and the accessibility of data could also contribute to the identification and understanding of deep aquifer systems.

2.5.6.3 Sedimentary basins of South Africa and their CO_2 storage suitability

Viljoen et al. (2010) stated that South Africa is well endowed with sedimentary basins, which cover most of the land surface. However, the rocks in most of these basins are metamorphosed and the basins are structurally complex. Viljoen et al. (2010) gave a short review of the metasedimentary basins in South Africa. These basins will be investigated from the perspective of potential deep aquifers.

- Pre-Karoo basins
    - Nama Group
    - Cape Supergroup
    - Natal Group

- Karoo Supergroup
    - Southern and south-western Karoo
    - Katberg Formation, Molteno-Indwe coalfield and Molteno and Clarens formations
    - Northern Karoo
    - Durban-Lembombo Belt/Basin
    - Springbok Flats Basin
    - Tuli Basin
    - Tshipise Basin
    - Ellisras (Lephalale) Basin
    - Karoo Basin northwest of Upington

- Mesozoic basins
    - Onshore Mesozoic basins
    - Offshore Mesozoic basins

- Cenozoic basins

2.6 PROTECTION OF DEEP GROUNDWATER

2.6.1 Impacts of mining on physical geohydrology

Mining activities have a significant effect on the world economy, and worldwide economic growth is dependent on mining. There are primarily two types of mining activity: deep underground mines and open-cast (surface) mines. A deep mine, such as the Witwatersrand mines, occurs at varying depths beneath the surface with soil and rock overburden. Open-cast mines, such as the Sishen Mine in the Northern Cape, comprise excavations that are left open and exposed at the surface. Mining involves the removal of material from the subsurface. This directly influences the void ratio and permeability of the geological units.

There are two common types of deep-mining methods: bord-and-pillar, and longwall mining. Bord-and-pillar mining is associated with a network of interconnected pathways (roads) and pillars (Younger, 2004). The pillars are left unmined to support the weight of the overburden rock in order to prevent collapse. Blasting in mining operations causes the development of additional fractures within a rock unit and can cause the destabilisation of the overlying rock unit. The pillars provide additional support in ensuring the possible stabilisation of the overlying rock unit. The bord-and-pillar method is the most cost-effective method of mining.

The longwall method involves mining along a horizontal section that is at least 250 m wide and 1,000 m long. It is usually carried out in coal mining. In this case, hydraulic roof supports are used to hold up the roof of the mine once the material has been extracted. Figure 2-29 and Figure 2-30 illustrate bord-and-pillar and longwall mining, respectively.

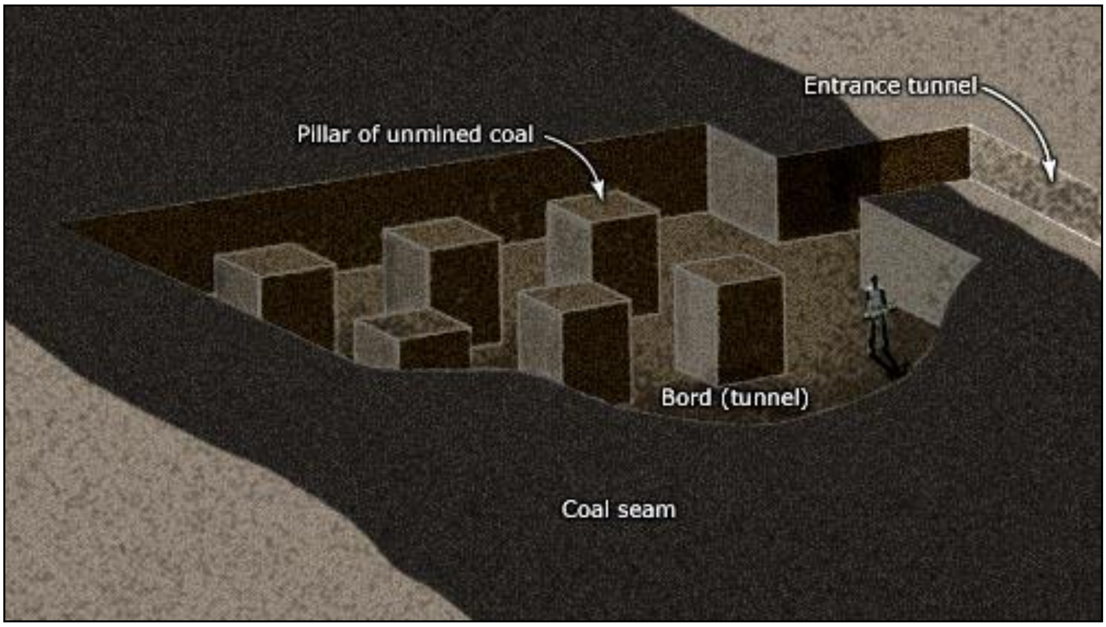


Figure 2-29: Bord-and-pillar mining (Teara, 2015)

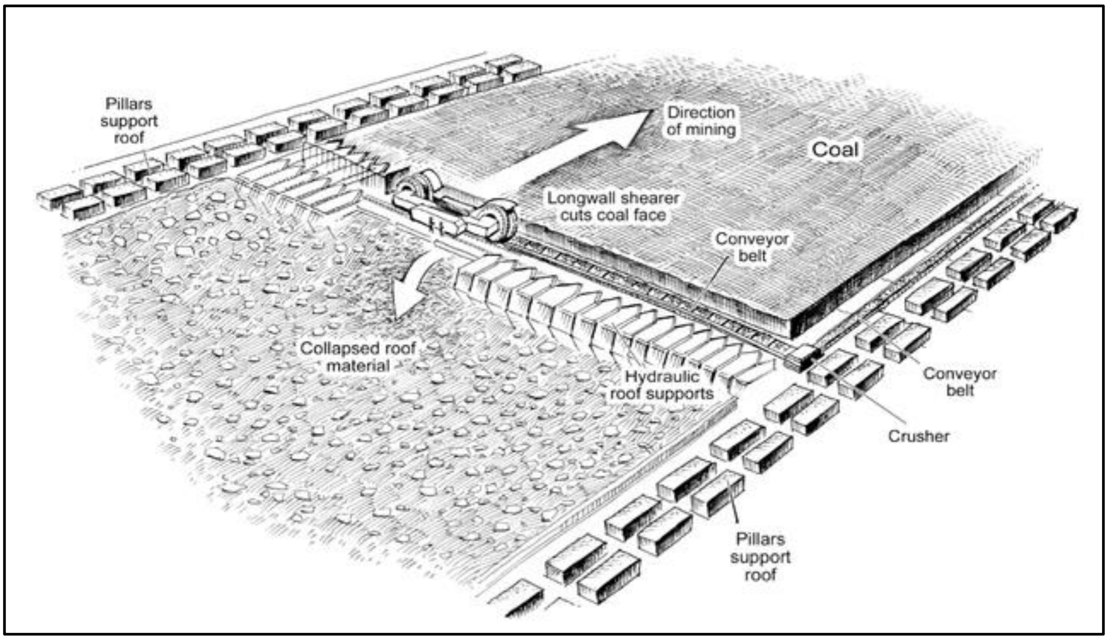


Figure 2-30: Longwall mining (USSEC, 2017)

According to Younger (2004), surface mines comprise at least 80% of mining operations. Surface mining involves stripping away the overburden and only mining the ore body. The open pits are then backfilled using the waste rock (spoils) upon completion of mining. In South Africa, there are commonly two types of surface mines: open-pit and open-cast mines. An open-pit mine involves the removal of overburden and stockpiling it in a disposal area. Open-pit mining is typically done in stepped benches, approximately 18 to 45 m wide. Each mined bench is separated by an *in situ* rock layer, 9 to 30 m high (Younger, 2004). An open-cast mine is similar to an open-pit mine, but the overburden material that is removed is directly backfilled into the adjacent mined-out panels (Younger, 2004).

Younger (2004) states that more than 70% of the mined-out material consists of waste rock. In Europe, approximately 400 million tonnes of mine waste is generated annually. The waste material is either stored in stockpiles or in tailings dam. The stockpiling of unconsolidated sediments of waste rock will create cobbly and fine-grained zones within the stockpile. Therefore, the stockpile will be considered heterogenic and the flow rates will be different throughout. The cobbly zone is considered to be the free draining zone due to its high porosity. It is regarded as the unsaturated zone of the stockpile. Conversely, the fine-grained zone will be less permeable than the cobbly zone, but will hold most of the water (Younger, 2004).

The preferential flow paths that are created within the stockpile can have a significant influence on the transportation of sediments. This would eventually lead to erosion of the stockpile and the surrounding environment. Figure 2-31 shows an example of a waste rock stockpile.

In conclusion, the development of mines in an area causes a change in the void ratio of the subsurface. The blasting for and removal of ore bodies creates fractures and increases the porosity and permeability of the rocks. This would cause some instability in the natural groundwater flow and create scenarios for the possible flooding of mines. The chemical reactions between the groundwater and the ore or ore wastes can create acidic waters, namely acid rock drainage. This would cause contamination of the groundwater supply to both shallow and deep aquifer systems. Another important aspect is that mines are continuously dewatering to keep working areas dry. This disrupts the natural groundwater flow (Younger, 2004).

Figure 2-31: Waste stockpile, Australia (S&R, 2007)

2.6.2 Geochemical processes controlling mine water pollution

Mine water is a type of groundwater that endures similar geochemical processes, but is very different from natural water (Banks, 2004). Mine water is generally associated with a high acid content, and an abundance of major salt ions and toxic metals. However, Banks (2004) indicated that some mine water is more alkaline than other mine water samples and that groundwater will tend to retain some of the characteristics of its recharge source. According to Banks (2004), newly recharged groundwater will have the following characteristics:

- An isotopic signature
- An atmospheric chloride content that decreases with distance from the coast
- Pollutants from industries such as nitrate and sulphate
- A high content of dissolved oxygen

There is high microbial activity within the subsoil horizon, and respirations cause the formation of CO_2. Therefore, any water percolating through the subsoil will have a higher concentration of CO_2. Groundwater and rock interaction is important in understanding the chemistry of water beneath the surface. The groundwater will react with the chemicals in the host rock and chemical reactions will precipitate certain minerals. Banks (2004) found that groundwater and rock interactions will consume dissolved O_2 and CO_2, increase the pH level, and release base cations. In certain areas, such as along coastlines, groundwater may interact with saline water and cause the water to have a salty taste (Banks, 2004).

Acid and base reactions are important for groundwater, as this will determine whether an acid or base is precipitated. Carbonates and silicates are the major rock-forming minerals. These are regarded as bases that consume acids through reduction reactions (Banks, 2004). Oxidation reactions may precipitate acids. In South Africa, pyrite that occurs in the ore and host rock often undergoes oxidation, which causes the creation of acidic conditions and the mobilisation of heavy metals. Typical acid and base reactions are as follows:

$CaCO_3 + CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$ (base reaction - calcite)

$2FeS_2 + 2H_2O + 7O_2 \leftrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$ (acid reaction - sulphide oxidation)

According to Banks (2004), oxidising minerals, such as pyrite, are of low concentration in natural groundwater and acid-base reactions dominate over oxidation reactions. Therefore, normal groundwater will have a neutral to alkaline pH level.

With the introduction of mines in an area, there is an increase in the chance of oxygen entering the aquifer system, allowing the oxidation reaction to occur. Similarly, when waste material is extracted from the mine and stockpiled in an open environment that is exposed to the atmosphere, oxidation reactions can occur rapidly (Banks, 2004).

Banks (2004) states that when sulphide oxidation occurs, mine water may be dominated by a low pH level, elevated sulphate concentrations and elevated concentrations of metals. Banks (2004) carried out numerous tests on groundwater samples from sulphide and coal mines. The results of these tests are listed in Table 2-6 and Table 2-7.

Based on the results in Table 2-6 and Table 2-7, Banks (2004) concluded the following:

- There are variations in mine water chemistry, even in similar mines.
- Metal mines have the potential to generate aggressive mine waters.
- Aggressive discharges would indicate a recently flooded mine.
- As the pH level increases, concentrations of metals and sulphides decrease.
- The chloride content is independent of pH level.

Table 2-6: Hydrochemical characteristics of three different metal sulphide mine waters (Banks, 2004)

Mine	San José Bolivia	Kongens Gruve Norway	Magpie Sough UK
Flow rate (l/s)	8	5.8 (average)	-
Temperature (°C)	20.8	n/a	n/a
pH	1.47	2.7	7.2
Alkalinity (meq/l)	0	0	4.28
Cl^- (mg/l)	32670	n/a	19
SO_4^{2-} (mg/l)	8477	901	33
Ca^{2+} (mg/l)	1780	47.8	98
Na^+ (mg/l)	17256	n/a	8
Fe (mg/l)	2460	134	<0.0005
Al (mg/l)	559	33.1	0.005
Mn (mg/l)	27.4	n/a	<0.0002
Zn (mg/l)	79.4	36.3	0.074

Table 2-7: Hydrochemical characteristics of four different coal mine waters (Banks, 2004)

Mine	Ynysarwed Wales	Dunston Chesterfield, UK	Morlais Wales	Mine No. 3 Svalbard
Flow rate (l/s)	15–35	c. 20	c. 100–200	c. 0.056
Temp. (°C)	-	9.4	14.2	4.7
pH	4.2	6.3	6.9	8.2
Alkalinity (meq/l)	2.76	3.74	6.07	36
Cl^- (mg/l)	32	26	25	236
SO_4^{2-} (mg/l)	1554	210	455	7.43
Ca^{2+} (mg/l)	222	64.5	91.8	15.5
Na^+ (mg/l)	109	51.4	155	925
Fe (mg/l)	180	10.6	26.6	<0.01
Al (mg/l)	<0.5	<0.045	<0.01	<0.02
Mn (mg/l)	6.1	1.26	0.93	0.004
Zn (mg/l)	0.061	<0.007	<0.002	0.055

Banks (2004) also pointed out that aggressive mine waters would be expected in the following areas:

- Mines and/or spoils that have a high pyrite concentration
- Areas where there is an adequate supply of oxygen
- Areas where water discharge throughout the mine is low
- Areas of the mine that underwent recent flooding, causing conditions favourable for the oxidation of pyrite within the host rock

The data in Table 2-6 and Table 2-7 are plotted in Figure 2-32 and Figure 2-33 to provide a comparison of the results from the two different mines. Referring to these figures, the conclusions of Banks (2004) can be confirmed as follows:

- The sulphide minewater is seen to be more acidic and has very low pH values.
- The concentration of sulphide is higher in sulphide metal mines (as expected).
- The coal mine water has a higher alkalinity and a higher pH level than that of the sulphide mine.
- Metal concentrations in the sulphide mine are higher.

An important phenomenon occurs in mines. This is known as the First Flush phenomenon, and would generally occur after the closure of a mine or during a flooding even while the mine is in operation. This basically involves a rush of water into the mine. Chemical reactions will alter the quality of the water.

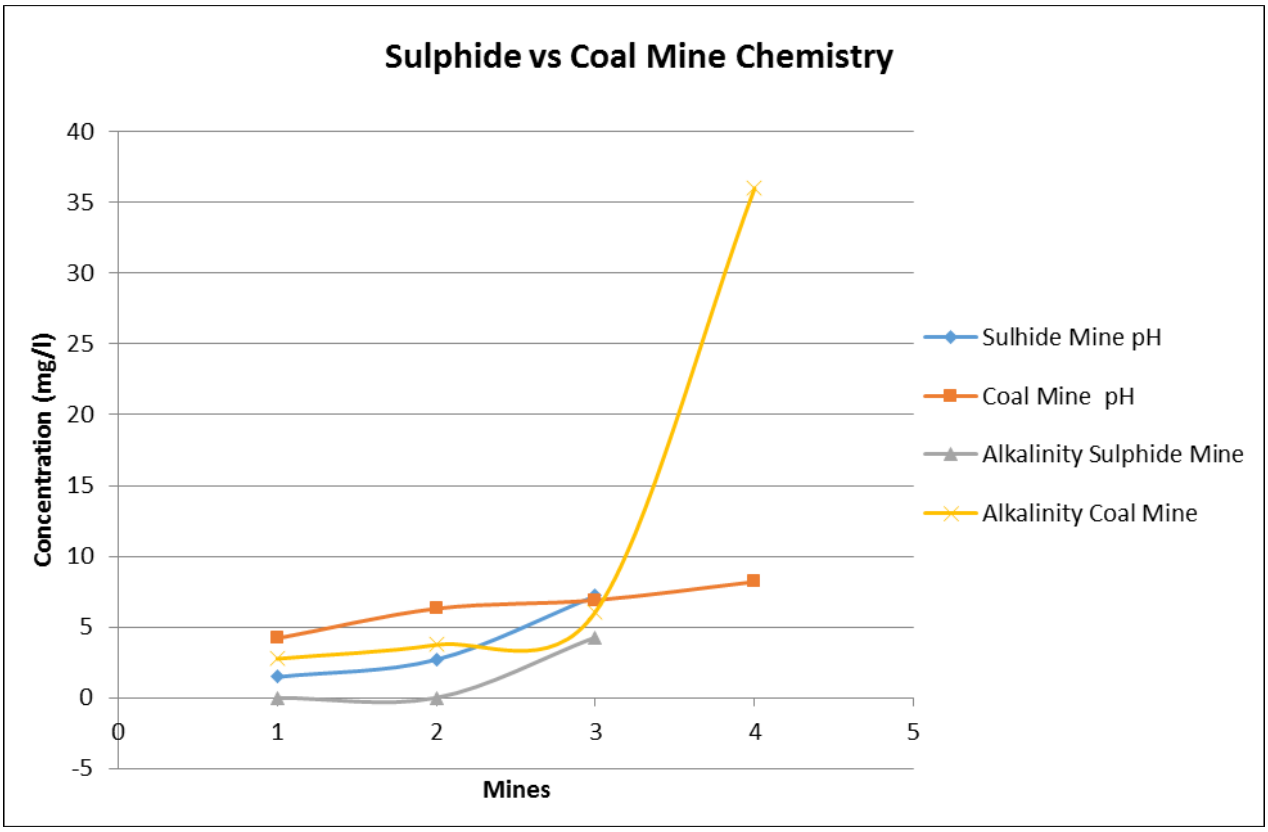


Figure 2-32: Comparison of the chemical constituents of sulphide and coal mines

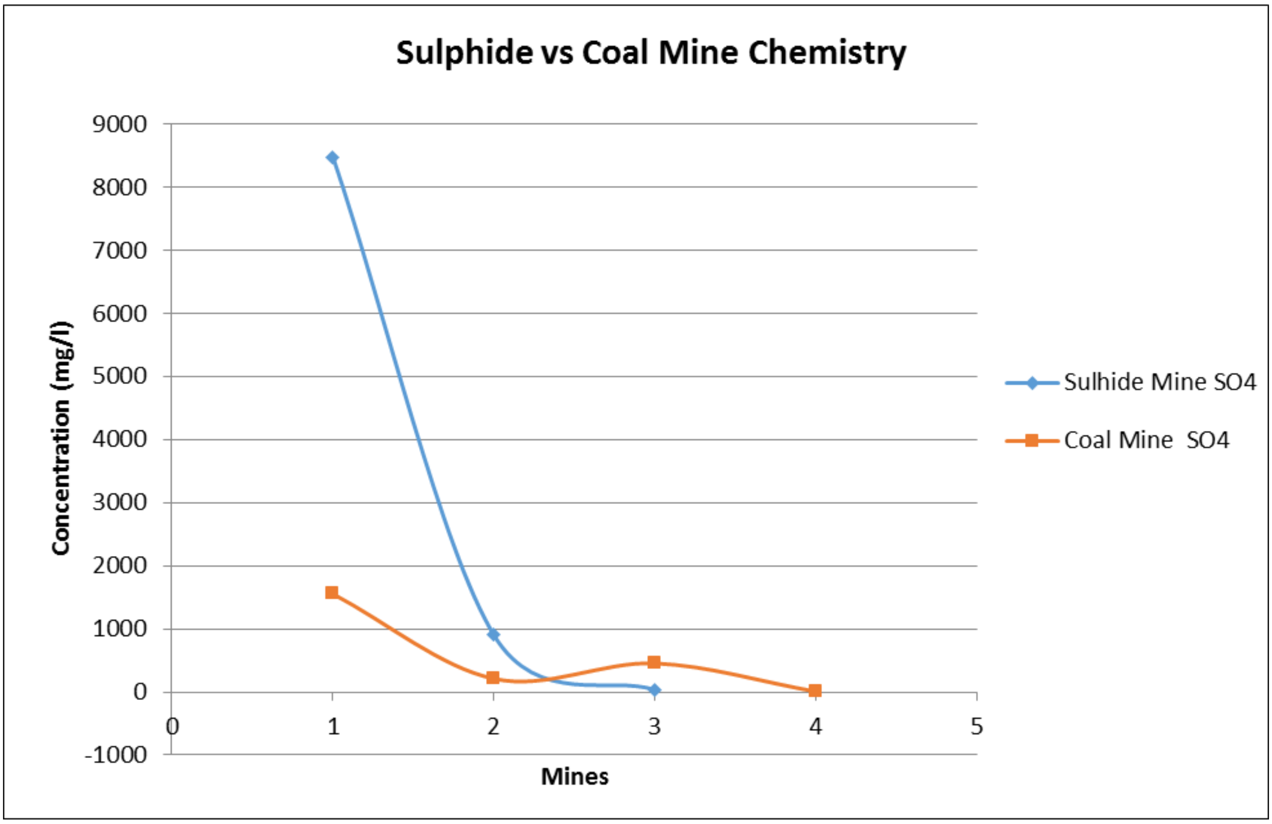


Figure 2-33: Comparison of the sulphate content in sulphide and coal mines

In conclusion, mining activities alter the void ratio of the subsurface and allow oxygen to enter the system, thus providing a catalyst for oxidation reactions. Mine water has a high acid content, high concentration of toxic metals and generally a very low pH level, particularly in areas of high acid rock drainage. Newly recharged groundwater is found to have a decreasing chloride content away from the coastal areas. The high concentration of CO_2 within the soil contributes to elevated concentrations of CO_2 in the groundwater from percolation.

2.7 CONCLUSION

In summary, a thorough understanding of geological structures at depth has been seen to be a precursor to understanding the potential of groundwater within those structures. In light of this, an emphasis of the current project will be to analyse the geology at depth from the perspective of potential deep aquifers.

From the literature review on deep aquifers, the following conclusions may be drawn:

- The nature and type of the bedrock control the type of aquifer found in the formation.
- Fracturing and weathering contribute to the (secondary) porosity of the formations in which the aquifers occur.
- The porosity of a formation is a determining factor in the storage potential of the aquifer.
- Storativity and transmissivity generally decrease with depth.
- Dolomite areas, especially karsts, are often associated with high-yielding aquifers.
- The groundwater at significant depth is considered to be saline and influenced directly by circulation depths.
- Elevated concentrations of sodium and chloride can be expected in deep aquifers.
- Changes in pressure within the deep aquifer can have an effect on the upper aquifers if these aquifer systems are connected hydraulically.

The Malmani dolomites can be considered the largest of aquifers in South Africa. The groundwater within the dolomite cavities can pose problems for gold mining along an interconnected network of fractures and faults. The transmissivity and storativity values decrease with depth in dolomite environments.

The best possible water source for deep aquifers would be in sedimentary basins, primarily within sandstone formations. Permeability, porosity and recharge in areas will determine the volume of recharge to an aquifer. Pressurisation from the confining layers plays a significant role in determining if the system will be artesian or not. The best possible areas for deep aquifer systems would be in folded geological formations in which the water will be trapped in the host rock and fractures. Natural springs may provide insight into the quality and type of water facies within the deeper aquifer system. Newly recharged groundwater is found to have a decreasing chloride content away from coastal areas. The high concentrations of CO_2 within the soil contribute to elevated concentrations of CO_2 in the groundwater from percolation.

In conclusion, the research efforts directed towards deep groundwater have increased slowly in the last decade in South Africa, driven by new developments such as shale gas exploration, the injection of brines into deep aquifers, carbon sequestration, deeper mineral exploration and geothermal energy. However, these investigations are site-specific in most cases. There is a need to consolidate all the site-specific research that has been done to allow for a more holistic view on deep groundwater in South Africa.

CHAPTER 3: ASSESSMENT OF POTENTIAL DEEP GROUNDWATER RESOURCES

Earth materials vary tremendously in their capacity to hold water (porosity) and their capacity to transmit water (hydraulic conductivity or permeability). As a result, our ability to find supplies of subsurface water or predict flow paths is only as good as our understanding of the distribution of porosity and permeability, which is a function of geological material. Usually, many different geological processes combine to produce the distribution of geological material in a region. The geology of South Africa is therefore analysed in this chapter to allow insight into the country's potential deep aquifers.

The geology of South Africa is reviewed from a deep groundwater perspective to provide an initial analysis of potential deep aquifer systems. The geology is subdivided into pre-Karoo, Karoo and post-Karoo geologies, where the geological groups under each geological period are analysed for deep groundwater based on the information that is currently available. Additionally, the information from thermal springs and the general depth of fracturing is considered and combined in a summary of the identified potential deep groundwater aquifers based on the geological groups.

3.1 BASIC AQUIFER CONCEPTS

Aquifers are the storage bodies of groundwater. To use of the groundwater resources associated with the aquifers responsibly, the aquifers should be well defined and understood. In this section, some basic concepts of aquifers are reviewed. First, aquifers are defined in terms of their water transport and storage characteristics. Then, the difference between primary and secondary aquifers is described.

3.1.1 Aquifer definitions

Aquifers are generally divided into three groups: aquifers, aquitards and aquicludes (Figure 3-1). Each of these groups is defined in terms of its water transport properties. An aquifer transmits water with ease, while an aquitard transmits water slowly, and an aquiclude is impermeable and thus transmits no, or very little, water (Figure 3-2).

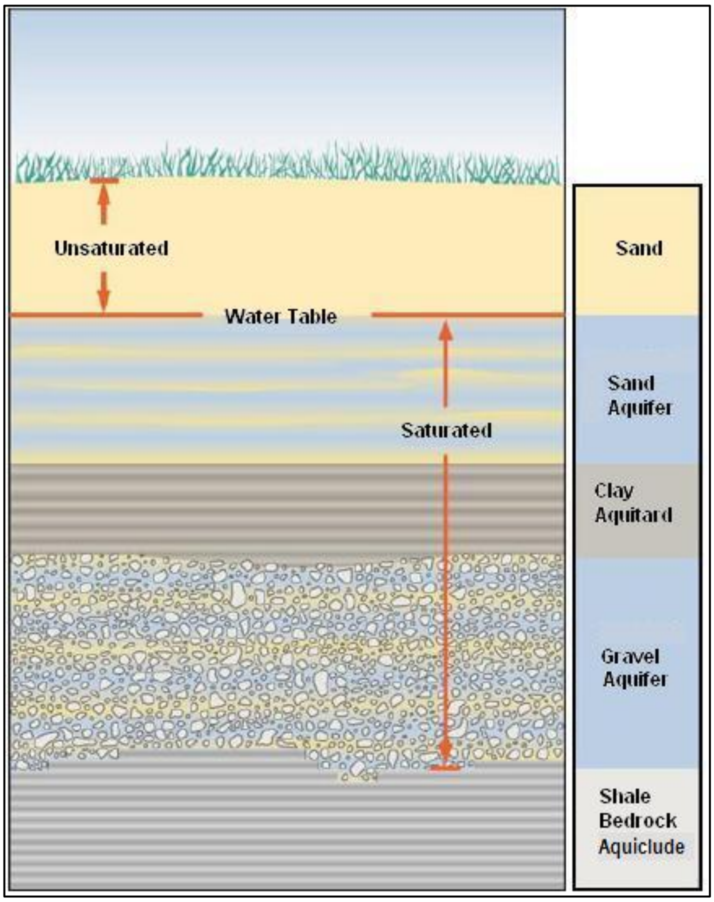


Figure 3-1: Types of aquifers

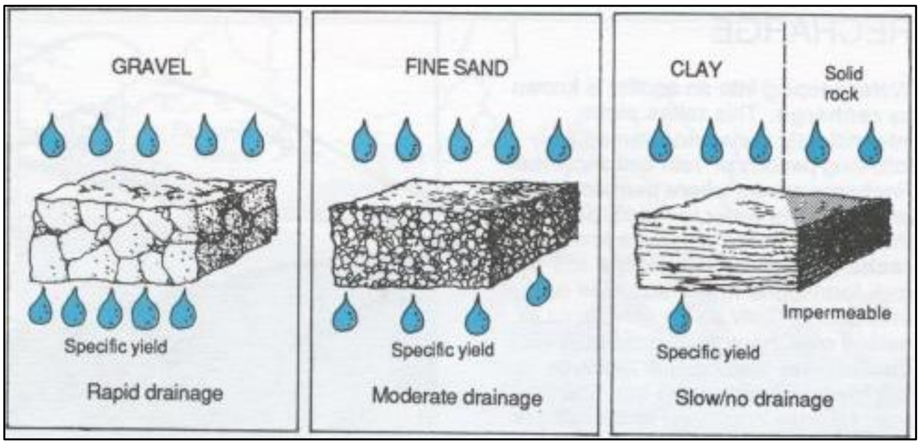


Figure 3-2: The rate at which water is transmitted through different materials

3.1.2 Types of aquifers

There are different types of aquifers, which correspond to the different ways in which a geological formation transmits and stores water. Aquifers are divided into two general types: primary and secondary aquifers (Figure 3-3).

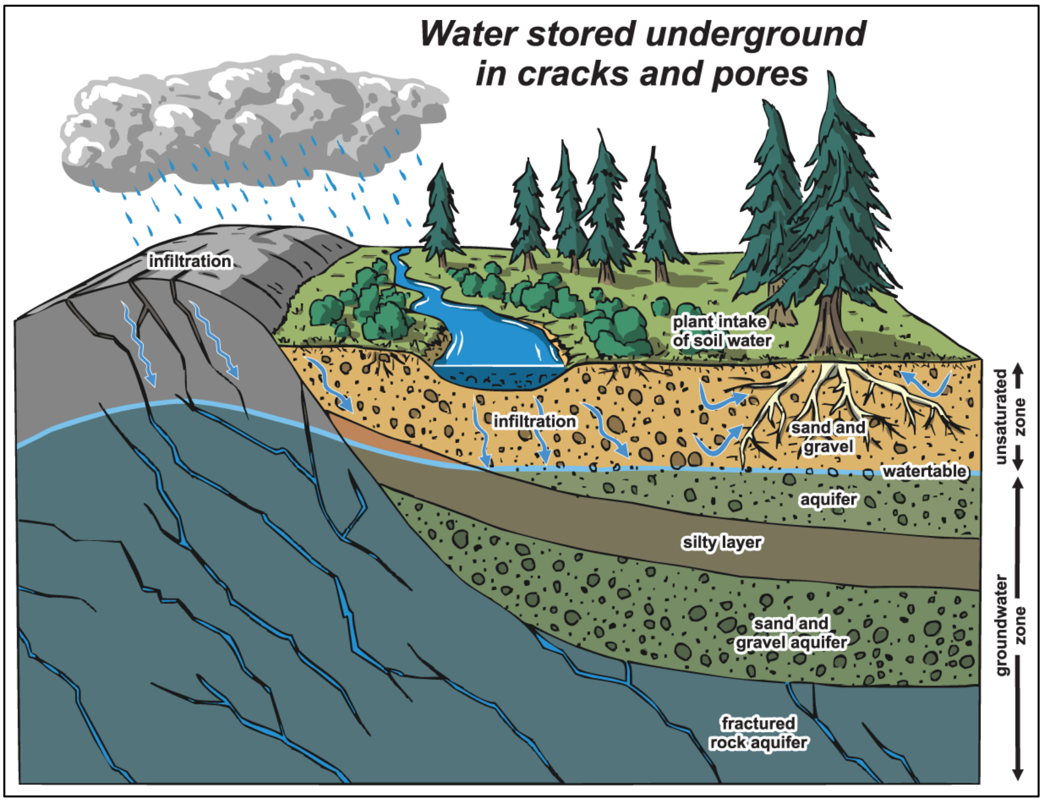


Figure 3-3: Primary and secondary aquifers

3.1.2.1 Primary or porous aquifers

A primary or porous aquifer is defined as an aquifer in which groundwater moves through the original (or primary) interstices (or openings) of the geological formation (Figure 3-4). Examples of primary aquifers include sand aquifers, alluvial aquifers, gravel aquifers and sandstone aquifers (Figure 3-5).

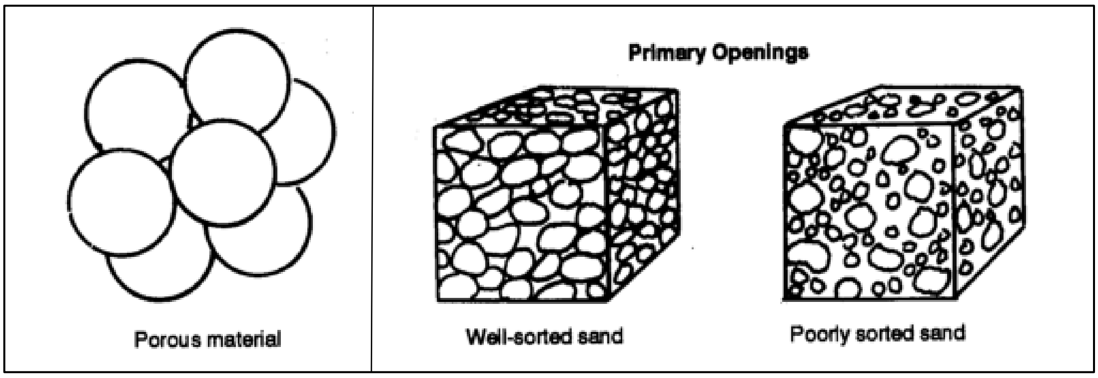


Figure 3-4: Primary openings in porous media

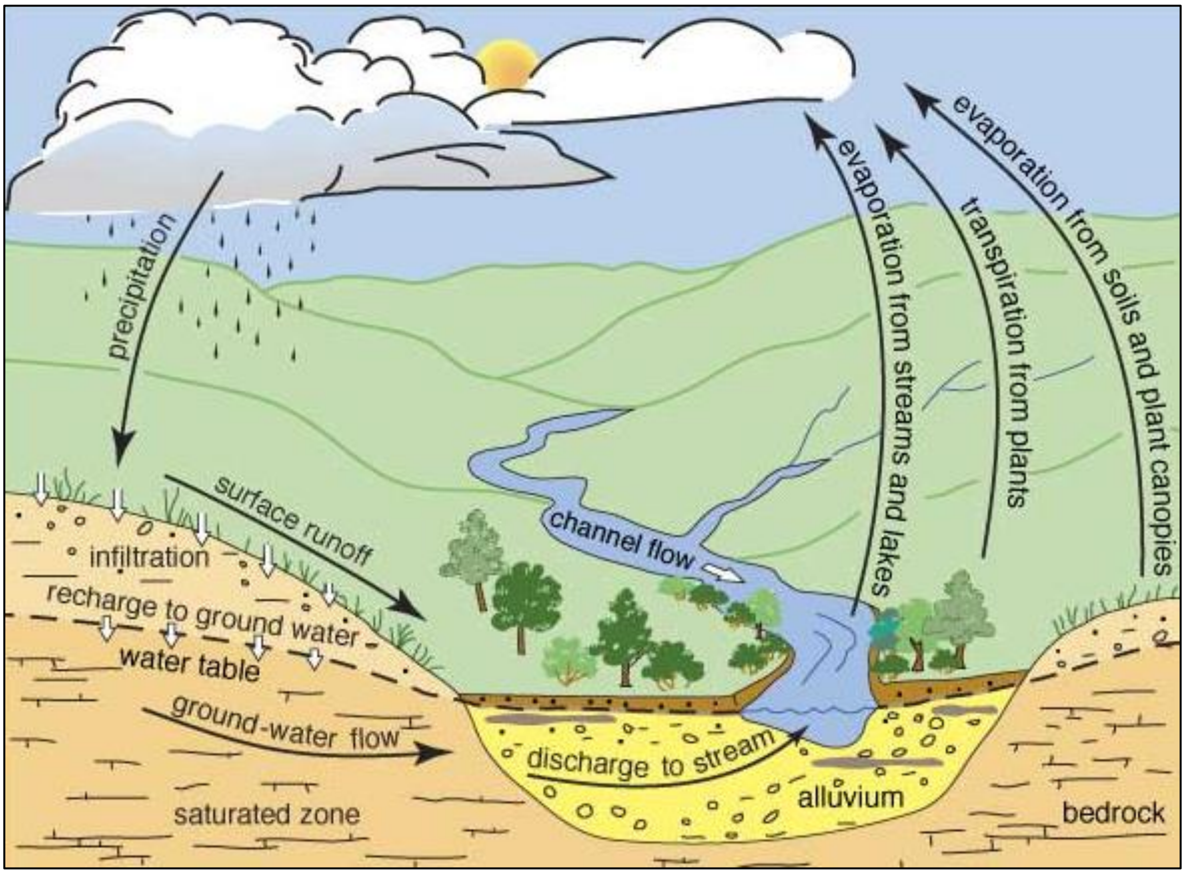


Figure 3-5: An example of a primary aquifer: an alluvial channel aquifer

3.1.2.2 Secondary or fractured aquifers

A secondary or fractured aquifer is defined as an aquifer in which groundwater moves through secondary openings and interstices, which developed after the rocks were formed (Figure 3-6). Secondary openings form as a result of weathering, fracturing, faulting and dissolution (Figure 3-7).

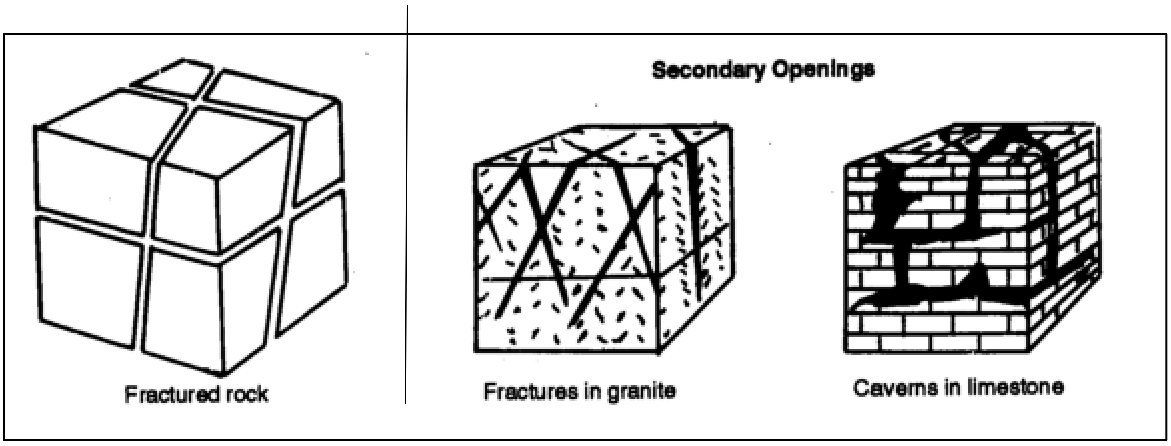


Figure 3-6: Secondary openings in aquifers

The water movement in these aquifers is dominantly through the secondary openings, and thus hydraulic behaviour is controlled by these structures. For example, in a fractured aquifer, the hydraulic behaviour is controlled by the fractures, and the porous matrix acts as a storage system, while the fractures are the transport channels (Figure 3-8).

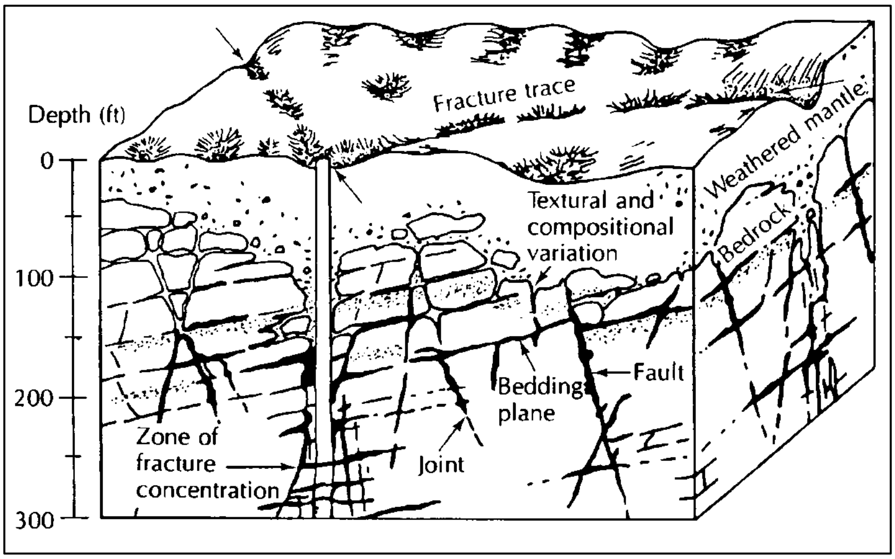


Figure 3-7: Secondary openings

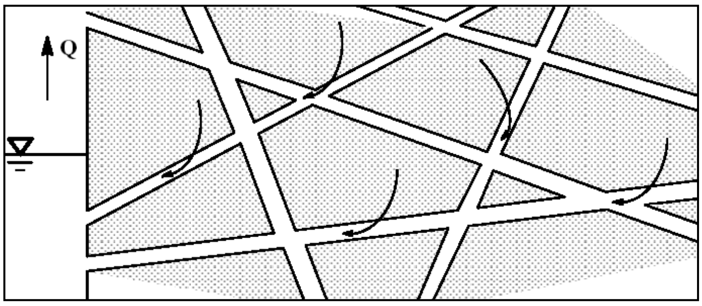


Figure 3-8: Groundwater movement within fractures

Other types of secondary aquifers include fractured basement rocks, fractured volcanic terrains and karst aquifers. Fractured basement rocks are conceptually one component of a large single system, comprising the underlying igneous basement rocks that are fractured and the overlying weathered aquifer (Figure 3-9). The fractured basement rocks can thus be considered to be a semi-confined layer between the upper weathered aquifer and the underlying unfractured bedrock aquifer. A typical geological profile of a fractured basement rock system is shown in Figure 3-10, indicating the changes in porosity and hydraulic conductivity with depth.

To summarise the types of aquifers in terms of the openings in which water is transported, Figure 3-11 includes a number of different lithologies, the corresponding types of openings in each and the percentage of void space. The upper layer in Figure 3-11 is a capping basalt layer. This layer has vesicles, as well as fractures. Vesicles are primary openings, while fractures are secondary openings. Thus, for this lithology type, both types of openings will be responsible for transporting water.

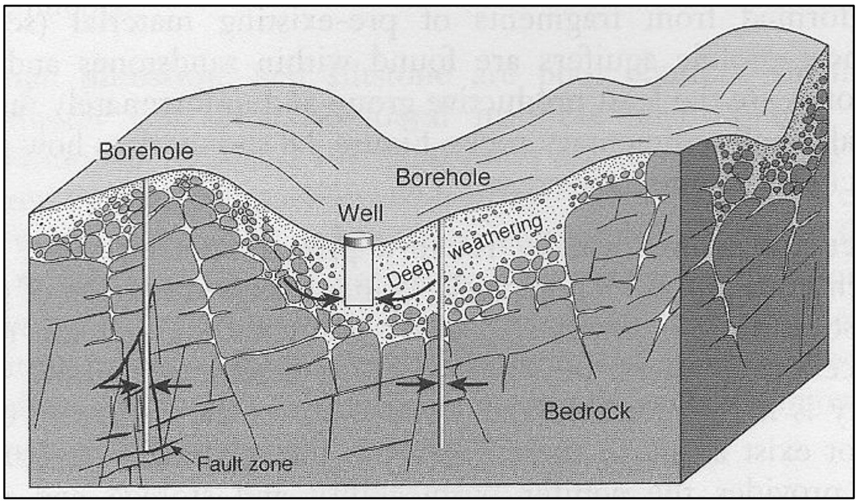


Figure 3-9: Basement (bedrock) fractured aquifer

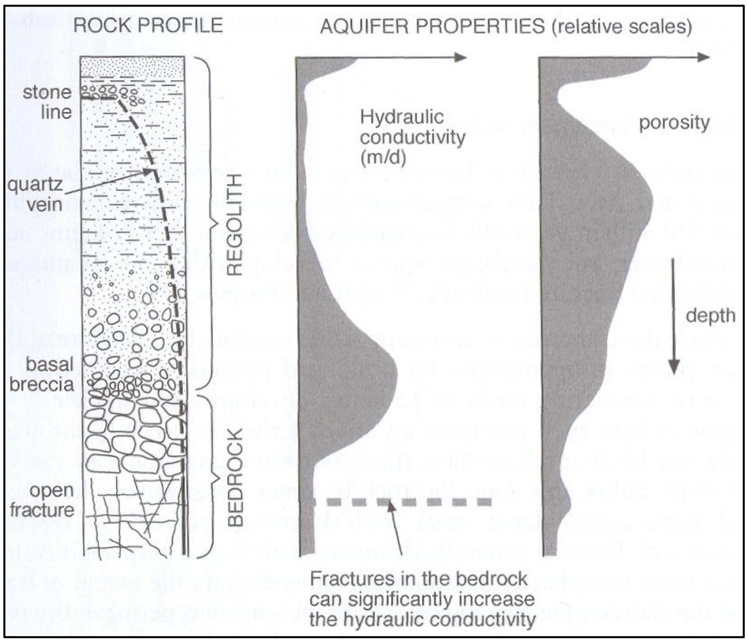


Figure 3-10: Increase in hydraulic conductivity due to the influence of fractures within the basement rocks

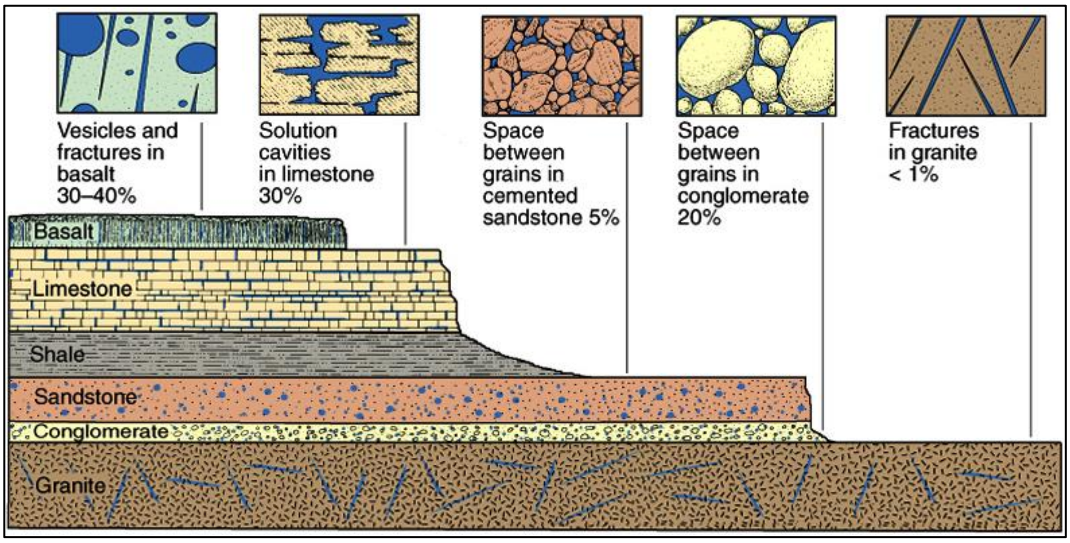


Figure 3-11: Different lithologies representing different types of openings

3.2 GENERAL GEOLOGY AND GEOHYDROLOGY OF SOUTH AFRICA

A simplified geological map of South Africa is shown in Figure 3-12. The main geological units that are investigated in this project are listed in Table 3-1. Each geological group is evaluated in terms of its geohydrological characteristics. The geohydrological characteristics are based on available information, which is typically mostly limited to the shallow systems that are utilised for water supply. The basics of aquifer type and porosity are described, followed by a discussion of South Africa's geology and geohydrology.

Table 3-1: South African geological units to be investigated

Pre-Karoo Geology	Karoo Geology	Post-Karoo Geology
Limpopo Belt	Main Karoo Basin	Mesozoic Geology
Archaean Greenstone Belts	Springbok Flats Basin	Cenzoic Geology
Archaean Granites and Gneisses	Ellisras Basin	
Pongola Supergroup	Tshipise and Tuli Basins	
Dominion Group	Karoo Dolerite Suite	
Witwatersrand Supergroup		
Ventersdorp Supergroup		
Transvaal Supergroup		
Bushveld Igneous Complex		
Waterberg and Soutpansberg Groups		
Namaqua-Natal Metamorphic Province		
Saldania Belt - Malmesburg Group		
Natal Group		
Cape Supergroup		

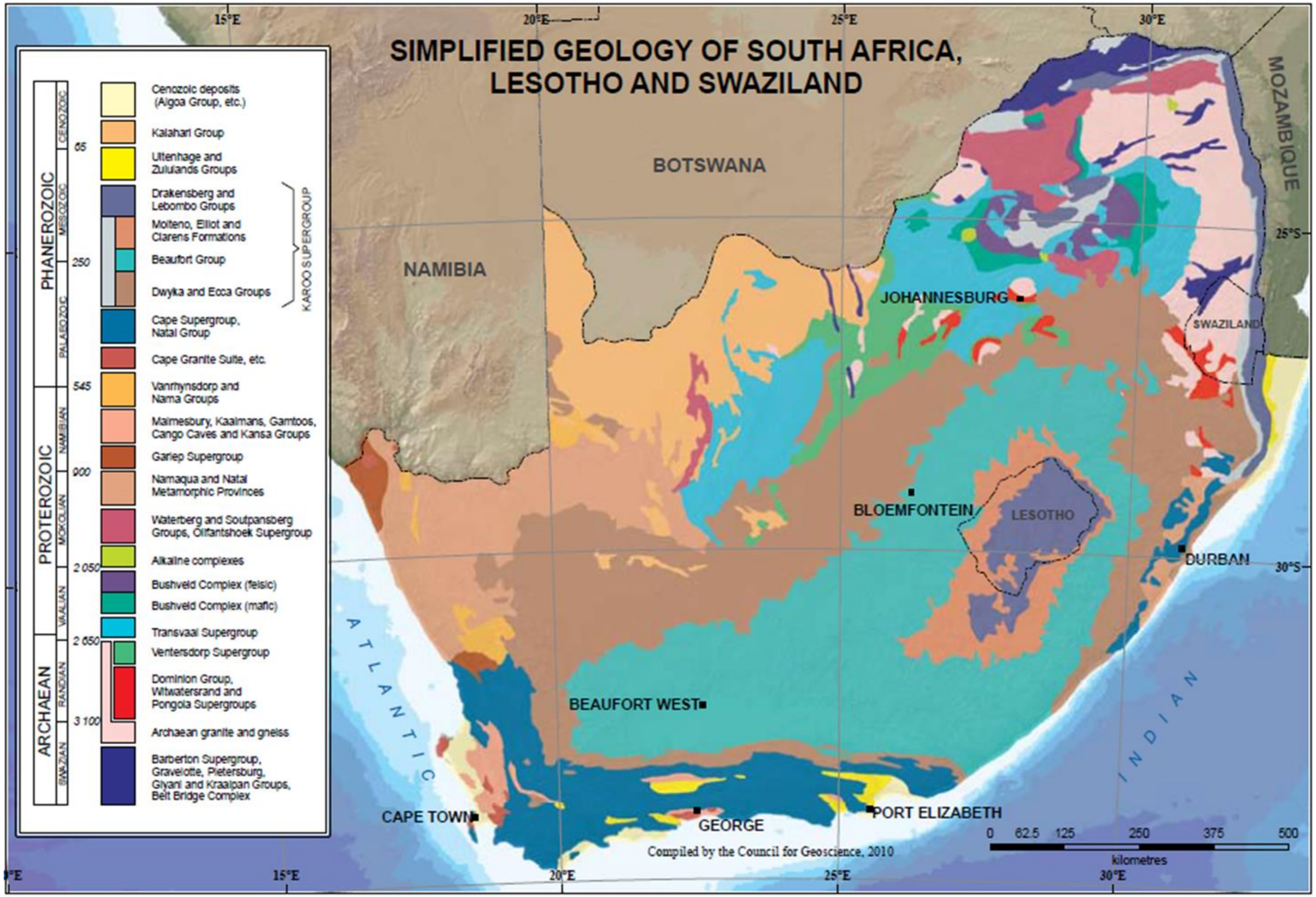


Figure 3-12: Simplified geology of South Africa (Viljoen et al., 2010)

3.3 PRE-KAROO GEOLOGY

South Africa has numerous sedimentary basins, most of which have been metamorphosed (Figure 3-13). From Figure 3-13, it can been seen that the largest portion of South Africa is underlain by fractured meta-sedimentary rocks. In this section, the pre-Karoo meta-sedimentary basins summarised in Table 3-2 are discussed. From Table 3-2, it can be seen that the sedimentary basins from approximately the Namibian age and older are highly deformed, with varying degrees of metamorphism, folding, faulting and thrusting. It can be concluded that only basins of the Namibian age and younger will have the potential to form large primary porosity aquifers. Viljoen et al. (2010) drew similar conclusions when evaluating the different sedimentary basins for their CO_2 storage potentials.

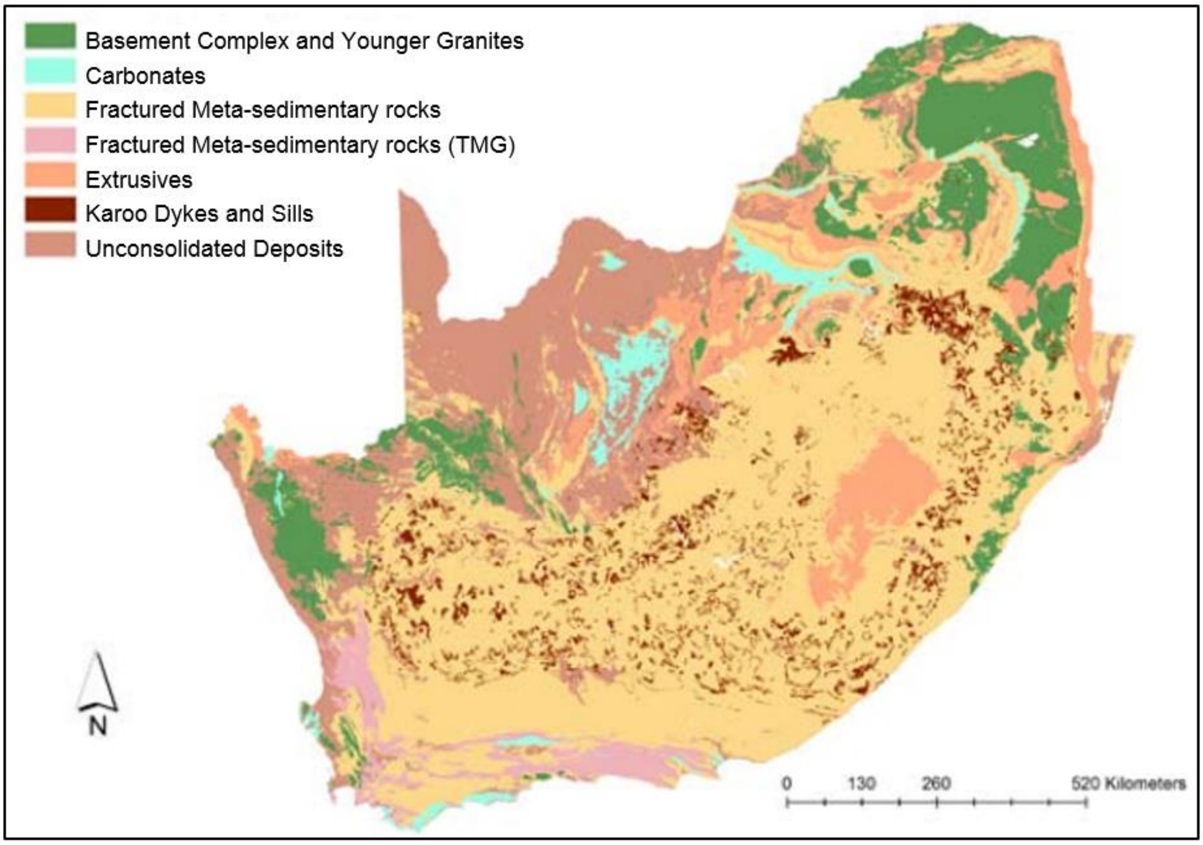


Figure 3-13: Principal aquifer types in South Africa (from LeMaître and Colvin, 2008)

Table 3-2: Features of the pre-Karoo sedimentary basins in South Africa (modified from Viljoen et al., 2010)

Basin/Sedimentary unit	Main rock types	Age	Deformation	Thickness
Archaean Greenstone belt	Ultra-mafic, mafic and felsic volcanics, shale, schist, greywacke, banded ironstone, chert, quartzite and conglomerate	3 500 - 2 700	folded; metamorphosed	uncertain
Pongola Supergroup	Mafic and felsic volcanics, conglomerates, quartzite, and sericite schist	2 800 - 3 000	folded; faulted; sheared; low-grade metamorphism	~ 8 000 m
Dominion Group	Mafic and felsic volcanics, conglomerates, quartzite, and sericite schist	~ 3 000	faulted; metamorphosed	~ 3 000 m
Witwatersrand Supergroup	Quartzite, shale, conglomerate, banded ironstone	2 900 - 2 700	faulted; folded; metamorphosed	~ 7 500 m
Ventersdorp Supergroup	Mafic and felsic volcanics, quartzite, conglomerate, shale limestone and chert	~ 2 700	faulted; thrusted	> 5 000 m
Transvaal Supergroup	Dolomite, banded ironstone, shale, quartzite, mafic volcanics	2 100 - 2 650	thrusting; faulting; contact metamorphism	> 8 000 m
Rooiberg Group	Mainly silicic and basic lavas with sandstone/shale lens, tuff	2 061 - 2 052	low-grade metamorphism	5 000 m
Soutpansberg, Blouberg and Waterberg Groups	Sandstone/quartzite, conglomerate, shale, greywacke and lava	2 060 - 1 700	faulted; folded and tilted blocks	> 7 000 m
Olifantshoek Supergroup	Quartzite, shale, conglomerate, basalt and tuff	~ 1 700 - 2 000	folded; thrusted; low-grade metamorphism,	max 5 000 m
Sedimentary basins of the Namaqua-Natal and Kheis Provinces	Amphibole, amphibole schist, quartz-sericite schist, biotite schist, quartzite, conglomerate, dolomite, volcanic rocks	~ 1 200 - 1 000	strongly folded; metamorphosed	unknown
Namibian to early Cambrian successions	Sandstone/quartzite, phyllite/shale, greywacke, marble/dolomite/limestone, schist, diamictite	770 - 530	strongly folded; metamorphosed	up to 5 000 m
Cape Supergroup	Orthoquartzite, sandstone and shale	470 - 340	strongly folded; faulted, metamorphism	4 200 m
Natal Group	Quartz arenite, sandstone and conglomerate	450	undeformed	< 800 m

3.3.1 Limpopo Belt

The Limpopo Belt is a broad zone of gneisses located between the Kaapvaal Craton and the Zimbabwe Craton (Figure 3-14), extending over eastern Botswana, southern Zimbabwe and northern South Africa (Kramers et al., 2006). The Limpopo Belt has been subdivided into three domains: the southern Marginal Zone, the Central Zone and the northern Marginal Zone (Lourens, 2013) (see Figure 3-15). These domains are characterised by high-grade metamorphism and shear zones along the borders (Kramers et al., 2006).

Lourens (2013) classified the aquifers of the Limpopo Belt as intergranular and fractured. These aquifers are structurally controlled with significant groundwater movement restricted to secondary features such as faults and fractures. The aquifers of the Limpopo Belt are thus highly variable due to their secondary aquifer characteristics (Bush, 1989, as cited by Lourens, 2013).

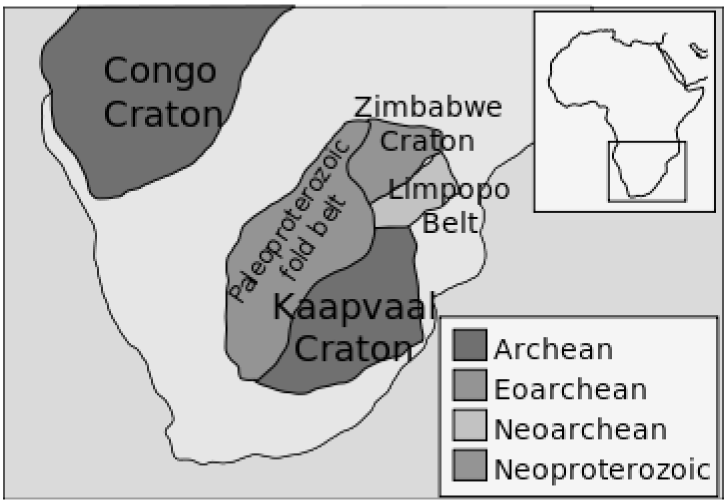


Figure 3-14: Location of the Limpopo Belt in southern Africa (Wikipedia, 2017)

The intergranular aquifers are restricted to the upper weathered zone and have limited groundwater potential due to a high clay content, but serve as a means of recharge to the lower fractured aquifer (Bush, 1989, as cited by Lourens, 2013).

The occurrence of thermal springs within the Limpopo Belt serves as an indication of long, deeper groundwater flow systems (Lourens, 2013). Figure 3-16 indicates the location of thermal springs in South Africa as reported by Kent (1949). The Limpopo Belt is represented as the main lithology, consisting of schists in Figure 3-16. The thermal springs located along the northern boundary of Limpopo are found within this formation. Dhansay et al. (2014) selected a site in the Limpopo Belt to evaluate the low-enthalpy geothermal potential for South Africa. The highest recorded hot spring was found near the geothermal test site. According to Dhansay et al. (2014), the spring reaches a surface temperature of 70 °C and circulates to a depth of 2 km.

However, reports by Vegter (2001) indicated poor groundwater quality (Lourens, 2013). Vegter (2001) analysed 750 samples, of which more than 50% were of non-potable quality. Lourens (2013) therefore concluded that the Limpopo Belt may be regarded as being associated with low-yielding aquifers. However, the analyses of Vegter (2001) were focused on shallow groundwater resources and did not consider the deeper aquifer systems. A maximum reported yield of 25 ℓ/s is likely due to a borehole intersecting a major fault or fracture within the deeper secondary aquifer.

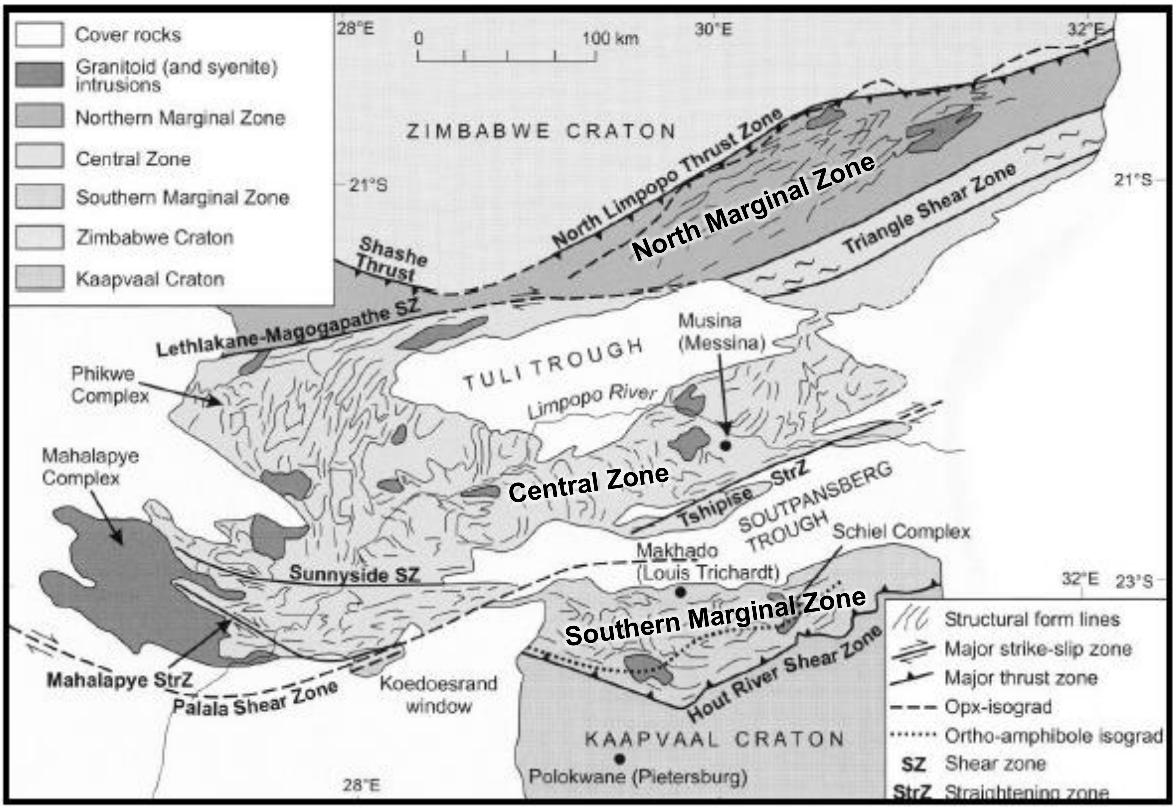


Figure 3-15: Limpopo Belt showing the three domains (modified from Kramers et al., 2006)

3.3.2 Archaean Greenstone belts

Archaean greenstone belts constitute the oldest preserved material on the earth's surface and commonly attain widths of 10 to 50 km and lengths of 100 to 300 km (Brandl et al., 2006). They are made up of extrusive mafic and, to a lesser degree, ultramafic and felsic rocks (Brandl et al., 2006). Sedimentary rocks can also occur within the igneous successions, but most commonly occur in the upper part of the greenstone belts (Brandl et al., 2006). Figure 3-17 is a schematic of a generalised profile through a greenstone belt.

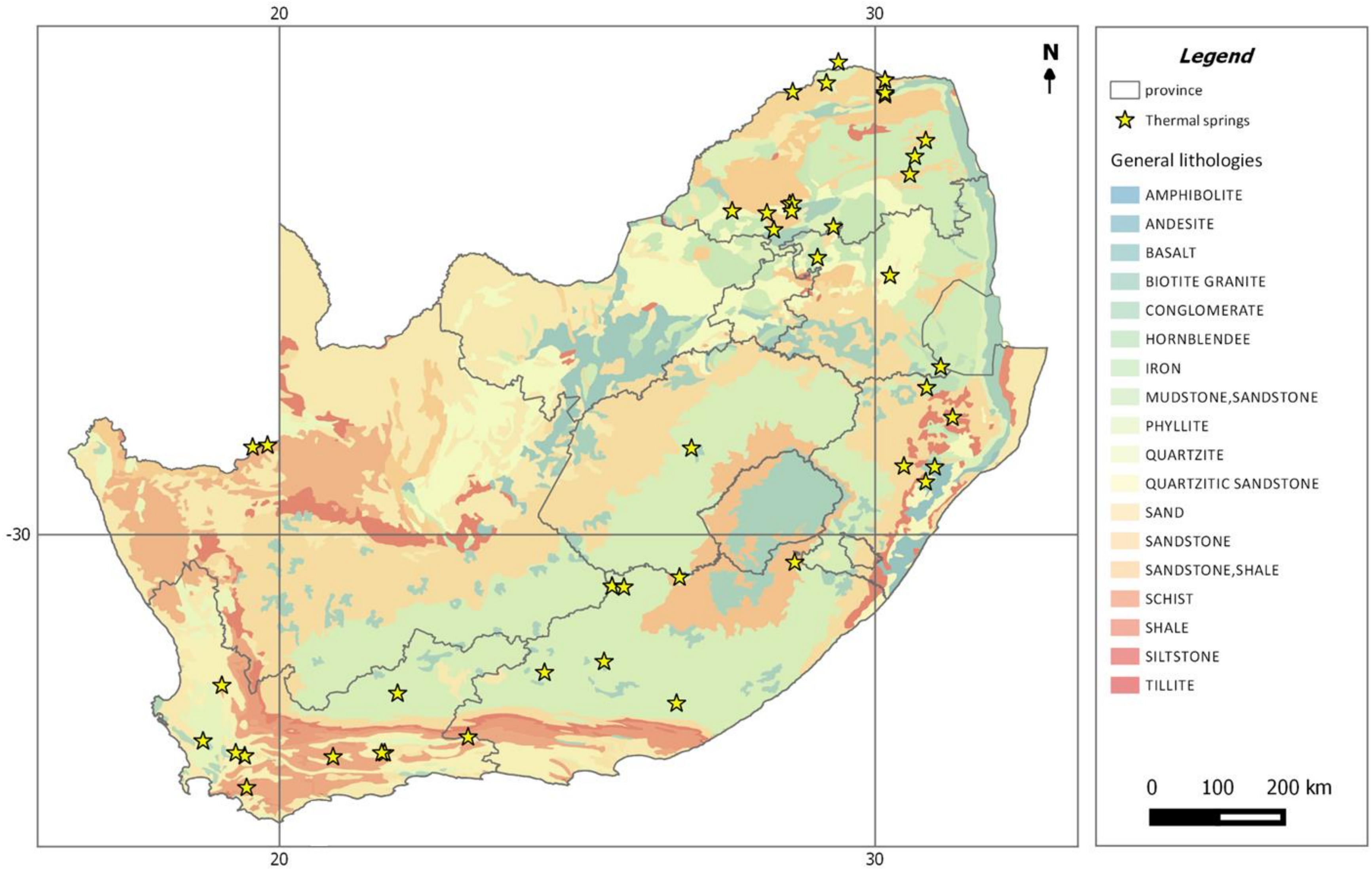


Figure 3-16: Location of thermal springs in South Africa (based on data from Kent, 1949)

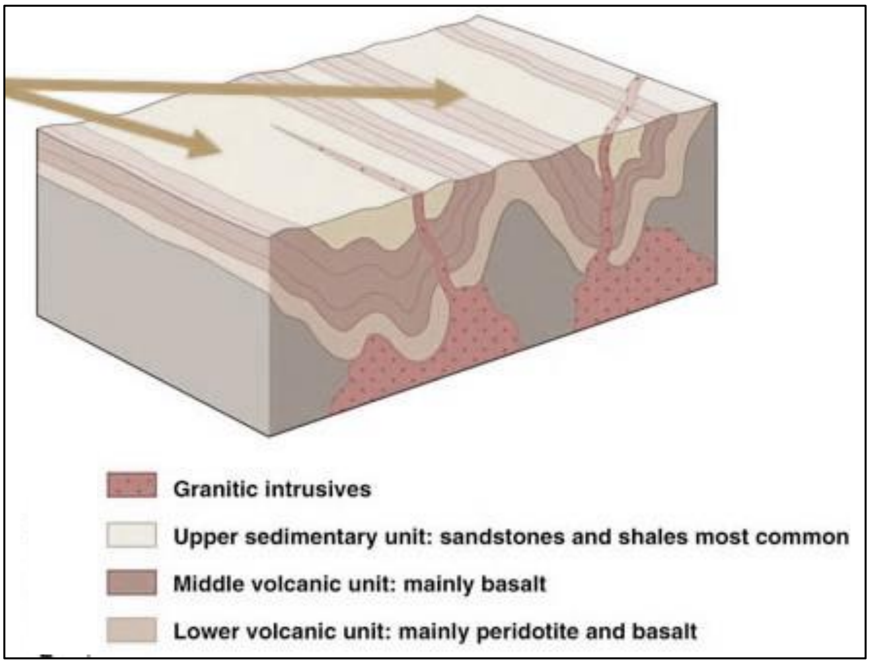


Figure 3-17: Typical profile of a greenstone belt showing two adjacent greenstone belts (TOE, 2017)

The Kaapvaal Craton in South Africa consists of a number of greenstone belts and remnants, the most important of which are the Barberton, Pietersburg, Murchison, Giyani and Kraaipan greenstone belts (Lourens, 2013) (Figure 3-18).

3.3.2.1 Barberton Greenstone Belt

The rocks of the Barberton Greenstone Belt are mostly impermeable (Lourens, 2013). Fractures related to faults and intrusive dykes enhance permeability, but low yields are still found for the deeper fractured aquifer (Sami et al., 2002, as cited by Lourens, 2013). Sami et al. (2002) performed analyses of 64 boreholes within the Barberton Greenstone Belt. Half of the boreholes that were analysed were dry, with the remainder having a yield range of 0.1 to 0.5 ℓ/s. However, these analyses were conducted for shallow groundwater systems. Sami et al. (2002) reported a relationship between yield and the depth of the water strike, where the higher yields were suggested to relate to shallower water strikes.

The Barberton Greenstone Belt or Barberton Supergroup is divided into three main groups: the Moodies Group, the Fig Tree Group and the Onverwacht Group. Owen and Madari (2009) evaluated the geohydrology of the Limpopo Basin, with a focus on the Moodies Group of the Archaean greenstone belts. The Moodies Group is made up of sedimentary rocks overlying the schistose and metabasic lavas and intrusions of the Onverwacht Series (Du Toit, 1954, as cited by Owen and Madari, 2009).

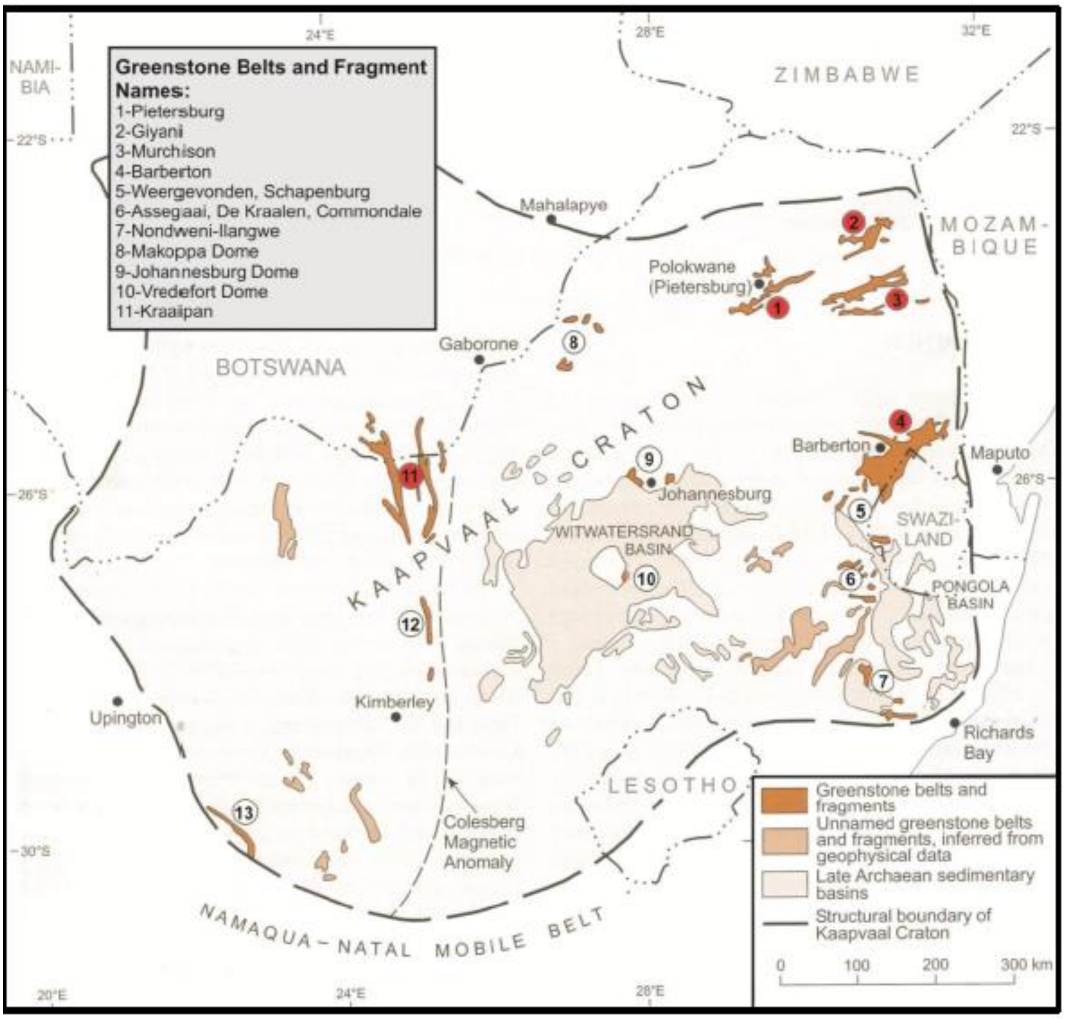


Figure 3-18: Location of the greenstone belts and fragments on the Kaapvaal Craton. The red circles represent important greenstone belts (Brandl et al., 2006).

The rocks of the Moodies Group have been altered and metamorphosed. Although the original sedimentary strata may have formed good aquifers, the alteration has reduced their water-bearing properties (Owen and Madari, 2009). These meta-sediments are further considered a poor groundwater resource because of the presence of phyllites, which consist of minute crystals of micaceous minerals arranged in a platy manner that hinders groundwater movement through these rocks (Owen and Madari, 2009).

On the other hand, the meta-sediments have also been highly folded by strong over-thrusting with brecciation and mylonitisation, which has increased the secondary porosity of the unit. The occurrence of groundwater is thus dependent on the development of fractures and openings, which improves porosity and permeability. Secondary porosity and permeability, especially along contacts, lead to high-yielding local aquifers.

3.3.2.2 Pietersburg Greenstone Belt

The Pietersburg Greenstone Belt is found near Polokwane and forms a narrow, elongated, north-east trending outcrop, with a length of 125 km and a width of 20 km (Brandl et al., 2006) (see Figure 3-18). A sequence of mainly volcanic rocks forms the basal sequence of the Pietersburg Greenstone Belt which is unconformably overlain by terrigeneous sediments known as the Uitkyk Formation (Brandl et al., 2006).

Lourens (2013) considered the Mothiba, Eersteling and Zandrivierspoort formations as the most important units in terms of groundwater. Lourens (2013) also stated that the permeability of the rocks generally decreases with an increase in weathering due to the production of clay in the weathering process. The storage capacity of the rocks is also limited (Du Toit and Sonnekus, 2010, as cited by Lourens, 2013). However, the groundwater quality of the Pietersburg Greenstone Belt has been found to be good, with only fluoride concentrations occasionally exceeding the maximum allowable limit (Du Toit and Sonnekus, 2010).

Lourens (2013) classified the belt as being associated with moderate- to high-yielding aquifer systems, with 63% of the boreholes analysed by Du Toit and Sonnekus (2010) having yields larger than 2 L/s. However, over-exploitation may cause borehole failure due to the low storage capacity of the aquifers.

3.3.2.3 Murchison and Giyani Greenstone belts

The Giyani and Murchison Greenstone belts are situated at the northeastern edge of the Kaapvaal Craton and have similar geohydrological characteristics to the Pietersburg Greenstone Belt (Lourens, 2013). However, the groundwater of the Murchison Greenstone Belt is not potable due to high levels of nitrates. The majority of the boreholes analysed by Du Toit and Lelyveld (2006), as cited by Lourens (2013), were found to have electrical conductivity values ranging from 70 to 300 mS/m. Conversely, the groundwater quality of the Giyani Greenstone Belt is usually good with an average electrical conductivity value of 58 mS/m (Lourens, 2013).

Lourens (2013) classified the Murchison Greenstone Belt as being associated with a low- to moderate-yielding aquifer system, with a maximum reported yield of 8 ℓ/s. The Giyani Greenstone Belt was classified as a moderate- to high-yielding shallow aquifer system, with a maximum reported yield of 21 ℓ/s (Lourens, 2013).

3.3.2.4 Kraaipan Greenstone Belt

Rocks belonging to the Kraaipan Greenstone Belt are found south of Botswana as three narrow north-northwest-trending sections (Brandl et al., 2006) (see Figure 3-18). Van Dyk and Kisten (2006), as cited by Lourens (2013), analysed 257 boreholes within the Kraaipan Greenstone Belt, and 233 were found to be dry. Thus, the Kraaipan Greenstone Belt is considered to be associated with a low-yielding aquifer system. However, along the contact area with granitic rocks, some high-yielding boreholes were found.

3.3.2.5 Summary

The Archaean greenstone belts are meta-sedimentary rocks that have both intergranular and secondary porosity (Owen and Madari, 2009), but the porosity has been reduced due to metamorphic processes, including recrystallisation. Owen and Madari (2009) considered the groundwater development potential of the Archaean greenstone rocks to range from low to high, being highly dependent on local conditions, with an average classification of moderate.

3.3.3 Archaean granites and gneisses

The Archaean granite and gneiss intrusions are situated on the Kaapvaal Craton (Figure 3-19). Lourens (2013) discussed the Archaean granites of Limpopo and Mpumalanga as two separate regions: the Polokwane/Pietersburg Plateau and the Lowveld region.

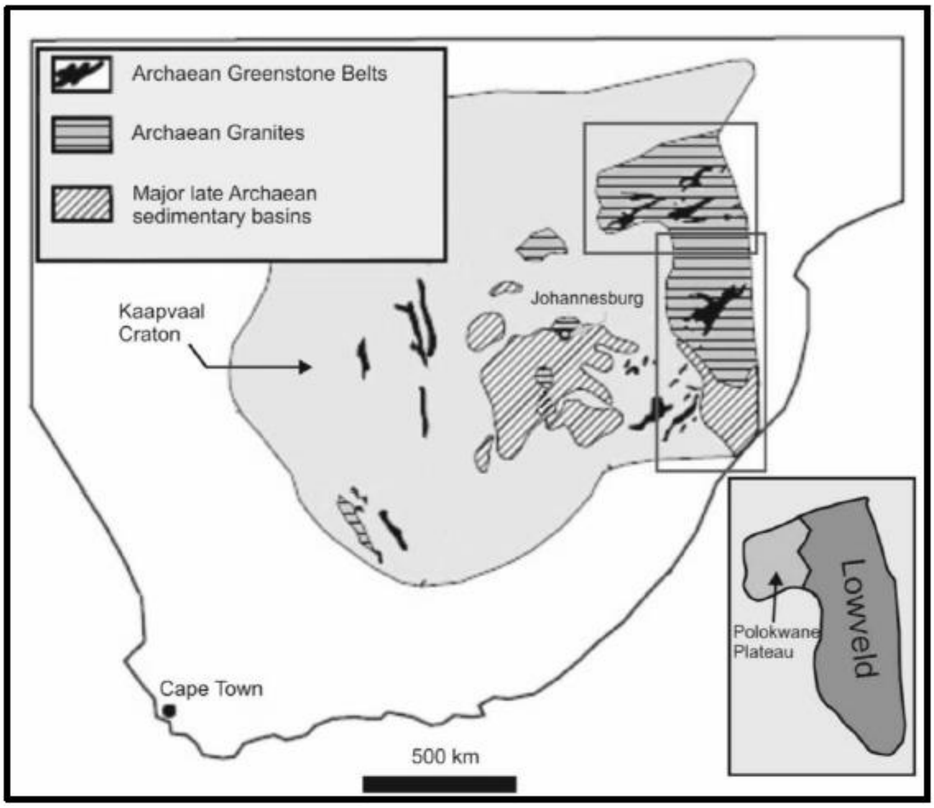


Figure 3-19: Location of Archaean granites on the Kaapvaal Craton (modified from Lana et al., 2003, as cited by Lourens, 2013)

The aquifers found in the Archaean granites and gneisses are classified as intergranular and fractured, structurally controlled and having a semi-confined to confined nature (Du Toit, 2001, as cited by Lourens, 2013). These aquifers have double porosity. The fractures are characterised by high permeability and low storage, while the rock matrix is characterised by low permeability and large storage (Du Toit, 2001). This combination is a common feature of hard rock aquifer systems (Lourens, 2013).

Holland (2011), as cited by Lourens (2013), developed a conceptual model of the Archaean granites and gneisses (Figure 3-20). From Figure 3-20, it can be seen that the weathered zone ranges from 15 to 50 m below ground level in the Limpopo Plateau, while, in the Lowveld region, the depth of weathering rarely exceeds 30 m below ground level (Holland, 2011). Botha (2011) and Holland (2011), as cited by Lourens (2013), found that the fracture zone of the Limpopo Plateau may exceed depths of 120 m below ground level, especially in the Dendron and Mogwadi regions. These regions are known for high-yielding boreholes that exceed the typical expectations of crystalline aquifer potentials. Du Toit and Lelyveld (2006), as cited by Lourens (2013), found that the groundwater quality of the Archaean granite and gneiss aquifers in the Lowveld area is generally good. Vegter (2003), as cited by Lourens (2013), also found the groundwater quality of the Archaean granite and gneiss in the Polokwane Plateau to be good. However, the analyses were limited to shallow groundwater systems.

The Goudplaats-Hout River gneiss of the Polokwane Plateau is classified to be associated with a moderate- to high-yielding aquifer system, with yields ranging from 2 to 5 ℓ/s (Du Toit and Sonnekus, 2010, as cited by Lourens, 2013). Large-scale groundwater irrigation schemes are currently running in the Dendron area due to the presence of high-yielding boreholes (Du Toit and Sonnekus, 2010; Botha, 2011, as cited by Lourens, 2013). The Archaean granites and gneisses of the Lowveld region are classified as being associated with low- to moderate-yielding aquifer systems, with yields ranging from 0.1 to 2 ℓ/s (Du Toit and Lelyveld, 2006).

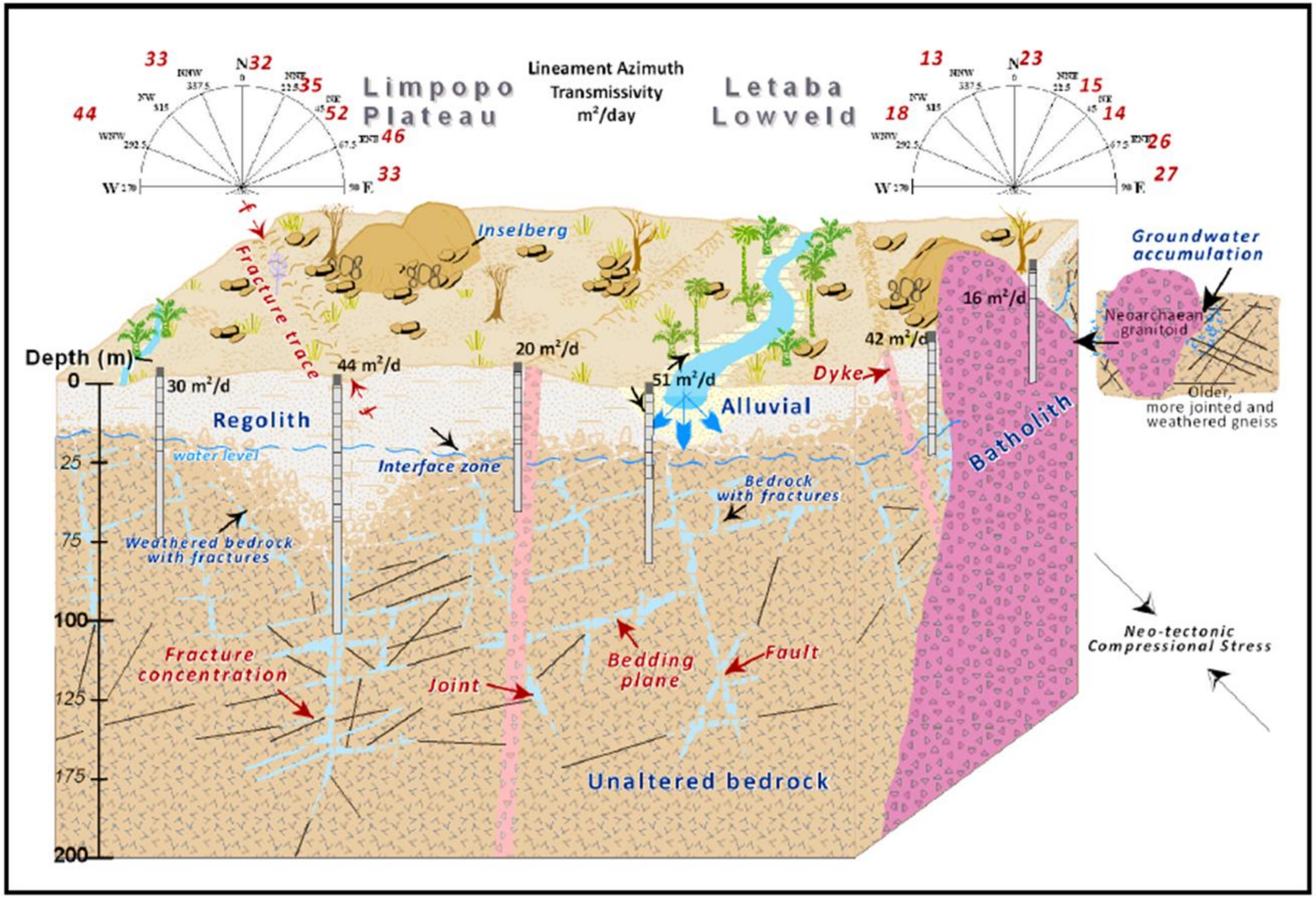


Figure 3-20: Conceptual model of aquifer systems found in the Archaean granites and gneisses of the Polokwane Plateau and Lowveld region (from Holland, 2011, as cited by Lourens, 2013)

3.3.4 Pongola Supergroup

The Pongola Supergroup is located on the southeastern section of the Kaapvaal Craton, spread across Mpumalanga and KwaZulu-Natal, as well as Swaziland (Figure 3-21). The Pongola Supergroup unconformably overlies the Archaean granites of the Kaapvaal Craton and reaches a maximum thickness of approximately 12 km (Strik et al., 2007, as cited by Lourens, 2013). The lithology consists of a lower volcano-sedimentary Nsuze Group and an upper sedimentary Mozaan Group (Gold, 2006) (Figure 3-22). The Mozaan Group mainly comprises argillaceous and arenaceous sedimentary rocks with an estimated thickness of 5 km (Gold, 2006).

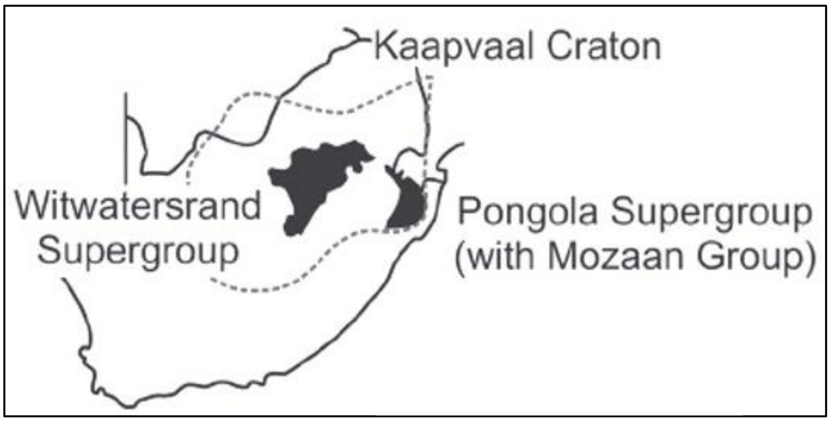


Figure 3-21: Location of the Pongola Supergroup on the Kaapvaal Craton

Lourens (2013) classified the Pongola Supergroup as being associated with intergranular and fractured aquifer systems, but stated that this classification was based on sparce geohydrological data. However, King (2003), as cited by Lourens (2013), analysed 60 boreholes in this group, with the majority yielding less than 2 ℓ/s. Based on the available information, Lourens (2013) concluded that aquifers of the Pongola Supergroup are low to moderate yielding.

3.3.5 Dominion Group

The Dominion Group is a succession of volcanic and sedimentary rocks that have since undergone metamorphosis (Marsh, 2006). The group overlies the granite-greenstone basement of the central Kaapvaal Craton, and is overlain by the Witwatersrand Supergroup (Marsh, 2006) (see Figure 3-23). Surface outcrops of the Dominion Group are limited, which hinders a complete understanding of the geology. This group is, however, important as it houses gold and uranium mineralisation (Marsh, 2006).

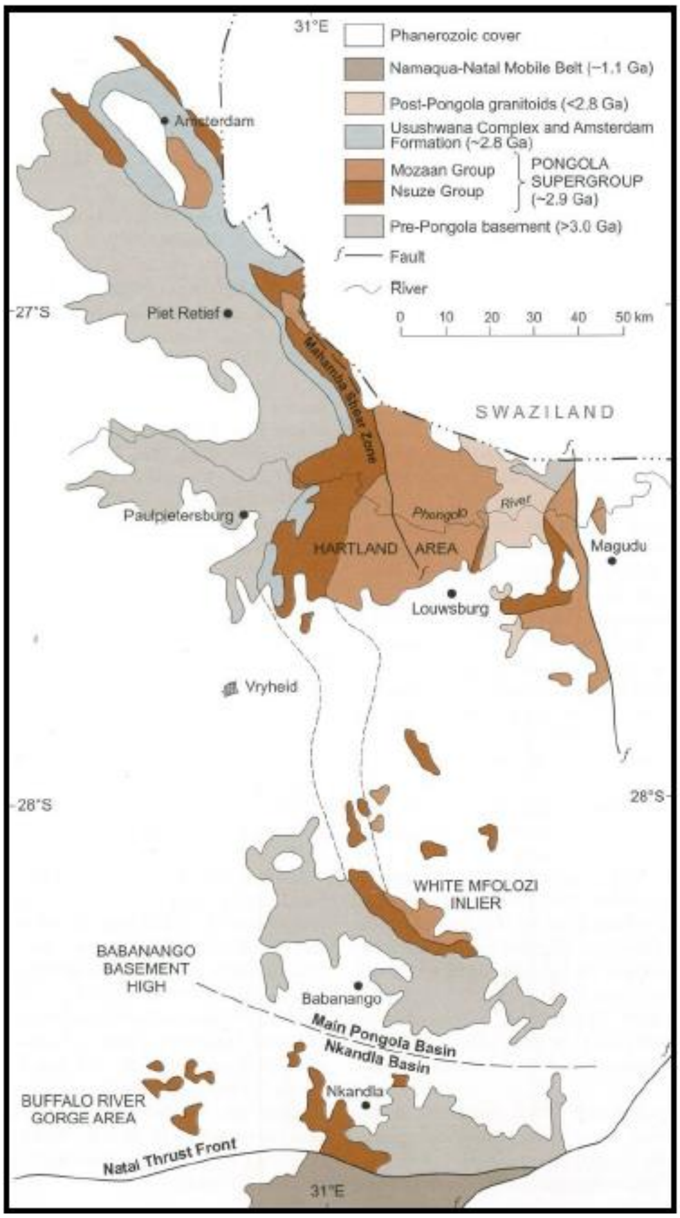


Figure 3-22: Simplified geology map of the Pongola Supergroup (Gold, 2006)

Owen and Madari (2009) evaluated the geohydrology of the Dominion Group. This group is described as having predominantly gritty quartzite, conglomerate, magnetic shale, phyllite and interbedded lava lithologies. The quartzite and conglomerates form secondary aquifers that are controlled by joints, fractures, faults and dyke contact zones (Barnard, 2000, as cited by Owen and Madari, 2009). The shale and diabase rocks are prone to weathering and can form good aquifers where deep weathering is present (Owen and Madari, 2009). Owen and Madari (2009) concluded that the Dominion Group can be classified as having a low to moderate groundwater development potential, which is strongly dependent on secondary porosity. However, the groundwater of the Dominion Group is saline with an average TDS concentration of 928 mg/ℓ (Owen and Madari, 2009).

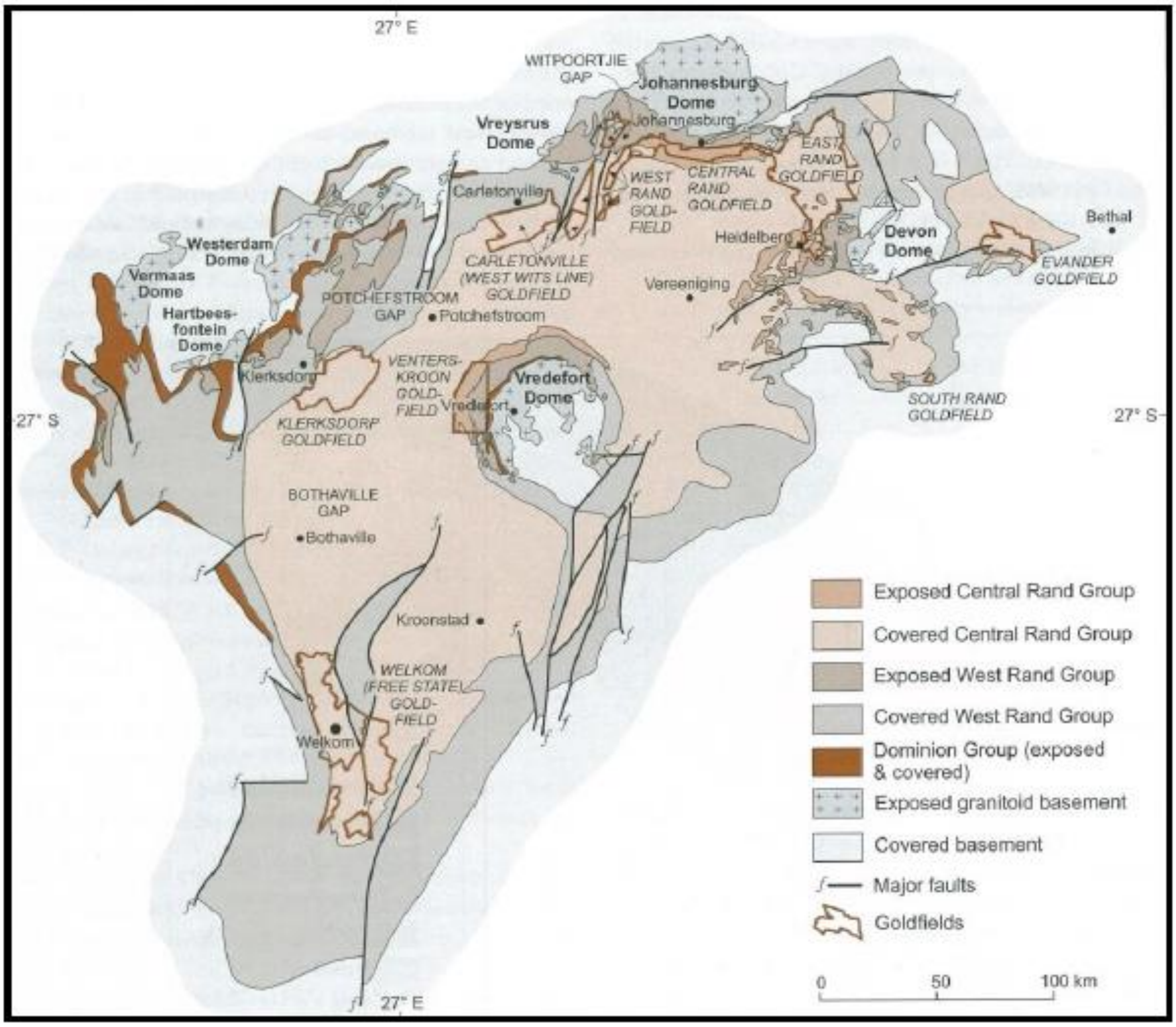


Figure 3-23: Location of the Dominion Group in relation to the goldfields of the Witwatersrand Supergroup (McCarthy, 2006)

3.3.6 Witwatersrand Supergroup

The Witwatersrand Supergroup has outcrops in Gauteng, North West and Free State, and is mostly overlain by younger rocks (Lourens, 2013) (see Figure 3-24). The Witwatersrand Supergroup overlies the sedimentary and volcanic rocks of the Dominion Group, and the Archaean basement rocks where the Dominion Group is not present (Lourens, 2013). The Witwatersrand Supergroup is divided into two main groups: the Central Rand Group and the West Rand Group (Lourens, 2013).

The West Rand Group predominantly consists of quartzite and shale, with a quartzite/shale ratio of 1 (Lourens, 2013). The West Rand Group is subdivided into three subgroups: the Hospital Hill, Government and Jeppestown subgroups (McCarthy, 2006). The Central Rand Group is different to the West Rand Group, which consists of quartzite and conglomerates, with a quartzite/conglomerate ratio of 12.6 (CGS, 2006, as cited by Lourens, 2013). The Central Rand Group is subdivided into two subgroups: the Johannesburg and Turffontein subgroups (McCarthy, 2006).

3.3.6.1 Mining

In 2002, there were 29 active gold mines in Gauteng, as shown in Figure 3-24. The South Deep mine of the Witwatersrand goldfields is shown schematically in Figure 3-25 to illustrate the geology of the Witwatersrand.

3.3.6.2 Geohydrology

Lourens (2013) classified the aquifers of the Witwatersrand Supergroup as fractured, where the groundwater flow takes place within secondary fracture systems that are associated with weathered areas, shear zones and intrusive formations. The groundwater quality of the Witwatersrand was also found to be good with an average electrical conductivity value of 37 mS/m for the West Rand Group and 29 mS/m for the Central Rand Group (Lourens, 2013). However, chloride and sulphate concentrations occasionally exceed the maximum recommended level. These contaminants have been suggested to be related to mining activities (Barnard, 2000, as cited by Lourens, 2013).

The Witwatersrand Supergroup is considered to be associated with low- to moderate-yielding aquifer systems, with most boreholes having yields of less than 2 ℓ/s, and a maximum reported yield of 30 ℓ/s (Barnard, 2000, as cited by Lourens, 2013). Lourens (2013) stated that the fault zones within the Witwatersrand Supergroup play an important role in the deep groundwater system, where deep gold mines (approximately 2 km deep) have intersected large volumes of groundwater at faults.

3.3.7 Ventersdorp Supergroup

The Ventersdorp Supergroup covers most of the distribution area of the Dominion Group and the Witwatersrand Supergroup, with the largest outcrops in the North West, Northern Cape and Gauteng, as well as southern Botswana (Van der Westhuizen et al., 2006). The Ventersdorp Supergroup extends from Johannesburg in the northwest to Kimberley in the southeast, and consists of unique volcano-sedimentary supracrustal records (Lourens, 2013) (see Figure 3-26). The Ventersdorp Supergroup unconformably overlies the Witwatersrand Supergroup, and is unconformably overlain by the Transvaal Supergroup (Van der Westhuizen et al., 2006). The Klipriviersberg Group forms the base of the Supergroup, followed by the Platberg Group, the sedimentary Bothaville Formation and the volcanic Allanridge Formation (Van der Westhuizen et al., 2006) (see Figure 3-27).

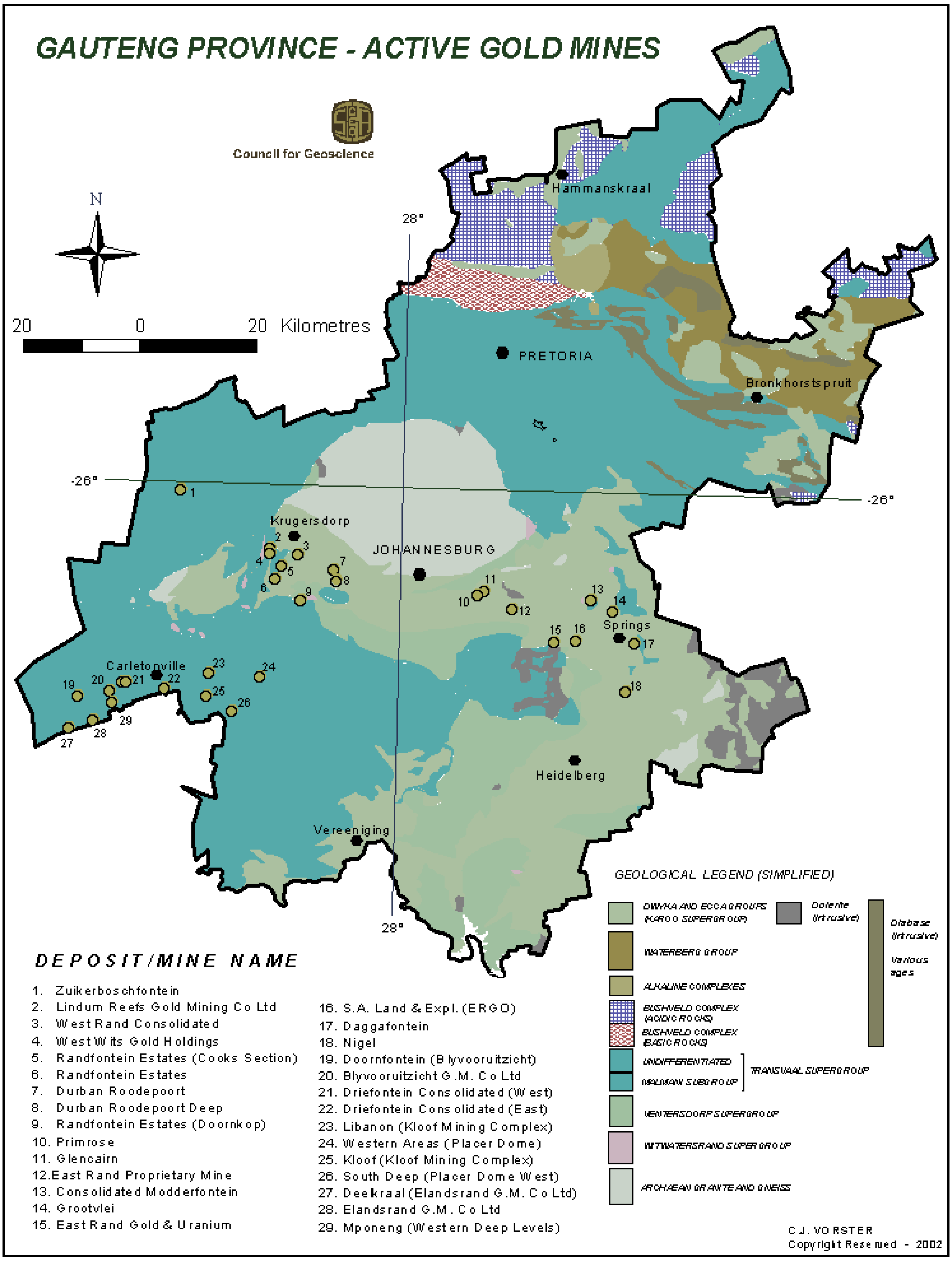


Figure 3-24: Active gold mines located within Gauteng (CGS, 2002)

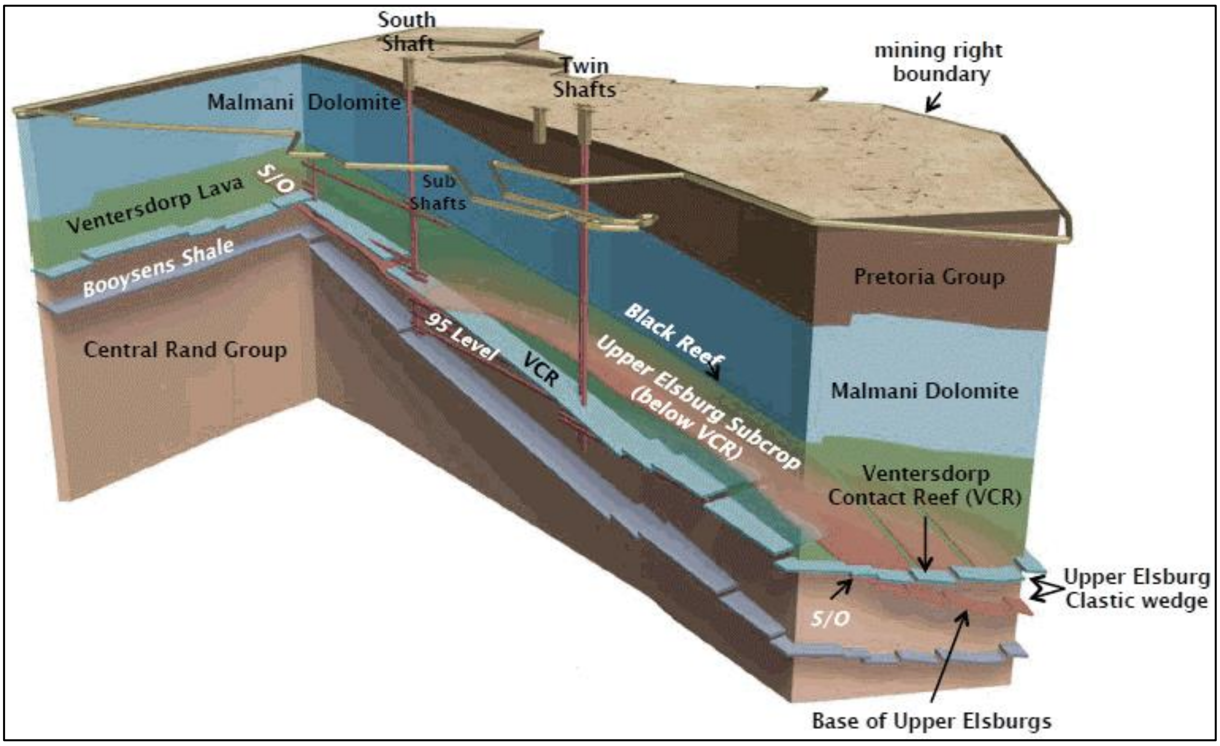


Figure 3-25: Three-dimensional schematic of the South Deep goldmine (Goldfields, 2011)

Lourens (2013) classified the aquifers of the Ventersdorp Supergroup as intergranular and fractured, but the volcanic and sedimentary rocks have been found to have low porosity and hydraulic conductivity. De Villiers (1961), as cited by Lourens (2013), found that the volcanic rocks weather to a clay material that reduces permeability, but that the rocks below the weathered zone that are fractured have the capacity to store and transmit significant volumes of groundwater. Conversely, Burger (2010), as cited by Lourens (2013), found that these rocks do not appear permeable at depth, but rather act as aquicludes.

The groundwater quality of the Ventersdorp Supergroup is generally good, with an average electrical conductivity value for the Klipriviersberg Formation of 60 mS/m, and a maximum of 264 mS/m (Lourens 2013). However, some high sulphate concentrations were reported with a maximum of 1,038 mg/ℓ (Lourens, 2013). Elevated sulphate concentrations within the Kameeldoorns Formation are associated with gypsum (Lourens, 2013). Baran (2003), as cited by Lourens (2013), suggested that this entire formation should be avoided for use as a water supply.

Lourens (2013) considered the volcanic rocks of the Ventersdorp Supergroup to be associated with low-yielding aquifer systems, with most boreholes yielding less than 2 ℓ/s. The aquifers within the sedimentary rocks of the Ventersdorp Supergroup were considered to be low to moderate yielding, with some boreholes yielding more than 2 ℓ/s. Interestingly, there are also areas of the Ventersdorp Supergroup where yields of up to 20 ℓ/s have been reported (Barnard, 2000; Baran, 2003; Van Wyk, 2011, as cited by Lourens, 2013). These high-yielding boreholes most probably intersected major fracture or fault systems.

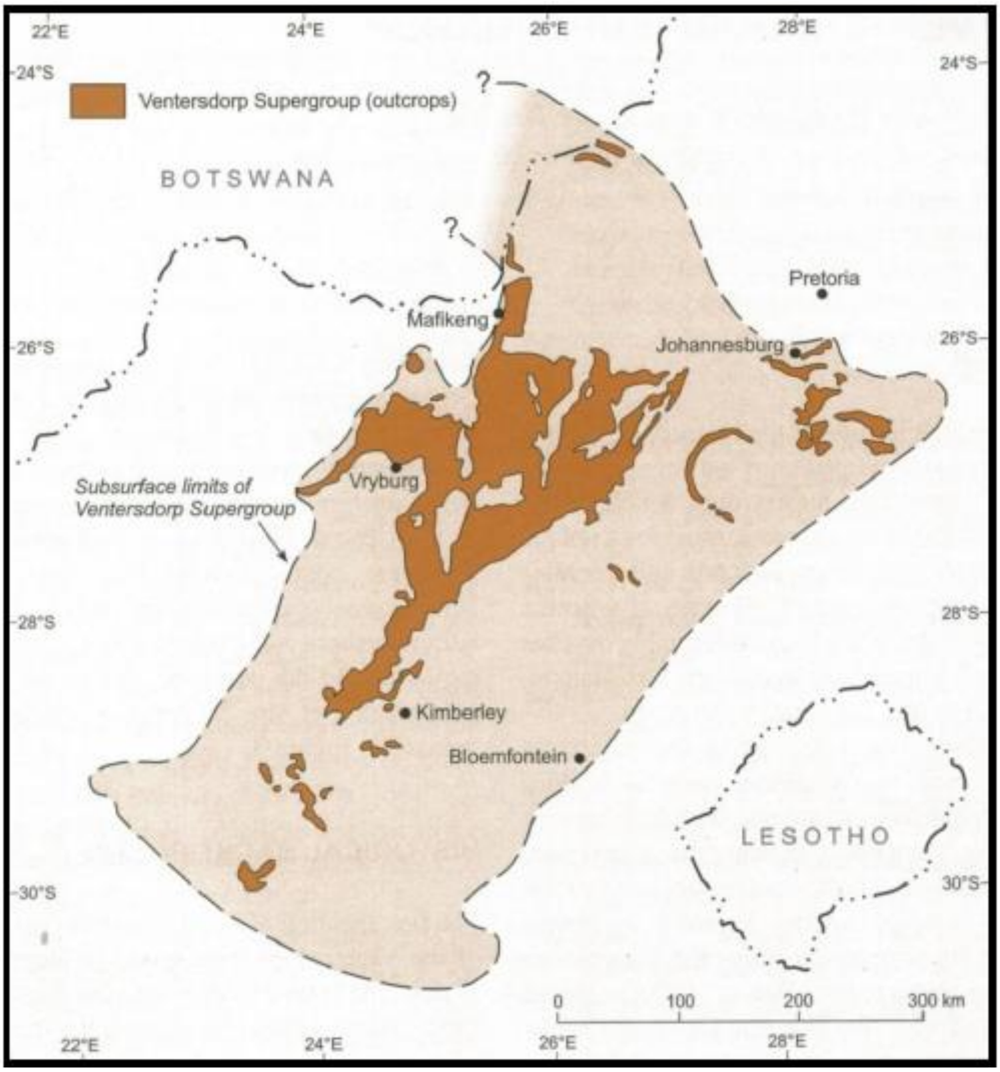


Figure 3-26: Distribution of the Ventersdorp Supergroup. The estimated sub-outcrop is shown as a dashed line (Van der Westhuizen et al., 2006).

3.3.8 Transvaal Supergroup

The Transvaal Supergroup forms three structural basins: two in South Africa (the Griqualand West and Transvaal basins), and one in Botswana (the Kanye Basin) (Eriksson et al., 2006) (see Figure 3-28). The Griqualand West Basin is located in the Northern Cape and North West, stretching from Prieska in the south to Vryburg in the north (Lourens, 2013). The Transvaal Basin reaches over North West, Gauteng, Mpumalanga and Limpopo, and is intruded by the Bushveld Igneous Complex (Lourens, 2013).

The geological successions within the three basins are mostly similar with a fair correlation (Eriksson et al., 2006). The basins can be divided into two groups and one formation: the Vryburg Formation in the Griqualand West Basin and the Black Reef Formation in the Transvaal Basin; the Ghaap Group in the Griqualand West Basin and the Chuniespoort Group in the Transvaal Basin; and the Postmasburg Group in the Griqualand West Basin and the Pretoria Group in the Transvaal Basin (Eriksson et al., 2006).

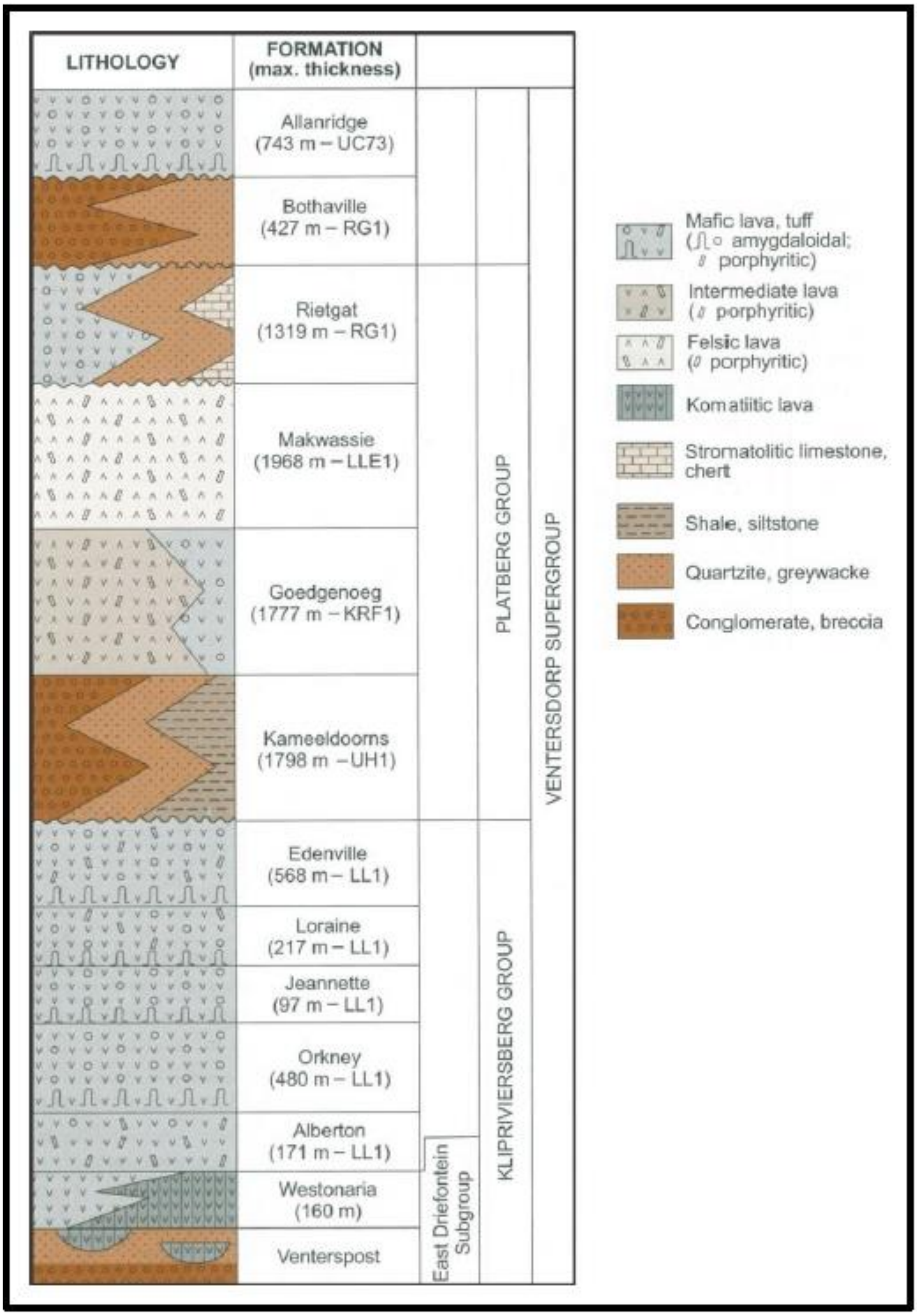


Figure 3-27: Stratigraphic column for the Ventersdorp Supergroup (Van der Westhuizen et al., 2006)

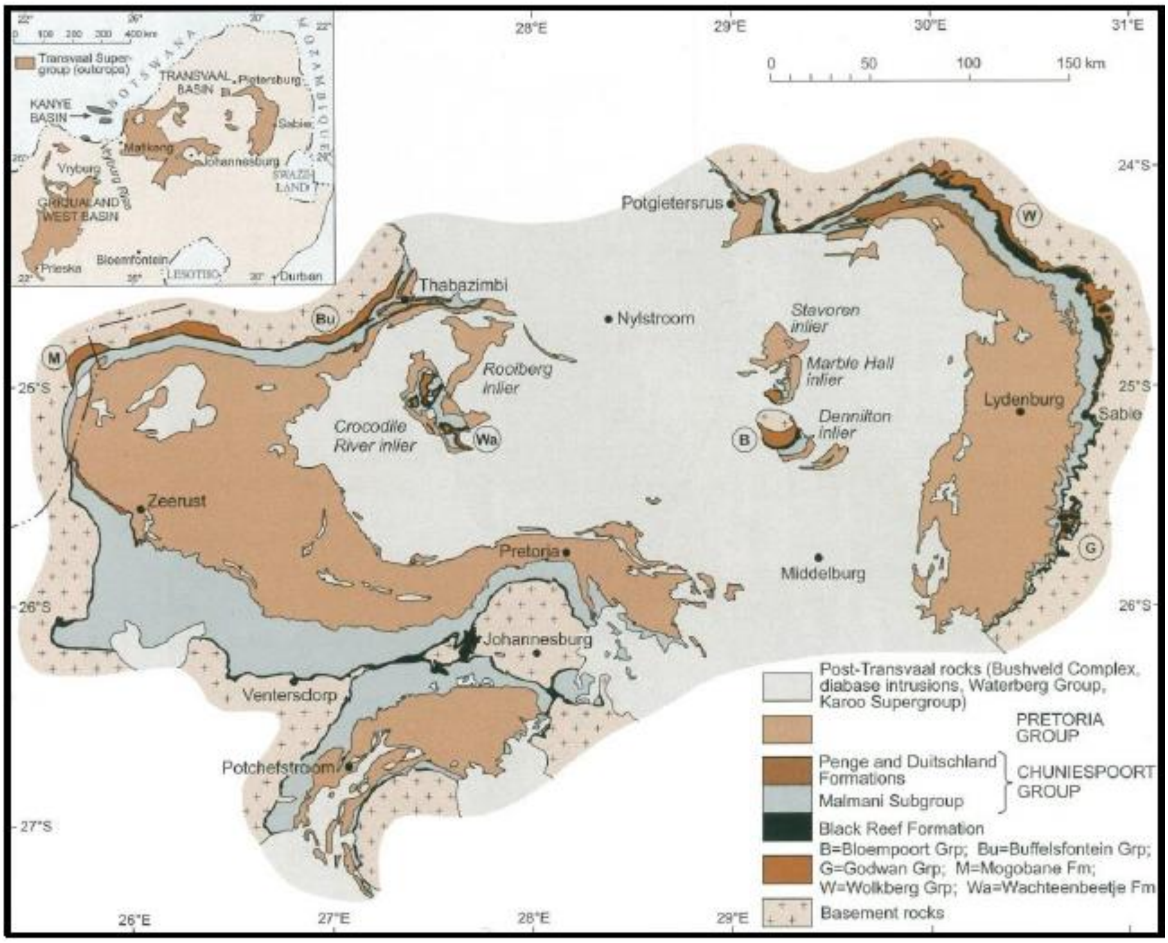


Figure 3-28: Outcrop geology of the Transvaal Basin of the Transvaal Supergroup. The entire Transvaal Supergroup is shown in the box in the top left-hand corner (Eriksson et al., 2006).

3.3.8.1 Black Reef and Vryburg formations

3.3.8.1.1 Geology

The Black Reef Formation predominantly consists of quartzite with lenses of grit and conglomerate, with a thickness range from 20 to 200 m (CGS, 1980, as cited by Lourens, 2013). The Black Reef Formation in the Transvaal Basin has been correlated to the Vryburg Formation of the Griqualand West Basin (Eriksson et al., 2006). The Vryburg Formation predominantly consists of siltstone, subordinate shale, quartzite and lava, with an average thickness of 100 m, but attaining thicknesses of up to 340 m (Eriksson et al., 2006).

3.3.8.1.2 Geohydrology

Lourens (2013) classified both the Black Reef and Vryburg formations as being associated with fractured aquifer systems. The quartzites of the Black Reef Formation have a low transmissivity, which creates a regional barrier for groundwater flow. The depth to the groundwater has been found to be related to the direction of flow between the Black Reef Formation and the adjoining dolomites of the Chuniespoort Group (Barnard, 2000; Van Dyk and Kisten, 2006, as cited by Lourens, 2013). The groundwater of the Black Reef and Vryburg formations is generally of a good quality, with an average electrical conductivity value of 34.3 mS/m and a maximum value of 139 mS/m (Barnard, 2000). Sulphate concentrations that exceed the maximum allowable limit were found, but were assumed to be related to mining activities (Barnard, 2000).

The aquifers of the Black Reef and Vryburg formations are regarded as low- to moderate-yielding aquifer systems (Lourens, 2013). Most boreholes have yields of less than 2 ℓ/s, but in some areas, yields greater than 5 ℓ/s have been recorded (Barnard, 2000; Van Dyk and Kisten, 2006).

3.3.8.2 Chuniespoort and Ghaap groups

3.3.8.2.1 Geology

The Ghaap Group in the Griqualand West Basin conformably overlies the Vryburg Formation (DGS, 1980, as cited by Lourens, 2013). The Ghaap Group is up to 3 km thick in the Sishen area (Eriksson et al., 1995, as cited by Lourens, 2013). The Chuniespoort Group in the Transvaal Basin overlies the Black Reef Formation and is separated from the overlying Pretoria Group by an unconformity (Lourens, 2013). The Ghaap Group is subdivided into the Koegas/Asbestos Hills Subgroup, the Campbell Subgroup and the Schmidtsdrif Subgroup/Clearwater Formation/Boomplaas Formation. The Chuniespoort Group is subdivided into the Malmani Subgroup, the Penge Formation and the Duitschland Formation.

The basal Schmidtsdrif Subgroup of the Ghaap Group has a thickness of up to 275 m, and consists of dolomites, limestone of the Boomplaas Formation and subsequently shale and a quartzite marker horizon of the Clearwater Formation (Eriksson et al., 1995).

The Campbell Rand Subgroup and its correlated Malmani Subgroup in the Transvaal Basin generally consists of dolomites and subordinate limestone, which are separated from each other on the basis of stromatolite facies, interbedded chert, shale and even low angle unconformities (Eriksson et al., 1995).

The Asbestos Hills Subgroup correlates with the Penge Formation of the Chuniespoort Group in the Transvaal Basin (Eriksson et al., 1995). These formations consist of banded iron formations (BIF), brown jaspilite, amphibolite and subordinate shale (CGS, 1980). Rocks of the Penge Formation are partly thermally metamorphosed due to the intrusion of the Bushveld Igneous Complex (Eriksson et al., 2006).

The Duitschland Formation consists of carbonaceous mudrock, limestone and dolomite, with subordinate conglomerates, diamictite and lava (Eriksson et al., 1995). On the other hand, the Koegas Subgroup in the Griqualand Basin (only preserved within the southern part of the basin) consists of shale, siltstone and quartzite with subordinate stromatolitic carbonates and a thin layer of BIF (Eriksson et al., 2006).

3.3.8.2.2 Geohydrology

The carbonate rocks of the Chuniespoort and Ghaap groups represent the most important aquifer system in South Africa (Lourens, 2013). These dolomitic aquifers are high yielding and are mainly used for irrigation purposes. However, the presence of impermeable vertical and subvertical intrusive dykes form groundwater compartments. The dolomitic aquifers are also characterised by an abundance of springs, with the majority occurring on or near the contact of a dyke (Lourens, 2013).

The original carbonate rocks do not have any primary porosity, but have a high storage capacity and high permeability due to secondary features that have been enlarged by dissolution processes. These dolomitic aquifers are thus classified as a karst aquifer system (Lourens, 2013). The storativity and transmissivity values for the dolomitic aquifers are highly variable due to the heterogeneous nature of karstification. Transmissivity values range from 10 to 29,000 m^2 per day, while storativity values range from 5×10^{-5} to 0.1 (Vegter, 1984, as cited by Lourens, 2013). However, Enslin and Kriel (1968), as cited by Lourens (2013), found that the storativity of the dolomites decreased with increasing depth. The authors reported a decrease in storage from approximately 9.1% at a depth of 61 m below ground level to 1.3% at a depth of 146 m below ground level. Lourens (2013) classified the dolomite of the Ghaap Group as being associated with a moderate-yielding aquifer systems, with the majority of boreholes having yields from 0.5 to 2 ℓ/s. Approximately 10% of the boreholes have yields above 5 ℓ/s.

Lourens (2013) classified the Chuniespoort Group dolomite as being associated with a moderate- to high-yielding aquifer system, with borehole yields usually over 5 ℓ/s, and with a maximum measured yield of 126 ℓ/s. Kafri et al. (1986), as cited by Lourens (2013), found the highest-yielding boreholes to be associated with the chert-rich dolomite formations of the Chuniespoort Group.

Lourens (2013) found that the quality of the groundwater within these karst aquifers is generally good, with electrical conductivity values ranging from 55 mS/m to a maximum of 397 mS/m. However, due to the high permeability of the karst system, the groundwater is vulnerable to contamination from surface sources.

The dolomitic rocks of the Transvaal Supergroup – the Ghaap Group and the Malmani Subgroup – are the main drilling targets for locating shallow groundwater resources. Specific target features within the abovementioned subgroups are karstification zones, dolerite/diabase intrusive dykes and major regional fault systems (Lourens, 2013).

3.3.8.3 Postmasburg and Pretoria groups

3.3.8.3.1 Geology

The Postmasburg and Pretoria groups have been correlated within the Transvaal Supergroup for the Griqualand West Basin and the Transvaal Basin, respectively. The Postmasburg Group in the Griqualand West Basin reaches a thickness of 1,500 m, while the Pretoria Group is approximately 6 to 7 km thick (Eriksson et al., 2006). The Postmasburg Group is subdivided into two formations and one subgroup, while the Pretoria Group is subdivided into ten formations.

The Pretoria Group consists of predominant mudrocks alternating with quartzitic sandstones, significant interbedded basaltic-andesite lavas and secondary conglomerates, diamictites and carbonate rocks (Eriksson et al., 2006). All these lithologies have been subjected to low-grade metamorphism. Figure 3-29 provides a schematic of the lithologies of the ten formations of the Pretoria Group. The Pretoria Group in the Transvaal Basin overlies the Chuniespoort Group with an angular unconformity, which is believed to represent a weathered palaeo-karst surface (Eriksson et al., 1995).

The Postmasburg Group consists of the Makganyene Formation, the Ongeluk Formation and the Voëlwater Subgroup, which is subdivided into the lower Hotazel Formation and the upper Mooidraai Formation (Lourens, 2013). The Makganyene Formation predominantly consists of massive, poorly sorted diamictite (Moore et al., 2001, as cited by Lourens, 2013) and, to a lesser degree, BIF, shales, sandstones and dolomite (CGS, 1980; Moore et al., 2001). The Makganyene Formation is unconformably overlain by the Ongeluk Formation. The Ongeluk Formation consists of andesitic pillow lavas, hyaloclastites and massive lava flows (Eriksson et al., 2006). The Voëlwater Subgroup is only preserved in the northern part of the Griqualand West Basin. The Hotazel Formation of the Voëlwater Subgroup conformably overlies the lavas of the Ongeluk Formation and consists of the BIF that is characterised by alterations of chert-rich and magnetite-rich bands (Polteau et al., 2006, as cited by Lourens, 2013). A gradational contact separates the Hotazel and Mooidraai formations, where the latter consists of limestone, dolomite and subordinate chert (Polteau et al., 2006).

FORMATIONS		WESTERN AREA	CENTRAL AREA	EASTERN AREA	SOUTHERN AREA	Inferred palaeoenvironments
Houtenbek	Mudrock (tuffaceous in places), sandstone, limestone	Rayton/Woodlands Formation in far west (mudrock, sandstone) ≤200 m	Rayton Formation (mudrock, sandstone, minor andesite and dolomite) ~1200 m	150–200 m	Absent	Fan, fan-delta, delta, shallow lacustrine
Steenkampsberg	Sandstone			450–600 m		
Nederhorst	Sandstone (arkosic in places) Mudrock (tuffaceous in places)			200–800 m		
Lakenvalei	Sandstone			200–350 m		
Vermont	Mudrock (tuffaceous in places)			500–700 m		
Magaliesberg	Sandstone with mudrock lenses and interbeds	150–430 m, significant mudrock, sandstones thicken westwards and eastwards	260–340 m, subordinate mudrocks thicken westwards	~225–550 m, subordinate mudrock	≤340 m, mostly eroded	Regressive sandy shoreline, braid-delta, high-energy tidal flat
Silverton	Carbonate rocks Lydenburg Shale Member (commonly tuffaceous) Machadodorp Volcanic Member (pyroclastic rocks, basalt) Boven Shale Member	~500–1328 m, reworked tuffs common, thins westwards, uppermost carbonates ~117–167 m thick, Machado-dorp Member absent, basal shale generally thin	~450–850 m, Machadodorp Member 1–2 m thick, upper shales thin	~1040–2230 m, lower shales generally thin, Machadodorp Member ~57–517 m thick	≤1365 m, Machadodorp Member thin (≤6 m), mostly eroded	Relatively deep-water, transgressive epeiric sea; volcanic activity, mainly in the east
Daspoort	Sandstone, mudrock	~65–120 m, sandstone pebbly in far west	~40–110 m, pebbly sandstone common	~10–120 m, sandstone pebbly, thicker in north, ironstones in northeast	~45–80 m, sandstone pebbly	Distal fan, fluvial braid-plain, braid-delta; transgressive epeiric sea in the east
Strubenkop	Mudrock, subordinate sandstone	~50–360 m, minor sandstone	~100–150 m, significant sandstone, minor tuff	~30–145 m, thickens to north and south	~80–185 m, thickens southwards	Transgressive lacustrine
Dwaalheuwel	Sandstone, conglomerate, subordinate mudrock	~15–70 m, basal conglo-merate in north	≤3–4 m, lenticular, absent in places	~40–110 m, minor conglomerates in north	Absent	Alluvial fan, fan-delta
Hekpoort	Basaltic andesite, pyroclastic rocks	~190–890 m, thins northwards	~340–630 m, air-fall and reworked pyroclastics relatively common	~90–500 m, thins northwards, pyroclastics common	~430–1140, significant tuffs (200–300 m thick), thickens southwards	Volcanic
Boshoek	Sandstone, conglomerate, diamictite	~35–70 m, significant conglomerates	≤2 m, mostly absent	~20–80 m, large channels	~30–60 m, localised diamictite	Alluvial fan, slump deposits
Timeball Hill	Upper mudrock unit Diamictite/conglomerate/arkose lens	Mudrock 200–430 m, thickens westwards	Mudrock 130–350 m, thick lens of diamictite/ conglomerate	Mudrock ~225–750 m, thickens northwards, thick arkose/diamictite lenses in north and northeast	Mudrock ~130–300 m	Relatively deep lacustrine (with suspension sedimentation and turbidity currents), distal fluvio-deltaic, basal volcanism in south and southwest
	Klapperkop Quartzite Member	Quartzite ~90–620 m, thickens westwards	Quartzite ~40	Quartzite ~70–230 m, thins southwards	Quartzite ~40–100 m, thins southwards	
	Lower mudrock unit	Mudrock 160–460 m, thickens westwards	Mudrock ~220–350 m	Mudrock ~300–580 m, thins to south, thin tuff bed	Mudrock ~80–540 m, thickens southwards	
	Bushy Bend Lava Member	Minor basal lavas			Bushy Bend Member ≤90 m	
Rooihoogte	Polo Ground Quartzite Member Mudrock, subordinate carbonate rocks Bevets Conglomerate/Breccia Member	~17–232 m, basal conglo-merate thick in north, shale thick in south	~10–50 m, breccia and conglomerate lenticular, Polo Ground Member thin	≤~2–140 m, thickest in Dennilton and Marble Hall fragments	~14–150 m, thick breccia	Karst-fill, alluvial fan, lacustrine

Figure 3-29: Schematic summary profile of the Pretoria Group, showing variations in lithology and thickness (Eriksson et al., 2006)

3.3.8.3.2 Geohydrology

Lourens (2013) classified the Pretoria Group as being associated with intergranular and fractured aquifer systems, while the aquifers of the Postmasburg Group were classified as fractured aquifer systems. The Pretoria Group was reported to be associated with a low- to moderate-yielding aquifer system, with borehole yields ranging from less than 2 ℓ/s to more than 5 ℓ/s (Lourens, 2013). However, Du Toit and Lelyveld (2006), as cited by Lourens (2013), reported yields greater than 20 ℓ/s for the Pretoria Group southwest of Phalaborwa.

The groundwater quality of the Pretoria Group is generally good to moderate, with reported electrical conductivity values ranging from 1.6 to 1,089 mS/m, with an average value of less than 300 mS/m (Lourens, 2013). Chloride, fluoride, nitrate, sodium and sulphate concentrations occasionally exceed the maximum allowable limits near villages (Barnard, 2000; Du Toit and Lelyveld, 2006; Du Toit and Sonnekus, 2010).

3.3.9 Bushveld Igneous Complex

The Bushveld Igneous Complex is located north and northeast of Pretoria, stretching across Limpopo, North West, Mpumalanga and Gauteng (Figure 3-30). The Bushveld Igneous Complex is the world's largest layered igneous intrusion, and intruded into the Transvaal Supergroup (Visser, 1989, as cited by Lourens, 2013). The Bushveld Igneous Complex is subdivided into three suites and one group: the Rashoop Granophyre Suite (felsic), the Lebowa Granite Group (felsic), the Rustenburg Layered Suite (RLS) (mafic), and the Rooiberg Group (Figure 3-31) (Cawthorn et al., 2006).

3.3.9.1 Geology

3.3.9.1.1 Rustenburg Layered Suite

The Rustenburg Layered Suite is characterised by magmatic layering, with rock types ranging from dunite and pyroxenite, norite, gabbro and anorthosite, to magnetite- and apatite-rich diorite (Cawthorn et al., 2006). The traditional zonal stratigraphy of the Rustenburg Layered Suite consists of the Marginal Zone, the Lower Zone, the Critical Zone, the Main Zone and the Upper Zone.

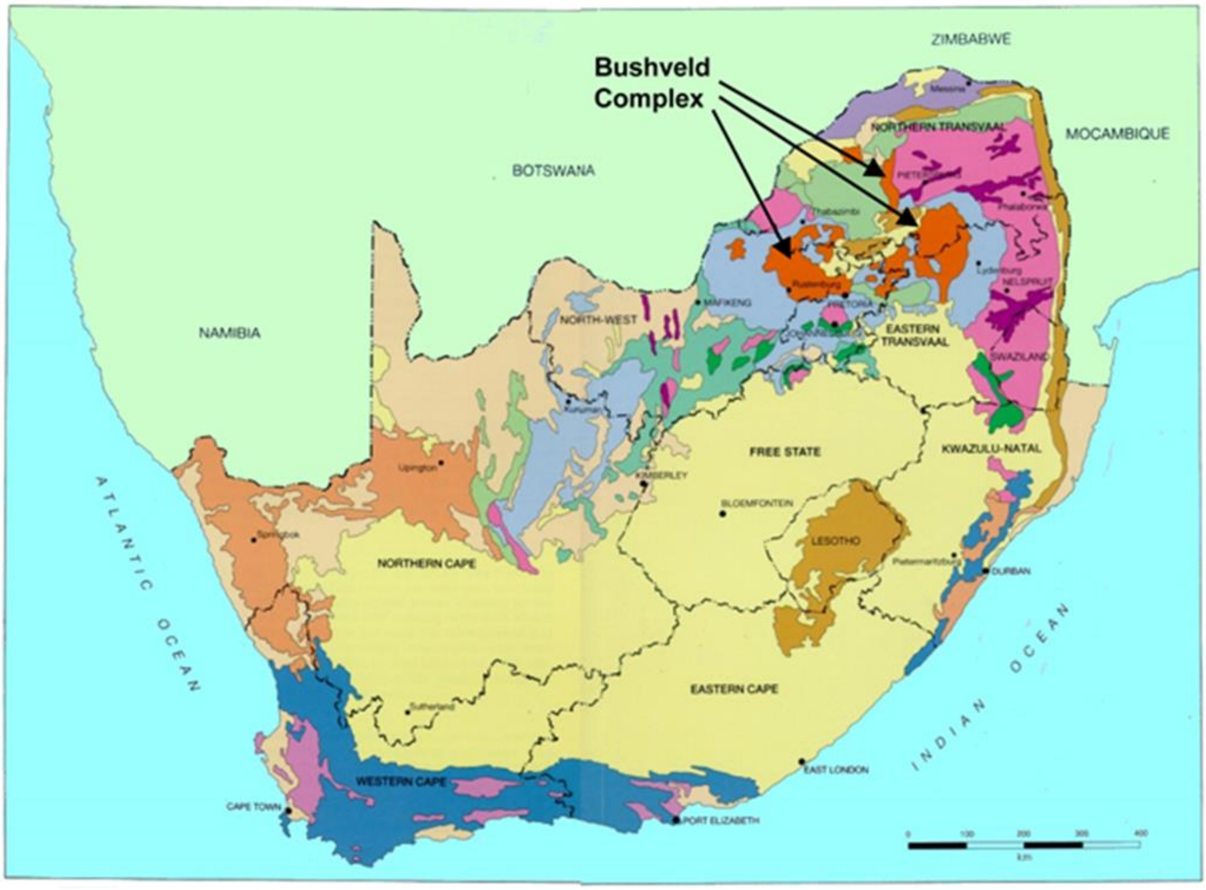


Figure 3-30: Simplified geology of South Africa indicating the location of the Bushveld Igneous Complex

The Rustenburg Layered Suite can also be characterized by the occurrence of marker reefs, i.e. the Merensky Reef at the top of the Critical Zone, the Thornhill pyroxenite layers in the Main Zone, and the main magnetite layer near the base of the Upper Zone (Eriksson et al., 1995).

3.3.9.1.2 Lebowa Suite

The Lebowa Granite Suite occurs as two semi-circular lobes within the Bushveld Igneous Complex, together with the Rashoop Granophyre Suite (RGS) (Figure 3-31). The CGS (1980), as cited by Lourens (2013), subdivided the Lebowa Granite Suite into different types of granite based on field relationships, radiometric dating and petrological/geochemical studies. They are the Nebo, Verena, Klipkloof, Bobbejaankop, Lease, Balmoral and Makhutso granites.

3.3.9.1.3 Rashoop Granophyre Suite

The Rashoop Granophyre Suite consists of granophyre that is defined as subvolcanic rock, which contains quartz and alkali feldspar in characteristic angular intergrowths. The Rashoop Granophyre Suite is subdivided into three formal units based on textural variations, and is subdivided into four units based on its classification as either magmatic or metamorphic (Lourens, 2013).

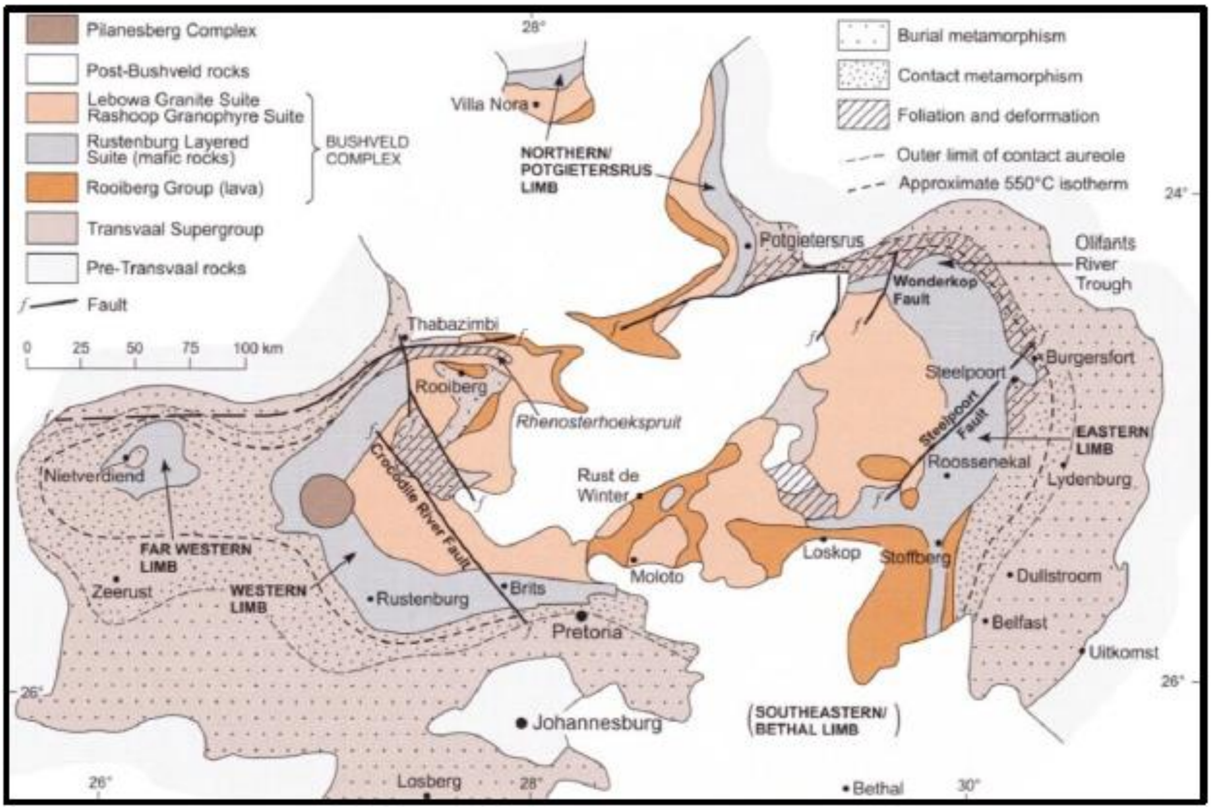


Figure 3-31: Simplified geology of the Bushveld Igneous Complex, indicating the major limbs of the Rustenburg Layered Suite (Cawthorn et al., 2006)

3.3.9.1.4 Rooiberg Group

The Rooiberg Group mainly occurs above the Rustenburg Layered Suite and can be subdivided into four formations from top to bottom: the Schrikkloof, Kwaggasnek, Damwal and Dullstroom formations (Cawthorn et al., 2006).

The Dullstroom Formation consists of volcanic flows that are up to 400 m thick, ranging in composition from basalts to dacite (Buchanan et al., 2004, as cited by Lourens, 2013). These volcanic flows are interbedded with thin, laterally extensive sedimentary rocks (Eriksson et al., 1995, as cited by Lourens, 2013). The sedimentary rocks consist of poorly sorted sandstone with smaller proportions of mudrock and chert (Buchanan and Reimold, 1998, as cited by Lourens, 2013).

The Damwal, Kwaggasnek and Schrikkloof formations are a thick sequence of increasingly siliceous extrusive rocks that overlies the Dullstroom Formation. Buchanan et al. (2004) found that these formations are a continuation of the same magmatic activity. These volcanic units of the Rooiberg Group are commonly composed of a fine-grained groundmass with variable proportions of phenocrysts, porphyroblasts and amygdales, and are characterised by manganese and iron hydroxide stains along fractures (Buchanan et al., 2004). This straining is caused by groundwater, acidified by CO_2 in the air, dissolving iron and manganese from the rocks as it passes through the fractures, and later precipitating the minerals as manganese and iron hydroxides (Lourens, 2013).

3.3.9.2 Geohydrology

Lourens (2013) classified the aquifers of the Bushveld Igneous Complex as fractured (crystalline) and intergranular aquifer systems, with the intergranular aquifer limited to the weathered zone that ranges in thickness from 12 to 50 m. The unweathered, fractured aquifer is found below the weathered zone and extends to a depth where fractures are closed due to the pressure from the overlying rocks.

The aquifers of the Bushveld Igneous Complex can be regarded as low to moderate yielding, with the majority of boreholes yielding less than 2 ℓ/s, but with some areas where yields are greater than 5 ℓ/s (Lourens, 2013). The Rooiberg Group, Rashoop Granophyre and Lebowa Granite suites have borehole yields generally less than 2 ℓ/s, but the Rustenburg Layered Suite appears to be associated with higher-yielding aquifers that may be classified as moderate to high yielding (Barnard, 2000; Du Toit and Lelyveld, 2006). The yields of the boreholes in the Rustenburg Layered Suite generally range from 0.5 to 5 ℓ/s, with a maximum measured yield of 25 ℓ/s.

The Bushveld Igneous Complex has abundant deposits of platinum group elements and chromium, which have led to numerous mining activities to extract these resources (Cawthorn, 2010). Data collectd in these mines has allowed for some characterisation of the groundwater systems within the Bushveld Igneous Complex. Titus et al. (2009b) characterised the shallow groundwater and mine fissure inflows for the Bushveld Igneous Complex. A two-layer aquifer model was developed to describe the groundwater regime in the Bushveld Igneous Complex on a regional scale. The model consists of an upper shallow, weathered bedrock aquifer system (intergranular aquifer) and a deeper fractured, bedrock aquifer (Titus et al., 2009b).

The deeper fractured aquifer consists of an unweathered bedrock matrix that has low hydraulic conductivity. The effective hydraulic conductivity of the deeper aquifer is controlled by fractures and mine voids (Titus et al., 2009b). Groundwater flows through interconnected fracture systems with the potential for rapid vertical inflow from the upper weathered aquifer, as well as great depths along interconnected conductive zones. Initial groundwater quality data has indicated that groundwater from the deeper fractures is chemically and isotopically different to groundwater from the shallow aquifer. A longer, slower groundwater flow system appears to occur at depth.

The Department of Water Affairs (DWA) (2011) investigated the norite and gabbro lithologies of the Bushveld Igneous Complex that lie within the Olifants River catchment. This investigation confirmed the regional groundwater regime described by Titus et al. (2009b), where groundwater occurs in an upper weathered aquifer and a deeper fractured aquifer. Measured borehole yields from this area range from 0.5 to 2 ℓ/s, with higher yields found along the dyke contacts (DWA, 2011). The average depth of boreholes drilled into the Bushveld Igneous Complex within the Olifants River catchment ranges from 30 to 80 m below ground level (DWA, 2011). The limited depth of groundwater boreholes in the Bushveld Igneous Complex has hindered an understanding of the deeper groundwater flow systems.

3.3.10 Waterberg and Soutpansberg groups

The Waterberg Group covers an area of approximately 20,000 km^2, spanning Limpopo, Gauteng and Mpumalanga (Barker et al., 2006) (Figure 3-32). The Soutpansberg Group is a mountainous, wedge-shaped terrain, partially buried beneath Karoo Supergroup rocks, and only occurs in Limpopo (Barker et al., 2006; Lourens, 2013).

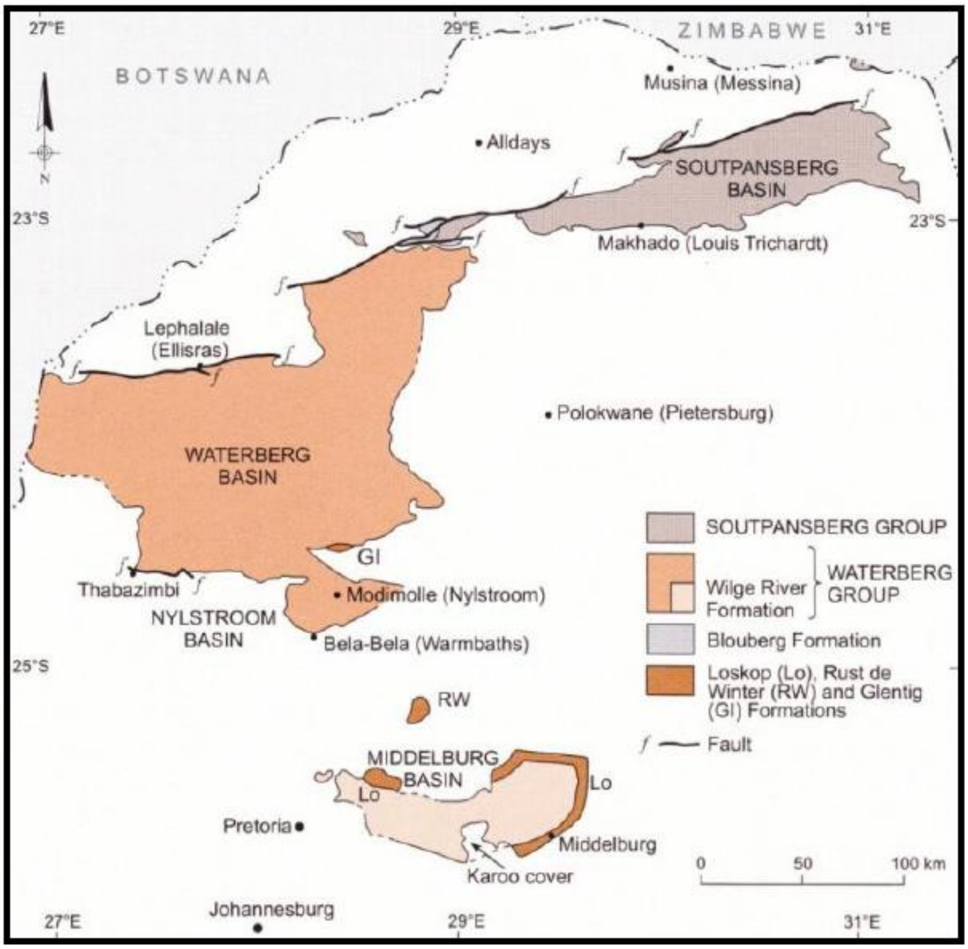


Figure 3-32: Soutpansberg and Waterberg groups in South Africa (from Barker et al., 2006)

3.3.10.1 Geology

The Waterberg Group can be subdivided into three different basins: the Waterberg, Nylstroom and Middelburg basins (Lourens, 2013) (Figure 3-32). The stratigraphy of the Waterberg Group is shown in Table 3-3, where three sub-groups are assigned: the Nylstroom, Matlabas and Kransberg sub-groups.

Table 3-3: Stratigraphic subdivision of the Waterberg Group in the Waterberg and Nylstroom basins (Barker et al., 2006)

	Subgroups	Formations		
		Main Basin (south/southwest & central area)	Main Basin (north/northeast & central area)	Nylstroom Basin
Waterberg Group	Kransberg	Vaalwater (≤475 m)	Vaalwater (≤475 m)	
		Cleremont (~125 m)	Cleremont (~125 m)	
		Sandriviersberg (1250 m)	Mogalakwena (≤1500 m)	
	Matlabas	Aasvoëlkop (≤600 m)	Makgabeng (≤1200 m)	
		Skilpadkop (≤600 m)	Setlaole (≤450 m)	
	Nylstroom	Alma (≤3000 m)		Alma (1200-1800 m)
		Swaershoek (≤1000 m)		Swaershoek (≤2500 m)

3.3.10.1.1 Waterberg and Nylstroom basins

In the Nylstroom Subgroup, the Swaershoek Formation forms the basal unit and consists of coarse-grained sandstone with locally interbedded shale, siltstone, pebble and boulder conglomerate, and trachytic lavas (Jansen, 1982, as cited by Lourens, 2013). The rocks of the Swaershoek Formation are overlain by rocks of the Alma Formation (Table 3-3). According to Jansen (1982), the middle portion of the Alma Formation consists of siltstone and mudstone, while the rest of the succession consists of medium- to coarse-grained feldspathic sandstones. The Alma Formation dips towards the north and can be up to 3,000 m thick (Visser, 1989, as cited by Lourens, 2013).

The Matlabas Subgroup is subdivided into four formations (Table 3-3): the Skilpadkop, Setlaole, Aasvoëlkop and Makgabeng formations (Barker et al., 2006). The Skilpadkop Formation consists of gritstone, sandstone and conglomerate (Visser, 1989). The Setlaole Formation also consists of gritstone, sandstone and conglomerate, but the base of the formation is interbedded with tuff, mudstone and clay-pebble conglomerate. The Setlaole Formation is approximately 450 m thick in the Sterkrivier Valley, and increases to a thickness of 600 m in the west (Visser, 1989).

The Aasvoëlkop Formation consists of fine-grained sandstone in the upper sections, siltstone, mudstone and shale with interbedded sandstone, followed by fine-grained conglomeritic sandstone in the lower sections (Visser, 1989). In the western part of the basin, the thickness of the formation varies from 500 to 600 m, and then decreases to approximately 300 m towards the east (Jansen, 1982). The Makgabeng Formation comprises sandstone that is characterised by large-scale cross-bedding (Visser, 1989). The thickness of the Makgabeng Formation varies from 300 to 600 m in the southern and western areas, and increases to 1,000 m in the northeast (Jansen, 1982).

The Kransberg Subgroup is subdivided into four formations: the Sandriviersberg, Mogalakwena, Cleremont and Vaalwater formations (Table 3-3). The Sandriviersberg Formation (the basal formation of the Kransberg Subgroup) is made up of coarse-grained sandstone (Jansen, 1982).

Towards the northeast, the Sandriviersberg Formation coarsens and grades into the Mogalakwena Formation (Barker et al., 2006). The Mogalakwena Formation consists of beds of coarse-grained sandstone, grit, conglomerate and shale (Jansen, 1982). In the Marken area, the formation is well developed and reaches thicknesses of 1,200 to 1,500 m (Visser, 1989). The overlying Cleremont Formation comprises coarse-grained and fine-grained sandstone, with an approximate thickness of 125 m that is fairly constant (Jansen, 1982; Visser, 1989). The Vaalwater Formation, overlying the Cleremont Formation, consists of fine- to medium-grained arenites and micaceous siltstone, and reaches a maximum thickness of 475 m (Barker et al., 2006; Jansen, 1982; Visser, 1989).

3.3.10.1.2 Middelburg Basin

The Wilge River Formation is only found in the Middelburg Basin of the Waterberg Group (Figure 3-32). This formation consists of medium- to coarse-grained sandstone with interbedded conglomerate and shale layers. Its thickness varies from 400 to 800 m in the west to 2,000 to 2,500 m in the east (Barker et al., 2006; Visser, 1989). The Wilge River Formation unconformably overlies the Loskop Formation along its northern, eastern and southeastern outcrop borders. Along its southern border, the formation overlies the Pretoria Group of the Transvaal Supergroup (Figure 3-32).

The Loskop Formation, along with the Rust de Winter and Glentig formations, is considered a proto-Waterberg deposit, with the upper contact with the Waterberg group being an angular unconformity (Barker et al., 2006). The Loskop Formation predominantly consists of argillaceous clastic sedimentary rocks, with interbedded lavas at the base of the formation (Barker et al., 2006). The Loskop Formation reaches a thickness of 1,000 m in the Middelburg area (Barker et al., 2006). The Rust de Winter and Glentig formations are characterised by similar clastic sedimentary lithologies, and both appear to have been intruded by porphyries (Barker et al., 2006).

3.3.10.1.3 Soutpansberg Basin

The rocks of the Soutpansberg Group are extensively faulted, as seen in Figure 3-33, and form a prominent feature in the landscape of northern Limpopo (Barker et al., 2006). The Soutpansberg Group consists of volcanic and sedimentary rocks, and lies unconformably on top of the Archaean granulite-grade gneisses and the Blouberg Formation (Lourens, 2013; Barker et al., 2006). The Soutpansberg Group is subdivided into six formations: the Nzhelele, Musekwa, Wyllie's Poort, Fundudzi, Sibasa and Tshifhefhe formations (Figure 3-22 and Figure 3-34).

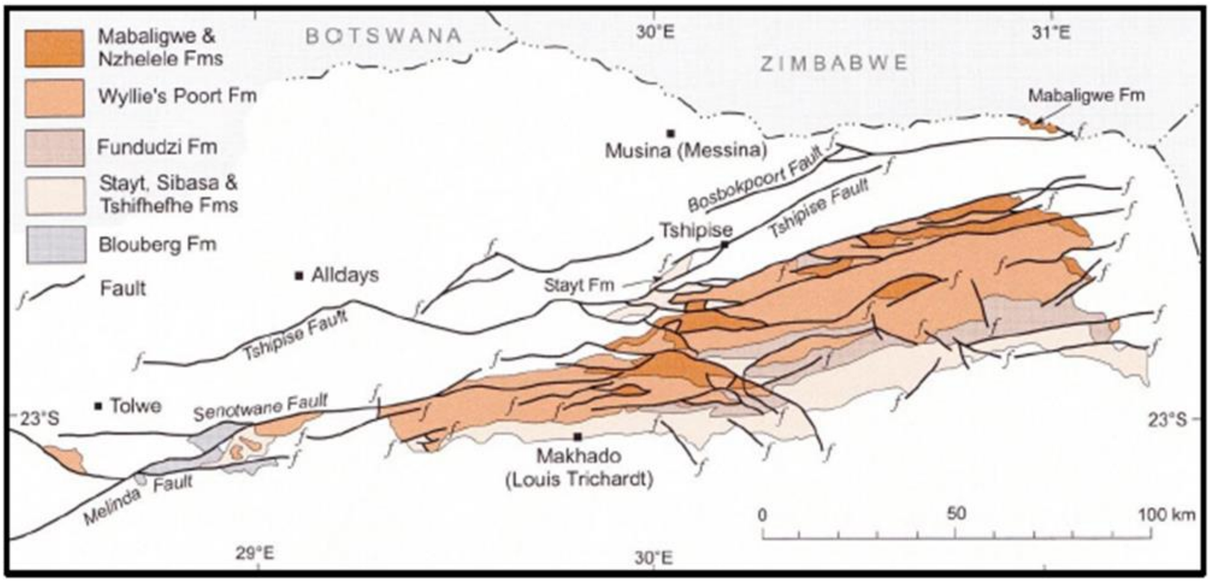


Figure 3-33: Formations of the Soutpansberg Group and Blouberg Formation, showing the faults within this area (Barker et al., 2006)

The Tshifhefhe Formation, at the bottom of the Soutpansberg Group, consists of epidotised clastic sediments, which include shale, greywacke and conglomerates (Barker et al., 2006). The Tshifhefhe Formation is only developed in the eastern and central areas (Figure 3-33) and is only a few metres thick (Bumby et al., 2002, as cited by Lourens, 2013). The overlying Sibasa Formation comprises massive volcanic rocks, with an intercalated pyroclastic and sandstone lens. It is estimated to reach a thickness of 3,000 m (Barker et al., 2006; Bumby et al., 2002). The Fundudzi Formation consists mostly of sandstone with a few pyroclastic beds and intercalated basaltic lava at the top of the formation (Barker et al. 2006). The Fundudzi Formation can be up to 1,900 m in thickness (Barker et al. 2006).

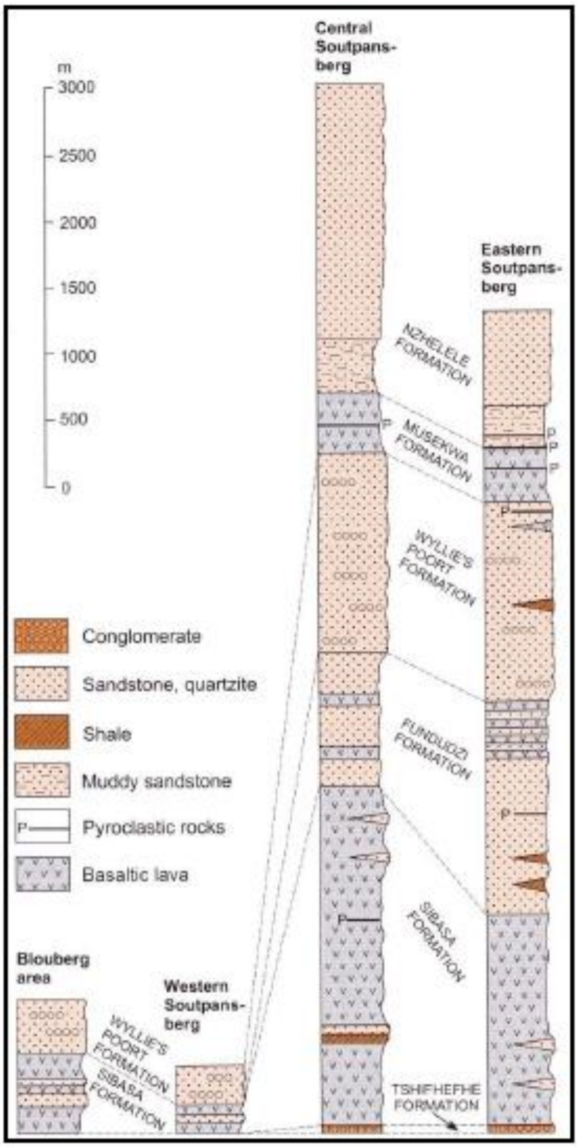


Figure 3-34: Stratigraphy of the Soutpansberg Group in the western, central and eastern areas, as well as in the Blouberg area (Barker et al., 2006)

The Wyllie's Poort Formation is mostly made up of a clastic succession, with a maximum thickness of 1,500 m (Barker et al., 2006). The Musekwa Formation comprises a volcanic succession that is 400 m thick (Barker et al., 2006). The Nzhelele Formation (the upper formation of the Soutpansberg Group) consists of argillaceous and arenaceous sediments with thin layers of pyroclastic beds, with a maximum thickness of 600 m (Barker et al., 2006; Lourens, 2013).

3.3.10.2 Geohydrology

3.3.10.2.1 Waterberg Group

The Waterberg Group is classified as being associated with secondary fractured aquifer systems because the rocks have little or no primary porosity with low original permeability and storage capacities, resulting in groundwater being controlled by fault or fracture zones and bedding planes (Owen and Madari, 2009; Du Toit and Sonnekus, 2010, as cited by Lourens, 2013). Aquifers of the Waterberg Group have been classified as low yielding, with most yields below 0.5 ℓ/s (Lourens, 2013). However, yields greater than 3 ℓ/s can be obtained when targeting fault and fracture zones (Levin, 2011, as cited by Lourens, 2013).

Lourens (2013) found that the groundwater quality of the Waterberg Group varies throughout the unit. The electrical conductivity values for the Cleremont Formation in the eastern parts of the Waterberg Group range from 2 to 50 mS/m (Du Toit and Sonnekus, 2010). In the central areas between Vaalwater, Marken and Ellisras, the electrical conductivity values range from 10 to 400 mS/m. The electrical conductivity values then increase towards the Botswana border in the west, with a maximum value of 1,100 mS/m.

3.3.10.2.2 Soutpansberg Group

The Soutpansberg Group has similar water-bearing characteristics as the Waterberg Group (Lourens, 2013). Lourens (2013) classified the Soutpansberg Group as being associated with an intergranular and fractured aquifer system. Groundwater is generally controlled by fault or shear zones and diorite dykes and sills. Lourens (2013) described the geohydrological characteristics of each formation within the Soutpansberg Group.

The Sibasa Formation hosts intergranular and fractured rock aquifer systems. The formation has a poor to moderate aquifer potential. The majority of water strikes are within the first 30 m below ground level with no strikes at depths greater than 50 m below ground level, indicating that the weathered or fractured zone is approximately 50 m thick. The Tshifhefhe Formation hosts intergranular and fractured rock aquifer systems with a low to moderate aquifer potential. The Fundudzi Formation hosts fractured rock aquifer systems, with a low to very low aquifer potential. Studies done in the Kruger National Park indicated that the transmissivity in the Fundudzi Formation decreases with depth. The formation is considered to be a double porous medium. The sedimentary rocks have a low to very low primary permeability with a low storage potential. The majority of water strikes range between 30 and 50 m below ground level, with no strikes at depths greater than 60 m below ground level, indicating that the weathered or fracture zone is approximately 60 m thick. The Wyllie's Poort Formation hosts fractured rock aquifer systems with a low aquifer potential. The primary porosity is almost zero and the majority of water strikes are within the first 50 m below ground level, with no strikes at depths greater than 100 m below ground level, indicating that the weathered or fractured zone is approximately 100 m thick. The Musekwa Formation hosts intergranular and fractured rock aquifer systems with a low to moderate aquifer potential. The Nzhelele Formation hosts fractured rock aquifer systems with a moderate aquifer potential.

Lourens (2013) classified the Soutpansberg Group as a whole as being associated with low- to moderate-yielding aquifer systems, with boreholes yields ranging from 0.5 to 2 ℓ/s, but yields greater than 5 ℓ/s have also been recorded. Lourens (2013) stated that studies done in the Kruger National Park concluded that there is no linear relationship between yields and the depth of the boreholes, and high-yielding boreholes were associated with fault zones. Fractures were found at depths of up to 250 m below ground level. These structures produce high-yielding boreholes when intersected (Du Toit and Sonnekus, 2010). However, determining the position of these features is complicated and associated with high uncertainty (Lourens, 2013).

The groundwater quality of the Soutpansberg Group is generally good (Lourens, 2013). The electrical conductivity values of the Nzhelele Formation range from 10 to 555 mS/m, with 4% of the tested samples exceeding the maximum allowable limit (Du Toit and Sonnekus, 2010). The electrical conductivity values of the Wyllie's Poort Formation range from 3 to 912 mS/m, whereas the Fundudzi Formation has average electrical conductivity values of less than 150 mS/m (Lourens, 2013). Areas with water of a poor quality are located near villages, indicating that inadequate sanitation practices, combined with shallow sandy overburden and open fracture systems, contribute to the contamination of the groundwater resource (Du Toit and Sonnekus, 2010).

3.3.11 Namaqua-Natal Metamorphic Province

The Namaqua-Natal Province is considered to be the igneous and metamorphic rocks that are formed during the Namaqua Orogeny, and has outcrops in the Northern Cape and KwaZulu-Natal (Cornell et al., 2006, as cited by Lourens, 2013). The outcrop in KwaZulu-Natal is called the Natal Section and the outcrop in the Northern Cape is called the Namaqua Section (Figure 3-35). Regional gravity and magnetic surveys, xenolith evidence from kimberlites and deep SOEKOR boreholes have been used to show that the two outcrops are actually connected by a continuous orogenic belt beneath the Karoo Supergroup (Cornell et al., 2006) (Figure 3-35). The Namaqua-Natal Province is subdivided into different tectonostratigraphic subprovinces and terranes based on marked changes in lithostratigraphy across structural discontinuities (Cornell et al., 2006).

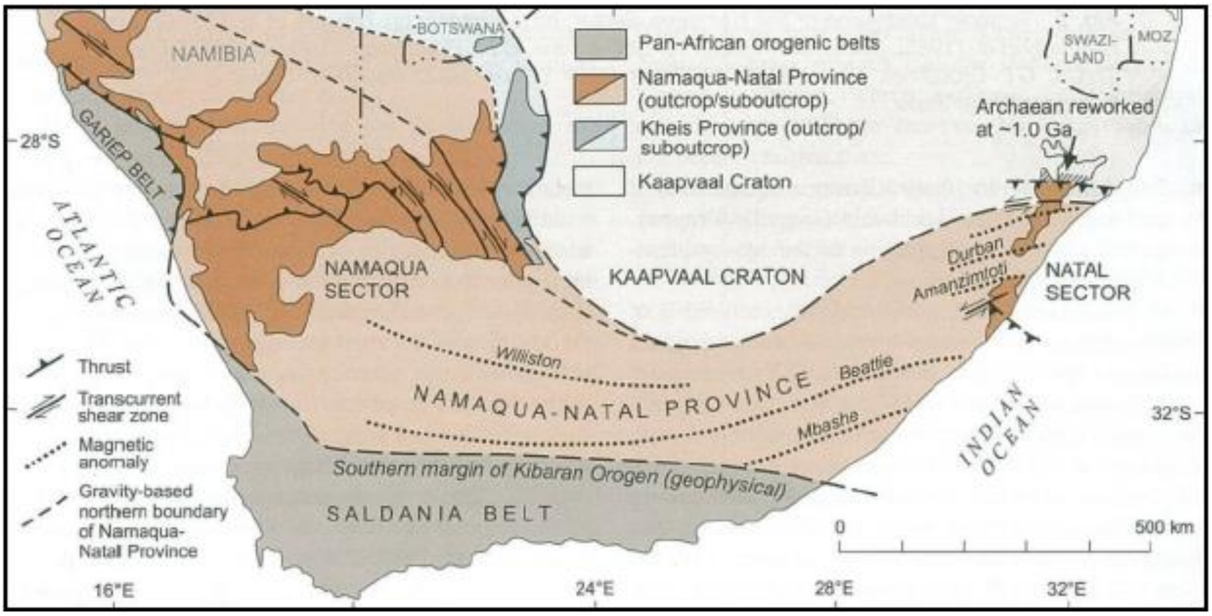


Figure 3-35: The geological setting of the Namaqua-Natal Province (Cornell et al., 2006)

3.3.11.1 Namaqua Section

3.3.11.1.1 Geology

The Namaqua Section is subdivided into the Richtersveld Subprovince, the Bushmanland Terrane, the Kakamas Terrane, the Areachap Terrane and the Kaaien Terrane (Cornell et al., 2006) (Figure 3-36). The Richtersveld Subprovince is a volcano-sedimentary sequence, called the Orange River Group, which consists of rhyolites and andesites, and an intrusive suite, called the Vioolsdrift Suite, which consists of gabbro complexes or plutons (Onstott et al., 1986, as cited by Lourens, 2013). The Richtersveld Subprovince was intruded by three generations of dyke swarms (Onstott et al., 1986).

The Bushmanland Terrane consists of a basement complex of granitic rock, a variety of supracrustal sequences (sedimentary and volcanic), and intrusive rocks that are granitic to charnochitic in composition (Cornell et al., 2006). The Kakamas Terrane is characterised by northwest trending stratigraphic units and structures (Cornell et al., 2006). The Kakamas Terrane is dominated by various intrusions with various degrees of deformation, along with sequences of metasedimentary rocks (Pettersson, 2008, as cited by Lourens, 2013). The rocks of the Kakamas Terrane are subdivided into various groups and suites and are composed of marbles, calc-silicates, sandstones, schists and metapelites, which are folded and intruded by undeformed granites (Lourens, 2013).

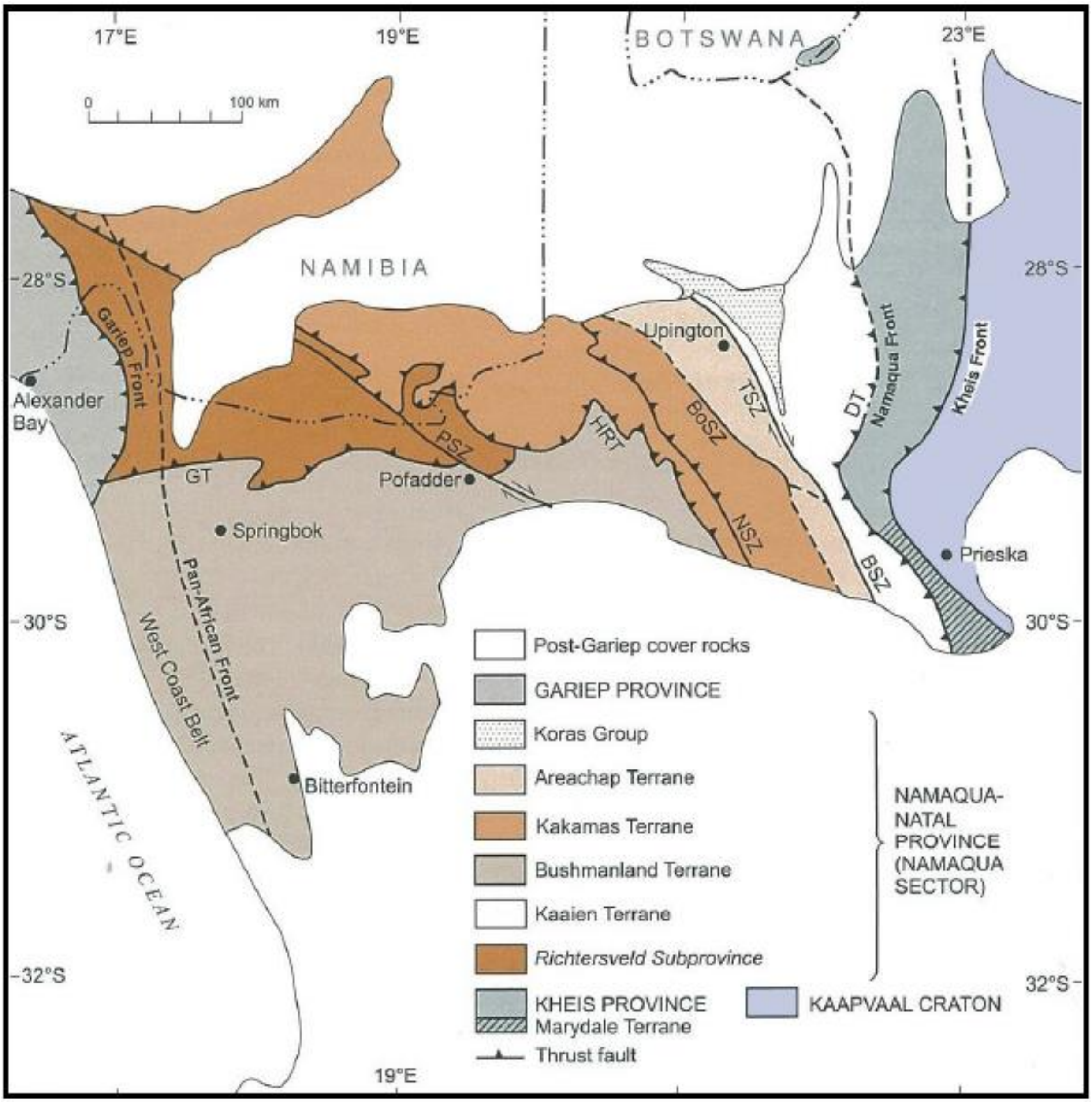


Figure 3-36: The tectonic subdivision of the Namaqua Section of the Namaqua-Natal Province (Cornell et al., 2006).

BoSZ: Boven Rugzeer Shear Zone; BSZ: Brakbosch Shear Zone; DT: Dabep Thrust; GT: Groothoek Thrust; HRT: Hartbees River Thrust; NSZ: Neusberg Shear Zone; PSZ: Pofadder Shear Zone

The Areachap Terrane consists of meta-volcanic rocks and immature sediments, which are occasionally magmatised and collectively known as the Areachap Group (Pettersson, 2008). The Kaaien Terrane is dominated by thick sequences of quartzite and minor volcanic layers (Cornell et al., 2006; Pettersson, 2008). The Kaaien Terrane is subdivided into four groups: the Brulpan, Vaalkoppies, Wilgenhoutsdrif and Koras groups. The Brulpan, Vaalkoppies and Wilgenhoutsdrif groups are highly deformed, but the Koras Group is relatively undeformed and unmetamorphosed (Cornell et al., 2006).

3.3.11.1.2 Geohydrology

Groundwater within the Namaqua Sector of the Namaqua-Natal Province occurs within three aquifer systems: a sandy/alluvial aquifer, a weathered aquifer and a fractured bedrock aquifer (Friese et al., 2006; Pietersen et al., 2009, as cited by Lourens, 2013). The geometry of these aquifer systems is controlled and influenced by the underlying geology of igneous and metamorphic rocks, its deformation history of metamorphic evolution, and the geomorphic development of the Namaqua Belt, including weathering (Pietersen et al., 2009). Despite the great variety of these metamorphic and igneous rocks, they are homogenous in two respects: the rocks have virtually no primary porosity, and secondary porosity is due to fracturing and weathering (Vegter, 2006, as cited by Lourens, 2013).

3.3.11.2 Natal Section

3.3.11.2.1 Geology

The lithostratigraphy of the Natal Section comprises supracrustal gneisses, granitoid gneisses and younger intrusive rocks (McCourt et al., 2006, as cited by Lourens, 2013). The Natal Section is subdivided into the Margate Terrane, the Mzumbe Terrane and the Tugela Terrane (Cornell et al., 2006) (Figure 3-37).

The lithostratigraphy of the Margate Terrane is dominated by granitoid gneisses and subordinate basic gneisses, with minor carbonate and pelitic supracrustal gneisses (McCourt et al., 2006). The Mzumbe Terrane consists of layered gneisses, migmatites and fine-grained felsic gneisses (Jacobs et al., 1997, as cited by Lourens, 2013). The Tugela Terrane can be grouped into the Natal Thrust Belt and the Natal Nappe Complex (McCourt et al., 2006). The Natal Thrust Belt forms a narrow, 2 to 5 km wide, southerly-dipping imbricate zone, subdivided into the Ntingwe and the Mfongosi groups. The Natal Nappe Complex consists of four west-plunging thrust sheets: the Tugela Nappe, the Mandleni Nappe, the Madidima Nappe and the Nkomo Nappe (Lourens, 2013).

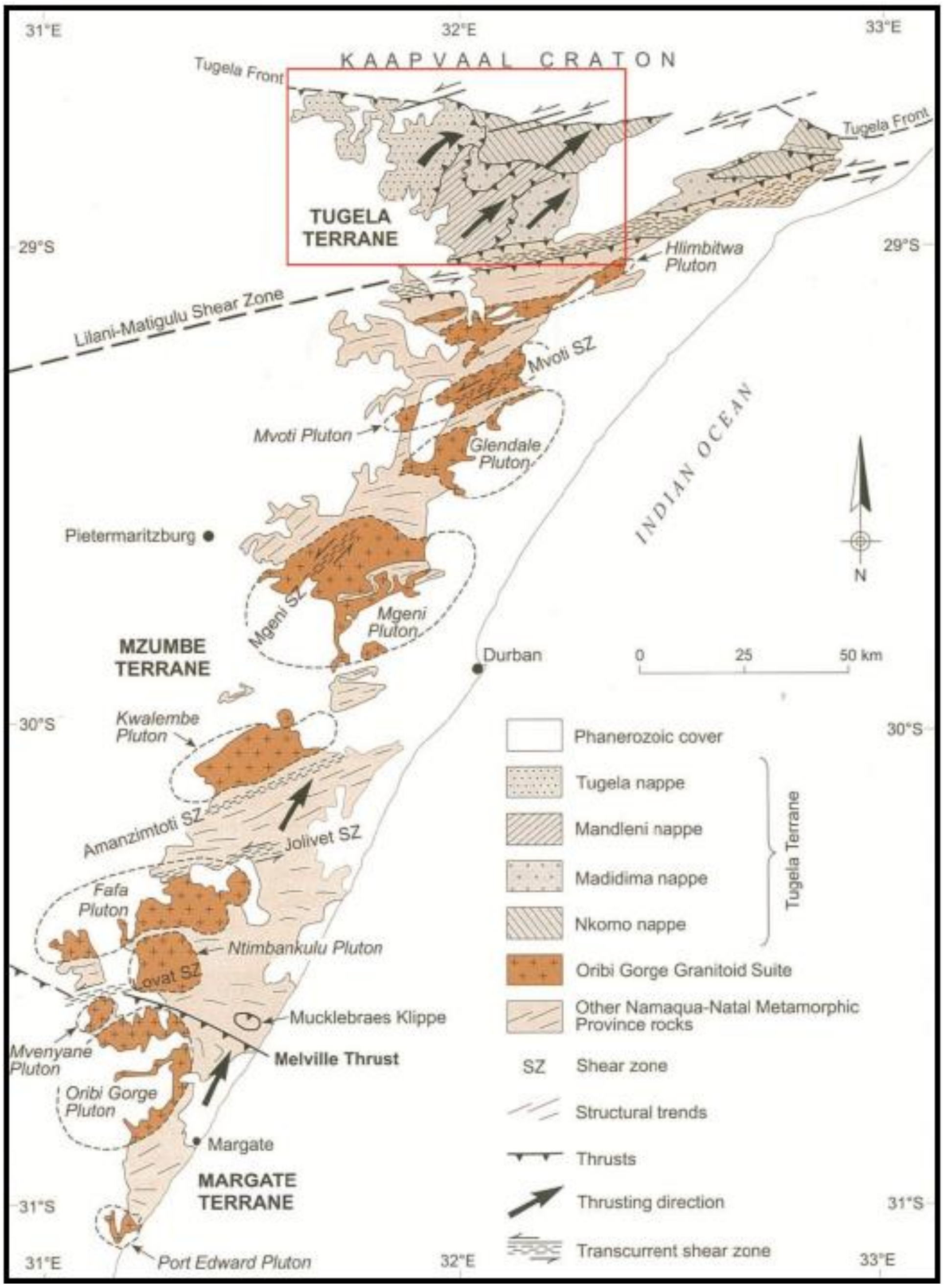


Figure 3-37: Simplified geology map of the Natal Sector of the Namaqua-Natal Metamorphic Province (Cornell et al., 2006)

3.3.11.2.2 Geohydrology

Groundwater in the Natal Section of the Namaqua-Natal Province has not been extensively exploited when compared to the drier parts of South Africa, resulting in limited information about the characteristics of the igneous and metamorphic rocks (Lourens, 2013). Lourens (2013) classified the Natal Section as being associated with intergranular and fractured aquifer systems, where the intergranular aquifer consists of weathering material that has high porosity and low hydraulic conductivity due to its clayey nature. The thickness of the weathered zone is generally less than 25 m (Lourens, 2013). The weathered zone is hydraulic, and is connected to the underlying fractured or solid bedrock.

The Natal Section hosts a low-yielding aquifer system, with measured yields ranging from 0.1 to 0.4 ℓ/s for the weathered zones, and up to 0.5 ℓ/s for the underlying fractures (Lourens, 2013). The probability of drilling a successful borehole within the rocks of the Natal Section is approximately 70% and the groundwater quality is generally good according to Lourens (2013).

3.3.12 Saldania Belt – Malmesburg Group

3.3.12.1 Geology

The Saldania Belt is a low-grade orogenic belt that is found along the southern and southwestern borders of the Kalahari Craton (Gresse et al., 2006). The Saldania Belt is subdivided into three tectonostratigraphic terranes: the Tygerberg, Swartland and Boland terranes (Figure 3-38 and Figure 3-39). The main outcrop of this belt is called the Malmesburg Group. It is located to the north and northeast of Cape Town (Gresse et al., 2006).

The Tygerberg Formation is the only component recognised within the Tygerberg Terrane (Figure 3-39). The Tygerberg Formation is characterised by alternating layers of greywacke, phyllitic shales and siltstone, immature quartzite and conglomerate beds (Gresse et al., 2006). There is also a locally developed volcanic succession, the Bloubergstrand Member, which is composed of tuff, agglomerate and altered amygdaloidal, calc-alkaline andesite (Rozendaal et al., 1999, as cited by Lourens, 2013).

The Swartland Terrane is bounded by the Boland in the northeast and the Tygerberg Terrane in the southwest (Figure 3-38). The Malmesbury Group in the Swartland Terrane is subdivided into the Franschhoek Formation, the Bridgetown Formation and the Swartland Subgroup (Gresse et al., 2006) (Figure 3-39). The Swartland Subgroup consists of chlorite and quartz schists, and greywacke with interbedded phyllite and limestone (Rozendaal et al., 1999). The Franschhoek Formation consists of feldspathic conglomerate and quartzite, grit, slate and phyllite. The Bridgetown Formation is a meta-volcanic succession, which consists of a complex of greenstone bodies, intrusive dykes, dolomite, chert and graphitic schists (Rozendaal et al., 1999).

The Boland Subgroup is subdivided into the Piketberg, Norree, Porterville and Brandwacht formations (Gresse et al., 2006) (Figure 3-39). The Piketberg Formation consists of foliated and lineated quartzites, greywackes, schist, BIF, grit, conglomerate and some impure marly limestones (Lourens, 2013). These lithologies are inter-fingered with the Porterville formations, which consist of limestone, chert and quartzite. The Brandwacht Formation consists of greywacke and pelite, with interbedded lenses of poorly sorted conglomerates and meta-volcanic rocks (Rozendaal et al., 1999).

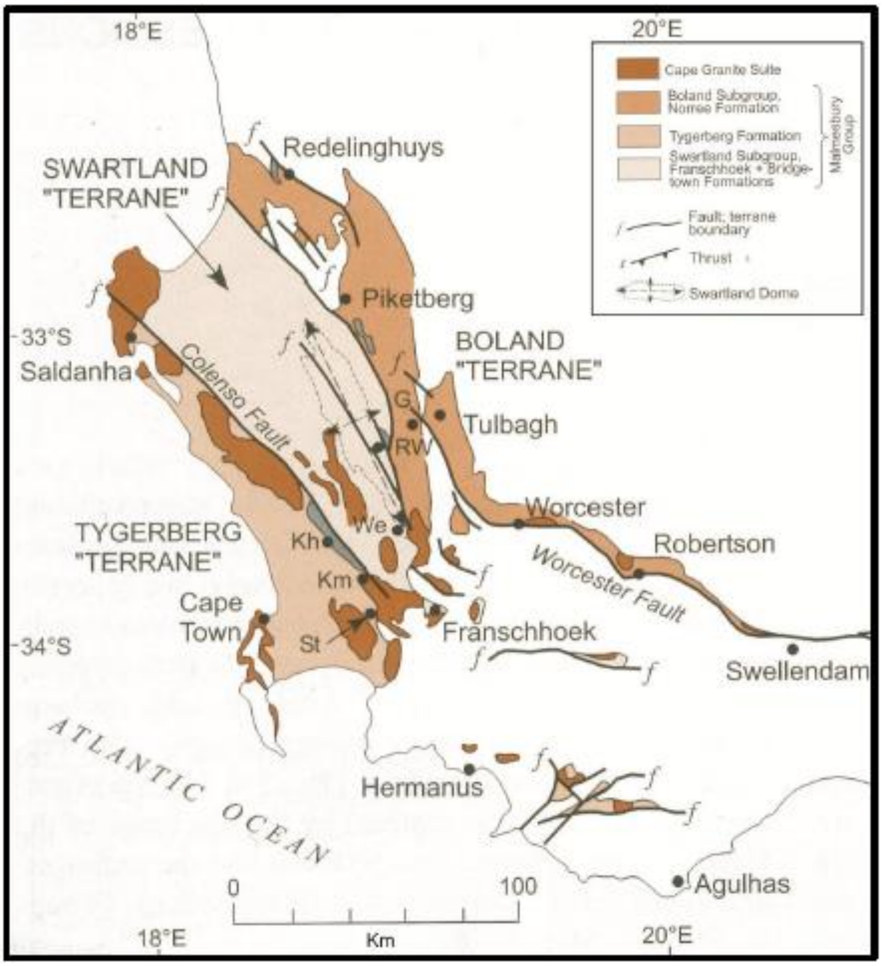


Figure 3-38: Simplified geology map of the Malmesbury Group indicating the distribution of the group in the Saldania Belt (modified from Gresse et al., 2006; Lourens, 2013)

3.3.12.2 Geohydrology

Lourens (2013) classified the Malmesburg Group as being associated with a fractured rock aquifer system, with a tendency to form confined and semi-confined aquifers. Lourens (2013) also considers the Malmesburg Group to host low-yielding aquifer systems, with most boreholes yielding less than 2 ℓ/s. However, high-yielding boreholes are also known, with yields of up to 12 ℓ/s reported (Lourens, 2013). These high-yielding boreholes are related to the intersection of water-bearing fractures. However, the aquifers of the Table Mountain Group are higher yielding and found close to the location of the Malmesburg Group, which has led to the latter group being targeted less often for water supply (Lourens, 2013).

The groundwater quality of the Malmesbury Group varies considerably, which is probably due to the variable lithologies and recharge conditions (Lourens, 2013). The groundwater of a better quality is generally associated with areas where groundwater movement takes place faster, i.e. a shallow groundwater system. Measured electrical conductivity values within the Malmesburg Group range from 10 to 1,000 mS/m (Meyer, 2001, as cited by Lourens, 2013).

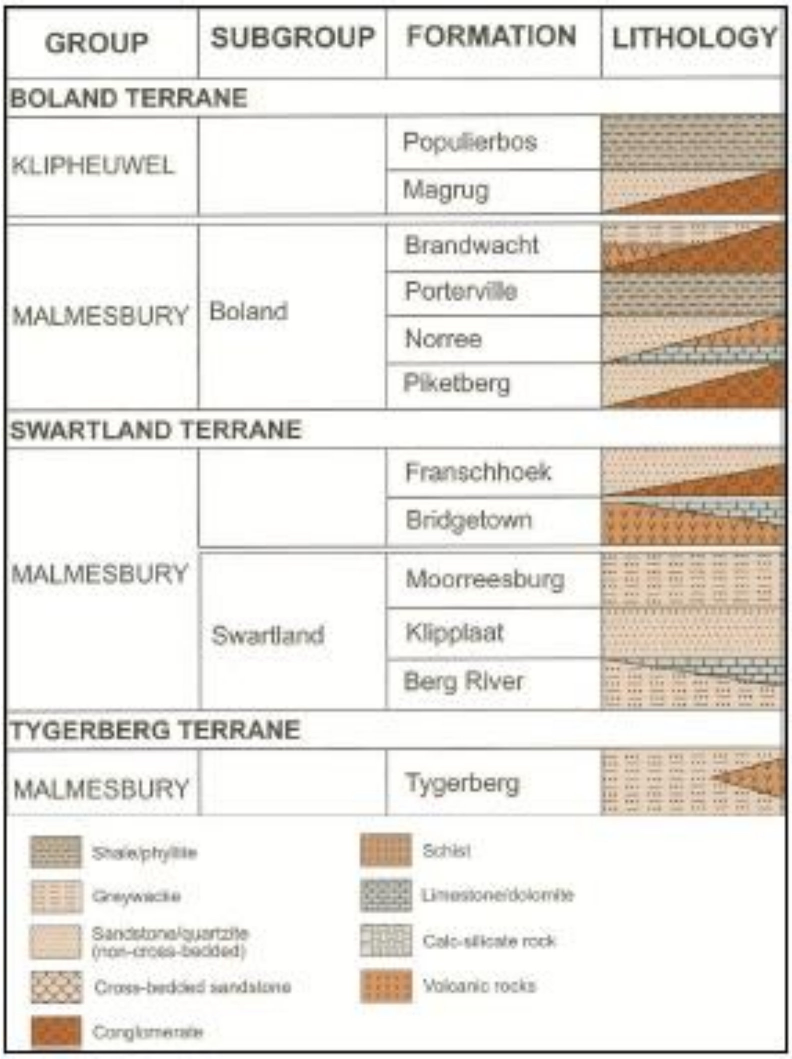


Figure 3-39: Lithostratigraphy of the Malmesbury Group (modified from Gresse et al., 2006; Lourens, 2013)

3.3.13 Natal Group

The Natal Group underlies the Dwyka Group and overlies the Archaean and Proterozoic basement. It consists of conglomerates, sandstones, siltstones and mudrocks (Marshall, 2006). The Natal Group was classed as part of the Table Mountain Group until 1980, because, lithologically, the group is similar to the Cape Supergroup. From 1980, the Natal Group was considered separate because none of the latter succession's formations can be recognised (Marshall, 2006). The Natal Group is located in KwaZulu-Natal, where the depositional basin of the group extends from Hlabisa in the north to Port Shepstone in the south (Lourens, 2013) (Figure 3-40).

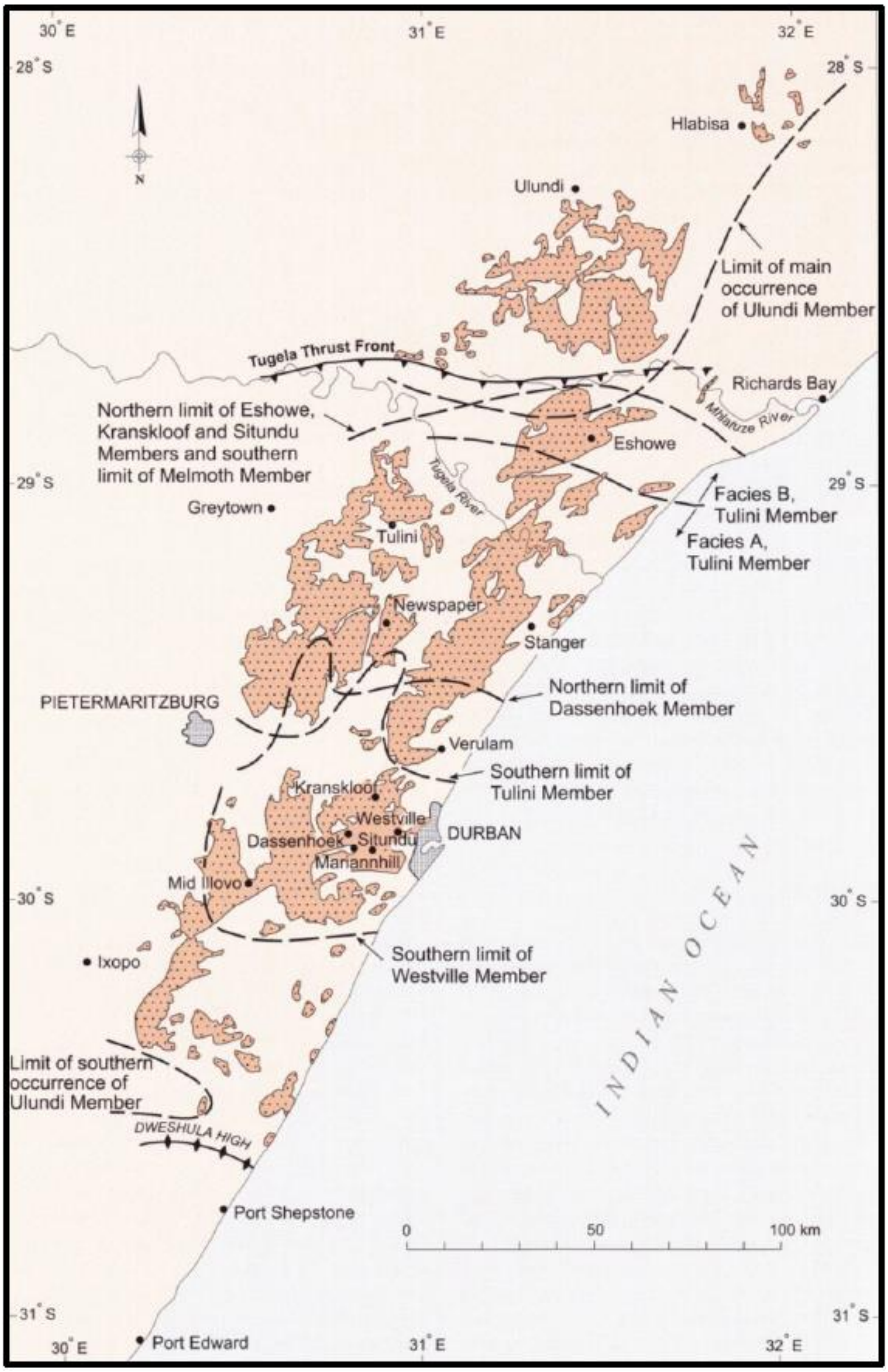


Figure 3-40: Distribution of the Natal Group and areal extent of the various members (Marshall, 2006)

3.3.13.1 Geology

The Natal Group is subdivided into two formations: the Mariannhill and the Durban formations. These two formations are subdivided into eight members: three in the Mariannhill Formation and five in the Durban Formation (Table 3-4). The maximum total thickness of the group is 500 to 600 m, with an average thickness of 200 m (Marshall, 2006). The lithostratigraphy of the Natal Group is shown in Table 3-4, where the estimated thicknesses for the individual members are given.

The Durban Formation is subdivided into the Ulandi, Eshowe, Kranskloof, Situndu, Dassenhoek and Melmoth members (Marshall, 2006) (Table 3-4). The upper part of the formation consists of more resistant lithologies, which are more prominent than the younger Marianhill Formation (Lourens, 2013). The Ulundi Member generally consists of matrix-poor/clast-supported, boulder-to-pebble conglomerates, with minor lenticular beds of sandstone and shale (Marshall, 2006; Lourens, 2013).

Table 3-4: Lithostratigraphy of the Natal Group (Marshall, 2006)

<table>
<tr><th>Formation</th><th colspan="2">Member</th><th colspan="2">Dominant Lithology</th><th colspan="2">Maximum Thickness (m)</th><th colspan="2">Mean Thickness (m)</th></tr>
<tr><td rowspan="3">Marianhill</td><td colspan="2">Westville</td><td colspan="2">Matrix-supported conglomerate</td><td colspan="2">30</td><td colspan="2">?</td></tr>
<tr><td colspan="2">Newspaper</td><td colspan="2">Arkosic sandstone</td><td colspan="2">>368</td><td colspan="2">?</td></tr>
<tr><td colspan="2">Tulini</td><td colspan="2">Small-pebble conglomerate</td><td colspan="2">28</td><td colspan="2">13</td></tr>
<tr><td rowspan="5">Durban</td><td>Dassenhoek</td><td rowspan="4">Melmoth</td><td>Silicified quartz arenite</td><td rowspan="4">Medium-coarse arkosic sandstone and shale</td><td>422</td><td rowspan="4">168</td><td>11</td><td rowspan="4">70</td></tr>
<tr><td>Situndu</td><td>Coarse arkosic sandstone</td><td>84</td><td>25</td></tr>
<tr><td>Kranskloof</td><td>Silicified quartz arenite</td><td>51</td><td>22</td></tr>
<tr><td>Eshowe</td><td>Arkosic sandstone and shale</td><td>142</td><td>44</td></tr>
<tr><td colspan="2">Ulundi</td><td colspan="2">Coarse clast-supported conglomerate</td><td colspan="2">59</td><td colspan="2">18</td></tr>
</table>

The Eshowe Member extends over the entire basin, except in the far north, where it grades into the Melmoth Member. The Eshowe Member consists of arkosic sandstones, interbedded with mudrocks and siltstones (Marshall, 2006). The Kranskloof Member consists of silicified quartz arenite and subarkose, with minor interbedded mudrock units. The resistant nature of this member creates cliff faces, which form a rugged scenery that is typical of the Natal Group (Marshall, 2006). The Situndu Member is lithologically similar to the Eshowe and Newspaper members, and indistinguishable on a regional scale, which results in its mapping being dependent on adjacent members (Marshall, 2006). The Dassenhoek Member forms the upper unit of the Durban Formation. It resembles the Kranskloof Member and also forms a resistant quartz arenite unit (Marshall, 2006).

The Mariannhill Formation is subdivided into the Tulini, Newspaper and Westville members (Table 3-4). The Tulini Member forms the basal unit of the Marianhill Formation and is classed into two distinct facies: Facies A and Facies B (Marshall, 2006). Facies A, found to the south, consists of vein quartz and conglomerates, with interbedded coarse- to very coarse-grained sandstone and granule conglomerate. Facies B, found to the north, consists of conglomerates, which consist of clasts that are larger and less well rounded than those of Facies A (Marshall, 2006). The Newspaper Member consists of medium- to very coarse-grained sandstone, granule conglomerates and interbedded shale and siltstone. The Westville Member occurs very intermittently throughout the basin, and consists of matrix-supported polymict conglomerates (Marshall, 2006).

3.3.13.2 Geohydrology

The Natal Group has not been highly exploited for groundwater when compared to drier areas of South Africa, resulting in limited geohydrological information on the group (Bell and Maud, 2000, as cited by Lourens, 2013). Lourens (2013) classified rocks in the Natal Group as being associated with fractured rock aquifers, with negligible primary porosity and permeability (Geomeasure Group, 2007; KV3 Engineers, 2009, as cited by Lourens, 2013). However, it was found that the Natal Group has higher hydraulic conductivities than the surrounding lithologies, ranging from 0.4 to 7.7 m/d (King, 2003, as cited by Lourens, 2013).

Lourens (2013) classified the sandstones of the Natal Group as hosting moderate- to low-yielding aquifer systems, with reported median yields ranging from 0.1 to 2 ℓ/s, but yields of up to 10 ℓ/s have been recorded (KV3 Engineers, 2009). High-yielding boreholes are assumed to have intersected water-bearing fractures or faults. The sandstones and quartzites of the Natal Group have a high quartz content and will behave in a brittle manner when deformed, forming local zones of intense fracturing (near faults and dolerite intrusions), which enhances the recharge and permeability, and creates preferential groundwater flow paths (Bell and Maud, 2000; Geomeasure Group, 2007; KV3 Engineers, 2009; King, 2003). These zones of intense fracturing are ideal targets for groundwater resources because groundwater movement mainly occurs within joints, fractures or bedding planes (KV3 Engineers, 2009).

The groundwater quality of the Natal Group is generally good, with average electrical conductivity values of less than 100 mS/m (King, 2002; King, 2003, as cited by Lourens, 2013). The groundwater electrical conductivity values of the Natal Group within the coastal zone (Durban area) range between 23 and 185 mS/m, while the electrical conductivity of groundwater in the inland area rarely exceeds 45 mS/m (Bell and Maud, 2002). The groundwater in the Natal Group was often found to be slightly acidic and occasionally showed high levels of iron and manganese (King, 2002; King, 2003; KV3 Engineers, 2009).

The Natal Group has a maximum thickness of approximately 600 m. From Figure 3-41, it can be seen that the geological sections D, E and F show sandstone units of the Eshowe Member at depths of approximately 600 m, bound from below by an erosional contact with underlying granitic basement rocks. If deep groundwater is to be found within this geological group, this contact zone would be a potential target.

3.3.14 Cape Supergroup

The Cape Supergroup is a siliciclastic sequence of lithologies, originally deposited in a passive basin, and generally consisting of sandstone, shale and minor conglomerates (Thamm and Johnson, 2006). The Cape Supergroup is situated in the Western Cape and Eastern Cape, extending from Vanrhynsdorp to Cape Agulhas, and eastwards towards Port Elizabeth (Lourens, 2013) (Figure 3-42). The Cape Supergroup is divided into three main groups, which are lithologically distinctive and show lateral continuity. These are the Witteberg, Bokkeveld and Table Mountain groups (Thamm and Johnson, 2006; Lourens, 2013) (Figure 3-42).

3.3.14.1 Geology

3.3.14.1.1 Table Mountain Group

The Table Mountain Group is subdivided into six lithostratigraphical units: the Piekenierskloof, Graafwater, Peninsula, Pakhuis and Cedergberg formations, and the Nardouw Subgroup, which contains the Goudini, Skurweburg and Rietvlei formations (Thamm and Johnson, 2006) (Table 3-5). Figure 3-43 shows the stratigraphic column at three points within the Table Mountain Group.

The Peninsula Formation is the most magnificent formation of the Cape Supergroup, with a thickness that varies from 1,800 to 2,700 m (Visser, 1989, as cited by Lourens, 2013). The Peninsula Formation consists of quartz arenite, with minor shale and conglomerates (Thamm and Johnson, 2006). The Nardouw Subgroup consists of quartzitic sandstone and reaches a maximum thickness of 1,200 m near Citrusdal in the western part of the basin, but thins out rapidly northwards (Thamm and Johnson, 2006) (Figure 3-44).

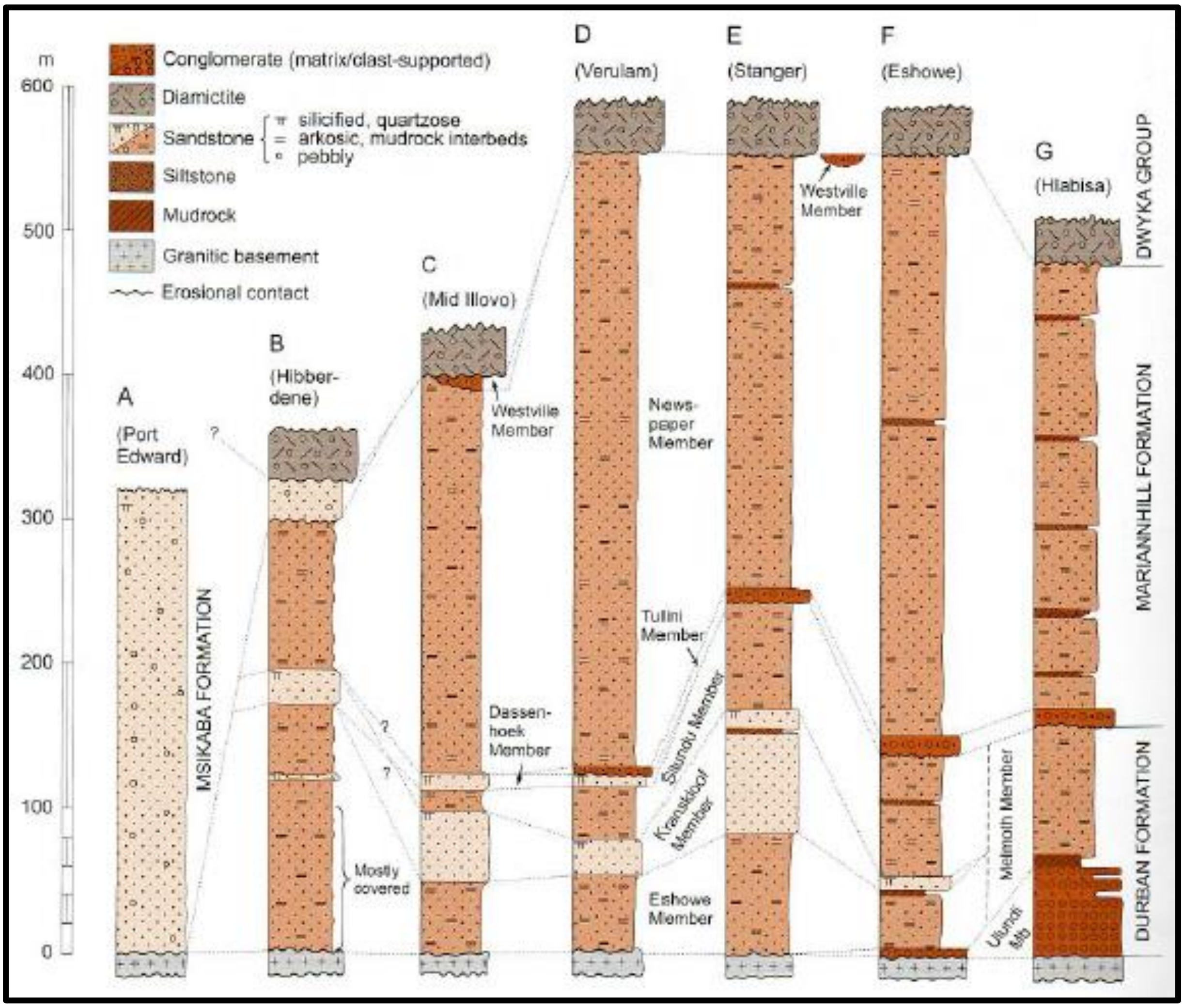


Figure 3-41: Representative composite sections of the Natal Group, extending from Port Edward to Hlabisa in the north (Marshall, 2006)

3.3.14.1.2 Bokkeveld Group

The Bokkeveld Group consists of a cyclic alternation of fine-grained sandstone and mudrock units (Thamm and Johnson, 2006). In the western section, the Bokkeveld Group is approximately 2,200 m thick, and the eastern section reaches a thickness of 3,500 m (Thamm and Johnson, 2006). The Bokkeveld Group is subdivided into three subgroups: the Ceres, Bidouw and Traka subgroups (Figure 3-45 and Table 3-6).

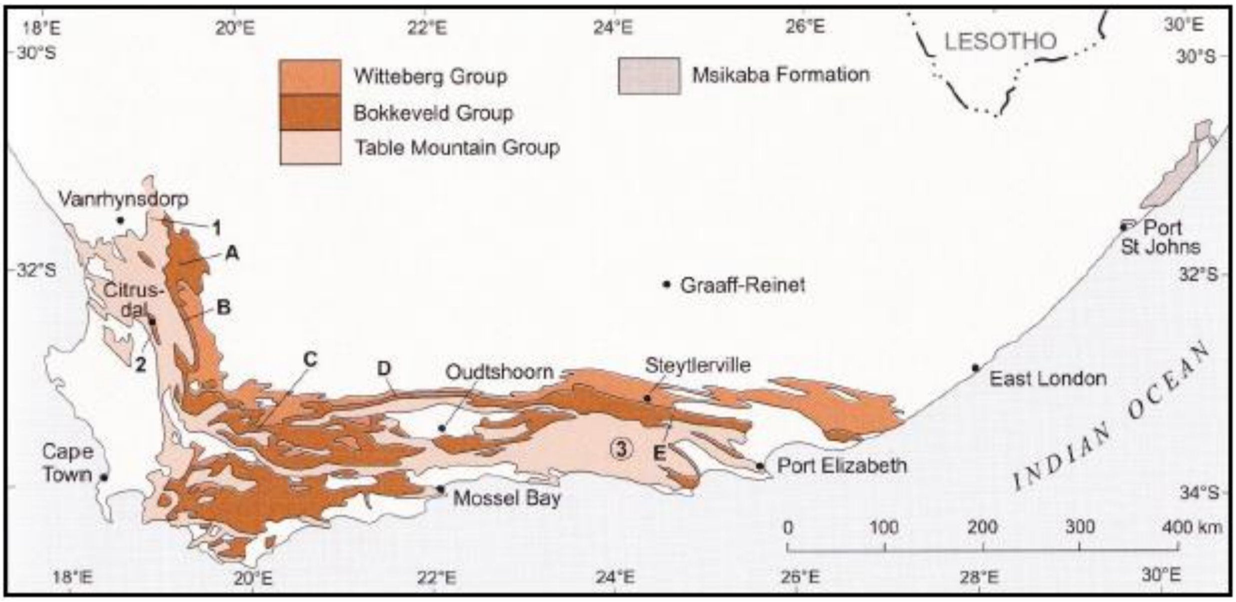


Figure 3-42: Distribution of the Cape Supergroup, indicating section lines of the Table Mountain Group (1-3) and Bokkeveld Group (A-E) (Thamm and Johnson, 2006)

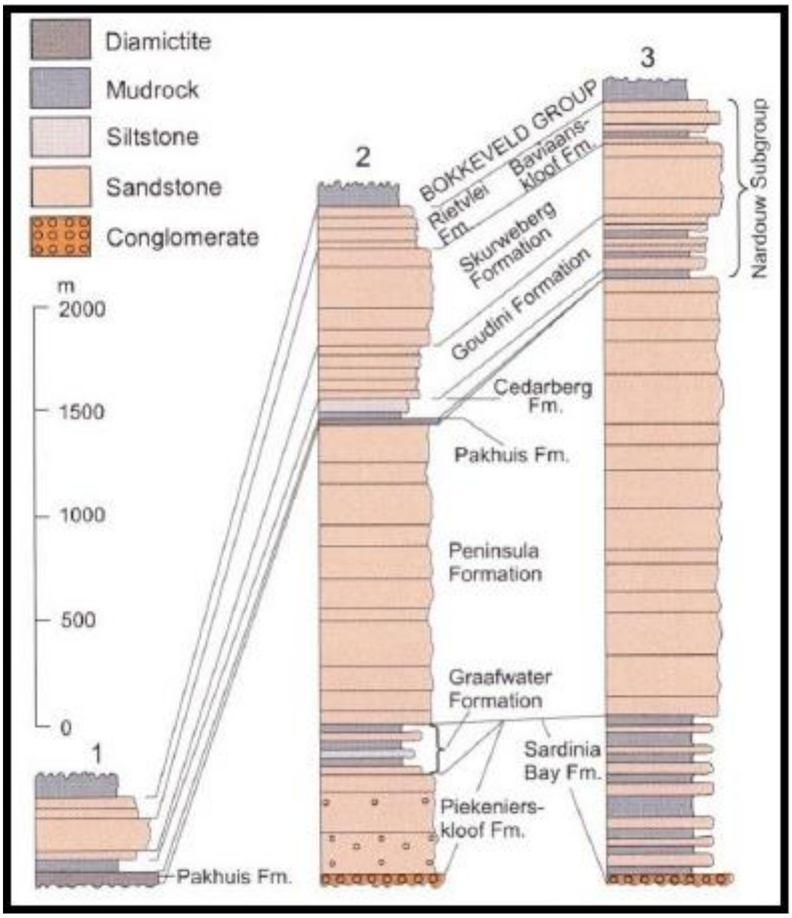


Figure 3-43: Representation sections (1-3) of the Table Mountain Group (Thamm and Johnson, 2006)

Table 3-5: Lithostratigraphy of the Table Mountain Group, with approximate maximum thicknesses (in metres) in brackets (Thamm and Johnson, 2006)

	West of ~21°E	East of 21°E	Lithology
	Formation	Formation	
Nardouw Subgroup	Rietvlei (200)	Baviaanskloof (200)	Sandstone (with shale in east)
	Skurweberg (300)	Skurweberg (400)	Sandstone (thick-bedded)
	Goudini (200)	Goudini (300)	Sandstone (red-brown)
	Cedarberg (120)	Cedarberg (50)	Shale, siltstone
	Pakhuis (80)		Diamictite, sandstone
	Peninsula (2000)	Peninsula (2700)	Sandstone
	Graafwater (430)	Sardinia Bay (900?)	Sandstone, siltstone, shale
	Piekenierskloof (900)		Sandstone, conglomerate

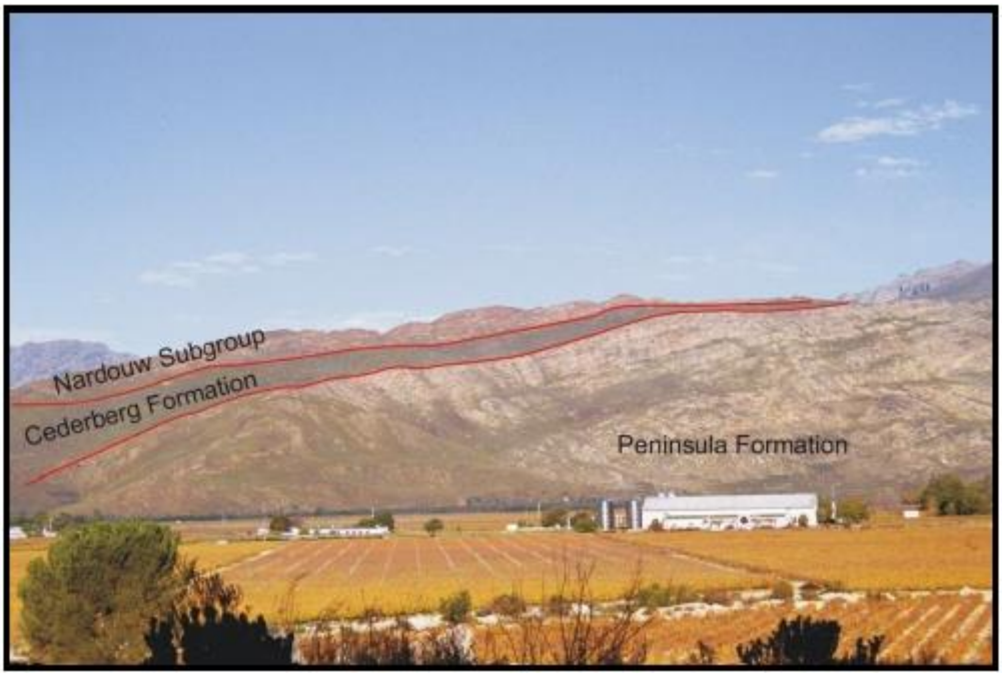


Figure 3-44: Peninsula Formation with Cedarberg Shale Formation on top (Lourens, 2013)

The Ceres Subgroup forms the base of the Bokkeveld Group, thickens towards the east and becomes progressively thinner north of the basin (Thamm and Johnson, 2006; Visser, 1989). Three upward-coarsening cycles can be recognised within the Ceres Subgroup, consisting of mudrock, siltstone and fine- to medium-grained sandstone layers (Thamm and Johnson, 2006). The Ceres Subgroup is overlain by the Bidouw and Traka subgroups in the western and eastern parts of the basin, respectively (Figure 3-45).

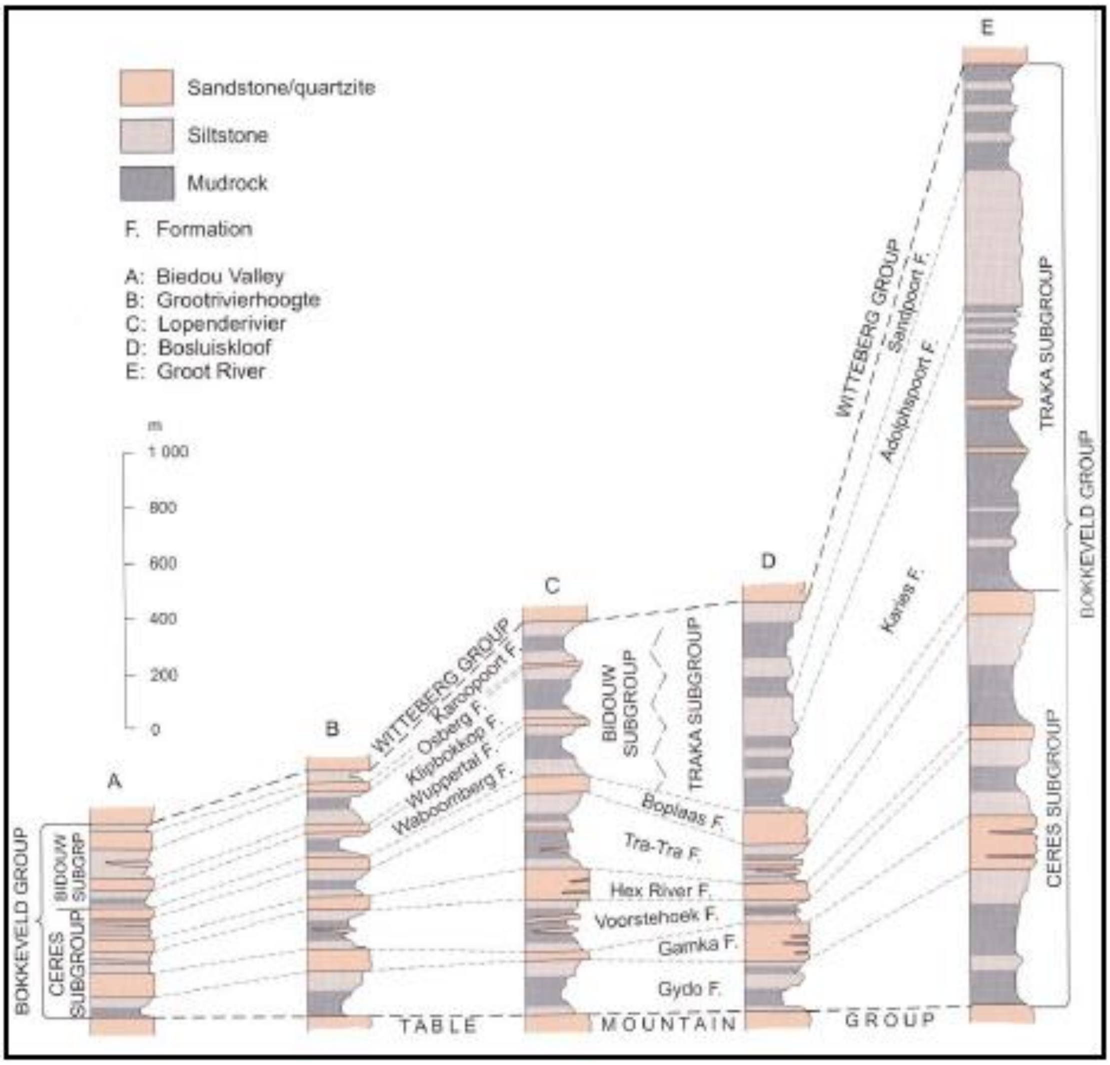


Figure 3-45: Representative sections (A-E) of the Bokkeveld Group (Thamm and Johnson, 2006)

The top of the Bidouw Subgroup is characterised by upward-coarsening cycles consisting of shale, micaceous siltstone and quartz arenite (Thamm and Johnson, 2006). The Traka Subgroup consists of dark rhythmites and shale, which becomes silty and lenticular-bedded upwards, with a thickness of 200 to 300 m (Thamm and Johnson, 2006; Visser, 1989).

3.3.14.1.3 Witteberg Group

The Witteberg Group consists of approximately equal portions of quartzitic sandstone and micaceous mudrock (Thamm and Johnson, 2006). The thickness of the Witteberg Group decreases from 1,700 m in the east to 1,200 m in the southwestern part of the basin, and then decreases rapidly northwards along the western margin (Thamm and Johnson, 2006). The Witteberg Group is subdivided into three subgroups: the Kommadagga, Lake Mentz and Weltevrede subgroups (Table 3-7 and Figure 3-46).

Table 3-6: Lithostratigraphy of the Bokkeveld Group, with approximate maximum thicknesses in brackets (m) (Thamm and Johnson, 2006)

	West of 21°E		East of 21°E	Lithology	
	Formation		Formation		
Bidouw Subgroup	Karoopoort (150)	Traka Subgroup	Sandpoort (400)	Mudrock, siltstone, sandstone	
	Osberg (55)		Adolphspoort (600)	Sandstone (siltstone in east)	
	Klipbokkop (300)		Karies (1300)	Mudrock, siltstone, sandstone	Karies Formation: Mudrock, rhythmite
	Wuppertal (70)			Sandstone, siltstone	
	Waboomberg (200)			Mudrock, siltstone, sandstone	
Ceres Subgroup	Boplaas (70)	Ceres Subgroup	Boplaas (100)	Sandstone	
	Tra-Tra (85)		Tra-Tra (350)	Mudrock, siltstone	
	Hex River (60)		Hex River (60)	Sandstone	
	Voorstehoek (200)		Voorstehoek (300)	Mudrock, siltstone	
	Gamka (70)		Gamka (200)	Sandstone	
	Gydo (150)		Gydo (600)	Mudrock, siltstone	

Table 3-7: Lithostratigraphy of the Witteberg Group, with approximate maximum thicknesses in brackets (in metres) (Thamm and Johnson, 2006)

	West of ~22°E		East of ~22°E	Lithology
	Formation		Formation	
		Kommadagga Subgroup	Dirkskraal (110)	Sandstone
			Soutkloof (165)	Shale, rhytmite
			Swartwaterpoort (6)	Sandstone
			Miller (95)	Diamictite
Lake Mentz Subgroup	Waaipoort (250)	Lake Mentz Subgroup	Waaipoort (460)	Mudrock, sandstone
	Floriskraal (120)		Floriskraal (120)	Shale, sandstone
	Kweekvlei (130)		Kweekvlei (200)	Shale
	Witpoort (400)		Witpoort (850)	Sandstone
Weltevrede Subgroup	Swartruggens (300)		Weltevrede (850)	Shale, siltstone, sandstone
	Blinkberg (100)			Sandstone, siltstone
	Wagen Drift (165)			Shale, siltstone, sandstone

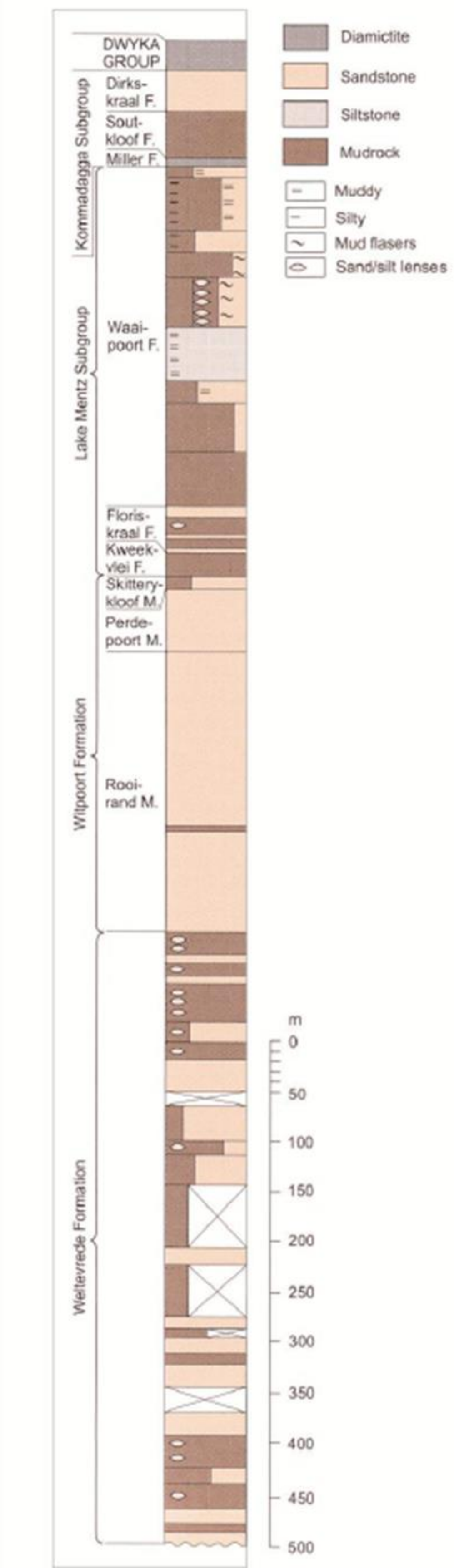


Figure 3-46: Section of the Witteberg Group at Waaipoort, northeast of Steytlerville (Thamm and Johnson, 2006)

3.3.14.2 Porosity and permeability

Viljoen et al. (2010) found that the rocks of the Cape Supergroup would be a potential CO_2 storage site because of the presence of thick quartzitic sandstones (of the Table Mountain Group) with good shale caprocks (of the Bokkeveld Group), and because of its wide lateral extent and thickness. However, it was concluded that the storage potential was not sufficient because of the low primary porosities (Table 3-8). Table 3-8 lists porosity and permeability values measured from deep SOEKOR boreholes drilled into the Cape Supergroup. Figure 3-47 gives a scale of permeability in units of log10 m^2 as shown in Table 3-8. Another reason why the Cape Supergroup was not selected for a potential storage site was the risk of contamination when considering the high usage of groundwater from these aquifers (Viljoen et al., 2010).

The Msikaba Formation outcrops near Durban and is correlated to the Witteberg Group. Viljoen et al. (2010) also concluded that this would not be a good CO_2 storage site for similar reasons as the Cape Supergroup. However, the formation is more than 800 m thick in places, and could potentially be associated with deep aquifer systems (Thamm and Johnson, 2006).

Table 3-8: Porosity and permeability values for sandstones of the Cape Supergroup in deep SOEKOR boreholes drilled in the Karoo (modified from Viljoen et al., 2010)

Borehole	Stratigraphic Interval (group)	Depth interval analysed (m)	No. of samples	Porosity		Hydraulic conductivity range (m/d)	Permeability Log_{10} m^2
				Range	Average		
OL 1/69	TMG	1 068 – 1 173	5	2.7 – 9.3	6.3	0.0 – 1.3 x 10^{-7}	-16
KL 1/65	Bokkeveld	2 041 – 2 717	53	0.0 – 4.3	0.5	0.0 – 7.3 x 10^{-7}	-15
	TMG	2 814 – 3 414	30	0.0 – 3.2	0.36	0.0	0
SA 1/66	Bokkeveld	3 596 – 3947	9	0.23 – 4.19	0.96	0.0	0
SC 3/67	Bokkeveld	5 334	1	1.02	1.02	0.0	0
Vrede 1/66	TMG	322 – 3 420	7	1.0 – 2.3	1.5	0.0	0

3.3.14.3 Geohydrology

3.3.14.3.1 Table Mountain Group

The Table Mountain Group hosts one of the most important regional groundwater aquifers in South Africa (Viljoen et al., 2010). The total flow of eight major springs occurring on the Table Mountain Group has been measured to be greater than 300 ℓ/s, and the total daily usage by 11 towns (with more than 30 major users) from the Table Mountain Group aquifer is approximately 18 000 m^3 (Rosewarne, 2002a, as cited by Viljoen et al., 2010).

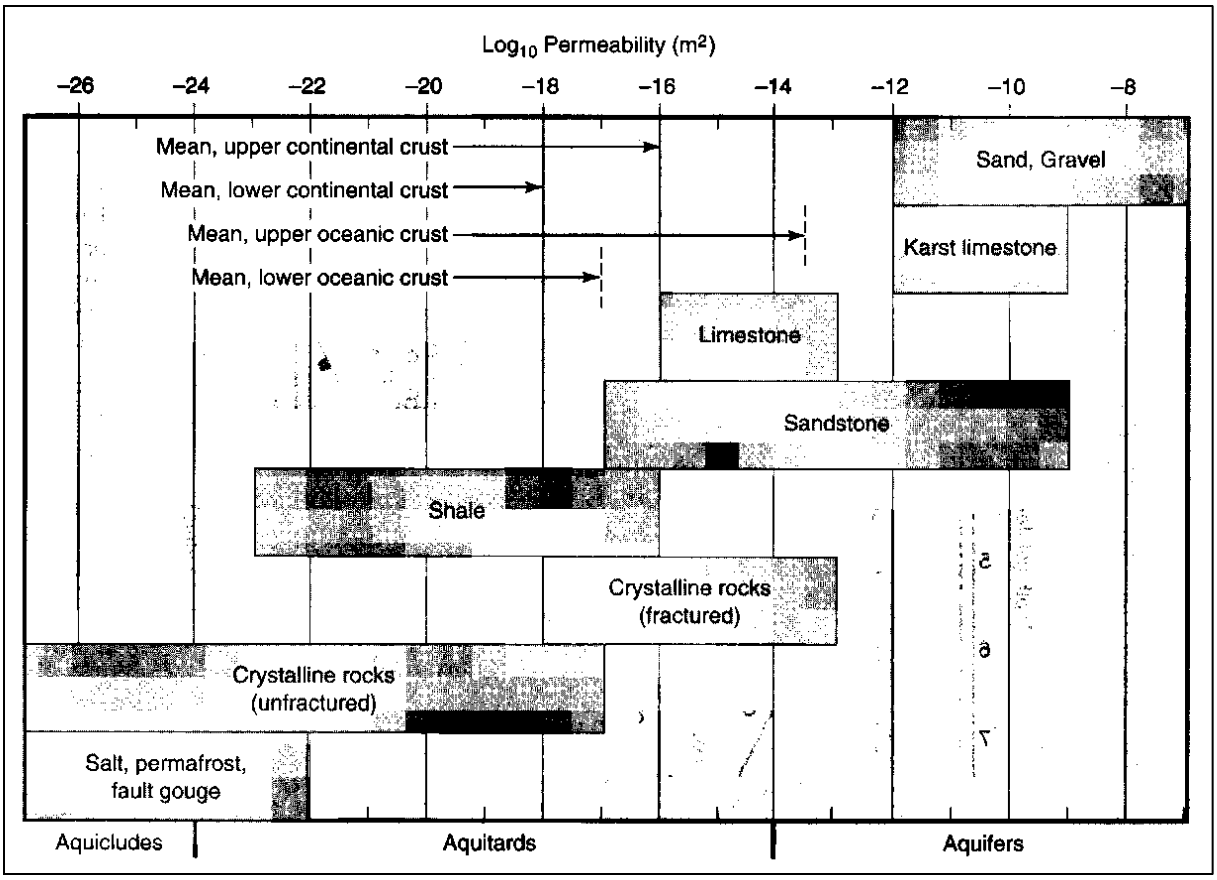


Figure 3-47: Permeability ranges for different lithologies showing the estimated divides between aquifer, aquitard and aquiclude

The Table Mountain Group is characterised by an abundance of springs (Meyer, 2001, as cited by Lourens, 2013). Meyer (2001) and Kotze (2002), as cited by Lourens (2013), identified three types of springs within the Table Mountain Group: shallow springs emanating at perched water tables, lithologically controlled springs (due to the presence of interbedded aquitards), and fault-controlled springs. The third type of spring (fault-controlled springs) is generally associated with deep circulating groundwater, which often supplies large and constant amounts of groundwater (Meyer, 2001). These springs are associated with elevated groundwater temperatures at the surface, ranging from 20 °C to more than 40 °C (Kotze, 2002).

Lourens (2013) classified the Table Mountain Group as being associated with secondary aquifer systems, where secondary porosity features control groundwater movement. The Table Mountain Group aquifers can be divided into four categories: horizontal strata, folded strata, the fracture zone and composite aquifer systems (Xu et al., 2007, as cited by Lourens, 2013). According to Viljoen et al. (2010), very good fracture porosity is created where folding and faulting are present.

The main groundwater intersections within the Table Mountain Group aquifer are at depths greater than 100 m below ground level (Rosewarne, 2002b, as cited by Lourens, 2013). Borehole yields have been found to increase with depth (Kotze, 2002; Rosewarne, 2002b) (Figure 3-48). This characteristic feature goes against conventional structural geological theory, which states that joint or fracture openings will close with increasing depth due to the pressure of the overlying rock mass (Rosewarne, 2002b). However, deep groundwater circulation has been confirmed within the Table Mountain Group (Cave and Clarke, 2003; Viljoen et al., 2010). For these reasons, the Table Mountain Group is considered to host deep aquifer systems.

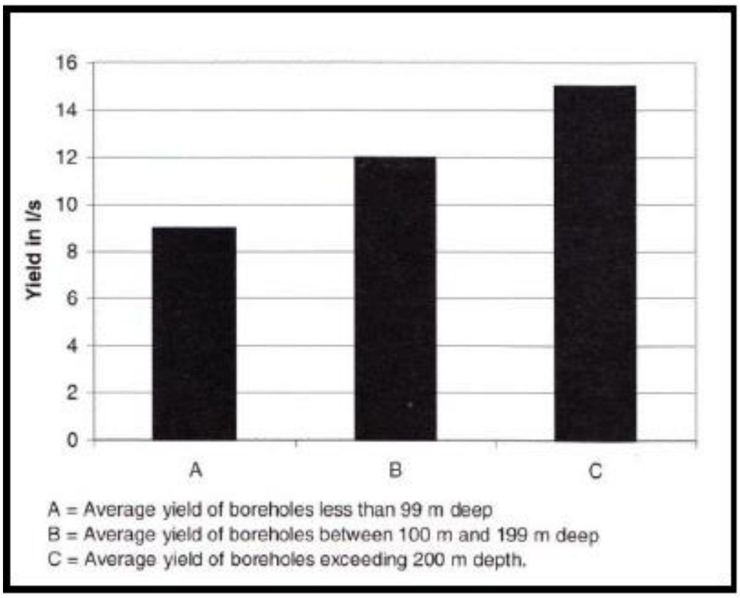


Figure 3-48: Graph of borehole yield and depth in the Grabouw-Villiersdorp area (Rosewarne, 2002b)

3.3.14.3.2 Bokkeveld Group

Lourens (2013) classified the Bokkeveld Group as being associated with secondary aquifer systems, where secondary porosity features control groundwater movement. The sandstone layers of the Ceres Subgroup are considered to host aquifers, but have limited yields over long periods of withdrawal (Weaver, 2011, as cited by Lourens, 2013). The more argillaceous Bidouw Subgroup hosts lower-yielding aquifers with groundwater of a poor quality (Parsons, 2011a, as cited by Lourens (2013).

Lourens (2013) classified the Bokkeveld Group as being associated with low-yielding aquifers with groundwater of a poor quality when compared to the aquifers of the Table Mountain Group (Parsons, 2011b, as cited by Lourens, 2013). In the Ceres Subgroup, yields of up to 5 ℓ/s are common, but the yield becomes less than 5 ℓ/s over time (Meyer, 1998; Meyer, 1999, as cited by Lourens, 2013). These higher yields are only found in areas where recharge conditions are favourable (Meyer, 2001, as cited by Lourens, 2013). However, the Traka and Bidouw subgroups have yields of less than 5 ℓ/s, with the majority of yields being less than 1 ℓ/s (Meyer, 1998; Meyer, 1999).

The water quality of the Bokkeveld Group has been found to deteriorate with an increase in the distance from the Nardouw Subgroup of the Table Mountain Group (Weaver, 2011). In the Ceres Subgroup, the electrical conductivity values range from 30 to 400 mS/m, but in the Steytlerville area and the area west of Port Alfred, these values commonly exceed 200 mS/m (Meyer, 1998; Meyer, 1999; Meyer, 2001). However, in the Traka/Bidouw Subgroup, the electrical conductivity values generally exceed 400 mS/m (Meyer, 2001; Meyer, 1999).

3.3.14.3.3 Witteberg Group

Lourens (2013) classified the Witteberg Group as being associated with secondary aquifer systems, where secondary porosity features control groundwater movement. Lourens (2013) did not classify the Witteberg Group according to yield because more research needs to be done on the geohydrology of the group before such classification would be possible (Weaver, 2011). Lourens (2013) found that borehole yields within the Witteberg Group are generally less than or equal to 0.5 ℓ/s, where the yield of the shale layers rarely exceeds 2 ℓ/s, while yields from the sandstone layers are generally higher with yields in excess of 2 ℓ/s and up to 5 ℓ/s reported (Meyer, 1998; Meyer, 1999; Meyer, 2001).

However, positioning boreholes on fractures in the sandstone units close to shale units may increase the chance of groundwater of a poor quality being drawn in from the shale units (Meyer, 1998; Meyer, 2001). The shale layers of the Witteberg Group have electrical conductivity values that range from 200 to 700 mS/m, while the sandstone layers have electrical conductivity values that range from 70 to 150 mS/m (Meyer, 1998; Meyer, 1999; Meyer, 2001).

3.3.14.3.4 Locating groundwater resources

The Table Mountain Group is the main drilling target for locating groundwater resources within the Cape Supergroup because of its large extent, high-yielding springs and boreholes, and water of a good quality (Lourens, 2013). Target formations within the Cape Supergroup include the Piekenierskloof, Peninsula and Nardouw formations and the Ceres Subgroup (Lourens, 2013). Specific features that are targeted include major regional fault systems, localised fractures or faults, and bedding planes. Lourens (2013) stated that these structures are very heterogeneous. For this reason, the fracture systems should be studied in detail.

3.3.15 Summary of the Pre-Karoo basins

A summary of the important information contained in Chapter 3 is provided below:

3.3.15.1 Limpopo Belt

The occurrence of thermal springs within the Limpopo Belt serves as an indication of long, deeper groundwater flow systems (Lourens, 2013). The Limpopo Belt is represented as the main lithology of schists, and the thermal springs located along the northern boundary of Limpopo are found within this formation. Dhansay et al. (2014) selected a site in the Limpopo Belt to evaluate the low-enthalpy geothermal potential for South Africa. The hot spring with the highest temperature is found near the geothermal test site. According to Dhansay et al. (2014), the spring reaches a surface temperature of 70 °C and circulates to a depth of 2 km.

However, Lourens (2013) reported that Vegter (2001) found groundwater of a poor quality within the aquifers of the Limpopo Belt. Vegter (2001) analysed 750 samples, more than 50% of which were of a non-potable qulaity. The analyses performed by Vegter (2001) were, however, focused on shallow groundwater resources. Lourens (2013) concluded that the Limpopo Belt may be regarded as being associated with low-yielding aquifers, although this investigation was limited to the shallow groundwater system. A maximum reported yield of 25 ℓ/s is likely to be due to the borehole intersecting a major fault or fracture of the deeper secondary aquifer.

3.3.15.2 Archaean Greenstone belts

3.3.15.2.1 Barberton Greenstone Belt

The rocks of the Barberton Greenstone Belt are mostly impermeable (Lourens, 2013). The occurrence of groundwater is thus dependent on the development of fractures and openings, which improve porosity and permeability. Secondary porosity and permeability, especially along contacts, form good local aquifers. Fractures related to faults and intrusive dykes enhance permeability, but low yields are still found for the deeper fractured aquifer (Sami et al., 2002).

Owen and Madari (2009) stated that the Archaean Greenstone belts consist of meta-sedimentary rocks that have both intergranular and secondary porosity. However, the porosity has been reduced due to metamorphic processes, including recrystallisation. Owen and Madari (2009) classed the groundwater development potential of the Archaean greenstone rocks as ranging from low to high, being highly dependent on local conditions, with an average classification of moderate.

3.3.15.3 Archaean granites and gneisses

The Archaean granites and gneisses are classified as hosting intergranular and fractured aquifer systems, which are structurally controlled and have a semi-confined to confined nature (Du Toit, 2001). Botha (2011) and Holland (2011) found that the fracture zones of the Limpopo Plateau may reach depths in excess of 120 m below ground level, which is especially true for the Dendron and Mogwadi regions. These regions are known for high-yielding boreholes that exceed the typical expectations of crystalline aquifer potentials.

3.3.15.4 Dominion Group

The Dominion Group is a succession of volcanic and sedimentary rocks that have undergone metamorphosis (Marsh, 2006). Owen and Madari (2009) evaluated the geohydrology of the Dominion Group, which is characterised by predominantly gritty quartzite, conglomerates, magnetic shale, phyllite and interbedded lava lithologies. The quartzite and conglomerates host secondary aquifers that are controlled by joints, fractures, faults and dyke contact zones (Barnard, 2000).

3.3.15.5 Witwatersrand Supergroup

Lourens (2013) classified the Witwatersrand Supergroup as being associated with fractured aquifer systems, where the groundwater flow takes place within secondary fracture systems, which are associated with weathered areas, shear zones and intrusive formations. The Witwatersrand Supergroup is considered to host low- to moderate-yielding aquifer systems, with most boreholes exhibiting yields of less than 2 ℓ/s, with a maximum reported yield of 30 ℓ/s (Barnard, 2000). Lourens (2013) stated that the fault zones within the Witwatersrand Supergroup play an important role in the deep groundwater system, where deep gold mines (with depths of approximately 2 km) have intersected large volumes of groundwater at faults.

3.3.15.6 Ventersdorp Supergroup

Lourens (2013) classified the Ventersdorp Supergroup as being associated with intergranular and fractured rock aquifer systems, but the volcanic and sedimentary rocks have been found to have low porosity and hydraulic conductivity. De Villiers (1961) found that the volcanic rocks weather to a clay material that reduces permeability, but that the fractured rocks below the weathered zone have the capacity to produce significant volumes of groundwater. Conversely, Burger (2010) found that these rocks do not appear permeable at depth, and rather act as aquicludes.

The volcanic rocks of the Ventersdorp Supergroup are considered to host a low-yielding aquifer system, with most boreholes yielding less than 2 ℓ/s (Lourens, 2013). The sedimentary rocks of the Ventersdorp Supergroup are considered to be associated with low- to moderate-yielding aquifer systems, with some boreholes yielding more than 2 ℓ/s. Interestingly, there are also areas of the Ventersdorp Supergroup where yields of up to 20 ℓ/s were reported (Barnard, 2000; Baran, 2003; Van Wyk, 2011). It can be assumed that the high-yielding borehole intersected a major fracture or fault.

3.3.15.7 Transvaal Supergroup

3.3.15.7.1 Black Reef and Vryburg formations

Lourens (2013) classified both the Black Reef and Vryburg formations as being associated with fractured rock aquifer systems. The quartzite of the Black Reef Formation has a low transmissivity, which creates a regional barrier for groundwater flow. The depth to groundwater has been found to be related to the direction of flow between the Black Reef Formation and the adjoining dolomites of the Chuniespoort Group (Barnard, 2000; Van Dyk and Kisten, 2006).

3.3.15.7.2 Chuniespoort and Ghaap groups

The carbonate rocks of the Chuniespoort and Ghaap groups represent the most important aquifer system in South Africa (Lourens, 2013). These dolomitic aquifers are high-yielding and are mainly used for irrigation purposes. However, the presence of impermeable vertical and subvertical intrusive dykes form groundwater compartments. The dolomite aquifers are also characterised by an abundance of springs, with the majority occurring on or near the contact of a dyke (Lourens, 2013).

The original carbonate rocks do not have any primary porosity, but have a high storage capacity and are highly permeable due to secondary features that have been enlarged by dissolution processes. These dolomitic aquifers have thus been classified as a karst aquifer system (Lourens, 2013). The storativity and transmissivity values for the dolomitic aquifers are highly variable due to the heterogeneous nature of karstification. Storativity values range from 5×10^{-5} to 0.1, and transmissivity values range from 10 to 29,000 m^2/d (Vegter, 1984). However, Enslin and Kriel (1968) found that the storativity of the dolomites decreased with increasing depth. A decrease in storage from approximately 9.1% at a depth of 61 m below ground level to 1.3% at a depth of 146 m below ground level was reported.

3.3.15.7.3 Postmasburg and Pretoria groups

The Postmasburg Group in the Griqualand West Basin reaches a thickness of 1,500 m, while the Pretoria Group is approximately 6 to 7 km thick (Eriksson et al., 2006). Lourens (2013) classified the Pretoria Group as hosting intergranular and fractured aquifer systems, while the Postmasburg Group was classified as being associated with fractured aquifer systems.

3.3.15.8 Bushveld Igneous Complex

Lourens (2013) classified the Bushveld Igneous Complex as being associated with fractured (crystalline) and intergranular aquifer systems, with the intergranular aquifers that are limited to the weathered zone, which ranges in thickness from 12 to 50 m. The unweathered, fractured aquifer is found below the weathered zone and extends to a depth where fractures are closed due to the pressure from the overlying rocks.

The Bushveld Igneous Complex has abundant deposits of PGE and chromium, which has led to numerous mining activities to extract these resources (Cawthorn, 2010). Data collected at these mines has allowed for some characterisation of the groundwater systems within the Bushveld Igneous Complex. Titus et al. (2009b) characterised the shallow groundwater and mine fissure inflows of the Bushveld Igneous Complex. A two-layer aquifer model was used to describe the groundwater regime in the Bushveld Igneous Complex on a regional scale. The model consisted of an upper, shallow, weathered bedrock aquifer system (intergranular aquifer), and a deeper, fractured, bedrock aquifer (Titus et al., 2009b).

The deeper fractured aquifer consists of an unweathered bedrock matrix that has low hydraulic conductivity. The effective hydraulic conductivity of the deeper aquifer is controlled by fractures and mine voids (Titus et al., 2009b). Titus et al. (2009b) stated that groundwater flows occur through interconnected fracture systems with the potential for rapid vertical inflow from the upper weathered aquifer, as well as great depths along interconnected conductive zones. Initial groundwater quality data has indicated that groundwater from the deeper fractured aquifer is chemically and isotopically different to groundwater from the shallow aquifer, suggesting a longer, slower groundwater flow system at depth.

The DWA (2011) investigated the norite and gabbro lithologies of the Bushveld Igneous Complex that lie within the Olifants River catchment. This investigation confirmed the regional groundwater regime described by Titus et al. (2009b), where groundwater occurs in an upper weathered aquifer and a deeper fractured aquifer. Measured borehole yields from this area range from 0.5 to 2 ℓ/s, with higher yields found along dyke contacts (DWA, 2011).

The average depth of boreholes drilled into the Bushveld Igneous Complex within the Olifants River catchment ranges from 30 to 80 m below ground level (DWA, 2011). The limited depth of groundwater boreholes in the Bushveld Igneous Complex has hindered understanding of the deeper groundwater flow system.

3.3.15.9 Waterberg and Soutpansberg groups

3.3.15.9.1 Waterberg Group

The Waterberg Group was classified as being associated with secondary fractured rock aquifer systems because the rocks have little or no primary porosity with low original permeability and storage capacities, resulting in groundwater being controlled by fault or fracture zones and bedding planes (Owen and Madari, 2009; Du Toit and Sonnekus, 2010). Lourens (2013) classified the rocks of the Waterberg Group as hosting low-yielding aquifer systems, with most yields being less than 0.5 ℓ/s. However, yields greater than 3 ℓ/s can be obtained when targeting fault and fracture zones (Levin, 2011).

3.3.15.9.2 Soutpansberg Group

The Soutpansberg Group has similar water-bearing characteristics as the Waterberg Group (Lourens, 2013). The Soutpansberg Group was classified as being associated with intergranular and fractured rock aquifer systems (Lourens, 2013). Groundwater is generally controlled by fault or shear zones and diorite dykes and sills.

Lourens (2013) classified the Soutpansberg Group as a whole as hosting a low- to moderate-yielding aquifer system, with boreholes yields ranging from 0.5 to 2 ℓ/s, although yields greater than 5 ℓ/s have also been recorded. Lourens (2013) stated that studies done in the Kruger National Park concluded that there was no linear relationship between yields and the depth of boreholes, and high-yielding boreholes were associated with fault zones. Fractures were found at depths of up to 250 m below ground level. These structures produced high-yielding boreholes when intersected (Du Toit and Sonnekus, 2010). However, it is complicated to determine the position of these features, as it is associated with high uncertainty (Lourens, 2013).

3.3.15.10 Namaqua-Natal Metamorphic Province

Groundwater within the Namaqua Section of the Namaqua-Natal Province occurs within three aquifer systems: a sandy/alluvial aquifer, a weathered aquifer and a fractured bedrock aquifer (Friese et al., 2006; Pietersen et al., 2009). The geometry of these aquifer systems is controlled and influenced by the underlying geology of igneous and metamorphic rocks, its deformation history of metamorphic evolution, and the geomorphic development of the Namaqua Belt, including weathering (Pietersen et al., 2009). Despite these metamorphic and igneous rocks' great variety, they are homogenous in two respects: the rocks have virtually no primary porosity, and secondary porosity is due to fracturing and weathering (Vegter, 2006).

3.3.15.10.1 Natal Section

The lithostratigraphy of the Natal Section comprises supracrustal gneisses, granitoid gneisses and younger intrusive rocks (McCourt et al., 2006). Groundwater in the Natal Section of the Namaqua-Natal Province has not been extensively exploited when compared to the drier parts of South Africa, resulting in limited information about the geohydrological characteristics of igneous and metamorphic rocks (Lourens, 2013). Lourens (2013) classified the Natal Section as being associated with intergranular and fractured aquifer systems, where the intergranular aquifers consist of weathering material that has a high porosity and a low hydraulic conductivity due to their clayey nature.

3.3.15.11 Saldania Belt – Malmesburg Group

Lourens (2013) classified the Malmesburg Group as hosting a fractured aquifer system, with a tendency to form confined and semi-confined aquifers. Lourens (2013) also considered the Malmesburg Group to be associated with low-yielding aquifer systems, with most boreholes yielding less than 2 ℓ/s. However, high-yielding boreholes with yields of up to 12 ℓ/s have been reported (Lourens, 2013).

These high-yielding boreholes are related to the intersection of water-bearing fractures. However, the Table Mountain Group aquifers, found close to the Malmesburg Group, are higher yielding. This has led to the Table Mountain Group being preferentially targeted for water supply (Lourens, 2013).

3.3.15.12 Natal Group

The Natal Group has not been highly exploited for groundwater when compared to drier areas of South Africa, resulting in limited geohydrological information on the group (Bell and Maud, 2000). Lourens (2013) classified the Natal Group as being associated with fractured rock aquifers, with negligible primary porosity and permeability (Geomeasure Group, 2007; KV3 Engineers, 2009). However, the Natal Group was found to have higher hydraulic conductivities than the surrounding lithologies, ranging from 0.4 to 7.7 m/d (King, 2003).

Lourens (2013) classified the sandstones of the Natal Group as hosting moderate- to low-yielding aquifer systems, with reported median yields ranging from 0.1 to 2 ℓ/s, but yields of up to 10 ℓ/s have been recorded (KV3 Engineers, 2009). High-yielding boreholes are assumed to have intersected water-bearing fractures or faults. The sandstones and quartzites of the Natal Group have a high quartz content and will behave in a brittle manner when deformed, forming local zones of intense fracturing (near faults and dolerite intrusions), which enhance recharge and permeability, and create preferential groundwater flow paths (Bell and Maud, 2000; Geomeasure Group, 2007; KV3 Engineers, 2009; King, 2003). These zones of intense fracturing are ideal targets for groundwater resources because groundwater movement mainly occurs within joints, fractures or bedding planes (KV3 Engineers, 2009).

The Natal Group has a maximum thickness of approximately 600 m, and the Eshowe Member occurs at depths of approximately 600 m. This member is bound from below by an erosional contact with underlying granitic basement rocks. If deep groundwater is to be found within this geological group, this contact zone would be a potential target.

3.3.15.13 Cape Supergroup

The Cape Supergroup is a siliciclastic sequence of lithologies, originally deposited in a passive basin, generally consisting of sandstone, shale and minor conglomerates (Thamm and Johnson, 2006). The Cape Supergroup is divided into three main groups, which are lithologically distinctive and show lateral continuity. These are the Witteberg, Bokkeveld and Table Mountain groups (Thamm and Johnson, 2006; Lourens, 2013).

The Peninsula Formation is the most magnificent formation of the Cape Supergroup, with a thickness that varies from 1,800 to 2,700 m (Visser, 1989). The Peninsula Formation consists of quartz arenite, with minor shale and conglomerates (Thamm and Johnson, 2006). The Nardouw Subgroup consists of quartzitic sandstone and reaches a maximum thickness of 1,200 m near Citrusdal in the western part of the basin, but thins out rapidly northwards (Thamm and Johnson, 2006).

The Table Mountain Group is one of the most important regional groundwater aquifers in South Africa (Viljoen et al., 2010). The total flow of eight major springs within the Table Mountain Group has been measured at greater than 300 ℓ/s, and the total daily usage by 11 towns (with more than 30 major users) from the Table Mountain Group is approximately 18,000 m^3 (Rosewarne, 2002a).

The Table Mountain Group is characterised by an abundance of springs (Meyer, 2001). Meyer (2001) and Kotze (2002) identified three types of springs within the Table Mountain Group: shallow springs emanating from perched water tables, lithologically controlled springs (due to the presence of interbedded aquitards) and fault-controlled springs. The third type of spring (the fault-controlled springs) are generally associated with deep circulating groundwater, often supplying large and constant amounts of groundwater (Meyer, 2001). These springs are associated with elevated groundwater temperatures at the surface, ranging from 20 °C to more than 40 °C (Kotze, 2002).

Lourens (2013) classified the Table Mountain Group as being associated with secondary aquifer systems, where secondary porosity features control groundwater movement. The Table Mountain Group aquifers can be divided into four categories: horizontal strata, folded strata, a fracture zone and composite aquifer systems (Xu et al., 2007). According to Viljoen et al. (2010), very good fracture porosity is created where folding and faulting are present.

The main groundwater intersections within the Table Mountain Group aquifer are at depths greater than 100 m below ground level (Rosewarne, 2002b), and borehole yields have been found to increase with depth (Kotze, 2002; Rosewarne, 2002b). This characteristic feature goes against conventional structural geological theory, which states that joint or fracture openings will close with increasing depth due to the pressure of the overlying rock mass (Rosewarne, 2002b). However, deep groundwater circulation has been confirmed within the Table Mountain Group (Cave and Clarke, 2003; Viljoen et al., 2010). For these reasons, the Table Mountain Group has been identified as a potential deep aquifer system.

3.4 KAROO GEOLOGY

The Karoo Supergroup covers roughly two thirds of the land surface of South Africa (Figure 3-12 and Figure 3-49). In South Africa, rocks of the Karoo Supergroup are preserved in six basins: the Main Karoo, Springbok Flats, Ellisras, Tshipise, Tuli and Durban-Lebombo basins (Johnson et al., 2006).

The Main Karoo Basin is the largest sedimentary basin in South Africa, underlying approximately 60% of the land surface area of South Africa (Figure 3-49). The rocks of the Main Karoo Basin range in age from Late Carboniferous to Early Jurassic (Johnson et al., 2006). The Main Karoo Basin covers an area of approximately 700,000 km^2, and a total cumulative thickness of approximately 12 km is reached in the southern part of the basin (Viljoen et al., 2010; Johnson et al., 2006). The Main Karoo Basin is largely undeformed and essentially lies flat, with small centripetal dips. The strata are only folded in the south, where they were affected by the Cape Orogeny (Viljoen et al., 2010; Johnson et al., 2006) (Figure 3-50).

Deposits of the Karoo Supergroup are also present in the smaller Springbok Flats, Ellisras (Lephalale), Tshipise and Tuli basins to the north of the main basin (Figure 3-49). An easterly dipping monocline has resulted in the preservation of a narrow strip of Karoo rocks in a linear belt along the eastern margin of South Africa in the Durban-Lebombo Basin, while Karoo rocks are also present in the west-forming part of the much larger Botswana (Kalahari) Karoo Basin (Viljoen et al., 2010; Johnson et al., 2006) (Figure 3-49).

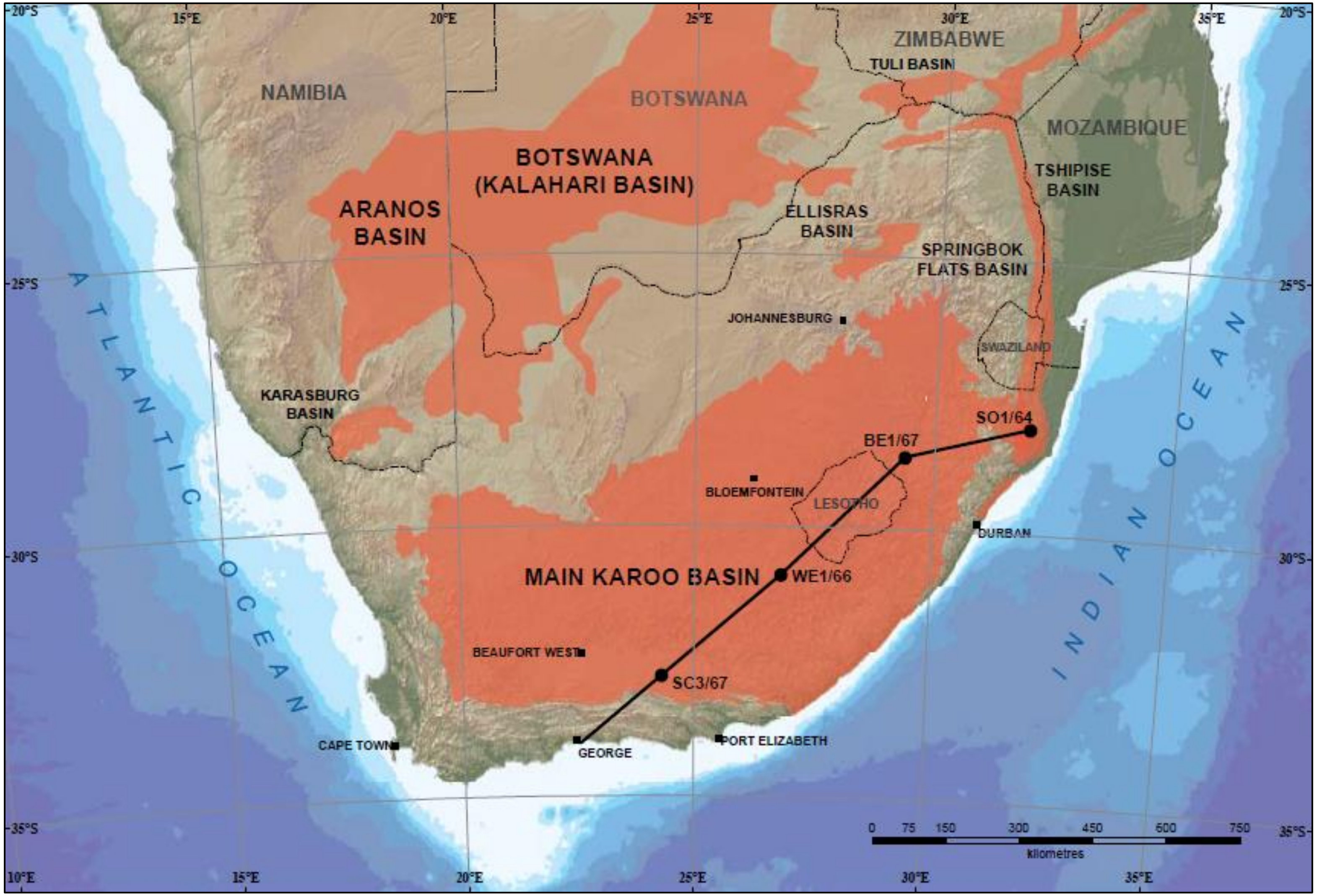


Figure 3-49: Location of the Karoo basins in South Africa, with the location of a cross-section line through the basin (Viljoen et al., 2010)

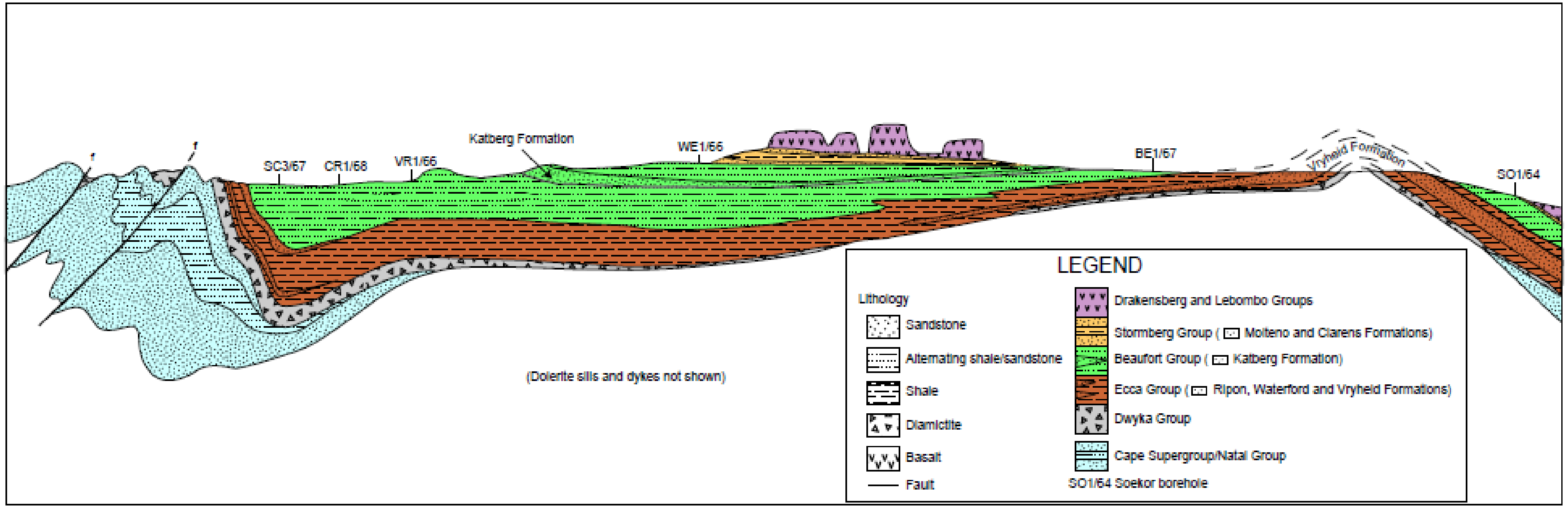


Figure 3-50: Southwest-northeast cross-section through the Cape and Karoo basins, along the line shown in Figure 3-49 (Viljoen et al., 2010)

3.4.1 Geology

3.4.1.1 Main Karoo Basin

The rocks of the Karoo Supergroup within the Main Karoo Basin are divided into various groups and formations (Figure 3-51) (Lourens, 2013). The main lithostratigraphic units are the Drakensberg, Lebombo, Stormberg, Beaufort, Ecca and Dwyka groups. The lithostratigraphic subdivisions of the Karoo Supergroup are given in Table 3-9.

3.4.1.1.1 Dwyka Group

The Dwyka Group is the basal unit of the Karoo Supergroup. It overlies glaciated Precambrian bedrock surfaces along the northern basin margin, the Cape Supergroup unconformably in the south, and the Natal Group and Msikaba Formation in the east (Johnson et al., 2006; Lourens, 2013). The Dwyka Group consists predominantly of diamictite with minor amounts of conglomerates, pebbly sandstone and mudrock with dispersed stones (Visser et al., 1990, as cited by Lourens, 2013). The thickness of the Dwyka Group is 500 to 800 m in the south, and 100 to 200 m at the northern margin of the southern facies, from where it is highly variable further northwards (0 to 600 m) (Du Toit, 1954; Visser et al., 1990, as cited by Lourens, 2013).

3.4.1.1.2 Ecca Group

The Ecca Group is subdivided into 14 formations: the Prince Albert, Whitehill, Tierberg, Skoorsteenberg, Kookfontein, Waterford, Collingham, Vischkruil, Lagingsburg, Ripon, Fort Brown, Pietermaritzburg, Vryheid and Volksrust formations. Except for the extensive Prince Albert and Whitehill formations, the individual formations can be grouped into three geographical areas or zones for descriptive purposes (Woodford and Chevallier, 2002, as cited by Lourens, 2013) (Table 3-10). The three geographical groupings are the western-northern, southern and northeastern zones (Lourens, 2013).

The Prince Albert Formation, which forms the base of the Ecca Group, has two facies: the southern and the northern facies (Johnson et al., 2006). The northern facies is characterised by micaceous shale, silty shale and a pronounced transition from the underlying glacial deposits of the Dwyka Group. The southern facies is characterised by shale, siltstone, as well as chert and phosphatic nodules and lenses (Johnson et al., 2006). The formation is approximately 50 to 165 m thick in the Main Karoo Basin and is considerably thicker in the area between Beaufort West and Brandvlei (225 to 320 m) (Cole, 2005, as cited by Lourens, 2013).

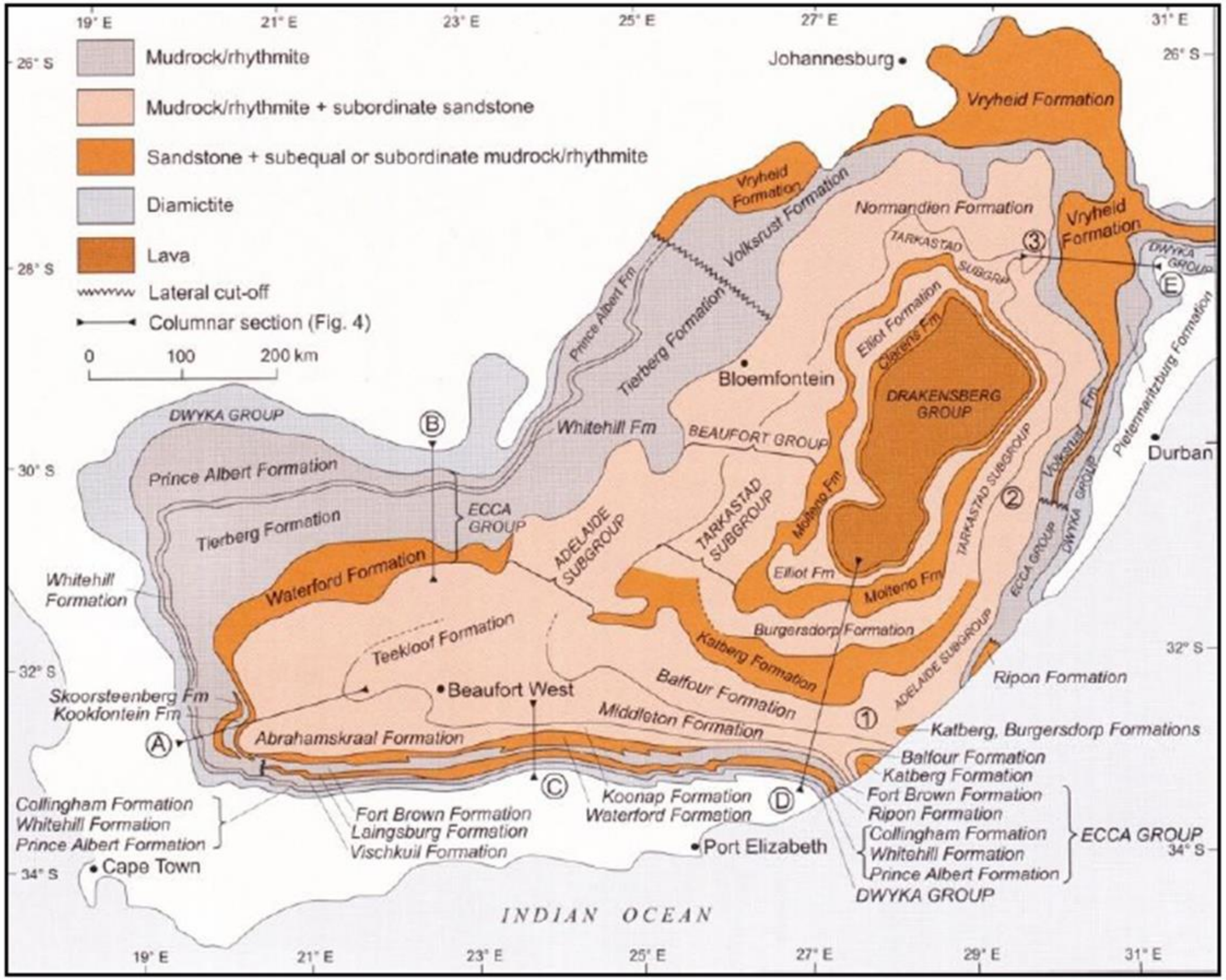


Figure 3-51: Schematic areal distribution of the lithostratigraphic units of the Karoo Supergroup in the Main Karoo Basin, indicating the location of Sections A-E and 1-3 (Johnson et al., 2006)

Table 3-9: Lithostratigraphic subdivision of the Karoo Supergroup (Lourens, 2013)

		Thickness	Main Rock Types
Lebombo Group		?	Mainly a succession of basaltic and rhyolitic lava flows
Drakensberg Group		>1200 m	Basalt with amygdales
Stormberg Group	Clarens Formation	<300 m	Fine-grained sandstone and siltstone
	Elliot Formation	<500 m	Red-maroon to green mudstones, with interbedded sandstones
	Molteno Formation	<600 m	Alternating sandstone, mudstone and shale, minor coal beds
Beaufort Group		<7 000 m	Mainly grey-green to reddish mudstones, thick river-channel sandstones; beds thin to the north of the central Karoo Basin
Ecca Group		<3 000 m	Dark shales, some sandstone layers and coal seams; deep-water sediment in the south grading to shallow-water sediments in the north
Dwyka Group		<700 m	Unsorted tillite, minor shale; thickest in the south

The Whitehill Formation consists of black, carbonaceous shale that weathers white, with intermittent chert lenses and pyritic stringers (Visser, 1989; Branch et al., 2007, as cited by Lourens, 2013). The thickness of the Whitehill Formation varies from 10 to 80 m (Johnson et al., 2006).

The Collingham Formation overlies the Whitehill Formation in the southern and western margins of the Karoo Basin (Lourens, 2013). The Collingham Formation consists of a rhythmic alternation of thin, continuous beds of hard mudrock and very thin beds of softer, yellowish tuff (Johnson et al., 2006; Lourens, 2013). The thickness of the Collingham Formation ranges from 30 to 70 m, and there is a distinctive constant chert layer (the Matjiesfontein Chert Bed) present in the lower half of the Formation (Johnson et al., 2006; Visser, 1989).

Table 3-10: Grouping of the individual formations within the Ecca Group, listed from bottom to top (Lourens, 2013)

	Western-Northwestern Zone	Southern Zone	Northeastern Zone
Formation	Prince Albert	Prince Albert	Pietermaritzburg
	Whitehill	Whitehill	Vryheid
	Tierberg	Collingham	Volksrust
	Skoorsteenberg	Vischkuil	
	Kookfontein	Laingsburg	
	Waterford	Ripon	
		Fort Brown	
		Waterford	

The Vischkuil Formation overlies the Collingham Formation in the southwestern part of the Karoo Basin. The Vischkuil Formation consists of shale, alternating with secondary sandstone, siltstone and minor yellowish tuff layers (Johnson et al., 2006; Visser, 1989). The thickness of the Vischkuil Formation ranges from 200 to 400 m. The formation becomes more arenaceous towards the east, where it grades into the Ripon Formation (Johnson et al., 2006; Lourens, 2013).

The Laingsburg Formation conformably overlies the Vischkuil Formation (Catuneanu et al., 2005, as cited by Lourens, 2013). The Laingsburg Formation consists of four sandstone layers, separated by thick shale units (Johnson et al., 2006). The formation attains a thickness of 750 m in the Laingsburg area and thins towards the east and north (Nguema Mve, 2005, as cited by Lourens, 2013).

The Ripon Formation occurs in the southern regions of the Karoo Basin and is regarded as the chronostratigraphic equivalent of the Vischkuil and Laingsburg formations (Visser, 1989, as cited by Lourens, 2013). The Ripon Formation consists of alternating sandstone and shale, with the sandstone constituting approximately one third of the total thickness (Visser, 1989; Johnson et al., 2006; CGS, 1980, as cited by Lourens, 2013). The Ripon Formation has a thickness between 600 and 700 m, but is over 1,000 m thick in the eastern part of its outcrop area (Johnson et al., 2006; Lourens, 2013).

The Fort Brown Formation outcrops in the southern section of the Main Karoo Basin, and consists of rhythmic layered shale with isolated sandstone intercalations (Lourens, 2013). The Fort Brown Formation displays an overall upward coarsening and ranges in thickness from 500 to 1,500 m, with an average thickness of 1,000 m (Johnson et al., 2006; Visser, 1989).

In the southern outcrop of the Waterford Formation, the formation overlies the Fort Brown Formation (Johnson et al., 2006). In the western and northwestern outcrop areas, the Waterford Formation overlies the Kookfontein and Tierberg formations (Johnson et al., 2006). The Waterford Formation consists of alternating sandstone and shale rhythmite units (Visser, 1989). The thickness of the formation varies between 200 and 800 m (Johnson et al., 2006).

The Tierberg Formation occurs in the western and northern regions of the Karoo Basin, where it conformably overlies the Collingham Formation (south of 32°S) and the Whitehill Formation (north of 32°S) and grades upward into the Waterford Formation, or where it is absent, into the Adelaide Subgroup of the Beaufort Group (Johnson et al., 2006; Viljoen, 2005, as cited by Lourens, 2013). The Tierberg Formation predominantly consists of shale with interbedded siltstone and fine-grained sandstone (Viljoen, 2005). The Tierberg Formation reaches a maximum thickness of 750 m along the western margin of the basin and thins towards the northeast to a thickness of approximately 350 m (Johnson et al., 2006; Viljoen, 2005).

The Skoorsteenberg Formation is made up of five sandstone-rich turbidite sequences, which are separated by 20 to 75 m thick intervals of siltstone and mudstone (Van der Werff and Johnson, 2003; Anderson et al., 2004, as cited by Lourens, 2013). The Skoorsteenberg Formation has a maximum thickness of roughly 200 m. The thickness of the individual turbidite sequences varies between 20 and 60 m (Visser, 1989; Van der Werff and Johnson, 2003).

The Kookfontein Formation has a sharp contact with the underlying Skoorsteenberg Formation, and grades upward into the Waterford Formation (Johnson et al., 2006; Lourens, 2013). The Kookfontein Formation is approximately 350 m thick and consists of rhythmic shale and siltstone with thin interbedded sandstone layers that are similar to those of the Tierberg Formation (Johnson et al., 2006; Visser, 1989).

The Pietermaritzburg Formation also has a sharp contact with the underlying Dwyka Group in the northeastern part of the Karoo Basin (Johnson et al., 2006). The Pietermaritzburg Formation consists of shale and mudstone, with interlayers of fine-grained sandstone (King, 2002). The Pietermaritzburg Formation reaches a maximum thickness of 400 m in the southeast and then thins out to less than 100 m towards the north (Johnson et al., 2006; King, 2003).

The Vryheid Formation normally overlies the Pietermaritzburg Formation and is made up of thick layers of sandstone with layers of soft sandy shale with single layers of coal (Visser, 1989). The Vryheid Formation reaches a maximum thickness of 500 m in the Vryheid-Nongoma area and then thins out towards the north, west and south (Johnson et al., 2006).

The Volksrust Formation overlies the Vryheid Formation and is made up of silty shale with thin siltstone or sandstone lenses and beds (Johnson et al., 2006; Visser, 1989). The thickness of the Volksrust Formation ranges from 270 m in the south to 170 m in the north (Visser, 1989).

3.4.1.1.3 Beaufort Group

The Beaufort Group covers an area of approximately 200,000 km^2 and reaches a maximum total thickness of roughly 7,000 m in the foredeep of the Karoo Basin. It then thins out quickly northwards. The Beaufort Group consists of fluvial-deposited Permo-Triassic rocks and is subdivided into two subgroups: the Tarkastad and Adelaide subgroups (Catuneanu et al., 2005, as cited by Lourens, 2013).

In the southern and central parts of the Main Karoo Basin, the Adelaide Subgroup consists of mudrock and lithofeldspathic sandstone, while in the northern part of the basin, it mostly consists of sandstone (Johnson et al., 2006). The Adelaide Subgroup is divided into four formations: the Koonap, Middleton, Balfour and Normandien formations (Catuneanu et al., 2005) (Figure 3-52). The Adelaide Subgroup reaches a maximum thickness of 5,000 m in the southeastern area of the Karoo Basin, but rapidly decreases in thickness towards the north to roughly 800 m (Johnson et al., 2006). The Koonap and Middleton formations form a single upward-fining unit that is made up of mudstone and sandstone.

The Tarkastad Subgroup reaches a maximum thickness of almost 2,000 m in the south, which decreases to approximately 800 m towards the middle of its outcrop area and to about 150 m in the far north (Johnson et al., 2006). The Tarkastad Subgroup is subdivided into four formations: the Katberg, Burgersdorp, Verkykerskop and Driekoppen formations.

The Katberg Formation mainly consists of sandstone (Johnson et al., 2006). The overlying Burgersdorp Formation consists of alternating mudstone and subordinate sandstone (Johnson and Hiller, 1990, as cited by Lourens, 2013). The individual sandstone layers of the Burgersdorp Formation are arranged in upward-fining cycles that can be up to 10 m thick with an average thickness of 2 to 3 m (Johnson and Hiller, 1990, as cited by Lourens, 2013). The Verkykerskop Formation consists of fine- to very coarse-grained sandstone with lenses of siltstone and mudstone, and is up to 80 m thick (Johnson et al., 2006; Kruidenier, 2007, as cited by Lourens, 2013). The Driekoppen Formation consists of mudstone with interlayered sandstone, and is up to 70 m thick (Johnson et al., 2006; Kruidenier, 2007).

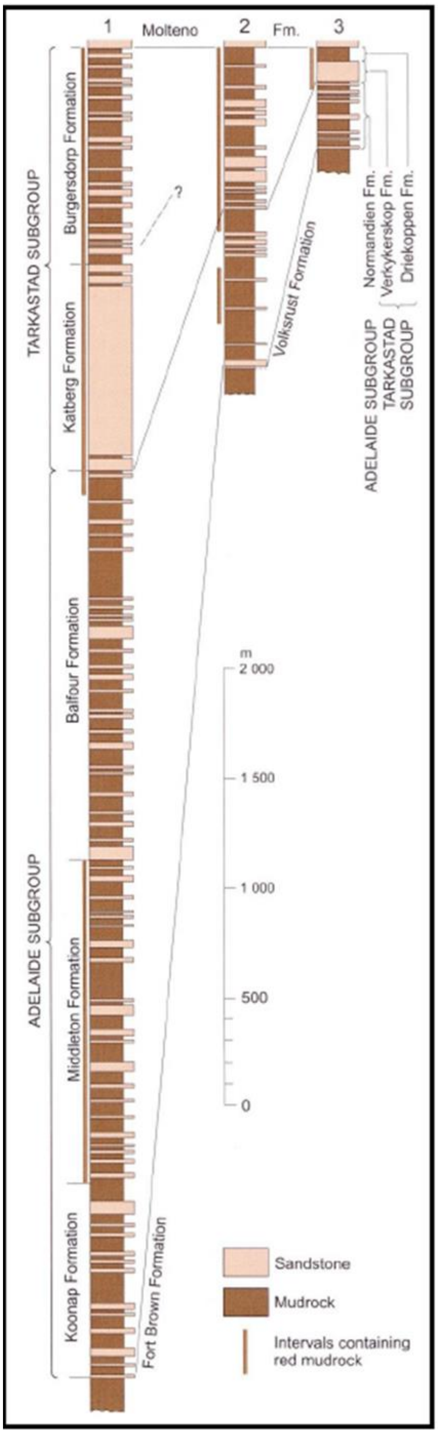


Figure 3-52: Geological sections through the Beaufort Group at localities 1, 2 and 3 in Figure 3-51 (Johnson et al., 2006)

3.4.1.1.4 Stormberg Group

The Stormberg Group is subdivided into the following three formations: the Molteno, Elliot and Clarens formations (Table 3-9). The Molteno Formation forms the base of the Stormberg Group and consists of alternating medium- to coarse-grained sandstones and sandy shale (Johnson et al., 2006; Visser, 1989). The Molteno Formation reaches a maximum thickness of 450 m in the southern outcrop area and decreases in thickness towards the north to a thickness of less than 10 m (Visser, 1989).

The Elliot Formation conformably overlies the Molteno Formation and consists of alternating mudstone, siltstone, shale and sandstone (Visser, 1989). The maximum total thickness of the Elliot Formation is 500 m in the southern outcrop area. The formation thins out towards the north (Johnson et al., 2006; Visser, 1989). The sandstone units are between 6 and 15 m thick, but can attain thicknesses of up to 22 m. The thicknesses of the mudstone units range from 25 to 100 m (Johnson et al., 2006).

The Clarens Formation consists of sandstone with a thickness that ranges from 300 to 400 m (Visser, 1989). However, the uppermost part of the formation can consist of minor interlayered basaltic lava flows (Johnson et al., 2006).

3.4.1.1.5 Drakensberg Group

The Drakensberg Group covers an area of approximately 140,000 km^2, which spreads across Lesotho and sections of the Free State, KwaZulu-Natal and the Eastern Cape (Visser, 1989). The Drakensberg Group consists of a series of basaltic lava flows with individual lava flows with thicknesses of 3 to 50 m (Duncan and Marsh, 2006, Lourens, 2013). The whole Drakensberg Group succession reaches a maximum thickness of 1,400 m in the northwest, with an average thickness of 1,000 m (Woodford and Chevallier, 2002). The Drakensberg Group can informally be divided into two formations: the Lower Barkly East and the Upper Lesotho formations (Visser, 1989; Woodford and Chevallier, 2002). The lower Barkly East Formation is 200 m thick and consists of thin lava flows. The Upper Lesotho Formation represents the majority of the Drakensberg Group with thick flows of more uniform composition (Woodford and Chevallier, 2002).

3.4.1.1.6 Lebombo Group

The Lebombo Group is made up of major lava formations, and is subdivided into the Movene, Mbuluzi, Jozini, Sabie River, Letaba and Mashikiri formations (Duncan and Marsh, 2006) (Figure 3-53). The Mashikiri Formation consists of nephelinite and forms a relatively thin unit (less than 170 m thick) at the base of the Karoo Supergroup volcanic sequence (Duncan and Marsh, 2006; Lourens, 2013). The overlying Letaba Formation conformably overlies the Clarens Formation, the Soutpansberg Group or the Archaean Granites and consists of picritic (olivine-rich) lava (Duncan and Marsh, 2006; Visser, 1989).

The Jozini Formation overlies the Sabie River Formation and is made up of dense and resistant rhyolitic rocks that form the Lebombo Mountain Range (Lourens, 2013). Individual flows of the Jozini Formation form extensive sheet-like bodies that are between 80 and 284 m thick, and are tilted between 10 and 35 degrees towards the east (Saggerson and Bristow, 1983; Visser, 1989, as cited by Lourens, 2013). The Movene Formation consists mainly of basaltic to andesitic lavas, interbedded with rhyolitic lava (Duncan and Marsh, 2006; Visser, 1989).

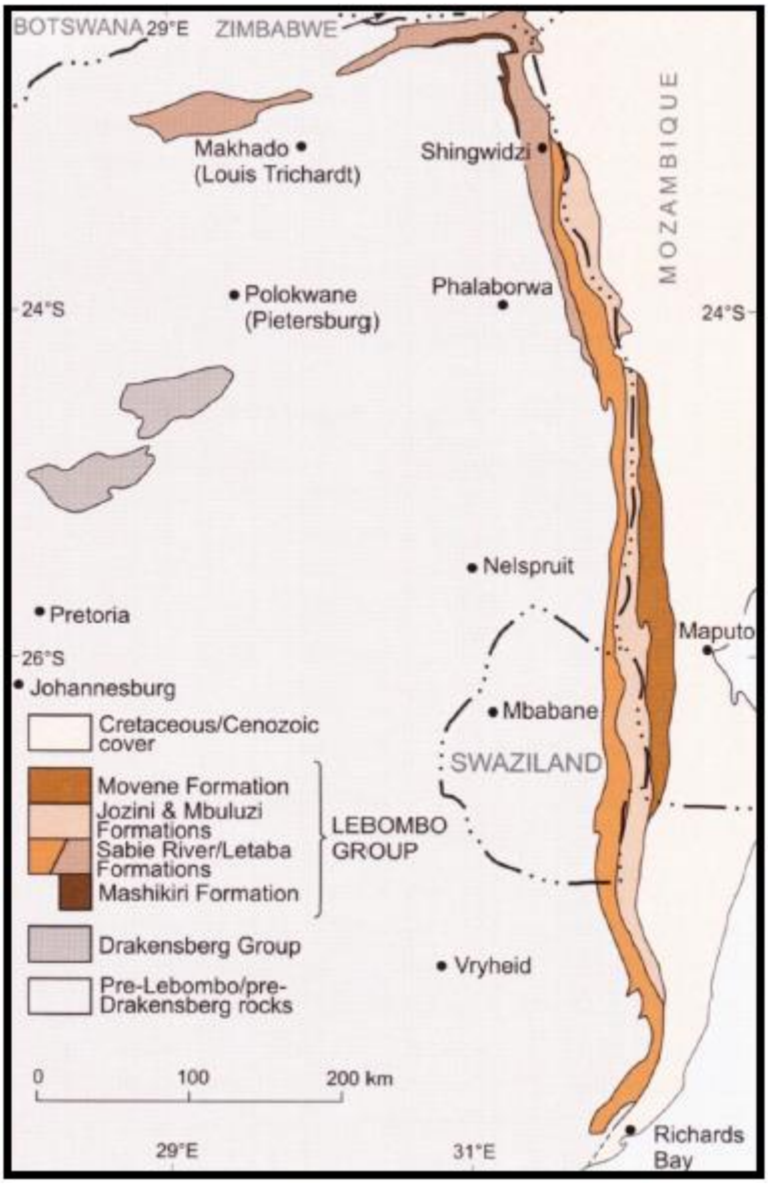


Figure 3-53: Distribution of the Lebombo Group formations (Duncan and Marsh, 2006)

3.4.1.2 Springbok Flats Basin

The Springbok Flats Basin is located above the northernmost section of the Main Karoo Basin (Figure 3-49). The Springbok Flats Basin is divided into two sub-basins that formed from a single basin by post-Karoo folding. The sub-basins are called the northern and southern basins, and are bounded by post-Karoo faulting along the northwestern margin (Mtimkulu, 2009, as cited by Lourens, 2013). The Springbok Flats Basin is subdivided into the Drakensberg Group, the Clarens Formation, the Irrigasie Formation (Elliot/Molteno), the Hammanskraal Formation (Ecca-Vryheid Formation) and the Dwyka Group.

3.4.1.2.1 Dwyka Group

The Dwyka Group of the Springbok Flats Basin can be correlated locally with the Dwyka Group of the Main Karoo Basin (De Jager, 1983, as cited by Lourens, 2013). The Dwyka Group of the Springbok Flats Basin consists of mudstone, diamictite and conglomerates with occasional coal seams. It is rarely more than a few metres thick. However, in local basement depressions, it can be up to 40 m thick (Johnson et al., 2006; Mtimkulu, 2009, as cited by Lourens, 2013).

3.4.1.2.2 Hammanskraal Formation

The Hammanskraal Formation has been described as the time equivalent of the Vryheid Formation of the Ecca Group in the Main Karoo Basin (De Jager, 1983). The base of the Hammanskraal Formation consists of sandstone with interbedded shaly coal that can be up to 12 m thick. It is overlain by a grey mudrock that coarsens upward into micaceous, fine- to medium-grained sandstone (Johnson et al., 2006).

3.4.1.2.3 Irrigasie Formation

The Irrigasie Formation is found between rocks of the Ecca Group (Hammanskraal Formation) and the Clarens Formation. The lower part of the Irrigasie Formation consists of dark-grey mudstone, overlain by a medium- to coarse-grained sandstone unit that also contains relatively small thicknesses of mudstone (Lourens, 2013). The Irrigasie Formation has a maximum thickness of approximately 200 m (Johnson et al., 2006).

3.4.1.2.4 Clarens Formation

The Clarens Formation in the Springbok Flats Basin consists of white to yellowish sandstone that is pinkish or faintly red in the lowermost parts of the formation, similar to the Clarens Formation of the Main Karoo Basin (Johnson et al., 2006). The Clarens Formation has a maximum thickness of 120 m and has sporadic mudstone intercalations (Johnson et al., 2006; Lourens, 2013).

3.4.1.2.5 Drakensberg Group

Remnants of the Drakensberg Group overlie the sedimentary rocks of the Springbok Flats Basin and consists of basaltic lava (Lourens, 2013).

3.4.1.3 Ellisras Basin

The Ellisras Basin is located in Limpopo at the western border of South Africa (Figure 3-49). The sediments of the Ellisras Basin are preserved in faulted blocks and a half-graben structure, parallel to the Limpopo Mobile Belt (Faure et al., 1996, as cited by Lourens, 2013). The Ellisras Basin strikes east to west for approximately 90 km, bounded in the north by the Zoetfontein Fault and in the south by the Eenzaamheid Fault (Lourens, 2013). The general landscape of the basin is extremely flat and is almost entirely covered by recent sands, grits and gravels (Lourens, 2013). The Ellisras Basin is subdivided into the Lebombo Group, the Clarens Formation, the Lisbon Formation, the Greenwich Formation, the Eendragtpan Formation, the Ecca Group and the Dwyka Group (Lourens, 2013).

3.4.1.3.1 Dwyka Group

The Dwyka Group is divided into two separate formations: the Wellington and Waterkloof formations (Lourens, 2013). The Waterkloof Formation overlies rocks of the Waterberg Group and Archaean basement rocks, and consists of diamictite, mudstone and conglomerates (Faure et al., 1996). The diamictite and conglomerates reach a thickness of over 9 m and the mudstones reach a thickness of 17 m (Johnson et al., 2006). The overlying Wellington Formation consists of mudstone and sandstone intercalations (Johnson et al., 2006). The Wellington Formation is around 20 to 30 m thick, but in the southwest and southeast, it reaches thicknesses of 160 to 180 m (Johnson et al., 2006).

3.4.1.3.2 Ecca Group

The Ecca Group of the Ellisras Basin is divided into three formations: the Grootegeluk, Goedgedacht and Swartrant formations (Lourens, 2013). The Swartrant Formation overlies the Wellington Formation and has a maximum thickness of 130 m in the central part of the basin (Johnson et al., 2006; Lourens, 2013). The Swartrant Formation consists of sandstone, siltstone, carbonaceous mudstones and locally developed coal seams (Faure et al., 1996).

The Goedgedacht Formation consists of mudstone units, ranging in thickness from 0.5 to 4 m, and sandstone (Johnson et al., 2006; Lourens, 2013). The Goedgedacht Formation is only present in the northern and northwestern part of the basin, and its thickness decreases from the north towards the south, where it interfingers with the underlying Swartrant Formation (Lourens, 2013).

The Grootegeluk Formation consists of a repetitious sequence of carbonaceous shales and mudstones with interbedded bright coal seams. It conformably overlies the Swartrant Formation (Faure et al., 1996). The Grootegeluk Formation is subdivided into 11 coal-bearing zones that are currently being mined at the Grootgeluk open-pit coal mine (Lourens, 2013).

3.4.1.3.3 Eendragtpan Formation (Beaufort Group)

The Eendragtpan Formation overlies the Grootgeluk Formation and consists of mudstone that is used to mark the contact between the Ecca and Beaufort groups in the Ellisras Basin (Faure et al., 1996). The Eendragtpan Formation has a maximum thickness of 110 m in the central part of the basin (Johnson et al., 2006).

3.4.1.3.4 Greenwich Formation (Molteno Formation)

The Greenwich Formation consists largely of sandstone and granulestone, separated from the Eendragtpan Formation by a sharp erosive contact. The thickness of the Greenwich Formation varies from 7 to 33 m (Johnson et al., 2006; Lourens, 2013).

3.4.1.3.5 Lisbon Formation (Elliot Formation)

The Lisbon Formation consists of mudstone, siltstone and minor sandstone, and has a fairly constant thickness of 100 to 110 m (Johnson et al., 2006).

3.4.1.3.6 Clarens Formation

The Clarens Formation of the Ellisras Basin forms prominent hills and ridges and has a maximum thickness of 130 m (Johnson et al., 2006; Lourens, 2013). The Clarens Formation of the Ellisras Basin is similar to that of the Main Karoo Basin and consists of white to yellowish sandstone that is pinkish in the lowermost parts of the formation.

3.4.1.3.7 Letaba Formation (Lebombo Group)

Only a small piece of the Letaba Formation is preserved within the Ellisras Basin and consists of picritic lava (Lourens, 2013).

3.4.1.4 Tshipise and Tuli basins

The Tshipise and Tuli basins are found in Limpopo, in the northernmost section of South Africa (Figure 3-49). The rocks of the Tshipise Basin are preserved in fault blocks that follow the trend (east-northeast-west-southwest) of the Limpopo Mobile Belt (Johnson et al., 2006). The Tuli Basin extends into Botswana and Zimbabwe, and only a small piece is preserved in South Africa (Johnson et al., 2006) (Figure 3-49). The Tshipise and Tuli basins are subdivided into the same lithostratigraphic units: the Lebombo Group and the Clarens, Bosbokpoort, Klopperfontein, Solitude, Fripp, Mikambeni, Madzaringwe and Tshidzi formations (Lourens, 2013).

3.4.1.4.1 Tshidzi Formation

In the Tshipise Basin the Tshidzi Formation consists of diamictite, with angular to rounded clasts of pink quartzite, up to 2 m in diameter, which are set in an argillaceous or sandy matrix (Lourens, 2013). The Tshidzi Formation of the Tshipise Basin is approximately 5 m thick, but there are areas where it is up to 20 m thick (Lourens, 2013).

In the Tuli Basin, the Tshidzi Formation is deposited on an uneven floor of Beitbridge gneisses (Lourens, 2013). In areas of topographic elevation, the basal layer is made up of coarse diamictite with angular clasts of up to 80 cm in diameter (Lourens, 2013). The diamictite deposits are overlain by coarse, micaceous grits that pass upward into the laminated shale of the Madzaringwe Formation (Durand, 2009, as cited by Lourens, 2013).

3.4.1.4.2 Madzaringwe Formation

In the Tshipise Basin, the Madzaringwe Formation is up to 200 m thick and thins out (to approximately 9 m) towards the Mogalakwena River area (Lourens, 2013). The Madzaringwe Formation of the Tshipise Basin consists of alternating sandstone, siltstone and shale, which contains thin coal seams (Lourens, 2013). The main coal seam is 2 to 3 m thick and developed between 85 and 100 m above the basal shale layer (Lourens, 2013).

In the Tuli Basin, the Madzaringwe Formation primarily consists of laminated shale with intermittent lenses of red-yellowish grit in its lower sequences (Lourens, 2013). The Madzaringwe Formation has a distinct coal zone higher up in the sequence that is up to 20 m thick (Lourens, 2013). The top of the Madzaringwe Formation is marked by micaceous, course-grained sandstone (Lourens, 2013).

3.4.1.4.3 Mikambeni Formation

In the Tshipise Basin, the Mikambeni Formation consists of three units (lower, middle and upper), which consist of mudstone, shale and laminated sandstone (Lourens, 2013). The Mikambeni Formation has a maximum thickness of 150 m (Lourens, 2013).

In the Tuli Basin, the Mikambeni Formation consists of shales and siltstones, with small coal seams. The rocks of the Mikambeni Formation in the Tuli Basin are identical to those of the Madzaringwe Formation (Lourens, 2013).

3.4.1.4.4 Fripp Formation

In the Tshipise Basin, the Fripp Formation rests unconformably on the Mikambeni Formation. The Fripp Formation consists of white sandstone with interbedded mudstone and siltstone (Lourens, 2013). The Fripp Formation is up to 110 m thick in the northeastern part of the Tshipise Basin, but its thickness generally ranges between 20 and 40 m (Lourens, 2013).

In the Tuli Basin, the Fripp Formation consists of a 5 to 10 m thick sandstone, together with gritty layers and coarse conglomerate lenses.

3.4.1.4.5 Solitude Formation

In the Tshipise Basin, the Solitude Formation has a gradational contact with the underlying Fripp Formation. The Solitude Formation consists of mudstone and shale, and has an average thickness of 120 m, but thins out to 60 m in the extreme west (Lourens, 2013).

In the Tuli Basin, the Solitude Formation consists of siltstone and very fine-grained sandstone with subordinate grey mudstone (Lourens, 2013). In the western part of the Tuli Basin, the Solitude Formation has a maximum thickness of approximately 25 m, and decreases to a thickness of 3.5 m in the eastern part (Lourens, 2013).

3.4.1.4.6 Klopperfontein Formation

In the Tshipise Basin, the Klopperfontein Formation has an unconformable relationship with the underlying Solitude Formation and is rarely exposed (Lourens, 2013). The Klopperfontein Formation consists of feldspathic sandstone and grit and has a maximum thickness of approximately 20 m, with an average thickness of 5 m (Lourens, 2013).

The Klopperfontein Formation of the Tuli Basin consists of sandstone and grit with frequent conglomerated horizons of 3 cm quartz clasts (Lourens, 2013). The Klopperfontein Formation is only developed or preserved in the central part of the Tuli Basin, where it reaches a maximum thickness of 10 to 12 m (Lourens, 2013).

3.4.1.4.7 Bosbokpoort Formation

In the Tshipise Basin, the Bosbokpoort Formation overlies the Solitude Formation, where the Klopperfontein Formation is not developed (Lourens, 2013). The Bosbokpoort Formation is characterised by red lithologies, varying from mudstone to very fine-grained sandstone, with a thickness that ranges from 120 to 150 m (Lourens, 2013).

In the Tuli Basin, the rocks of the Bosbokpoort Formation are rarely exposed, but are up to 60 m thick. The Bosbokpoort Formation consists of mudstones with subordinate siltstone layers and occasional intra-formational conglomerates (Lourens, 2013).

3.4.1.4.8 Clarens Formation

The Clarens Formation in both the Tshipise and Tuli basins is subdivided into the Red Rocks and Tshipise members, with the Red Rocks Member forming the base. In the Tshipise Basin, the Red Rocks Member consists of light red sandstone with occasional layers of cream-coloured sandstone, with a constant thickness of approximately 100 m (Lourens, 2013).

In the Tuli Basin, the Red Rocks Member has a thickness of 30 to 40 m, and consists of sandstone with a characteristic mottled appearance (Lourens, 2013). The overlying Tshipise Member consists of fine-grained, well sorted, white or cream-coloured sandstone, with a thickness that ranges from 5 to 140 m (Lourens, 2013). The Tshipise Member covers much of the area, and forms characteristic flat-topped hills, underlain by Red Rocks lithologies (Lourens, 2013).

3.4.1.4.9 Letaba Formation

In the Tshipise Basin, the Letaba Formation covers extensive areas and consists almost entirely of basalt. The thickness of the Letaba Formation is difficult to estimate, but it is thought to not exceed 100 to 200 m (Lourens, 2013).

In the Tuli Basin, only the lowermost part of the Letaba Formation has outcrops in the South African part of the basin (Lourens, 2013). The Letaba Formation forms complex outcrop patterns, which reflect the flow of lava around and between the dunes of the Clarens Formation (Lourens, 2013).

3.4.1.5 Karoo Dolerite Suite

The dolerite intrusions of the Karoo Supergroup are best developed within the Main Karoo Basin, but are present in most of South Africa (Lourens, 2013). The dolerite intrusions of the Karoo Supergroup are an interconnected network of dykes and sills, intruded into the sediments of the Karoo Supergroup during a period of extensive magmatic activity (Chevallier et al., 2001, as cited by Lourens, 2013). It appears that there is a lithological control on the emplacement of dykes within the Western Karoo Basin, because the dykes are mostly strata-bound and concentrated in the Upper Ecca and Beaufort groups (Woodford and Chevallier, 2002) (Figure 3-54).

Lourens (2013) stated that the dolerite dykes of the Karoo Supergroup are all sub-vertical with a dip rarely below 70°. Intense fracturing is commonly associated with this vertical segmentation (Woodford and Chevallier, 2002). The host rock of a dolerite intrusion is often fractured during and after dyke emplacement, with these fractures being either parallel to its strike or perpendicular to it (Lourens, 2013).

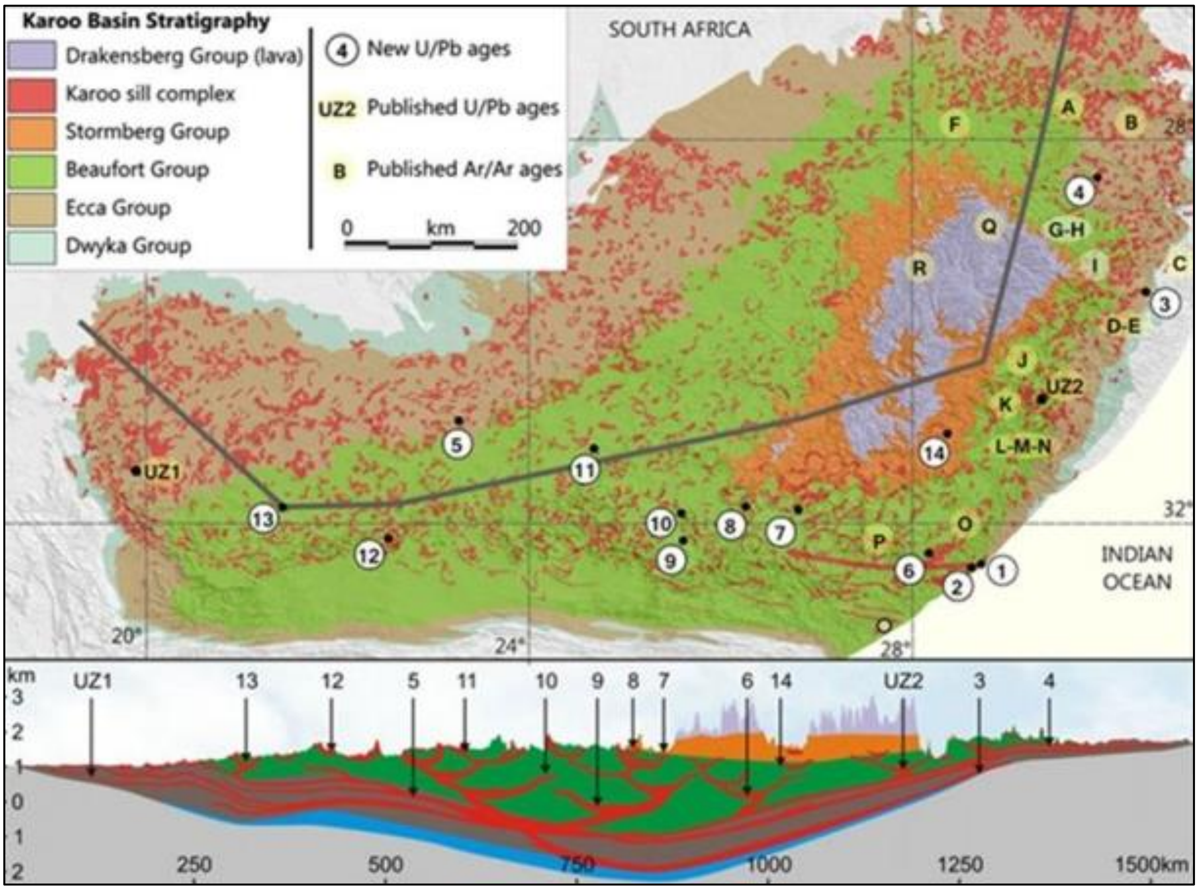


Figure 3-54: Interconnected dykes and sills of the Main Karoo Basin, including a schematic cross-section through the basin (Lourens, 2013)

3.4.2 Geohydrology

In this section, the geohydrology of the Karoo Supergroup is discussed according to the lithological groups, as well as according to the individual area or basin.

3.4.2.1 Dwyka Group

Lourens (2013) considers the Dwyka Group to be an aquitard rather than an aquifer, as the diamictite and shales have very low hydraulic conductivities and virtually no primary voids (Vivier, 1996, as cited by Lourens, 2013). However, where sand and gravel were deposited on beaches or where the Dwyka Group was fractured significantly, the Dwyka Group was found to host exploitable aquifers (Woodford and Chevallier, 2002). Nevertheless, Lourens (2013) concluded that the Dwyka Group was not ideal for the large-scale development of groundwater supply.

Lourens (2013) and others classified the Dwyka Group as being associated with low-yielding aquifers, with yields generally lower than 0.5 ℓ/s. However, where the Dwyka Group is significantly fractured, yields of up to 10 ℓ/s have been measured (King, 2002). Unfortunately, the occurrence of high-yielding boreholes is rare and can be related to the tendency of fractures or joints within the Dwyka Group to be mineralised (kaolinised), which decreases the potential yield (Schapers, 2011, as cited by Lourens, 2013).

The groundwater of the Dwyka Group is generally brackish, with electrical conductivity values often exceeding 300 mS/m, but decreasing inland (Lourens, 2013). The quality of the groundwater improves in the fractures or jointed zones of the Dwyka Group where significant groundwater movement takes place. The electrical conductivity values in these zones range from 25 to 200 mS/m (Meyer, 2001, as cited by Lourens, 2013).

3.4.2.2 Ecca Group

The Ecca Group is usually overlooked as a significant source of groundwater because it mainly consists of shales that are generally very dense (Lourens, 2013). The porosity of the shales is approximately 0.1 (10%) in the north, and decreases to less than 0.02 (2%) in the southern and southeastern parts of the Main Karoo Basin (Lourens, 2013) (Figure 3-55). The density follows a similar trend, decreasing from north to south from approximately 2,680 to 2 400 kg.m^{-3} (Lourens, 2013) (Figure 3-55). Lourens (2013) found that the rocks of the Ecca Group act as aquitards vertically, but as aquifers horizontally. Figure 3-56 displays the porosity and permeability variations in the sandstone/siltstone of the Ecca Group.

Lourens (2013) considered the Ecca Group to be associated with low-yielding aquifer systems, with yields between 0.1 and 2 ℓ/s. However, higher yields (greater than 2 ℓ/s) have been obtained in fold, fault and joint structures, where favourable recharge conditions exist (Lourens, 2013).

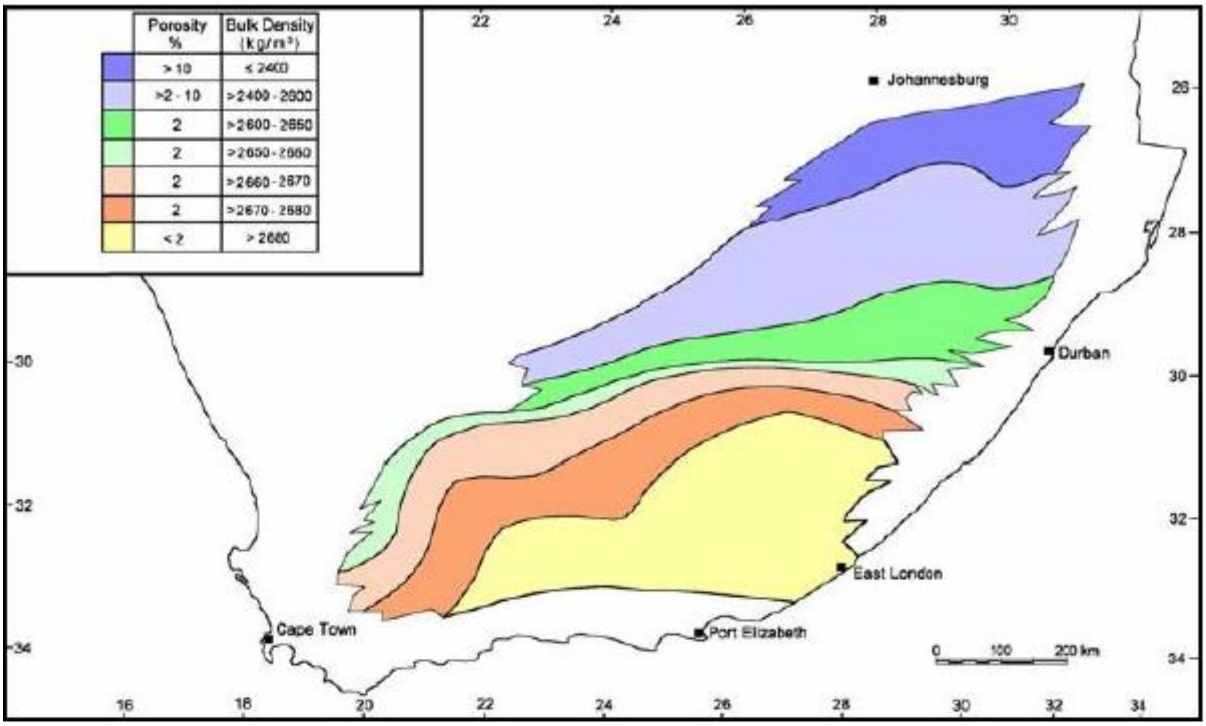


Figure 3-55: Contour map of porosities and bulk densities of the Ecca shale (Lourens, 2013)

3.4.2.3 Beaufort Group

The sandstones and mudstones of the Beaufort Group are also characterised by significantly low primary porosity and permeability (Lourens, 2013). This results in the secondary properties of these rocks (such as the degree, density, continuity and interconnection of fracturing), which control the occurrence, storage and movement of groundwater (Van Wyk and Witthüser, 2011, as cited by Lourens, 2013).

According to Baran (2003), as cited by Lourens (2013), the lithology of the sedimentary deposits of the Beaufort Group has little effect on the borehole yields, with yields between 0.1 and 2 ℓ/s. Higher yields can occasionally be obtained by targeting occasional folds, faults and joint structures where favourable recharge conditions exist (Lourens, 2013).

Lourens (2013) found that the groundwater of the Beaufort Group is generally potable, although in some areas this is not the case. The electrical conductivity values vary between 70 and 1,200 mS/m, with the majority of the values below 300 mS/m (Lourens, 2013).

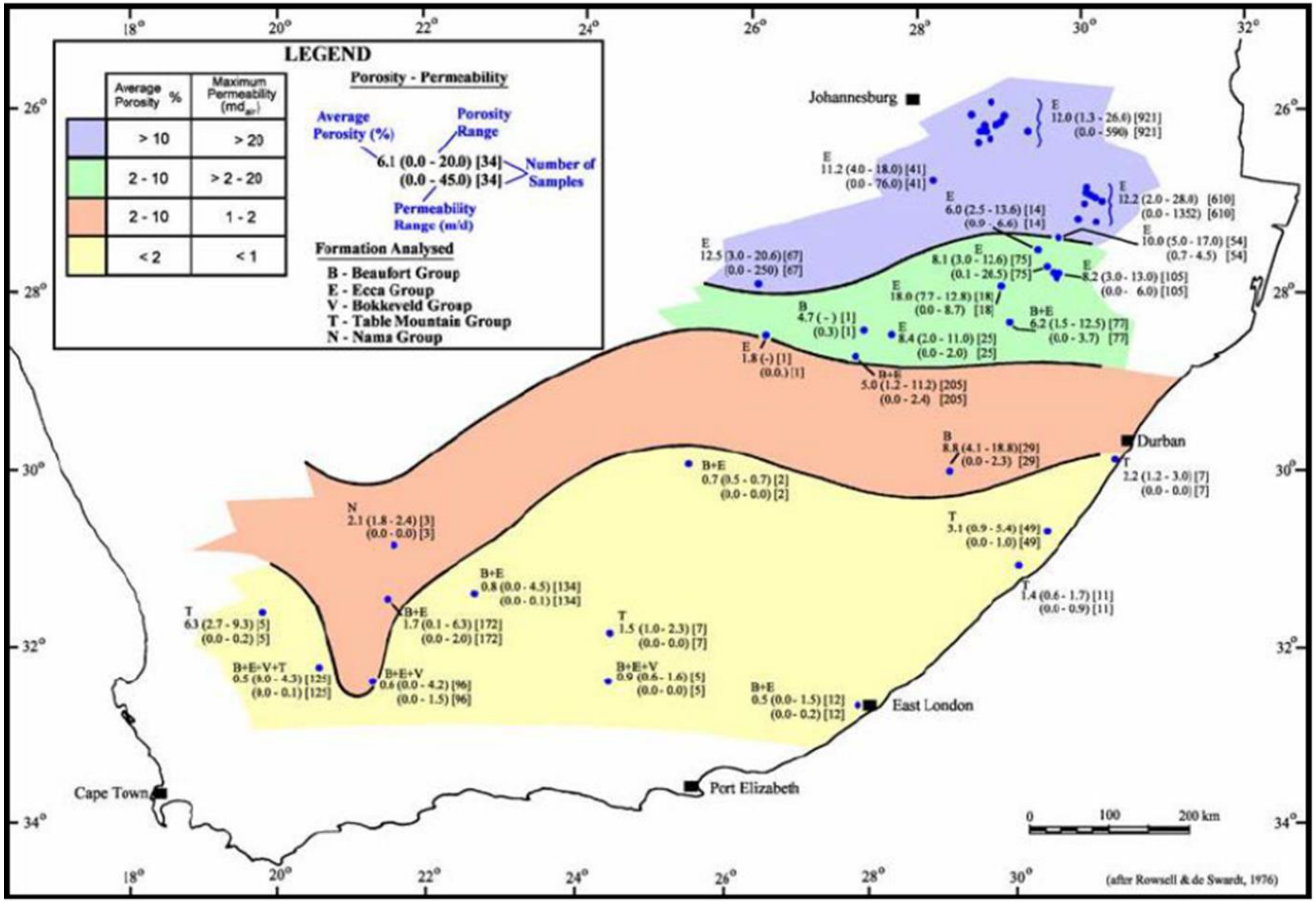


Figure 3-56: Porosity and permeability variations in the sandstone/siltstone of the Ecca Group (Woodford and Chevallier, 2002, as cited by Lourens, 2013)

3.4.2.4 Stormberg Group

Lourens (2013) regarded the Stormberg Group as being associated with low-yielding aquifer systems, with most boreholes yielding less than 2 ℓ/s. However, borehole yields occasionally exceed 2 ℓ/s (Barnard, 2000; Baran, 2003; Meyer, 2003, as cited by Lourens, 2013). The quality of the groundwater in the Stormberg Group is generally good (Lourens, 2013). Electrical conductivity values are generally less than 300 mS/m (Barnard, 2000; Baran, 2003; Meyer, 2003).

The Molteno Formation of the Stormberg Group is considered an "ideal" aquifer in terms of storativity due to its characteristics, depositional history and sheet-like geometry (Vivier, 1996; Woodford and Chevallier, 2002, as cited by Lourens, 2013). However, Lourens (2013) stated that the Molteno Formation tends to form topographical highs and does not extend over a large area, thus the siting of high-yielding boreholes can be a challenge.

The Elliot Formation of the Stormberg Group consists almost entirely of mudstones that are relatively impermeable, but highly porous (Vivier, 1996). The Elliot Formation is thus considered to act as an aquitard (Lourens, 2013).

The Clarens Formation of the Stormberg Group is the most homogeneous formation of the Karoo Supergroup, with a relatively high and uniform porosity (average of 8.46%) (Lourens, 2013) (Table 3-11). Based on its porosity values, the Clarens Formation should form an "ideal" aquifer. However, it is poorly fractured, resulting in a low hydraulic conductivity value (Lourens, 2013). The sandstones are able to store large quantities of water, but are unable to release it easily (Vivier, 1996; Woodford and Chevallier, 2002, as cited by Lourens, 2013).

Table 3-11: Porosity of the sandstone of the Clarens Formation (Lourens, 2013)

Type of Sandstone	Porosity (%)
Very Fine Grained	6.19-9.82
Cross-bedded Sandstone	8.87-10.75
Average	8.46

3.4.2.5 Drakensberg and Lebombo groups

Lourens (2013) classified the Drakensberg and Lebombo groups as hosting intergranular and fractured aquifer systems. The volcanic rocks of the Drakensberg and Lebombo groups are generally dense, with limited transmissivities. Groundwater movement is consequently restricted to weathered and fractured zones within the volcanic rocks (Lourens, 2013).

Lourens (2013) classified the Drakensberg Group as being associated with a low-yielding aquifer system, with most borehole yields ranging from 0.5 to 2 ℓ/s. A characteristic feature of the Drakensberg Group is the numerous low-yielding springs that emerge in elevated areas (Lourens, 2013). These springs are usually found along the contacts between weathered and solid basalts, and along the contacts between the basalts of the Drakensberg Group and the sandstones of the Clarens Formation (King, 2002; Meyer, 2003).

Springs are also fairly common within the Lebombo Group, especially on the eastern slopes of the Lebombo Mountain Range south of Swaziland (King, 2003).

Lourens (2013) classified the basalts (Letaba Formation) of the Lebombo Group as hosting low- to moderate-yielding aquifer systems, with the majority of boreholes having yields ranging between 0.5 and 2 ℓ/s (Du Toit and Lelyveld, 2006, as cited by Lourens, 2013). However, borehole yields within the Lebombo Group have been found to exceed 2 ℓ/s, with a maximum reported yield of 14 ℓ/s (Lourens, 2013).

3.4.2.6 Karoo Dolerite Suite

Dolerite dykes act as semi-impermeable to impermeable barriers to the movement of groundwater in directions perpendicular to their strikes, while being associated with thin, linear zones of relatively high permeability along their sides, and acting as conduits for groundwater flow in directions parallel to their strikes (Lourens, 2013).

On a local scale, the geometry, attitude, grain size, degree of weathering and fracturing of dykes influence the geohydrological properties of individual structures (Woodford and Chevallier, 2002). The geohydrology of a particular dyke is related to a complex interplay of these parameters, and can thus vary dramatically along the strike of the structure (Woodford and Chevallier, 2002).

On a regional scale, the structural domains have not as yet been shown to influence the regional geohydrology of the Karoo Supergroup. However, the east-west striking Victoria dyke, the north-northwest striking Middelburg dyke and the dykes near East London form major magma feeders and are accompanied by extensive fracturing due to shearing and jointing. These dykes form regional discontinuities that extend to great depths within the earth's crust and could theoretically form part of a fracture network in which deeper-seated groundwater flows on a more regional scale (Woodford and Chevallier, 2002).

3.4.2.7 Main Karoo Basin

SOEKOR drilled oil exploration boreholes in the Main Karoo Basin to explore economic deposits (Viljoen et al., 2010) (Figure 3-57). Some small oil shows and gas were found at shallow depths (<400 m) in the northeastern part of the Main Karoo Basin, but these occurrences were not economically viable because of the low permeability of the host sandstones in which they occur (Roswell and De Swart, 1976; Van Vuuren et al., 1998, as cited by Viljoen et al., 2010).

The geohydrological regime in the Main Karoo Basin is complicated by the occurrence of widely distributed dolerite sills and dykes, which divide the basin into relatively small compartments or confined aquifers (Viljoen et al., 2010) (Figure 3-58). The dolerite intrusions cause secondary porosity by metamorphism, local faulting and deformation around the intrusion. These fractures along dolerite dykes could create pathways for groundwater to move along (Viljoen et al., 2010).

Other than the dolerite control on groundwater flow, the occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding-plane fractures (Viljoen et al., 2010). The porosity thus occurs along the bedding planes and not in the rock itself (Woodford and Chevallier, 2002, as cited by Viljoen et al., 2010). Viljoen et al. (2010) stated that it is not certain if these bedding-plane porosities are also present at depth because groundwater is mostly prospected in the upper few hundred metres from the ground surface.

The Karoo rocks were fractured along bedding planes during episodes of isostatic rebound and erosional unloading due to the difference in elasticity between the various rock units (Botha et al., 1998; Botha and Cloot, 2004, as cited by Viljoen et al., 2010). The accepted hypothesis is that, since there is an increase in overburden pressures with depth, most deep-seated bedding-parallel fractures are closed. However, groundwater was struck at a depth of 3,700 m below ground level in Dwyka diamictite in borehole SP 1/69 near East London (Roswell and De Swart, 1976).

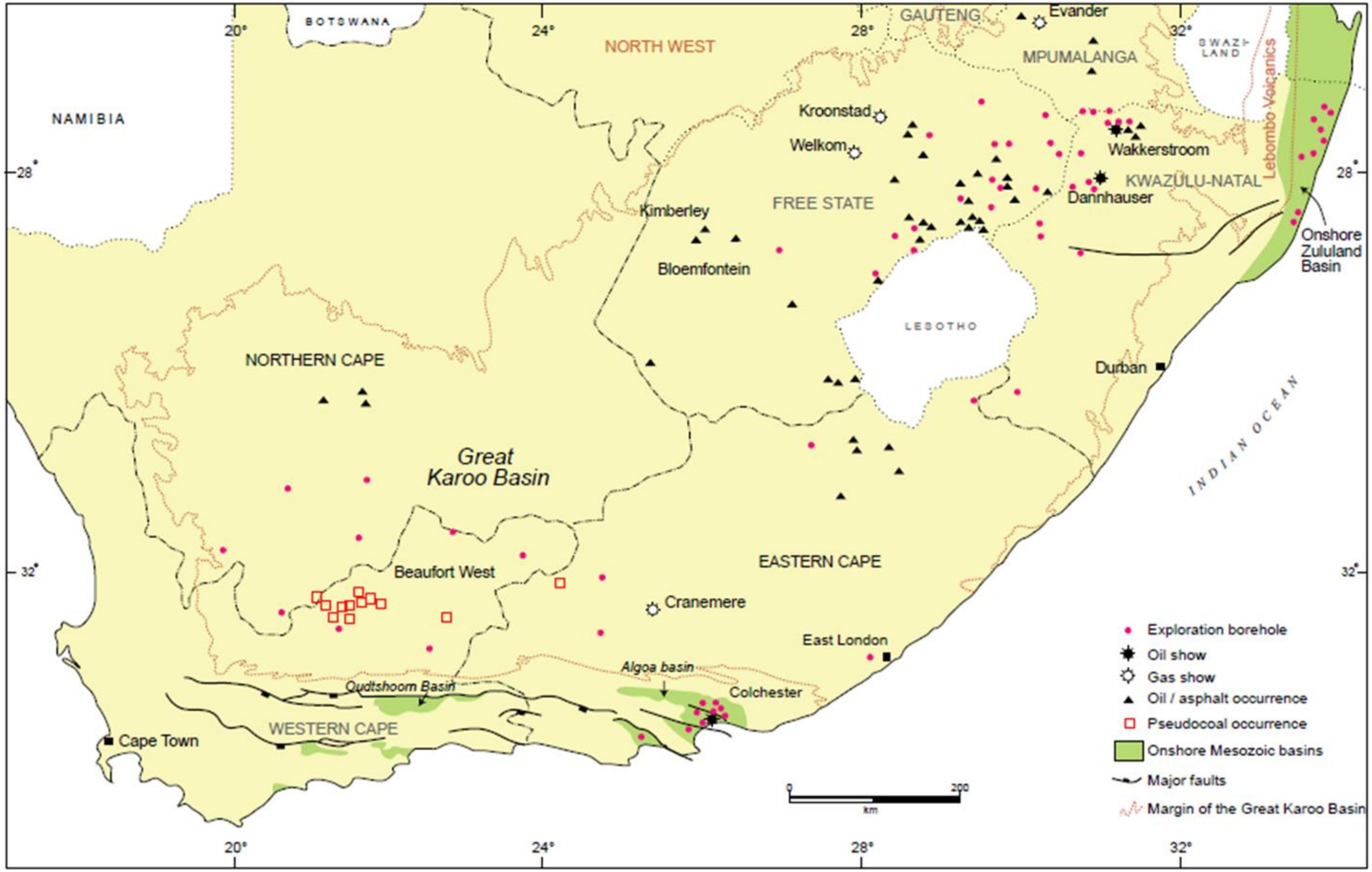


Figure 3-57: Location of onshore SOEKOR boreholes in South Africa (Viljoen et al., 2010)

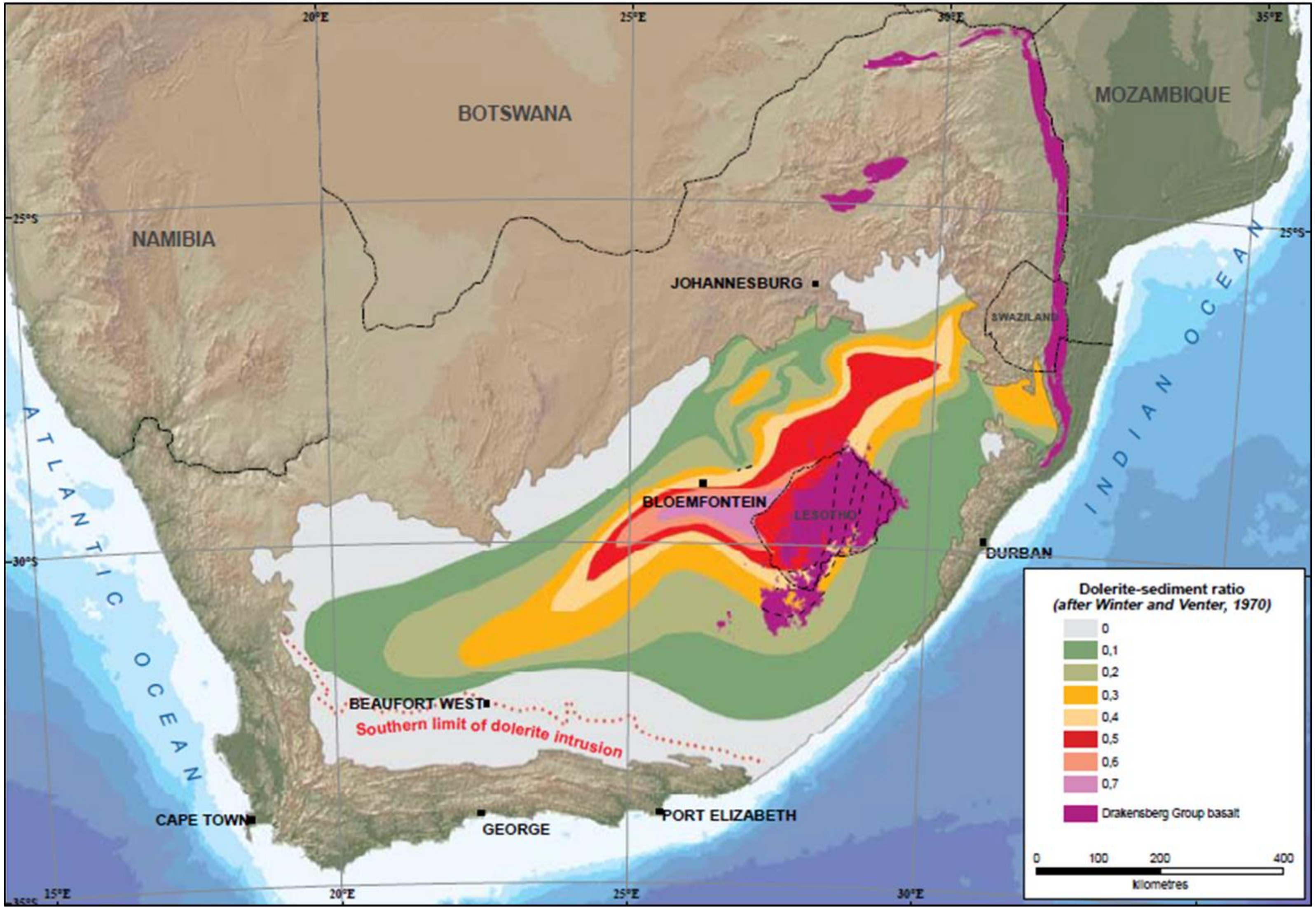


Figure 3-58: Dolerite/sediment ratio map for the Karoo Basin (after Winter and Venter, 1970, as cited by Viljoen et al., 2010)

As the primary porosities and permeabilities of the Main Karoo Basin are low, secondary porosities need to be investigated. Secondary porosity is best developed in baked shales and sandstones below thick dolerite sills and inclined sills, and at intersections of sills and dykes (Viljoen et al., 2010). Good connectivity between the secondary features (fractures) were found at relatively shallow depths (<400 m) below a sill (Chevallier et al., 2004, as cited by Viljoen et al., 2010). It was found that the sill created an upper and lower confined aquifer (Chevallier et al., 2004). Viljoen et al. (2010) concluded that these fractures may be filled with saline groundwater at depth. However, prospecting for this deep groundwater is hampered by the presence of thick dolerite sills because the depth of penetration for deep resistivity soundings is confined to the depth of the top of the first thick dolerite sheet (Viljoen et al., 2010).

For the purpose of this discussion, the Main Karoo Basin is divided into three areas: the southern and southwestern area, the central area, and the northern area (Figure 3-59).

3.4.2.7.1 South and Southwestern Karoo

In the south and southwestern section of the Main Karoo Basin, Viljoen et al. (2010) identified the turbiditic sands of the Skoorsteenberg, Laingsburg and Ripon formations and the deltaic and shallow marine sandstones of the Waterford Formation as potential reservoirs for CO_2 storage due to their lithologies (Figure 3-59). A petrographic study of the Skoorsteenberg Formation in the Tankwa Karoo indicated that the reservoir quality of these sandstones is extremely poor, with no visible porosity or permeability (Marot, 1992, as cited by Viljoen et al., 2010).

Viljoen et al. (2010) drew similar conclusions for the equivalent sandstones of the Laingsburg and Ripon formations in the southern Karoo area. The same applies to the Waterford Formation, which is intruded by a large number of dolerite sills and dykes north of the dolerite line (Figure 3-58) (Johnson, 1991; Siebrits, 1987, as cited by Viljoen et al., 2010).

The poor to non-existent porosities and permeabilities of Karoo rocks in this part of the Karoo Basin were confirmed by work done by Roswell and De Swart (1976), as cited by Viljoen et al. (2010). Table 3-12 and Figure 3-60 summarise the results found by Roswell and De Swart (1976). Table 3-12 is a summary of the measured porosities and permeabilities for tested boreholes, while Figure 3-60 graphically displays the distribution of the different porosity and permeability ranges across South Africa.

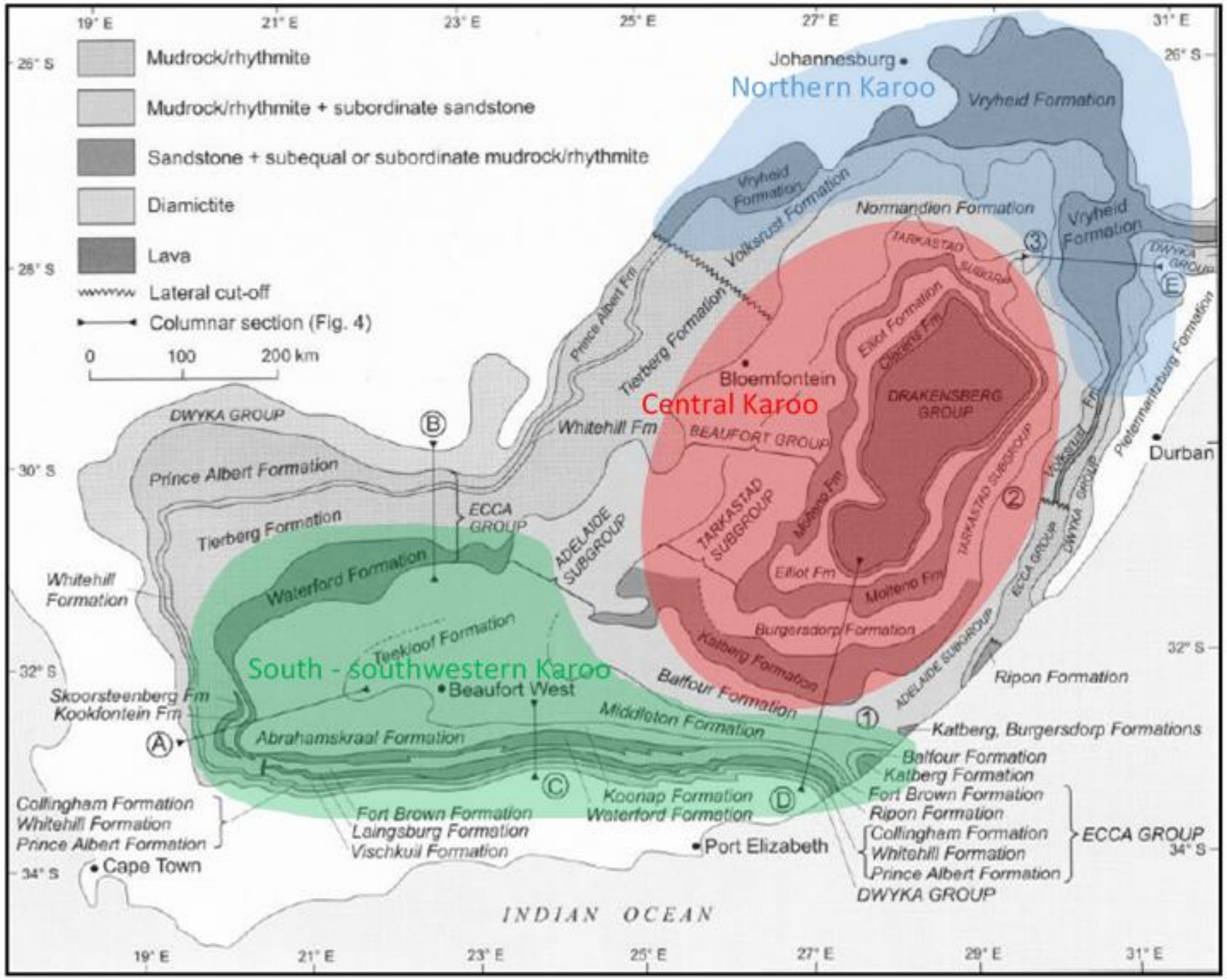


Figure 3-59: Schematic areal distribution of the lithostratigraphic units of the Karoo Supergroup, showing the three main divisions (modified from Johnson et al., 2006)

Table 3-12: Porosity and permeability values for the Beaufort and Ecca sandstones in the southern section of the Main Karoo Basin (after Roswell and De Swart, 1976, as cited by Viljoen et al., 2010)

Borehole	Stratigraphic Interval (group)	Depth interval analysed (m)	No. of samples	Porosity		Hydraulic Conductivity range (m/d)	Permeability Log_{10} m^2
				Range	Average		
KL 1/65	Beaufort	7	1	1.9	1.9	0.0	0
	Ecca	14 – 1 524	41	0.1 – 1.9	0.6	< 8.3×10^{-9}	-17
SA 1/66	Beaufort	34 – 1 215	84	0.2 – 2.9	0.5	0.0 – 1.2×10^{-6}	-15
	Ecca	1 296 – 1 429	3	0.37 – 0.5	0.45	0.0	0
QU 1/65	Beaufort	7 – 778	134	0.1 – 6.3	1.8	0.0 – 7.5×10^{-7}	-15
	Ecca	1 313 – 1 494	38	0.3 – 3.7	1.3	0.0 – 1.6×10^{-6}	-15
AB 1/65	Beaufort	283 – 764	78	0.0 – 3.8	1.3	0.0	0
	Ecca	762 – 1 563	56	0.0 – 4.5	0.8	0.0 – 8.3×10^{-8}	-16
SC 3/67	Ecca	3 961 – 3 963	4	0.59 – 1.18	0.77	0.0	0
SP 1/69	Beaufort	601 – 1 938	7	0.0 – 1.5	0.7	0.0 – 1.6×10^{-7}	-16
	Ecca	3 047 – 3 053	5	0.0 – 0.57	0.2	0.0	0
TU	Beaufort	78	1	0.48	0.48	0.0	0
	Ecca	1 311	1	0.87	0.87	0.0	0
MA 1/69	Beaufort	434 – 1 390	30	4.1 – 18.1	8.8	0.0 – 1.9×10^{-6}	-15

The Cape Fold Belt formed while sedimentation of the Karoo units was still in progress (Johnson et al., 2006). This Cape orogeny caused intense deformation of the Cape Supergroup, the underlying basement, and the lower units of the Karoo Supergroup along the southern basin edge (Johnson et al., 2006). Lourens (2013) found that weathered and fractured zones associated with faulting and folding are confined to the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines that are formed due to folding have characteristic open joints and fractures. These structures are seldom dry when intersected by drilling, although the groundwater quality may be problematic (Van Tonder, 1978; Wellman, 2011, as cited by Lourens, 2013).

3.4.2.7.2 Central Karoo

The central Karoo comprises the Katberg, Clarens and Molteno formations (Figure 3-59). Fine- to coarse-grained sandstones of the Katberg Formation are approximately 800 m thick in the south, containing more than 90% sandstone, but the sandstone-to-mudstone ratio decreases steadily northwards until the formation becomes difficult to distinguish from the overlying mudstone-rich Burgersdorp Formation (Viljoen et al., 2010) (Figure 3-59). Relatively good porosities and permeabilities were measured in the SOEKOR borehole MA 1/69 (Table 3-13), which was probably drilled into the Katberg Formation. The geological log of borehole MA 1/69 also indicated well-developed jointing in parts of the core (Viljoen et al., 2010).

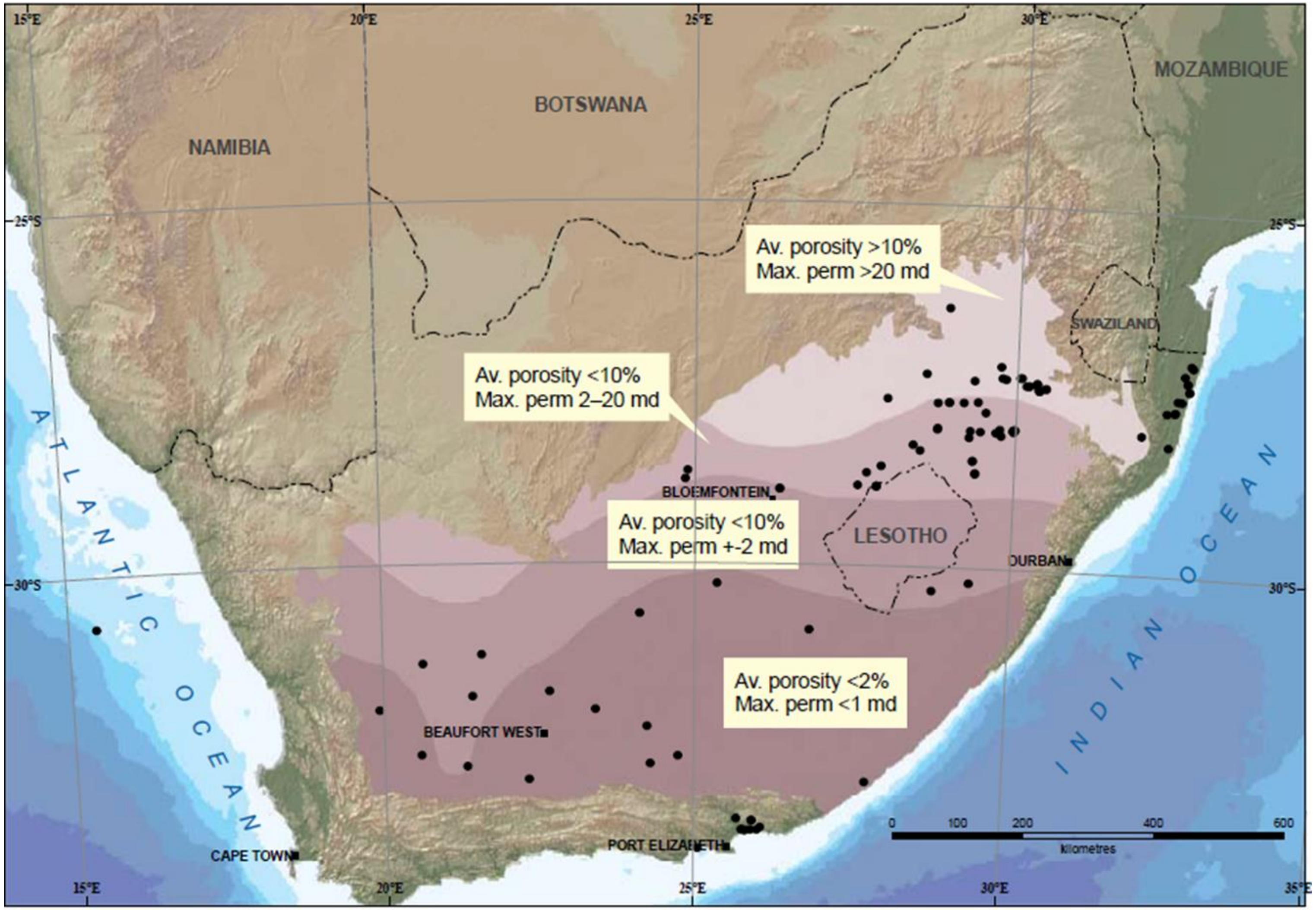


Figure 3-60: Porosity and permeability trends in the Cape and Karoo Supergroups (after Roswell and De Swart, 1976, as cited by Viljoen et al., 2010)

Viljoen et al. (2010) stated that, to target the sandstones of the Katberg Formation at a depth of more than 800 m below ground level (for CO_2 storage), the injection sites would have to be at least in the vicinity of Barkly East. In the SOEKOR borehole WE 1/66, the Katberg Formation occurs at depths of 550 to 1,000 m below ground level (Viljoen et al., 2010).

The Molteno Formation has extensive dolerite dykes (up to 20 m thick) and sills (up to 200 m thick) that have caused localised updoming of the strata (Viljoen et al., 2010). Faults associated with the dolerites are present, with displacements of 50 m to more than 300 m in some places (Christie, 1986, as cited by Viljoen et al., 2010). The presence of a warm water spring in Aliwal North indicates that deep circulating groundwater systems are present in this area (Viljoen et al., 2010).

The Clarens Formation consists almost entirely of sandstones and is 300 m thick in the south, thinning to almost 100 m in the north (Viljoen et al., 2010). Although the formation shows high porosities (an average of 8.5%) and permeabilities in the central Main Karoo Basin, these measurements were taken from very shallow depths (Viljoen et al., 2010) (Table 3-13). No dolerite sills are present in the formation, but dolerite dykes and volcanic vents are extensively developed (Viljoen et al., 2010).

Table 3-13: Porosity and permeability values for the Clarens Formation (after Beukes, 1969, and Roswell and De Swart, 1976*, as cited by Viljoen et al., 2010)

Lithology	Depth interval analysed (m)	No. of samples	Porosity		Hydraulic Conductivity range (m/d)	Permeability Log_{10} m²
			Range	Average		
Very fine sandstone	-	-	6.2 – 9.8	-	-	-
Cross-bedded sandstone	-	-	8.9 – 10.8	-	-	-
Sandstone	-	-	6.19 – 10.75	8.46	-	-
Sandstone*	26 - 130	43	4.7 – 21	15.1	$8.3 \times 10^{-7} – 6.1 \times 10^{-5}$	-15 to -13

3.4.2.7.3 Northern Karoo

Viljoen et al. (2010) considered the northern part of the Main Karoo Basin to have the best potential for the storage of CO_2 because of the presence of the sandstone-rich Vryheid Formation, which has higher porosities and permeabilities than the rest of the basin (Viljoen et al., 2010) (Figure 3-60 and Table 3-14). However, most of the porosity and permeability measurements listed in Table 3-14 were done on samples from very shallow depths (Viljoen et al., 2010). Approximately 30 to 60% of the lithological column in this area consists of dolerite, which could create additional secondary porosity for groundwater movement (Viljoen et al., 2010).

Table 3-14: Porosity and permeability values for the Northern Karoo Basin (after Roswell and De Swart, 1976, as cited by Viljoen et al., 2010)

Borehole or area	Stratigraphic Interval (Group)	Depth interval analysed (m)	No. of samples	Porosity		Hydraulic Conductivity range (m/d)	Max Permeability Log_{10} m^2
				Range	Average		
LA 1/68	Beaufort	210 – 1 240	138	1.2 – 10.7	4.7	0.0 – 2 x 10^{-6}	-15
	Ecca	1 540 – 1 600	67	1.2 – 11.2	5.6	0.0 – 1.2 x 10^{-6}	-15
FL 1/72 WL 1/72	Ecca	450 – 1 500	25	2.0 – 11.0	8.4	0.0 – 1.6 x 10^{-6}	-15
Glen	Beaufort	635	1	1.8	1.8	0.0	0
CL 4/68	Beaufort	700	1	4.7	4.7	2.5 x 10^{-7}	-16
Welkom-Virginia	Ecca	10 – 40	67	3.0 – 20.6	12.5	0.0 – 0.0002	-13
BE 1/67	Beaufort	80 – 850	77	1.5 – 12.5	6.2	0.0 – 3 x 10^{-6}	-14
	Middle Ecca	780 – 900	18	7.7 – 12.8	11.0	0.0 – 7.2 x 10^{-6}	-14
ME 1/72	Middle Ecca	80 – 400	105	3.0 – 13.0	8.2	0.0 – 5 x 10^{-6}	-14
GSO 14 Dannhauser	Middle Ecca	300 – 450	75	30. – 12.6	8.1	8.3 x 10^{-8} – 1.7 x 10^{-5}	-14
OM 1/73	Middle Ecca	640 – 680	14	2.5 – 13.6	6.0	7.5 x 10^{-7} – 3.7 x 10^{-6}	-14
North of Dannhauser	Middle Ecca	100 – 200	54	5.0 – 17.0	10.0	5.8 x 10^{-7} – 3.7 x 10^{-6}	-14
Wakkerstroom	Middle Ecca	20 – 70	610	2.0 – 28.0	12.2	0.0 – 0.001	-12
SE of Standerton	Middle Ecca	200 – 500	41	4.0 – 18.0	11.2	0.0 – 6.3 x 10^{-5}	-13

)

Viljoen et al. (2010) stated that the area where the Vryheid Formation occurs at depths of more than 800 m is situated in an arc from west of Bergville in the east towards the area just north of Bethlehem and south-westwards to Ladybrand (Figure 3-61). In the SOEKOR borehole SL 1/77 (south of Bethlehem), the sandstones in the Vryheid Formation are about 90 m thick, occurring at a depth of approximately 1,000 m below ground level (Viljoen et al., 2010). The sandstones thin out to a thickness of approximately 50 m at Ladybrand (borehole LA 1/68). In SOEKOR borehole LA 1/68, a 150 m thick jointed dolerite occurs at a depth of between 1,110 and 1,260 m below ground level. A 25 m thick sandstone with medium visual porosity is also present in the LA 1/68 borehole between depths of 1,051 and 1,076 m below ground level, as well as at a depth of 1,600 m below ground level, where a 13 m thick sandstone occurs with good porosity as judged from visual observations (Viljoen et al., 2010) (Table 3-14).

3.4.2.8 Springbok Flats Basin

The Springbok Flats Basin of the Karoo Supergroup is connected on the surface, but is divided at depth into two smaller basins by an east-west-striking normal fault (Roberts, 1992, as cited by Viljoen et al., 2010). The northeastern sub-basin has a maximum thickness of approximately 700 m and the southwestern sub-basin has a maximum thickness of 1,000 m, with an area of about 200 km^2 at depths greater than 800 m below ground level (Viljoen et al., 2010) (Figure 3-62).

Figure 3-62 is a map of the thickness of the Karoo Supergroup within the Springbok Flats Basin. Viljoen et al. (2010) considered the southwestern sub-basin zone as a potential saline reservoir for CO_2 storage. However, no porosity or permeability data was available for this zone.

The Springbok Flats Basin is underlain by rocks of the Bushveld Igneous Complex, which could be mined in future where it is underlain by shallower parts of the basin (Viljoen et al., 2010). A large number of exploration boreholes has been drilled in the Springbok Flats Basin (more than 2,000), but no active mining is currently taking place (Viljoen et al., 2010).

3.4.2.9 Ellisras Basin

The Ellisras Basin is a small, elongated, east-west striking, fault-controlled basin (Figure 3-59). All the faults of the Ellisras Basin are post-Karoo, with a maximum displacement of about 300 m (Brandl, 1993; Brandl, 1996; Siepker, 1986, as cited by Viljoen et al., 2010). The maximum thickness of the basin was estimated to be less than 800 m (Viljoen et al., 2010). Unfortunately, there are no boreholes that intersect the basement in the deepest part of the basin (Venter, 1944; Cillié, 1951; Cillié, 1957; Cillié and Visser, 1945, as cited by Viljoen et al., 2010).

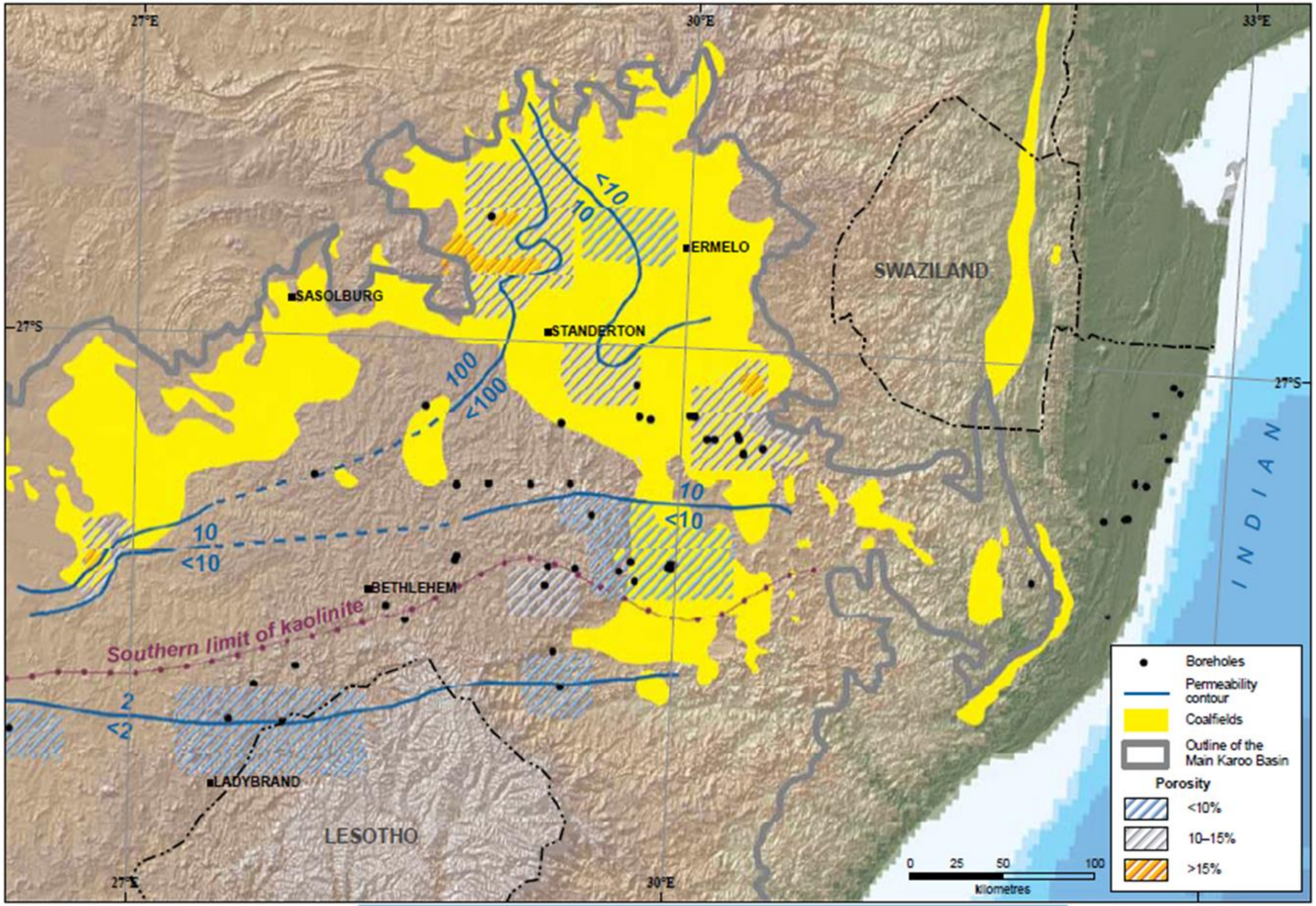


Figure 3-61: Distribution of porosity and permeability in the Vryheid Formation (Roswell and De Swart, 1976, as cited by Viljoen et al., 2010)

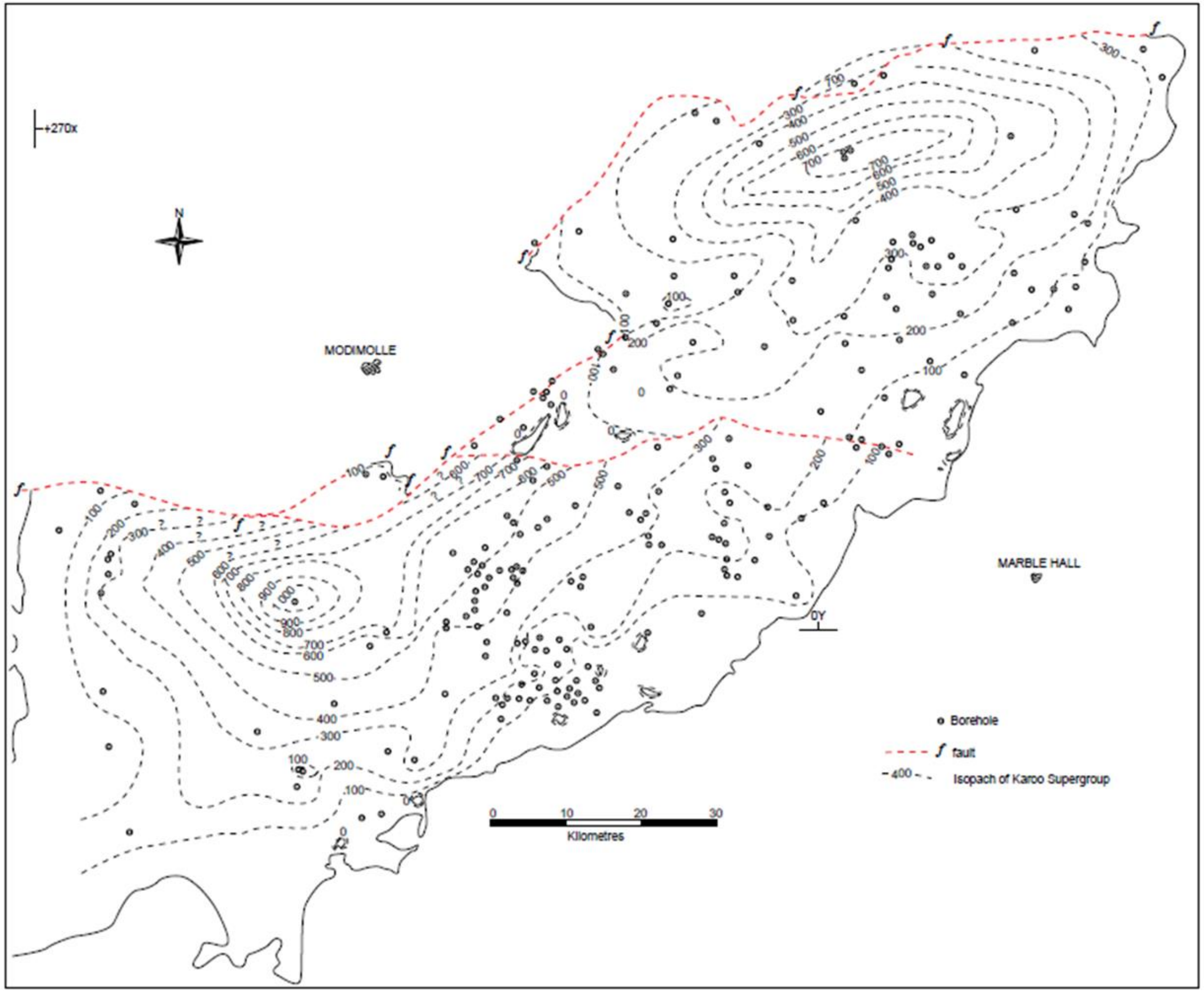


Figure 3-62: Thickness in the Springbok Flats Basin (modified from Roberts, 1992, as cited by Viljoen et al., 2010)

3.4.2.10 Tshipise and Tuli basins

Viljoen et al. (2010) stated that deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with a maximum water temperature of 59 to 60 °C. These warm springs are associated with some of the major faults (Viljoen et al., 2010) (Figure 3-4).

The Tuli Basin is a relatively small basin (1,150 km^2), elongated in the west-east direction and fault-controlled. The basin has a maximum thickness of approximately 500 m (Viljoen et al., 2010) (Figure 3-59). Intrusive dykes and faulting are locally present and contain almost flat-lying coal seams near the base of the basin that are generally less than 300 m deep (Brandl and Pretorius, 2000; Brandl, 2002, as cited by Viljoen et al., 2010).

3.4.3 Summary of the Karoo Supergroup

The Karoo Supergroup covers roughly two thirds of the land surface of South Africa. A summary of the important information on the geology and geohydrology of the Karoo Supergroup is provided below according to geological subdivision.

3.4.3.1 Dwyka Group

Lourens (2013) considered the Dwyka Group to act as an aquitard rather than an aquifer, as the diamictite and shales have very low hydraulic conductivities and virtually no primary voids (Vivier, 1996). However, where sand and gravel are deposited on beaches or where the Dwyka Group is fractured significantly, the Dwyka Group can become an exploitable aquifer (Woodford and Chevallier, 2002). Nevertheless, Lourens (2013) concluded that the Dwyka Group is not ideal for the development of a large-scale groundwater supply.

Lourens (2013) and others classified the Dwyka Group as being associated with low-yielding aquifers, with yields generally lower than 0.5 ℓ/s. However, where the Dwyka Group is significantly fractured, yields of up to 10 ℓ/s have been measured (King, 2002). Unfortunately, the occurrence of such high-yielding boreholes is rare and could be related to the tendency of fractures or joints within the Dwyka Group to be mineralised (kaolinised), which decreases the potential yield (Schapers, 2011).

3.4.3.2 Ecca Group

Lourens (2013) found that the rocks of the Ecca Group act as aquitards vertically, but as aquifers horizontally. Lourens (2013) considered the Ecca Group to host low-yielding aquifer systems, with yields between 0.1 and 2 ℓ/s. However, higher yields (greater than 2 ℓ/s) have been obtained in fold, fault and joint structures, where favourable recharge conditions exist (Lourens, 2013).

3.4.3.3 Beaufort Group

The sandstones and mudstones of the Beaufort Group are also characterised by significantly low primary porosity and permeability (Lourens, 2013). This results in the secondary properties of these rocks (such as the degree, density, continuity and interconnection of fracturing), which control the occurrence, storage and movement of groundwater (Van Wyk and Witthüser, 2011).

According to Baran (2003), the lithology of the sedimentary deposits of the Beaufort Group has little effect on the borehole yields, with yields between 0.1 and 2 ℓ/s having been reported. Higher yields can occasionally be obtained by targeting occasional folds, faults and joint structures, where favourable recharge conditions exist (Lourens, 2013).

3.4.3.4 Stormberg Group

Lourens (2013) regarded the Stormberg Group as being associated with low-yielding aquifer systems, with most boreholes yielding less than 2 ℓ/s, but yields occasionally exceed 2 ℓ/s (Barnard, 2000; Baran, 2003; Meyer, 2003).

The Molteno Formation of the Stormberg Group is considered an “ideal” aquifer in terms of storativity due to its characteristics, depositional history and sheet-like geometry (Vivier, 1996; Woodford and Chevallier, 2002). However, Lourens (2013) stated that the Molteno Formation tends to form topographical highs and does not extend over a large area, thus the siting of high-yielding boreholes can be difficult.

The Elliot Formation of the Stormberg Group consists almost entirely of mudstones that are relatively impermeable, but highly porous (Vivier, 1996). The Elliot Formation is thus considered an aquitard instead of an aquifer (Lourens, 2013).

The Clarens Formation of the Stormberg Group is the most homogeneous formation of the Karoo Supergroup, with a relatively high and uniform porosity (average of 8.46%) (Lourens, 2013). This suggests that the Clarens Formation can be considered an “ideal” aquifer. However, it is poorly fractured, resulting in low hydraulic conductivity (Lourens, 2013). Although the sandstones can store large quantities of water, they are unable to release the water easily (Vivier, 1996; Woodford and Chevallier, 2002).

3.4.3.5 Drakensberg and Lebombo groups

Lourens (2013) classified the Drakensberg and Lebombo groups as hosting intergranular and fractured aquifer systems. The volcanic rocks of the Drakensberg and Lebombo groups are generally dense, with limited transmissivities. Groundwater movement is consequently restricted to weathered and fractured zones within the volcanic rocks (Lourens, 2013).

Lourens (2013) classified the Drakensberg Group as being associated with low-yielding aquifer systems, with most borehole yields ranging from 0.5 to 2 ℓ/s. A characteristic feature of the Drakensberg Group is the numerous low-yielding springs that emerge in elevated areas (Lourens, 2013). These springs are usually found along the contacts between weathered and solid basalts, and along the contacts between the basalts of the Drakensberg Group and the sandstones of the Clarens Formation (King, 2002; Meyer, 2003).

Springs are also fairly common within the Lebombo Group, especially on the eastern slopes of the Lebombo Mountain Range south of Swaziland (King, 2003).

Lourens (2013) classified the basalts (Letaba Formation) of the Lebombo Group as hosting low- to moderate-yielding aquifer systems, with the majority of boreholes having yields ranging between 0.5 and 2 ℓ/s (Du Toit and Lelyveld, 2006). However, borehole yields within the Lebombo Group have been found to exceed 2 ℓ/s, with a maximum reported yield of 14 ℓ/s (Lourens, 2013).

3.4.3.6 Karoo Dolerite Suite

Dolerite dykes act as semi-impermeable to impermeable barriers to the movement of groundwater in directions perpendicular to their strikes, while being associated with thin, linear zones of relatively high permeability along their sides, which act as conduits for groundwater flow in directions parallel to their strikes (Lourens, 2013).

On a regional scale, the structural domains have not, as yet, been shown to influence the regional geohydrology of the Karoo Supergroup. However, the east-west-striking Victoria dyke, the north-northwest-striking Middelburg dyke and dykes near East London form major magma feeders and are accompanied by extensive fracturing due to shearing and jointing.

These dykes form regional discontinuities that extend to great depths within the earth's crust and could theoretically form part of a fracture network in which deeper-seated groundwater flows on a more regional scale (Woodford and Chevallier, 2002).

3.4.3.7 Main Karoo Basin

Other than the dolerite control on groundwater flow, the occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding-plane fractures (Viljoen et al., 2010). The porosity thus occurs along the bedding planes and not in the rock itself (Woodford and Chevallier, 2002). Viljoen et al. (2010) stated that it is not certain if these bedding-plane porosities are also present at depth because groundwater is mostly prospected in the upper few hundred metres from the ground surface. The Karoo rocks were fractured along bedding planes during episodes of isostatic rebound and erosional unloading due to the difference in elasticity between the various rock units (Botha et al., 1998; Botha and Cloot, 2004, as cited by Viljoen et al., 2010). The accepted hypothesis is that, since there is an increase in overburden pressures with depth, most deep-seated bedding-parallel fractures are closed. However, groundwater was struck at a depth of 3,700 m below ground level in Dwyka diamictite in borehole SP 1/69 near East London (Roswell and De Swart, 1976).

Seeing that the primary porosities and permeabilities of the Main Karoo Basin are low, secondary porosities need to be investigated. Secondary porosity is best developed in baked shales and sandstones below thick dolerite sills and inclined sills, and at intersections of sills and dykes (Viljoen et al., 2010). Good connectivity between the secondary features (fractures) were found at relatively shallow depths (<400 m below ground level) below a sill (Chevallier et al., 2004). It was found that the sill created an upper and lower confined aquifer (Chevallier et al., 2004). Viljoen et al. (2010) concluded that these fractures may be filled with saline groundwater at depth. However, prospecting for this deep groundwater is hampered by the presence of thick dolerite sills because the depth of penetration for deep resistivity soundings is confined to the depth of the top of the first thick dolerite sheet (Viljoen et al., 2010).

3.4.3.7.1 South and Southwestern Karoo

The Cape Fold Belt formed while sedimentation of the Karoo units was still in progress (Johnson et al., 2006). The Cape orogeny caused intense deformation of the Cape Supergroup, the underlying basement, and the lower units of the Karoo Supergroup along the southern basin edge (Johnson et al., 2006). Lourens (2013) found that weathered and fractured zones that are associated with faulting and folding are confined to the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines that are formed due to folding have characteristic open joints and fractures. These structures are seldom dry when intersected by drilling, although the groundwater quality may be problematic (Van Tonder, 1978; Wellman, 2011).

3.4.3.7.2 Central Karoo

Viljoen et al. (2010) stated that, to target the sandstones of the Katberg Formation at a depth of more than 800 m below ground level (for CO_2 storage), the injection sites would have to be at least in the vicinity of Barkly East. In the SOEKOR borehole WE 1/66, the Katberg Formation occurs at depths of 550 to 1,000 m below ground level (Viljoen et al., 2010).

The Molteno Formation has extensive dolerite dykes (up to 20 m thick) and sills (up to 200 m thick) that have caused localised updoming of the strata (Viljoen et al., 2010). Faults associated with the dolerites are present, with displacements of 50 m to more than 300 m in some places (Christie, 1986, as cited by Viljoen et al., 2010). The presence of a warm water spring in Aliwal North indicates that deep circulating groundwater systems are present in this area (Viljoen et al., 2010).

The Clarens Formation consists almost entirely of sandstone and is 300 m thick in the south, thinning out to almost 100 m in the north (Viljoen et al., 2010). Although the formation shows high porosities (an average of 8.5%) and permeabilities in the central Main Karoo Basin, these measurements were taken from very shallow depths (Viljoen et al., 2010). No dolerite sills are present in the formation, but dolerite dykes and volcanic vents are extensively developed (Viljoen et al., 2010).

3.4.3.7.3 Northern Karoo

Viljoen et al. (2010) considered the northern part of the Main Karoo Basin to have the best potential for the storage of CO_2 because of the presence of the sandstone-rich Vryheid Formation, which has higher porosities and permeabilities than the rest of the basin (Viljoen et al., 2010). However, most of the porosity and permeability measurements were done on samples from very shallow depths (Viljoen et al., 2010). Approximately 30 to 60% of the lithological column in this area consists of dolerite, which could create additional secondary porosity for groundwater movement (Viljoen et al., 2010). Viljoen et al. (2010) stated that the area where the Vryheid Formation occurs at depths of more than 800 m is situated in an arc from west of Bergville in the east towards the area just north of Bethlehem and south-westwards to Ladybrand.

3.4.3.8 Springbok Flats Basin

The northeastern sub-basin has a maximum thickness of approximately 700 m and the southwestern sub-basin has a maximum thickness of 1,000 m, with an area of approximately 200 km^2 at depths greater than 800 m (Viljoen et al., 2010). The Springbok Flats Basin is underlain by rocks of the Bushveld Igneous Complex, which could be mined in future where it is underlain by shallower parts of the basin (Viljoen et al., 2010). A large number of exploration boreholes (more than 2,000) has been drilled in the Springbok Flats Basin, but no active mining is currently taking place (Viljoen et al., 2010).

3.4.3.9 Ellisras Basin

The maximum thickness of the basin was estimated to be less than 800 m (Viljoen et al., 2010). Unfortunately, no boreholes have been drilled into the basement in the deepest part of the Ellisras Basin (Venter, 1944; Cillié, 1951; Cillié 1957; Cillié and Visser, 1945).

3.4.3.10 Tshipise and Tuli basins

The Tshipise Basin of the Karoo Supergroup consists of a number of basins that are preserved in graben and half-graben fault blocks (Viljoen et al., 2010). Most of the sub-basins are less than 300 m deep, but some are more than 2,000 m deep, mainly because of a thick cover of basaltic lava of the Letaba Formation (Van Vuuren, 1979; McCourt and Brandl, 1980; Van der Berg, 1980; Brandl, 1981a; Brandl, 1981b; Brandl and Pretorius, 2000; Brandl, 2002).

Viljoen et al. (2010) stated that deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with a maximum water temperature of 59 to 60 °C. These warm springs are associated with some of the major faults (Viljoen et al., 2010).

The Tuli Basin is a relatively small basin (1,150 km^2), which is elongated in the west-east direction and fault controlled. The basin has a maximum thickness of approximately 500 m (Viljoen et al., 2010). Intrusive dykes and faulting are locally present and contain almost flat-lying coal seams near the base of the basin that are generally less than 300 m deep (Brandl and Pretorius, 2000; Brandl, 2002).

3.5 POST-KAROO GEOLOGY

3.5.1 Mesozoic deposits

The onshore Mesozoic basins range in age from Jurassic to Cretaceous, occurring along the eastern and southern margins of South Africa, from northern KwaZulu-Natal to Worcester in the Western Cape (Shone, 2006) (Figure 3-63). The Mesozoic deposits are subdivided into two main groups: the Uitenhage Group and the Zululand Group.

There are extensive Mesozoic deposits in northern KwaZulu-Natal (Figure 3-63), which form the Zululand Group. In the south, there are scattered Mesozoic deposits from Worcester to Port Elizabeth, which form the Uitenhage Group (Figure 3-63).

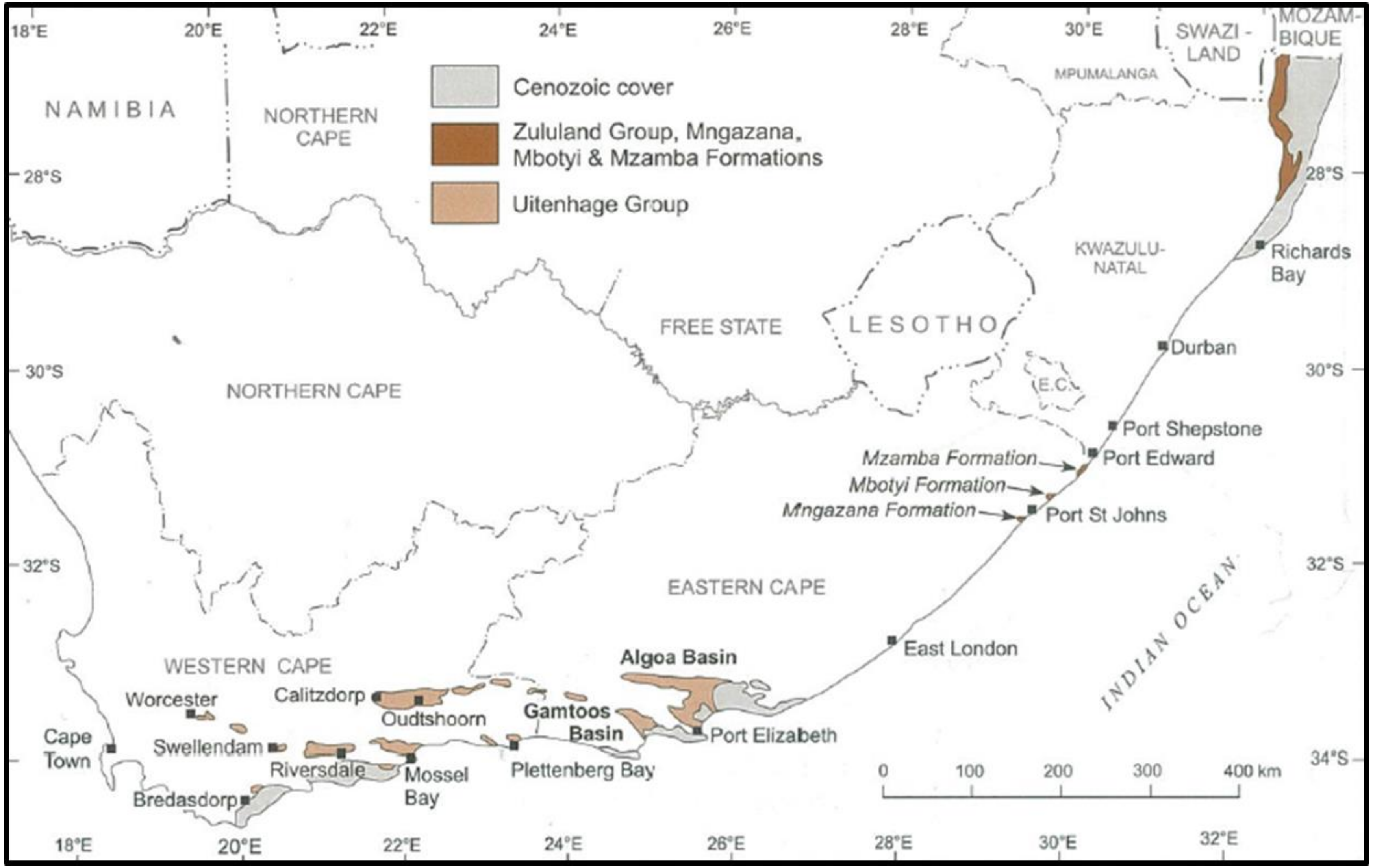


Figure 3-63: Distribution of post-Karoo Jurassic and Cretaceous strata in the coastal regions of South Africa (Shone, 2006)

The Riversdale, Mossel Bay, Oudtshoorn, Gamtoos and Algoa basins are the most important basins of the Uitenhage Group (Shone, 2006). These Mesozoic deposits are generally fault-bounded along their northern margins and isolated from each other, although some have been theorised to have been linked at the time of deposition (Shone, 2006).

Along the east coast from East London to Port Edward, there are also some small, partially fault-bounded Mesozoic deposits: the Mbotyi, Mngazana and Mzamba formations (Shone, 2006) (Figure 3-63). The Mesozoic basins of South Africa will be discussed in two main divisions: the Uitenhage Group and the Zululand Group.

3.5.1.1 Uitenhage Group

The Uitenhage Group occurs in half-graben-type basins that developed along the southern margin of South Africa from Port Elizabeth to Worcester (Shone, 2006). The most important basins are the Algoa, Gamtoos, Oudtshoorn, Mossel Bay and Riversdale basins, of which the Algoa Basin is the largest with a preserved sediment cover of over 3,500 m (Shone, 2006) (Figure 3-63).

3.5.1.1.1 Geology

The Uitenhage Group can be subdivided into three formations: the Enon, Kirkwood and Sundays River formations (Shone, 2006) (Figure 3-64). The geology of each basin in the Uitenhage Group is discussed below.

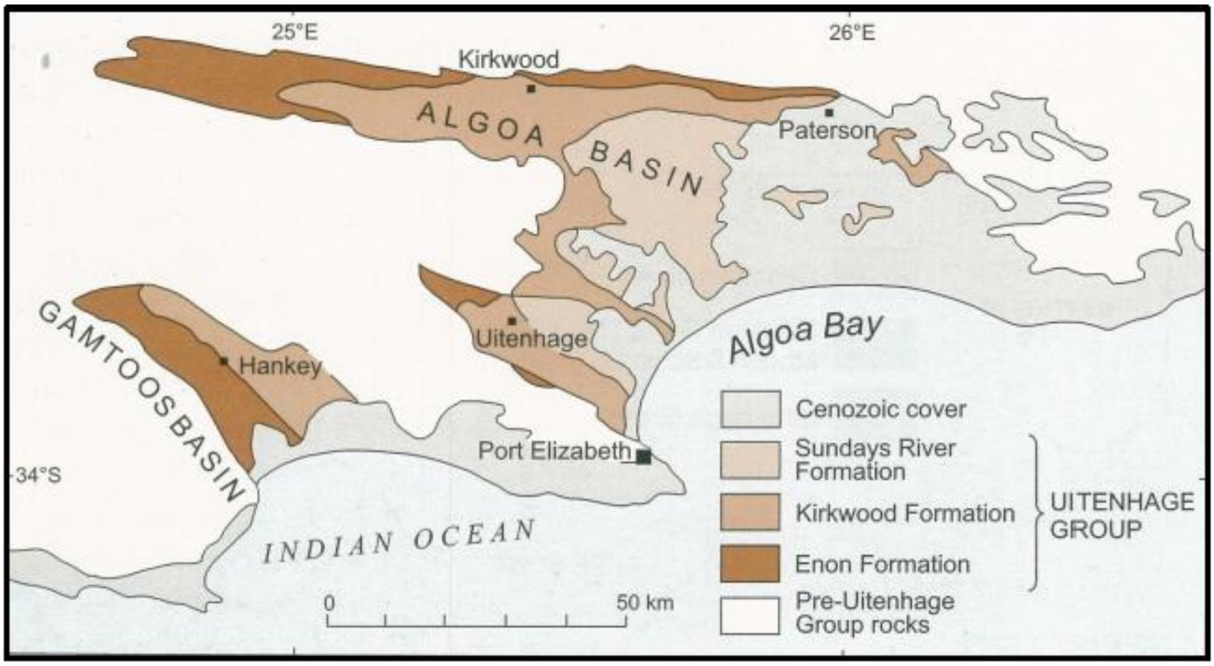


Figure 3-64: Simplified geology of the Uitenhage Group in the Algoa and Gamtoos basins (Shone, 2006)

Algoa Basin

The Algoa Basin of the Uitenhage Group is the largest of the half-graben type basins and has more than 3,500 m of sediment that is preserved in the Addo trough adjacent to the Commando Kraal Fault (Shone, 2006). The Algoa Basin is also more complex than the other half-graben basins, with full graben structures, horst blocks and diagonal faults cutting the horsts (Shone, 2006).

The Enon Formation forms the lowermost unit of the Uitenhage Group and has a thickness of 490 m east of Kirkwood (Shone, 2006) (Figure 3-64). The Enon Formation consists of poorly sorted, yellowish to red conglomerates with large sub-rounded pebbles and cobbles (Shone, 2006; Visser, 1989). Metre-thick lenses of silty sandstone of generally limited lateral extent are also found within the conglomerates (Lourens, 2013). According to Shone (2006), the Enon Formation is absent over large parts of the basin floor. It is interpreted to have been formed in alluvial piedmont fans (Lourens, 2013).

The Kirkwood Formation overlies the Enon Formation and has a thickness of approximately 2,000 m in parts of the basin (Shone, 2006). The base of the Kirkwood Formation consists of a non-fossilferous sandstone unit (the Swartkops Sandstone Member). This is followed by shales, siltstone and minor sandstone (the Colchester Shale Member), which is rich in marine fossils (CGS, 1980).

The Sundays River Formation is the upper unit of the Uitenhage Group and has a maximum thickness of approximately 1,860 m. The Sundays River Formation consists of grey clays, siltstone and sandstone (CGS, 1980). The sandstones of the Sundays River Formation are fine- to medium-grained, but less porous and permeable than the sandstones of the Kirkwood Formation (Shone, 2006).

Gamtoos and Oudtshoorn basins

The Gamtoos and Oudtshoorn basins are the largest Mesozoic deposits other than those of the Algoa Basin (Shone, 2006). However, in these basins, only the Enon and Kirkwood formations are present (Shone, 2006).

The Gamtoos Basin covers an area of approximately 650 km^2. It deepens towards the coast, where it reaches a thickness of more than 3,000 m (Viljoen et al., 2010; Lourens, 2013). The Enon Formation in the Gamtoos Basin has exposed sections greater than 150 m in thickness, but thicknesses of up to 2,000 m have been found in borehole samples (Lourens, 2013). The Kirkwood Formation does not reach the thickness observed in the Algoa Basin, and consists of thin, relatively continuous interbeds of siltstone and sandstone (Shone, 2006).

The Oudtshoorn Basin is approximately 1,800 m deep in the central parts of the basin, with the largest part of the basin being less than 800 m deep (Viljoen et al., 2010; Lourens, 2013). The Kirkwood Formation lies in the axial portion of the basin and consists of red and white siltstone and sandstone beds (Lourens, 2013). The Enon Formation commonly consists of conglomerates (Lourens, 2013; Shone, 2006).

Mossel Bay and Riversdale basins

In the Mossel Bay Basin of the Uitenhage Group, the Enon and Kirkwood formations are present, where the Kirkwood Formation contains subordinate tuff and lenticular conglomerate beds (Shone, 2006; Lourens, 2013).

The Riversdale Basin of the Uitenhage Group is approximately 462 m deep, consisting mainly of mudstones and clayed sandstones of the Kirkwood Formation, and minor conglomerates and breccias of the basal Enon Formation (Viljoen et al., 2010; Lourens, 2013).

3.5.1.1.2 Geohydrology

According to Lourens (2013), most of the geohydrological characteristics of the Uitenhage Group were obtained from studies done on the Uitenhage Artesian Aquifer in the Uitenhage Basin. The name of the aquifer can be rather misleading as it refers to the major aquifer system within the Uitenhage Basin, rather than the aquifer within the Uitenhage Group rocks (Lourens, 2013). The Uitenhage Artesian Aquifer is actually situated within rocks of the Table Mountain Group of the Cape Supergroup, which underlies the rocks of the Uitenhage Group (Maclear, 2001, as cited by Lourens, 2013) (Figure 3-65).

However, groundwater from the Table Mountain Group Aquifer recharges the basal sandstone units of the aquifers within the Kirkwood and Enon formations by lateral and vertical pressure leakage from the bounding quartzite units (Maclear, 2001).

Lourens (2013) classified the Uitenhage Group as being associated with secondary aquifer systems, because the rocks are dense and have low permeability, which creates limited groundwater potential (Meyer, 1998; Meyer, 1999). The mudstones of the Kirkwood Formation, which overlie the Enon Formation, act as an aquitard, which produces artesian and sub-artesian conditions within the Enon Formation (Maclear, 2001). Lourens (2013) also classified the Uitenhage Group as hosting a low-yielding aquifer with water of a poor quality, where yields rarely exceed 1 ℓ/s (Meyer, 1998; Meyer, 1999).

The electrical conductivity values of the Uitenhage Group are commonly in excess of 300 mS/m, but quality analysis samples taken during pumping tests showed that there was a decrease in salinity and an increase in acidity as pumping continued (Meyer, 1998; Meyer, 1999). This trend was considered to be a function of the progressive increase in groundwater contributions from the Table Mountain Group quartzites and a decrease in groundwater derived from the Uitenhage Group (Lourens, 2013).

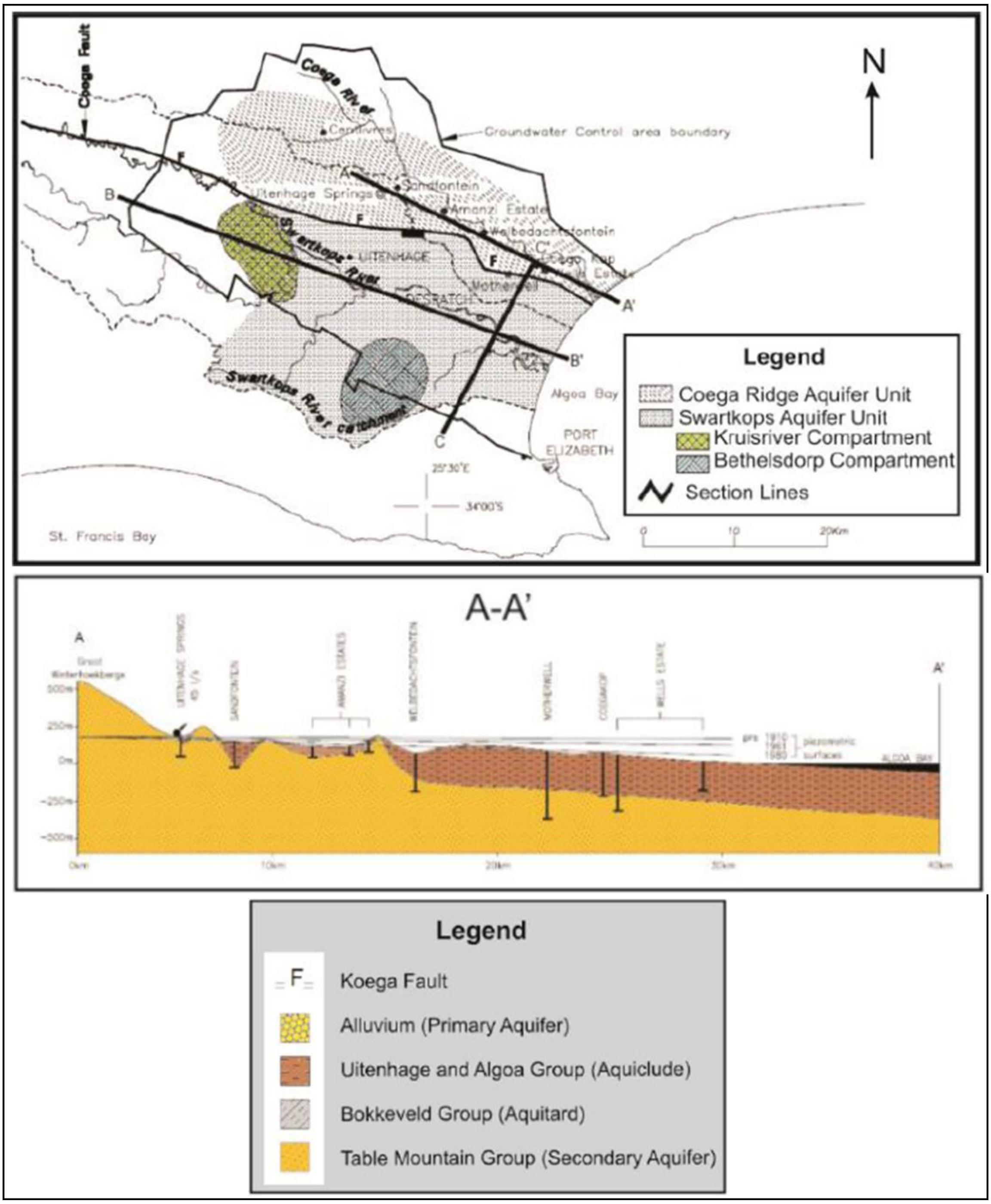


Figure 3-65: Aquifer delineation of the Uitenhage Artesian Aquifer, including cross-sections of the geology and position of boreholes (modified after Maclear, 2001, as cited by Lourens, 2013)

Algoa Basin

The Algoa Basin has a maximum depth of approximately 4,600 m, deepening in an offshore direction (Viljoen et al., 2010). Viljoen et al. (2010) found that fair to large yields of groundwater are known from sandy horizons in the Uitenhage Group, which comprise the fill of the Algoa Basin (Winter, 1973, as cited by Viljoen et al., 2010). However, the water is normally brackish and is generally unsuitable for domestic or irrigation purposes (Meyer, 1998, as cited by Viljoen et al., 2010). The generally impervious nature of the mainly muddy sediments of the Uitenhage Group usually cause these sediments to act as an aquitard (Le Roux, 2000, as cited by Viljoen et al., 2010).

Viljoen et al. (2010) reported on 22 boreholes that were drilled in the onshore Algoa Basin (Figure 3-66). Three of the boreholes were core boreholes (PA 1/68, AD 1/65 and CO 1/67), while the rest were drilled using rotary percussion. In the latter holes, coring was only done for sections of some boreholes.

There is a linear decrease in porosity with depth, varying between 10 and 30%, with the highest porosity in the basin being 30% (Viljoen et al., 2010). The best porosities occur in the upper Kirkwood Formation, and good porosities have been measured in the basin up to a depth of 2,500 m, but below this depth, the porosity becomes very low (Venter, 1971, as cited by Viljoen et al., 2010).

While the porosities appear to be good, the high clay content of the sandstone causes permeabilities to be generally low (Viljoen et al., 2010). The permeability of the rocks of the Algoa Basin also decreases linearly with depth, from 1,000 mD to less than 1 mD (Winter, 1973, as cited by Viljoen et al., 2010). Again, the best porosities are found in the upper Kirkwood Formation (Venter, 1971, as cited by Viljoen et al., 2010).

3.5.1.2 Zululand Group

The Zululand Group comprises extensive Mesozoic deposits in northern KwaZulu-Natal (Figure 3-63). The outcrop area of the Zululand Group extends in a narrow north-south trending belt from just north of Ndumo towards Mtubatuba in the south (Figure 3-67) (Lourens, 2013). Drilling confirmed that the sediments of the Zululand Group extend towards the coastal plain that underlies the younger Cenozoic sediments and that the group is bounded in the west by the volcanic rocks of the Lebombo Group (Shone, 2006; Lourens, 2013). The onshore part of the Zululand Basin covers an area of 7 500 km^2, with sediment thicknesses of up to 2,000 m, deepening north-eastwards (Viljoen et al., 2010).

3.5.1.2.1 Geology

The Zululand Group is subdivided into the Makatini, Mzinene and St Lucia formations (Figure 3-67). The basal Makatini Formation unconformably overlies the volcanic rocks of the Lebombo Group and predominantly consists of conglomerates with minor sandstone, siltstone and limestone (Shone, 2006). The pebbles of the conglomerate are volcanic and quartzitic in composition (Visser, 1989, as cited by Lourens, 2013).

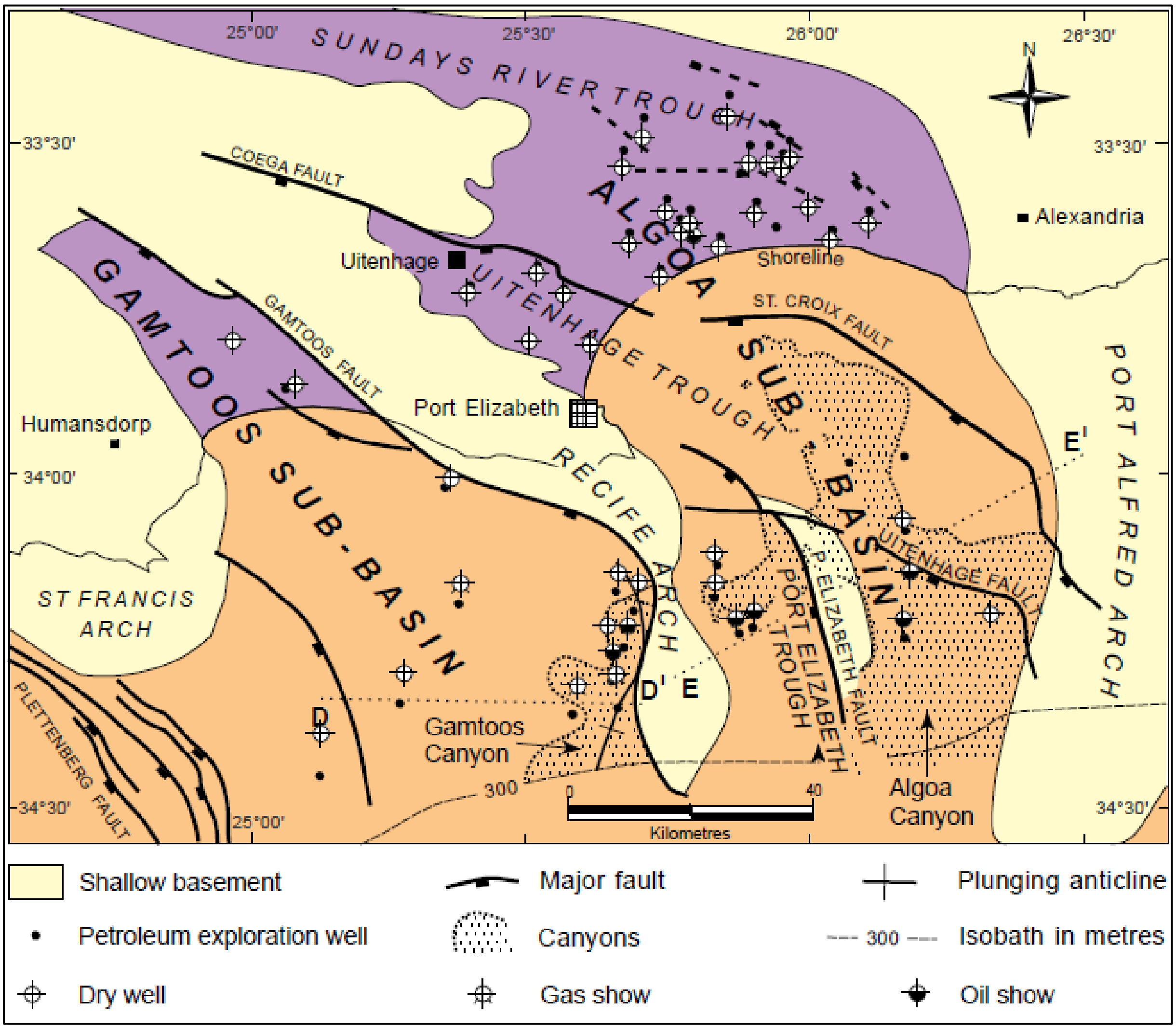


Figure 3-66: Structural map and borehole locations of the onshore and offshore Algoa Basin (after Beckering Vinckers, 2007, as cited by Viljoen et al., 2010)

The base of the Mzinene Formation consists of conglomerates, followed by glauconitic siltstone with interbedded sandstone (Shone, 2006; Lourens, 2013).

The lithology of the St. Lucia Formation is very similar to that of the Mzinene Formation, but the formations are separated by a slight angular unconformity (Shone, 2006; Lourens, 2013). The St. Lucia Formation consists of a repetitive sequence of bored concretions, shelly glauconitic sandstones and bioturbated siltstones (Figure 3-68), where thin clay lenses and thin bands of hard sandy limestone are found within the siltstones (Mkhwanazi, 2010, as cited by Lourens, 2013).

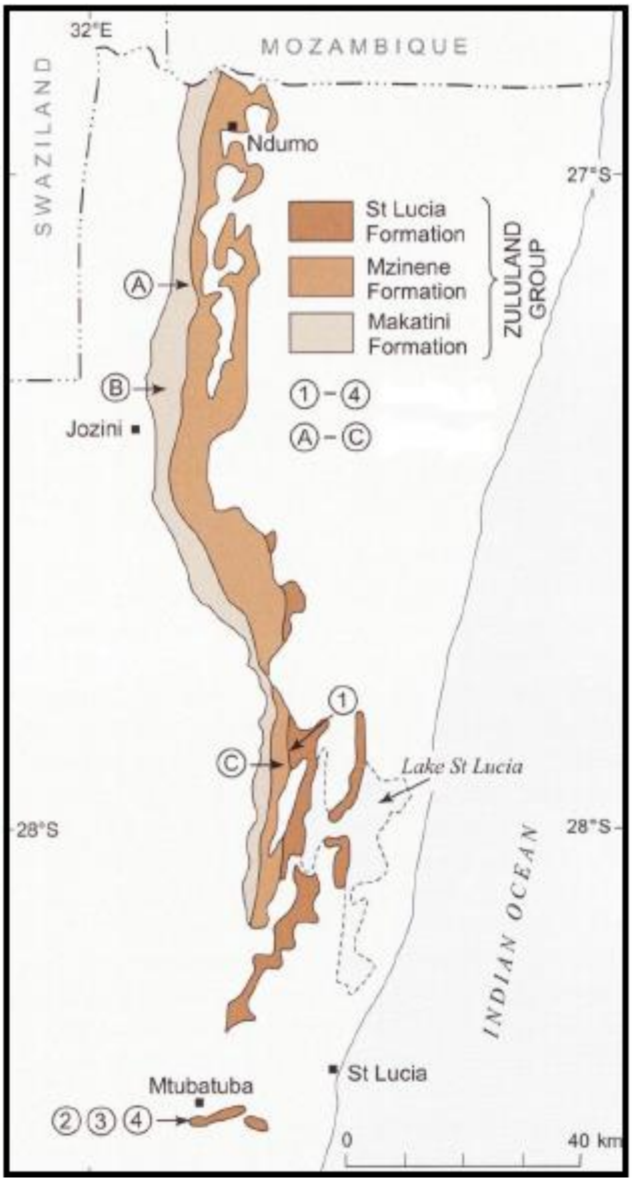


Figure 3-67: Simplified geology of the Zululand Group showing the distribution of the three formations (Shone, 2006)

3.5.1.2.2 Geohydrology

The Mzinene and St. Lucia formations are associated with extremely poor aquifers and are therefore regarded as aquicludes (King, 2003). The Makatini Formation is the only formation within the Zululand Group that is considered to host aquifers (Lourens, 2013). The Zululand Group can be considered to be associated with low-yielding aquifer systems, with measured yields generally less than 0.4 ℓ/s, while yields of up to 0.4 ℓ/s can be obtained within the conglomerate of the Makatini Formation (Lourens, 2013). The groundwater of the Zululand Group is highly saline with electrical conductivity values generally higher than 800 mS/m (King, 2003). Lourens (2013) stated that it is not advisable to target the Zululand Group for groundwater resources because of the limited groundwater potential and poor-quality groundwater.

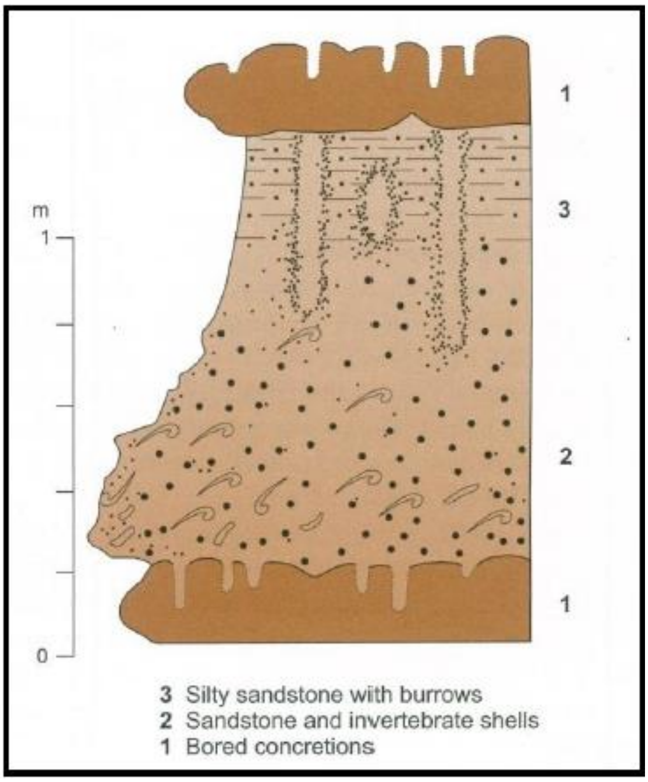


Figure 3-68: Typical sedimentary cycle of the St. Lucia formation (Shone, 2006)

Viljoen et al. (2010) reported on 10 petroleum exploration boreholes that were drilled in the onshore part of the Cretaceous Zululand Basin. No hydrocarbons were found in the basin, except for traces of bitumen and a methane show in borehole ZU 1/77 (Gerrard, 1972; Stojcic, 1979, as cited by Viljoen et al., 2010). Four potential sandstone reservoirs were identified by the drilling, with the lower and middle sandstone units occurring deeper than 800 m below ground level (Viljoen et al., 2010).

Porosity and permeability analyses were performed on cores from the boreholes. The results of the analyses indicated that the middle sandstone has very good porosities and permeabilities, but the lower sandstone unit mainly has very low permeabilities (Viljoen et al., 2010) (Table 3-15 and Table 3-16).

3.5.2 Cenzoic deposits

The Cenzoic deposits in South Africa are divided into coastal and interior deposits, where the interior deposits are grouped into the Kalahari and Bushveld basins (Figure 3-69) and the coastal deposits are grouped into the Maputaland, Algoa, Bredasdorp, Sandveld and West Coast groups (Figure 3-70). The Cenzoic deposits are discussed below in terms of the coastal and interior divisions.

Table 3-15: Core analysis data for the middle sandstone unit of the Zululand Group (from Gerrard, 1972, as cited by Viljoen et al., 2010)

Borehole		ZE 1/71	ZF 1/72	ZG 1/72
Gas expansion porosity (percent)	Range	27,2–33,7	24,8–30,8	26,2–31,0
	Average (no. of samples)	30,7 (6)	28,5 (3)	28,8 (8)
Summation of fluid porosity (percent)	Range	21,7–34,8	37,7–45,8*	30,9–41,0
	Average (no. of samples)	31,8 (6)	42,2* (3)	35,1 (7)
Horizontal permeability to air (mD)	Range	4,6–47,8	0,4–495,0	19,0–175,0
	Average (no. of samples)	20,2 (6)	229 (3)	115 (8)

*Values too high owing to operator error

Table 3-16: Core analysis data for the lower sandstone unit of the Zululand Group (from Gerrard, 1972, as cited by Viljoen et al., 2010)

Borehole		ZE 1/71	ZF 1/72
Gas expansion porosity (percent)	Range	0,86–10,8	1,25–19,6
	Average (no. of samples)	7,0 (6)	14,2 (7)
Summation of fluid porosity (percent)	Range	15,25–39,6	4,65–22,8
	Average (no. of samples)	27,5 (6)	17,1 (7)
Horizontal permeability to air (mD)	Range	0*	0,2–0,3
	Average (no. of samples)	0 (6)	0,3 (7)

*Analyst regarded everything below 1 mD as having no permeability, thus values could range up to 0,9 mD.

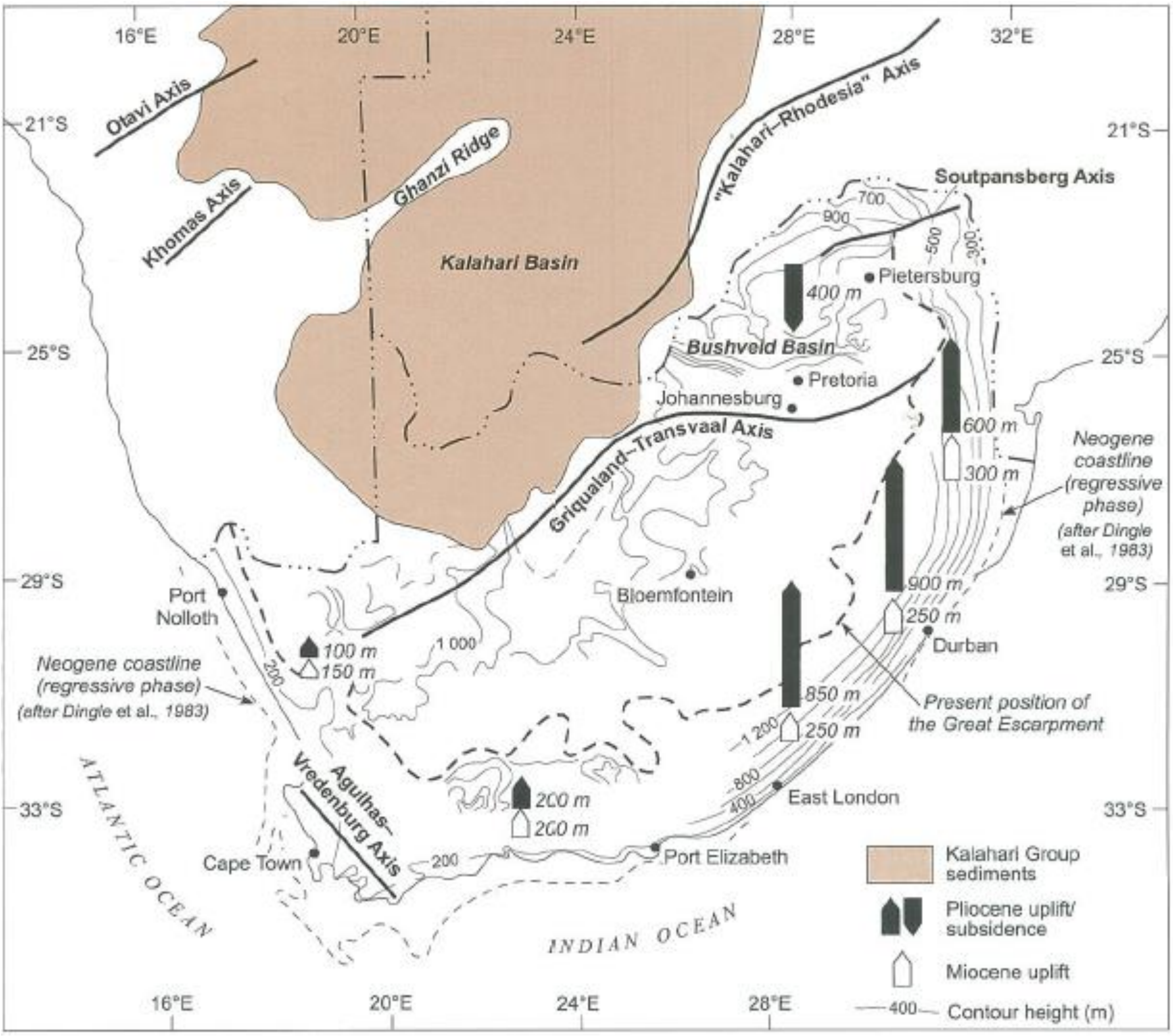


Figure 3-69: The location of the Kalahari and Bushveld basins and generalised contours on the Post-African erosion surface (Partridge et al., 2006)

3.5.2.1 Kalahari and Bushveld groups (interior Cenzoic deposits)

During the Cenzoic, the interior of southern Africa was dominated by two major basins: the Kalahari and the Bushveld basins (Partridge et al., 2006). The Kalahari Group constitutes the most extensive body of terrestrial sediments of the Cenzoic age in southern Africa (Partridge et al., 2006) (Figure 3-69). The Kalahari Group is situated in the centre of southern Africa, while in South Africa, the Kalahari Group is situated in the Northern Cape adjacent to the Botswana and Namibia borders (Lourens, 2013) (Figure 3-69 and Figure 3-71). Figure 3-71 indicates the total thickness of the Kalahari Group within South Africa. The Kalahari Group forms a tectonic and a morphological basin, filled with several metres of unconsolidated sandy deposits of Cenozoic age (De Vries et al., 2000, as cited by Lourens, 2013).

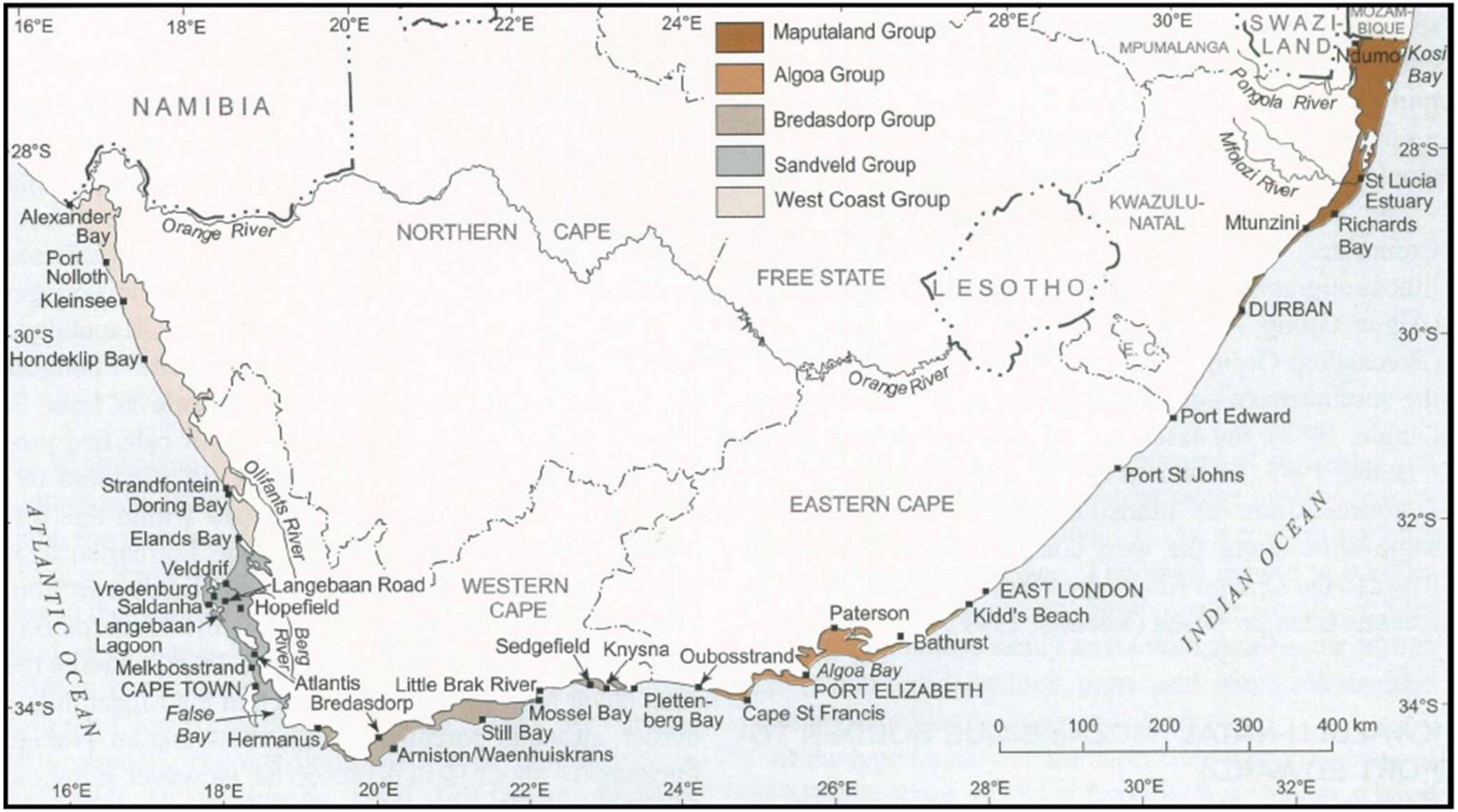


Figure 3-70: Distribution of coastal Cenozoic deposits in South Africa (Roberts et al., 2006)

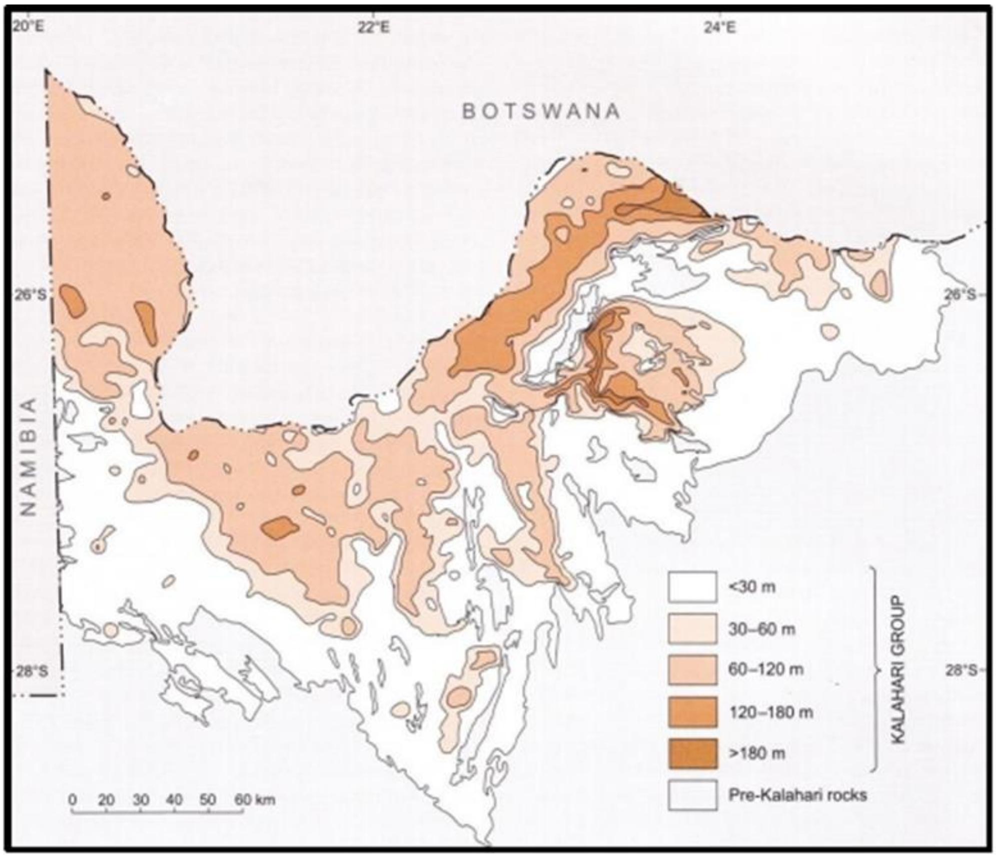


Figure 3-71: Isopach map showing the thickness and distribution of the Kalahari Group sediments in South Africa (Partridge et al., 2006)

3.5.2.1.1 Geology

The Kalahari Group is divided into six formations: the Gordinia, Obobogorop, Mokalanen, Eden, Budin and Wessels formations (Figure 3-72). The Wessels Formation forms the base of the Kalahari Group and consists of clayey, poorly sorted gravel (CGS, 1980). The Budin Formation consists of red and brown calcareous clays, interbedded with gravel. It is widely distributed within the deeper pre-Kalahari channels (Partridge et al., 2006; Visser, 1989).

The Eden Formation consists mainly of poorly consolidated sandstones, with thin pebble beds occurring locally (Partridge et al., 2006). The Mokalanen Formation consists of calcretes that can be divided into a sandy limestone and overlying conglomerates with a calcareous matrix (Partridge et al., 2006). The Obobogorop Formation consists of pebble and boulder clasts that eroded away from the Dwyka tillite (Partridge et al., 2006). The Gordinia Formation consists of sands with rounded quartz grains coloured by a thin coating of haematite. It is up to 30 m thick (Partridge et al., 2006; Lourens, 2013).

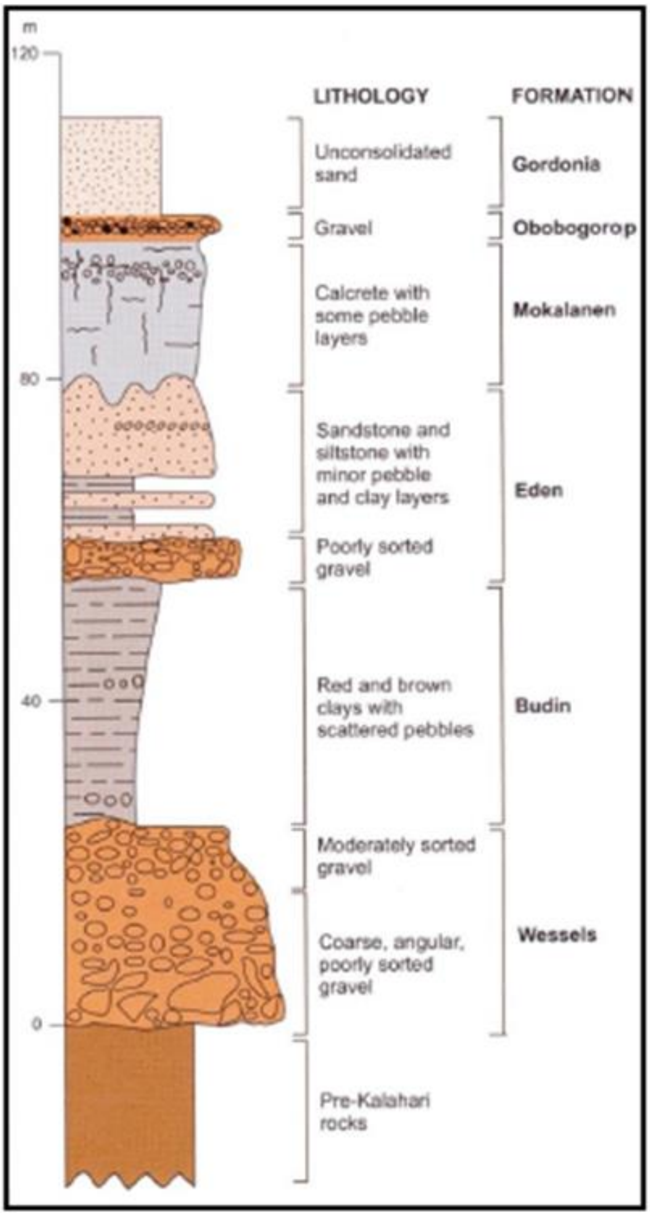


Figure 3-72: Generalised section of the Kalahari Group (Partridge et al., 2006)

The Bushveld Basin and adjoining areas contain fluvial deposits that are overlain by superficial grey clays and sands (Partridge et al., 2006). These sediments differ significantly from the units that comprise the Kalahari Group. These fluvial deposits of the Bushveld Basin form the Rooibokkraal Formation (Partridge et al., 2006).

3.5.2.1.2 Geohydrology

Lourens (2013) considered the Kalahari Group to host a primary aquifer system because the group consists mainly of unconsolidated materials. The Kalahari Group basically forms a closed basin with an internal groundwater drainage system, where the underlying rocks of the Karoo Supergroup play an important role in locating groundwater in the Kalahari Group (Lourens, 2013). Lourens (2013) found that the storage of the clayey gravels of the Kalahari Group is an order of magnitude higher than that of the aquifers of the underlying secondary Karoo Supergroup, but the clay content reduces its permeability.

Groundwater is generally intersected within the lowest formations of the Kalahari Group: the Wessels, Budin and Eden formations (Van Wyk, 1987; Van Wyk, 2011, as cited by Lourens, 2013).

Van Wyk (1987) considered the Wessels Formation to exhibit good aquifer potential, but it is restricted to thin deposits in palaeo-drainage channels. In addition, the groundwater is usually saline due to its direct contact with the saline Karoo interface, which is often associated with a high clay content (Van Wyk, 1987). The Budin Formation has a low permeability due to the high clay content, while clay and gravel layers occasionally serve as aquifers (Van Wyk, 1987). The Eden Formation is considered to have good aquifer potential, but in some places the formation is situated above the regional groundwater level (Van Wyk, 1987).

The Kalahari Group can be considered a low- to moderate-yielding aquifer system, with yields that vary between 0.2 and 1 ℓ/s (Van Wyk, 1987; Dziembowski and Appelcryn, 1987, as cited by Lourens, 2013). However, higher yields have been measured and a trend was identified that indicated that yield tends to increase with depth. Similar increases in salinity with depth are, however, also observed (Van Wyk, 1987).

Lourens (2013) found that the groundwater quality distribution of the Kalahari aquifer system is complex. Groundwater quality varies both vertically and horizontally (Van Wyk, 1987; Van Wyk, 2011, as cited by Lourens, 2013). Electrical conductivity values have been found to vary from 60 to 30,000 mS/m, and can increase two or more fold within a metre laterally or in depth (Lourens, 2013).

Viljoen et al. (2010) found that the Kalahari Basin is the only extensive onshore Cenzoic basin, and is too shallow for CO_2 storage, having a maximum depth of 450 m. This basin is a potential deep groundwater aquifer, but only to a depth of 450 m. Lourens (2013) reported that the groundwater levels of the Kalahari aquifer system generally vary between 40 and 50 m below ground level, but that there are areas where water levels vary between 120 and 180 m below ground level. Water levels as deep as 250 m below ground level have also been reported (Van Wyk, 2011).

The Bushveld Group has a smaller areal extent to the Kalahari Group. Unfortunately, information on the geohydrology of this group is not readily available.

3.5.2.2 Coastal Cenzoic deposits

Cenzoic deposits of marine, estuarine, fluvial, lacustrine and Aeolian origin are extensively developed along the coastal plains of southern Africa (Roberts et al., 2006) (Figure 3-70).

3.5.2.2.1 Geology

The Coastal Cenozoic deposits are subdivided into five groups: the Maputaland, Algoa, Bredasdorp, Sandveld and West Coast groups (Figure 3-70).

Maputaland Group

The Maputaland Group extends from the border of Mozambique southwards to the Durban area, and is subdivided into seven formations: the Sibayi, KwaMbonambi, Isipingo, Kosi Bay, Port Durnford, Umkwelane and Uloa formations (Figure 3-73). The Uloa Formation consists of a thin basal conglomerate that is overlain by a 2 to 3 m thick coquina succession, and has an average thickness of 10 m and a maximum thickness of 35 m (Roberts et al., 2006; Wright et al., 2000, as cited by Lourens, 2013). The Port Durnford Formation consists of mudrock, calcarenites and sandstone with a distinctive lignite horizon, with a total thickness of about 20 m (King, 2003). The Kosi Bay Formation consists of unconsolidated aeolian sands, with localised calcarenites (King, 2003). The Isipingo Formation consists of basal aeolianite that contains oyster beds within karst potholes in certain localities, and calcified beach and dune deposits (Roberts et al., 2006). The KwaMbonambi Formation consists of yellowish red, grey and white dune sand that is reworked material of the Kosi Bay Formation. It has a thickness of up to 10 m (Roberts et al., 2006; King, 2003). The Sibayi Formation consists of stacked calcareous and siliceous sand units. It has a maximum thickness of 182 m along the coastal barrier dune in Maputaland (Roberts et al., 2006; King, 2003).

Algoa Group

The Algoa Group extends from Oubosstrand eastwards to East London (Figure 3-70), and unconformably overlies the Cape Supergroup, Karoo sediments, or Uitenhage Group (Le Roux, 1990, as cited by Lourens, 2013). The Algoa Group can be divided into six formations: the Schelm Hoek, Nahoon, Salnova, Nanaga, Alexandria and Bathurst formations (Figure 3-74).

The Bathurst Formation consists of a soft marine limestone that is overlain by a pebbly coquina. It is generally less than 10 m thick (Roberts et al., 2006; Maud and Partridge, 1990, as cited by Lourens, 2013). The Alexandria Formation consists of a basal conglomerate or bed of oyster shales, overlain by interbedded calcareous sandstone, pebbly coquina and thin conglomerates with a sandy upper part, with a maximum thickness of 18 m (Roberts et al., 2006).

The Nanaga Formation consists of coastal palaeo dunefields, with sandstones and calcretes up to 250 m thick (Roberts et al., 2006).

The Salnova Formation consists of calcareous sand, sandstone, conglomerate and coquina, and varies in thickness from 1.6 to 6.5 m (Roberts et al., 2006). The Nahoon Formation consists of calcareous sandstone with interbedded palaeosols and occasionally very thin calcrete layers. It has an average thickness of 15 m, although its thickness may vary from 6 to 60 m (Le Roux, 1990).

The Schelm Hoek Formation consists of unconsolidated windblown calcareous sand, which occurs in coastal dunefields (Illenberger, 1992, as cited by Lourens, 2013).

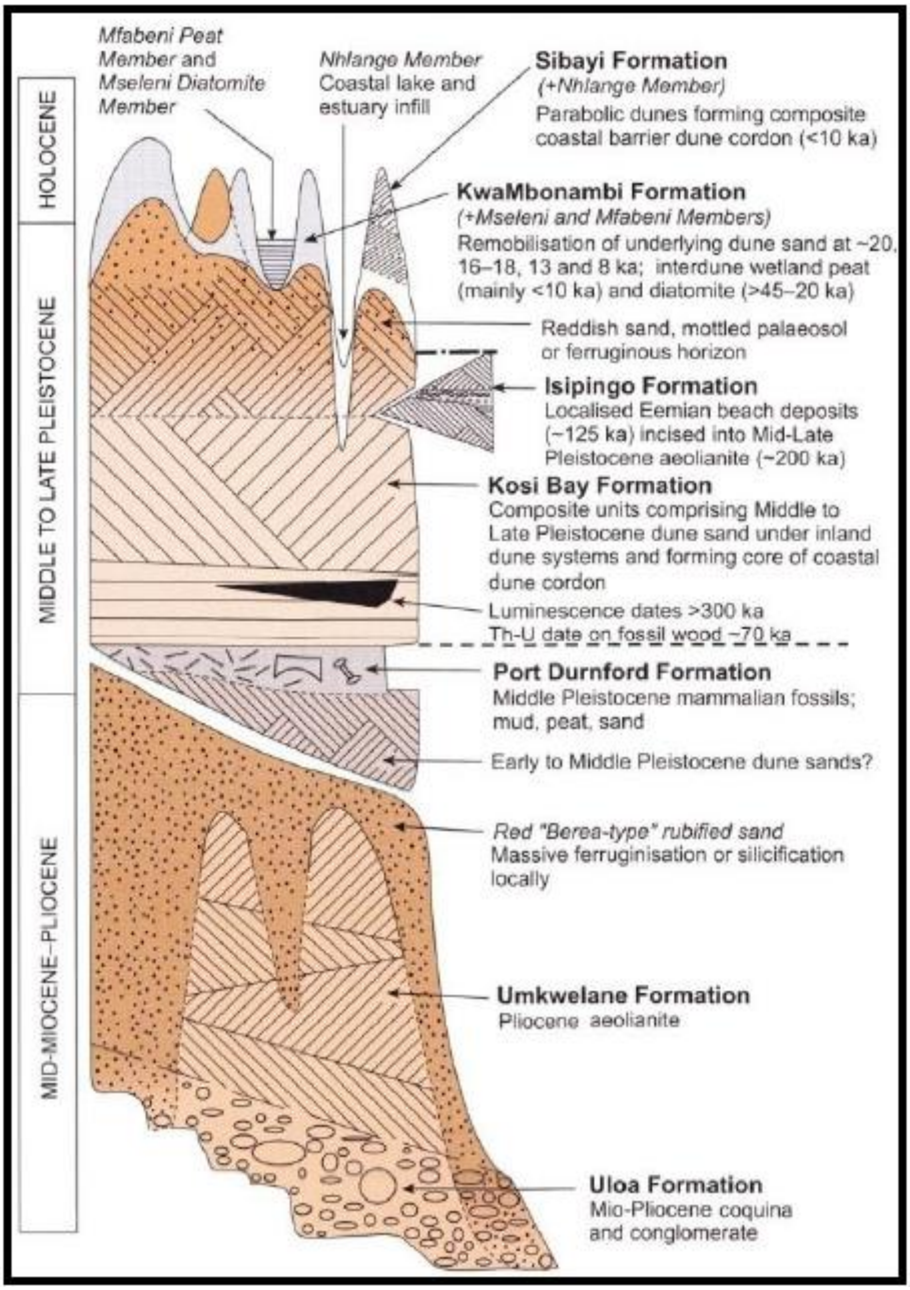


Figure 3-73: Idealised composite section of the Maputaland Group (Roberts et al., 2006)

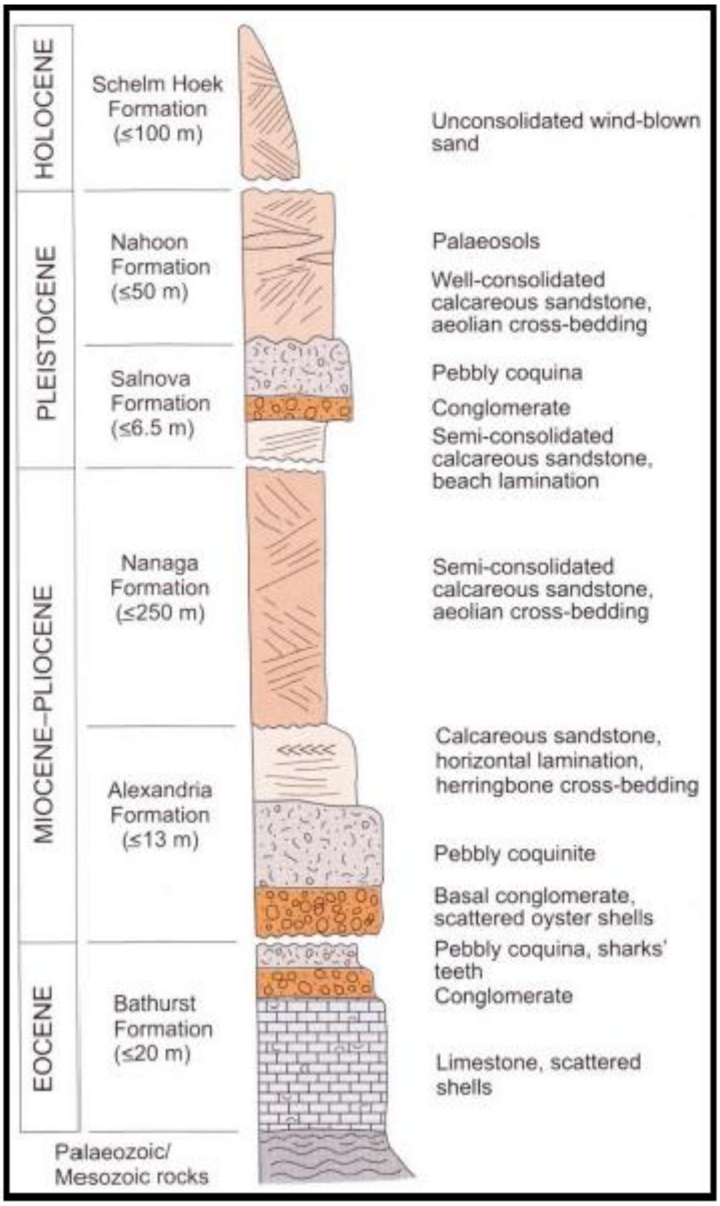


Figure 3-74: Generalised composite section of the Algoa Group (Roberts et al., 2006)

Bredasdorp Group

The Bredasdorp Group is a series of coastal limestones, calcarenites, calcirudites, conglomerates, conquinites and calcareous sandstones (Malan, 1989, as cited by Roberts et al., 2006). The Bredasdorp Group is divided into five formations: the Strandveld, Waenhuiskrans, Klein Brak, Wankoe and De Hoopvlei formations (Figure 3-75).

The Wankoe Formation forms the bulk of the Bredasdorp Group and consists of prominent ridges of calcified dune sand outcrops (Malan, 1989). The Klein Brak and Waenhuiskrans formations occupy a narrow strip along the present coastline, where the Strandveld Formation is represented by recent dunes adjoining the present coast (Malan, 1989).

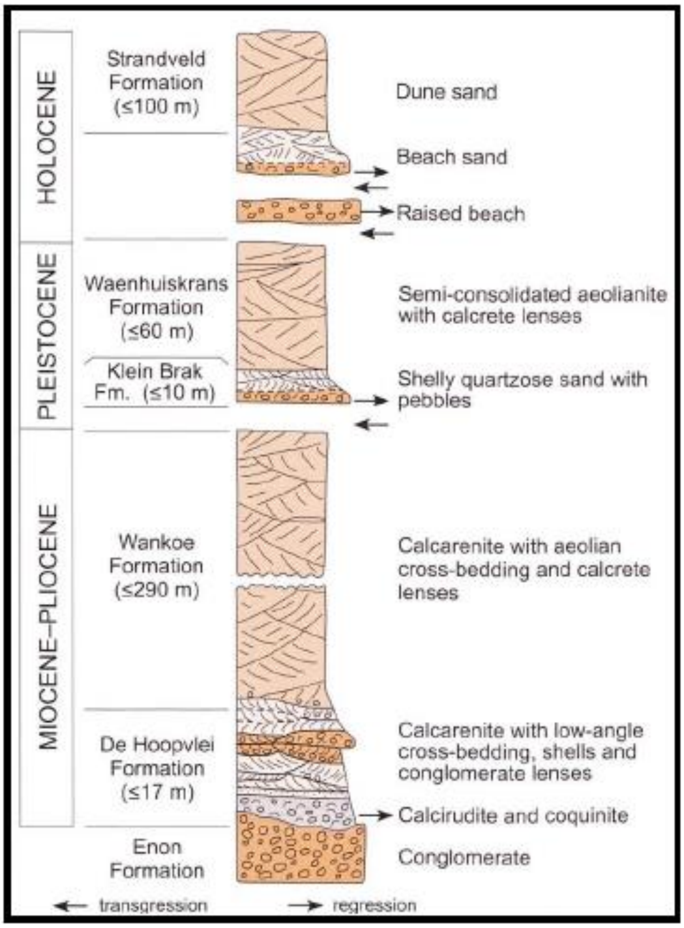


Figure 3-75: Generalised composite section of the Bredasdorp Group (Roberts et al., 2006)

Sandveld Group

The Sandveld Group can be divided into seven formations: the Witzand, Springfontyn, Velddrif, Langebaan, Varswater, Prospect Hill and Elandsfontyn formations (Figure 3-76). The Sandveld Group consists of quartzose sands, gravel, clay, lignite, calcareous aeolianites, bioclastic-silicilastic aeolianites and coquina (Roberts et al., 2006; Lourens, 2013). The Sandveld Group can typically be correlated with the Bredasdorp Group (Roberts et al., 2006; Lourens, 2013).

West Coast Group

The West Coast Group (Namaqualand Coast) extends from Elands Bay in the south to the mouth of the Orange River at Alexander Bay. The group is divided into Neogene and Early post-Gondwana deposits, where the Neogene deposits consist of aeolian deposits, the Curlew Strand and Alexander Bay formations (Roberts et al., 2006; Lourens, 2013).

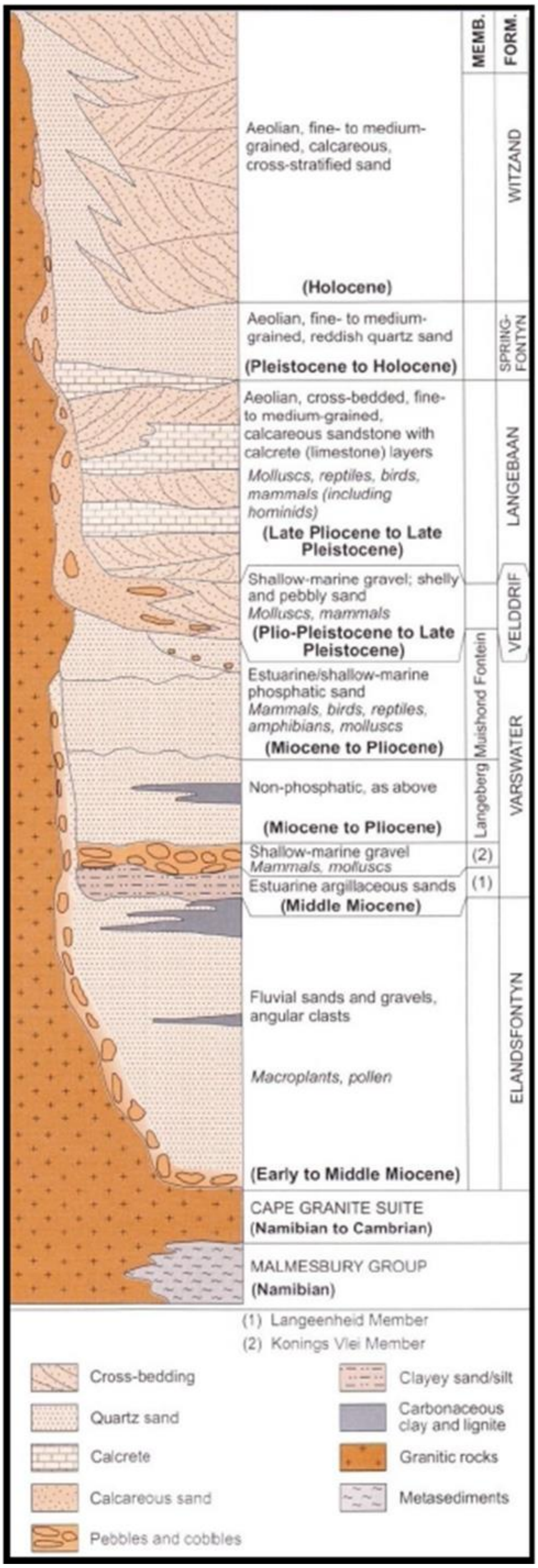


Figure 3-76: Generalised composite section of the Sandveld Group, showing the lateral interrelationships of units (Roberts et al., 2006)

The deposits of the Alexander Bay and Curlew Strand formations are made up of quartzose sands, rich in heavy minerals and feldspathic in parts (Roberts et al., 2006; Lourens, 2013). The Alexander Bay Formation consists of three marine units: the Hondeklip Bay Member (30 m package), the Avontuur Member (50 m package) and the Kleinsee Member (90 m package) (Roberts et al., 2006; Lourens, 2013).

Each of the members of the Alexander Bay Formation consists of basal gravels that contain diamonds, followed by shoreface sand deposits (Roberts et al., 2006; Lourens, 2013). The deposits of the Alexander Bay Formation are followed by the deposits of the Curlew Strand Formation, which are made up of sandy to gravelly deposits, similar to those found at the coast today (Roberts et al., 2006; Lourens, 2013).

The early post-Gondwana deposits of the West Coast Group are fluvial palaeo-channel deposits that are kaolinised in places, consisting of conglomerates, overlain by partly silicified marine sand, clayey sand, clay and carbonaceous material which contains plant fossils, topped by calcareous and ferruginous pedocretes (Roberts et al., 2006; Lourens, 2013).

3.5.2.2.2 Geohydrology

Lourens (2013) classified the Coastal Cenzoic deposits as primary aquifer systems, where groundwater moves through the original interstices of the geological formation. Viljoen et al. (2010) concluded that all the deposits of this age, including the West Coast, Sandveld, Bredasdorp, Algoa and Maputaland groups, are too thin and sporadically developed for CO_2 storage (Partridge et al., 2006; Roberts et al., 2006). Lourens (2013) found that these aquifers have moderate to high aquifer potentials, but these deposits are fairly thin, and are not assumed to play an important role in the consideration of deep aquifer systems.

3.5.3 Summary of the Post-Karoo geology

The important information on the post-Karoo geology and geohydrology is summarised below for each geological group.

3.5.3.1 Mesozoic deposits

3.5.3.1.1. Uitenhage Group

The most important basins of the Uitenhage Group are the Algoa, Gamtoos, Oudtshoorn, Mossel Bay and Riversdale basins. Of these basins, the Algoa Basin is the largest with a preserved sediment cover of over 3,500 m (Shone, 2006).

Lourens (2013) classified the Uitenhage Group as hosting secondary aquifer systems because the rocks are dense and have low permeability, which creates limited groundwater potential (Meyer, 1998; Meyer, 1999). The mudstones of the Kirkwood Formation, which overlie the Enon Formation, act as an aquitard, which produces artesian and sub-artesian conditions within the Enon Formation (Maclear, 2001). Lourens (2013) also classified the Uitenhage Group as being associated with low-yielding aquifers with water of a poor quality, where yields rarely exceed 1 ℓ/s (Meyer, 1998; Meyer, 1999).

The Uitenhage Artesian Aquifer is actually situated within rocks of the Table Mountain Group of the Cape Supergroup, which underlie the Uitenhage Group rocks (Maclear, 2001). However, groundwater from the Table Mountain Group aquifer recharges the basal sandstone units of the aquifers within the Kirkwood and Enon formations by lateral and vertical pressure leakage from the bounding quartzite units (Maclear, 2001).

Algoa Basin

The Algoa Basin of the Uitenhage Group is the largest of the half-graben-type basins and has more than 3,500 m of sediment that is preserved in the Addo trough adjacent to the Commando Kraal Fault (Shone, 2006). Viljoen et al. (2010) found that fair to large yields of groundwater are known from sandy horizons in the Uitenhage Group, which comprise the fill of the Algoa Basin (Winter, 1973, as cited by Viljoen et al., 2010).

However, the water is normally brackish and is generally unsuitable for domestic or irrigation purposes (Meyer, 1998, as cited by Viljoen et al., 2010). The generally impervious nature of the mainly muddy sediments of the Uitenhage Group usually cause these sediments to act as an aquitard (Le Roux, 2000).

Viljoen et al. (2010) reported on 22 boreholes drilled in the onshore Algoa Basin. Three core boreholes (PA 1/68, AD 1/65 and CO 1/67) were drilled, while the remaining boreholes were drilled with rotary percussion. In the latter holes, coring was only done for sections of some boreholes. The rocks of the Algoa Basin display a linear decrease in porosity with depth, varying between 10 and 30%, with the highest porosity in the basin being 30% (Viljoen et al., 2010). The highest porosities occur in the upper Kirkwood Formation. High porosities have been measured in the basin up to a depth of 2,500 m, but the porosity becomes very low below this depth (Venter, 1971).

Gamtoos and Oudtshoorn basins

The Gamtoos and Oudtshoorn basins are the largest Mesozoic deposits besides those of the Algoa Basin (Shone, 2006). The Gamtoos Basin covers an area of approximately 650 km^2 and deepens towards the coast, where it reaches a thickness of more than 3,000 m (Viljoen et al., 2010; Lourens, 2013). The Oudtshoorn Basin is about 1,800 m deep in the central parts of the basin, with the largest part of the basin being less than 800 m deep (Viljoen et al., 2010; Lourens, 2013).

Mossel Bay and Riversdale basins

The Riversdale Basin of the Uitenhage Group is approximately 462 m deep. It consists mainly of mudstones and clayed sandstones of the Kirkwood Formation, and minor conglomerates and breccias of the basal Enon Formation (Viljoen et al., 2010; Lourens, 2013).

3.5.3.1.2 Zululand Group

The Zululand Group consists of conglomerates with minor sandstone, siltstone and limestone (Shone, 2006). The Mzinene and St. Lucia formations host extremely poor aquifers and are therefore regarded as aquicludes (King, 2003). The Makatini Formation is the only formation within the Zululand Group that is considered to be associated with aquifers (Lourens, 2013).

Viljoen et al. (2010) reported on 10 petroleum exploration boreholes that were drilled in the onshore part of the Cretaceous Zululand Basin. No hydrocarbons were found in the basin, except for traces of bitumen and a methane show in borehole ZU 1/77 (Gerrard, 1972; Stojcic, 1979). The drilling identified four potential sandstone reservoirs, with the lower and middle sandstone units occurring at depths greater than 800 m below ground level (Viljoen et al., 2010).

Porosity and permeability analyses were performed on cores from the boreholes. The results of the analyses indicated that the middle sandstone has very good porosities and permeabilities, but the lower sandstone unit mainly has very low permeabilities (Viljoen et al., 2010).

3.5.3.2 Cenzoic deposits

3.5.3.2.1 Kalahari and Bushveld groups (interior Cenzoic deposits)

The Kalahari Group constitutes the most extensive body of terrestrial sediments of Cenzoic age in southern Africa (Partridge et al., 2006). Lourens (2013) considered the Kalahari Group to be a primary aquifer system because it consists mainly of unconsolidated materials. The Kalahari Group basically forms a closed basin with an internal groundwater drainage system, where the underlying rocks of the Karoo Supergroup play an important role in locating groundwater in the Kalahari Group (Lourens, 2013). Lourens (2013) found that the storage of the clayey gravels of the Kalahari Group is an order of magnitude higher than that of the aquifers of the underlying secondary Karoo Supergroup, but the clay content reduces the permeability of these gravels.

The Kalahari Group can be considered a low- to moderate-yielding aquifer system, with yields that vary between 0.2 and 1 ℓ/s (Van Wyk, 1987; Dziembowski and Appelcryn, 1987). However, higher yields have been measured and a trend was identified that indicated that both borehole yield and groundwater salinity tend to increase with depth (Van Wyk, 1987).

Viljoen et al. (2010) found that the Kalahari Basin is the only extensive onshore Cenzoic basin, and is too shallow for CO_2 storage, with its maximum depth of 450 m. The basin may be considered a potential deep groundwater aquifer, but only to a depth of 450 m. Lourens (2013) reported that the groundwater levels of the Kalahari aquifer system generally vary between 40 and 50 m below ground level, but that there are areas where water levels vary between 120 and 180 m below ground level. Water levels deeper than 250 m below ground level have also been reported (Van Wyk, 2011).

3.5.3.2.2 Coastal Cenzoic deposits

Cenzoic deposits of marine, estuarine, fluvial, lacustrine and Aeolian origin are extensively developed along the coastal plains of southern Africa (Roberts et al., 2006). Lourens (2013) classified the coastal Cenzoic deposits as primary aquifer systems, where groundwater moves through the original interstices of the geological formation. Viljoen et al. (2010) concluded that all the deposits of this age, including the West Coast, Sandveld, Bredasdorp, Algoa and Maputaland groups, are too thin and sporadically developed for CO_2 storage (Partridge et al., 2006; Roberts et al., 2006). Lourens (2013) found that these aquifers have moderate to high aquifer potentials, but all these deposits are fairly thin, and are not assumed to play an important role in the consideration of deep aquifer systems.

3.6 THERMAL SPRINGS OF SOUTH AFRICA

Not much research has been done on the thermal springs of South Africa. Most of the research on these springs was done in the 1950s (Olivier et al., 2008). Geothermal springs around the world have been studied primarily for the use of their geothermal energy, with New Zealand being the first country to develop a geothermal power plant. According to Olivier et al. (2008), South Africa has an abundance of thermal springs, the majority being in Limpopo.

Thermal springs are known to originate in areas with recent volcanic activity or from meteoric water flow through fractures in the bedrock (LaMoreaux and Tanner, 2001). LaMoreaux and Tanner (2001) state that the flow rate of a thermal spring is determined by the size of the aquifer, the extent of recharge, the aquifer storage capacity, and the transmissivity and discharge capacity of both the aquifer and conduit through which the water rises to the surface.

South Africa is not situated in an area that has experienced any recent volcanic activity. Instead, the country’s thermal springs are linked to geological structures such as faults and folds (Kent, 1949). Kent (1949) identified 74 thermal springs and nine thermal artesian wells in South Africa. Kent (1949) further devised a classification scheme for thermal springs based on the recorded water temperatures:

- Warm springs (25 to 37 °C)
- Hyperthermic (hot) spring (38 to 50 °C)
- Scalding spring (>50 °C)

Bond (1946) classified thermal springs based on the recorded groundwater chemistries (Table 3-17).

Table 3-17: Classification of thermal water (Bond, 1946)

Class	Water	Chemical Composition
A	Highly mineralised chloride-sulphate water	TDS>1000mg/l; Cl > 270 g/kg; SO_4 > 50 g/kg
B	Slightly saline chloride water	TDS 300-500mg/l; Cl > 270 g/kg; SO_4 < 3 g/kg
C	Temporary hard carbonate water	TDS<800mg/l; pH >7.6
D	Alkaline sodium carbonate water	TDS<1000 mg/l; Na_2CO_3 or $NaHCO_3$>150 mg/l
E	Pure water	TDS <150 mg/l; pH<7.1

3.6.1 Thermal springs of KwaZulu-Natal

Thermal springs provide insight into the water quality of deep aquifer systems, as well as the depths at which these aquifers occur. Demlie and Watkeys (2011) studied five thermal springs located in KwaZulu-Natal. Table 3-18 gives some basic information on these springs, as found by Demlie and Watkeys (2011).

Table 3-18: Thermal springs in KwaZulu-Natal (Demlie and Watkeys, 2011)

Spring Name	Location	Temperature (°C)	Altitude (mamsl)
Black Mfolozi	Ulundi	37	560
Lilani	Greytown	40	622
Natal Spa	Paulpietersburg	41	940
Shushu	Kranskop	51	217
Warmbad	Paulpietersburg	31	878

As shown in Table 3-18, the temperatures of the springs vary from 31 to 51 °C. Although thermal springs usually occur in volcanically active areas, the thermal springs of South Africa are unique in that they occur in a tectonically stable region (Demlie and Watkeys, 2011). Figure 3-77, adapted from Demlie and Watkeys (2011), shows the locations of the thermal springs in KwaZulu-Natal.

Demlie and Watkeys (2011) found that the thermal springs in KwaZulu-Natal are associated with various geological structures. Geologically, thermal springs occur in an area that is underlain by pre-Karoo igneous and metamorphic rocks and Karoo sedimentary rocks. The geological settings of each of the thermal springs, as found from the geological maps of the areas in which the springs occur, are summarised below:

- **Lilani:** The geology comprises gneiss, schist and granulite bedrock. It is situated adjacent to a southwest to northeast-trending fault (Figure 3-78).
- **Shu-Shu:** The geology comprises diorite, granite, schist and amphibolite. It is situated on a southwest to northeast-trending thrust fault (Figure 3-79).
- **Black Mfolozi:** The geology comprises tillite bedrock of the Dwyka Group (Figure 3-80).
- **Natal Spa:** The geology comprises granite bedrock (Figure 3-81).
- **Warmbad:** The geology comprises tillite basalt and rhyolite bedrock. These rocks were intruded by dolerite that originated in the Jurassic age (Figure 3-82).

From a geological perspective, all five springs are situated within the Natal Structural and Metamorphic Complex. The area is associated with numerous folds and faults that are considered to be planes of weakness within the stratigraphic sequence, hence, they are preferential flow paths for fluids. These fractures are known to originate at great depths beneath the earth's surface.

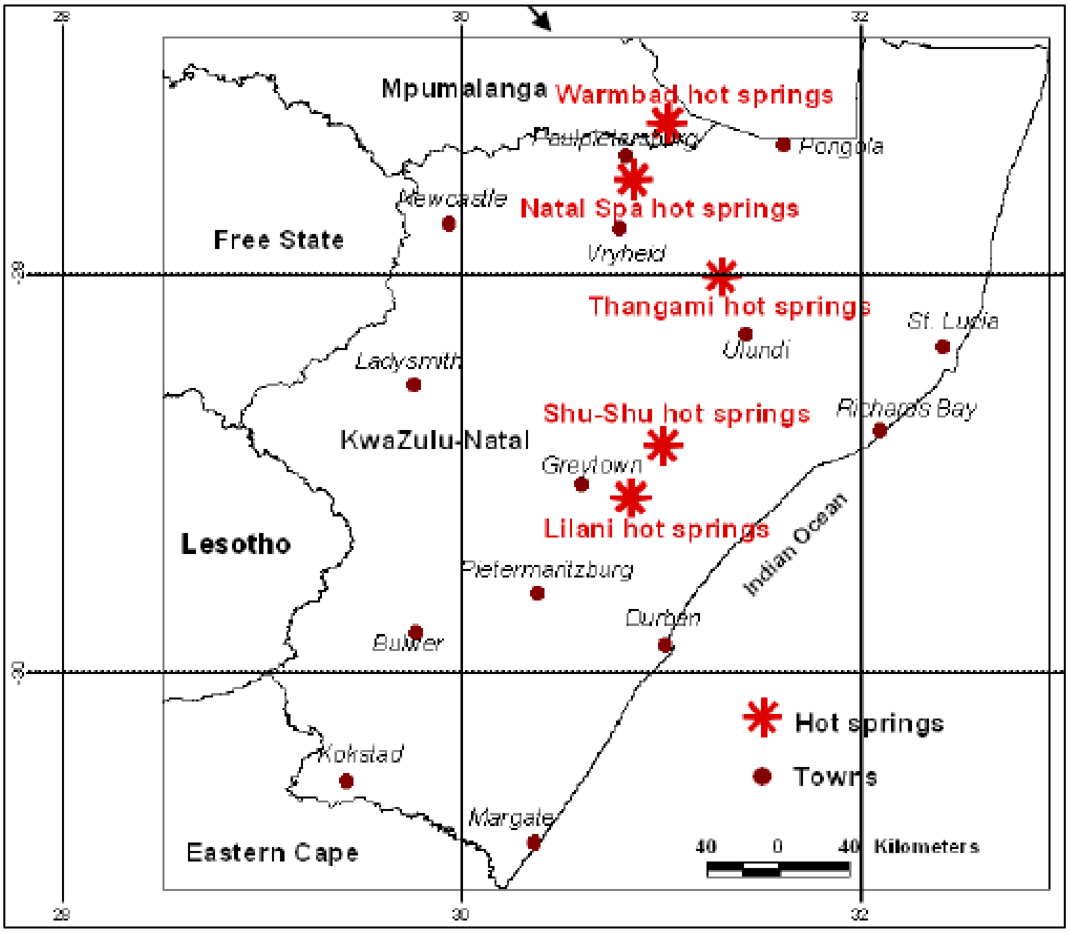


Figure 3-77: Locality plan of the thermal springs in KwaZulu-Natal (Demlie and Watkeys, 2011)

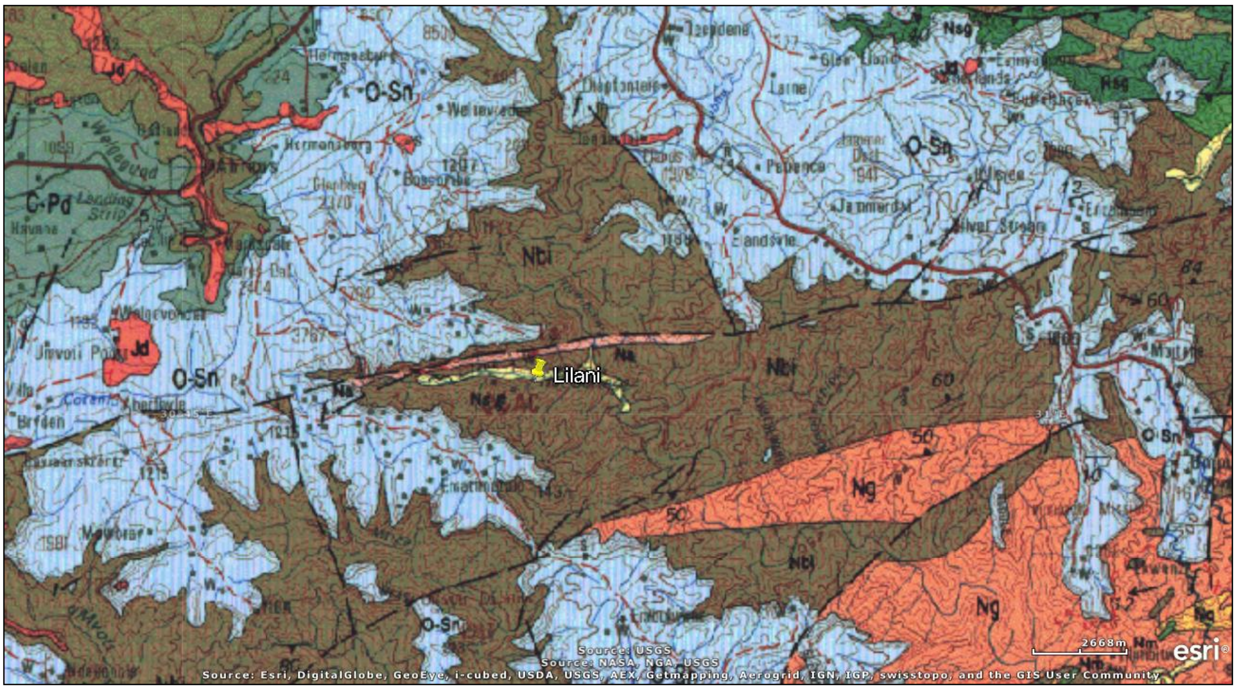


Figure 3-78: Geological map sheet 2930 of Lilani Hot Springs (CGS, 1988c)

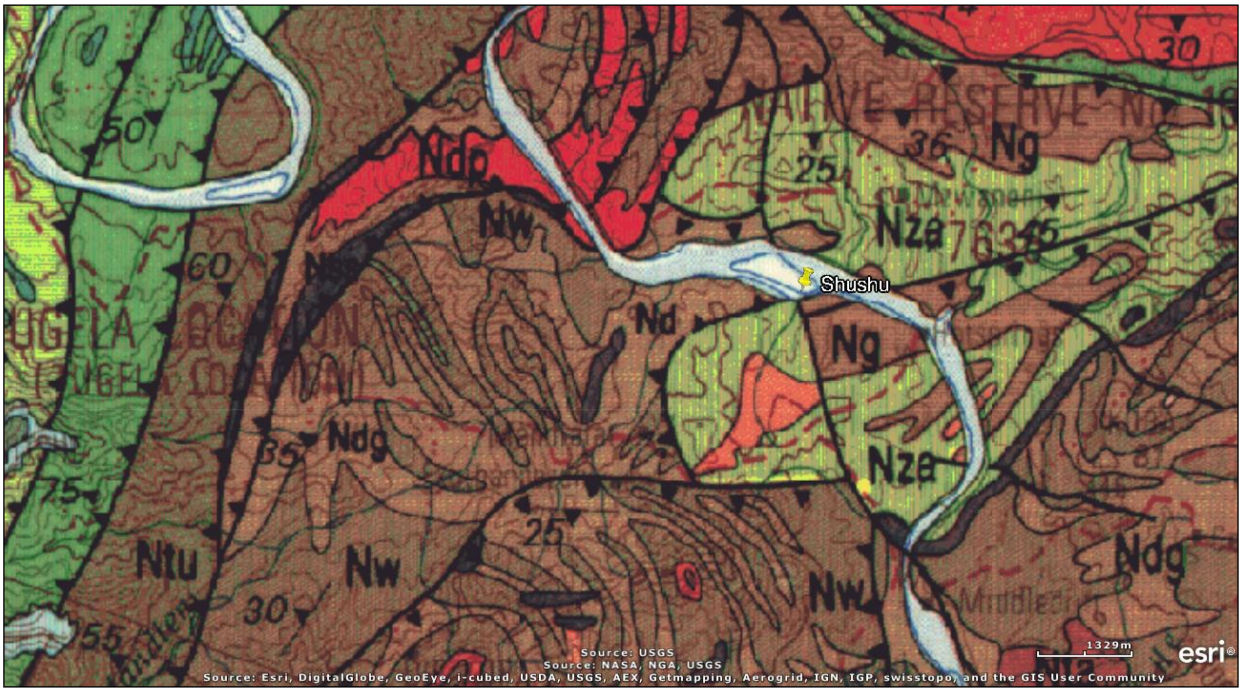


Figure 3-79: Geological map sheet 2830 of Shu-Shu Hot Springs (CGS, 1988b)

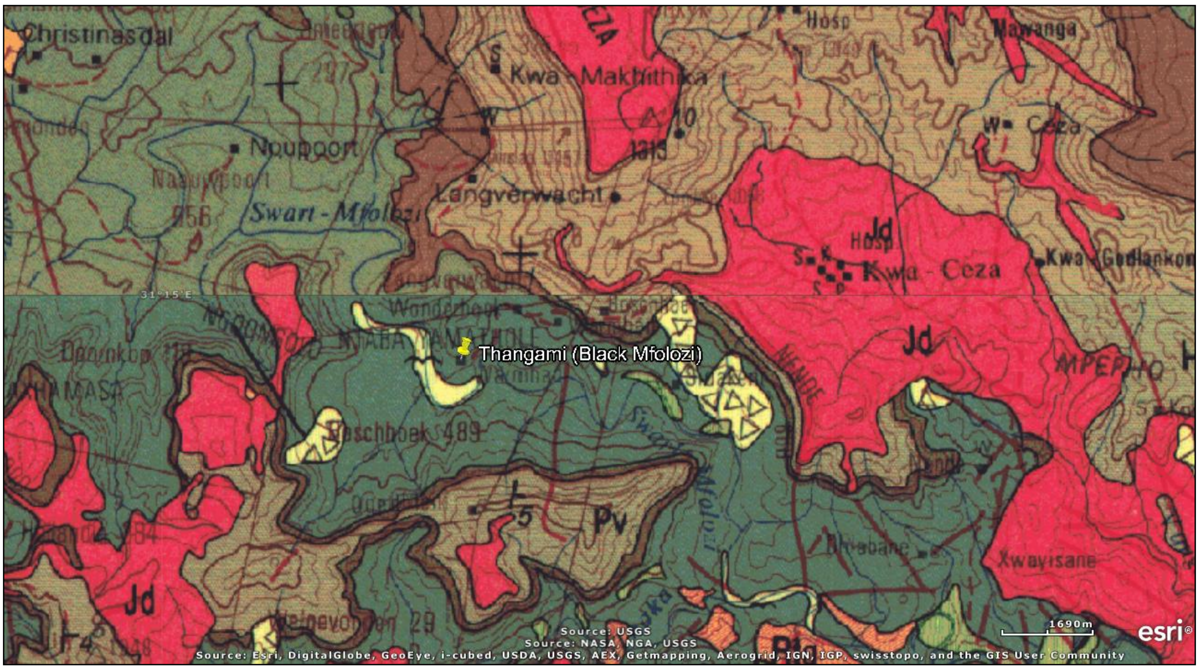


Figure 3-80: Geological map sheet 2830 of Black Mfolozi Hot Springs (CGS, 1988b)

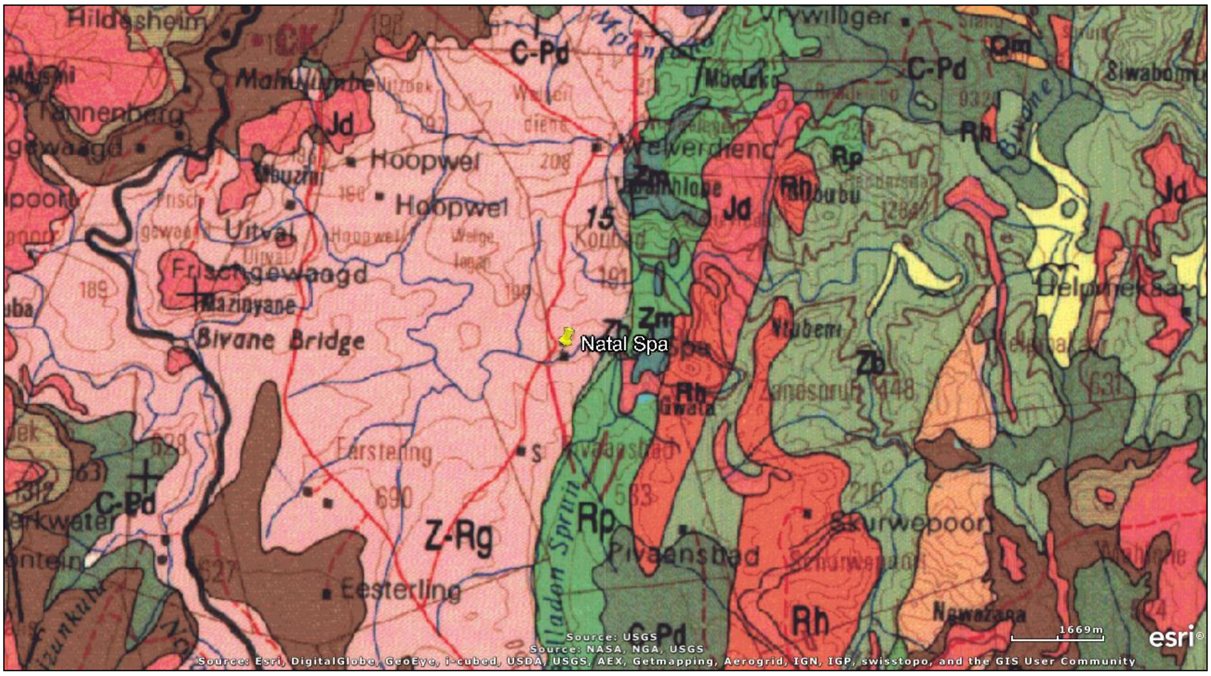


Figure 3-81: Geological map sheet 2730 of Natal Spa Hot Springs (CGS, 1988a)

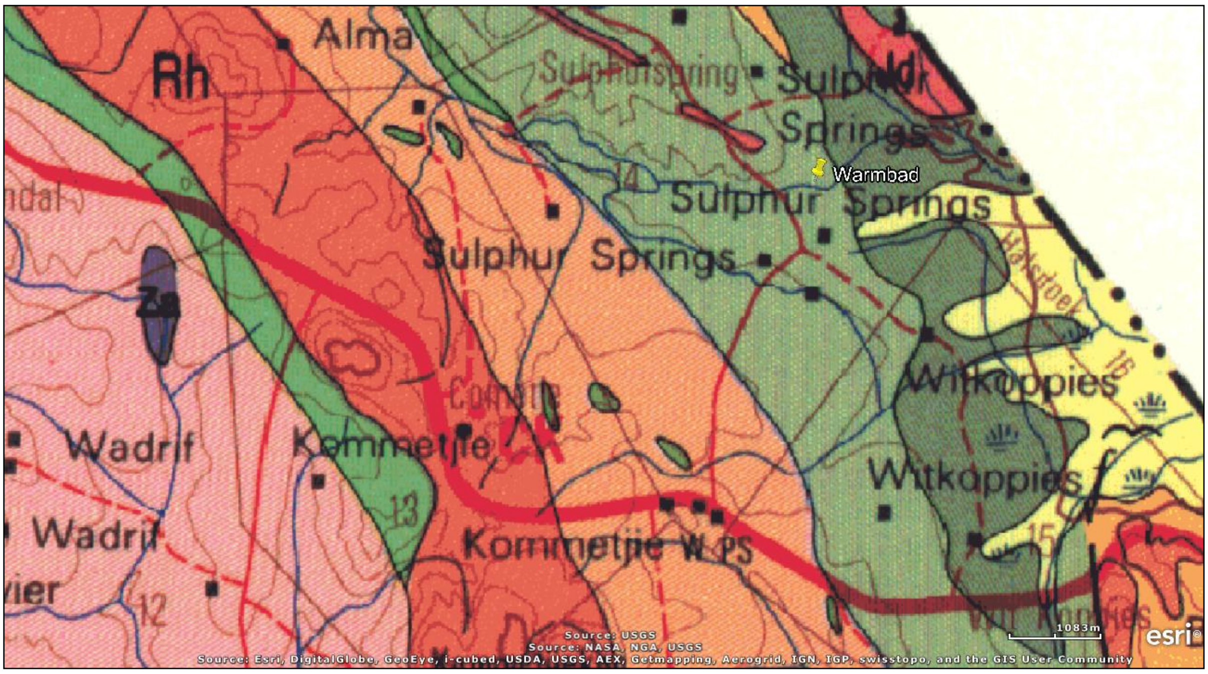


Figure 3-82: Geological map sheet 2730 of Warmbad Hot Springs (CGS, 1988a)

According to Demlie and Watkeys (2011), a 3 °C change per 100 m depth is considered applicable for geothermal gradients in South Africa. Considering the recorded temperature values listed in Table 3-19 allows the calculation of the approximate depths of origin. Referring to Table 3-19, the approximate depth of water origin is seen to be in the range of 1 035 to 1 700 m below ground level.

Table 3-19: Temperature and water origin depth of the thermal springs

Spring Name	Temperature (°C)	Depth of Origin (mbgl)
Black Mfolozi	37	1235
Lilani	40	1335
Natal Spa	41	1370
Shushu	51	1700
Warmbad	31	1035

According to Demlie and Watleys (2011), the water temperature recorded at the surface is only an estimate of the actual temperature at depth. The true temperature can only be determined by drilling boreholes into the aquifer. Demlie and Watleys (2011) collected water samples from the thermal springs of KwaZulu-Natal and analysed these samples for various chemical elements. Some of the results of the analyses are listed in Table 3-20.

Table 3-20: Basic water quality results for the sampled springs

Spring Name/ Sampling Point	Temperature (°C)	pH	TDS (mg/l)	EC (µS/cm)
Black Mfolozi 1	36.53	8.64	319	638
Black Mfolozi 2	34.05	8.67	317	635
Lilani 2	40.0	9.22	219	438
Lilani 3	38.70	9.18	218	436
Lilani River	17.63	7.80	82	163
Natal Spa	40.73	9.07	172	343
Natal Spa Borehole	22.01	6.41	120	240
Bivane River	18.16	8.06	48	95
Shu-Shu	51.0	7.7	789	1 554
Warmbad 1	30.10	9.67	139	278
Warmbad 2	31.20	9.56	141	278
Average	**32.74**	**8.54**	**233.09**	**463.45**
Minimum	**17.63**	**6.41**	**48**	**95**
Maximum	**51**	**9.67**	**789**	**1 554**
SANS 241 Standard		**5.5 - 9.5**	**1 200**	**1 700**

With reference to Table 3-20, the following comments can be made:

- The average water temperature is 32.74 °C, with minimum and maximum values of 17.63 and 51 °C, respectively.
- The average pH value of the water is 8.54, with minimum and maximum values of 6.41 and 9.67, respectively.
- The average TDS of the water is 233.09 mg/ℓ, with minimum and maximum values of 48 and 789 mg/ℓ, respectively.
- The average electrical conductivity value of the water is 463.45 µS/cm (46.35 mS/m), with minimum and maximum values of 95 µS/cm (9.5 mS/m) and 1,554 µS/cm (155.4 mS/m), respectively.

According to the spring classification system of Bond (1946) (refer to Table 3-17), the TDS values of all the springs except Shu-Shu lead to a Class B classification, indicating slightly saline chloride water.

According to South African National Standard (SANS) for drinking water (SANS 241), all the water samples, with the exception of Warmbad 1, fall within the recommended limits for safe drinking water. The Warmbad 1 sample did not meet the requirements for safe drinking water, primarily due to a very slightly elevated pH level. The analyses of the water samples indicate that the water quality of the thermal springs is very good to pristine. This observation suggests that the deep aquifer systems (depths greater than 1,000 m below ground level) are associated with groundwater of a good quality.

3.6.2 Thermal springs of Limpopo

According to Kent (1949), 24 of South Africa's 83 thermal springs and thermal wells are situated within Limpopo, with the majority being located in the Waterberg area (Figure 3-83). As discussed above, thermal springs in South Africa are associated with geological structures. According to Kent (1949), there are three known geological formations in which thermal springs are situated: the Rooiberg felsites, Bushveld granites and Waterberg sandstones. According to Olivier et al. (2008), these geological formations are known to be highly fractured, faulted and have been intruded by dykes. Table 3-21, taken from Olivier et al. (2008), lists some of the thermal springs in Limpopo and the associated geological structures along which groundwater mobilisation takes place.

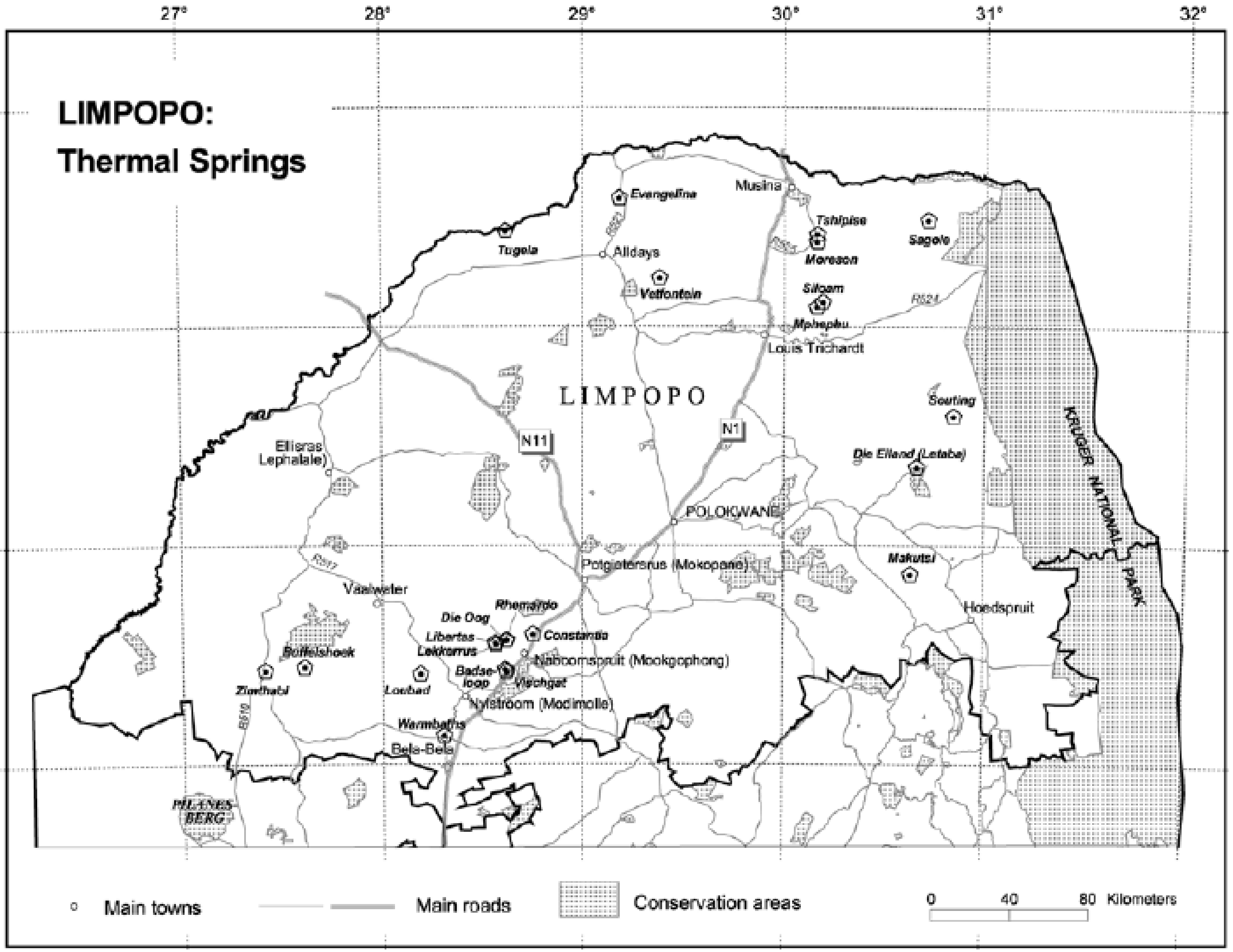


Figure 3-83: Location of thermal springs in Limpopo (Olivier et al., 2008)

Table 3-21: Thermal springs in Limpopo and associated geological structures (Olivier et al., 2008)

Spring Name	Geological Structure
Warmbaths (Bela-Bela)	Intersection of two post-Permian faults in Waterberg system
Loubad	Diabase dyke in sandstones in the Waterberg system
Buffelshoek	Diabase dyke as a barrier on artesian slope of Bushveld granite
Vischgat	Post-Karoo fault in Bushveld granite
Die Oog	Diabase dyke along post-Karoo fault in Rooiberg felsites
Welgevonden/Rhemardo	Diabase dyke along post-Karoo fault in Rooiberg felsites
Lekkerrus	Diabase dyke along post-Karoo fault in Rooiberg felsites
Libertas	Diabase dyke along post-Karoo fault in Rooiberg felsites

According to Olivier et al*.* (2008), faulting and weathering may have resulted in significant changes in the geology at the surface near thermal springs. The geology identified at the surface of some of the springs include the following:

- **Warmbaths:** Basalt from the Letaba Formation
- **Loubad:** Sandstone and trachyte from the Swaershoek Formation
- **Die Oog:** Porphyritic rhyolite from the Kwaggasnek Formation

The geology at the surface is not an indication of the origin of the thermal water. According to Olivier et al*.* (2008), the origin of thermal water can only be identified once chemical tests have been carried out on water samples and the structural geology of the area is known, including geothermal gradients. Taking the temperatures in the area into consideration and classifying them according to Kent (1949), Table 3-22 lists the thermal characteristics of the springs of Limpopo.

Table 3-23 lists the chemical composition of water samples from the thermal springs in Limpopo. Olivier et al. (2008) compared the chemical results with the 1999 standards for drinking water provided by the South African Bureau of Standards (SABS) (now SANS 241). Referring to the results in Table 3-23, all springs, with the exception of Warmbad, are considered to be pristine water. Warmbad shows significant concentrations of fluoride. The water quality results from the Limpopo springs are similar to those of the KwaZulu-Natal springs, in that the thermal water originating from significant depths appears to be pristine.

Considering the thermal gradient change of 3 °C per 100 m, the estimated depths of origin are listed in Table 3-24. Referring to Table 3-24, the inferred origin of the water is from depths in the range from 1,000 to 1,735 m below ground level.

Table 3-22: Temperature and water origin depths of the thermal springs

Spring Name	Temperature (°C)	Classification (according to Kent 1949)
Loubad	30#*	Warm
Buffelshoek	31*	Warm
Vischgat	40#	Hot
Die Oog	40#*	Hot
Welgevonden/Rhemardo	44#*	Hot
Lekkerrus	46**	Hot
Warmbaths (Bela-Bela)	52#* (38**)	Scalding
Libertas	52#* (60**)	Scalding

* Kent, 1949; Hoffmann, 1979 (#) and 2003 (**)

Table 3-23: Chemical composition of thermal springs in Limpopo (Olivier et al., 2008)

Chemical composition of thermal springs in Limpopo								
	SABS 1999	Warmbad*	Loubad	Buffelshoek*	Vischgat	Die Oog	Rhemardo	Libertas
pH	6 - 9	8.3	6.81	Not available	7.07	7.27	7.33	6.98
pH_s			7.79		7.82	8.01	7.96	8.00
SAR			0.34		2.39	1.72	1.62	1.13
TDS	<450	340	134.18		302.85	175.48	179.90	137.90
Conduct. (mS/m)	<150	69	25.00		52.00	32.00	34.00	25.00
CATIONS (mg/ℓ)								
Sodium	<200	132.5	7.87	151.6	55.95	34.21	32.72	21.98
Potassium	<50	2.9	2.90	5.7	6.13	3.62	3.58	3.57
Calcium	ns	13.0	30.92	27.1	36.13	24.80	25.57	23.02
Magnesium	ns	1.8	6.44	4.7	3.30	3.14	3.28	3.46
Boron	<1.5		0.04		0.06	0.05	0.05	0.05
ANIONS (mg/ℓ)								
Fluoride	1.5 (1[a])	11.0	0.95	6.6	6.54	5.66	5.39	5.95
Nitrite	Ns	-	0.00	-	0.12	0.00	0.00	<0.1
Nitrate	Ns	0	0.59	0	0.68	0.60	0.88	0.41
Chloride	<200	85.2	2.21	138.5	31.70	28.31	28.64	7.24
Sulphate	<400	12.1	2.16	35.1	92.82	12.96	13.68	5.86
Phosphate	ns	< 0.2	0.00	-	0.00	0.00	0.00	<0.2
Carbonate	ns	-	0.00	-	0.00	0.00	0.00	0.00
Bicarb	ns	102.0	161.65	213.5	140.30	125.05	134.20	134.2
Classific. (Bond 1946)		D	E	D	E	E	E	E

Source: *Kent, 1949; Temperley, 1975 (as reported in Hoffmann, 1979 p8) ; **Hoffmann, 1979 p15
[a]DWAF, 1996; ns: not stipulated

Table 3-24: Temperature and water origin depths of the thermal springs in Limpopo

Spring Name	Temperature (°C)	Depth of Origin (mbgl)
Loubad	30	1000
Buffelshoek	31	1035
Vischgat	40	1335
Die Oog	40	1335
Welgevonden/Rhemardo	44	1470
Lekkerrus	46	1535
Warmbaths (Bela-Bela)	52	1735
Libertas	52	1735

3.7 POTENTIAL DEEP AQUIFERS

In this section, potential deep aquifer systems in South Africa are discussed in terms of the identified potential geological divisions, thermal springs and the depth of fracturing influence.

3.7.1 Identified potential deep aquifers

Based on the current data collected, the main potential deep aquifers are identified for further investigation.

A ranking system is implemented, using a ranking from 1 to 4:

Rank 1 shows a positive indication for deep groundwater systems
Rank 2 shows some indication for deep groundwater systems
Rank 3 shows a neutral indication for deep groundwater systems
Rank 4 shows a negative indication for deep groundwater systems

3.7.1.1 Pre-Karoo geology

Rank 1 geological groups

- **Limpopo Belt:** The occurrence of thermal springs within the Limpopo Belt serves as an indication of long, deeper groundwater flow systems.
- **Witwatersrand Supergroup:** It was found that the fault zones within the Witwatersrand Supergroup play an important role in the deep groundwater system, where deep gold mines (±2 km) have intersected large volumes of groundwater at faults.
- **Transvaal Supergroup:** The carbonate rocks of the Chuniespoort and Ghaap groups represent an important aquifer system in South Africa. It was found that the storativity of the dolomites decreases with increasing depth. A decrease in storage from approximately 9.1% at a depth of 61 m below ground level to 1.3% at a depth of 146 m below ground level was observed.
- **Waterberg and Soutpansberg groups:** Fractures were found at depths of up to 250 m below ground level. These structures produce high-yielding boreholes when intersected.
- **Natal Group:** High-yielding boreholes are assumed to have intersected water-bearing fractures or faults. The sandstones and quartzites of the Natal Group have a high quartz content and will behave in a brittle manner when deformed, forming local zones of intense fracturing (near faults and dolerite intrusions), which enhances the recharge and permeability, and creates preferential groundwater flow paths. These zones of intense fracturing are ideal targets for groundwater resources because groundwater movement occurs mainly within joints, fractures or bedding planes.
- **Cape Supergroup:** The main groundwater intersections within the Table Mountain Group aquifer are at depths greater than 100 m below ground level. Borehole yields have been found to increase with depth. This characteristic feature goes against conventional structural geological theory, which states that joint or fracture openings close with increasing depth due to the pressure of the overlying rock mass. However, deep groundwater circulation has been confirmed within the Table Mountain Group. For these reasons, the Table Mountain Group is identified as a potential deep aquifer system.

Rank 2 geological groups

- **Archean Greenstone belts:** The occurrence of groundwater is dependent on the development of fractures and openings, which improves porosity and permeability. Secondary porosity and permeability, especially along contacts, form good local aquifers. Fractures related to faults and intrusive dykes enhance permeability, but low yields are still found for the deeper fractured aquifer.

- **Archaean granites and gneisses:** The Archaean granites and gneisss are classified as hosting intergranular and fractured aquifer systems, which are structurally controlled and have a semi-confined to confined nature. It was found that the fracture zone of the Limpopo Plateau may have depths of 120 m below ground level, which is especially true for the Dendron and Mogwadi regions. These regions are known for high-yielding boreholes that exceed the typical expectations of crystalline aquifer potentials.

- **Bushveld Complex:** Groundwater flows through interconnected fracture systems with the potential for rapid vertical inflow from the upper weathered aquifer, as well as at great depths along interconnected conductive zones. Initial groundwater quality data has indicated that groundwater from the deeper fractures is chemically and isotopically different to groundwater from the shallow aquifer and indicates a longer, slower groundwater flow system at depth.

- **Namaqua-Natal Province:** High-yielding boreholes are assumed to be related to the intersection of water-bearing fractures.

Rank 3 geological groups

- **Dominion Group:** The quartzites and conglomerates host secondary aquifers, which are controlled by joints, fractures, faults and dyke contact zones.

- **Ventersdorp Supergroup:** It was found that the volcanic rocks weather to a clay material that reduces permeability, but that fractured rocks below the weathered zone have the capacity to produce significant volumes of groundwater. However, there are also indications that these rocks are not permeable at depth, and rather act as an aquiclude.

Rank 4 geological groups

None.

3.7.1.2 Karoo geology

Rank 1 geological groups

- **Main Karoo Basin (bedding planes):** The occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding-plane fractures. It is not certain if these bedding-plane porosities are also present at depth, but it has been reported that water was struck at a depth of 3,700 m below ground level in borehole SP 1/69, which intersects the Dwyka diamictite near East London.

- **Main Karoo Basin (south and southwestern Karoo):** It was found that the weathered and fractured zones that are associated with faulting and folding are confined to the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines that are formed due to folding have characteristic open joints and fractures. These structures are seldom dry when drilled, although the quality of the groundwater may be problematic.

- **Main Karoo Basin (central Karoo):** The presence of a warm water spring in Aliwal North (Molteno Formation), indicates that deep circulating groundwater systems are present in this area.

- **Tshipise and Tuli basins:** Deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with a maximum water temperature of 59 to 60 °C. These warm springs are associated with some of the major faults.

Rank 2 geological groups

- **Karoo Dolerite Suite:** On a regional scale, the structural domains have not as yet been shown to influence the regional geohydrology of the Karoo Supergroup. However, the east-west-striking Victoria dyke, the north-northwest-striking Middelburg dyke and the dykes near East London form major magma feeders and are accompanied by extensive fracturing due to shearing and jointing. These dykes form regional discontinuities that extend to great depths within the earth's crust and could theoretically form part of a fracture network in which deeper-seated groundwater flows on a more regional scale.
- **Main Karoo Basin (Northern Karoo):** The northern part of the Main Karoo Basin is considered to have higher porosities and permeabilities than the rest of the basin. Approximately 30 to 60% of the lithological column in this area consists of dolerite, which could create additional secondary porosity for groundwater movement. The sandstone-rich Vryheid Formation occurs at depths of more than 800 m below ground level. It is situated in an arc from west of Bergville in the east, towards the area just north of Bethlehem and southwestwards to Ladybrand.

Rank 3 geological groups

- **Dwyka Group (as a whole):** The Dwyka Group is considered to act as an aquitard rather than an aquifer, as the diamictite and shales have very low hydraulic conductivities and virtually no primary voids. However, where the Dwyka Group is significantly fractured, high yields have been measured. Unfortunately, the occurrence of zones of extensive fracturing is rare and could be related to the tendency of fractures or joints in the Dwyka Group to be mineralised (kaolinised), which decreases the potential yield.
- **Ecca Group (as a whole):** The Ecca Group is considered to be associated with low-yielding aquifer systems, but higher yields have been obtained in fold, fault and joint structures, where favourable recharge conditions exist.
- **Beaufort Group (as a whole):** The Beaufort Group is considered to be associated with low-yielding aquifer systems, but higher yields have been obtained in fold, fault and joint structures, where favourable recharge conditions exist.
- **Stormberg Group (as a whole):** The Stormberg Group is considered to be associated with low-yielding aquifer systems, but higher yields have been obtained in fold, fault and joint structures, where favourable recharge conditions exist.
- **Drakensberg and Lebombo groups:** The Drakensberg and Lebombo groups were classified as hosting intergranular and fractured aquifer systems. A characteristic feature of the Drakensberg Group is the numerous low-yielding springs that emerge in elevated areas. The basalts (Letaba Formation) of the Lebombo Group are classified as hosting low- to moderate-yielding aquifer systems.
- **Springbok Flats Basin:** The northeastern sub-basin has a maximum thickness of approximately 700 m and the southwestern sub-basin has a maximum thickness of 1,000 m. The basin is underlain by rocks of the Bushveld Igneous Complex, which could be mined in future where it is underlain by shallower parts of the basin.
- **Ellisras Basin:** The maximum thickness of the basin was estimated to be less than 800 m. Unfortunately, no boreholes intersect the basement in the deepest part of the Ellisras Basin.

Rank 4 geological groups

None.

3.7.1.3 Post-Karoo geology

Rank 1 geological groups

None.

Rank 2 geological groups

- **Uitenhage Group:** The Algoa Basin of the Uitenhage Group has more than 3,500 m of sediment that is preserved in the Addo trough. There is a linear decrease in porosity with depth, varying between 10 and 30%, with the highest porosity in the basin being 30%. The highest porosities occur in the upper Kirkwood Formation, and high porosities have been measured in the basin up to a depth of 2,500 m. Below this depth, the porosity becomes very low.

- **Zululand Group:** Four potential sandstone reservoirs were identified by drilling, with the lower and middle sandstone units occurring at depths greater than 800 m below ground level. Porosity and permeability analyses were performed on core samples from the boreholes and indicated that the middle sandstone had very high porosities and permeabilities, but the lower sandstone unit mainly had very low permeabilities.

Rank 3 geological groups

- **Kalahari Group:** The Kalahari Basin is the only extensive onshore Cenzoic basin and has a maximum depth of 450 m. A potential deep aquifer may be associated with this basin, but only to a depth of 450 m. The groundwater levels of the Kalahari aquifer system generally vary between 40 and 50 m below ground level, but there are areas where water levels vary between 120 and 180 m below ground level. Water level depths of up to 250 m below ground level have been reported.

Rank 4 geological groups

- **Coastal Cenzoic deposits:** The Coastal Cenzoic deposits are classified as primary aquifer systems, where groundwater moves through the original interstices of the geological formation. These aquifers have moderate to high aquifer potentials, but these deposits are fairly thin, and are not assumed to play an important role in the consideration of deep aquifer systems.

3.7.2 Thermal springs

The flow rate of a thermal spring is determined by the size of the aquifer, the extent of recharge, the aquifer storage capacity, and the transmissivity and discharge capacity of both the aquifer and conduit through which the water rises to the surface (LaMoreaux and Tanner, 2001). Thermal springs are known to originate either in areas with recent volcanic activity or from meteoric water flow through fractures in bedrock. South Africa is not situated in an area that has experienced any recent volcanic activity. Instead, the origin of thermal springs is linked to geological structures such as faults and folds (Kent, 1949). Kent (1949) identified 74 thermal springs and nine thermal artesian wells in South Africa (Figure 3-84).

In a number of the identified potential deep aquifers, the indication of deep groundwater flow systems is a thermal spring. Cave and Clarke (2003) have tested data from thermal springs to trace deep groundwater flow. Murray et al. (2015) also used data from springs in the Karoo to identify deep groundwater in the Main Karoo Basin. It follows that the characterisation of potential deep aquifers needs to make use of the information available at these thermal springs in South Africa.

3.7.3 Depth of fractures

Murray et al. (2000) stated that more than 90% of South Africa's groundwater occurs within hard rock, fractured aquifers. Other authors have also found that the rocks in most of South Africa's sedimentary basins are metamorphosed and have little or no primary porosity, only secondary porosity where they have been faulted and fractured (Figure 3-85).

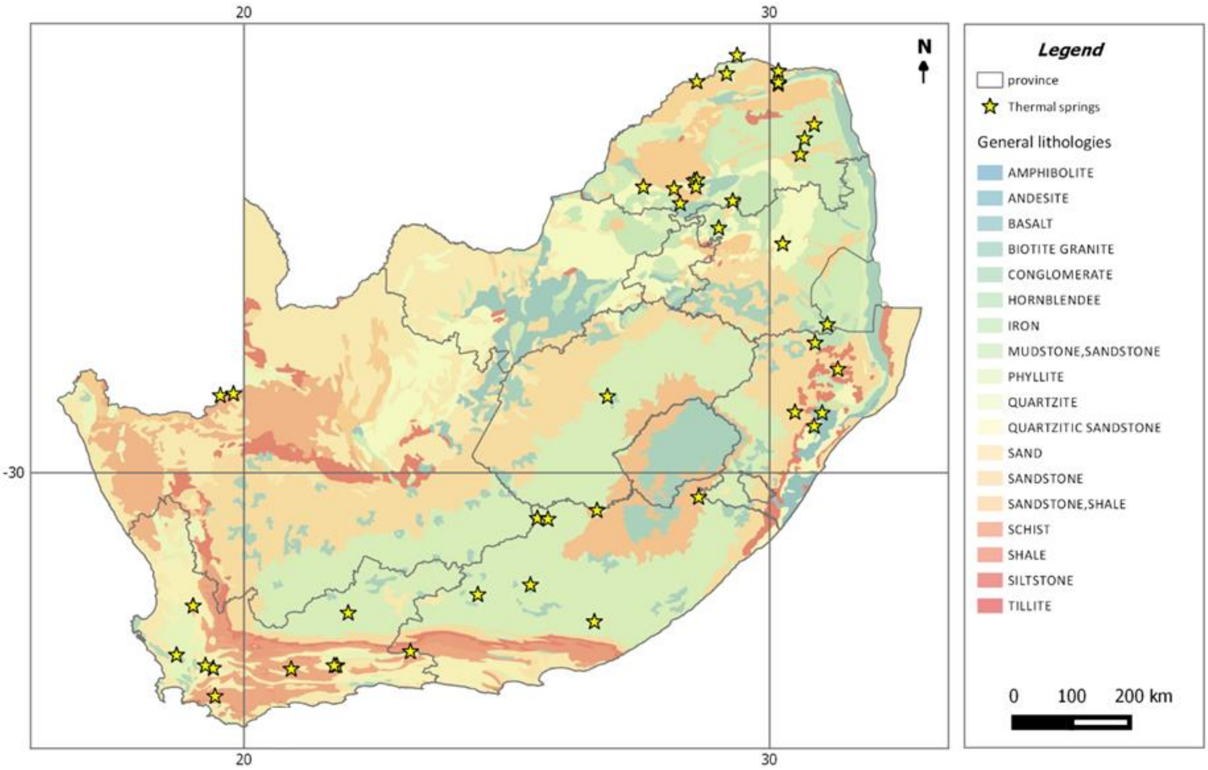


Figure 3-84: Location of thermal springs in South Africa (based on data from Kent, 1949)

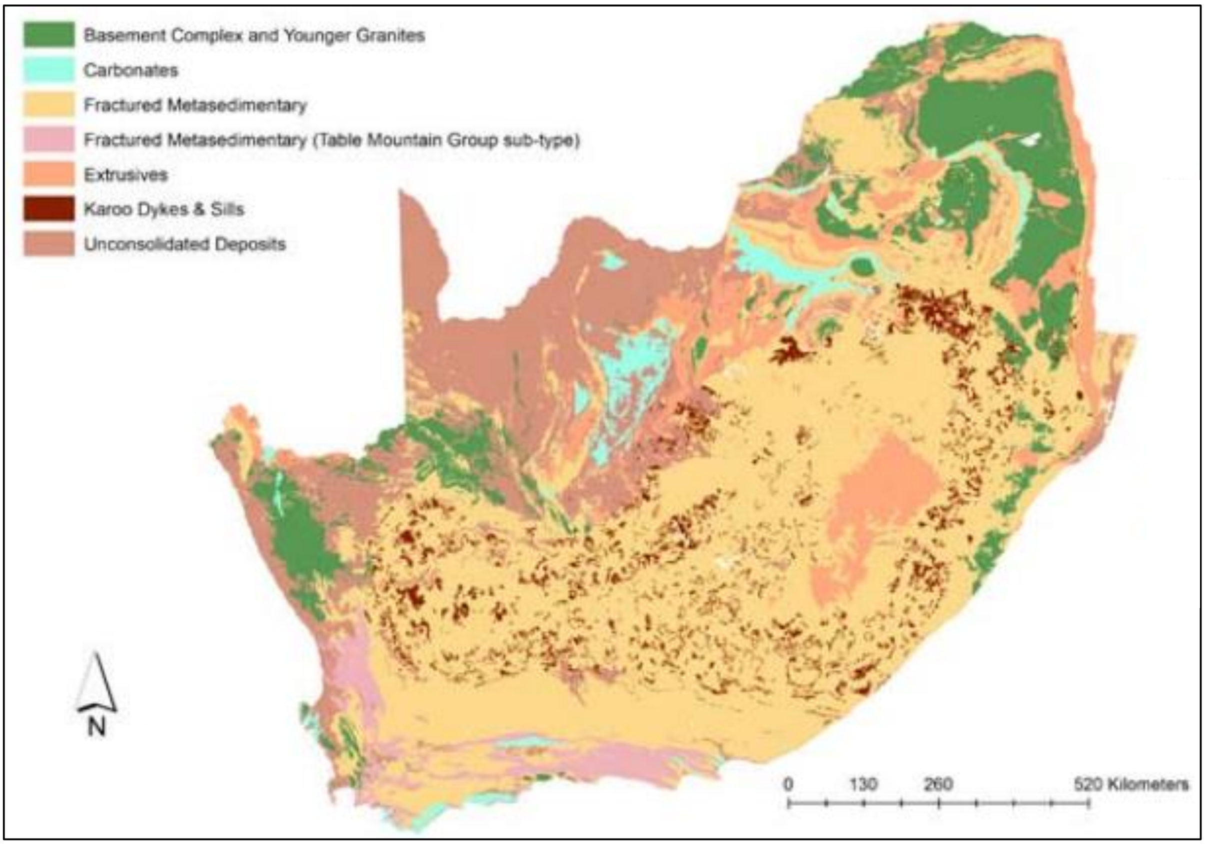


Figure 3-85: Principal aquifer types in South Africa (LeMaître and Colvin, 2008)

The porosity and permeability of geological layers tend to decease with increasing depth (Fitts, 2002). This is the conventional geological or structural theory that joint or fracture openings close with increasing depth due to the pressure of the overlying rock mass (Rosewarne, 2002a).

Lin et al. (2007) analysed a deep borehole in the Graafwater area in the Western Cape to determine the fracture network characteristics of the Table Mountain Group. The analysed borehole was 800 m deep, and was divided into four zones, based on the degree to which the fractures are hydraulically active. The zones are as follows: high (0 to 150 m below ground level), medium (150 to 400 m below ground level), low (400 to 570 m below ground level) and hydraulically inactive (570 to 800 m below ground level or deeper). Lin et al. (2007) stated that the top of the hydraulically inactive fracture zone clearly indicated that groundwater flow could not take place below a depth of approximately 570 m. However, this analysis was based on a single borehole, and Lin et al. (2007) concluded that the depth model of groundwater circulation that had been developed was not necessarily applicable to all areas of the Table Mountain Group rock aquifers.

However, there are special cases where this conventional theory does not apply. For example, circulation depths of up to 2,000 m have been found in the Table Mountain Group aquifers (Rosewarne, 2002a). The Table Mountain Group aquifers form a special case due to a number of factors. Firstly, the main lithology consists of fairly uniform, brittle quarzitic sandstones, which fracture readily under pressure, and the continental-scale orogeny that formed the Cape Fold Belt provided sufficient levels of stress to produce widespread and deep fracturing. Secondly, the groundwater is usually acidic and low in dissolved solids, which lessen the likelihood of deposition of minerals that could block fractures. Furthermore, the sandstones are predominantly composed of silica, which lessens the likelihood of weathering products that could also block fractures (Rosewarne, 2002a).

Considering that deep groundwater generally occurs below the traditionally exploited weathered zone (shallow aquifers), the occurrence and distribution of fracturing in the deeper formations is paramount in the investigation of potential deep aquifers.

The key to delineating future deep groundwater resources will be to determine the following:

- The depth to the fractured aquifer (below the extent of weathering)
- The depth to which fractures remain open (in different geological mediums)
- The methods to accurately locate such fractured aquifers

3.8 CONCLUSIONS

In this chapter, South Africa's geology was reviewed from a deep groundwater perspective to provide an initial analysis of the potential deep aquifer systems in the country. The South African geology was subdivided into pre-Karoo, Karoo and post-Karoo geologies, and the geological groups under each geological period were analysed for deep groundwater based on the currently available information. Additionally, information from thermal springs and the general depth of fracturing were considered, and combined in a summary of the identified potential deep groundwater aquifers based on the geological groups.

To assess the potential for deep exploitable aquifer systems within the different geological formations of South Africa, a ranking system was used in which the formations were rated according to their likelihood of hosting, or being associated with, deep aquifers. Formations with Rank 1 were considered to show positive indications for the presence of deep aquifer systems, while formations with Rank 2 were considered to show some indications of deep groundwater. Ranks 3 and 4 were assigned to those formations that show neutral and negative indications for deep aquifers, respectively. The results of this ranking are summarised in Table 3-25 for the geological units assigned ranks 1 and 2.

Considering that deep groundwater generally occurs below the traditionally exploited weathered zone (shallow aquifer), the study of deep fractured zones becomes paramount in the investigation of potential deep aquifers.

Table 3-25: Summary of potential deep groundwater aquifers (ranks 1 and 2) with physical indications and identified potential targets

	Rank	Physical indication description	Specific target (feature/formation/zone)	Comments
Limpopo Belt	1	The occurrence of thermal springs within the Limpopo Belt serve as an indication of long, deeper groundwater flow systems	Contacts of: Messina Suite, Alldays Gneiss, Malala Drift Gneiss	Thermal springs appear at lithology contacts within the Limpopo Belt
Witwatersrand Supergroup	1	It was found that the fault zones within the Witwatersrand Supergroup play an important role in the deep groundwater system, where deep gold mines (± 2 km) have intersected large volumes of groundwater at faults.	Fault zones at depth No specific lithology targets identified	The primary porosity/permeability at depth is low, thus on specific formation, but rather secondary features of faults and fractures
Transvaal Supergroup	1	The carbonate rocks of the Chuniespoort and Ghaap Groups represents an important aquifer system in South Africa. It was found that the storativity of the dolomites decreased with increasing depth. A decrease from approx. 9.1% storage at a depth of 61 mbgl to 1.3% storage at a depth of 146 mbgl.	Schmidtsdrif and Campbell Rand Sub-groups (Ghaap Group) Malmani Subgroup (Chuniespoort Group) Dolomite/Limestone formations	Paleo-karstic erosion (paleo-karst horizons) may be found buried at depth
Waterberg and Soutpansberg Groups	1	Fractures were found at depths of up to 250 m and these structures produce high yielding boreholes when intersected.	East-west striking fault system (bounds Soutpansberg Group)	Groundwater occurrences are mainly associated with secondary geological structures as boreholes drilled into these rocks tend to be dry if these structures are not intersected
Natal Group	1	Intense fracturing (near faults and dolerite intrusions), ideal targets for groundwater resources	Contact of Eshowe member with bounding granitic basement rocks at depth greater than 300m.	Traditionally not utilised for groundwater, which results in limited data. Yet, previously classes with the TMG, and could potentially house deep groundwater
Cape Supergroup	1	The main groundwater intersections within the TMG Aquifer are at depths of greater than 100 mbgl, and borehole yields have been found to increase with depth. Deep groundwater circulation has been confirmed within the Table Mountain Group.	Intermontane Domain (inland): Piekenierskloof Fm, Peninsula Fm, Nardouw Fm, Lower Bokkeveld Fm (Ceres	At depth secondary features will control the movement of deep groundwater – fault systems/fractures/bedding planes to be targeted

Main Karoo Basin (south and southwestern Karoo)	1	Sporadic thermal spring within the Main Karoo Basin (southern). Reported that water was struck at 3 700 m below the ground surface in Dwyka diamictite in borehole SP 1/69 near East London.	Fractured zones associated with faulting and folding in the south, adjacent to the Cape Supergroup. Contact zones of the Clarens Fm (Stormberg Group) at depth	The occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding- plane fractures. It is not certain if these bedding-plane porosities are also present at depth.
Main Karoo Basin (central Karoo)	1	Sporadic thermal spring within the Main Karoo Basin (central). The presence of a warm-water spring in Aliwal North, indicates that deep circulating groundwater systems are present at suitable localities in this area. Relatively good porosities and permeabilities were measured in the SOEKOR borehole MA 1/69, which was probably drilled into the Katberg Formation. The SOEKOR borehole MA 1/69 also indicated that parts of the core are well jointed.	Contact zones of the Clarens Fm (Stormberg Group), Katberg Fm and Molteno Fm Fractured/fault zones at depth	
Tshipise and Tuli Basins	1	Deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with a maximum water temperature of 59°C – 60°C. These warm springs are associated with some of the major faults	Fractured/fault zones at depth No specific lithology targets identified	
Archean Greenstone Belts	2	Barberton Greenstone Belt: meta-sediments have been highly folded by strong over-thrusting with brecciation and mylonitisation, which has increased the secondary porosity of the unit. Pietersburg greenstone belt: Mothiba Fm, Eersteling Fm and Zandrivierspoort Fm are considered the most important layers in terms of groundwater.	Secondary features at depth Contacts with granitic rocks No specific lithology targets identified	Secondary features (fractures, fault and intrusive dykes) enhance permeability, but low-yields are still found for the deeper fractured aquifer
Archaean Granites and Gneisses	2	Fracture zone of the Limpopo Plateau may exceed down to 120 mbgl, which is especially true for the Dendron and Mogwadi regions. These regions are	Fractures at depth	Analyses was limited to shallow groundwater systems

Bushveld Complex	2	Below the weathered zone, the unweathered, fractured aquifer is found and extents to a depth where fractures will be closed due to the pressure from the overlying rocks. The effective hydraulic conductivity of the deeper aquifer is controlled by fractures and mine voids Initial groundwater quality data has indicated that groundwater from the deeper fractured is chemically and isotopically different to groundwater from the shallow aquifer which indicates a longer, slower groundwater flow system at depth.	Fractures at depth Contact zone between intrusive dykes and host rock Intrusive carbonatite complexes (i.e. Spitskop Carbonatite Complex)	
Namaqua-Natal Province	2	Highly deformed lithologies from Namaqua Orogeny (secondary features control deep groundwater) Presence of thermal springs, and these fractures are known to originate at deep depths beneath the earth's surface.	Fault or fracture zone striking north-northeast and north-northwest are generally though to represent zones where the fractures are open	Very limited groundwater exploitation, thus limited information about the characteristics of the igneous and metamorphic rocks of the Natal Belt.
Karoo Dolerite Suite	2	East-west Victoria dyke, north northwest Middelburg dyke and dykes near East London form regional discontinuities that extend to great depths within the earth's crust and theoretically could form part of a fracture network wherein deeper-seated groundwater flows on a more regional scale.	Dolerite contact zones at depth	
Main Karoo Basin (Northern Karoo)	2	Vryheid Formation occurs at depths of more than 800 m and about 90 m thick. In SOEKOR borehole LA 1/68, a 150 m thick jointed dolerite occurs at a depth of between 1 110 m and 1 260 m. A 25 m thick sandstone, with medium visual porosity is also present in the LA 1/68 borehole from 1 051–1 076 m, as well as at 1 600 m, where a 13 m thick sandstone has good visual porosity.	Sandstones of the Vryheid Fm at depth Fractured/fault zones at depth	

Uitenhage Group	2	The Uitenhage Artesian Aquifer (UAA) is actually situated within rocks of the Table Mountain Group of the Cape Supergroup underlying the Uitenhage Group rocks. Groundwater from the Table Mountain Group Aquifer recharges the basal sandstone units of the aquifers within the Kirkwood and Enon Formations by lateral and vertical pressure leakage from the bounding quartzite units. Algoa Basin has a maximum depth of approximately 4 600 m, deepening in an offshore direction. There is a linear decrease in porosity with depth. The best porosities occur in the upper Kirkwood Formation, and good porosities have been measured in the basin up to a depth of 2 500 m, but below this depth it becomes very poor.	Kirkwood Fm	
Zululand Group	2	The Makatini Formation is the only formation within the Zululand Group that is considered an aquifer Four potential sandstone reservoirs were identified by petroleum drilling, with the lower and middle sandstone units occur deep than 800 m below the ground surface Porosity and permeability analysis was performed on core which indicated that the middle sandstone has very good porosities and permeabilities, but the lower sandstone unit has mainly very low permeabilities.	Makatini Fm Deep sandstone layers	

CHAPTER 4: DATA SOURCES CONSOLIDATION

4.1 INTRODUCTION

This chapter deals with the consolidation of the available data sources on deep aquifers and deep groundwater conditions in South Africa. Various confirmed and potential sources of data on deep aquifers and groundwater conditions were identified during this investigation. These included the following:

- Boreholes of the International Heat Flow Commission. The IHFC database indicates the location of 39 deep boreholes, which range in depth from 300 to 800 m, with an average depth of 535 m.
- The Pangea database of the International Council for Science. The Pangea database has information on 119 boreholes in South Africa, of which 116 are deeper than 300 m.
- The Council for Geoscience's database on deep boreholes. This database contains information on 5,221 boreholes with depths exceeding 300 m.
- The SOEKOR reports, which contain information on at least 25 deep boreholes.
- Boreholes drilled as part of the Karoo Research Initiative.
- Information on deep boreholes from the Petroleum Agency South Africa.
- The National Groundwater Archive of the Department of Water and Sanitation.
- Information on the occurrence of thermal springs in South Africa.
- Information on the location and depth of underground mines in South Africa. Information on the occurrence of deep groundwater could potentially be obtained from these mines.

Apart from the above sources of data, information on a proposed deep drilling project, the Bushveld Igneous Complex Drilling Project (BICDP), is provided. The drilling phase of this project should commence soon, allowing investigation of the deep aquifer systems in the Bushveld Igneous Complex.

The project focused on identifying data sources that contain information on geohydrological conditions at the various deep boreholes, springs and mines. Although some of these data sources contain only limited information, the project endeavoured to identify sources containing as much of the following information as possible:

- Location (GPS coordinates)
- Geological information
- Geohydrological information (groundwater quality, groundwater quantity and depth of aquifers)

For data sources containing information on deep boreholes, the following information was deemed important:

- Depth
- Date drilled
- Drilled by whom
- Purpose
- Construction
- Equipment
- Accessibility (sealed or open)
- Current application

4.2 BOREHOLES OF THE INTERNATIONAL HEAT FLOW COMMISSION AND PANGEA

The temperature database was originally assembled to determine the historical heat flow of the earth, but now serves as a good indication of where deep boreholes are located, their depth and the temperature of the groundwater at these locations. Data from climate reconstruction investigations are considered to supplement the current framework of deep boreholes. The climate reconstruction data consists of temperature gradients, temperature profiles and heat flow rates. The presence of temperature data at these depths is indicative of the existence of deep boreholes, from which data could potentially be collected without having to drill new deep boreholes at those locations.

Two main databases were drawn upon to create this initial framework on deep boreholes: that of the IHFC and that of Pangea, a data publisher for earth and environmental science, which forms part of the ICSU.

The Pangea database (http://doi.pangaea.de/10.1594/PANGAEA.804801?format=html#download) has 119 boreholes within South Africa, one on the border of South Africa and Namibia, and 13 in Lesotho. Of the boreholes in South Africa, 114 have depths of 300 m or more. These deep boreholes have a range in depth of 345 to 2,880 m, with an average depth of 1,327 m. Apart from one borehole, the boreholes located in Lesotho are all shallower than 300 m. The depth distribution of the Pangaea boreholes with depths exceeding 300 m is shown graphically in Figure 4-1.

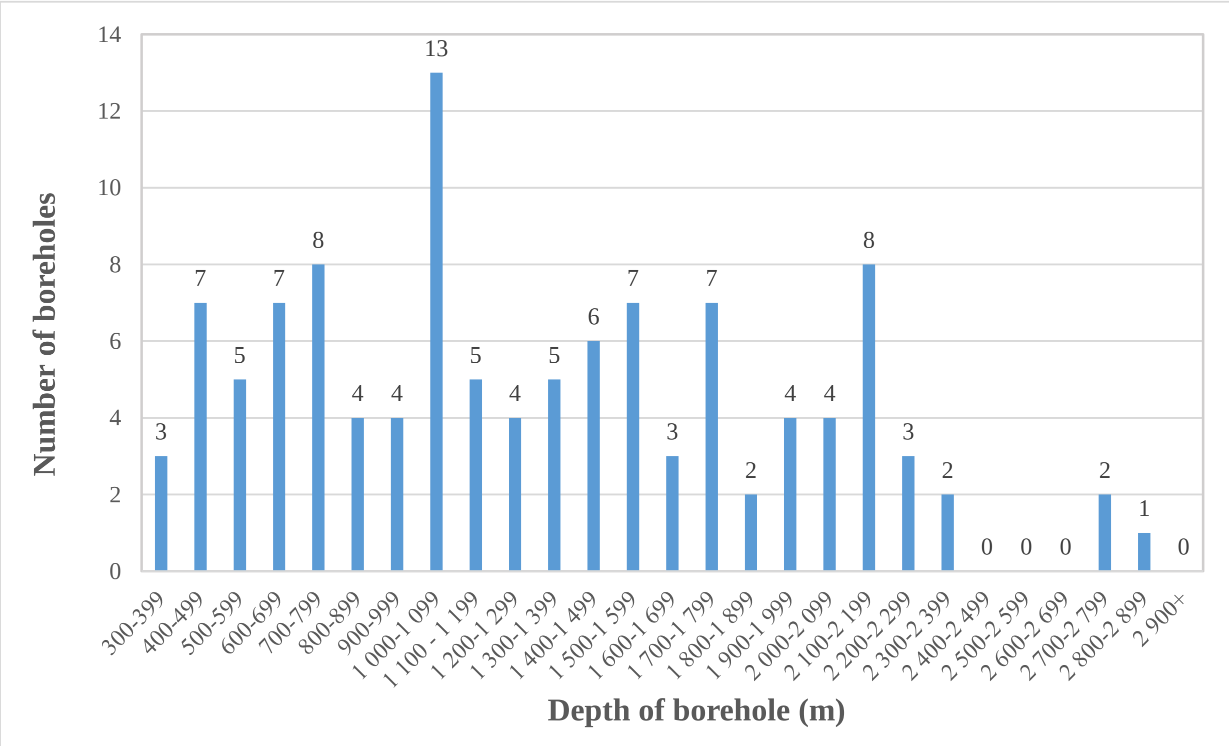


Figure 4-1: Depth distribution of boreholes in the Pangaea database with depths exceeding 300 m

The IHFC database (http://www.heatflow.und.edu/data.html) contains 48 boreholes located in South Africa for which temperature gradient data is available. The database lists the location of 39 boreholes with depths greater than 300 m. The depths of these boreholes range from 300 to 800 m, with an average depth of 532 m. The depth distribution of the IHFC boreholes with depths exceeding 300 m is shown graphically in Figure 4-2.

The distribution of the deep boreholes in the Pangaea and IHFC databases across South Africa is shown in Figure 4-4. The IHFC boreholes are clustered within Limpopo and North West, while the deep boreholes of the Pangea database have a smoother distribution across South Africa, with a few boreholes in each province. However, there are dense clusters of boreholes in the Free State, Gauteng, North West and Mpumalanga.

Although the data listed in the IHFC and Pangaea databases is focused on parameters related to heat flow, it is likely that other data related to geological and geohydrological conditions was also recorded during the drilling of the boreholes. Unfortunately, such data is not held at the organisations hosting the databases. It will therefore be necessary to obtain the required data from the original drilling reports. This may prove to be a challenging endeavour.

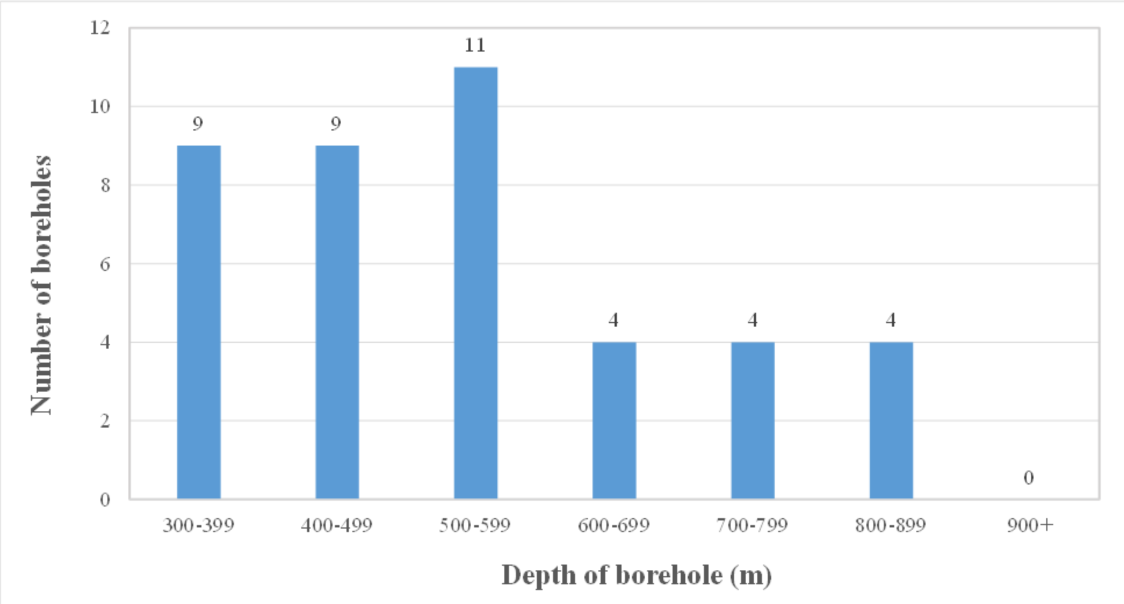


Figure 4-2: Depth distribution of boreholes with depths exceeding 300 m in the IHFC database

4.3 BOREHOLES IN THE DATABASE OF THE COUNCIL FOR GEOSCIENCE

The Council for Geoscience maintains a database of borehole information received from the mining and energy sector. The database includes information on the mining or energy company for which the borehole was drilled, the date of installation, as well as the depth and coordinates of the borehole. The results of coal analyses performed on samples from some of the boreholes drilled during coal exploration are also listed in the database. The coal analyses include water content analyses.

The database of the CGS contains information on 5,221 boreholes with depths exceeding 300 m. The depth distribution of these boreholes is shown in Figure 4-3, while the spatial distribution of these boreholes across South Africa is shown in Figure 4-5. The boreholes in the CGS database are seen to be clustered on and around the coalfields of South Africa.

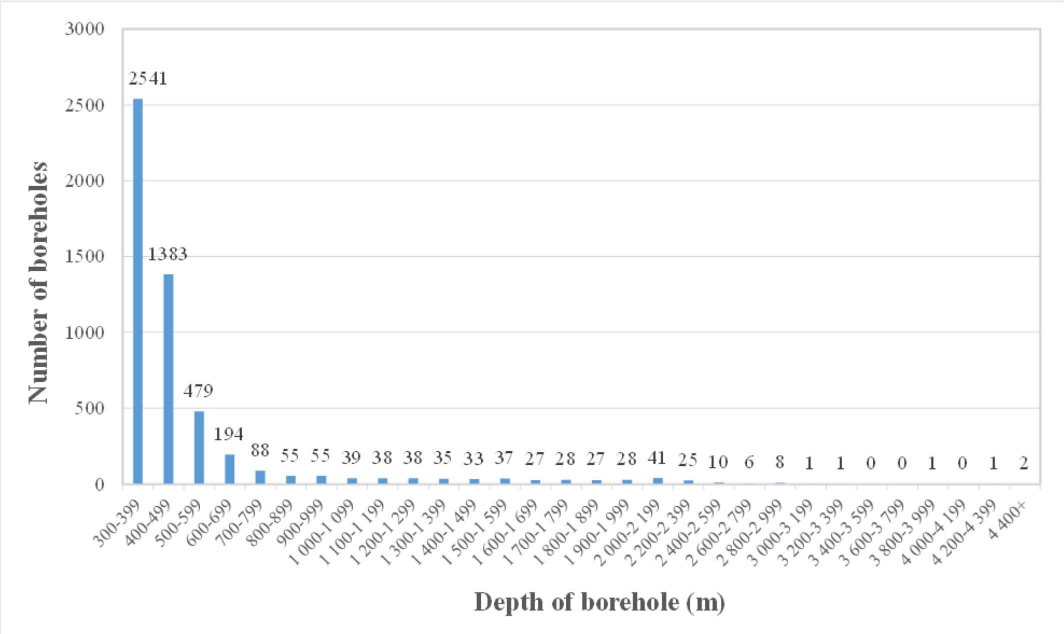


Figure 4-3: Depth distribution of boreholes with depths exceeding 300 m in the CGS database

4.4 THE SOEKOR BOREHOLES

Between 1965 and 1975, SOEKOR (now known as PetroSA) drilled at least 25 deep boreholes (with depths in excess of 2,000 m) as part of an oil and gas exploration programme (Vermeulen, 2012; Swana, 2016). These boreholes were installed at locations where the rocks of the Karoo Supergroup were thought to be potentially favourable for oil and gas production. The distribution of the SOEKOR boreholes is shown in Figure 4-5.

The Karoo Groundwater Expert Group (KGEG) (2014) summarised the available information on the SOEKOR boreholes. This includes information on the following:

- Borehole construction (depth and diameter)
- Borehole logs (geological, chromato, gamma, neutron, density, sonic, electric and caliper)
- Water strikes (depth and flow rate)
- Groundwater quality (information from only two samples taken during 2012 and 2013)

Not all the above information is available for all the SOEKOR boreholes. For some boreholes, the information is limited to the depth of the borehole, accompanied by a brief description of the lithologies intersected.

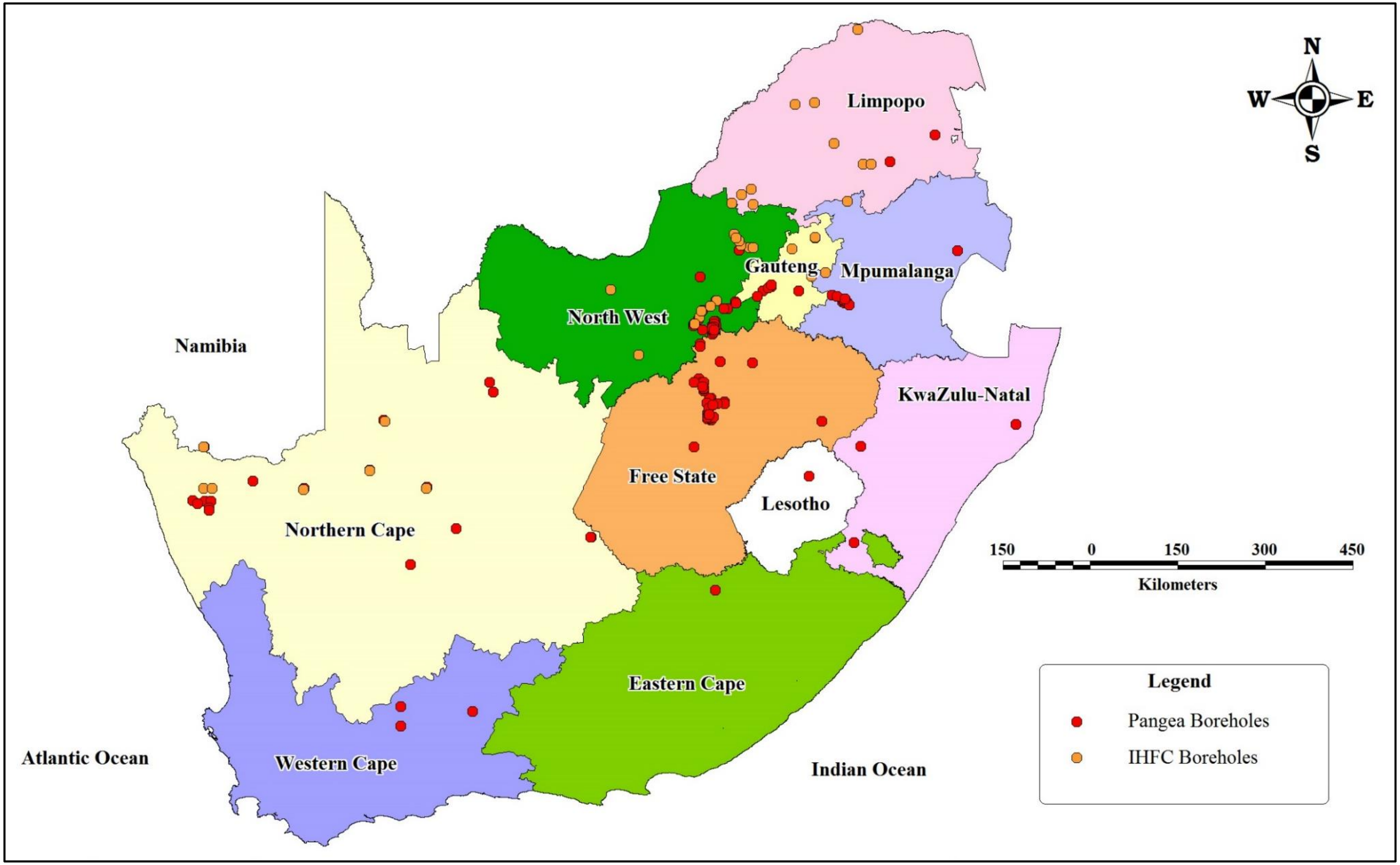


Figure 4-4: Distribution of boreholes with depths greater than 300 m in the IHFC and Pangea databases

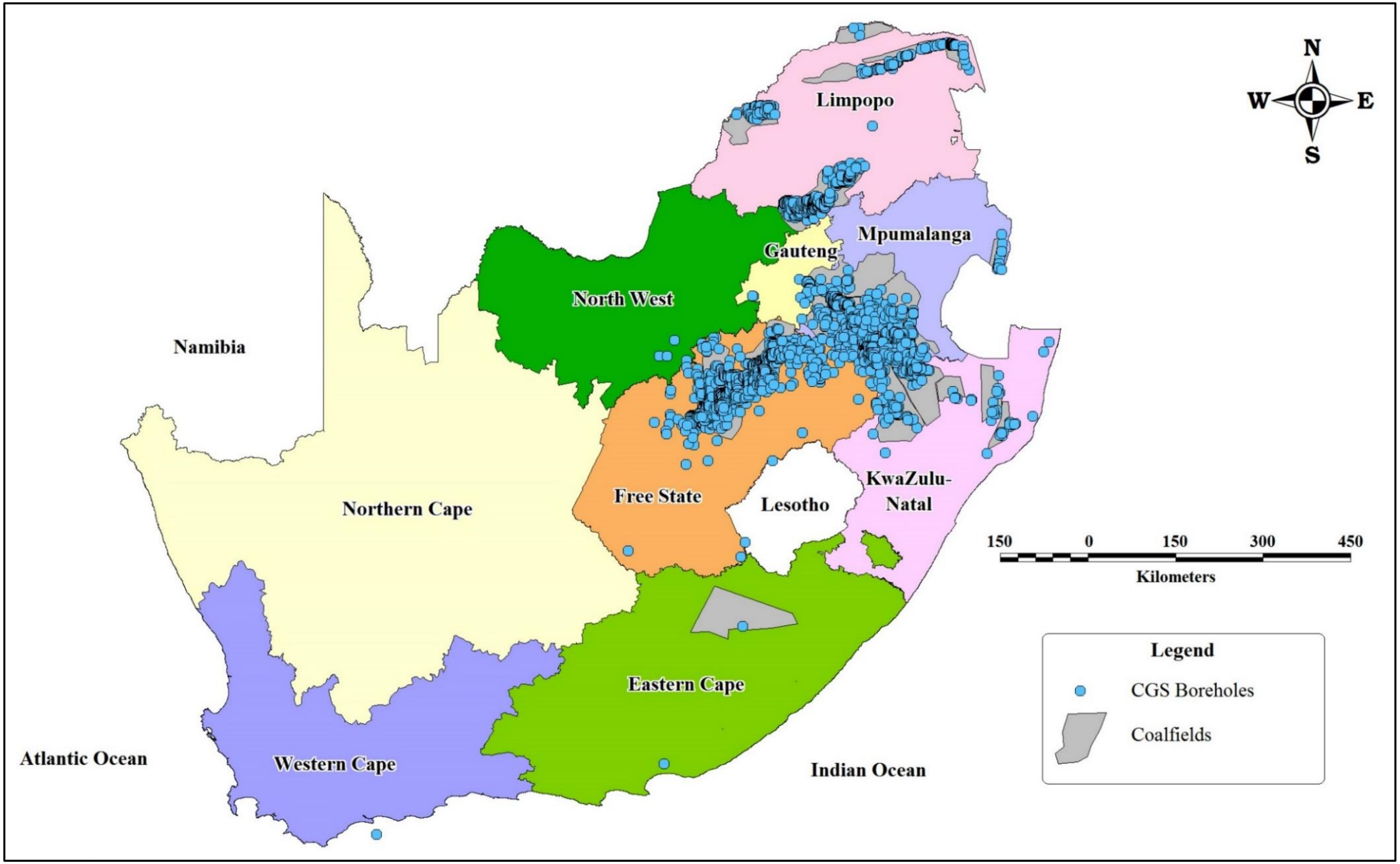


Figure 4-5: Distribution of boreholes with depths greater than 300 m in the CGS database

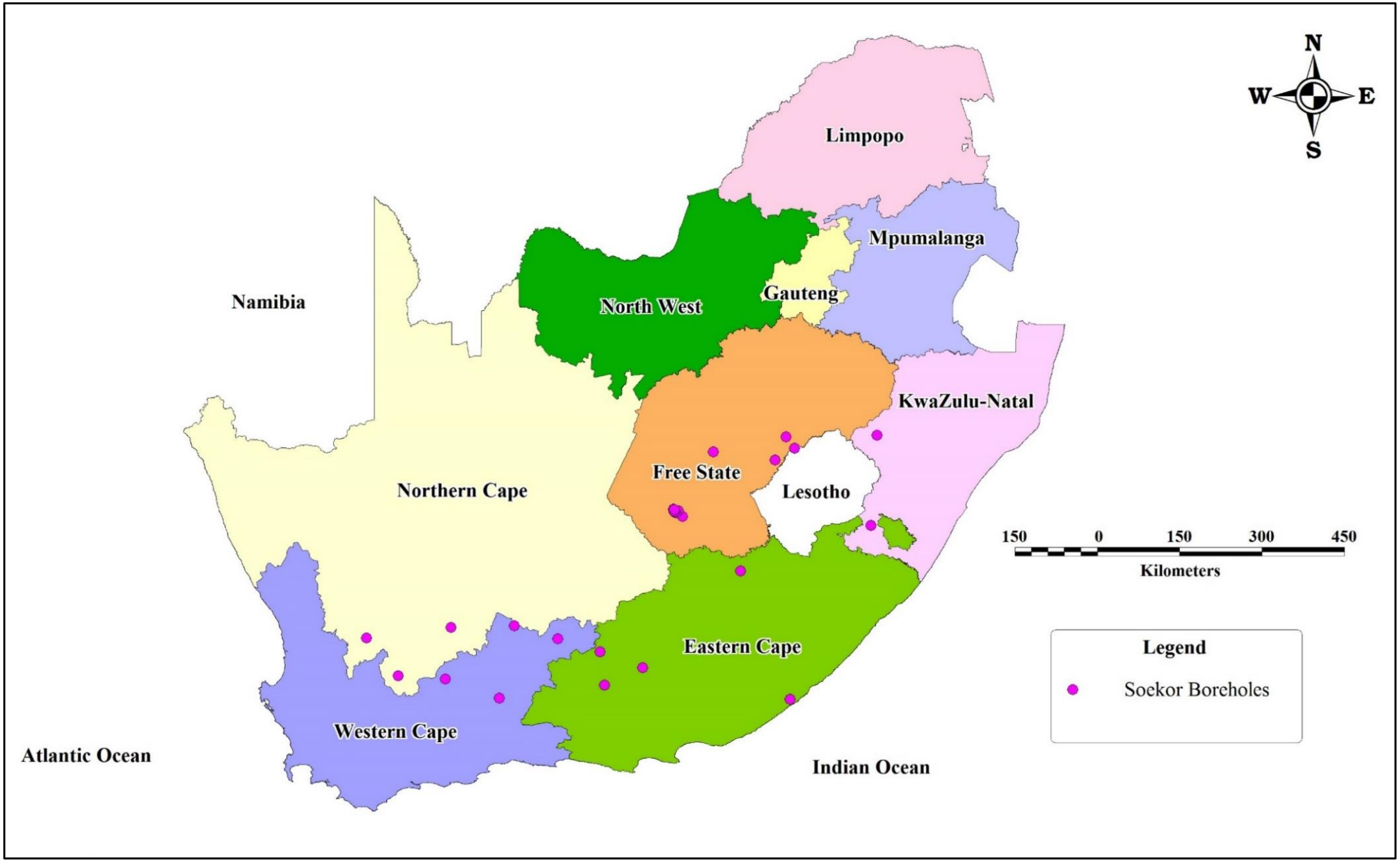


Figure 4-6: Distribution of the SOEKOR boreholes

4.5 BOREHOLES IN THE DATABASE OF THE PETROLEUM AGENCY SOUTH AFRICA

On behalf of the South African government, PASA promotes exploration for onshore and offshore resources of oil and gas, as well as the optimal development of these resources. The agency also regulates exploration and production activities. It acts as the custodian of the national petroleum exploration and production database.

The database currently contains information on 598 exploration and production wells, both onshore and offshore. The distribution of the onshore and offshore boreholes in the database is shown in Figure 4-7. Information on these wells may be ordered using the Storefront Web Mapping Application (https://geoportal.petroleumagencysa.com/Storefront/Viewer/index.htm) on the agency's website.

Unfortunately, the depths of only 13 offshore boreholes are listed in the database of PASA. These boreholes have depths ranging from 2,443.4 to 3,548.5 m. The positions of these boreholes are shown in Figure 4-8. Eleven of the boreholes occur to the south of Mossel Bay and were probably drilled during exploration for the Mossgas fuel-from-gas project. One borehole is located southeast of Port Elizabeth, approximately 60 km from the shore, while another occurs south of Richards Bay, approximately 30 km from the shore.

Various reports may be ordered from the website for each of the 13 boreholes. Some of these reports are likely to contain valuable information on the aquifer systems intersected during drilling. The 13 boreholes with depth information are listed in Table 4-1. Also listed in the table are some of the reports available for each borehole, as well as the costs of these reports.

Although information on borehole depth is only explicitly listed in the database for these 13 boreholes, it is very likely that depth information on the other boreholes in the database is also available in the various reports compiled for these boreholes. Unfortunately, these reports would first need to be purchased to ascertain whether such information is available.

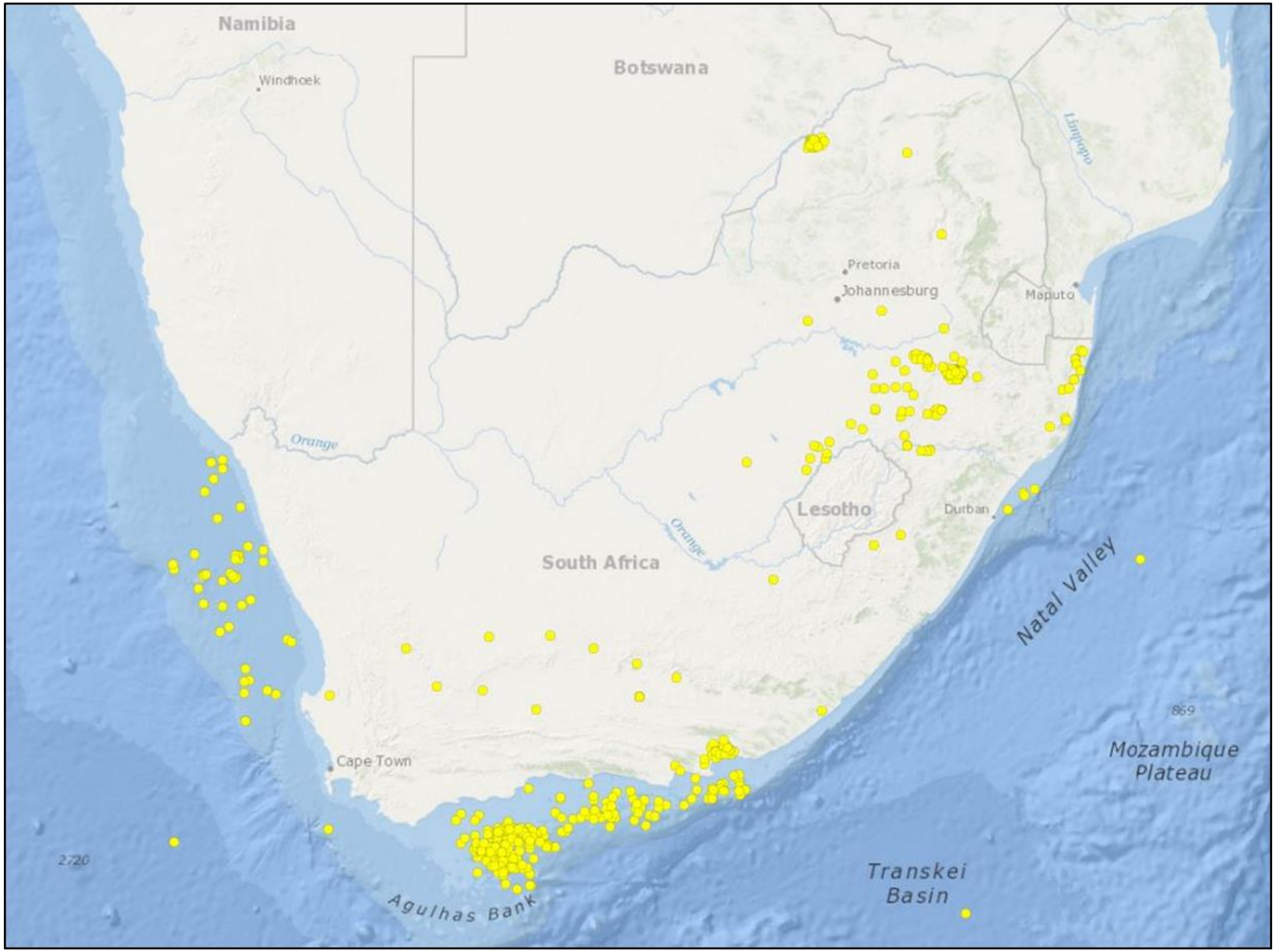


Figure 4-7: Distribution of onshore and offshore boreholes in the database of PASA

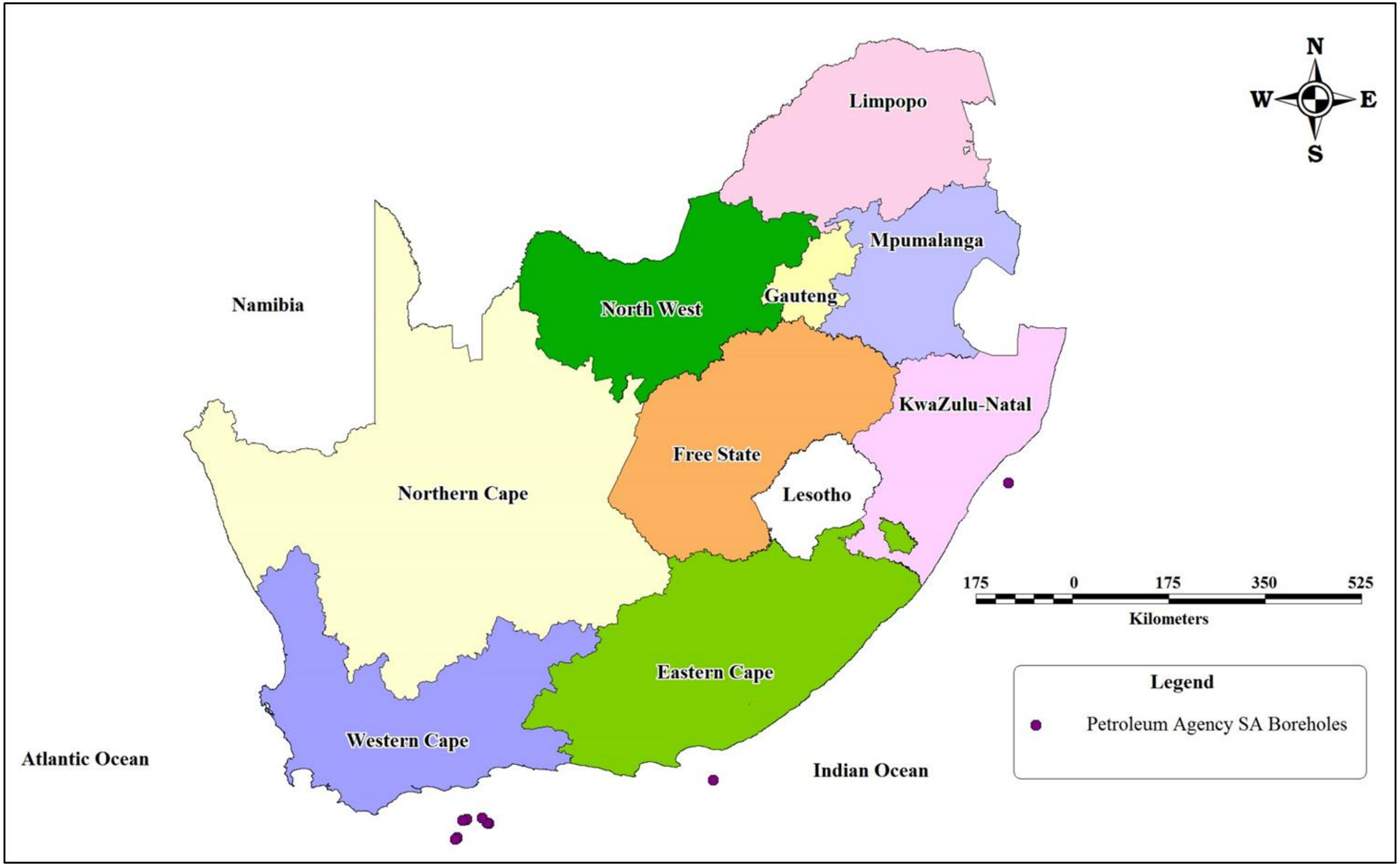


Figure 4-8: Distribution of boreholes with depths greater than 300 m in the database of PASA

Table 4-1: Reports available for the deep boreholes in the database of PASA

Name/ Number	Longitude (°E)	Latitude (°S)	Depth (m)	Nearest City / Town	Available Reports	Cost (R)
Jc-D1	31.80843	-29.39672	2 888.00	Richards Bay	Geophysical Survey of the Rhino Drill Site	120.00
					Interpretation of Fluid Inclusion Stratigraphy	30.00
					Intermediate Survey	120.00
					Final Drilling Report	100.00
					Geophysical Log	0.00
					Environmental Close Out Management Programme	100.00
					End of Well Report	100.00
					Waveform Slowness Analysis Results	0.00
					Environmental Management Programme Report	50.00
					Geochemical Analysis of Ten Rock Extracts	30.00
					Well Plan	100.00
					Description of Sidewall Cores	30.00
					Final Geological Report	300.00
					Geochemical Analysis of Samples	30.00
					Statigraphic Reconstruction	100.00
					Drilling	600.00
Hb-Q1	26.31084	-34.26289	3 548.50	Port Elizabeth	End of Well Report	100.00
					Well Drilling Close Out Report	100.00
					Petrophysical Evaluation	0.00
					Well Report	100.00
					Drilling Programme	100.00
					Geological Well Completion Report	300.00
F-BE1	22.12559	-34.97216	2 559.70	Mossel Bay	End of Well Report	180.00
					Drilling Well Completion Report	100.00
					Geological Well Completion Report	300.00
F-AD01P	22.09705	-34.96309	2 725.80	Mossel Bay	Drilling Programme	100.00
E-BF01PZ1	21.71210	-34.91439	2 529.75	Mossel Bay	Well Installation Report	100.00
					Completion and Well Testing Report	30.00
					Drilling Well Completion Report	100.00
					Petroleum Engineering Report	30.00
E-AR02P	21.53840	-35.19910	2 514.55	Mossel Bay	Geophysical Log	0.00
E-BT01P	21.49777	-35.23359	2 550.98	Mossel Bay	Geochemistry Data and Summary Report	30.00
					Petrography Core Analysis and Interpretattion Report	30.00
E-H2	21.71502	-34.90437	2 830.30	Mossel Bay	Completion and Well Testing Report	30.00
					Drilling Programme	100.00
					Well Completion Report	0.00
					End of Well Report	100.00
					Drilling Well Completion Report	100.00
					Geophysical Log	0.00
E-M01P	21.63407	-34.91917	2 563.40	Mossel Bay	End of Well Report	100.00
					Completion and Well Testing Report	30.00
E-M03P	21.65096	-34.91630	2 596.40	Mossel Bay	Geophysical Log	0.00
					Drilling Well Completion Report	0.00
E-AR03P	21.53990	-35.20467	2 443.40	Mossel Bay	No Report Available	
E-M02P	21.63489	-34.91912	2 569.40	Mossel Bay	No Report Available	
F-AH02P	22.00067	-34.87946	2 577.00	Mossel Bay	No Report Available	

4.6 BOREHOLES IN THE NATIONAL GROUNDWATER ARCHIVE

The National Groundwater Archive is a web-enabled database managed DWS. It allows the capture, viewing, extraction and modification of groundwater-related data. The database was developed as part of the DWS's obligation to manage and develop the water resources (including groundwater) of South Africa in a sustainable and equitable manner. Access to groundwater data is becoming increasingly important for projects aimed at providing water to rural and urban communities, as well as for agricultural use.

When the NGA was accessed on 4 March 2016, it contained information on 264,232 groundwater sites in South Africa, including information on 253,441 boreholes, five drains, 1,661 dug wells, 13 mines, 436 seepage ponds, 12 sinkholes, 8,047 springs and 617 well points. Of the groundwater sites in the database, 1,116 have depths equal to or exceeding 300 m. The depth distribution of the boreholes with depths exceeding 300 m is shown in Figure 4-9. Most boreholes have depths in the 300 to 399 m range, while similar numbers of boreholes are seen for the other depth ranges. No boreholes with depths in excess of 1,000 m are listed in the NGA. The locations of these deep boreholes are shown in Figure 4-10. Deep boreholes are seen to occur in all the provinces of South Africa, with particularly dense distributions of boreholes in the northern parts of Limpopo and the Northern Cape, as well as in the eastern parts of the Free State.

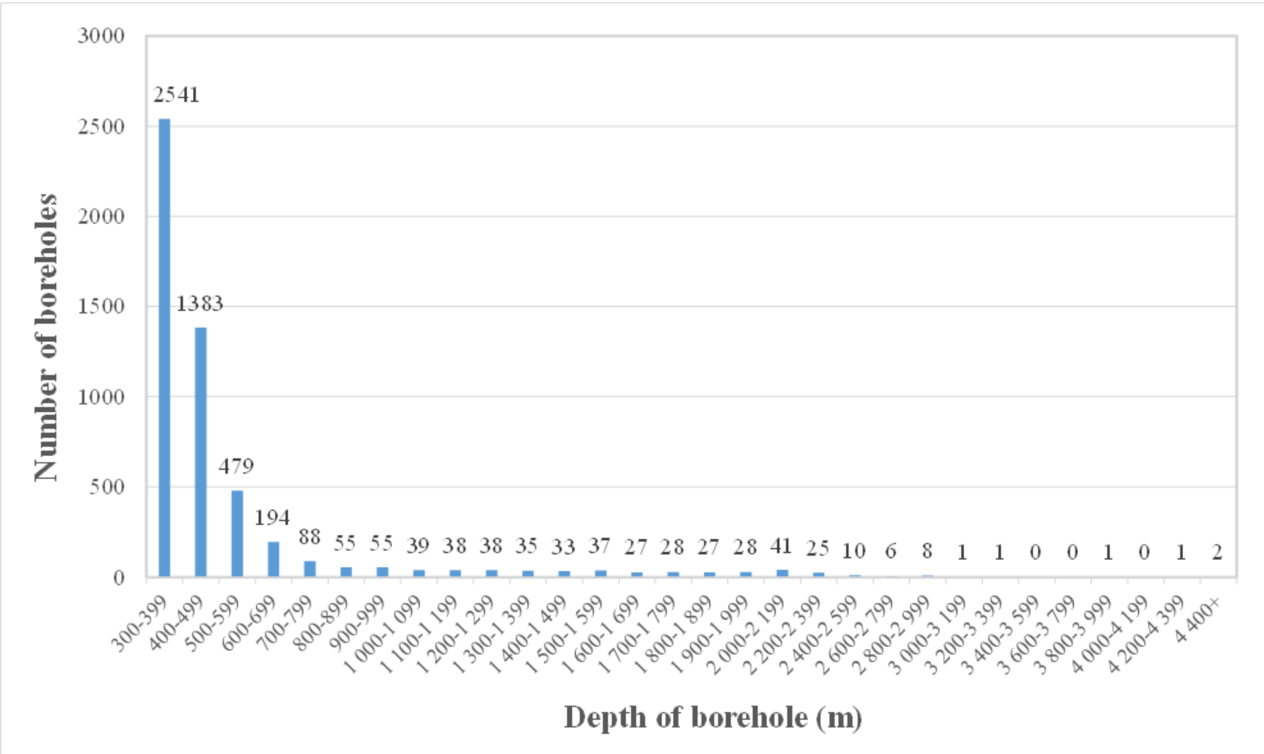


Figure 4-9: Depth distribution of boreholes with depths exceeding 300 m in the NGA

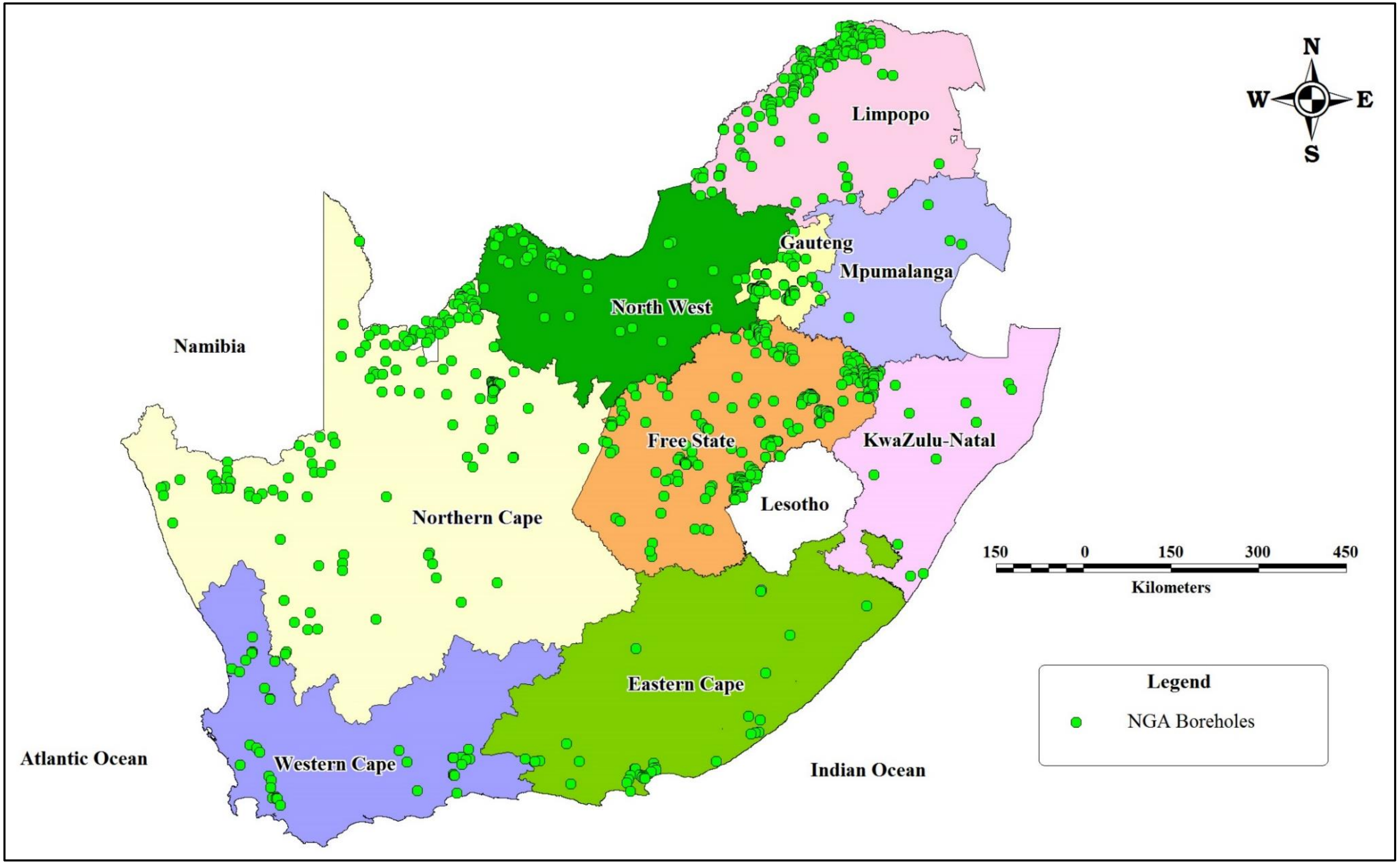


Figure 4-10: Distribution of boreholes with depths greater than 300 m in the NGA

The NGA allows the capture of an extensive array of information on the different groundwater sites. This includes the following:

- General site information
- Construction of the site
- Lithology intersected
- Depth and diameter of borehole sites
- Casings installed in boreholes
- Measured water levels
- Depths and yields of water strikes
- Abstraction rates
- Discharge rates
- Field measurements taken (e.g. pH level, electrical conductivity)
- Water quality
- Equipment installed
- Downhole geophysics
- Pumping test data
- Yield tests performed

Not all the above information has been captured for all the sites in the NGA. In fact, for most sites, the information is very sparse.

4.7 THERMAL SPRINGS IN SOUTH AFRICA

4.7.1 Introduction

Thermal springs are the surface occurrences of water heated geothermally, and therefore represent water that circulates deep in the earth's crust. Thermal springs are thus likely to provide useful information on geohydrological conditions in the deep aquifer systems. Thermal springs develop when surface water descends into the earth and gets heated by either the geothermal gradient in the earth's crust or by the presence of shallow magma chambers. The water is heated and returns along preferential pathways, such as faults and fissures, to the surface of the earth. Thermal springs are either of volcanic or of meteoric origin.

4.7.1.1 Thermal springs of volcanic origin

According to Scheffel and Wernert (1980), thermal springs occur in volcanic areas where reservoirs of molten or slowly cooling magma lie close to the surface and have heated the rocks above. The water is heated as it flows through cracks in the rocks, and if the passage of water to the surface is unobstructed, the heated water continuously bubbles up to the surface and forms a thermal spring.

4.7.1.2 Thermal springs of meteoric origin

Thermal springs of meteoric origin are formed due to the effect of the geothermal gradient rather than due to volcanic activity. Temperature increases with increasing depth in the earth. Cold water from rain, rivers or lakes may descend along a fault to a depth of several kilometres. This underground water is heated due to the geothermal gradient of 2.5 to 3 °C per 100 m, which causes it to expand and rise up another fault and so create a convection system (Hoole, 2001; LaMoeaux and Tanner, 2001). Figure 4-11 illustrates diagrammatically how meteoric and volcanic hot springs are formed.

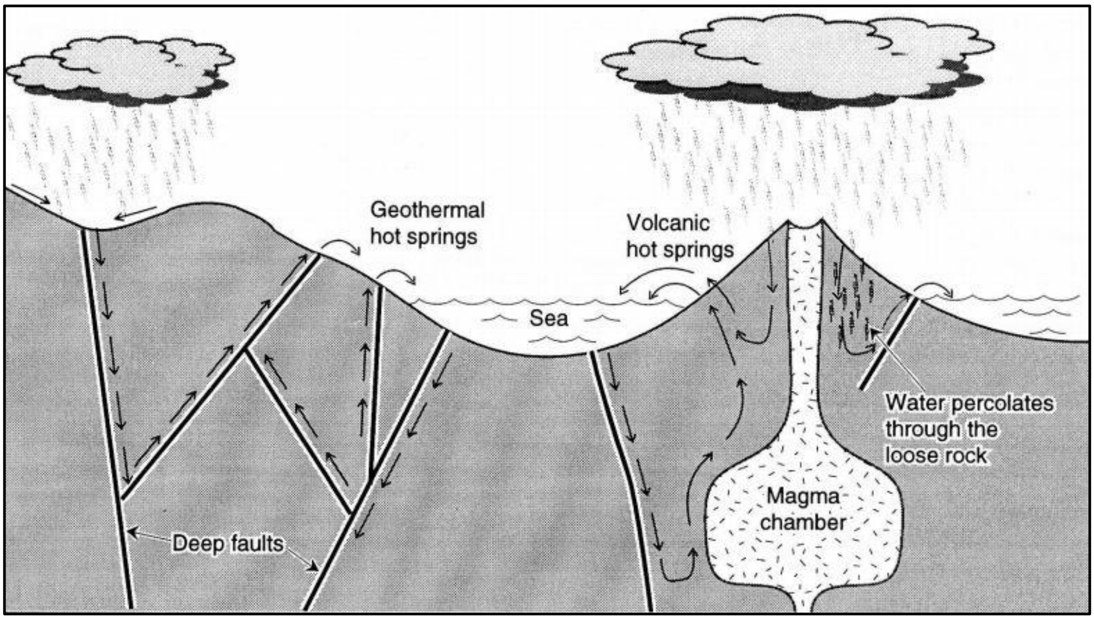


Figure 4-11: Diagrammatic representation of the origin of thermal springs (Higgins and Higgins, 1996)

South African thermal springs are normally used for tourism and recreational purposes. Since there is no evidence of recent volcanic activity, it is generally assumed that all thermal springs in South Africa are of meteoric origin (Rindl, 1936; Kent, 1949). According to Witcher (1981), thermal springs originate from a combination of special conditions. These conditions include the following:

- A heat source
- A recharge source
- A circulation framework or storage reservoir
- A discharge mechanism

The hottest geothermal spring in South Africa is Siloam in Limpopo. Siloam is situated on the Nzhelele Fault in a relatively active geological area. Before 2000, the temperature of the water was significantly lower in the area. However, after a period of tremendously heavy rain, the Siloam hot spring emerged with a water temperature measuring 67.5 °C.

4.7.2 Distribution of thermal springs in South Africa

South Africa has 87 known thermal springs (Hoole, 2001; Olivier et al., 2010; Tuwani, 2011), of which more than 30 are run as resorts (Boekstein, 1998). However, the exact number of thermal springs in the country is not known. According to Kent (1952), the majority of South Africa's thermal springs are confined to a broad band (approximately 400 km wide) that extends across more than half the country, starting at Piketberg in the Western Cape through KwaZulu-Natal, the Free State and Gauteng, up to the Soutpansberg in Limpopo. Information extracted from maps by Kent (1949), Boekstein (1998), Hoole (2001) and Baiyegunhi et al. (2014) shows that Limpopo and the Western Cape are the most richly endowed with thermal springs (Figure 4-12).

Since there is no evidence of recent volcanic activity in South Africa, geological studies have shown conclusively that the origin of each individual thermal spring can be attributed to the local presence of deep geological structures such as fractures, folds, faults and dykes that provide a means for circulation to depth and the return of the heated waters to the surface. The secondary permeability of the rocks is very important for South African hot springs, as it is not only responsible for the formation of the fractured rock aquifers that host the spring water, but also provides preferential flow paths for the hot water to reach the surface.

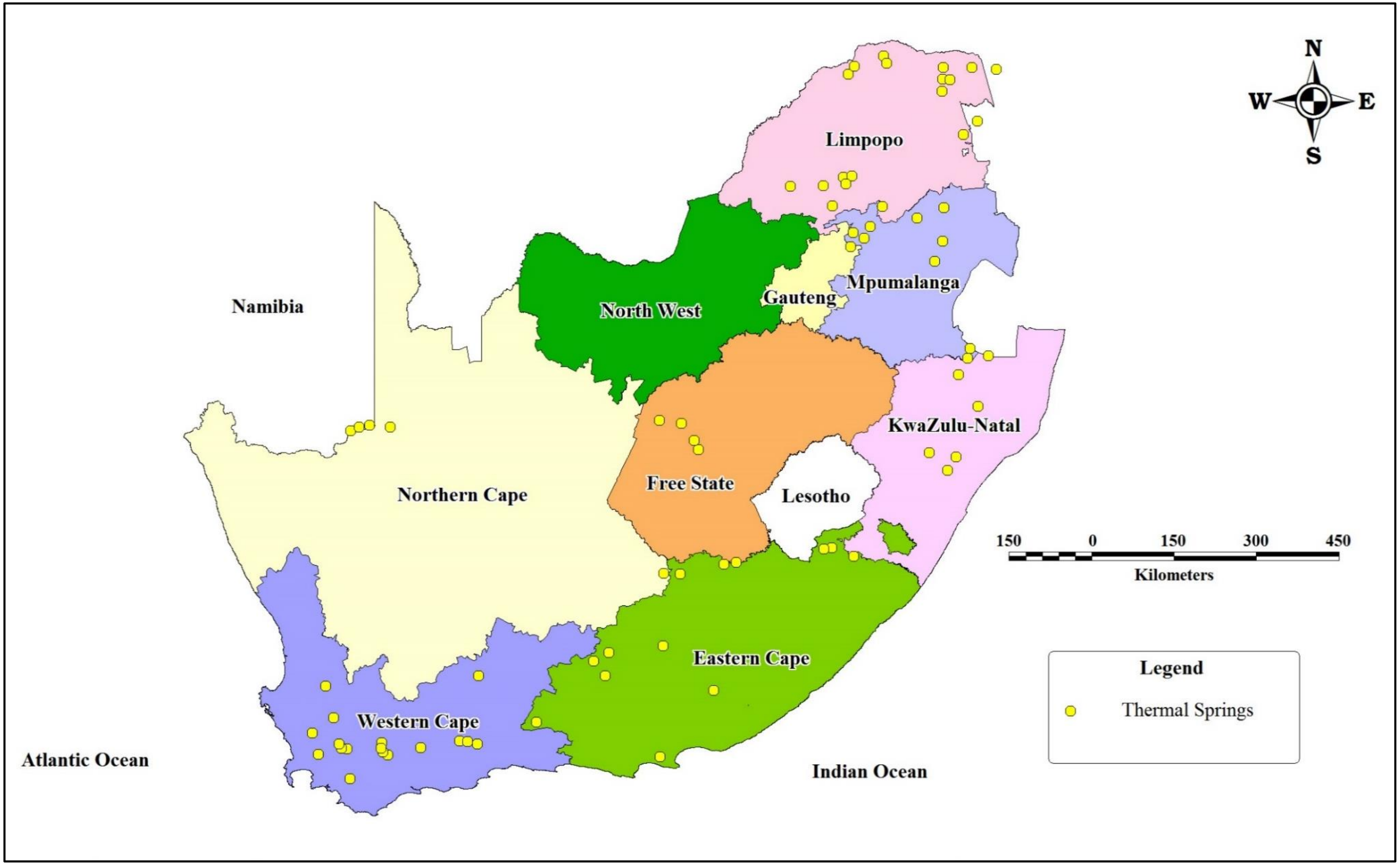


Figure 4-12: Distribution of thermal springs in South Africa (after Baiyegunhi et al., 2014)

4.7.3 Information on the hydrochemical characteristics of water from thermal springs

Water from the majority of the thermal springs in South Africa does not reflect the surface geology. The chemical characteristics of thermal water are largely determined by the rocks through which the hot water circulates. It is not always straightforward to match the composition of thermal spring water to the geological formations known to occur in the area of the spring (Kent, 1949).

Various studies have been conducted on the hydrochemical characteristics of water from thermal springs in South Africa. Kent (1949) listed and discussed the results of chemical analyses performed on the water from several thermal springs that occur in different geological formations across South Africa. Olivier et al. (2008; 2010; 2011) presented the results of chemical analyses performed on the water from thermal springs in Limpopo. Tshibalo and Olivier (2010) and Tshibalo (2011) listed and discussed the results of hydrochemical analyses performed on waters from the Sagole thermal spring in the Vhembe district of Limpopo. Boekstein (2012) described the hydrochemistry of thermal springs in the Western Cape. Zonker et al. (2013) discussed the association between the geochemical characteristics of thermal springs in Limpopo and algal diversity. Samod (2015) discussed the trace element concentration in geothermal springs and its impact on soil and vegetation. The author focused on the Siloam and Tshipise thermal springs in Limpopo.

4.8 BOREHOLES OF THE KAROO RESEARCH INITIATIVE

The Karoo Research Initiative is an academic contribution to geoscientific research in South Africa. The research team includes researchers from six of South Africa's leading universities (the University of Johannesburg, University of the Witwatersrand, University of Pretoria, University of the Free State, University of Cape Town and Stellenbosch University), as well as from Keele University in the United Kingdom (Beukes et al., 2015) and the CGS. International partners in the project are TU Darmstadt (Germany), the University of Texas at Dallas (USA) and the Kazan Federal University (Russia). The KARIN project is incorporated under CIMERA (the Centre of Excellence for Integrated Mineral and Energy Resource Analysis of the National Research Foundation (NRF)-Department of Science and Technology (DST)).

The KARIN project entails the installation of two deep core boreholes in the southern parts of the Karoo Basin. The main aim of the project is to improve the understanding of the stratigraphy and basinal settings of potential shale gas reserves in the Karoo Basin south of the dolerite line. Core from the two deep boreholes will be examined and will allow reconstruction of the depositional history of the basin, determining the physical and petrochemical character of the rocks and unravelling the deep structure of the basin and dolerite intrusions.

The main objectives of the KARIN project are as follows:

- Gain an increased understanding of the stratigraphy and structure of the southern part of the main Karoo Basin
- Study the palynology to establish a biostratigraphic framework of the Ecca Group
- Determine the gas content, total organic carbon and thermal maturity of the Ecca Group shales, specifically the Whitehill Formation
- Study the paleomagnetic record in order to establish a magnetostratigraphic framework for the Karoo Basin
- Investigate Karoo dolerite sills in order to understand the process of magma differentiation and crystallisation operating in mafic sills of the Karoo Basin
- Study the effect of dolerite sill intrusions on the thermal maturation of organic-rich shales, principally the Whitehill formation
- Study the petrophysical and geomechanical properties of core samples of the Ecca Group shales

- Study the geomechanical properties of the various lithologies of the Karoo Supergroup intersected in the deep boreholes
- Study the properties and geohydrological conditions of deep aquifers encountered in the boreholes

The two core boreholes were installed during the latter half of 2015. Borehole KFZ-01 was drilled on the farm Zandfontein, approximately 85 km northeast of Ceres in the Western Cape. This borehole was drilled to a depth of 671 m. Borehole KWV-01 is located approximately 10 km east of Willowvale in the Eastern Cape. This borehole was drilled to a depth of 2,353.5 m. The location of the two core boreholes is shown in Figure 4-13.

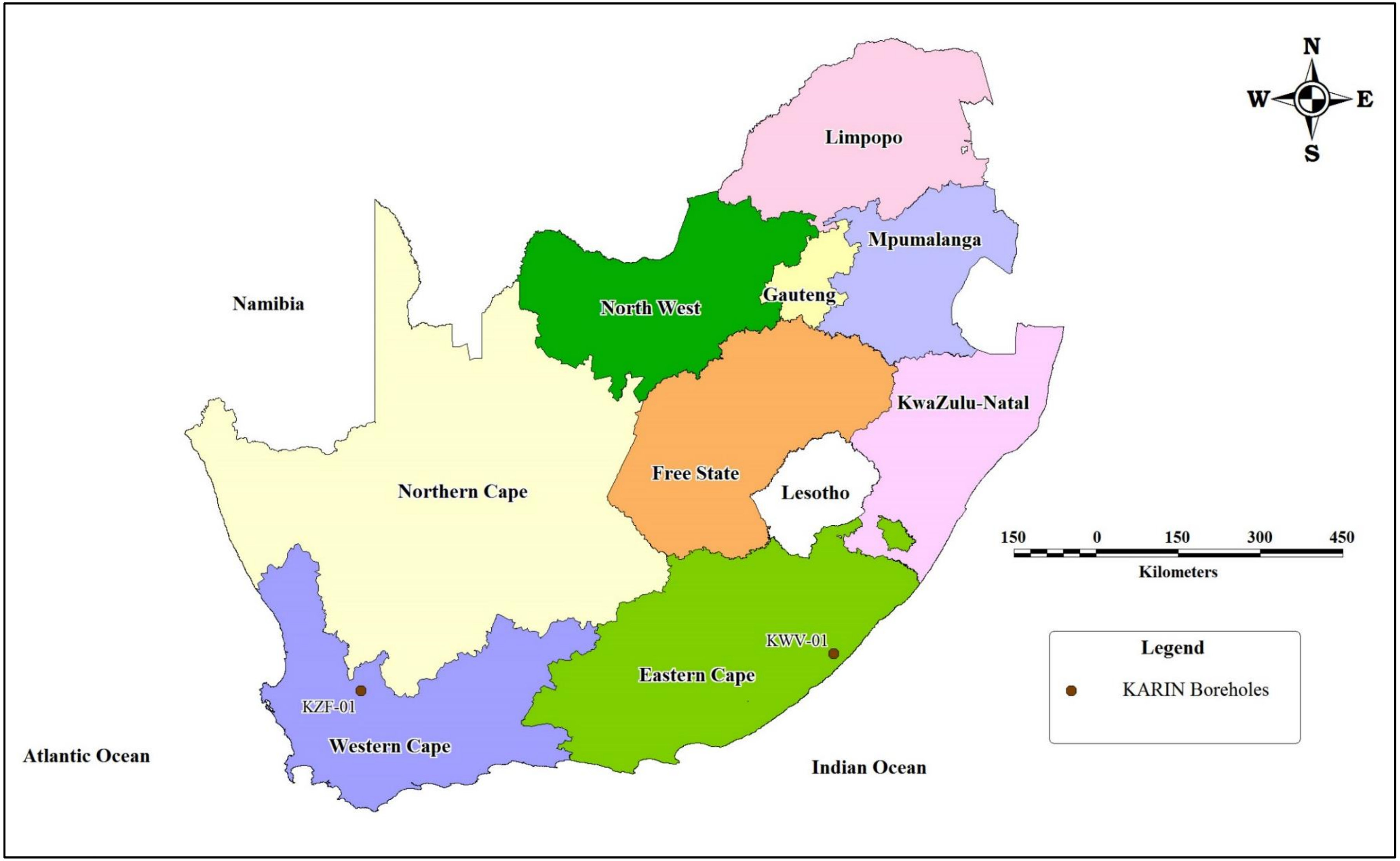


Figure 4-13: Location of the two KARIN boreholes

Apart from detailed geological core logging, geophysical logging of both boreholes was done. Water strikes were noted during drilling, and groundwater samples were collected from various depths for chemical and isotope analyses. Gas sampling was also done at selected depths. In addition, detailed geophysical logs (calliper, resistivity, density, acoustic televiewer, neutron, formation dip, groundwater flow and verticality) were compiled along the entire length of the boreholes to provide *in-situ* measurements of physical rock and water properties, and fracture orientations to supplement knowledge gained from drilled core analyses.

The geological, geophysical and geohydrological data collected from the two KARIN boreholes is extensive and will likely contribute to a much greater understanding of the deep fractured aquifer systems in the southern Karoo Basin.

4.9 GROUNDWATER INFORMATION FROM OPEN-CAST AND UNDERGROUND MINES

4.9.1 Mining history of South Africa

South Africa has an abundance of mineral resources and is a world leader in mining. The country is estimated to have the fifth largest mining sector in terms of the GDP value. It has the world's largest reserves of manganese and the platinum group metals (PGMs), and among the largest reserves of gold, diamonds, chromite ore and vanadium. South Africa is also a major producer of coal.

The era of modern commercial mining in South Africa has its roots in the copper-rich region of Namaqualand in the Northern Cape (SAN, 2017). The first mine was established on the farm Springbokfontein, where the town of Springbok is now located, in 1852. However, the real catalyst of the mineral revolution, on the back of which the country's modern industrial economy has been built, was the discovery of diamonds in the Northern Cape in the late 1860s. While the history of gold mining is often presumed to post-date diamond mining, in reality, the precious metal was discovered and the first mine was established at approximately the same time as the diamond rush. Gold was discovered on the farm Eersteling, approximately 40 km southeast of Polokwane, in the closing months of 1870. During February 1886, gold was discovered in the Witwatersrand Basin. The Witwatersrand gold-mining industry rapidly developed, despite various challenges, including the large depth and pyritic nature of the conglomerate reefs, the very low grade of the resource, the high costs of production and the enormous labour requirements of the mines (SAN, 2017).

While the success of South Africa's modern economy was underpinned by the growth of the gold- and diamond-mining sectors, the industrialisation of the economy could not have been achieved without coal and iron ore. Vast resources of coal, discovered in the 1850s, but developed on a significantly large scale from the 1890s onwards as the needs of the mining industry began to expand, provided the power base of the country (SAN, 2017).

The exploitation of the country's vast iron-ore resources in the North West and Northern Cape, and the establishment of a state-controlled iron and steel industry in the 1920s facilitated the growth of a secondary industry and enabled South Africa to develop into the most industrially self-sufficient country in Africa (SAN, 2017).

Platinum, the precious metal that now constitutes South Africa's flagship mining sector, was discovered in 1924, but it was only in the early 1970s that South Africa's platinum sector began to experience significant growth (SAN, 2017).

In the latter half of the 20th century, the mining industry underwent considerable diversification with the growth of new sectors, such as uranium, chromium, vanadium and manganese (SAN, 2017).

4.9.2 Information on deep aquifer systems potentially obtainable from mines

The deep mines in South Africa are potentially a wealthy source of data and information on the deep aquifer systems intersected by mining. Information gathered during the mineral exploration and production phases of mining could greatly contribute to the understanding of the deep groundwater and aquifer conditions. Some of the potential sources of information at mines are briefly described below.

4.9.2.1 Exploration drilling

During the exploration drilling phase, core boreholes are typically installed on a grid above the targeted ore body. The cores that are retrieved from drilling are then studied for mineral content, stratigraphic contacts and secondary geological features, such as faults, fissures and weathering.

Although the cores are not typically studied to gain an understanding of the properties of the aquifers intersected by drilling, these cores are potentially a rich source of information on the deep geohydrology in the vicinity of the mine. Geohydrological information that could be obtained from the cores includes the following:

- The vertical extent of the different aquifers that are intersected by drilling. Information on the stratigraphy could help assess which layers are likely to act as aquifers, aquicludes and aquitards.
- The presence of faults, fractures, fissures, joints and other features that contribute to the secondary porosity of the intersected aquifers.
- Evidence of groundwater movement. Fractures along which groundwater migration takes place may be distinguished from those that do not carry water by considering the weathering of the fractures and the leaching of minerals from the host rock.
- The presence of mineralisation that could potentially influence groundwater quality. For example, the presence of pyrite in the host rock could indicate the likelihood of the formation of acidic conditions, which could lead to the mobilisation of trace metals.

4.9.2.2 Borehole logs

Borehole logging is the process of measuring the physical, chemical and structural properties of penetrated geological formations, usually using logging tools that are lowered into a borehole on a wireline cable. Geophysical borehole logging could provide in-situ information, not only on the physical properties of the rock strata, but also on the groundwater within the borehole.

Geological borehole logging is often performed on the core boreholes that are installed at mines. While mining companies typically use the borehole logs to extract information relevant to mining operations, these logs may also contain information that could be used to characterise the aquifer systems that are intersected by the core boreholes. Geohydrological information that could be obtained from the borehole logs includes the following:

- Information on the porosities of the different geological units that are intersected (neutron logs)
- Information on the salinity of the groundwater that is encountered at different depths in the borehole (electromagnetic and resistivity logs)
- Information on the presence and orientation of fractures (optical logs)
- Information on groundwater flow direction and speed (flow logs)
- Information on groundwater quality (electrical conductivity, pH and Eh values and temperature logs)

4.9.2.3 Ground and airborne geophysics

Although geophysical investigations for mines are usually done with mineral exploration in mind, the recorded geophysical data is also potentially valuable from a groundwater perspective. Existing geophysical data may be reprocessed and/or reinterpreted to gain a better understanding of the structural geological controls that influence the deep aquifer systems.

The data may be used to define the lateral and vertical extents of the aquifers, and to obtain first estimates of the quality of the groundwater present in the aquifer systems.

4.9.2.4 Mine dewatering

Mine dewatering is often done at both open-cast and underground mines to allow mining to proceed efficiently and to ensure the safety of the mining personnel. The groundwater abstraction rates that are required to dewater the mines are direct measures of the rates of groundwater influx into the mine, and therefore of the yields of the intersected aquifers.

Apart from the information on the quantity of groundwater at the mine, mine dewatering may also provide information on the quality of the groundwater. Groundwater abstracted from the mines is often used for various applications, including process water at the refineries and plants, road wetting for dust suppression, irrigation and even domestic use. Since information on the quality of the abstracted groundwater is required before it can be used for the different applications, mines often do regular sampling and chemical analyses of the water. The water quality data is typically stored in databases kept at the mine.

4.9.2.5 Exposure of the geological units and aquifers

Mining allows direct access to deep aquifer systems that are intersected by pits and shafts. Visual observations of the exposed rock units that form the aquifers, aquitards and aquicludes may therefore be made. The frequency, orientations, aperture widths, yield and interconnectivity of the fracture networks in the rock may be documented.

4.9.3 Current mining activities in South Africa

The Department of Mineral Resources (DMR) annually releases a series of documents that provides information on mining activities in South Africa. These documents may be downloaded from the Department's website at http://www.dmr.gov.za/publications/viewcategory/121-directories.html. The most recent editions of these documents include the following:

- *Operating mines and quarries and mineral processing plants in the Republic of South Africa, 2015*
- *Operating gold mines and recovery plants in the Republic of South Africa, 2015*
- *Operating and developing coal mines in the Republic of South Africa, 2015*

Apart from the abovementioned documents, information on the various mines in the country are also listed in a downloadable Excel sheet (http://www.dmr.gov.za/publications/summary/121-directories/1168-d1-operating-mines-2015-excel-.html). The Excel sheet list 1,779 registered mines in South Africa, including 1,493 mines at which open-cast activities take place, 172 mines where underground mining is done and 134 mines at which surface mining takes place (at some mines, more than one type of mining is done).

4.9.3.1 Deep open-cast mining

Although the depths of open-cast mines rarely exceed 300 m, a few deep open-cast mines occur. Information on deep aquifer systems could potentially be obtained from these mines. An example of a deep open-cast pit is the open pit at Phalaborwa Copper, which has a depth of 898 m.

4.9.3.2 Underground coal mining

In South Africa, coal is found in 19 coalfields. These coalfields are mainly located in Mpumalanga, Limpopo, KwaZulu-Natal and the Free State (Figure 4-14). Lesser coal deposits also occur in Gauteng, North West and the Eastern Cape (Jeffrey, 2006). Coal seams are generally thick and close to the surface, allowing for low-cost mining.

Approximately 25% of South Africa's bituminous coal occurs at depths of less than 50 m below the surface, with much of the remainder occurring below depths of 200 m (Eberhard, 2011). However, seams of the Waterberg Coalfield occur at depths of up to 400 m, while seams of the Springbok Flats Coalfield occur at depths in excess of 1,000 m (Jeffrey, 2006). Underground mining accounts for approximately half of South Africa's coal-mining operations.

The DMR's 2015 database on mining operations in South Africa lists 59 underground coal mines. These mines typically operate up to depths of around 200 m below the surface, but some may extend to greater depths and thus provide access to deep aquifer systems.

4.9.3.3 Mining in the Bushveld Igneous Complex

The Bushveld Igneous Complex is a massive crustal emplacement of extrusive and intrusive igneous rocks (Coffin and Eldholm, 1994). The Bushveld Igneous Complex comprises four volcanic sequences:

- The Upper Rooiberg Group
- The Rustenburg Layered Suite
- The Rashoop Granophyre Suite
- The Lebowa Granite Suite

The Bushveld Igneous Complex is richly endowed with platinum, palladium, rhodium, chromium and vanadium ore bodies. It is mined extensively from Burgersfort in the east to Rustenburg in the west. The distribution of outcrops of the Bushveld Igneous Complex is shown in Figure 4-15.

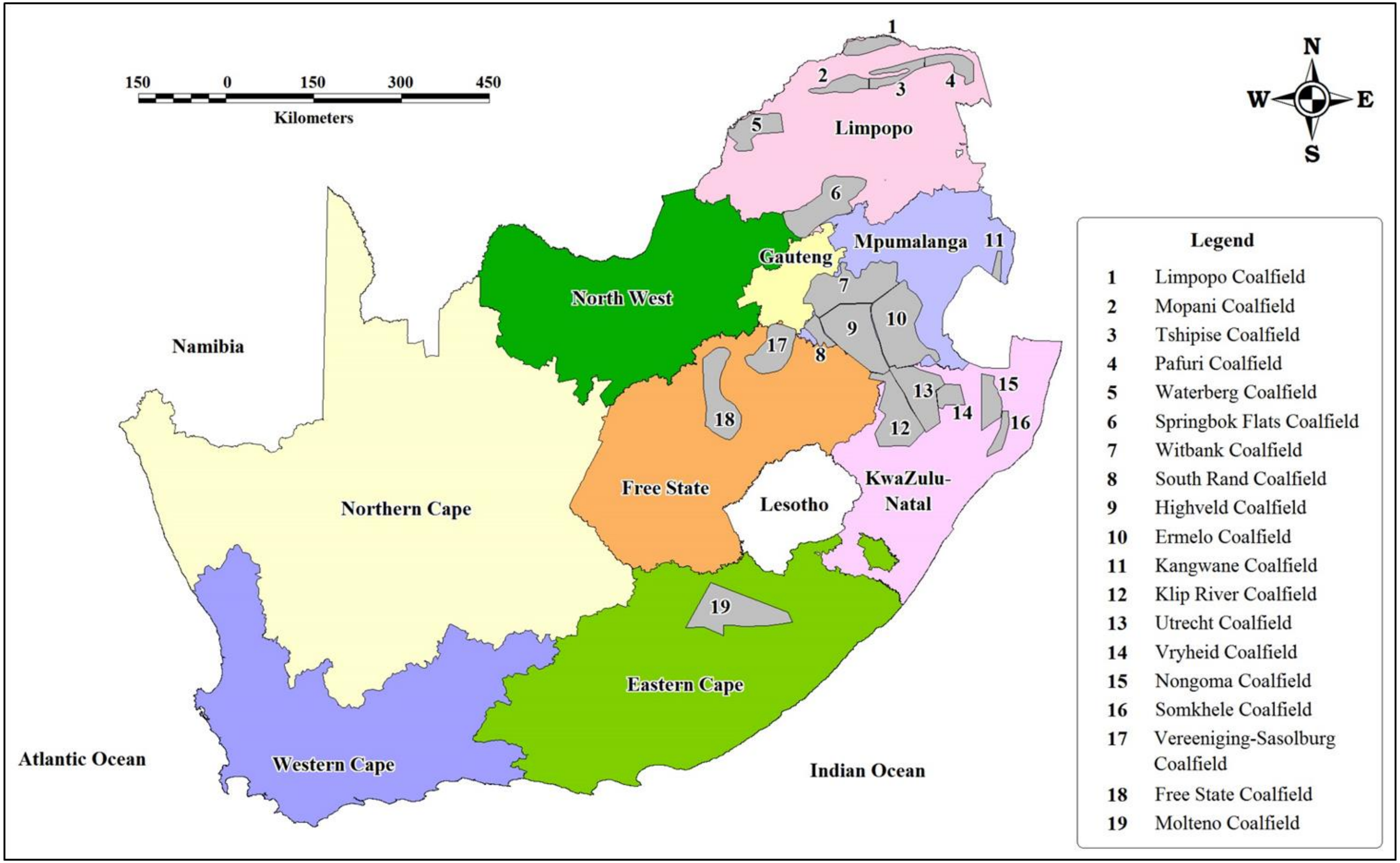


Figure 4-14: Coalfields of South Africa

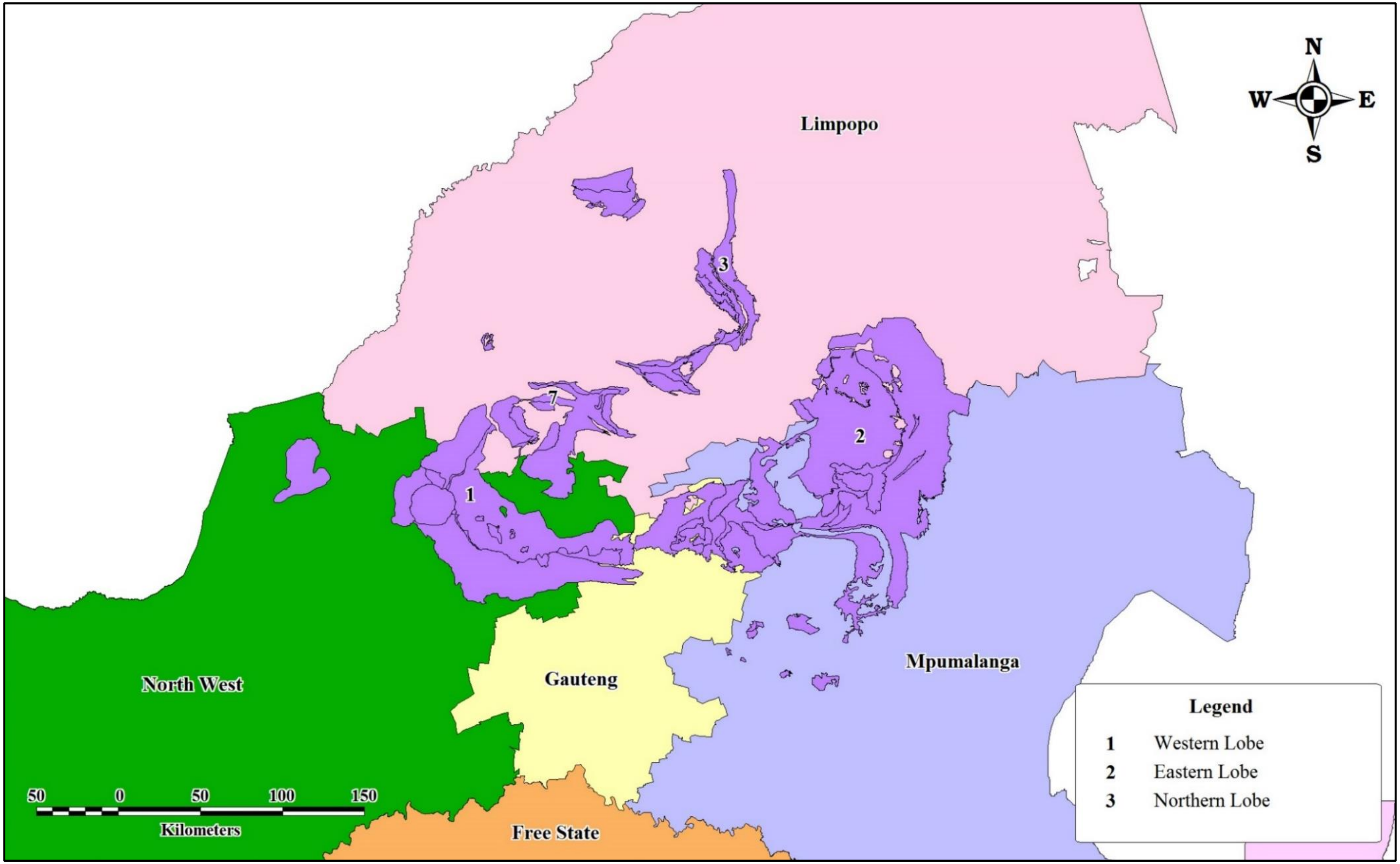


Figure 4-15: Outcrops of the Bushveld Igneous Complex

The Bushveld Igneous Complex intruded the meta-sedimentary rocks of the Transvaal Supergroup along an unconformity between the Magaliesberg quartzites (Eriksson et al., 2006). According to Cawthorne et al. (2006), the Rustenburg Layered Suite of the Bushveld Igneous Complex is divided into three lobes: the eastern, western and northern lobes (Figure 4-15). The maximum thickness of the Bushveld Igneous Complex is approximately 8 km, while outcrops of the Bushveld Igneous Complex cover an approximate length of 370 km east to west, and 200 km north to south.

The Rustenburg Layered Suite is divided into five zones:

- The Upper Zone
- The Main Zone
- The Critical Zone
- The Lower Zone
- The Marginal Zone

The subdivisions of the Bushveld Igneous Complex are shown in Table 4-2.

Table 4-2: Subdivisions of the Bushveld Igneous Complex

Major Unit	Subdivisions
Lebowa Granite Suite	Nebo, Makhutso, Klipkloof, Bobbejaanskop and Verena Granites
Rashoop Granophyre Suite	Stavoren and Diepkloof Granophyres Rooikop Porphyritic Granite Zwartberg Pseudogranophyre
Rustenburg Layered Suite	Upper Zone Main Zone Critical Zone Lower Zone Marginal Zone
Rooiberg Group	Schrikkloof, Kwaggasnek, Damwal and Dullstroom Formations

The Critical Zone contains several seams of rich mineral deposits. These seams have been divided into the Lower Group (LG1-7), Middle Group (MG1-4) and Upper Group (UG1-2), as well as the Merensky reef. Huge deposits of chromite occur in these seams, particularly in the LG6, MG1, MG2 and UG2 seams. The world's richest platinum group element deposits occur within the Merensky Reef and UG2 seam (Kruger, 2005). These reefs are extensively mined for their mineral wealth.

A south-to-north cross-section through the Bushveld Igneous Complex is shown in Figure 4-16. It is that of the Critical Zone with its rich mineral seams, which have outcrops in the southern parts of the southern limb of the Bushveld Igneous Complex, but dip towards the north, attaining depths of several kilometres. Underground mines that extract ore from these seams are hence also several kilometres deep and are likely to intersect the deep aquifer systems associated with the Bushveld Igneous Complex.

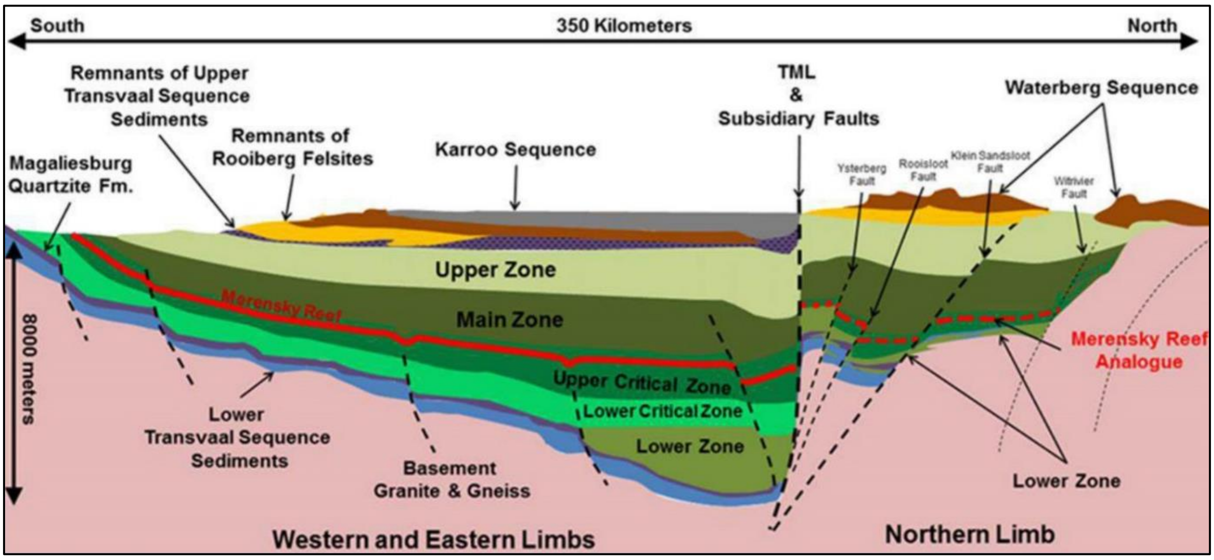


Figure 4-16: South-to-north cross-section through the Bushveld Igneous Complex (Ivanhoe Mines, 2015, after Kruger, 2005)

A list of deep mines that exploit the mineral wealth of the Bushveld Igneous Complex is given in Table 4-3. This list is not comprehensive, but gives an indication of the depths of mining in the Bushveld Igneous Complex.

4.9.3.4 Mining in the goldfields of South Africa

The Witwatersrand Basin is a largely underground geological formation that holds the world's largest known gold reserves and has produced over 1.5 billion ounces (over 40,000 metric tonnes) of gold. This represents approximately 50% of all the gold ever mined on earth (Norman and Whitfield, 2006).

The Witwatersrand Basin formed over a period of 360 Ma. Pulses of sedimentation occurred in the basin between 3 086 Ma and 2 714 Ma. Three metamorphic events followed the sedimentation events at approximately 2 500, 2 300 and 2 000 Ma. The first two metamorphic event coincided with the progressive loading of the basin by Ventersdorp and Transvaal cover sequences. The youngest metamorphic event reflects intrusion of the Bushveld Igneous Complex and/or Vredefort catastrophism (Robb and Meyer, 1995). This metamorphic event also resulted in widespread redistribution of gold in the basin, as well as the formation of a variety of secondary sulphides. Gold occurs along the northern and western margins of the basin, but not as a continuous band.

Table 4-3: Subdivisions of the Bushveld Igneous Complex

Mine Name	Commodity Mined	Maximum Mining Depth (m)
Bafokeng Rasimone Platinum Mine	PGM, Gold, Cobalt, Copper, Nickel	>500
Bakubeng Minerals (Pty) Ltd	PGM	>920
Barplats Mines Ltd	PGM, Gold, Cobalt, Copper, Nickel	?
Bathopele Mine	PGM, Gold, Cobalt, Copper, Nickel	350
Bokoni Platinum Mines (Pty) Ltd	PGM, Gold, Cobalt, Copper, Nickel	650
Buffelsfontein Mine	Chrome	2 500
Dishaba Mine	PGM, Gold, Cobalt, Copper, Nickel	1 250
Eastern Chrome Mines	Chrome	>1 000
Everest Platinum Mine	PGM, Gold, Cobalt, Copper, Nickel	>800
Hernic Ferrochrome	Chrome	700
Horizon Chrome Mine	Chrome	350
Impala Platinum Ltd	PGM, Gold, Silver, Chrome, Cobalt, Copper, Nickel	1 000
Kroondal Mine	PGM, Gold, Cobalt, Copper, Nickel	450
Kroondal Mine	Chrome	750
Lanxess Chrome Mining (Pty) Ltd	Chrome	450
Leeuwkop Mine	PGM, Gold, Cobalt, Copper, Nickel	1 350
Lonmin Platinum - Marikana Mining	PGM, Gold, Cobalt, Copper, Nickel	3 585
Magareng Mine	Chrome	750
Marula Platinum Mine	PGM, Gold, Cobalt, Copper, Nickel	770
Messina Platinum Mine Ltd	PGM, Gold, Cobalt, Copper, Nickel	>575
Modikwa Platinum Mine	PGM, Gold, Cobalt, Copper, Nickel	450
Mototolo Mine	PGM, Gold, Cobalt, Copper, Nickel	450
Siphumelele Mine	PGM, Gold, Cobalt, Copper, Nickel	1 350
Styldrift	PGM	>1 000
Thembelani Mine	PGM; Gold; Chrome; Cobalt; Copper; Nickel	900
Thorncliffe Mine	Chrome	>500
Tumela Mine	PGM, Gold, Cobalt, Copper, Nickel	850
Twickenham Platinum Mine	PGM, Gold, Cobalt, Copper, Nickel	1 181
Two Rivers Platinum	PGM, Gold, Cobalt, Copper, Nickel	935
Waterval Chrome	Chrome	1 200
Maseve Platinum Mine	PGM	>1 000
Western Chrome Mines	Chrome	300
Zondereinde Platinum Mine	Gold, Silver, PGM, Chrome, Cobalt, Copper, Nickel	2 200

The Witwatersrand Supergroup is divided into two groups: the older West Rand Group (2,500 to 4,500 m thick), and the younger Central Rand Group (2,500 m thick). Mineralisation is concentrated in the conglomerates of the Central Rand Group (McCarthy, 2006; Robb and Meyer, 1995). The distribution of the goldfields of the Witwatersrand Supergroup is shown in Figure 4-17. The goldfields occur in Gauteng, the Free State, Mpumalanga and North West.

Some of the deepest mines in the world occur in the goldfields of South Africa. A number of these mines extend to depths of approximately 4,000 m, allowing direct access to the deep aquifer systems that are intersected by mining. Some of the deep mines in the goldfields of South Africa are listed in Table 4-4.

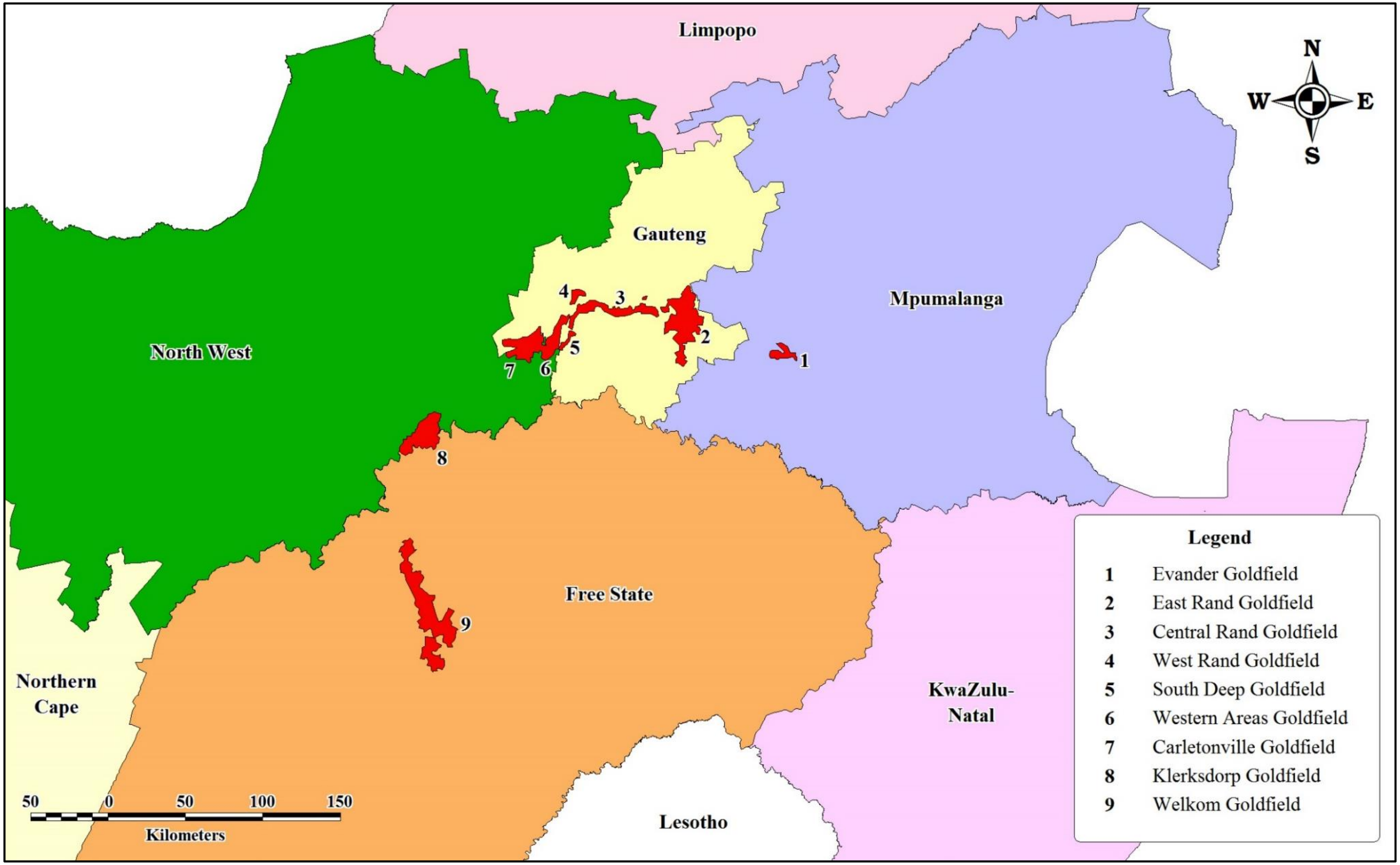


Figure 4-17: The goldfields of South Africa

Table 4-4: The deep mines in the goldfields of South Africa

Mine Name	Commodity Mined	Maximum Mining Depth (m)
Driefontein Mine	Gold	>3 420
East Rand Proprietary Mines	Gold, Silver	3 585
Evander Gold Mine	Gold	2 500
Ezulwini Gold Mine	Gold, Silver, Uranium	1 518
Great Noligwa Gold Mine	Gold, Uranium	2 600
Kasasalethu Mine	Gold, Silver	3 388
Kloof Gold Mine	Gold, Silver	3 350
Kopanang	Gold, Silver, Uranium	2 600
Maob Khotsong Mine	Gold, Silver, Uranium	3 054
Mponeng Gold Mine	Gold	>3 900
Savuka Gold Mine	Gold, Silver	>3 700
South Deep Gold Mine	Gold, Uranium	2 995
Target Gold Mine	Gold	2 500
Tau Lekoa Gold Mine	Gold	1 650
TauTona Gold Mine	Gold	3 900

4.9.3.5 Deep open-cast and underground diamond mining in South Africa

Natural diamonds were formed approximately 3.3 billion years ago in conditions of intense heat and pressure, at depths of approximately 150 km below the earth's surface (COM, 2016). Near-vertical kimberlite pipes are the primary source of South Africa's diamonds. Alluvial diamonds also occur along the Orange River, as well as along and off-shore of the west coast of South Africa. Diamond-bearing gravels are also found in palaeo channels and sinkholes in the North West. The alluvial diamond deposits are the result of millions of years of erosion of the kimberlite pipes and fluvial transport of the eroded diamonds along the prevailing drainage systems.

Since the kimberlite pipes generally occur at shallow depths, open-cast mining was initially used to extract diamonds. The famous open-cast pit at Kimberley was mined to a depth of 215 m. Underground mining has now largely replaced open-cast mining as the method to extract diamonds from ever-increasing depths.

Figure 4-18 shows the distribution of some of the deep open-cast (>300 m) and underground diamond mines in South Africa, while Table 4-5 provides information on these mines.

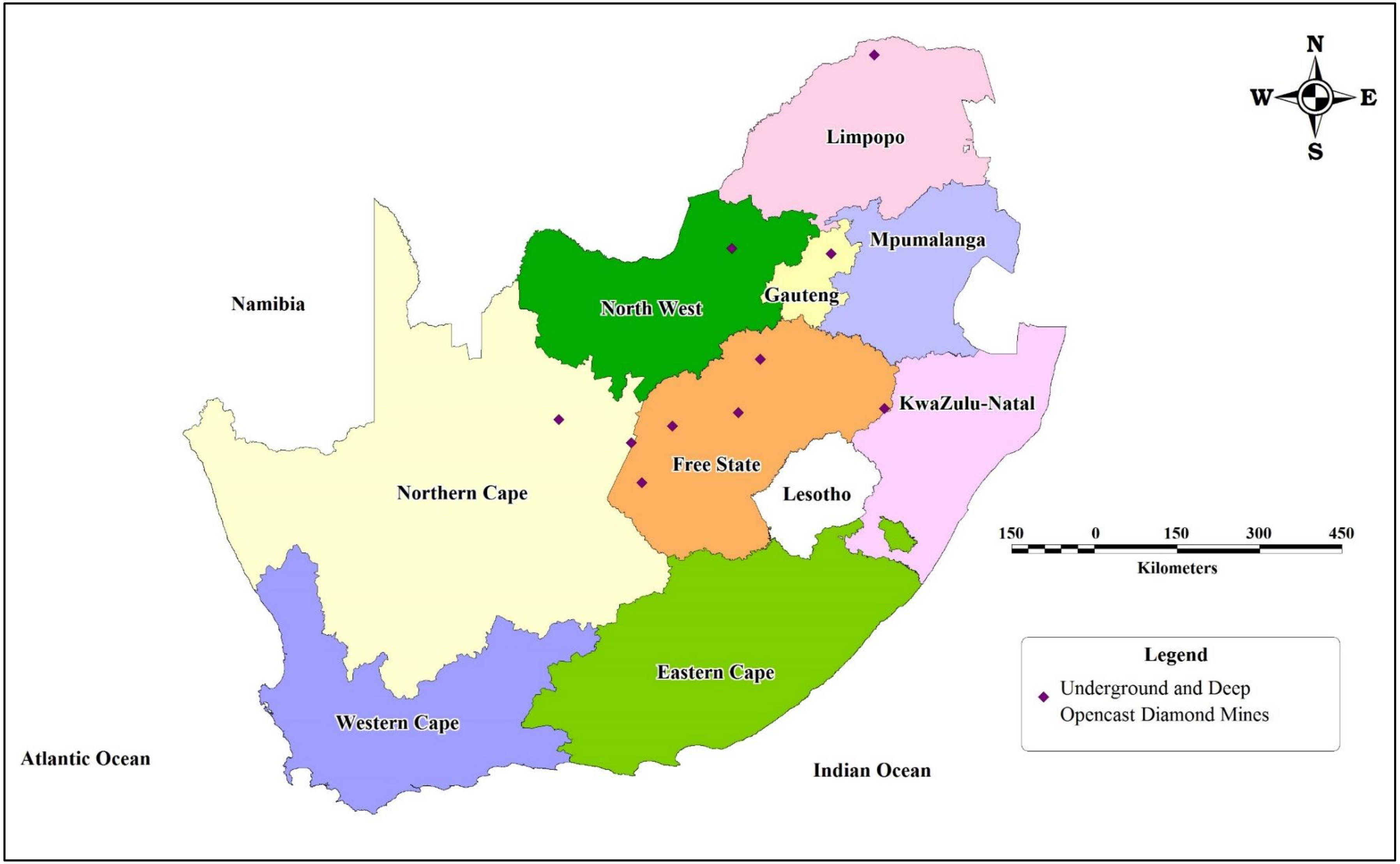


Figure 4-18: Underground and deep open-cast diamond mines of South Africa

Table 4-5: Deep diamond mines of South Africa

Mine Name	Commodity Mined	Maximum Mining Depth (m)
Cullinan Diamond Mine	Diamonds	747
Finch Diamond Mine	Diamonds	630
Helam Diamond Mine	Diamonds	600 - 750
Kimberley Underground	Diamonds	1 097
Koffiefontein Mine	Diamonds	490
Rovic Diamond Mine	Diamonds	>1 000
Sedibeng Diamond Mine	Diamonds	600 - 750
Star Diamond Mine	Diamonds	600 - 750
Venetia Diamond Mine	Diamonds	400
Voorspoed Diamond Mine	Diamonds	420

4.10 THE BUSHVELD IGNEOUS COMPLEX DRILLING PROJECT

The BICDP is a scientific drilling project in the Bushveld Igneous Complex. A proposal on the BICDP was submitted to the ICDP in 2017. The BICDP aims to contribute to the following ICDP science themes: large igneous provinces and mantle plumes, natural resources, volcanic systems and thermal regimes, and deep life. The main aim of the BICDP is to construct a complete vertical reference section through the Bushveld Igneous Complex by providing new geological reference core sections for identified gaps (Trumbull et al., 2015).

4.10.1 Target drilling sites

The scientific team of the BICDP have identified three target drilling sites: Target A, Target B and Target C (Figure 4-19). A total of 12 km of core will be drilled between the selected sites, but the exact depths of each individual borehole has not yet been decided. The boreholes will have a minimum depth of 3 km, with a potential maximum depth of 10 km.

4.10.2 Potential deep groundwater data

South Africa's available deep groundwater data is limited. This can be attributed to the cost of drilling deep boreholes and the absence of a multidisciplinary approach to mineral exploration drilling. For this reason, a parallel geohydrological project with the proposed BICDP was recommended. The addition of a geohydrological component will ensure a multidisciplinary approach to the acquisition of data from the scientific boreholes to ensure an optimal dataset for all further studies (Trumbull et al., 2015).

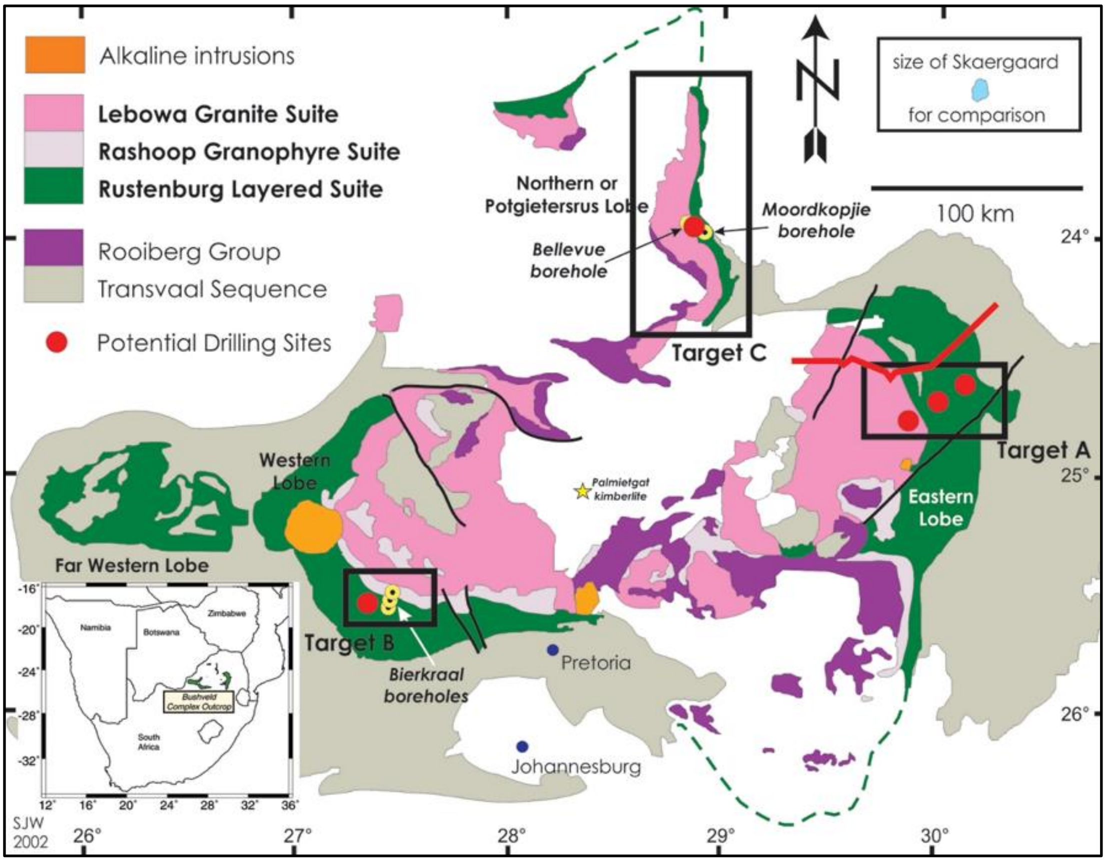


Figure 4-19: A simplified geological map of the Bushveld Igneous Complex with the location of existing reference sections (yellow dots) and possible ICDP targets (red dots) (Trumbull et al., 2015)

The groundwater-related research objectives of the BICDP include the following (Trumbull et al., 2015):

- Does groundwater occur at depths within the Bushveld Igneous Complex?
- If there is groundwater, how much is there?
- What is the quality of groundwater found at these depths and can the quantities of groundwater be considered sufficient for classifying the water-bearing rocks as a deep-fractured rock aquifer?
- To what depth do groundwater-bearing fractures remain open to provide sufficient hydraulic conductivity for groundwater extraction?

South Africa's craton foundation does not promote large geothermal discovery, but rather suggests that the naturally generated heat would be found deeper in the earth's crust and would thus require drilling to these depths to obtain clear information on the feasibility of exploiting this energy source. Thus, an additional research question was added (Trumbull et al., 2015):

- Is the geothermal gradient at depth within the Bushveld Igneous Complex sufficient for geothermal energy production or alternative methods?

The potential geohydrological data to be collected will include, but will not be limited to, geophysical borehole water surveys (fluid temperature, fluid resistivity, etc.) and depth-specific water sampling and analysis (groundwater chemistry). An analysis of the geohydrological data could potentially be realised in the form of a geohydrological characterisation of geological layers, a description of the groundwater chemistry of the Bushveld Igneous Complex, a characterisation of the hydrochemical characteristics as a function of depth in the Bushveld Igneous Complex, a groundwater flow model of the study area and a simulated geothermal energy model (Trumbull et al., 2015).

4.11 CONSOLIDATION OF DATA SOURCES

The distribution of the boreholes and thermal springs discussed in sections 4.2 to 4.8 is shown in Figure 4-20. Deep boreholes can be seen to be widely distributed across South Africa, with particularly dense distributions in the northern parts of the Free State, the southwestern parts of Mpumalanga and the northern parts of Limpopo.

From the distribution of deep boreholes, it would seem that a great deal of information on South Africa's deep aquifer systems should be available. It should, however, be kept in mind that very limited information on the geohydrological conditions for many of these boreholes exists. The data sources identified in this study will therefore have to be carefully interrogated to extract useful information that could be used to characterise the deep geohydrology of South Africa.

Not shown in Figure 4-20 are the thousands of core boreholes that the various mining companies operating in South Africa have drilled. Information from these boreholes could potentially allow a greater understanding of the deep aquifer systems in the different parts of the country where mining takes place.

4.12 CONCLUSION

This chapter focused on the identification of data sources that could potentially contain information on the deep geohydrology of South Africa. Different databases, which contain information on deep boreholes, were identified. In addition, South Africa's thermal springs, as well as its deep mines, were considered as locations at which valuable information on deep aquifers could be obtained.

Although information on a vast number of deep boreholes is listed in the various databases, the data relevant to the geohydrological conditions is very sparse for most boreholes. This implies that very limited data is available that could be used to characterise the deep aquifers of South Africa. Useful data from the databases will have to be extracted after a careful interrogation of these databases. This is likely to prove a laborious and time-consuming endeavour.

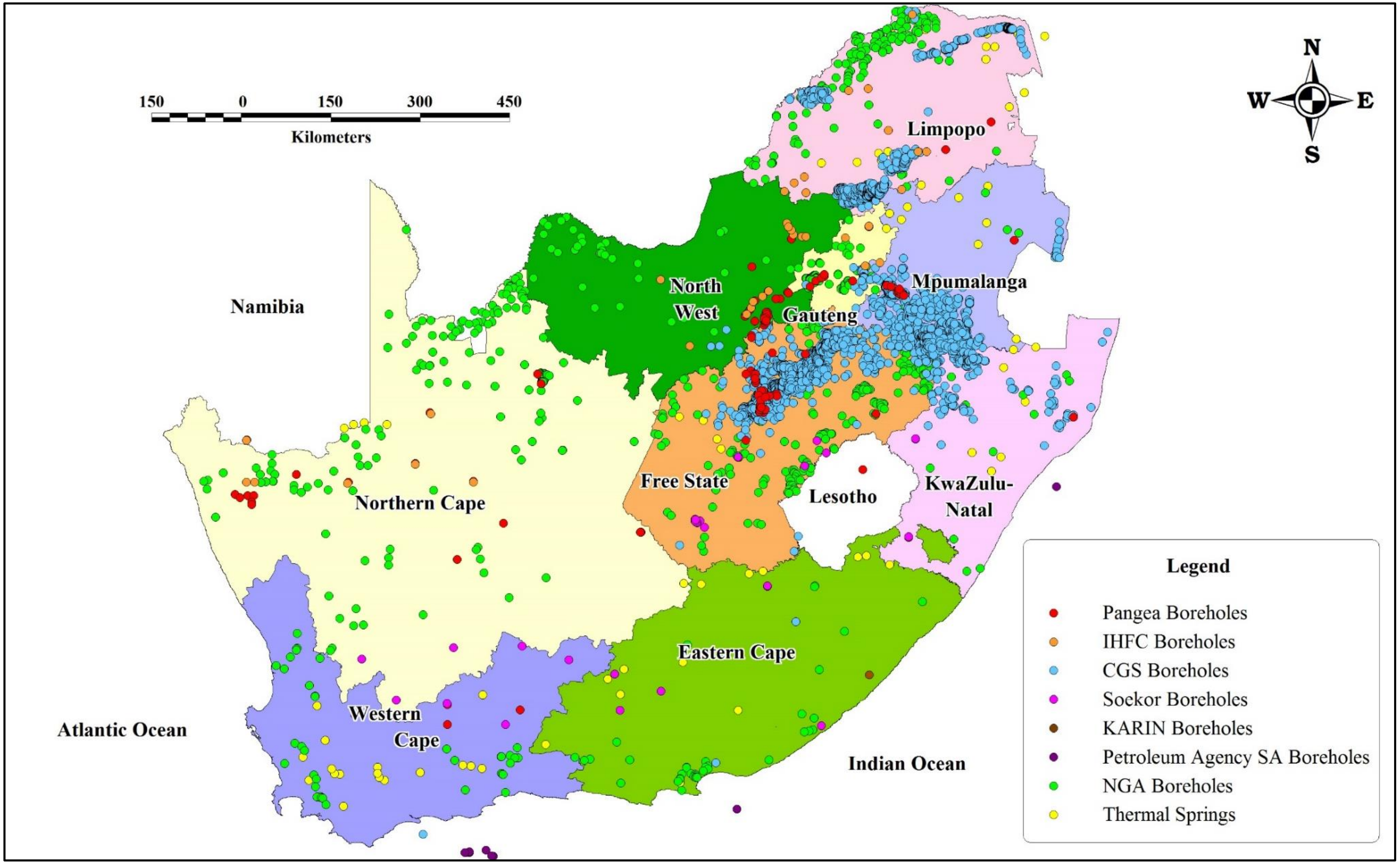


Figure 4-20: Distribution of all known deep boreholes and thermal springs in South Africa

CHAPTER 5: CHARACTERISATION OF THE DEEP AQUIFER SYSTEMS IN SOUTH AFRICA

5.1 INTRODUCTION

This chapter focuses on the characterisation of the deep aquifer systems in South Africa. In Chapter 4, nine potential sources of information on deep aquifer systems were identified. These sources were as follows:

- Boreholes of the International Heat Flow Commission
- The Pangea database of the International Council for Science
- The Council for Geoscience's database on deep boreholes
- The SOEKOR reports containing information on at least 25 deep boreholes
- Boreholes drilled as part of the Karoo Research Initiative
- Information on deep boreholes from the Petroleum Agency South Africa
- The National Groundwater Archive of the Department of Water and Sanitation
- Information on the occurrence of thermal springs in South Africa
- Deep open-cast and underground mines in South Africa. Information on the occurrence of deep groundwater could potentially be obtained from such mines.

In this chapter, these potential sources of information are interrogated to gain information on the deep aquifer systems and to characterise aquifer systems in terms of their physical and hydraulic properties, and in terms of the groundwater quality expected from these aquifers. Not all the potential sources listed above yielded useful information. The first two sources (the IHFC database and the Pangea database of the ICSU) mostly contain information on temperatures and heat production in deep boreholes. It is, however, possible that the original reports from which these databases were constructed could be located and that some information relating to the characteristics of the aquifer systems may thus be obtained.

The database of the CGS also contains very little information of relevance to deep aquifer systems, although the results of water content analyses performed on rock samples from deep boreholes are listed. The Petroleum Agency South Africa did not respond to requests for access to their reports on the deep exploration boreholes included in their database. The current project therefore focused on the information derived from the SOEKOR reports, the KARIN database, DWS's NGA, information on the occurrence of thermal springs in South Africa, as well as information on South Africa's deep open-cast and underground mines to characterise deep aquifer systems in South Africa.

In addition, a literature review of publications relevant to potential deep aquifers in South Africa was performed to allow further characterisation of these aquifer systems. This literature review focused on deep aquifers in the Karoo Supergroup, the basement and crystalline bedrock aquifers, the Table Mountain Group and the Bushveld Igneous Complex. The literature review also considered publications on geophysical surveys that could shed further light on characteristics of deep aquifer systems. Furthermore, four case studies are discussed in which the geohydrological conditions at four deep mines are characterised.

5.2 AQUIFER CHARACTERISATION

To characterise the deep aquifers in South Africa, the classification systems commonly used in the field of geohydrology may be used as reference. Aquifers may be classified in terms of various physical and chemical parameters, including the following:

- Lithology (rock type)
- Occurrence (depth)
- Physical dimensions (thickness, lateral extent)

- Aquifer type (fractured, granular, double porosity)
- Saturation level (saturated, unsaturated)
- Heterogeneity and degree of isotropy
- Formation properties (porosity, pore size distribution, bulk density, mechanical properties)
- Hydraulic parameters (hydraulic conductivity, storativity, transmissivity, specific yield, permeability)
- Pressurisation (confined, unconfined, artesian)
- Yield
- Groundwater quality (inorganic parameters, organic parameters)
- Aquifer vulnerability and susceptibility

In the current project, the available information on South Africa's deep aquifers systems is evaluated to characterise the aquifer systems as thoroughly as possible, based on the above classification systems. It should, however, be kept in mind that only limited information exists from which inferences about the characteristics of aquifer systems may be made.

5.3 LITERATURE REVIEW ON DEEP AQUIFER SYSTEMS IN SOUTH AFRICA

5.3.1 Introduction

Although deep aquifer systems in South Africa have not been studied extensively, some information on these systems has been published. This section focuses on the available literature on deep aquifer systems. The following aquifer systems are discussed:

- Deep aquifers in the Karoo Supergroup
- Deep crystalline basement aquifers
- Deep aquifers in the Table Mountain Group
- Deep aquifers in the Bushveld Igneous Complex

Furthermore, information on deep aquifer systems, as derived from geophysical investigations, is also presented.

5.3.2 Characterisation of deep aquifers in the Karoo Supergroup

5.3.2.1 Introduction

The Karoo Basin is an arid area of South Africa, which occupies approximately a third of the country's land surface and consists of a thick sequence of sedimentary rocks that are intruded by dolerite dykes and sills (KGEG, 2013b). Groundwater from weathered and fractured rock aquifers is an important resource for local communities who rely on the aquifers for their domestic, livestock and irrigation water supply. Although the shallow aquifers (<300 m depth) in this basin are relatively well understood (see Woodford and Chevallier, 2002), groundwater occurrences in the deeper Karoo formations, as well as the characteristics of the deep aquifer systems, are largely unknown.

The available information on the deep geohydrology is limited and sparsely distributed across the basin (KGEG, 2013b). One source of information on deeper aquifer systems is the deep SOEKOR boreholes drilled during the 1960s and 1970s (discussed in Section 5.6). Thermal springs (discussed in Section 5.3.8) also allow insight into the deep aquifer conditions. Recent drilling exercises of the Karoo Research Initiative also provide useful information on deep aquifer systems (refer to Section 5.7).

The KGEG (2013b) compiled a conceptual model of the deep Karoo formations, based on published geological maps and cross-sections, as well as a review of the available literature. It made the following generalisations about the deeper Karoo formations:

- The thickness of the Karoo sedimentary rocks increases from north to south across the Main Karoo Basin.
- Thermal springs in the Karoo Basin (e.g. at Aliwal North) suggest groundwater circulation to depths of approximately 1,000 m and possibly deeper as the groundwater is likely to cool somewhat during its upward flow.
- Groundwater salinity and age increase with depth due to slow movement and longer residence times, leading to greater dissolution of constituent minerals.
- The sedimentary rocks are intruded by dolerite sills and dykes, which leads to compartmentalisation of the subsurface.

Some of the SOEKOR boreholes drilled south of the Great Escarpment had free-flowing artesian water strikes. The KGEG (2013b) used information on the depths of the water strikes, artesian flow rates, measured water temperatures and groundwater qualities to update the conceptual model of the deep Karoo formations. The conceptual geohydrological model is shown in Figure 5-1.

The relative thicknesses and densities of the dolerite intrusives in Figure 5-1 are only rough representations. However, the conceptual model indicates where certain types of intrusives are more likely to occur (KGEG, 2013b):

- Thick dolerite sills may occur at the contact between the Ecca and Dwyka groups (these intrusives may have led to widespread hydrothermic activity)
- Laterally persistent, closely spaced, relatively thin undulating sheets or flat sills may occur in the Ecca Group
- Discrete, thick, laterally extensive sills may occur in the Beaufort Group
- Ring structures may occur in the Middle Beaufort Group

A schematic cross-section through the Main Karoo Basin from George in the south to Fraserburg in the north is shown in Figure 5-2. The cross-section illustrates that free-flowing artesian conditions are expected for deep boreholes below the Great Escarpment, while sub-artesian conditions are expected on the Great Escarpment (KGEG, 2013b). In addition, the cross-section shows the possible connection of the deep Karoo aquifers with the Cape Supergroup in the southern parts of the cross-section.

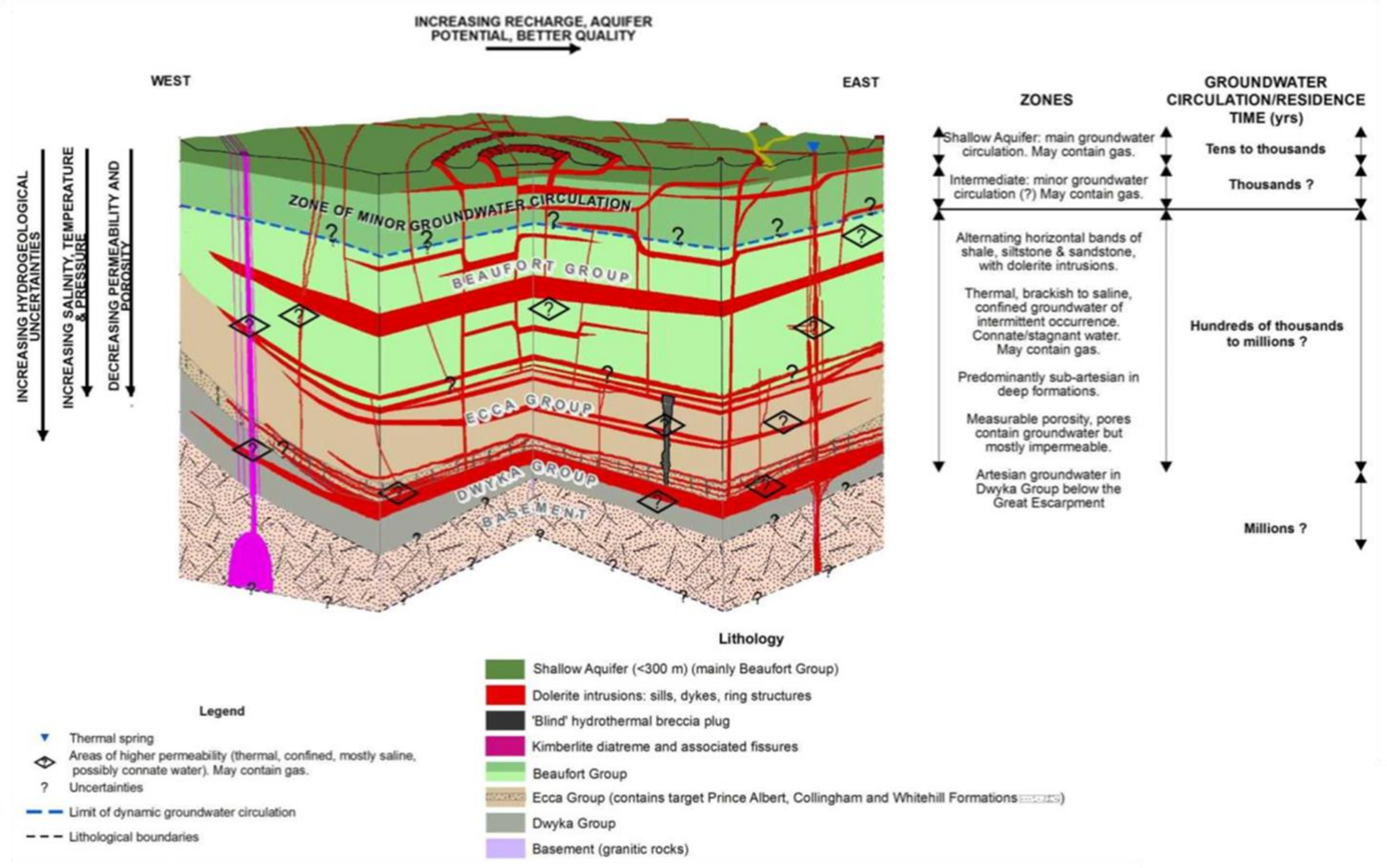


Figure 5-1: Conceptual geohydrological model for the deep Karoo formations (adapted from KGEG, 2013b)

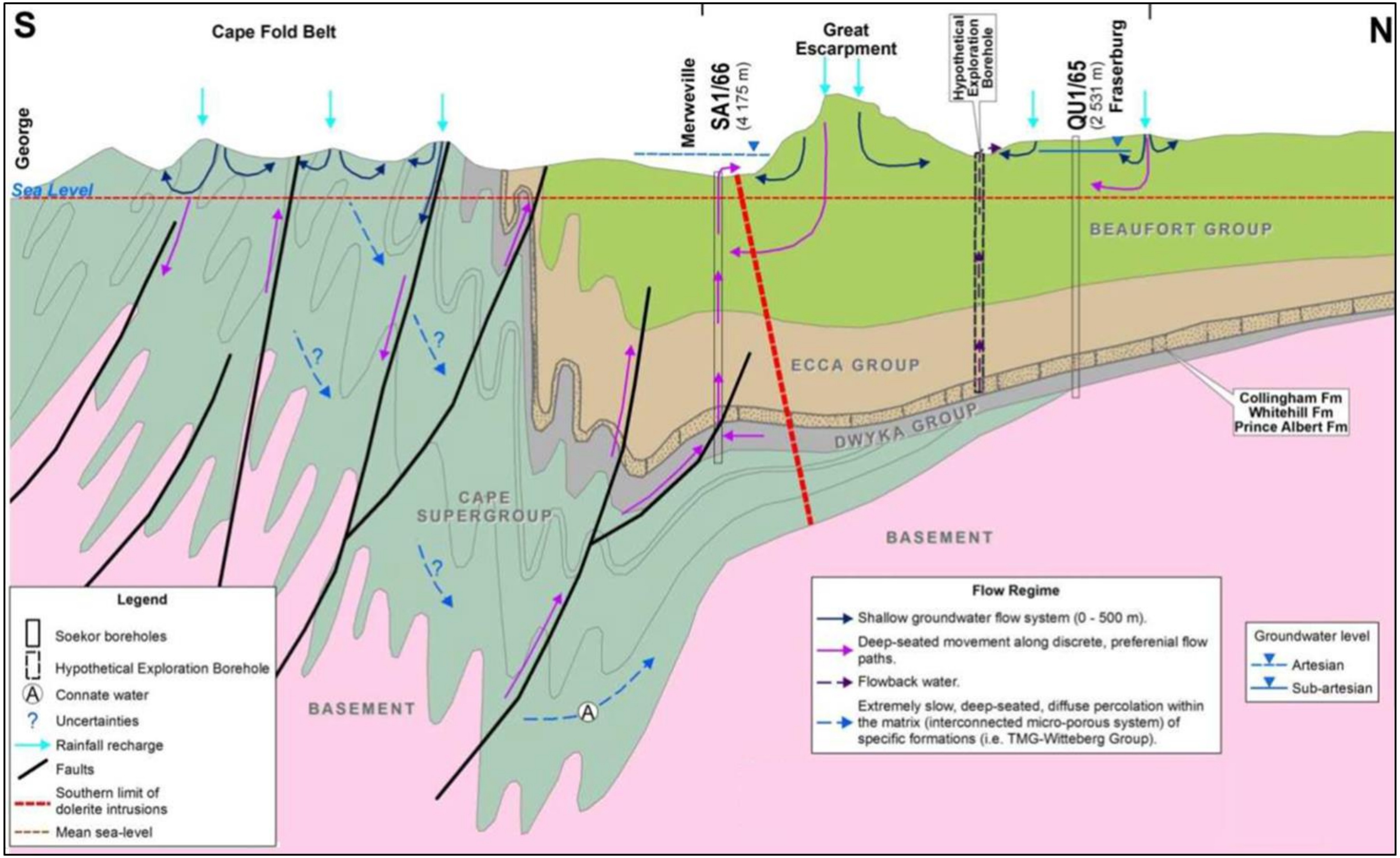


Figure 5-2: Schematic cross-section through the Main Karoo Basin (adapted from KGEG, 2013b)

Figure 5-2 shows that deep circulation of groundwater through the formations of the Karoo Supergroup and the Cape Supergroup is expected to occur along preferential flow paths, such a fault zones. These fault zones may extend from the Cape Supergroup to the Karoo Supergroup. Recharge of the deep aquifer system may also occur along such fault zones, although deep aquifer systems may also be recharged by slow percolation through the matrices of the rocks.

The dolerite intrusives in the Karoo Supergroup play a major role in the occurrence and movement of groundwater. The high pressure and heat that reigned during intrusion caused an alteration to the intruded host rock. The altered (or “baked”) contact zones are often associated with higher degrees of fracturing and weathering. Van Wyk (1963) speculated that the high permeability of the dyke contact zones is a result of shrinkage joints developed during the cooling of the intrusion. The fracture-forming nature of Karoo dolerite rings and sills is responsible for the presence of deep-seated fractured aquifers (Chevallier et al., 2001).

Dolerite dykes are vertical to sub-vertical intrusives, which are associated with near linear zones of relatively higher permeabilities in directions parallel to their strikes. The dykes may also act as semi-impermeable to impermeable boundaries for groundwater flow in directions perpendicular to their strikes (Woodford and Chevallier, 2002).

The Karoo dolerite sills and ring complexes have the same geographic distribution as the dolerite dykes and are by far the most common type of intrusion in the Karoo Basin. Woodford and Chevallier (2002) developed a hydro-morphotectonic model of the dolerite sill and ring complexes (Figure 5-3).

From the results of exploration drilling, the likely positions for the occurrence of water-bearing fractures along these intrusives are also shown. These positions include the junction between feeder dykes or inclined sheets and sills, the sedimentary rocks above an upstepping sill and the sedimentary rocks at the base of an inner sill (Woodford and Chevallier, 2002). In the first case, fracturing is usually very localised, while in the other two cases, shear and “open” fractures may extend some distance away from the dolerite contact into the host rock. These zones represent challenging exploration targets that may require drilling to depths of 200 to 350 m.

The permeabilities of the fractured contact zones along the dolerite intrusives are dependent on the host rock. For example, contact zones in sandstone are typically more permeable than those in mudstone. The high porosities and permeabilities of the fractured contact zones are also likely to decrease with depth due to compaction and the closing of fractures as a result of the increasing pressures associated with the increasing depths of burial (SRK, 2012). The deep fractured aquifers of the Karoo Supergroup are therefore likely to be lower yielding than the shallow fractured aquifers.

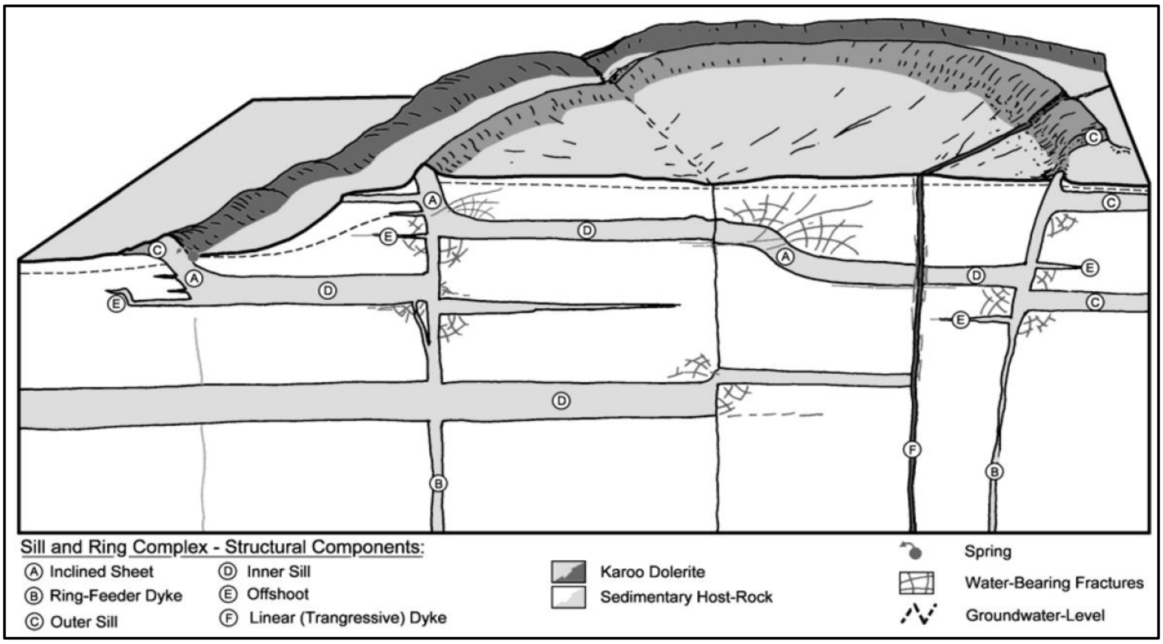


Figure 5-3: Hydro-morphotechtonic model of the dolerite sill and ring complexes in the Karoo Supergroup (Woodford and Chevallier, 2002)

5.3.2.2 Summary

Only limited information on deep aquifer systems in the Karoo is available in the published literature. The KGEG (2013a) provided a summary of the available information on the deep Karoo formations and their aquifer systems. From the available data, they made the following generalisations:

- Sedimentary strata in the Karoo Supergroup are generally sub-horizontal, dipping at 1 to 2 degrees to the south. However, in the south, in the proximity of the Cape Fold Belt, steeper dips occur.
- Dolerite sills most often have thicknesses of less than 20 m, although thicker sills occur (the thickest sill intersected by the SOEKOR boreholes had a thickness of approximately 250 m).
- Although dykes and their associated contact zones may extend for tens to hundreds of kilometres along their strikes, their vertical extent is uncertain. Some dykes could extend to the base of the Karoo sedimentary rocks.
- The hydraulic conductivity of the contact zones varies with depth. Different sedimentary units are likely to be associated with different degrees of fracturing in the contact zone. In addition, the increasing pressures due to increasing depths may lead to compaction and closure of the fracture networks.
- Groundwater salinity generally increases with depth due to the influence of gravity, longer residence times and lower recharge rates.
- The shallow aquifer systems (depths of <300 m) are unlikely to be hydraulically connected to the deep aquifer systems.

Table 5-1 summarises the characteristics of deep aquifer systems as derived from the available literature.

5.3.3 Characterisation of deep crystalline basement aquifers

5.3.3.1 Introduction

Most of the groundwater in South Africa is stored in sedimentary rocks. However, secondary aquifers occur in the basement rocks that underlie the country. These basement rocks include granite, gneiss, migmatites and granitoids. Titus et al. (2009a) give a comprehensive description of the basement aquifers of southern Africa. However, the basement aquifers that are described are generally shallow aquifers that are associated with outcropping or near-surface basement rocks.

Very little information on the deep (>300 m) basement aquifers is available. In this section, the characteristics of the deep basement aquifers are estimated by considering the available information on the shallow basement aquifers and extrapolating it to greater depths.

5.3.3.2 Basement aquifers in South Africa

The surface distribution of rock types in South Africa is shown in Figure 5-4. Numerous sedimentary basins occur in the country, but the rocks in many of the sedimentary basins have undergone metamorphosis. From Figure 5-4, one can see that a large portion of South Africa's surface geology consists of meta-sedimentary basins. The thickness of these basins varies, but generally ranges from approximately 3,000 m to more than 8,000 m (Viljoen et al., 2010). The sedimentary basins are all underlain by basement rocks. Many of the deep SOEKOR boreholes that are drilled in the Main Karoo Basin extended through the Karoo formations and intersected the underlying basement rocks (see Section 5.6).

In South Africa, basement rocks occur at the surface in the northern, northeastern and western parts of the country, particularly in Limpopo, Mpumalanga, KwaZulu-Natal and the Northern Cape (see Figure 5-4).

Table 5-1: Characterisation of the deep aquifer systems of the Karoo Supergroup

Criteria	Description
Lithology	The Karoo Supergroup consists of various sedimentary rocks, intruded by dolerites if Jurassic age. The dolerite intrusives led to the formation of fractured zones in the host rock. The deep Karoo aquifers are likely to be fractured rock aquifers, occuring in the sedimentary rocks of the Beaufort, Ecca and Dwyka Groups.
Occurrence	The deep fractured rock aquifers could potentially occur anywhere within the Karoo Basin, but are more likely where dolerite intrusives caused secondary porosity in the form of fractures. Fault zones may similarly be associated with deep fractures aquifer systems in the Karoo rocks.
Physical dimensions	The vertical extents of the deep fracture zones are expected to be very limited (a few metres at most). However, the sedimentary rocks hosting the fractures are likely to act as the main storage unit for the water. These sedimentary rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers systems are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing.
Saturation level	The deep fractured rock aquifers are expected to be under positive pressure, and are therefore likely to be fully saturated.
Heterogeneity and isotropy	The aquifer systems are expected to be highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks and the presence of impermeable dolerite intrusives.
Formation properties	The primary porosities of the sedimentary rocks forming part of the aquifer systems are expected to be very low due to compaction as a result of the large depths of burial. Despite the small porosties, the sedimentary rock matrices are expected to act as the main water storage units. The fractures, by contrast, are expected to create localised zones with very high secondary porosities.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.
Yield	The yield of the deep fractured aquifers is expected to be low due to compaction and the closure of fractures as a result of the large depths of burial.
Groundwater quality	The groundwater quality is expected to deteriorate with depth as the salinity is likely to increase with depth due to slow movement and longer residence times, leading to greater dissolution of constituent minerals.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be vulnerable to over-exploitation since little information is available on their rates of recharge and hence on the sustainable abstraction rates that can be employed.

Aquifers in the basement rocks are generally considered to be of minor importance in geohydrological terms. Boreholes drilled into these aquifers often have yields of less than 1 ℓ/s (Holland, 2010). Yet, these aquifers provide water to many rural communities. Constraints in developing basement aquifers for water supply include the low success rate of drilling water-yielding boreholes in basement rocks, the low storage capacity of these rocks and the low recharge rates often associated with these rocks (Titus et al., 2009a).

Crystalline basement aquifers are generally hard-rock aquifers, which comprise fractured igneous and metamorphic rocks that have negligible matrix porosity and permeability (Gustafson and Krázný, 1994; Nyagwambo, 2006). These rocks have generally been subjected to multiple tectonic events under different stress conditions, which lead to complex patterns of ductile folding and brittle fracturing, particularly near the surface (Adams, 2009). Apart from regional tectonic events, the intrusion of dykes, and quartzite and pegmatite veins also cause fracturing of the rock. The secondary porosity created by the fracturing may facilitate the movement and storage of groundwater (Nyagwambo, 2006).

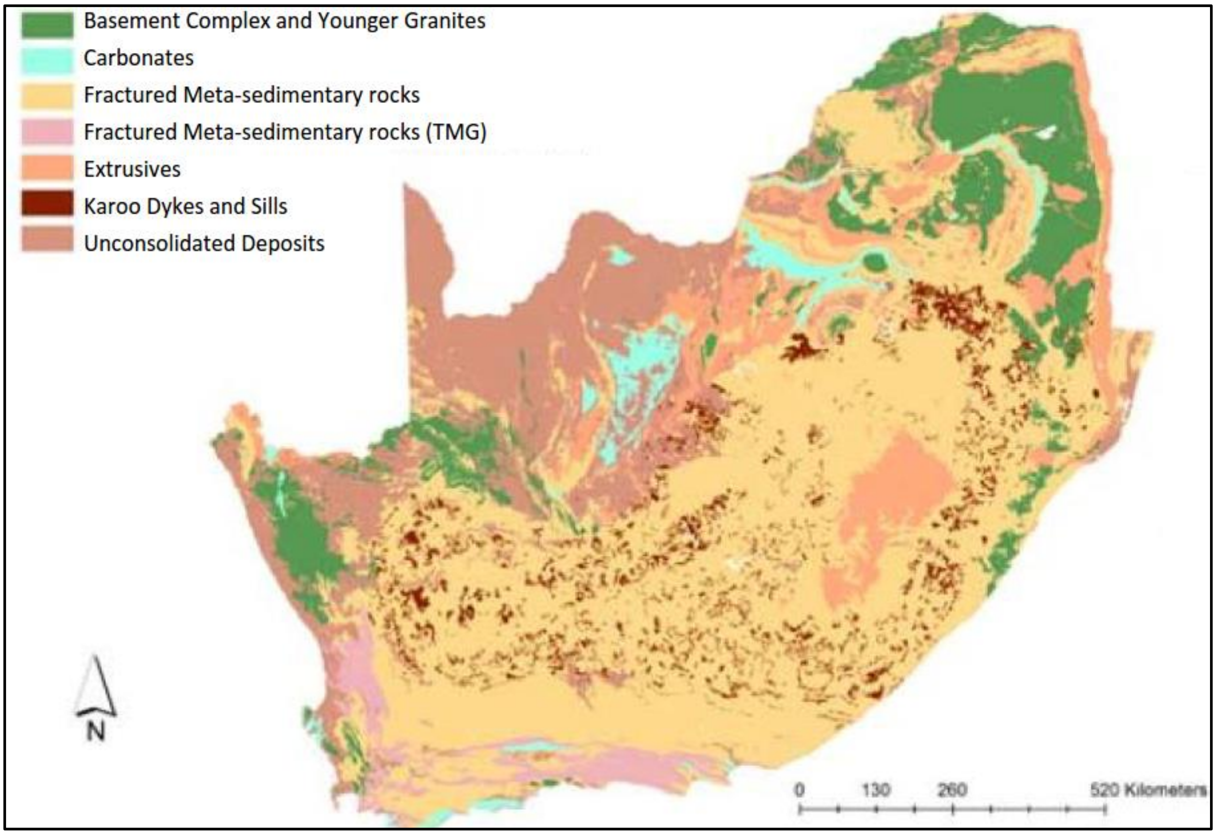


Figure 5-4: Surface distribution of rock types in South Africa (LeMaître and Colvin, 2008)

Crystalline basement aquifers are usually classified as two-layer systems, which consist of fractured bedrock overlain by weathered regoliths. The basal part of the regolith and the top part of the bedrock often have adequate permeability and storage capacity to sustain low abstraction rates that are sufficient for rural water supply. The weathered overburden is usually described as the main groundwater storage compartment, although productive boreholes may be developed in the underlying fractured bedrock. Viable aquifers that lie completely within the fractured bedrock are rare due to the typically low storativity of fracture systems (<1%) (Wright, 1992). Groundwater in the unweathered basement rocks is stored in interconnected systems of fractures, joints and fissures that are associated with regional tectonism (Titus, 2009). To be useful from a geohydrological perspective, the fractured bedrock component of the aquifer system requires interaction with storage available in overlying saturated regolith, or other suitable formations such as alluvium (Wright, 1992; Kirchner, 2009).

The permeability of the fractured basement aquifers is likely to correlate to some degree with the frequency of fracture occurrence. In addition, both fracture frequency and permeability are generally expected to decrease with depth (Wright, 1992).

Fractures, intrusives dykes and zones of deeper weathering are typically considered targets during a groundwater exploration programme in basement rocks. Kellet (2004), Linn (2009) and Sami (2009) emphasised that the location of suitable targets in often complex terrains requires the use of local knowledge, airborne and/or ground geophysics, detailed structural and geological mapping, and exploratory drilling.

5.3.3.3 Hydraulic properties of shallow basement aquifers

Basement aquifers are typically extremely heterogeneous in their hydraulic properties. The rock matrices are characterised by low porosities (typically less than 10%) (Kirchner, 2009) and permeabilities. Fractures that are present in the bedrock usually display poor connectivity. Depending on the degree and connectivity of fracturing, the hydraulic conductivity may vary by orders of magnitude over very short distances in the same rock mass (Titus et al., 2009a).

Structural features such as fractures and fissures in the crystalline basement rock are often described as hydraulic conductors, instead of aquifers, since the term aquifer implies that the groundwater reservoir is related to the formation rather than to the structures within it (Titus et al., 2009a). Zones of intense fracturing are referred to as compound conductors (Gustafson and Krázný, 1994). These structural features are typically very variable in terms of their frequency of occurrence, their spatial extents and their interconnectedness (Titus et al., 2009a).

Various authors have investigated the hydraulic properties of shallow basement aquifers in southern Africa. Wright (1992) listed the transmissivities and apparent hydraulic conductivities of four types of fissured crystalline rock in Zimbabwe and Malawi (Table 5-2). These rocks are expected to have very similar properties to the shallow basement aquifers in South Africa. The apparent hydraulic conductivities were derived from either packer or pumping tests correlated with the penetrated section or packer length.

Table 5-2: Hydraulic parameters in fissured crystalline rocks (modified from Wright, 1992)

Country	Rock type	Borehole numbers	Mean transmissivity (m^2d^{-1})	Transmissivity range (m^2d^{-1})	Hydraulic conductivity range (md^{-1})
Zimbabwe	Mobile belt gneiss	228	4.2	0.5 - 79	0.01 - 2.3
	Younger granite	309	3.6	0.5 - 71	0.01 - 1.9
	Older gneiss	392		0.5 - 101	0.01 - 2.8
Malawi	Biotite gneiss	2			0.1 - 0.2

Boreholes typically include thin saturated regolith, but majority derive principal yields from bedrock.

From Table 5-2, one can see that the measured transmissivities in the fractured crystalline rocks vary over a large range, but that the mean transmissivities are low (<5 m^2d^{-1}). The apparent hydraulic conductivities of the more significant fracture systems are also low, falling in the range of 0.01 to approximately 0.3 md^{-1}.

Chilton and Foster (1995) studied basement aquifers in tropical Africa and reported transmissivities of between 0.5 and 100 m^2d^{-1}, although most values fell within the range of 2 to 5 $m^2.d^{-1}$. Holland and Witthüser (2009; 2011), Holland (2010; 2011; 2012) and Witthüser et al. (2011) investigated the basement rock aquifers of Limpopo. Although the authors stated that transmissivity values ranging from 5 $m^2.d^{-1}$ to approximately 40 $m^2.d^{-1}$ can generally be expected for these basement aquifers, they reported transmissivity values that ranged from 5.1 to 94 $m^2.d^{-1}$.

5.3.3.4 Groundwater quality of shallow basement aquifers

Natural groundwater quality in most basement environments is generally good, with low salinities and neutral to slightly acidic pH values (Clark, 1985; Chilton and Foster, 1995; Holland, 2011). However, salinities are often elevated in areas of low recharge and/or prolonged residence times (Holland, 2011).

Chimphamba et al. (2009) discussed the groundwater quality of basement aquifers in Malawi. The authors stated that groundwater from the basement aquifers is characterised by the dominance of alkaline earths in the cation group and carbonates in the anion group. Low total mineralisation of the groundwater was noted, and the authors concluded that the water was derived from recent recharge. The most common ranges for the various chemical and physical parameters of groundwater from the basement aquifers of Malawi are listed in Table 5-3. Based on the standards for drinking water specified by the government of Malawi, the water quality of the basement aquifers may be classified as good to fair, although the high sulphate and iron concentrations at some sampling sites render the water of poor quality. Chimphamba et al. (2009) also noted that the groundwater quality in the basement aquifers often varied greatly over short distances. They concluded that aquifer heterogeneity had a strong influence on groundwater quality.

Table 5-3: Common ranges for chemical and physical parameters of groundwater from basement aquifers in Malawi (modified from Chiphamba et al., 2009)

Parameter	Unit	Range
EC	µS/cm	100 - 1 000
TDS	mg/L	60 - 600
Ca	mg/L	10 - 100
Mg	mg/L	5 - 50
Na	mg/L	5 - 70
K	mg/L	1 - 6
Fe	mg/L	1 - 5
HCO_3	mg/L	100 - 500
SO_4	mg/L	5 - 1 000
Cl	mg/L	<20
NO_3	mg/L	<5
Fl	mg/L	<1

Holland (2010) investigated the groundwater quality from basement aquifers in Limpopo. He found that most of the chemical parameter concentrations in the groundwater were low enough to allow the water quality to fall within the recommended drinking water limits. However, elevated concentrations of some of the parameters were observed at some boreholes. High nitrate and fluoride concentrations, in particular, were detected at many of the boreholes. Elevated nitrate concentrations were considered to be due to human activities, while the high fluoride concentration probably had a natural origin.

5.3.3.5 Recharge of shallow basement aquifers

Recharge of basement aquifers is an important parameter to consider since these aquifers typically have small storage capacities (Wright, 1992). Groundwater abstraction from these aquifers could therefore rapidly lead to over-exploitation if the mechanisms and rate of recharge are not taken into account. Recharge to crystalline basement rocks is a function of the mode of the chemical weathering of the surface and degree of fracturing (Lerner et al., 1990).

Abiye et al. (2011) stated that dykes and faults play an important role in the recharge of both shallow and deep aquifers. In areas where evaporation is greater than rainfall, recharge usually occurs through preferential flow pathways, such as fracture zones (Holland, 2011). The most reliable technique to determine recharge in crystalline aquifers is the Chloride Mass Balance method (Holland, 2011).

In the literature, recharge rates for crystalline basement aquifers are often quoted as being between 0 and 25% of the annual rainfall (Nyagwambo, 2006). However, due to the heterogeneity and discontinuity of the aquifers, as well as the complex nature of the resultant flow system, these estimated recharge rates are often only locally representative and do not reflect the regional recharge rate to the basement aquifer system (De Vries and Simmers, 2002). Nyagwambo (2006) studied groundwater recharge in crystalline basement aquifers in Zimbabwe. He used various methods to estimate the recharge and found that all the methods yielded a recharge rate of between 8 and 15% of the annual rainfall. However, he noted that all the methods of recharge estimation showed large spatial variability. He concluded that no single point measurement of recharge is a good indicator of regional recharge in basement aquifers.

Adams et al. (2009) proposed a methodological approach to recharge estimation for basement aquifers in semi-arid regions. The authors estimated the recharge to a basement aquifer in central Namaqualand using different methods of estimation, and found recharge rates ranging between 0.1 and 10.6 mm per annum (Table 5-4). Expressed as a percentage of the mean annual precipitation, these recharge rates correspond to recharge percentages ranging from 0.02 to 3.4%.

Table 5-4: Recharge estimation for the basement aquifer in central Namaqualand (modified from Adams et al., 2009)

Site	Mean annual precipitation (mm)	Recharge estimation (mm/a)			
		CMB	SVF	CRD	GIS
Buffels River Town	188	0.7	5.3	6.4	1.2
Bulletrap	172	1.1	0.3	0.1	1.0
Klipfontein	196	0.2	0.3	0.1	1.2
Komaggas	229	1.0	4.4	0.7	1.1
Leliefontein	395	10.6			2.8
Rooifontein	138	0.4	2.6	3.1	1.3
Spoeg River	200	0.2	0.2	0.1	1.3
Tweerivier	296	3.5	0.6	1.8	1.6
Vyemond	239		0.1	0.1	2.3

CMB: Chloride mass balance; SVF: saturated volume fluctuation; CRD: Cumulative rainfall departure; GIS: Geographical information systems

5.3.3.6 Characteristics of deep basement aquifers

Although very little information is available on South Africa's deep (>300 m) basement aquifers, some expected characteristics of these aquifers may be inferred from the known characteristics of shallow basement aquifers. The greater depth of the deep basement aquifer systems implies that, unlike the shallow basement aquifers, these aquifers are not in contact with weathered regoliths in which groundwater storage can take place. Water storage is therefore limited to the volumes that can be stored in the rock matrix and within the fractures. The density of fracture networks is also expected to decrease with depth, leading to reduced water transfer and storage capacities. The expected characteristics of the deep basement aquifer systems are summarised in Table 5-5.

Table 5-5: Characteristics of South Africa's deep basement aquifers

Criteria	Description
Lithology	The deep basement aquifers occur in fractured basement rocks, such as granites, gneisses, migmatites and granitoids.
Occurrence	The basment rocks underlie all of South Africa, although they may occur at depths in excess of 8 000 m under the meta-sedimentary basins. Basement rocks outcrop in the northern, eastern and western parts of the country. Deep basement aquifers may therefore occur anywhere in the country.
Physical dimensions	The vertical extents of the deep fracture zones are expected to be very limited (a few metres at most). However, the matrices of the rocks hosting the fractures are likely to act as the main storage unit for the water. These rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers systems are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing. However, the porosity of the rock matrix is expected to be very low.
Saturation level	The deep fractured rock aquifers are expected to be under positive pressure, and are therefore likely to be fully saturated.
Heterogeneity and isotropy	The aquifer systems are expected to be highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks and the presence of impermeable dolerite intrusives.
Formation properties	The primary porosities of the rocks forming part of the aquifer systems are expected to be very low. Very little water is therefore expected to be stored in the rock matrix. The fractures are expected to create localised zones with high secondary porosities. The physical dimensions of the fractures, however, imply that little water can be stored within the fractures.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.
Yield	Despite the possibility that the fractures will have high hydraulic conductiviities, the yield of the deep fractured aquifers is expected to be very low due to the low volumes of water that can be stored in the matrix and fractures. Furthermore, the large depths at which the fractured aquifers occur imply that very little recharge will take place.
Groundwater quality	The groundwater quality from the deep fractured aquifers is expected to be good, although the long residence times may have led to elevated concentrations of certain chemical constituents, such as fluoride.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be very vulnerable to over-exploitation since little recharge is expected.

5.3.4 Characterisation of deep aquifers in the Table Mountain Group

5.3.4.1 Introduction

Fractured rocks of the Table Mountain Group form a regional aquifer with the potential to be a major source of water in the Western Cape and the Eastern Cape (Wu, 2005). It is estimated that the Table Mountain Group has a deposit area of 248,000 km^2 and a thickness that varies from approximately 900 to 4,000 m (Lin, 2008) (Figure 5-5). These rocks have an outcrop area of approximately 37,000 km^2 along the west and south coast of South Africa (Jia, 2007). The vast distribution of the Table Mountain Group leads to great variability in its geohydrological properties, resulting in an uneven distribution of groundwater occurrences in the Table Mountain Group area (Jia, 2007).

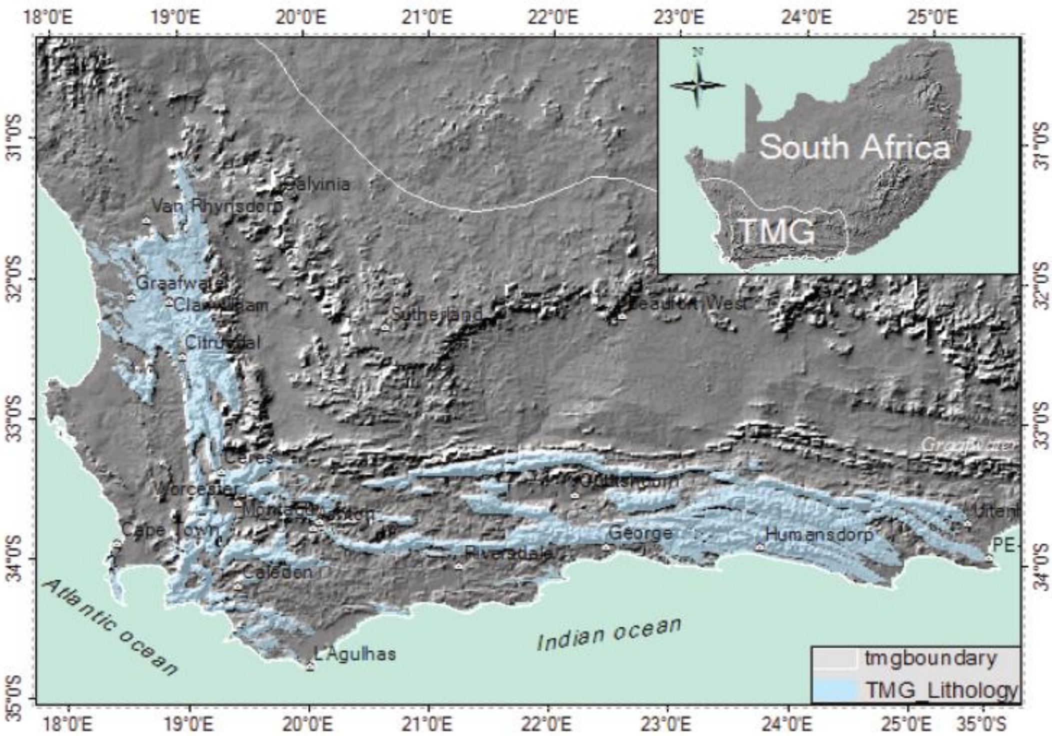


Figure 5-5: Distribution of the deposit area and outcrops of the Table Mountain Group in South Africa (Jia, 2007)

The significance of the Table Mountain Group as a regional aquifer was overlooked until around 1995. Before this time, the aquifer was considered to be of little importance. Du Toit (1954) thought that the low primary porosity of the rock matrix and the high transmissivity of the fractures limited the potential of the rocks in the Table Mountain Group to act as an important aquifer (Jia, 2007). However, after a visit to a high-yielding artesian borehole drilled in the Peninsula Formation, Issar (1995) predicted that deep boreholes in the Table Mountain Group would play an important role in the future development of water resources in South Africa (Jia, 2007). In 2002, the then Minister of Water Affairs and Forestry, Ronnie Kasrils, announced that the Table Mountain Group aquifers represented a significant water resource, particularly for the Western Cape (TMGA Alliance, 2016).

5.3.4.2 Geology of the Table Mountain Group

Thorough descriptions of the geology of the Table Mountain Group are given by De Beer (2002), Wu (2005), Jia (2007), Netili (2007) and Lin (2008). The Table Mountain Group is the lowest geological unit of the Cape Supergroup. The sediments of the Cape Supergroup were deposited in a shallow marine environment, as well as in a braided fluvial environment (Wu, 2005).

The sediments were deposited over a period of approximately 170 Ma from the early Ordovician to early Carboniferous eras (Aston, 2007). The Table Mountain Group mostly consists of quartz arenites, shales and siltstone, with minor conglomerates and a thin diamictite unit.

The geological succession of the Cape Supergroup is given in Table 5-6. Also listed in Table 5-6 are the approximate thicknesses of the various geological units of the supergroup. The Cape Supergroup has been divided into the Table Mountain Group, the Bokkeveld Group and the Witteberg Group. The Table Mountain Group has, in turn, been divided into the Nardouw and Peninsula subgroups, each consisting of various formations.

5.3.4.3 Geomorphology of the Table Mountain Group

Between 280 and 235 Ma, the South American and African continents collided to form part of Pangaea, giving rise to the Cape Fold Mountains (Aston, 2007). The associated compressional forces resulted in widespread deep fracturing throughout the Table Mountain Group with larger faults running for tens of kilometres (Hartnady and Hay, 2002b). Some of the larger faults are expected to extend deep into the folded and fractured rock formations (Figure 5-2).

Regionally, the Table Mountain Group occurs in the form of mountains, wave-cut plains and intermountain drainage basins. The modern landform patterns of the Table Mountain Group area largely resulted from quaternary processes, including crust heaves, and physical and chemical erosions. These processes led to the formation of rolling landscapes with a topographical elevation of approximately 200 to 1,700 m above sea level. The mountain peak can reach elevations of 1,900 to 2,250 m above sea level in the Hex River Mountain, 1,500 to 2,000 m above sea level along Langeberg, and 1,700 to 2,000 m above sea level on the Swartberg Mountains (Jia, 2007; Lin, 2008).

Compared to overlaying argillaceous rock formations and the underlying basement rocks, the geomorphologic patterns of the Table Mountain Group are characterised by sharp mountains with steep slopes, and thin or even no soil covers over its outcrops (Jia, 2007; Lin, 2008).

Table 5-6: Stratigraphy of the Cape Supergroup (Jia, 2007)

Supergroup	Group	Subgroup	Formation	Thickness (m)	Lithology
Karoo				7 000	Basin sedimentary sequence (Permian to Cretaceous)
Cape	Witteberg	Lake Mentz	Waaipoort	340	Shale, siltstone, thin sandstone
			Floriskraal	80	Sandstone, siltstone, shale and grit
			Kweekvlei	200	Shale
		Weltevrede	Witpoort	850	Quartzitic sandstone, minor siltstone
			Swartruggens	300	Siltstone, mudstone and thin-bedded sandstone
			Blinkberg	15-90	Thick-bedded quartzitic sandstone
			Wagendrift	135-165	Siltstone, sandy shale, mudstone and lithic sandstone
	Bokkeveld	Traka	Karoopoort	40	Siltstone, sandy shale and minor mudstone
			Bidohn Adolphspoort	1 000	Siltstone, shale, sandstone
			Klipbokkop/Karies	1 200	Shale
			Wuppertal	26	Sandstone, siltstone
		Bidouw	Waboomberg	200	Siltstone, shale
		Ceres	Boplaas	100	Sandstone
			Tra-Tra	350	Shale, siltstone
			Hex River	70	Sandstone, siltstone
			Voorstehoek/ Swartkrans	300	Shale, siltstone
			Gamka	200	Sandstone, siltstone
			Gydo	600	Shale, siltstone
	Table Mountain	Nardouw	Rietvlei/ Baviaanskloof	300	Feldspathic quartz arenite
			Skurweberg/Kouga	500	Quartz arenite
			Goudini/Tchando	400	Brown-weathering arenite, minor siltstone, shale
			Cedarberg	50-150	Silty shales and shaly siltstone
		Peninsula	Pakhuis	70	Fluvio-glacial tillite, folded diamicite, quartz arenite and thin-bedded quartzitic sandstone
			Peninsula	1 500	Largely thick-bedded, coarse-grained quartz arenite
			Graafwater	25-65	Thin-bedded sandstone, siltstone, shale and mudstone
			Piekenierskloof	10-150	Quartzitic sandstone with coarse-grained to gritty zones and rudites
Basement	A suite of moderately to lightly metamorphic Precambrian sedimentary rocks, and Cape Granite Suite.				

5.3.4.4 The Table Mountain Group aquifer

From a geohydrological point of view, the rocks in the Table Mountain Group represent a multiporous medium, which essentially consists of two major components: fractures and inter-fracture “blocks” or rock matrices. In general, the fractures act as the more permeable conduits for groundwater movement, while the matrix blocks form the main storage unit or reservoir (Duah, 2010). The matrix may be either permeable or impermeable. However, the rock mass probably contains many fractures of different scales and is thus expected to have its own secondary porosity. The rocks of the Table Mountain Group are therefore generally considered to form a dual porosity, fractured-rock aquifer system (Duah, 2010).

The Table Mountain Group aquifer is classified as a semi-confined aquifer since it is phreatic in some areas, but confined below an impermeable layer in others. The installation of groundwater abstraction boreholes in the Table Mountain Group aquifer often requires drilling through a confining layer (Aston, 2007). Some boreholes in the Table Mountain Group have free-flowing artesian conditions, confirming that the aquifer is confined and under positive pressure.

The formations that make up the Table Mountain Group differ widely in their ability to store and transmit water. The sandstones of the Nardouw and Peninsula subgroups generally act as aquifers, while the shale layers in these subgroups act as aquitards (Aston, 2007). Two main aquifer systems have been identified in the Table Mountain Group: the Nardouw aquifer and the Peninsula aquifer. The Nardouw aquifer consists of two sub-aquifers (the Rietvlei and Skurweberg sub-aquifers), which are separated by the Verlorenvalley mini-aquitard. The Peninsula aquifer is separated from the Nardouw aquifer by the Winterhoek mega-aquitard, which consists of the Goudini, Cedarberg and Pakhuis meso-aquitards. The Peninsula aquifer itself is subdivided into two sub-aquifers: the Platteklip and Leeukop sub-aquifers (Blake et al., 2010).

Many farmers extract groundwater from the Nardouw aquifer for their farm water supply. The deeper Peninsula aquifer requires deeper drilling and has been exploited to a lesser extent (TMGA Alliance, 2016). However, the Peninsula aquifer is thought to have a greater potential for bulk abstraction than the Nardouw aquifer (Rosewarne and Weaver, 2002). It is much thicker but, more importantly, has a lower shale content and faults are therefore expected to remain open to great depths (Rosewarne and Weaver, 2002).

Extensive deep groundwater reserves have been reported in the fractured rock aquifers of the Table Mountain Group. Rosewarne (1998) (cited in Smakhtin et al., 2001) quoted groundwater storage estimates of approximately 50,000 million m^3 and annual recharge as high as 2,000 million m^3. However, a more detailed investigation of a section of the aquifer system suggested a much lower annual recharge volume of approximately 260 million m^3 (Smakhtin et al., 2001). Weaver and Talma (2000) suggested that, within a radius of 200 km from Cape Town, the total volume of groundwater stored in the Table Mountain Group aquifer may be as high as 66,000 million m^3, with an annual recharge of approximately 2,600 million m^3 a year.

The TMGA Alliance (2016) summarised information on the Nardouw and Peninsula aquifers gained from experience:

- Both hot and cold springs occur in the Table Mountain Group. The hot springs are produced by deep flow through the Peninsula formations. The cold springs come from the near to surface flows through the Nardouw and Peninsula formations.
- The water quality of the Nardouw aquifer is often poorer than the quality of the Peninsula aquifer, but not always.
- Springs, water courses and wetlands may be connected to a borehole by fractures and this can lead to competition for the same finite water resource. This can have implications for the landowner and the natural vegetation and ecology of the abstraction area.
- Borehole yield is variable because it depends on the openings available in the rock mass. Where a particularly good fracture system exists, yields of up to 100 ℓ/s can be obtained. However, most boreholes are lower yielding, with an average yield of less than 5 ℓ/s.

5.3.4.4.1 Porosity

Jia (2007) lists some results of porosity analyses performed on core samples from the Table Mountain Group. These results are presented in Table 5-7. The results show that the porosity of the sandstones in the Table Mountain Group vary between 0.01 and 5.4%, with an average value of approximately 2.5%.

Table 5-7: Porosities of Table Mountain Group sandstones derived from core samples and pumping tests (Jia, 2007)

Type	Sampling depth (mbgl)	Porosity range (%)	Average porosity (%)	Reference
Core samples	3 322 - 3 420 (7 samples)	1.9 - 2.3	1.5	Core samples from the Soekor boreholes (Rowsell and de Swardt, 1967)
	122 - 154 (11 samles)	0.6 - 1.7	1.4	
	1 - 152 (49 samples)	0.9 - 5.4	3.1	
	10 - 107 (7 samples)	1.2 - 3.0	2.2	
	42.5 - 135.5 (6 samples)	1.0 - 3.6	2.5	Core samples from BH1 in TMG, near Rawsonville
Pumping tests	Koo Valley	0.01 - 0.35	0.06	Pumping test
	Kammanassie	0.11 - 0.22	0.15	Kotze (2002)
	Boschkloof	0.01 - 0.1	0.05	Umvoto (2000)
	Gevonden	0.21 - 1.2	0.57	Pumping test

Jia (2007) also estimated the secondary porosities of Table Mountain Group aquifers by estimating the volume of fractures to the bulk volume of the rock material, and found porosity values ranging from 0.041 to 0.52%.

5.3.4.4.2 Hydraulic conductivity, transmissivity and storativity

Due to the low primary porosity of the rocks in the Table Mountain Group, the rock matrix is expected to have a very low hydraulic conductivity. Rosewarne (2002a) suggested negligible hydraulic conductivities for unfractured rocks in the Table Mountain Group and very high hydraulic conductivities for fractured rocks in the Table Mountain Group. The author mentioned a number of studies in which the hydraulic conductivity of the Table Mountain Group formations was found to range between 0 and 1.73 m/d. The means that values of the hydraulic conductivity for the Nardouw and Peninsula aquifers were between 0.07 and 0.26 m/d.

Rosewarne (2002a) also listed transmissivity values obtained by various authors for the Table Mountain Group aquifers and outcrops. He concluded that transmissivities in the order of a few hundred m^2 per day are associated with productive fractures zones. Various authors have suggested storativity values for the rocks of the Table Mountain Group ranging from less than 1E-04 to 1E-02. Rosewarne (2002a) concluded that a storativity value of 1E-02 is a fair estimate for the bulk storativity of the Nardouw and Peninsula formations.

5.3.4.5 Recharge to the Table Mountain Group

Wu (2005) summarised the estimated recharge rates to the Table Mountain Group aquifer as described in the literature. His summary is presented in Table 5-8. The recharge estimates at the various locations are seen to vary significantly with a wide range of recharge percentages (from 0.3 to 83%). Furthermore, different recharge estimation methods yield different estimates at the same location. For example, near the Vermaaks River, the groundwater recharge estimates vary from 0.3 to 43.5% for the aquifers in the Nardouw sandstones, and from 2.7 to 23.9% for the Peninsula Formation (Jia, 2007).

5.3.4.6 Groundwater quality

Groundwater associated from the Table Mountain Group aquifers is known to be of very high quality. Electrical conductivity values as low as 4 mS/m have been measured for a production borehole at the base of the Skurweberg, while electrical conductivity values in the pristine mountain catchments are typically below 10 mS/m (Rosewarne, 2002a). The rock matrices of the Table Mountain Group are very inert and do not contribute much to the mineral content of the groundwater in the aquifers. As a result, the macro-chemical character of the groundwater is determined more by the character of the precipitation than by the mineralogy of the rock through which it percolates (Rosewarne, 2002a). Groundwater from the Table Mountain Group aquifers is generally of the Na-Cl type, reflecting the fact that precipitation generally derives from frontal systems in the Atlantic and Indian oceans.

Table 5-8: Review of recharge rates in the Table Mountain G area (Wu, 2005)

Place	Method	Aquifer	MAP	RE %	Source
Vermaaks River	Base flow	Peninsula	560	8.9	Bredenkamp, 1995
	Unknown	Peninsula	299-714	17	
	CMB	Nardouw / Peninsula		43.5 /11.1	Kotze, 2000 and 2002
	SVF			3.1 /19.7	
	SVF (fit)			3.4 /16.4	
	CRD			3.2 /14.4	
	Base flow			21.4 /12.5	
	EARTH			2.9 /23.9	
	^{2}H displacemen			0.3 /2.7	
	^{14}C age			1.8 /2.0	
	GIS raster	TMG		2.5-4.8	Woodford, 2002
	CMB			5	Weaver et al., 2002
Langebaan Road Field	CMB	Bredas-dorp	396.4-648.9	9.7	Weaver and Talma, 2002
	CMB			11.2	
	CMB			13.5	
	CMB			11.5	
Greater Oudtshoorn Districts	Empirical	Peninsula	165-1049	14	Hartnady and Hay, 2002
	Empirical	Nardouw		7	
Struibaai	CMB	TMG	436	17.4	Weaver and Talma, 1999, 2002
Agter Witzenberg	CMB	Nardouw	579-777	50, 44	
Botriver		Nardouw	477.2-1546.2	20	
Hermanus	^{14}C		635	22 (20-24)	Rosewarne and Kotze, 1996
Uitenhage Artesian Basin	Spring flow		298.2-1202.6	10	Kok, 1992
	CMB	Groot Winterhoek		25	Maclear, 1996
	CMB			55	R Parson, 2002
Whole TMG (within a radius of 200km from Cape Town)	GIS	13200km^{2} outcrop	600-2,020	33	Weaver and Tama, 2002
CAGE – Low rainfall	GIS	Low lying	285.8-371.2	8	Hartnady and Hay, 2000 and 2002
CAGE – High mountain		TMG		23	
CAGE – Mountain area				30-40	
CAGE	Isotopes			50	Weaver et al., 1999
Uitenhage, Coega aquifers	WB	TMG	460	83	Kok, 1992
	CMB	TMG	250-850	24-55	Maclear, 1996
	WB			11	Bredenkamp, 2000; Xu and Maclear, 2003

Elevated iron and manganese concentrations are sometimes observed in the groundwater of the Table Mountain Group. These concentrations are due to iron and manganese compounds sometimes being associated with the joints and fractures within the rocks in the Table Mountain Group. Due to the lack of buffer minerals in the rocks in the Table Mountain Group, low pH values are also common in the Table Mountain Group aquifers. The acidic conditions may cause mobilisation of the dissolved iron and manganese minerals (Rosewarne, 2002a).

5.3.4.7 Characteristics of the deep Table Mountain Group aquifers

Based on the available information, the expected characteristics of the deep Table Mountain Group aquifers may be derived. Table 5-9 summarises these characteristics.

5.3.5 Characterisation of deep aquifers in the Bushveld Igneous Complex

5.3.5.1 Geological description of the Bushveld Igneous Complex

The Bushveld Igneous Complex is a massive crustal emplacement of extrusive and intrusive igneous rocks (Coffin and Eldholm, 1994). It comprises four volcanic sequences:

- The Upper Rooiberg Group
- The Rustenburg Layered Suite
- The Rashoop Granophyre Suite
- The Lebowa Granite Suiten

The Bushveld Igneous Complex is richly endowed with platinum, palladium, rhodium, chromium and vanadium ore bodies and is mined extensively from Burgersfort in the east to Rustenburg in the west. The distribution of outcrops of the Bushveld Igneous Complex is shown in Figure 5-6.

The Bushveld Igneous Complex intruded the meta-sedimentary rocks of the Transvaal Supergroup along an unconformity between the Magaliesberg quartzites (Eriksson et al., 2006). The Rustenburg Layered Suite in the Bushveld Igneous Complex is divided into three lobes: the eastern, western and northern lobes (Figure 4-15) (Cawthorne et al., 2006). The maximum thickness of the Bushveld Igneous Complex is approximately 8 km, while outcrops of the Bushveld Igneous Complex cover an approximate length of 370 km east to west and 200 km north to south.

Table 5-9: Characteristics of the deep Table Mountain Group aquifers

Criteria	Description
Lithology	The deep aquifers in the TMG are found in the Nardouw and Peninsula Subgroups. The rocks in which the aquifers occur are predominantly fractured sandstones and quartz arenites.
Occurrence	The TMG aquifers occur in the coastal areas of the Western and Eastern Cape.
Physical dimensions	The TMG rocks occur in an area with a surface area of aproximately 248 000 km^2. Due to the folding of the rocks of the Cape Supergroup, these aquifers extend from surface to depths in excess of 1 000 mbgl. The total volume of the aquifer systems is large and it has been estimated that up to 50 000 Mm^3 of groundwater is stored in the TMG aquifers.
Aquifer type	The aquifers systems are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing.
Saturation level	The deep fractured rock aquifers are expected to be under positive pressure, and are therefore likely to be fully saturated.
Heterogeneity and isotropy	The aquifer systems are expected to be highly heterogeneous due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The folding of the rocks of the Cape Supergroup is likely to add to the heterogeneity and anisotropy of the aquifer systems.
Formation properties	The primary porosities of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Secondary porosity due to fracturing of the brittle sandstones is responsible for the water storage and transmission. Fractured zones are expected to be associated with very high secondary porosities.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractured zones, by contrast, are likely to have very high hydraulic conductivities. Groundwater storage in the fractured aquifers is likely to occur in the highly fractured zones.
Pressurisation	The deep aquifers systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.
Yield	The yield of the deep fractured aquifers could be very high. There are indications that the yields of deep boreholes could exceed 50 L/s.
Groundwater quality	The groundwater quality of the deep TMG aquifers is expected to be very good due to the inert nature of the matrix. However, low pH values and elevated iron and manganese concentrations could occur.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. However, the folding of the rock of the Cape Supergroup means that deep aquifers may extend to surface where such aquifers could be exposed to surface contaminants. In addition, the complex nature of the fracture networks in the TMG aquifers means that abstraction at a specific location could have impacts on groundwater availablity at another. Many surface (and possibly marine) ecosystems depend on discharge of groundwater from the TMG aquifers.

The Rustenburg Layered Suite is divided into five zones:

- The Upper Zone
- The Main Zone
- The Critical Zone
- The Lower Zone
- The Marginal Zone

The subdivisions of the Bushveld Igneous Complex are shown in Table 5-10. The Marginal Zone is the lowermost zone and consists of gabbronorite, norite and hybrid meta-sedimentary rocks (Kruger, 2005). The Lower Zone comprises a rich sequence of pyroxene and olive rick rocks, i.e. pyroxenites and hartzburgite (Viljoen and Shurmann, 1998).

Table 5-10: Subdivisions of the Bushveld Igneous Complex

Major Unit	Subdivisions
Lebowa Granite Suite	Nebo, Makhutso, Klipkloof, Bobbejaanskop and Verena Granites
Rashoop Granophyre Suite	Stavoren and Diepkloof Granophyres Rooikop Porphyritic Granite Zwartberg Pseudogranophyre
Rustenburg Layered Suite	Upper Zone Main Zone Critical Zone Lower Zone Marginal Zone
Rooiberg Group	Schrikkloof, Kwaggasnek, Damwal and Dullstroom Formations

The Critical Zone is subdivided into the Lower and Upper Critical zones. The Lower Critical Zone mainly comprises ultramafic rocks, such as orthopyroxenite, harztburgite and chromite layers, while the Upper Critical Zone consists of ultramafic and mafic layers, such as chromite, feldspathic orthopyroxene, nortite and anorthosite (Kruger, 2005). The Critical Zone contains several seams of rich mineral deposits. These seams have been divided into the Lower Group (LG1-7), the Middle Group (MG1-4) and the Upper Group (UG1-2), as well as the Merensky Reef. Huge deposits of chromite occur in these seams, particularly in the LG6, MG1, MG2 and UG2 seams. The world's richest PGE deposits occur within the Merensky Reef and UG2 seam (Kruger, 2005). These reefs are extensively mined for their mineral wealth.

The Main Zone comprises anorthosite at the base, grading into norite and then gabbronorite towards the top with isolated anorthosite and pyroxenite bands. The Upper Zone comprises gabbro, magnetite-gabbro, anorthosite and troctolite layers.

A south-to-north cross-section through the Bushveld Igneous Complex is shown in Figure 4-16. The Critical Zone, with its rich mineral seams, is seen to have outcrops in the southern parts of the southern limb of the Bushveld Igneous Complex, but dips towards the north, attaining depths of several kilometres. Underground mines that extract ore from these seams are hence also several kilometres deep and are likely to intersect the deep aquifer systems associated with the Bushveld Igneous Complex.

5.3.5.2 Tectonic setting of the Bushveld Igneous Complex

The Bushveld Igneous Complex is situated in the northeastern portion of the Kaapvaal Craton and was created during an intracratonic and anorogenic event. The formation of the Bushveld Igneous Complex was controlled by crustal structures that had east-northeast to west-southwest and north-northwest to south-southeast trends (Kinnaird, 2005). These structures may be seen as the Thabazimbi Murchison lineament, the Magaliesburg-Barberton lineament and the Palalazoetfontein fault.

The Bushveld Igneous Complex experienced some disruptions along the western lobe, which occurred during the formation of the Rustenberg Fault (Hayhoe, 2013). Aeromagnetic surveys of the western limb have revealed the presence of faults and dykes (Figure 5-6). According to Hayhoe (2013), there are two major faults within the Bushveld Igneous Complex: a 2,600 m sub-vertical fault, trending in a northeast to southwest direction, and a 1,600 m sub-vertical fault trending in an east to west direction.

5.3.5.3 Geohydrological characteristics of the Bushveld Igneous Complex

The general aquifer model for the Bushveld Igneous Complex consists of a shallow, perched aquifer in the weathered zone, overlying a deeper, semi-confined fractured bedrock aquifer. The infiltration and flow of groundwater in such a system is largely controlled by the fracture network, and can vary both spatially and temporally (Titus et al., 2009b). The shallow aquifer is associated with weathered rock profiles down to an approximate depth of 50 m below ground level. These are primarily associated with saprolitic rocks (highly weathered igneous rocks of low density). The deeper aquifer is associated with highly fractured norites, anorthosites and pyroxenites, and has a hydraulic conductivity (generally low), which is dependent on the fracture network within the host rock (Titus et al., 2009b).

The shallow aquifer is associated with low to moderate transmissivity (3 to 8 m^2/d), although pumping tests performed on some boreholes have indicated transmissivity values of up to 50 m^2/d. Storativity values typically range from E-03 to E-04. Abstraction rates for boreholes are typically 0.5 to 1 ℓ/s. However, there are isolated areas with higher borehole yields of around 2 ℓ/s (Titus et al., 2009b). Higher transmissivity values of up to 285 m^2/d were observed during pumping tests performed on shallow aquifers in the vicinity of the Brits Graben. These aquifers displayed storativity values of up to E-01. Furthermore, much higher transmissivity values (up to 500 m^2/d) and storativity values (in the range of 0.15) have been observed for aquifer systems consisting of both the shallow weathered and the deeper fractured aquifers (Titus et al., 2009b).

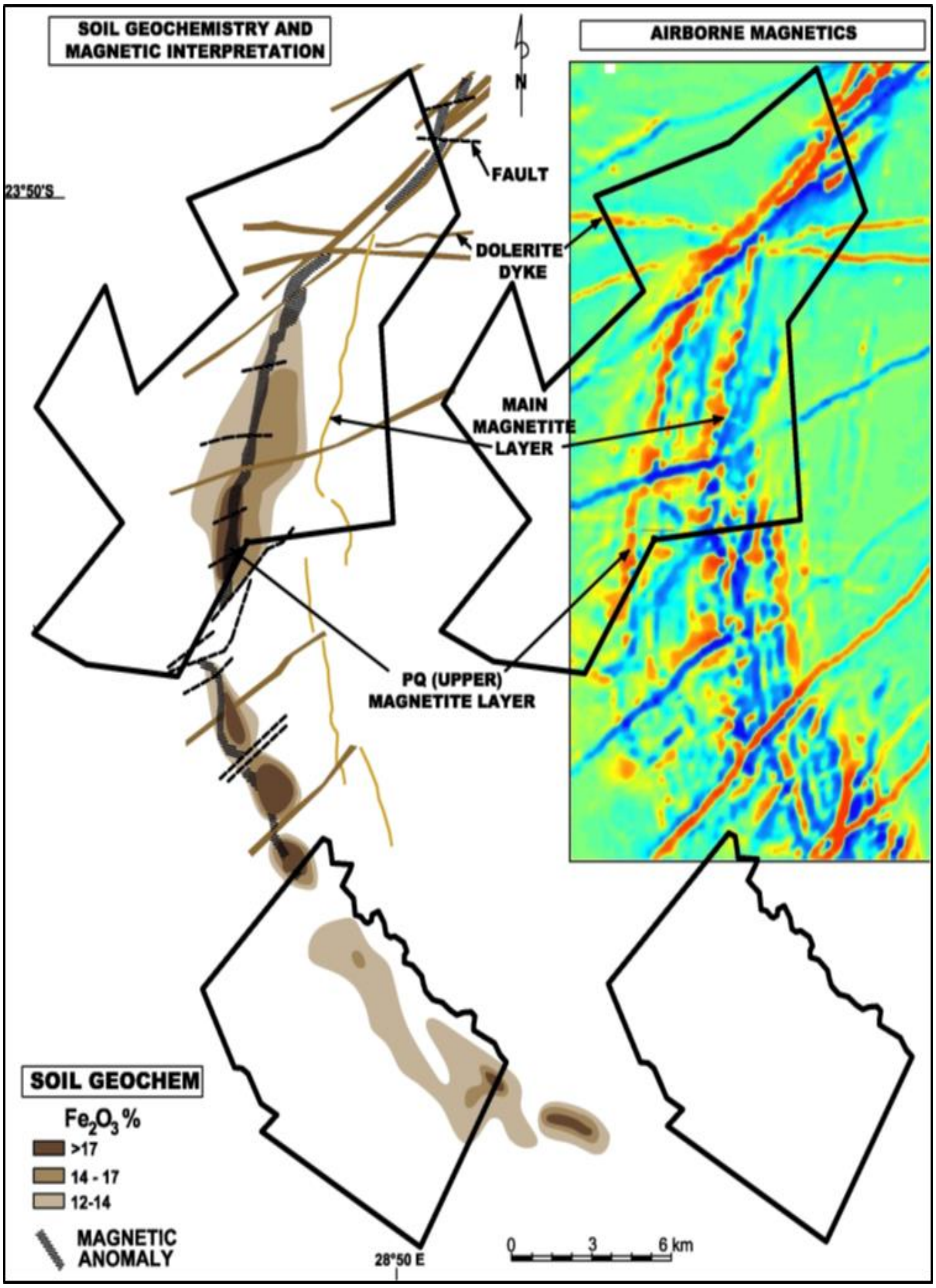


Figure 5-6: Aeromagnetic map of a part of the western limb of the Rustenburg Layered Suite, indicating the presence of faults and dykes (Hayhoe, 2013)

The deeper aquifer system is associated with low porosity and higher hydraulic conductivity along fractures (Titus et al., 2009b). Water is generally stored and transmitted in fractures and fissures within a relatively impermeable matrix. The aquifers in the Bushveld Igneous Complex are furthermore associated with severe heterogeneity, and their hydraulic properties are subject to large variations over short distances (Gustafson and Krásný, 1994). This heterogeneity hinders the estimation of regional hydraulic properties. However, regional hydraulic conductivity values of E-03 to E-01 have yielded satisfactory calibration of numerical groundwater models (Titus et al., 2009b). In general, very little groundwater is found in the deeper unweathered rocks of the Bushveld Igneous Complex.

5.3.5.4 Groundwater characteristics

The following water facies are typically encountered in the Bushveld Igneous Complex (Titus et al., 2009b):

- Water of the Mg-Ca-HCO_3 type is associated with the shallow weathered aquifer. The water type may change to Mg-Ca-HCO_3-Cl in the alluvial aquifers along the major river systems.
- Water of the Na-Cl type is associated with the deeper fissure flow, having longer residence times.

Titus et al. (2009b) compiled a Piper Diagram of water samples from the shallow weathered aquifer and the deeper fissured aquifer encountered in mines (Figure 5-7). The separation of the shallow and deep groundwater in the Piper Diagram confirms that the water has different origins. The dominant Mg-Ca-HCO_3 character of the shallow groundwater samples indicates a recently recharged groundwater, the character of which may be attributed to silicate mineral weathering processes associated with the Bushveld Igneous Complex. The deeper groundwater is typically classified as Na-Ca-Cl or Ca-Na-Cl water facies, and has TDS concentrations that range from 350 mg/ℓ to more than 1,000 mg/ℓ. The TDS concentrations are expected to be increase with increasing residence times in the subsurface (Titus et al., 2009b).

The shallow groundwater from the weathered aquifer also has a different isotope character to the deeper groundwater. When plotting the stable isotope ratios (i.e. $\delta^{18}O$ and $\delta^{2}H$ ratios) and the tritium concentrations, clear distinctions may be made between the characteristics of the shallow and deep groundwater (Titus et al., 2009b).

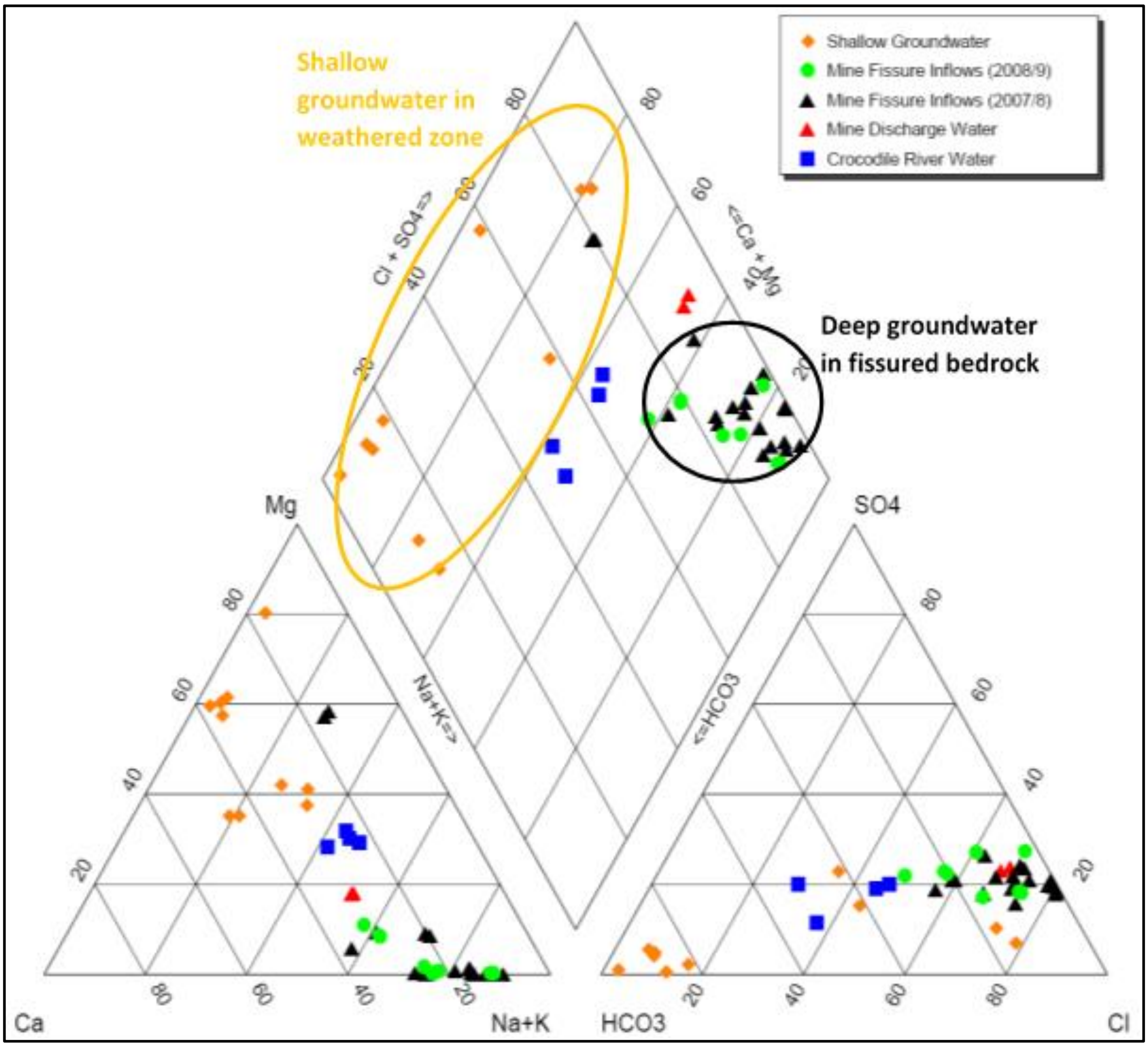


Figure 5-7: Piper Diagram depicting shallow groundwater, as well as deep mine fissure inflows (modified from Titus et al., 2009b)

5.3.5.5 The UG2 aquifer

According to Gebrekristos and Cheshire (2012), the UG2 pyroxenite layer has a unique aquifer property as it is responsible for the majority of the groundwater inflow into the mines intersecting this layer. The UG2 pyroxenite layer weathers much more than the surrounding rock and has an improved porosity and permeability.

The upper bedrock horizons of the Bushveld Igneous Complex, i.e. from the surface down to 35 m, display degrees of weathering and are much more permeable, fractured and porous than rock at greater depths (Gebrekristos and Cheshire, 2012). The rocks below this zone are less weathered and are generally low yielding. However, if secondary structures are present, these could increase the permeability of the rock. Such aquifers are usually encountered at depths of 130 to 140 m below ground level.

The UG2 pyroxenite unit contains a series of chromitite layers, including the UGS (stringers), the UGL (leader) and the UG2. Most of the groundwater is stored in UG2S. Due to the aquifer properties of UG2S, the mining activities are restricted to UG2 and UG2L. Mining in the area usually takes place approximately 5 to 7 m below the UG2 pyroxenite aquifer (Gebrekristos and Cheshire, 2012). A conceptual model of the UG2 aquifer in relation to underground mining is shown in Figure 5-10. The position of three boreholes (PD01, PD11 and PD20) that were drilled into the UG2 aquifer is also indicated.

The aquifer yields vary across the three borehole sites (Gebrekristos and Cheshire, 2012):

- Borehole PD20 has a yield of 12.8 ℓ/s and intersects the aquifer at a depth of 38 m below ground level
- Borehole PD11 has a yield of 4.4 ℓ/s and intersects the aquifer at a depth of 45 m below ground level
- Borehole PD01 has a yield of 0.7 ℓ/s and intersects the aquifer at a depth of 49 m below ground level

A decrease in weathering occurs with depth, probably as a result of increasing overburden pressure. This decrease in weathering is associated with a decrease in the transmissivities of the rock units. Gebrekristos and Cheshire (2012) reported transmissivity values of 10 m^2d^{-1} at 40 m below ground level, 1 m^2d^{-1} at 50 m below ground level and 0 m^2d^{-1} at 80 m below ground level.

5.3.5.6 Characteristics of deep aquifers in the Bushveld Igneous Complex

Although very limited information on the deep fractured aquifer systems in the Bushveld Igneous Complex is available, the characteristics of these deep aquifers may be deduced by considering the characteristics of the shallower fractured aquifers. The deduced characteristics of the deep fractured aquifers are summarised in Table 5-11.

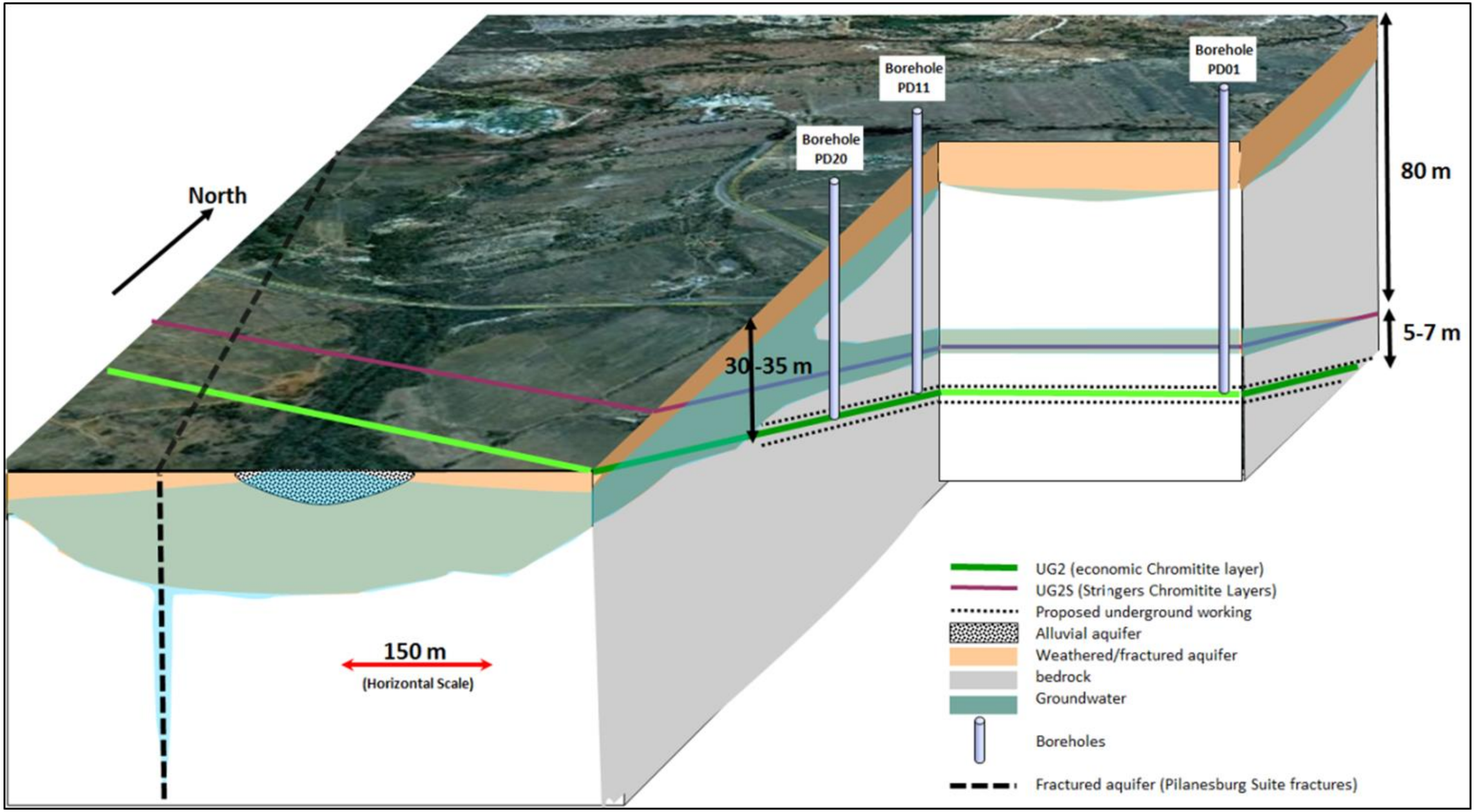


Figure 5-8: Simplified geohydrological conceptual model of the Bushveld Igneous Complex showing the UG2 aquifer associated with the UGS chromitite layer (Gebrekristos and Cheshire, 2012)

Table 5-11: Characteristics of the deep fractured aquifers in the Bushveld Igneous Complex

Criteria	Description
Lithology	The deep fractured aquifers occur in mafic, ultramafic and felsic rocks of the BIC.
Occurrence	The BIC has a very localised occurrence in South Africa. The deep fractured aquifers of the BIC are therefore also very localised.
Physical dimensions	The vertical extents of the deep fracture zones are expected to be very limited (a few metres at most). However, the matrices of the rocks hosting the fractures are likely to act as the main storage unit for the water. These rocks therefore form part of the aquifer system. The thicknesses of the host rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers systems are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing. However, the porosity of the rock matrix is expected to be very low.
Saturation level	The deep fractured rock aquifers are expected to be under positive pressure, and are therefore likely to be fully saturated.
Heterogeneity and isotropy	The aquifer systems are expected to be highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks and the presence of impermeable dolerite intrusives.
Formation properties	The primary porosities of the rocks forming part of the aquifer systems are expected to be very low. Very little water is therefore expected to be stored in the rock matrix. The fractures are expected to create localised zones with high secondary porosities. The physical dimensions of the fractures, however, imply that little water can be stored within the fractures.
Hydraulic parameters	The hydraulic conductivities of the rock matrices forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the host rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.
Yield	Despite the possibility that the fractures will have high hydraulic conductiviities, the yield of the deep fractured aquifers is expected to be very low due to the low volumes of water that can be stored in the matrix and fractures. Yield is expected to decrease with depth. Furthermore, the large depths at which the fractured aquifers occur imply that very little recharge will take place.
Groundwater quality	The groundwater quality from the deep fractured aquifers may be poor with high TDS concentrations due to the long residence times.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be very vulnerable to over-exploitation since little recharge is expected.

5.3.6 Characteristics of South Africa's deep dolomite aquifers

5.3.6.1 Introduction

Dolomite aquifers form the largest and most important aquifers in South Africa. These aquifers store large volumes of water and are extensively used to supply water for domestic use and to the agricultural, mining and industrial sectors (DWAF, 2006a; Schrader and Winde, 2015).

The more than 1,000 m thick dolomite sequence in Gauteng constitutes one of the most important groundwater reserves in South Africa (Smakhtin et al., 2001). Unfortunately, the dolomite aquifer also overlies some of the most important gold- and uranium-bearing deposits in the Witwatersrand Supergroup (Schrader and Winde, 2015). Many of the deep gold mines have experienced challenges due to the inrush of groundwater from the overlying dolomitic aquifers along faults, fissures and joints. In certain areas, fracture zones extend through the entire thickness of the dolomites, presenting a serious hazard to mine workings. (DWAF, 2006b).

Mining, in turn, has posed a significant threat to the quality of the groundwater resource. The presence of sulphide minerals in the rocks of the Witwatersrand Supergroup has led to the formation of acid mine drainage and the associated mobilisation of trace metals. In addition, radioactive isotopes of uranium and thorium have contributed to groundwater contamination (Smakhtin et al., 2001). Dewatering of mines has furthermore had a significant influence on the groundwater levels within some of the dolomite compartments (DWAF, 2006b). Mining through aquicludes (such as dykes) has also linked previously disconnected compartments of the karst aquifers (Schrader et al., 2014b).

5.3.6.2 Dolomitic rocks in South Africa

The surface distribution of dolomite outcrops in South Africa is shown in Figure 5-9. The subsurface distribution of dolomite rocks is, however, significantly larger than the surface outcrops (DWAF, 2006a). South Africa's dolomite outcrops are often grouped according to their location and/or their association with structural or morphological features. The seven main dolomite units are as follows:

- The East Rand compartments
- The West Rand compartments
- The North West compartments
- The Vredefort Unit
- The Ghaap Plateau Unit
- The Limpopo/Mpumalanga compartments
- The North West/Limpopo compartments

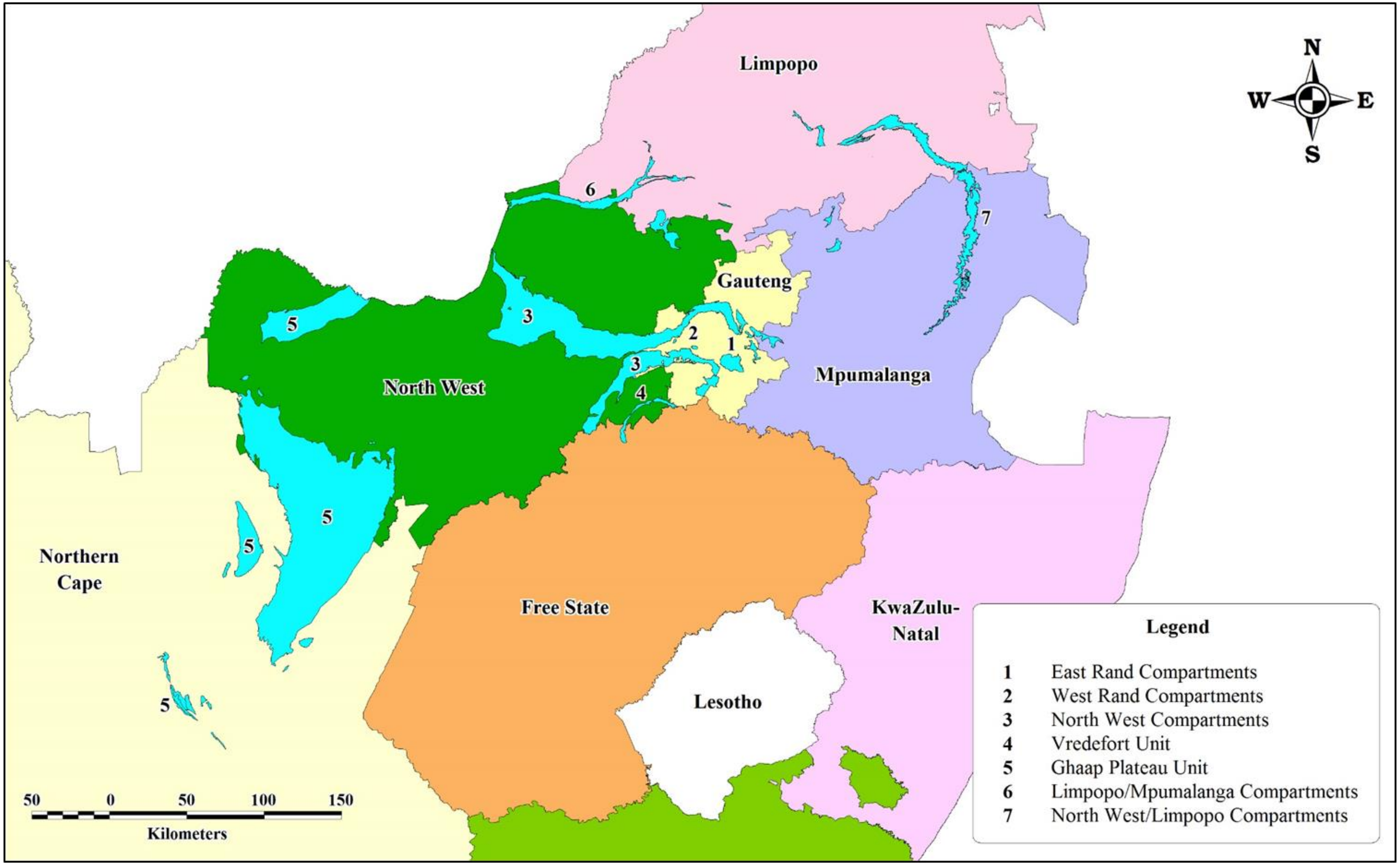


Figure 5-9: Distribution of dolomite outcrops in South Africa

Apart from a few minor depositions (such as the Matjies River Formation of the Kango Group), South Africa's dolomites all belong to the Transvaal Supergroup. Sediments of the Transvaal Supergroup were deposited in shallow sea environments in three structural basins: the Griqualand West Basin in central South Africa, the Kanye Basin in eastern Botswana and the Transvaal Basin in northern South Africa (Eriksson and Altermann, 1998). The dolomites and subordinate limestones and shales of these three basins represent one of the oldest preserved carbonate platforms, which probably extended across all three basins and covered an area of approximately 600,000 km^2 (Eriksson and Altermann, 1998).

The stratigraphic correlation and geochronology of the different formations within the basins are summarised in Figure 5-10. The Griqualand West carbonate succession is cut by the major Griquatown fault in the southwestern portion of the basin, which has led to a subdivision of the succession into the Prieska carbonate facies and the Ghaap Plateau carbonate facies (Eriksson and Altermann, 1998). The carbonate successions of the Griqualand West and Transvaal basins are represented by the Campbell Rand and Malmani subgroups, respectively. The rock formations of these subgroups attain total thicknesses in excess of 2,000 and 1,000 m, respectively (Figure 5-10).

The dolomite outcrops of the Vredefort Unit occur in a semi-circular zone centred on the Vredefort Dome. These carbonate rocks belong to the Malmani Subgroup and were uplifted as a result of the impact of the Vredefort Asteroid and subsequently exposed through erosion. The presence of Malmani dolomites at depth in the vicinity of the Vredefort Dome confirms that the subsurface distribution of dolomites in South Africa is much larger than the distribution of surface outcrops.

5.3.6.3 Karst geohydrology

The term "karst" refers to carbonate rock that has been subjected to dissolution through the action of circulating water, creating such features as dissolution cavities, sinkholes and grikes (linear dissolution cavities). Dolomite is only moderately soluble in water. However, the presence of CO_2 in water leads to increased acidity and hence an increased potential to dissolve carbonate rocks. Rainwater is generally slightly acidic due to atmospheric pollution. Its acidity may further increase as it percolates through the soil to the groundwater table (Foster, 1988). The weakly acidic groundwater that circulates through the dolomitic rock causes the dissolution of carbonate minerals, leading to the development of open cavities and caves (Holland et al., 2010). The dissolution cavities that are formed in the dolomite allow the rapid migration of groundwater (CSIR, 2003).

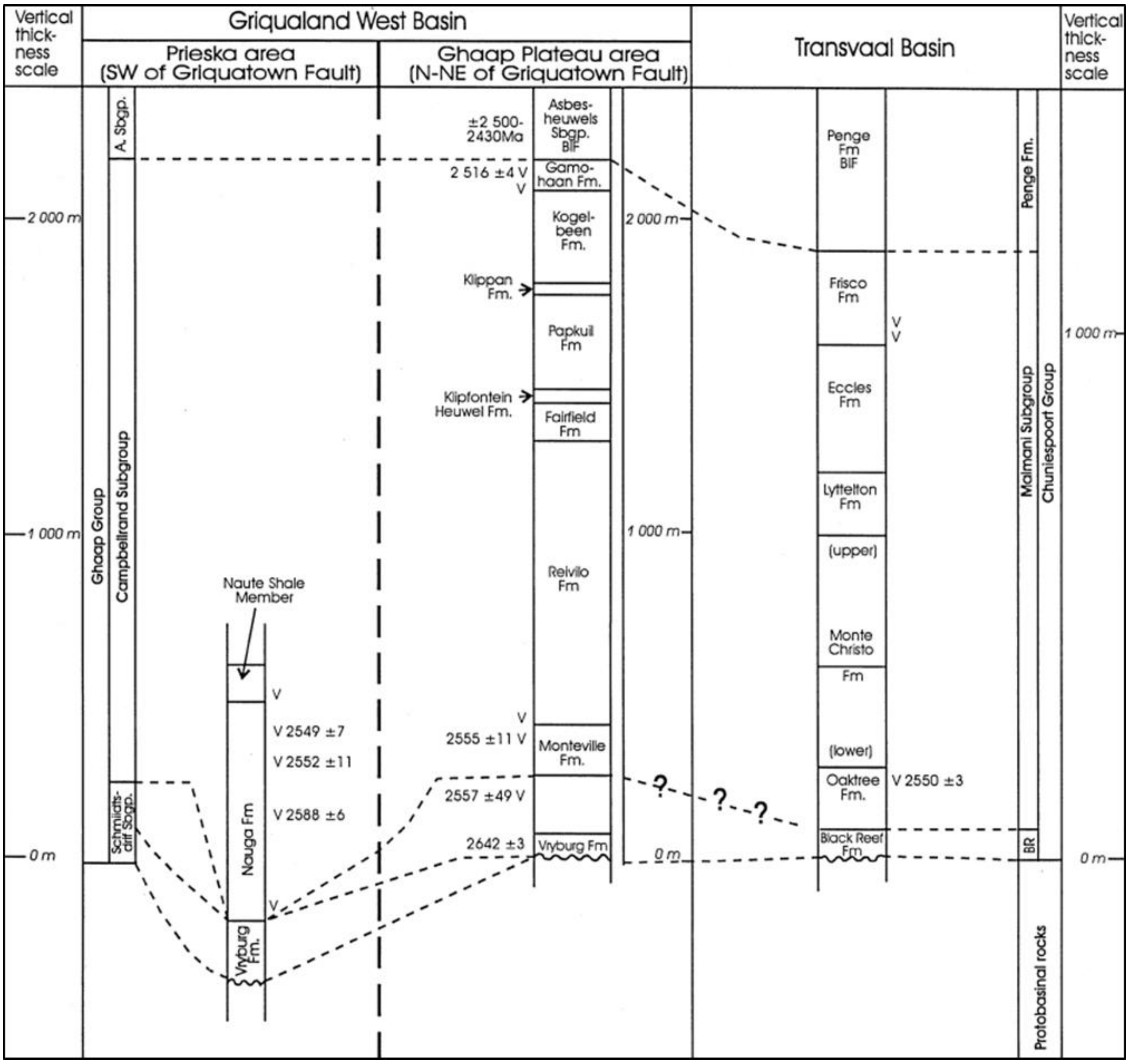


Figure 5-10: Stratigraphic subdivision and correlation of the Transvaal Supergroup dolomites within the preserved Transvaal and Griqualand West basins (Eriksson and Altermann, 1998)

A schematic cross-section through a dolomite aquifer in which karst development has taken place is shown in Figure 5-11. Cavities in the dolomite are generally more frequent near the surface than at greater depths due to greater exposure to atmospheric conditions and circulating groundwater. However, enhanced dissolution may also occur at greater depths along geological structures, such as faults, fissures and dykes (Kafri and Foster, 1989; Holland et al., 2010). Furthermore, dykes are often impermeable to groundwater flow in directions perpendicular to their strikes, resulting in compartmentalisation of the dolomite aquifers. Springs often occur at the dyke boundaries (Figure 5-11).

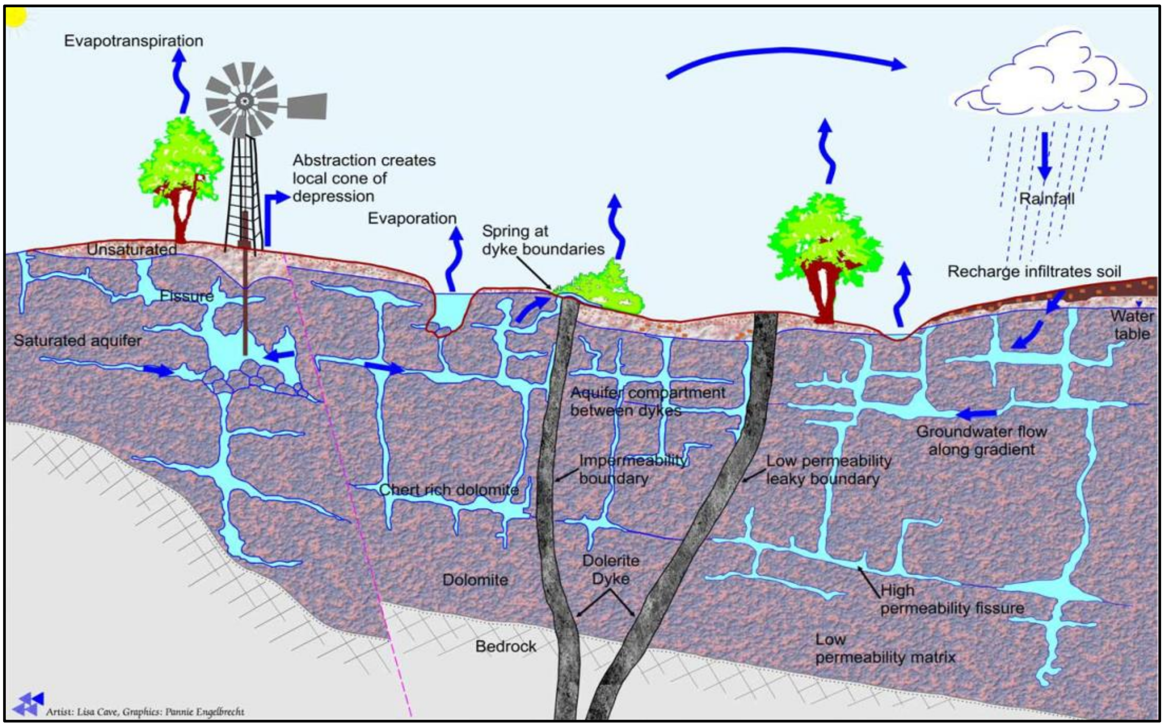


Figure 5-11: Cross-section through a dolomite aquifer (CSIR, 2003)

The carbonate rocks of the Transvaal Supergroup were subject to various karst episodes. Studies of rocks of the Chuniespoort Group showed that these rocks experienced at least four karst episodes (Foster, 1988; Naidoo, 2014). This implies that, apart from near-surface karstification, palaeokarst environments exist at greater depths within the formations. Palaeokarst horizons of varying ages are widespread along the upper contacts of the Malmani Subgroup with the overlying Pretoria Group and Karoo deposits (DWAF, 2006). From a study of the aquifer properties of the Chuniespoort Group in the Klip River Valley and Natalspruit Basin, Foster (1998) concluded that the occurrence of palaeokarst horizons is a major control of aquifer properties.

5.3.6.4 Hydraulic properties

Compact ancient carbonate rocks are characterised by very low porosity and primary permeability. Secondary porosity is usually developed by dissolution along discontinuities such as joints, fissures, fractures and bedding planes (Brink, 1979; Foster, 1988). The effective porosity, permeability and storage properties of carbonate aquifers generally decrease with depth from the water table (Foster, 1988). Various authors studying karst aquifers in South Africa have reported effective porosities that range from 1 to 20% (Naidoo, 2014).

Transmissivity values are very variable in dolomites, ranging from nearly 0 m^2 per day in fresh dolomite to values in excess of 30,000 m^2 per day in karstic areas (DWAF, 2006b). Naidoo (2014) listed the estimated transmissivity ranges for South African karst aquifers as determined by different authors. Transmissivity values were reported to range between 10 and 30,000 m^2 per day.

Transmissivities of karst aquifers appear to increase in the vicinity of dykes (Holland et al., 2010). In the Zuurbekom Compartment, for example, the transmissivities increase from an average of 260 m^2 per day to 25 000 m^2 per day near the Gemsbokfontein Dyke (DWAF, 2006b).

Results of a hydrocensus conducted by Foster (1988) show that transmissivity values in excess of 500 m^2 per day are associated with aquifers occurring in the different formations of the Malmani Subgroup. However, most of the high transmissivity values were recorded at boreholes that intersected the Eccles Formation.

Eighteen of the 30 boreholes in this formation had transmissivities greater than 100 m^2 per day. In general, the chert-rich units of the Malmani Subgroup are significantly more fractured and jointed than the chert-poor dolomites, and are hence also more susceptible to dissolution. The transmissivities of the chert-rich units are correspondingly greater than those of chert-poor units (Foster, 1988; Kafri and Foster, 1989).

Foster (1988) found that boreholes that intersect palaeokarst horizons were often associated with significantly larger transmissivities. At some of these boreholes, transmissivities as high as 9,755 and 11,575 m^2 per day were reported. Faults and lineaments were found to be associated with zones of higher transmissivities in the Eccles and Lyttelton formations. In the Eccles Formation, highly transmissive zones were found to occur within 100 m of dykes intersecting this formation (Foster, 1988).

Kafri and Foster (1989) studied the geohydrology of the Malmani Dolomites in the Klip River and Natalspruit basins. They estimated the transmissivity values of the dolomitic aquifers in these basins (and adjacent dolomitic areas) by finding an empirical relationship between the transmissivities and the specific capacities of these aquifers. Their results show that transmissivities of up to 50,000 m^2 per day are common for these aquifers.

A recent study by Schrader et al. (2014) used historical data derived from draining a large dolomitic karst aquifer by deep-level gold mines. The conditions under which the aquifer had been drained were considered similar to an ultra-large pumping test that covered the entire thickness (almost a kilometre) of the karst aquifer. Apart from the long-term dewatering data, the authors also considered data from a single inrush event, as well as data from a one-day, steady-state dewatering exercise. From various analyses of the drawdown and pumping data, the authors estimated the transmissivity and storativity of the karst aquifer. Although the estimated transmissivity and storativity values from the different datasets and different analytical techniques varied significantly, the authors suggested that the values obtained from the inrush data best represented the hydraulic properties of the entire thickness of the karst aquifer. The geometric mean of the transmissivity values calculated at a number of observation boreholes for this dataset was found to be 2,468 m^2 per day, in agreement with a previous estimate obtained by Enslin and Kriel (1959) (2,983 m^2 per day). The most reliable estimate of the storativity value was 0.0067.

Storativities of South African dolomitic aquifers generally vary between 0.010 and 0.050%, but depend strongly on the degree and extent of dissolution and weathering (Barnard, 2000, cited in Pietersen et al., 2011). Storativity values found for dolomites of the North West compartments range between 0.008 and 0.044 (DWAF, 2006b). The storativities' values generally decrease with depth.

5.3.6.5 Recharge and storage

Recharge in dolomite areas can vary from 0% of the mean annual precipitation during periods of low rainfall to more than 50% during periods of exceptionally high rainfall (Bredenkamp et al. 1995, cited in DWAF, 2006a). The wide range of recharge rates in dolomitic areas is due to the presence of high permeability zones in the form of dissolution cavities in the otherwise impermeable dolomite. Where such zones extend to the surface, rapid recharge of the aquifer system can occur (DWAF, 2006a). Pietersen et al. (2011) reported that groundwater levels of the Botleng dolomite aquifer showed an immediate response after rainfall events.

By using the Chloride Method, Kafri and Foster (1989) estimated the recharge of the Malmani Dolomites in selected parts of the Klip River and Natalspruit basins. They found a recharge value of 25% of the mean annual precipitation. Various other authors have reported recharge rates ranging from 2.5 to 28% for the Malmani Dolomites (Kafri and Foster, 1989). DWAF (2006b) summarised some of the recharge estimates obtained by different authors for various dolomite compartments of the West Rand. These estimates range from 3.6 to 27.4%

In undisturbed dolomite compartments, most of the recharge to the compartments discharges naturally at springs within the compartments. From the flow rates recorded at springs in West Rand compartments, the volumes of recharge were estimated to range between 9.2 Mℓ per day (Gemsbokfontein Compartment) and 55.9 Mℓ per day (Oberholzer Compartment) (Connelly and Ward, 2006). The Kuruman Spring flows at a rate of approximately 20 Mℓ per day, with very little seasonal variation, while the Dinokana Spring west of Zeerust has a flow rate of approximately 12.96 Mℓ per day. The Gerhard Minnebron Spring west of Carletonville has a flow rate that corresponds to a recharge rate of 51.84 Mℓ per day (DWAF, 2006a). The two springs that emanate from the karst aquifer in the City of Tshwane Metropolitan Municipality currently supply 46 Mℓ/day to the inhabitants of Pretoria (Naidoo, 2014).

The volumes of water stored in the dolomites are very large. The total water storage in South African dolomitic aquifers has been estimated at 5×10^6 Mℓ (CSIR, 2003). However, Schwartz and Midgley (1975) estimated that, in the Bank Compartment of the West Rand Dolomites alone, a volume of 2.2×10^6 Mℓ of water was stored. The total volume of water stored in the dolomitic aquifers of South Africa is therefore likely to be much larger than 5×10^6 Mℓ. It has been reported that the dolomitic aquifers of the East and West Rand have a higher storage capacity than Lake Kariba (MCSA, 2012).

The large volumes of water that have to be removed from gold and uranium mines in areas where the Witwatersrand Supergroup is overlain by dolomites also attest to the large volumes of water stored in the dolomitic aquifers. By 1956, up to 50 Mℓ per day had to be removed from the Venterspost Mine. In 1963, mine dewatering of the West Driefontein and Blyvooruitzicht goldmines had to be done at a rate of approximately 170 Mℓ per day to allow operations to continue. Western Areas Goldmine similarly had to dewater at a rate of up to 130 Mℓ per day in 1984 (Connelly and Ward, 2006). In 1968, the collapse of a stope at West Driefontein Goldmine caused a groundwater inrush of approximately 385 Mℓ per day (DWAF, 2006b). To allow underground mining to continue, dewatering of the Oberholzer Compartment began in 1955 and was achieved in 1973, after which an average pumping rate of approximately 45 Mℓ per day was employed to maintain a balance with groundwater ingress (DWAF, 2006b; Schrader et al., 2014b). From the early 1980s, an equilibrium pumping rate of approximately 69 Mℓ per day was employed to counter groundwater ingress from the Bank Compartment (Schrader et al., 2014b).

DWAF (2006b) listed some of the estimates for the storage of South African dolomites that had been made by various authors. Values range from less than 1% for depths in excess of 60 m to 15% for depths below 30 m.

5.3.6.6 Yield

Vegter (1984) estimated the sustainable yield of the dolomitic aquifers in the Pretoria-Witwatersrand-Vereeniging (PWV) area at approximately 240 Mℓ per day. The presence of zones of high transmissivity associated with dissolution cavities in dolomites allows very high-yielding boreholes to be installed in dolomitic aquifers (DWAF, 2006a). Since such cavities are more common in the near-surface environment that is exposed to dissolution factors, the potential for high-yielding boreholes is also greater in the first 100 m, and particularly in the first 30 m below the water table (DWAF, 2006a). However, high-yielding water strikes have been reported to occur at depths greater than 130 m in some boreholes. A water-bearing fracture (14 ℓ/s) that occurred in solid dolomite at a depth of 680 m was also reported (DWAF, 2006b).

Foster (1988) reported yields of boreholes drilled in the different formations of the Malmani Subgroup. In the Upper Klip River Valley, average borehole yields of 4.5, 6.5, 8.5 and 7.2 ℓ/s were calculated for boreholes intersecting the Oaktree, Monte Christo, Lyttelton and Eccles formations, respectively. Yields of up to 59 and 64 ℓ/s were recorded at specific boreholes in the Monte Christo Formation, while the maximum borehole yields in the Lyttelton and Eccles formations were 12 and 29 ℓ/s, respectively. The presence of dykes appeared to affect the yields of boreholes intersecting these latter two formations, Higher yields were generally observed near dykes. However, no association between the presence of dykes and the yields of boreholes drilled in the Oaktree and Monte Christo formations was noted (Foster, 1988).

5.3.6.7 Groundwater quality

The groundwater of dolomitic aquifers is usually of the bicarbonate group, characterised by the major ions Ca^{2+}, Mg^{2+} and HCO_3^- (DWAF, 2006b). The TDS concentration of dolomitic groundwater generally ranges between 100 and 400 mg/ℓ, with groundwater of a better quality usually associated with higher rainfall areas (Vegter, 1984). Bond (1946) analysed 22 groundwater samples from dolomitic areas in South Africa and reported TDS concentrations of 200 to 300 mg/ℓ, rising to 750 mg/ℓ in the more arid areas (DWAF, 2006a). Bond (1946) also found consistent pH values of approximately 7.8 for the groundwater samples.

Kafri and Foster (1989) reported that TDS concentrations in the Klip River and Natalspruit basins rarely exceed 500 mg/ℓ. They found that sites with higher TDS concentrations were associated with sources of groundwater contamination. Dolomitic aquifers are extremely vulnerable to contamination due to the ease with which contaminants can infiltrate, relatively unfiltered, into the subsurface in karst environments. Contaminants can also be rapidly transported along the preferential pathways formed by dissolution cavities in the dolomites (DWAF, 2006a; Pietersen et al., 2011). Contamination at the surface could therefore rapidly impact on the quality of groundwater at depth.

5.3.6.8 Summary

From the information presented above, the characteristics of South Africa's deep dolomitic aquifers may be summarised as in Table 5-12.

Table 5-12: Characterisation of the deep dolomitic aquifer systems

Criteria	Description
Lithology	The main dolomite units of South Africa were deposited in shallow sea conditions in two structural basins, namely the Transvaal Basin and the Griqualand West Basin. These dolomites all form part of the Transvaal Supergroup. In the Transvaal Basin, the dolomites belong to the Malmani Subgroup of the Chuniespoort Group, while in the Griqualand West Basin, the dolomites belong to the Campbellrand Subgroup of the Ghaap Group.
Occurrence	The dolomite outcrops in South Africa occur in broad and elongated zones extending across the Northern Cape, North West, Gauteng, Limpopo and Mpumalanga Provinces. The subsurface distribution of the dolomite is, however, much larger han the surface distribution.
Physical dimensions	Dolomite outcrops occur over vast areas in the northern parts of South Africa. The lateral extent of the dolomite aquifers is likely to be much larger than the distributions of surface outcrops, since it is known that the subsurface distribution of dolomites is larger than the areas in which surface outcrops occur. The dolomites attain thicknesses in excess of 1000 m (Transvaal Basin) and 2000 m (Griqualand West Basin). Although the dissolution cavities associated with the important aquifers are more common in the near-surface, the presence of major faults and dykes extending through the dolomite layers is likely to have created conditions favourable for the formation of aquifers at depth. In addition, favourable conditions for important aquifers are also present in palaeokarst horizons which occur at various depths in the dolomites. The dolomite aquifers are, however, not continuous, but compartmentalised by intrusive dykes.
Aquifer type	The aquifers systems are of the double-porosity type, consisting of rock matrix of very low porosity in which secondary porosity was developed through fracturing and dissolution of the rock matrix.
Saturation level	The deep fractured rock aquifers are expected to be fully saturated.
Heterogeneity and isotropy	Due to the large difference between the water-bearing and -transport properties of the solid rock matrix and the dissolution cavities, the aquifer systems are expected to be highly heterogeneous and anisotropic. The distribution of dissolution cavities in the subsurface is generally irregular. Dissolution cavities are more common in the near-surface than at depth, although palaeokart environments do occur at certain horizons at depth.
Formation properties	The primary porosity of the dolomite matrix is very low. However, where dissolution cavities occur, the average bulk porosity may be very high. Some estimates suggest porosity values of approximately 15% for the first 30 m of karst aquifers. These high porosities are also likely to occur at the palaeokarst horizons at depth, and along major geological structures (faults, dykes) intersecting the dolomites.
Hydraulic parameters	The hydraulic conductivity, transmissivity and storativity of the dolomite matrix is very low. Most of the groundwater storage in transport occurs in the networks of dissolution cavities within the dense dolomite rock. Very high transmissivities and storativities are generally associated with dolomite rock containing such dissolution networks.

Criteria	Description
Pressurisation	The aquifers systems could be under normal atmospheric pressure if the networks of dissolution cavities forming the aquifers extend to surface. However, impermable layers (dolerite sills, zones of solid dolomite) could act as aquitards or aquicludes, resulting in positive pressurisation of the dolomite aquifers underlying them.
Yield	The yield of the dolomite aquifers is very large. Individual boreholes with yields greater than 60 L/s have been drilled in the dolomite aquifers. Similar yields can be expected from the dolomite aquifers associated with the deep palaeokarst horizons, as well as from the deep aquifers associated with major faults and dykes.
Groundwater quality	The groundwater quality of dolomite aquifers is generally very good. However, these aquifers are very vulnerable to pollution from surface and subsurface sources.
Aquifer vulnerability and susceptibility	Dolomite aquifers are notoriously vulnerable to contamination from surface and subsurface sources. The high rates at which groundwater migration occurs through the networks of dissolution cavities means that contaminants can spread rapidly through the aquifers system. Deep aquifer systems my be less vulnerable if their networks of dissolution cavities do not extend to the near-surface. However, these deeper aquifers may be more vulnerable to over-exploitation since their rates of recharge may be lower.

5.3.7 Characteristics of deep aquifers derived from geophysical investigations

5.3.7.1 Introduction

Surface geophysical methods can reduce the risk and unnecessary costs of deep groundwater exploration programmes by guiding the siting of deep boreholes in locations with the highest potential to produce acceptable quantities of water (Hasbrouck and Morgan, 2003). However, the depth of investigation for the different methods available varies. A summary of geophysical methods by Hoover et al. (1995) is simplified and shown in Table 5-13. For the investigation of deep groundwater, only the methods with an appropriate depth of investigation should be considered for future applications. From the summary of Hoover et al. (1995), the most applicable methods for deep groundwater investigations would be gravity, seismic, electrical and electromagnetic methods.

Guideline D6429-99 of the American Society for Testing and Materials (ASTM) gives guidelines for selecting surface geophysical methods for different conditions or features that could potentially be investigated (ASTM, 2011) (Table 5-14). The seismic and ground-penetrating methods are most appropriate for investigating the depth to bedrock or depth to water table. For the identification of rock layers, the seismic (reflection) method is most appropriate. However, for the identification of fractures and faults, the electromagnetic Very Low Frequency (VLF) method is most appropriate (McGinnis et al., 2011).

Table 5-13: Summary of geophysical methods, characteristics and general depth of investigation (modified from Hoover et al., 1995)

Method	Relevant physical property	Typical source of anomaly	Depth of investigation
Gravity	Density	Rock density contrasts	All
Magnetic	Magnetic susceptibility and remanent magnetization	Magnetic susceptibility and remanent magnetization	Surface to Curie isotherm
Gamma-ray	Quantity of K, U, Th	K, U, Th contrasts	Upper 50 cm
Seismic refraction Seismic reflection	Velocity of P and S waves	Structures of velocity layer contrasts	All
Thermal (borehole/remote sensing)	Thermal conductivity/inertia	Thermal flux or conductivity variations	Hole depth (borehole) or 5cm (remote sensing)
Electrical (direct current resistivity)	Resistivity	Lateral or vertical changes in the Earth's resistivity	2 km
Electromagnetic methods	Conductivity (inverse of resistivity)	Lateral or vertical changes in the Earth's conductivity	Shallow (10 – 100 m) Intermediate (1 km) Deep (10 km)
Remote sensing	Spectral reflectance	Changes in spectral reflectance	Surface only

Surface geophysical methods have been used for decades to successfully and economically explore groundwater resources (Hasbrouck and Morgan, 2003). More recently, geophysical methods have been applied, on an international scale, to specifically explore deeper groundwater resources (Marigiotta and Negri, 2005; Sharma and Baranwal, 2005; Kumar et al., 2014).

In this chapter, the application of deep geophysical methods and their application to the South African landscape is investigated. However, the scope of these applications is limited. In the following sections, only geophysical surveys conducted in the Karoo Supergroup, Cape Supergroup and Limpopo areas are discussed.

5.3.7.2 Karoo and Cape supergroups

5.3.7.2.1 Agulhas-Karoo Geophysical Transect

The South African landscape is shaped by the Cape Fold Belt (CFB) in the south, with the adjacent Cape-Karoo Basin and underlying Precambrian basement. Lindeque et al. (2011) state that the deep crustal manifestations of these surface features are essentially unknown, due to the lack of geophysical information at these great depths. To facilitate research into these unknowns, the Inkaba yeAfrica research initiative designed the Agulhas-Karoo Geophysical Transect (AKGT) to examine deep crustal features using geophysical data.

Table 5-14: Selection of geophysical methods for common applications (ASTM D 6429-99). Black boxes correspond to primary methods, while grey boxes correspond to secondary methods (McGinnis et al., 2011)

	Seismic		Electrical		Electromagnetic							
	Refraction	Reflection	DC Resistivity	SP	Frequency Domain	Time Domain	VLF	Pipe/Cable Locator	Metal Detectors	Ground-Penetrating Radar	Magnetics	Gravity
Natural geologic and hydrologic conditions												
Soil/unconsolidated layers	■	▒	■		▒	■	▒			■		
Rock layers	▒	■	▒			▒				▒		
Depth to bedrock	■	■	▒		▒	▒	▒			■		▒
Depth to water table	■	■	▒			▒	▒			■		
Fractures and fault zones	▒	▒	▒			▒	■			▒	▒	▒
Voids and sinkholes	▒	▒	▒			▒				■		■
Soil and rock properties	■		■									
Dam and lagoon leakage			▒							▒		
Inorganic contaminants												
Landfill leachate			■			■	▒			▒		
Saltwater intrusion			■			■	▒			▒		
Soil salinity			■									
Organic contaminants												
Light, nonaqueous phase liquids	▒		▒		▒	▒				▒		
Dissolved phase												
Dense nonaqueous phase liquids												
Manmade burial objects												
Utilities					▒			■	▒	■		
Drums and USTs					■			■	■	■	■	
UXO									■	▒	■	
Abandoned wells					▒			▒	▒		■	
Landfill and trench boundaries	▒		▒		■	▒				■		
Forensics			▒		■			▒	▒	■	▒	
Archeological features	▒	▒	▒		■					■	■	▒

*ASTM International. "Standard Guide for Selecting Surface Geophysical Methods." ASTM D6429–99, Philadelphia, Pennsylvania: American Society for Testing and Materials. 2006.

The AKGT consists of two roughly parallel north-south lines, which intersect onshore/offshore areas (Figure 5-12). Lindeque et al. (2011) focused on a smaller 100 km segment of the larger AKGT line, which covers the Karoo Supergroup transition over the escarpment to the Cape Supergroup (Figure 5-12). Geophysical data acquired by Lindeque et al. (2011) along the AKGT, between 2004 and 2007, includes the following:

- Archive data comprising surface geology, aeromagnetic data, nearby deep boreholes, teleseismic receiver functions and regional seismic reflection profiles
- Newly acquired line-coincident, high-resolution geophysical data consisting of near-vertical seismic reflection data, shallow P- and S-wave velocity data, wide-angle refraction data, high-resolution magnetotelluric data and impedance spectroscopy measurements on borehole samples

Lindeque et al. (2011) analysed the geophysical data that had been collected to create the first high-resolution deep seismic reflection profile and deep crustal model through the Palaeozoic-Mesozoic sediments of the Cape Karoo Basin and its underlying basement, both overprinted in the south by the mid-Phanerozoic Cape Fold Belt deformation (Figure 5-13). The resulting model produced by Lindeque et al. (2011) differentiates four components (Figure 5-13):

- The Karoo Supergroup (approximately 5 km thick folded), resting para-conformably on:
- a wedge of the Cape Supergroup (continuous undeformed subhorizontal, approximately 1.5 to 10 km thick), resting unconformably on:
- the middle crust (approximately 13 to 21 km thick), interpreted as the Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB) crust, and separated by a detachment to the:
- lower crust (highly reflective, approximately 10 to 24 km thick), interpreted as an older Palaeoproterozoic section of the Namaqua-Natal Metamorphic Belt (or even Archean cratonic basement), and bounded by a 2 to 5 km thick bottom layer below that lies subparallel to a clear Moho (interpreted as a mafic underplate, metasomatic reaction zone, or lower-crust to mantle transition zone).

The integrated crustal model produced by Lindeque et al. (2011) was compared to previous crustal models of southern South Africa by Hälbich (1993), Chevallier et al. (2004) and Lindeque et al. (2007), as cited by Lindeque et al. (2011) (Figure 5-15). The main differences identified between the integrated crustal model produced by Lindeque et al. (2011) and the previous model are discussed.

For the Karoo Basin, the integrated crustal model produced by Lindeque et al. (2011) maintains a near constant thickness in the upper 2 to 3 km, and the Cape Supergroup varies from 2.5 to 5 km in thickness. The previous models postulated a Karoo Basin approximately 8 km thick and significant stratigraphic fore-deep thickening at the Cape Fold Belt Front. For the Cape Supergroup, the integrated crustal model produced by Lindeque et al. (2011) shows a continuous Cape Supergroup as an undeformed subhorizontal wedge (1.5 km thick at the escarpment in the north and 10 km thick at the Cape Fold Belt Front in the south). This differs from the previous models where the Cape Supergroup was thought to pinch out.

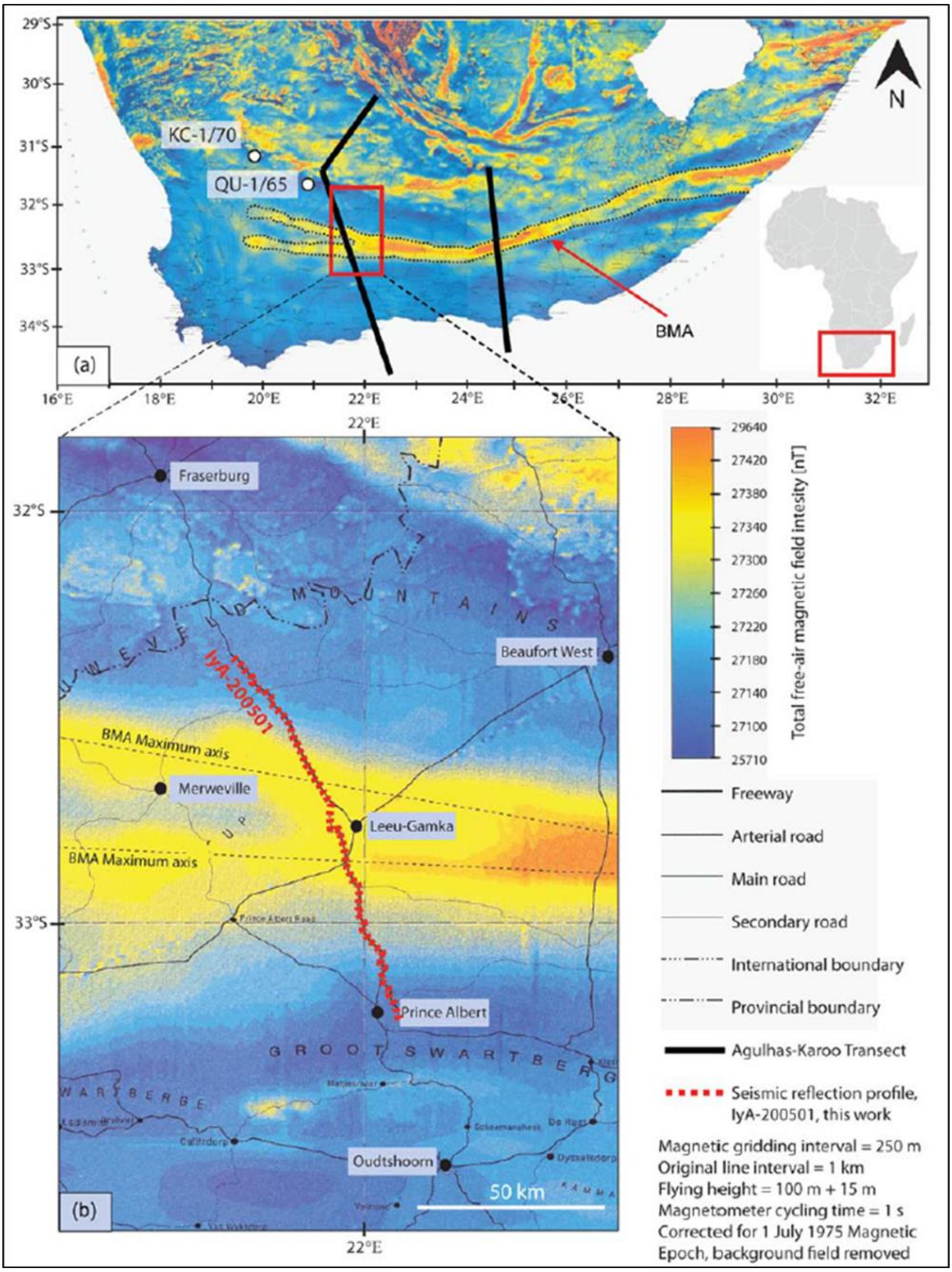


Figure 5-12: Total field free-air aeromagnetic map showing the western and eastern lines of the Agulhas-Karoo Geophysical Transect, the Beattie Magnetic Anomaly and the 100 km section used for this study (Lindeque et al., 2011)

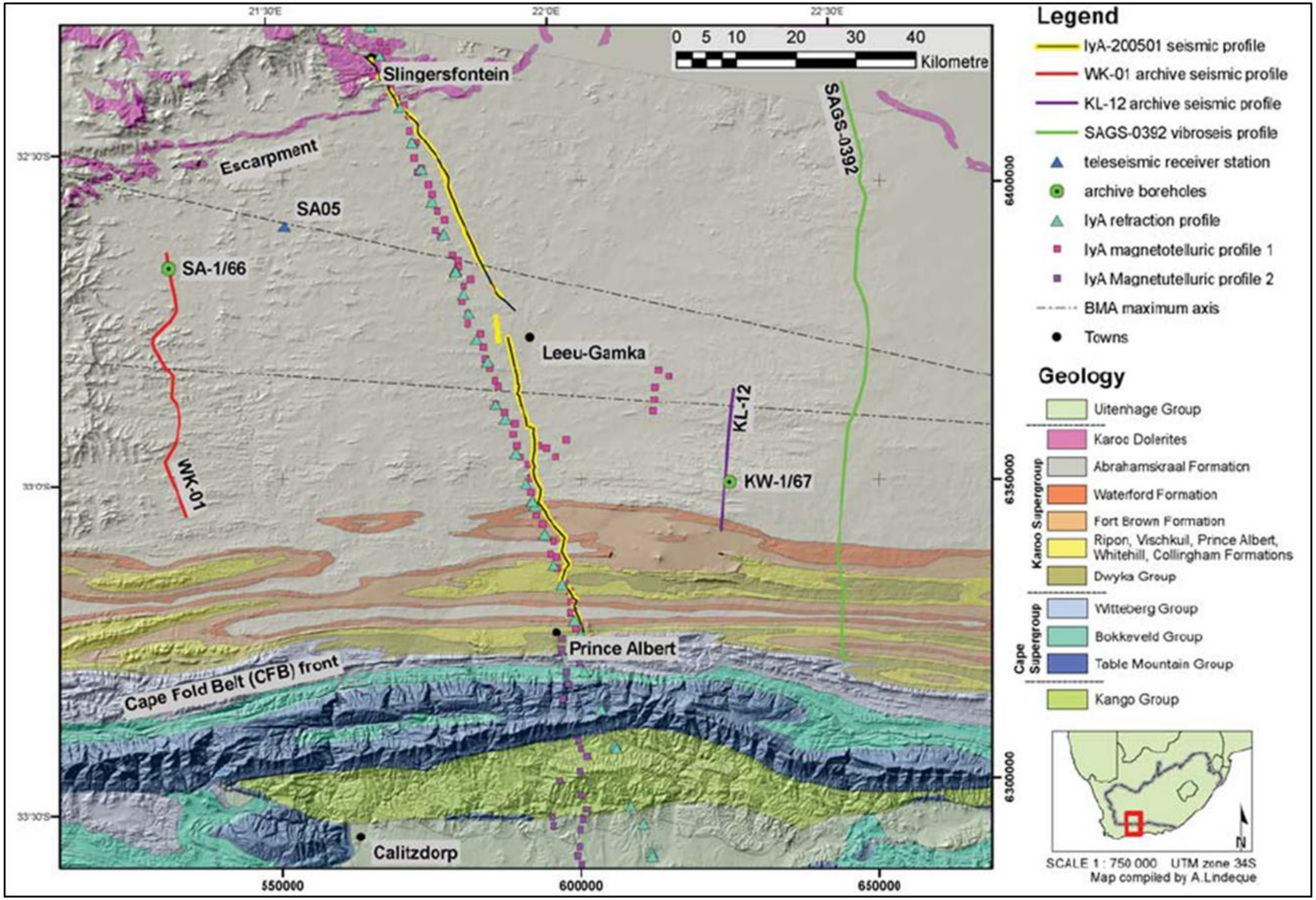


Figure 5-13: Geological and digital elevation map indicating the locations of the collected geophysical data (Lindeque et al., 2011)

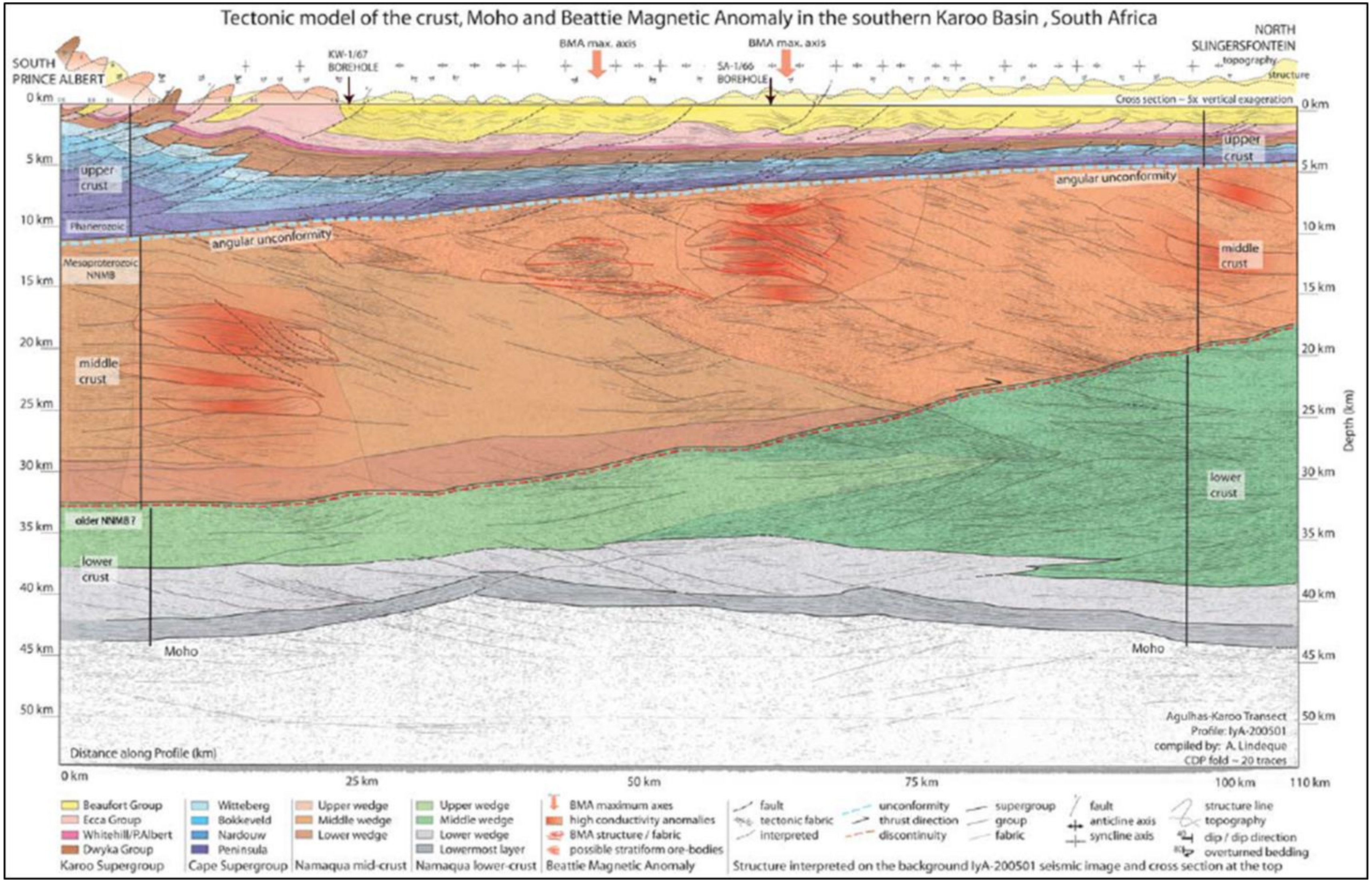


Figure 5-14: Geological and digital elevation map indicating the locations of the collected geophysical data (Lindeque et al., 2011)

Implications for deep groundwater

The study of Lindeque et al. (2011) did not explicitly discuss the potential occurrence of deep groundwater in the study area. However, it has been established that thermal springs are found along the Cape Fold Belt due to the deformation and resulting fracture and fault systems. Figure 5-16 shows the location of springs in South Africa, classed from cold to thermal types, and the approximate location of the AKGT lines. Cave and Clarke (2003) studied the thermal springs in the Western Cape and the Eastern Cape to determine circulation depths based on geothermometer methods, and estimated a maximum circulation depth at the Warmwaterberg Spring (close to the AKGT line) of 7.4 km. Cave and Clarke (2003) thought this depth to be extreme, yet the geophysical crustal model indicates that the Table Mountain Group formations extend to these depths and fractures are evident at these depths as well.

In conclusion, the integrated crustal model produced by Lindeque et al. (2011) gives a more accurate indication of the potential depth of groundwater in the Cape Supergroup and Karoo Supergroup lithologies.

5.3.7.2.2 Depth maps of the Karoo Basin

The Main Karoo Basin is the largest sedimentary basin in South Africa, underlying approximately 60% of the land surface area of South Africa, covering an area of approximately 700,000 km^2. The Main Karoo Basin is largely undeformed and essentially lies flat, with small centripetal dips. The strata are only folded in the south, where these were affected by the Cape orogeny. Figure 5-17 illustrates the size of the Karoo Basin within South Africa and delineates the tectonic provinces.

The Karoo Basin has become the focus of investigations at depth in response to proposed shale gas exploration. Understanding how the depth of the basin changes from region to region is therefore important (Scheiber-Enslin et al., 2015). According to Scheiber-Enslin et al. (2015), previous studies have provided extensive borehole data, digitised historical seismic data in the southern part of the basin and reflection seismic data from the Inkaba yeAfrica project. These resources can be combined to refine the depth map for the Karoo Basin.

Data

The datasets used by Scheiber-Enslin et al. (2015) to create the depth map for the top of the Whitehill Formation and the base of the Karoo Basin are shown in Figure 5-18. An extensive borehole database, which was compiled by Doug Cole at CGS, was used to compile this map. The database consists of industry, as well as deep SOEKOR and CGS boreholes. Scheiber-Enslin et al. (2015) included depths to the base of the Karoo strata from two 100 km reflection seismic lines. One extends south of Fraserburg and the other is a vibroseis line just west of Beaufort-West in the southwestern Karoo. Seismic data in the southern Karoo that was originally collected by SOEKOR in the late 1960s and early 1970s and recently digitised by Falcon Oil and Gas was also included (Scheiber-Enslin et al., 2015).

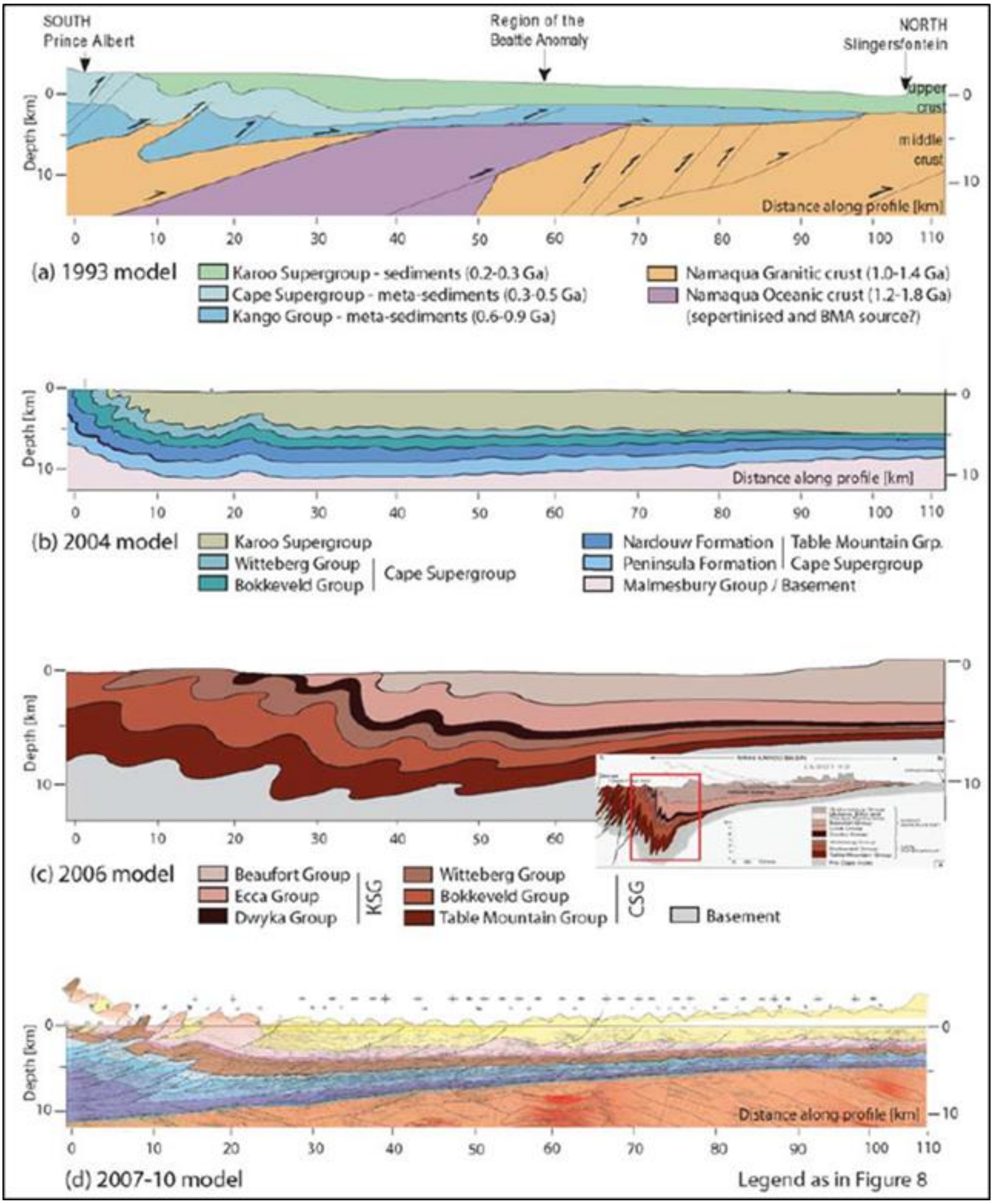


Figure 5-15: Comparing models of the Cape and Karoo basins in the upper crust (<15 km): (a) the model of Hälbich (1993); (b) the model of Chevallier et al. (2004); (c) the model of Johnson et al. (2006); and (d) the current model (Lindeque et al., 2011)

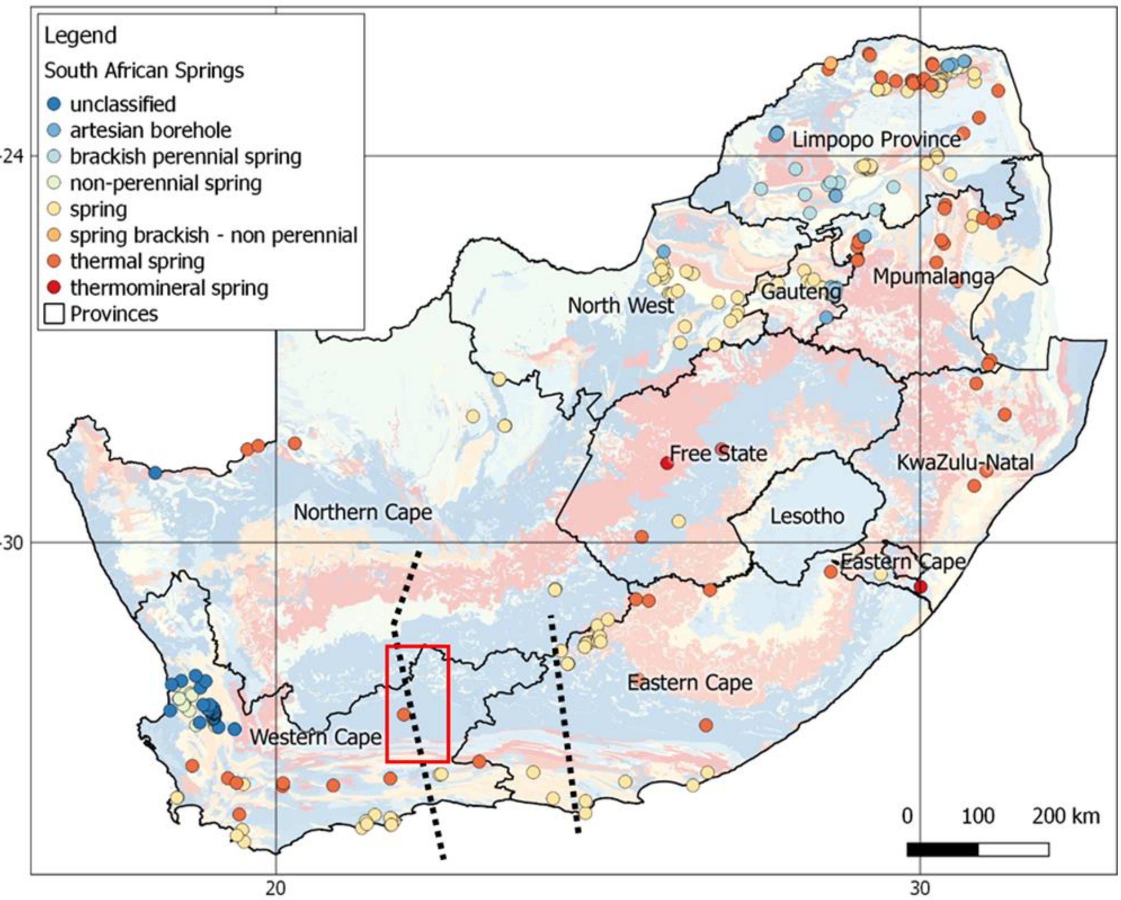


Figure 5-16: Springs in South Africa, classed from cold to thermal types, indicating the approximate location of the AKGT lines

In Figure 5-18, the orange triangles indicate the deep SOEKOR boreholes, as well as the CGS and industry boreholes, while the blue triangles indicate industry boreholes that give basement depths in the northeastern part of the basin. Seismic data includes reflection seismics (the yellow lines), refraction seismic profiles (the green lines), offshore seismic lines (the blue lines) and SOEKOR seismic data (the black lines). Moho depth estimates are indicated by the black circles, with the values given in kilometres. Cities are indicated by white circles and include Aliwal North (AN), Beaufort West (BW), Coffee Bay (CB), Fraserburg (FB), Graaff-Reinet (GR), Hertzogville (HV), Mossel Bay (MB), Port Elizabeth (PE), Queenstown (QT), Somerset-East (SE) and Cape St Francis (StF).

Results

The depth map of Scheiber-Enslin et al. (2015) for the Main Karoo Basin is shown in Figure 5-19, while the thickness maps for the main Karoo Basin and the Cape Supergroup are shown in Figure 5-20 and Figure 5-21, respectively. The deepest section of the Main Karoo Basin is found adjacent to the northern boundary of the Cape Fold Belt. However, the depths along this boundary are not constant, with greater depths in the southwestern and southeastern Karoo (Scheiber-Enslin et al., 2015).

There are some uncertainties associated with the depth map, where limited boreholes in the southeastern Karoo show a broad deepening of the basin in this region. Care must be taken when interpreting the gridded maps as the large low south of Queenstown is a gridding artefact, with only the western part of the low being associated with seismic data. Additional data is needed in this region to help reduce uncertainties. These basin sediment thicknesses were also calculated by assuming that the Witteberg Group does not extend below the Karoo Basin and that the Bokkeveld Group represents the top of the Cape Supergroup in this region (Scheiber-Enslin et al., 2015).

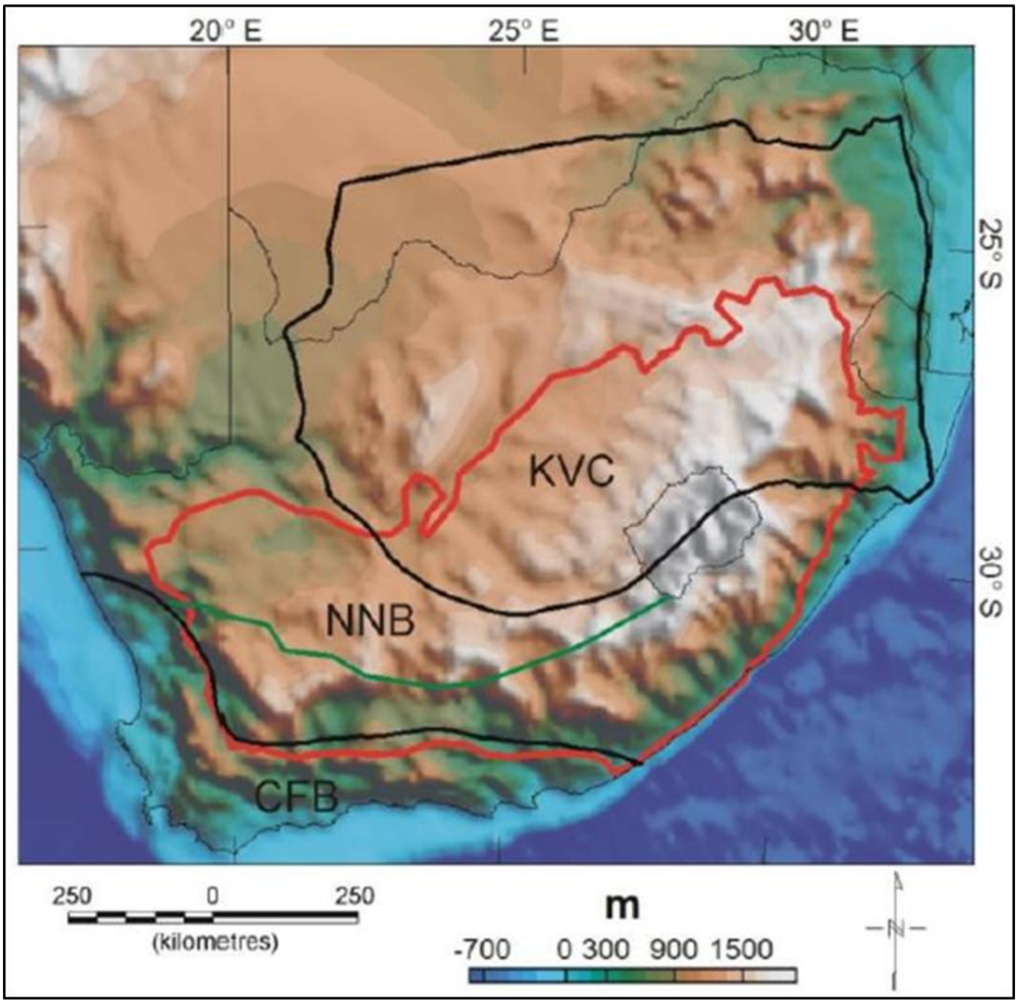


Figure 5-17: Topographic map of South Africa showing the tectonic provinces: Kaapvaal craton (KVC), Namaqua-Natal Belt (NNB) and Cape Fold Belt (CFB). The Main Karoo Basin (red outline) covers a large portion of the high inland plateau (Scheiber-Enslin et al., 2015).

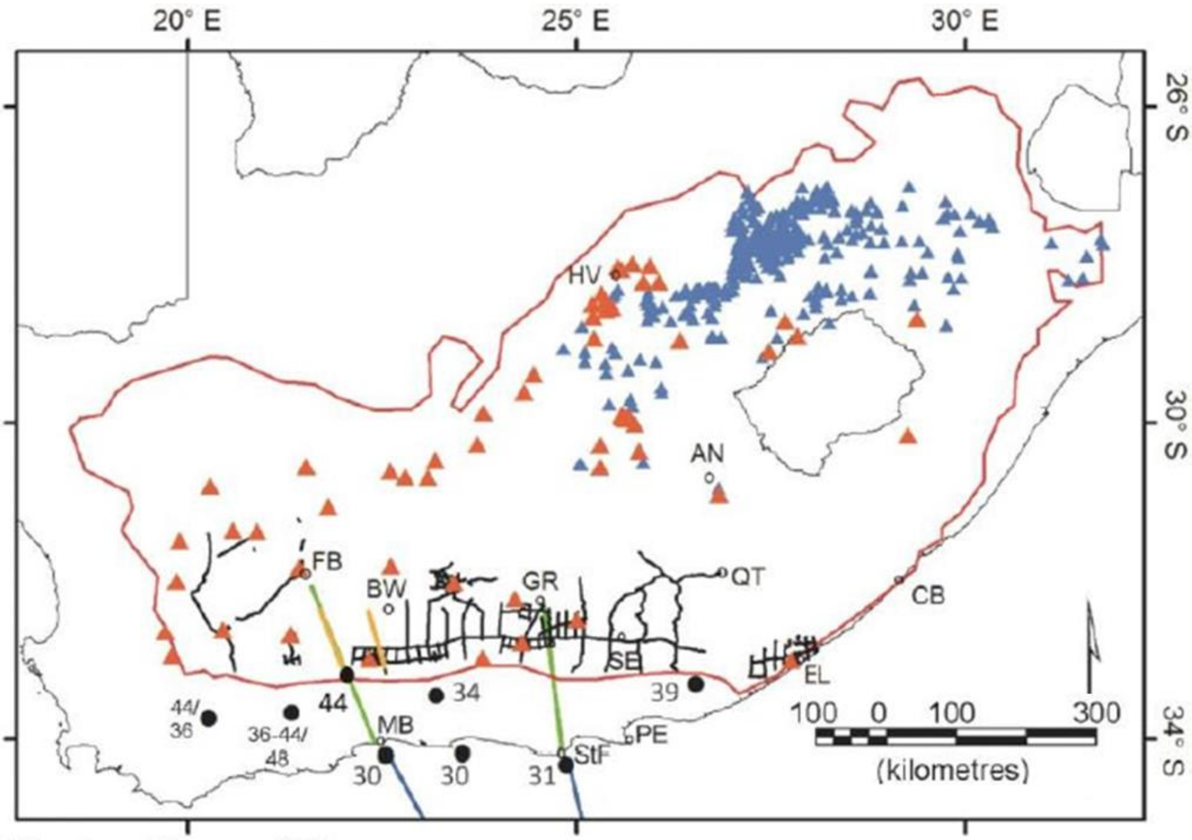


Figure 5-18 Available data used to constrain the Main Karoo Basin (red line) depth maps (Scheiber-Enslin et al., 2015)

Scheiber-Enslin et al. (2015) highlighted the fact that Lindeque et al. (2011) had found that the Witteberg Group in the southwestern part of the basin extends for around 60 km below the Karoo Basin. Therefore, the assumption Scheiber-Enslin et al. (2015) made resulted in a slight overestimation of the thickness of the Karoo in the south of the basin, and an underestimation of the thickness of the Cape Supergroup by 2 to 3 km or less. The northern pinch-outs of the Bokkeveld Group (in red) and Table Mountain Group (in yellow) are shown in Figure 5-19. However, the western and eastern extents were approximated due to poor seismic data and limited borehole data in the east (Scheiber-Enslin et al., 2015).

From Figure 5-1, one can see that the Cape Supergroup reaches thicknesses of around 4 km below the Karoo Basin in the south. According to Scheiber-Enslin et al. (2015), these estimates correspond with previous estimates. However, the thickening of the Cape Supergroup in the west should be interpreted with caution as seismic data in this area is scarce (Scheiber-Enslin et al., 2015).

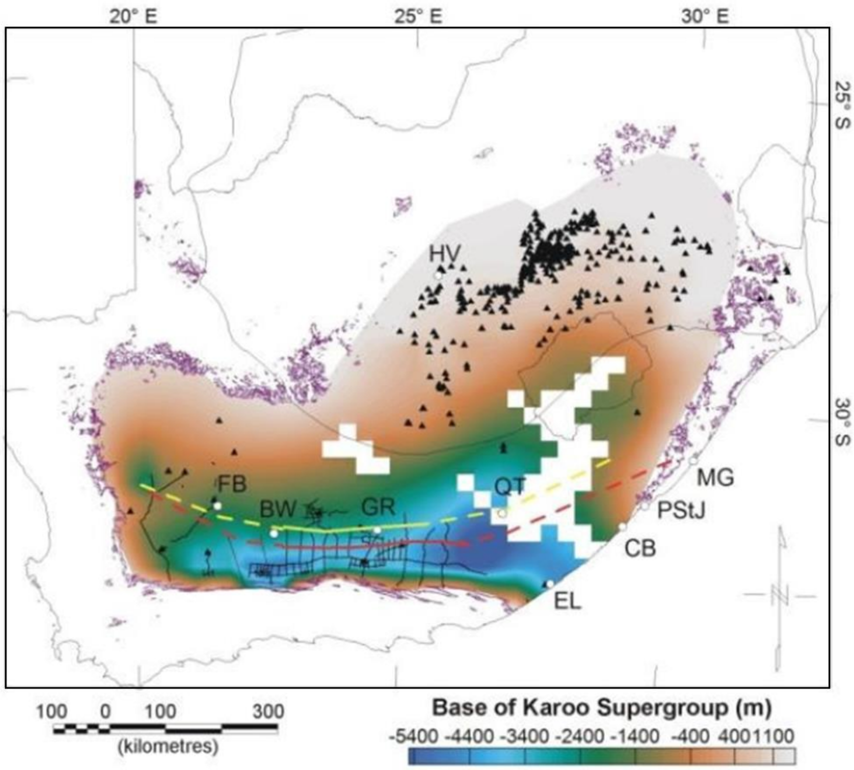


Figure 5-19: Depth maps for the base of the Main Karoo Basin (base of the depth of the bottom contact of the Dwyka Group)

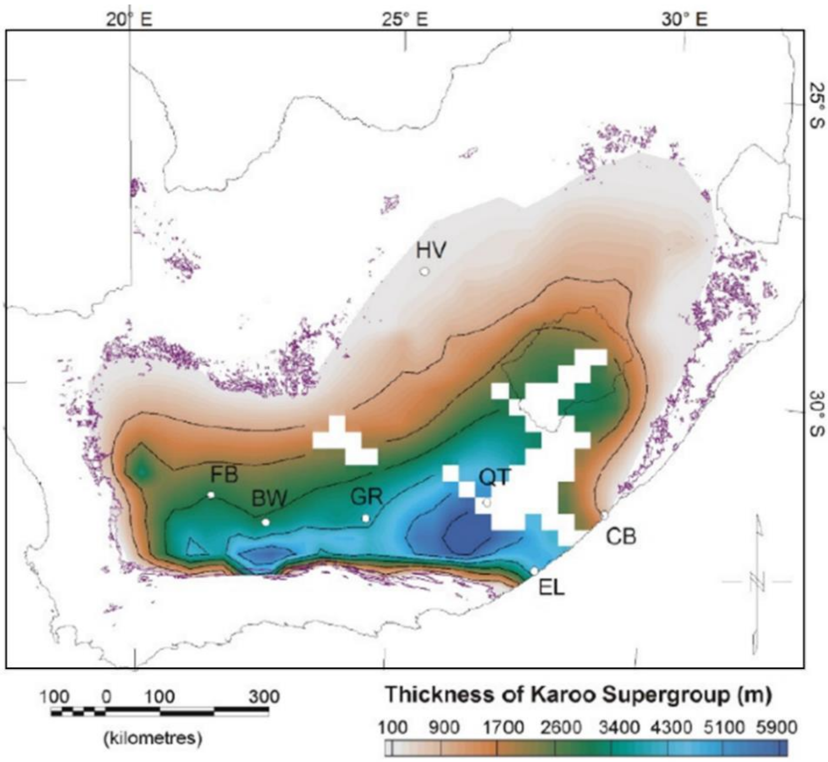


Figure 5-20: Thickness map for the Main Karoo Basin (1,000 m contour intervals). Outcropping Dwyka and Witteberg Group rocks are shown in purple (Scheiber-Enslin et al., 2015).

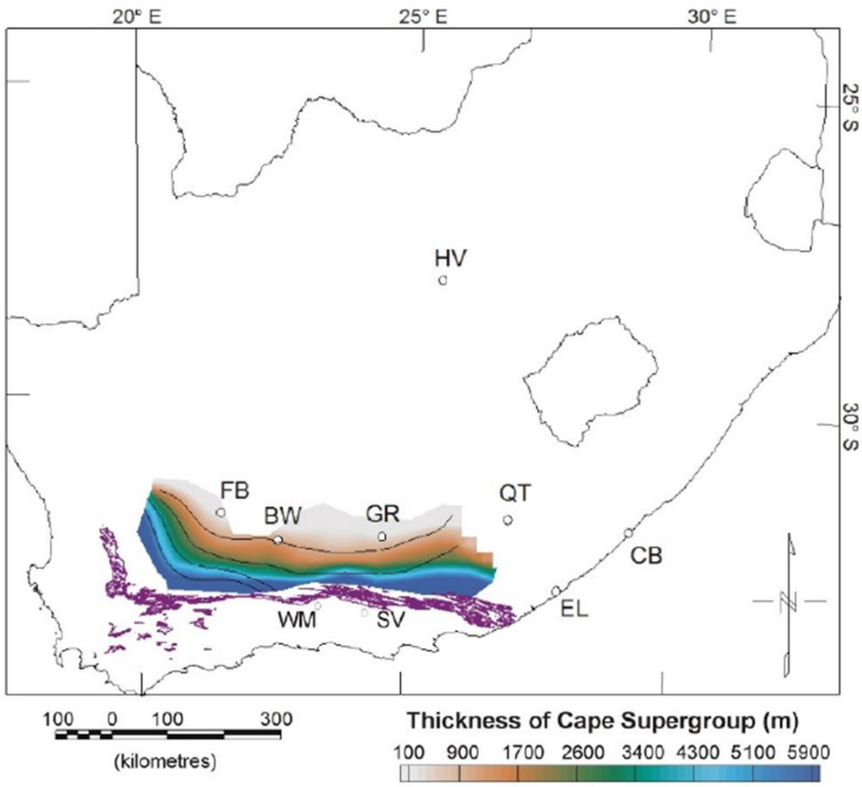


Figure 5-21: Thickness map for the Cape Supergroup (1.000 m contour intervals). Outcropping Dwyka and Witteberg Group rocks are shown in purple (Scheiber-Enslin et al., 2015).

Implications for deep groundwater

Similarly to the previous study, the study of Scheiber-Enslin et al. (2015) did not explicitly discuss the potential occurrence of deep groundwater. However, it has again been established that thermal springs are found along the Cape Fold Belt due to the deformation and resulting fracture and fault systems (Figure 5-16). The depth and thickness maps of the Main Karoo Basin and the Cape Supergroup that were used in conjunction with the positive indications for deep groundwater from thermal springs in both the Karoo Basin and the Cape Supergroup could be useful when evaluating South Africa's potential deep groundwater resources.

5.3.7.3 Limpopo

5.3.7.3.1 Sagole thermal spring structures

Nyabeze et al. (2014) used geophysical information to characterise the deep aquifer associated with the Sagole Thermal Spring. The Sagole Thermal Spring is situated in northern Limpopo (Figure 5-22). According to Nyabeze et al. (2014), the recorded water temperature at the Sagole Spring is 45 °C, and the inferred heat source is at an estimated depth of 4 to 6 km.

The Tshipise Fault, which displaces the Karoo Supergroup adjacent to the Soutpansberg Group, is the main geological structure that controls the discharge at the Sagole Spring (Figure 5-23). The Karoo Supergroup in the Sagole Spring area consists of the Madzaringwe and Mikambeni formations, and the Soutpansberg Group consists of the Nzhelele and Musekwa formations. The Musekwa Formation is a volcanic assemblage, approximately 400 m thick. The Nzhelele Formation consists of red argillaceous and arenaceous sediments with an approximate thickness of 600 m (Nyabeze et al., 2014).

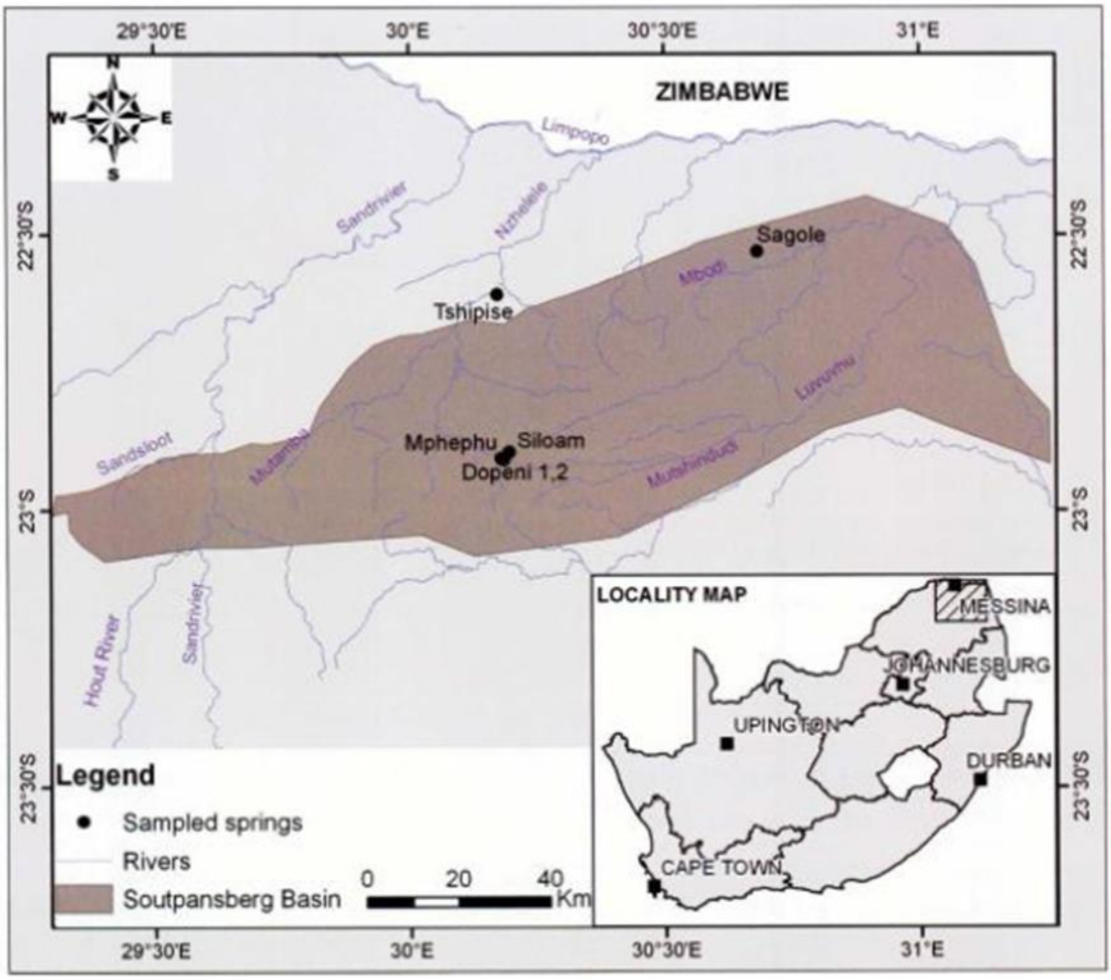


Figure 5-22: Location of the Sagole Thermal Spring (Shabalala et al., 2015)

Data

Regional aeromagnetic data was collected for the study area, and Nyabeze et al. (2014) conducted magnetic, electrical resistivity tomography, frequency domain electromagnetic profiling and radiometric geophysical surveys.

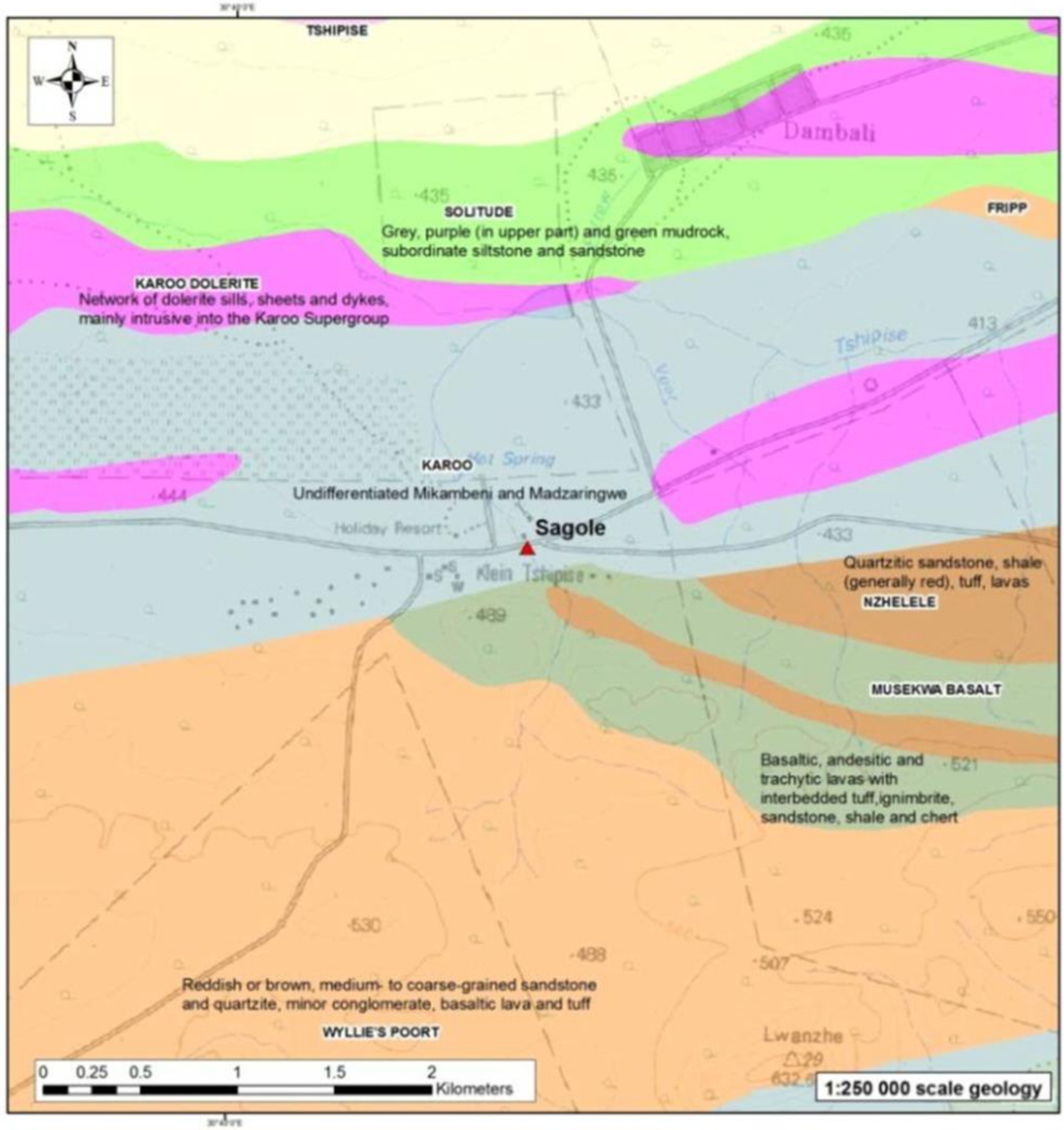


Figure 5-23: Geological outcrops around the Sagole Thermal Spring in Limpopo. The different lithologies are described with the Tshipise Fault (the black dashed line) displaced Karoo Supergroup (blue/green) adjacent to the Soutpansberg Group (orange/green) (Nyabeze et al., 2014)

Results

The airborne geophysical data for the Sagole Spring area were interpreted by Nyabeze et al. (2014) and dolerite dykes in the east-west, north-east and north-west directions were identified. Faulting and fracturing was inferred from the discontinuous nature of the magnetic lineaments, and the Sagole Spring is found at the intersection of two lineaments (Figure 5-25).

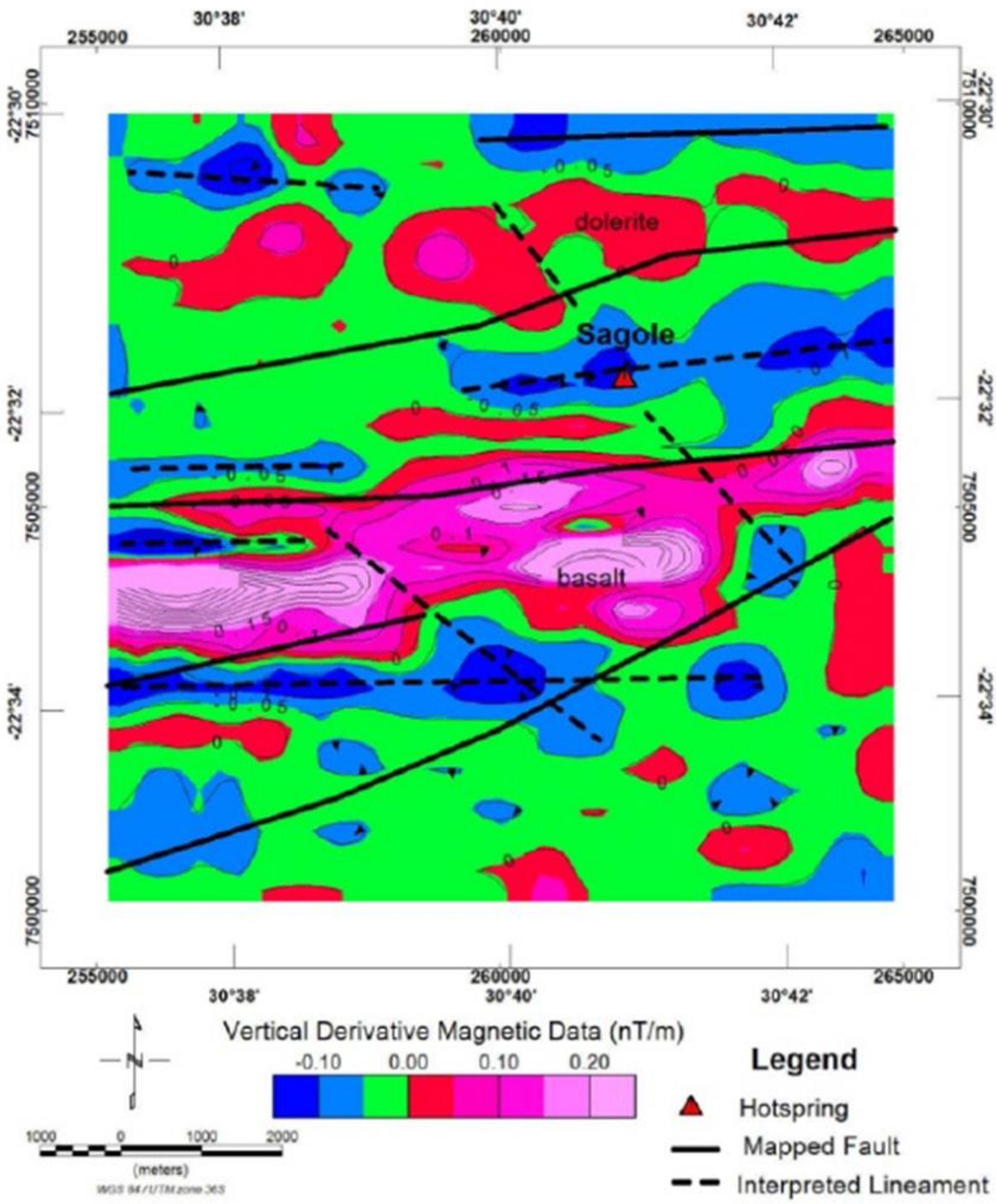


Figure 5-24: Vertical derivative magnetic image, indicating interpreted lineaments (Nyabeze et al., 2014)

The results from the field magnetic survey are shown in Figure 5-25A, where the basalt of the Musekwa Formation is identified to the south. Dolerite intrusion into the Karoo Supergroup is also identified to the north. Nyabeze et al. (2014) interpreted a number of lineaments, including east-west and north-west-trending lineaments. Intersecting lineaments were identified near the Sagole Spring (Nyabeze et al., 2014). The results from the field electrical conductivity, using the Frequency-Domain Electromagnetic Method (FDEM), are shown in Figure 25B.

Nyabeze et al. (2014) used these results to infer potential groundwater flow paths and the location of a fault. However, the maximum depth of the investigation was approximately 15 m. To investigate below 15 m, Nyabeze et al. (2014) produced a depth section from the results of a 10 m dipole-dipole Electrical Resistivity Tomography (ERT) survey (Figure 5-26). The results of the ERT were interpreted to show a low resistivity vadose zone with an approximate thickness of 30 m, with resistivity increasing with depth. The location of faults on the depth profile were additionally interpreted (Figure 5-26).

In conclusion, Nyabeze et al. (2014) stated that the thermal aquifer is deep-seated, occurring below the inferred basalt of the Musekwa Formation. Further geophysical investigation is required at depths below the basalt to better define the thermal aquifer at this depth, and Nyabeze et al. (2014) suggested a 3D model.

Implications for deep groundwater

The investigation of Nyabeze et al. (2014) into the structures controlling the Sagole Thermal Spring identified the Tshipise Fault as the main structure controlling the Sagole Spring, with a number of intersecting faults. However, the study was limited to shallow geophysical surveys, which prevented the thermal aquifer, below the basalts of the Soutpansberg Group, to be characterised. The implication then for further deep groundwater investigations would be to make sure that the estimated depth of the source water would be investigated by the selected geophysical methods. Additionally, the study of Nyabeze et al. (2014) highlights the importance of fractures and faults on the movement of deep groundwater, where the Tshipise Fault, and smaller intersecting faults and fractures, allows the thermal water to be brought to the surface at the Sagole Thermal Spring.

5.3.7.4 Summary

The Karoo Basin has been extensively investigated with deep geophysical investigations to accurately delineate the depth of the Main Karoo Basin, as well as the adjacent Cape Supergroup. The depth and thickness maps of the Main Karoo Basin and the Cape Supergroup, used in conjunction with the positive indications for deep groundwater from thermal springs within both the Karoo Basin and the Cape Supergroup, will form useful tools for future investigations into deep aquifer conditions. A summary of the information extracted from geophysical investigations is presented in Table 5-15.

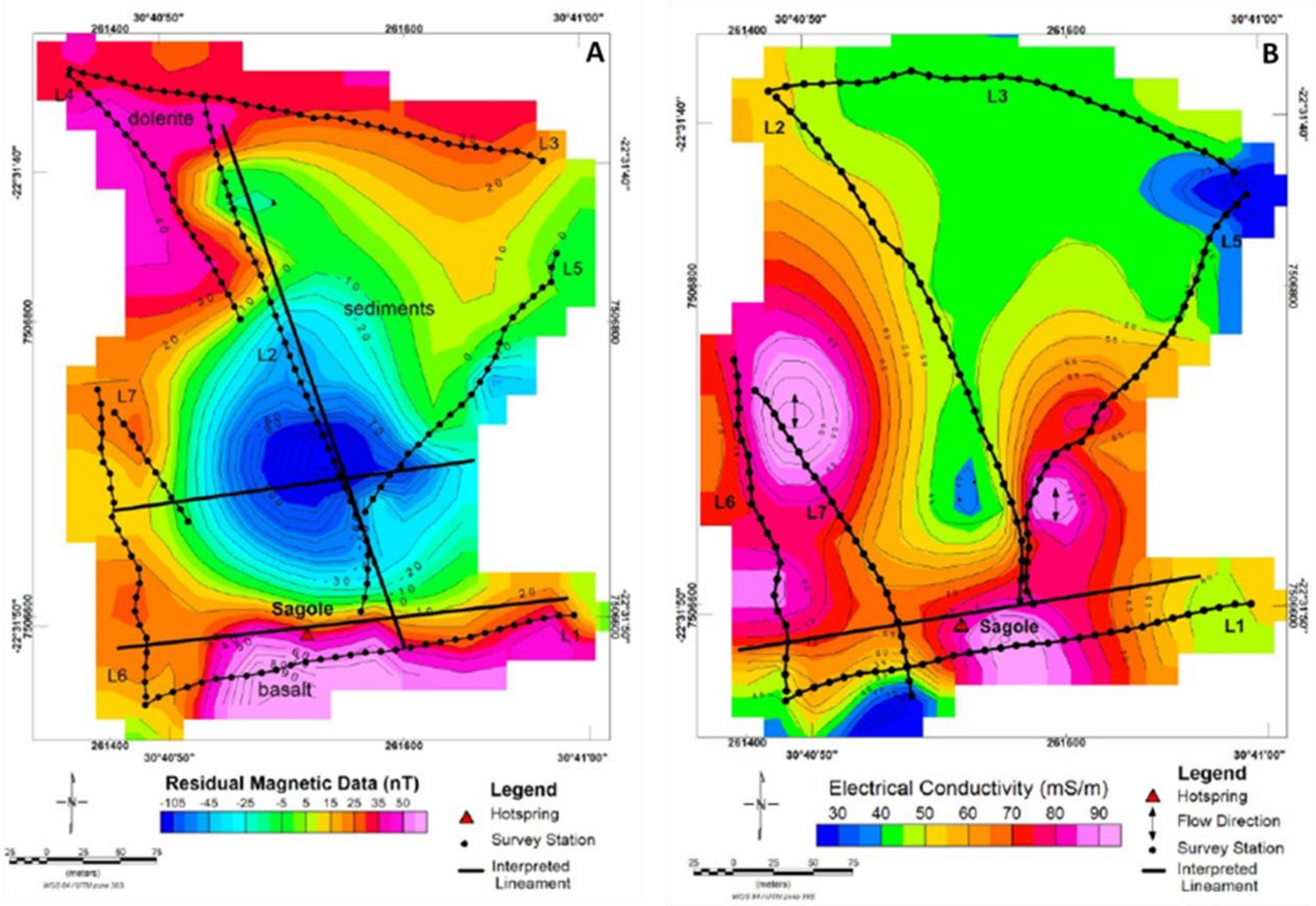


Figure 5-25: Results from the field geophysical surveys: a) magnetic survey with the survey stations, interpreted geology and lineaments; and b) the FDEM electrical conductivity tests

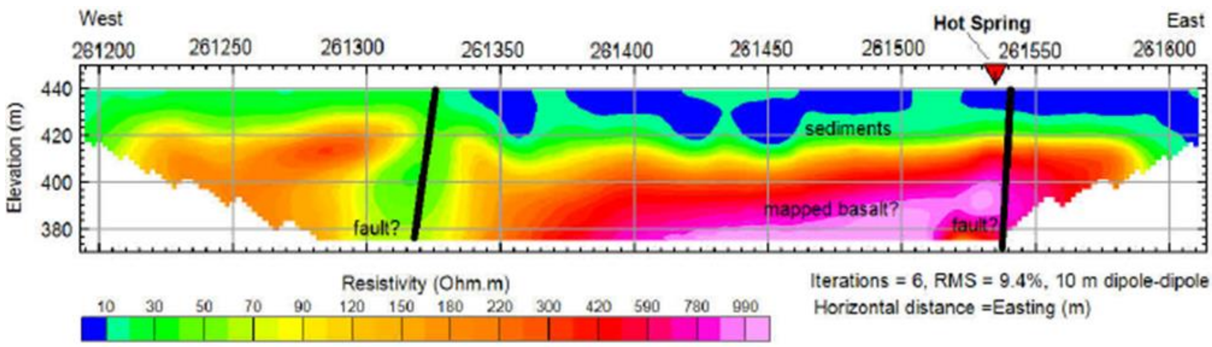


Figure 5-26: Electrical resistivity tomography results for the profile along an east-west oriented profile L1, showing a low resistivity top layer with a thickness of about 30 m and increasing resistivity with depth (from Nyabeze et al., 2014)

However, geophysical studies within the remaining geological regions of South Africa tend to be site specific and aimed at investigating single features, i.e. a single fault or economical formation. The proposal for shale gas development in the Karoo Basin has encouraged large-scale investigations into the depth of the basin and economically important formations. Going forward, these large-scale geophysical applications, which have proven useful within the Karoo Basin, should be applied to the remaining geological regions of South Africa to help identify the depth of these potential aquifers.

5.3.8 Characteristics of deep aquifers derived from thermal springs

South Africa lacks geohydrological data from deep boreholes to directly measure and characterise the deep groundwater aquifers. In light of this restriction, an alternative option is the analysis of water emanating from thermal springs. Thermal springs thus form the most readily available source of information to characterise deep groundwater, because the heat required to warm the water above the ambient groundwater temperature can only come from the geothermal gradient at greater depths than the typical regional groundwater flow system.

5.3.8.1 Location and type

Thermal springs are known to originate either in areas with recent volcanic activity or from meteoric water flow through fractures in bedrock (Figure 5-27). South Africa is not situated in an area that has experienced any recent volcanic activity. However, the origin of thermal springs is linked to geological structures such as faults and folds (Kent, 1949; LaMoreaux and Tanner, 2001).

Table 5-15: Characterisation of the deep aquifer systems from geophysical information

Criteria	Description
Lithology	The main lithologies investigated are the Karoo Supergroup and Cape Supergroup.
Occurrence	The Karoo Basin covers approx. 60% of the land surface in South Africa, and the Cape Supergroup is found within the Cape Fold Belt. Deep groundwater has been identified within the deformed area of the Cape Fold Belt, due to the prevalence of fractures/faults. Deep groundwater has also been identified within the Karoo Basin, based on the existence of thermal springs.
Physical dimensions	The Main Basin Karoo Supergroup has a surface area of approx. 700 000 m^2 and the depth increases from north to south, with a maximum depth of approx. 5 500 meters below sea level. The Cape Supergroup has a maximum thickness of approx. 6 000 m.
Aquifer type	Aquifer type not discussed, though confined aquifer systems can be assumed.
Saturation level	Saturation levels are not discussed, however a fully saturated confined system can be assumed.
Heterogeneity and isotropy	Heterogeneity and isotropy are not explicitly investigated, yet a highly heterogeneous and anisotropic system can be assumed. Especially due to the importance of faults/fractures which are inherently irregular.
Formation properties	Specific formation properties are not discussed. Density of formations, identified by geophysical methods, can infer the porosity of formations, where a denser formation can be assumed to have a lower porosity.
Hydraulic parameters	Hydraulic parameters were not defined.
Pressurisation	Pressure distributions were not explicitly discussed, yet the deeper formations are overlain by confining layers and can be assumed to be under pressure.
Yield	Yields were not discussed.
Groundwater quality	Groundwater samples at depth are not investigated, only the analysis of thermal spring water is commonly analysed for deep groundwater quality extrapolation.
Aquifer vulnerability and susceptibility	Aquifer vulnerability is uncertain. The confined nature of the aquifers indicates a low vulnerability and susceptibility, yet the nature of fractured systems can provide the pathways for rapid contamination. The thermal aquifer supplying the Sagole Thermal Spring was found to underlie a thick basalt formation, which in that specific case would prevent possible pollution of the source aquifer.

Considering that the country has no record of recent volcanic activity, South Africa has a relatively large number of thermal springs (Kent, 1949). Kent (1949) identified that South Africa has approximately 74 thermal springs and nine thermal artesian wells (Figure 5-28). Geological studies have shown that the origin of each individual thermal spring is related to the local manifestation of deep geological structures (folds, fractures, faults or dykes), which provides a preferential pathway for the circulation of groundwater to great depths and the subsequent return of heated water to the ground surface. Most of the thermal springs in South Africa originate in valleys or low-lying areas, which can be explained by their meteoric nature. South African thermal springs are confined to areas with an annual rainfall in excess of 254 mm because sufficient rain is required for the development of springs (Kent, 1952).

5.3.8.2 Available data

Available data for the thermal springs of South Africa includes physical and chemical components, but is mostly found in individual, area-specific research projects. Physical data includes once-off flow rates, geological structures, temperature and altitude. Chemical data is extensive, ranging from cation/anion analysis to trace element and isotope analyses.

Temporal spring discharge rates for the thermal springs in South Africa are not currently available, yet this information might be held by the private owners of springs. However, the DWS measures spring discharges from a number of cold springs, shown in Figure 5-29.

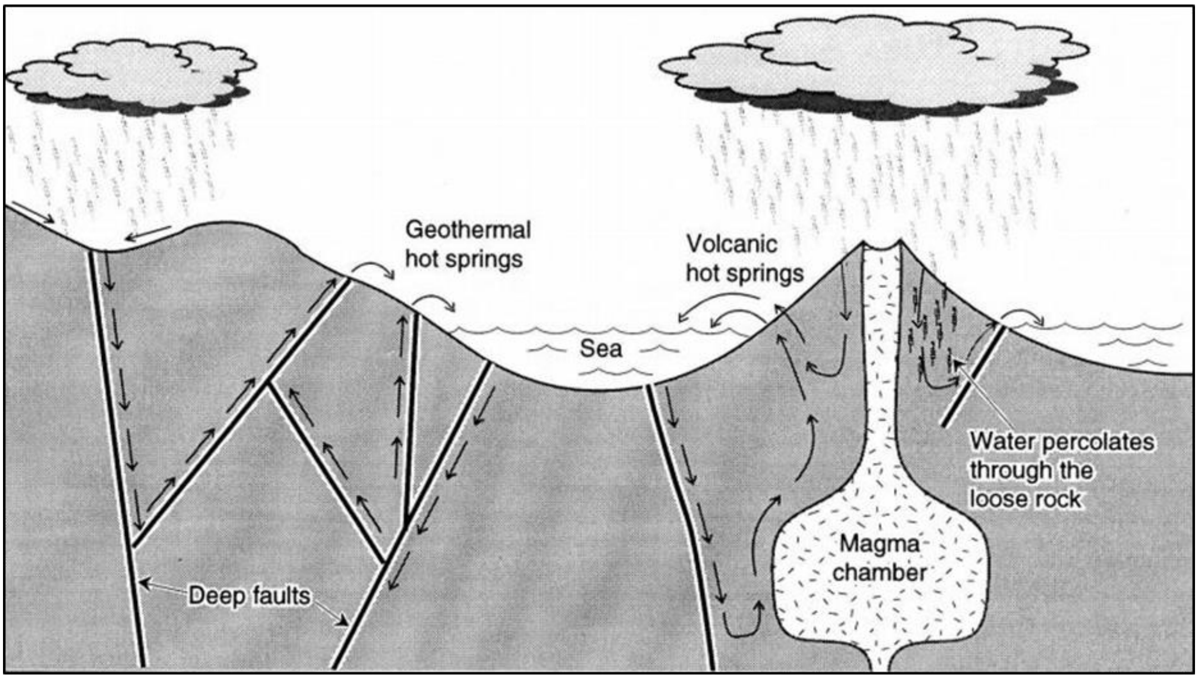


Figure 5-27: Main types of springs: volcanic springs associated with a magma body, or geothermal (meteoric) springs associated with deep circulating groundwater in faults and fractures

5.3.8.3 Towards the characterisation of deep aquifers

5.3.8.3.1 Chemical indicators of deep groundwater

Murray et al. (2015) conducted a study to identify indicators of deep groundwater flow in the Main Karoo Basin, using mainly water samples collected from thermal springs. The study identified specific determinands that can be used to differentiate and characterise deep and shallow groundwater. A provisional guide on the limits for these determinands was provided, which can be used as a guideline to differentiate deep water from shallow water for future studies. Additionally, Murray et al. (2015) reported the most reliable determinands that could be prioritised for future monitoring programmes.

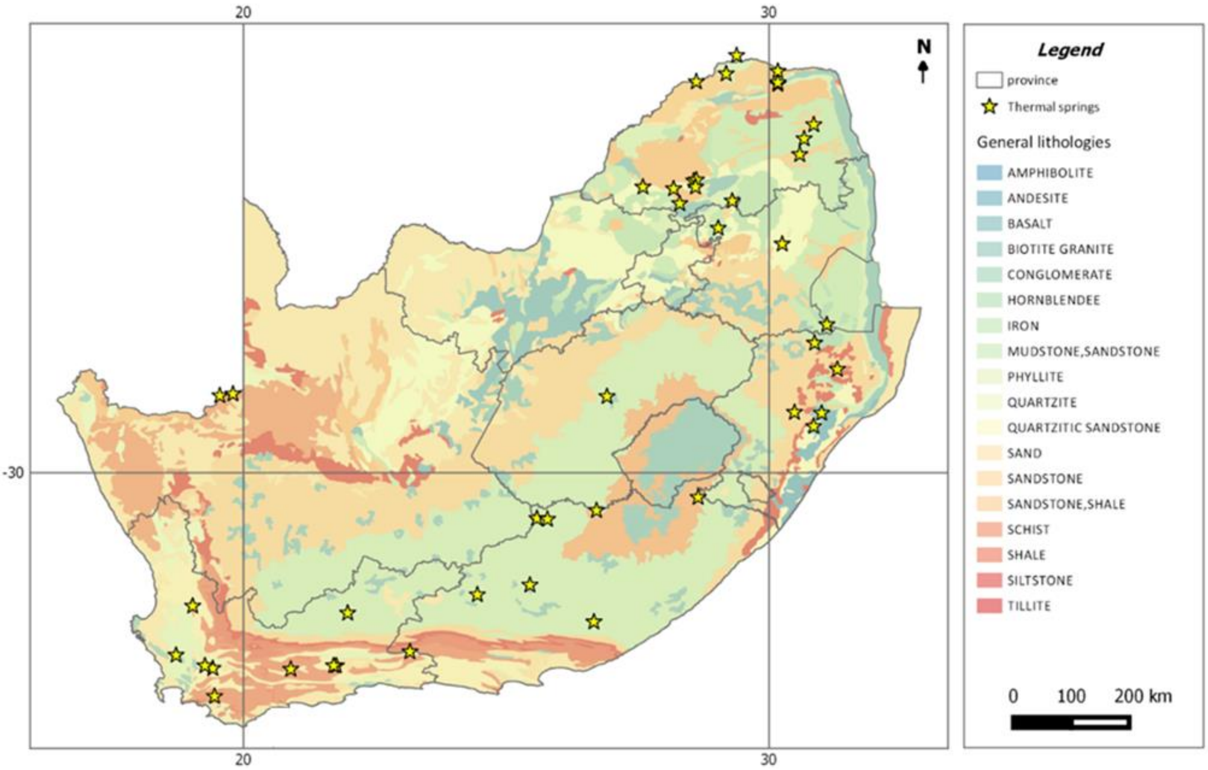


Figure 5-28: Location of thermal springs in South Africa, as identified by Kent (1949)

The results from Murray et al. (2015) could potentially be extrapolated to other areas of South Africa, where thermal springs can be sampled and the recommended determinands measured to characterise the deep groundwater within these areas. In this way, springs showing similar trends could be identified as intersecting the same deep aquifer system and potentially delineate the extent of the aquifers. Figure 5-30 shows the thermal springs in South Africa, including the springs identified by Kent (1949), with the area investigated by Murray et al. (2015) delineated in a grey circle. Red circles are used to delineate potential areas where determinands identified by Murray et al. (2015) could be applied to thermal springs in relative proximity to each other and potentially intersecting the same deep aquifer. Future studies on the characterisation of the deep groundwater aquifers should apply the approach developed by Murray et al. (2015) to define the indictor ranges for the thermal springs in South Africa and use these to analyse connections and the extent of potential deep aquifers.

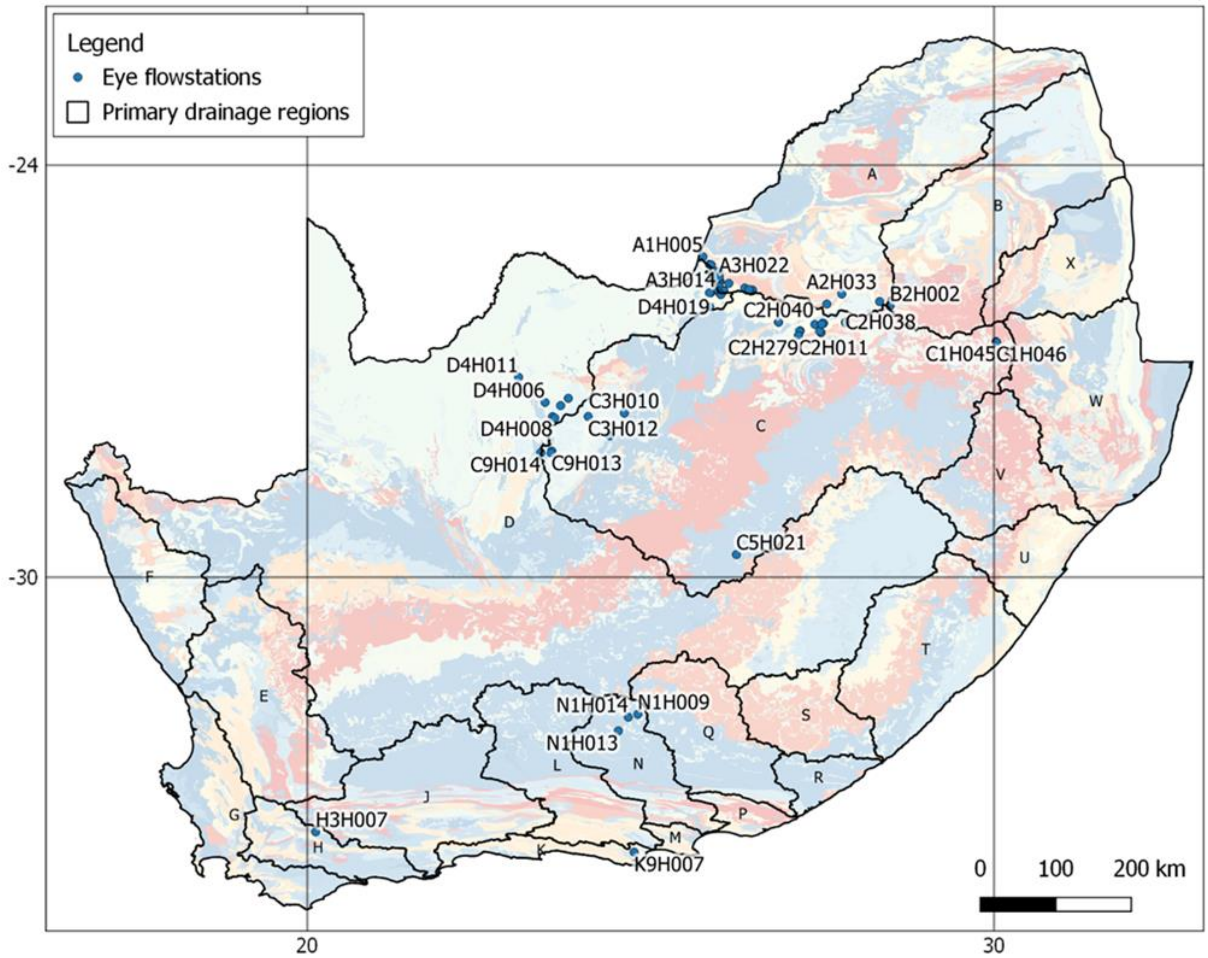


Figure 5-29: Location of DWS measure points for spring discharges overlain on the simplified geology of South Africa

The provisional guide of Murray et al. (2015) on the limits for identified determinands to be used as a guideline to differentiate deep water from shallow water for future studies is given in Table 5-16. Additionally, the more reliable determinands identified by Murray et al. (2015), which could be prioritised for future monitoring programmes, are given in Table 5-17.

5.3.8.3.2 Circulation depths of deep groundwater

In a number of the identified potential deep aquifers, the indication of deep groundwater flow systems is a thermal spring. Cave and Clarke (2003) tested geothermometers, using data from thermal springs, to trace deep groundwater flow. Geothermometers can be used to assess the circulation depth of thermal spring water based on the principal relationship between temperature and depth below the earth's surface (the geothermal gradient), and the relationship between the composition of a solution in contact with a mineral assemblage and the temperature of the system.

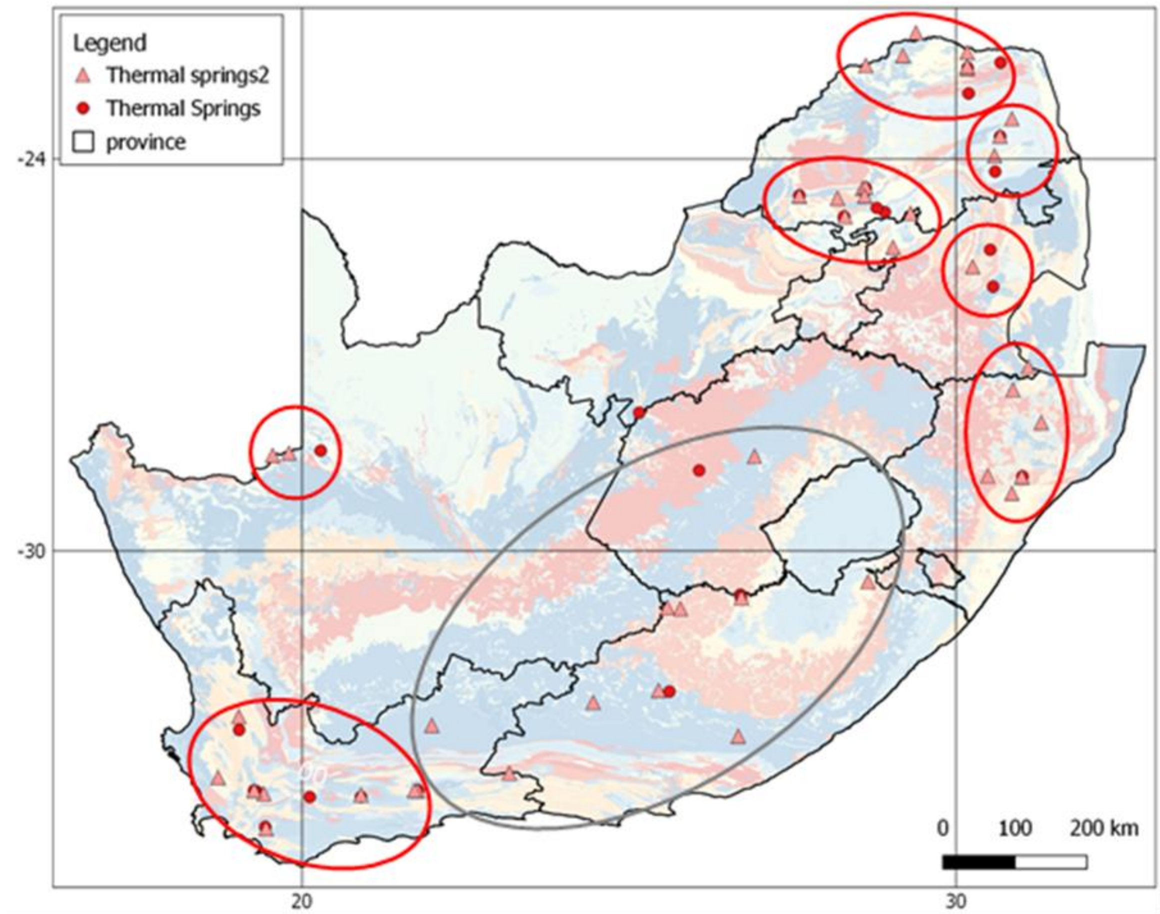


Figure 5-30: Location of thermal springs in South Africa, including the thermal springs identified by Kent (1949)

Decreasing equilibration rates with decreasing temperature create a chemical fingerprint that can identify the temperature at which the groundwater equilibrated, even if the water has cooled on ascending to the surface. Geothermometers can be grouped into two main categories: silica and cation geothermometers. Silica geothermometers are based on temperature-dependent variations in the solubility of individual silica minerals, such as quartz, chalcedony and amorphous silica. Cation geothermometers make use of temperature-dependent exchange reactions with hydrothermal minerals, such as clays and feldspars that fix the ratios of dissolved cations according to the equilibrium temperature.

Cave and Clarke (2003) experienced challenges in applying geothermometers in South Africa due to their poor performance in lower-enthalpy geothermal environments. It was concluded that cation geothermometers are unsuitable for the South African geological environment. However silica geothermometers were applied with moderate success in the quartzitic Table Mountain Group, as well as hot springs in the Western Cape and the Eastern Cape. Chalcedony geothermometers were found to be unacceptable for the Transvaal Group dolomite due to the small temperature changes. Cave and Clarke (2003) concluded that substantially deep groundwater flow was unlikely.

Table 5-16: Indicators for deep groundwater (Murray et al., 2015)

Determinand	Deep groundwater criteria	Units
^{14}C	<60	pmC
$\delta^{18}O$	<-6	‰ SMOW
F^-	>3	mg/L
$\%Na^+$	>70	%
Mg^{2+}	<10	mg/L
U	<0.05	µg/L
Alkalinity	<100	mg/L HCO_3^-
B	>300	µg/L
V	<1	µg/L
Li	>100	µg/L
$\delta^{11}B$	<+30	‰
NO_3^-	<1	mg NO_3/L
$^{36}Cl/Cl$	<100	10^{-15}
Rn	<10	Bq/L
H_2S	>1	µcc/kg
^3H	<1	TU
Na^+	>300	mg/L
pH	>9	
^4He	>30000	µcc/kg
$^3He/^4He$	<0.1	R/R_0
Temperature	>25	°C
CH_4	>10	cc/L

Table 5-17: Success rate and prioritisation of different determinands for identifying deep groundwater (Murray et al., 2015)

Group	Success Rate	Determinands
Group 1	100% success rate	^{14}C, $\delta^{18}O$, fluoride, %sodium, magnesium, uranium, alkalinity
Group 2	>75% success rate	Boron, vanadium, lithium, $\delta^{11}B$, $^{36}Cl/Cl$, ^{222}Radon, H_2S
Group 3	50-75% success rate	Sodium, pH, tritium, nitrate, temperature, ^4He, $^3He/^4He$, CH_4
Group 4	< 50% success rate	$^{87}Sr/^{86}Sr$, $\delta^{13}C$, rare earth elements, other trace elements

Geothermometers could be considered for future deep groundwater studies, but should be restricted to aquifers with simple quartz mineralogy, where accurate field and laboratory data is available, and where the geological and flow environment is understood. Geothermometers could also be used to compare samples in the same geological settings and draw conclusions about their relative depths and ages, and, in this way, delineate potential deep aquifer systems.

Cave and Clarke (2003) estimated circulating depths for the three study areas: the Table Mountain Group area, the hot springs in the Western Cape and the Eastern Cape, and Transvaal dolomitic springs. The Table Mountain Group study area utilised boreholes in the area. The summarised results are given in Table 5-18. Linear and polynomial quartz geothermometers are used for two potential geothermal gradients, resulting in a range of depth values. The average results indicate circulating depths of 500 m in the Peninsula Group and up to 2,000 m in the Nardouw Group.

The investigated dolomitic aquifer forms part of the Transvaal Supergroup and is located in the northern provinces of South Africa. Field measurements and chemical analyses of 56 dolomitic springs were used for the geothermometer application, divided between the Delmas, Northern Cape and West Rand areas. The average circulation depth for the Delmas area is 1,130 m, for the Northern Cape it is 2,300 m, and for the West Rand it is 400 m (Figure 5-31).

Table 5-18: Circulation depths for the Table Mountain Group using geothermometers (Cave and Clarke, 2003)

Lithology	Circulating depth (m)		
	Maximum	Minimum	Average
Peninsula	1 700	200	500
Nardouw	7 000	300	2 000

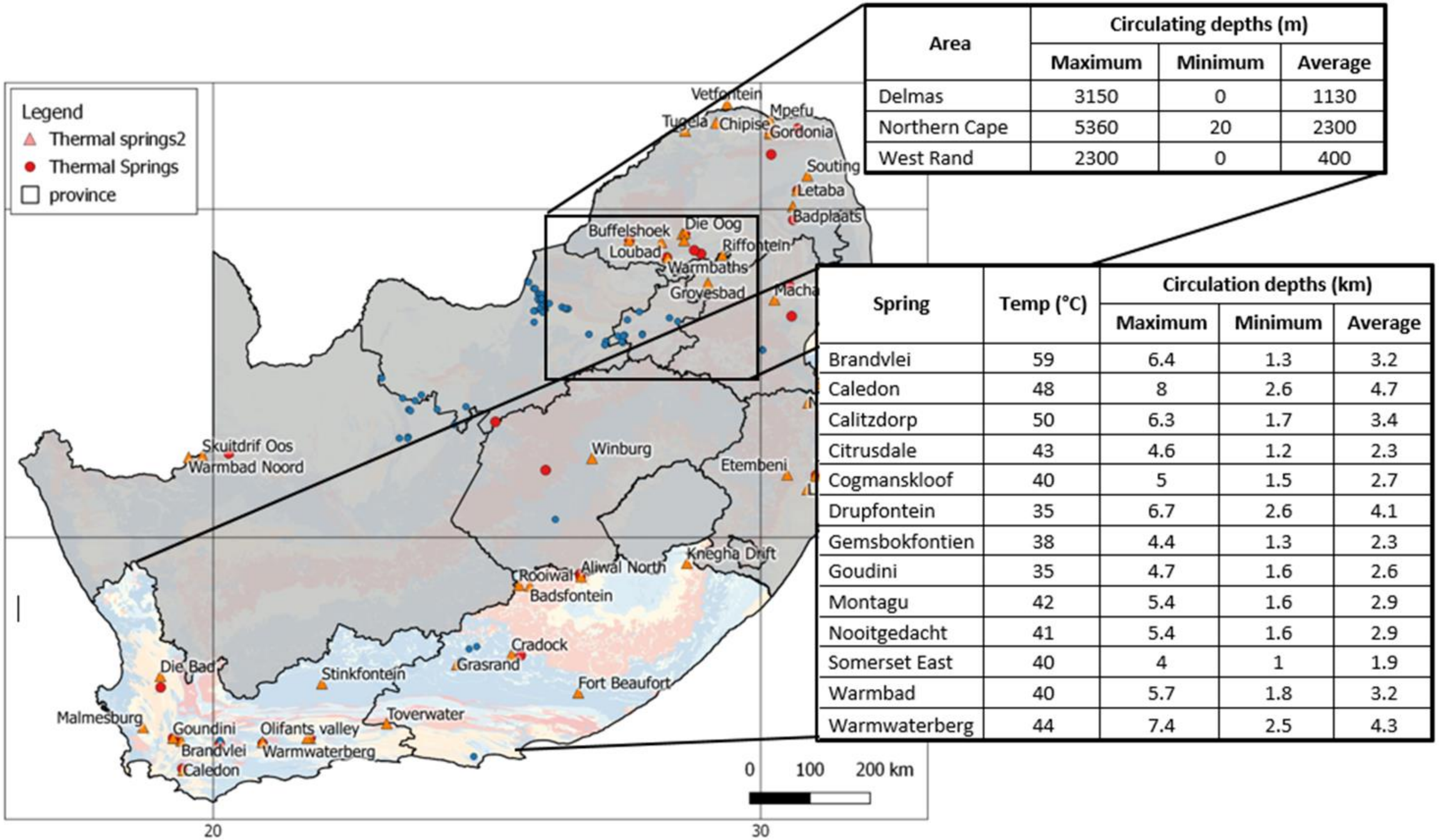
Cave and Clarke (2003) applied silica and cation geothermometers to chemical data from hot springs in the Western Cape and the Eastern Cape, where most of the hot springs are related to the fractured Table Mountain Group. The temperatures measured for the 13 selected springs range from 35 to 59 °C, and average circulation depths range from 4,700 to 1,900 m. The individual measurements have a maximum of 7,400 m and a minimum of 1,000 m. The depth calculations vary due to the use of three geothermometers and two different geothermal gradients due to uncertainty, but as a minimum, groundwater is circulating to a depth of 1 km in these areas.

5.3.8.3.3 Chemical characterisation of thermal springs

Olivier et al. (2008) investigated the physical and chemical characteristics of eight thermal springs in Limpopo to ensure the optimal use of these springs. Thermal springs of meteoric origin were investigated. These were the Warmbaths, Loubad, Vischgat, Die Oog, Rhemardo, Lekkerrus, Libertas and Buffelshoek springs, with water temperatures ranging from 30 to 52 °C. Olivier et al. (2008) characterised the geological structures associated with each spring, the average temperature of the spring water and their classification according to Kent (1949), flow rate and chemical characteristics of each spring, including trace elements and a temporal analysis (Figure 5-32 and Table 5-19 and Table 5-20).

The study conducted by Olivier et al. (2008) does not include the scope of analysing deep groundwater, but does potentially provide chemical characteristics that can be used to characterise deep groundwater. Isotopes did not form part of the scope of the study, yet the chemical characteristics of the Limpopo springs could be applied to the list of determinands reported by Murray et al. (2015). From Table 5-20, one can see that the fluoride concentrations measured for the Limpopo springs indicated deep groundwater in all the springs except the Loubad Spring, based on the deep groundwater characteristics established by Murray et al. (2015), where concentrations greater than 3 mg/ℓ could be considered deep groundwater.

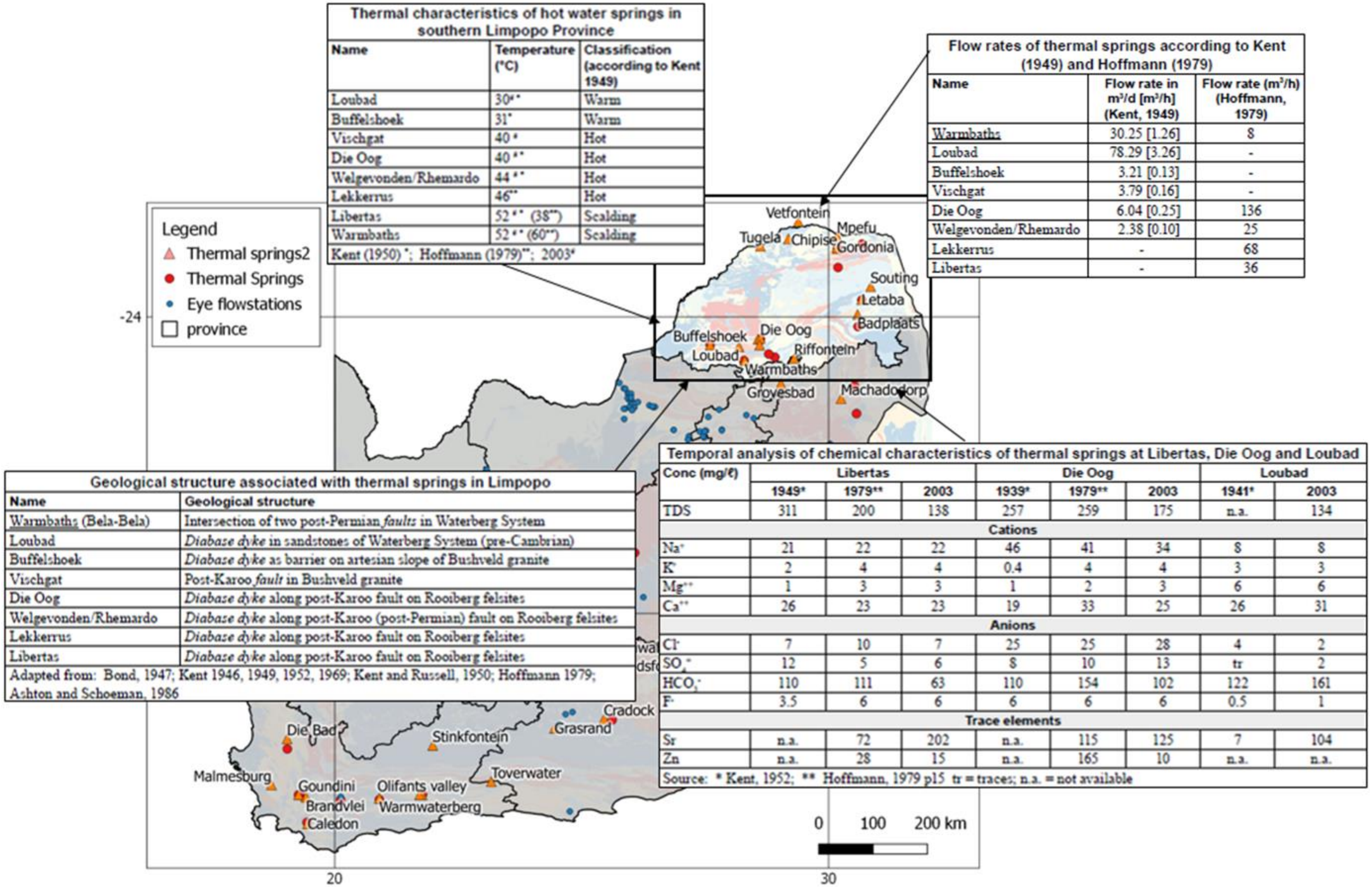
Olivier et al. (2008; 2011) conducted a similar study where the geological structures associated with each spring, the average temperature of the spring water and its classification according to Kent (1949), and the chemical characteristics of each spring, including trace elements and a temporal analysis, were characterised for eight thermal springs in the northern part of Limpopo. These springs included the Evangelina, Tshipise, Sagole, Môreson, Siloam, Mphephu, Minwamadi and Die Eiland springs.



Area	Circulating depths (m)		
	Maximum	Minimum	Average
Delmas	3150	0	1130
Northern Cape	5360	20	2300
West Rand	2300	0	400

Spring	Temp (°C)	Circulation depths (km)		
		Maximum	Minimum	Average
Brandvlei	59	6.4	1.3	3.2
Caledon	48	8	2.6	4.7
Calitzdorp	50	6.3	1.7	3.4
Citrusdale	43	4.6	1.2	2.3
Cogmanskloof	40	5	1.5	2.7
Drupfontein	35	6.7	2.6	4.1
Gemsbokfontien	38	4.4	1.3	2.3
Goudini	35	4.7	1.6	2.6
Montagu	42	5.4	1.6	2.9
Nooitgedacht	41	5.4	1.6	2.9
Somerset East	40	4	1	1.9
Warmbad	40	5.7	1.8	3.2
Warmwaterberg	44	7.4	2.5	4.3

Figure 5-31: Springs located in South Africa indicating areas where circulation depths have been calculated. Red circles indicate known hot springs; orange triangles indicate the thermal springs identified by Kent (1949); and blue circles indicate cool water springs where the discharge is measured.



Thermal characteristics of hot water springs in southern Limpopo Province

Name	Temperature (°C)	Classification (according to Kent 1949)
Loubad	30#*	Warm
Buffelshoek	31*	Warm
Vischgat	40 #	Hot
Die Oog	40 #*	Hot
Welgevonden/Rhemardo	44 #*	Hot
Lekkerrus	46**	Hot
Libertas	52 #* (38**)	Scalding
Warmbaths	52 #* (60**)	Scalding
Kent (1950) *; Hoffmann (1979)**; 2003#		

Flow rates of thermal springs according to Kent (1949) and Hoffmann (1979)

Name	Flow rate in m^3/d [m^3/h] (Kent, 1949)	Flow rate (m^3/h) (Hoffmann, 1979)
Warmbaths	30.25 [1.26]	8
Loubad	78.29 [3.26]	-
Buffelshoek	3.21 [0.13]	-
Vischgat	3.79 [0.16]	-
Die Oog	6.04 [0.25]	136
Welgevonden/Rhemardo	2.38 [0.10]	25
Lekkerrus	-	68
Libertas	-	36

Geological structure associated with thermal springs in Limpopo

Name	Geological structure
Warmbaths (Bela-Bela)	Intersection of two post-Permian *faults* in Waterberg System
Loubad	*Diabase dyke* in sandstones of Waterberg System (pre-Cambrian)
Buffelshoek	*Diabase dyke* as barrier on artesian slope of Bushveld granite
Vischgat	Post-Karoo *fault* in Bushveld granite
Die Oog	*Diabase dyke* along post-Karoo fault on Rooiberg felsites
Welgevonden/Rhemardo	*Diabase dyke* along post-Karoo (post-Permian) fault on Rooiberg felsites
Lekkerrus	*Diabase dyke* along post-Karoo fault on Rooiberg felsites
Libertas	*Diabase dyke* along post-Karoo fault on Rooiberg felsites
Adapted from: Bond, 1947; Kent 1946, 1949, 1952, 1969; Kent and Russell, 1950; Hoffmann 1979; Ashton and Schoeman, 1986	

Temporal analysis of chemical characteristics of thermal springs at Libertas, Die Oog and Loubad

Conc (mg/ℓ)	Libertas			Die Oog			Loubad	
	1949*	1979**	2003	1939*	1979**	2003	1941*	2003
TDS	311	200	138	257	259	175	n.a.	134
Cations								
Na^+	21	22	22	46	41	34	8	8
K^+	2	4	4	0.4	4	4	3	3
Mg^{++}	1	3	3	1	2	3	6	6
Ca^{++}	26	23	23	19	33	25	26	31
Anions								
Cl^-	7	10	7	25	25	28	4	2
$SO_4^=$	12	5	6	8	10	13	tr	2
HCO_3^-	110	111	63	110	154	102	122	161
F^-	3.5	6	6	6	6	6	0.5	1
Trace elements								
Sr	n.a.	72	202	n.a.	115	125	7	104
Zn	n.a.	28	15	n.a.	165	10	n.a.	n.a.
Source: * Kent, 1952; ** Hoffmann, 1979 p15 tr = traces; n.a. = not available								

Figure 5-32: Spring locations in South Africa, showing specifically the springs in Limpopo and the thermal, flow geological and temporal characteristics identified by Olivier et al. (2008)

Table 5-19: Concentration of trace elements in southern Limpopo's thermal spring waters (taken from Olivier et al., 2008)

Element	DWAF 1996 * SABS 1999** Standards (µg/ℓ)	Vischgat µg/ℓ	Die Oog (µg/ℓ)	Welgevonden/ Rhemardo (µg/ℓ)	Libertas (µg/ℓ)	Loubad (µg/ℓ)
Molybdenum	ns	9.67	11.63	11.07	12.49	6.30
Beryllium	ns	0.60	0.63	0.68	1.07	0.44
Boron	1500	47.63	49.38	47.96	43.78	33.07
Titanium	ns	*228.59*	*134.50*	*144.68*	*141.64*	*178.96*
Vanadium	100*	3.78	4.18	4.30	3.17	3.71
Chromium	50* 100**	2.84	3.31	3.56	3.39	5.52
Manganese	50* 100**	9.63	3.13	3.52	*14.22*	*20.14*
Cobalt	150**	2.13	1.13	1.56	2.15	3.50
Nickel	1000**	8.80	4.43	7.07	10.18	17.33
Copper	1000* 5000**	6.07	1.14	4.97	5.77	5.54
Zinc	3000*	*37.54*	9.93	19.53	14.63	8.65
Arsenic	10*	1.35	3.25	4.48	*6.63*	4.23
Bromine	ns	39.64	*60.93*	31.36	0.00	20.73
Lithium	ns	*79.54*	*45.42*	*47.14*	*37.21*	16.43
Strontium	ns	*227.27*	*125.11*	*127.36*	*202.39*	*104.34*
Uranium	70***	0.00	1.37	4.12	2.98	1.28
Cadmium	5*	1.79	0.47	1.20	0.034	0.93
Antimony	ns	1.03	0.00	2.49	0.05	0.00
Tellurium	ns	0.00	3.46	0.00	2.11	4.92
Iodine	ns	*15.90*	6.96	7.75	*20.08*	0.00
Barium	ns	9.47	13.26	13.27	*29.00*	*42.26*
Lanthanum	ns	0.00	0.00	0.00	0.00	0.00
Tungsten	ns	1.10	0.00	3.21	0.00	0.00
Platinum	ns	0.00	0.00	0.00	0.00	0.00
Mercury	1* 2**	0.00	0.00	0.00	*1.77*	0.00
Thallium	ns	0.77	0.64	0.66	0.39	0.37
Lead	10* 50**	3.73	5.69	*6.96*	5.70	5.64
Bismuth	ns	3.80	3.85	3.70	3.60	3.62
Selenium	20*	0.00	0.00	0.00	0.00	1.66

ns = not stipulated
***Tentative water quality guideline for Uranium (Kempster et al., 1996)

Diamond and Harris (2000) measured oxygen and hydrogen isotopes at 12 thermal springs in the Western Cape to determine where these springs are recharged (Figure 5-33). These springs include Baden-Baden, Brandvlei, Caledon, Calitzdorp, Citrusdale, Goudini, Malmesburg, Montagu, Rietfontein, Toowerwater, Warmwarmberg and Witzenberg. The temperature, flow, altitude, distance from the coast and geological structure were additionally characterised for each spring (Figure 5-34). Applying the deep groundwater indictor $^{18}\delta O$ of Murray et al. (2015), where values less than and equal to 6 could be considered deep groundwater, the springs analysed by Diamond and Harris (2000) showed positive $^{18}\delta O$ indicators for deep groundwater at the Brandvlei, Caledon, Citrusdale, Goudini, Malmesburg, Montagu, Rietfontein and Witzenberg springs, but negative $^{18}\delta O$ indicators at the Baden-Baden, Calitzdorp, Montagu, Toowerwater and Warmwaterberg springs.

Table 5-20: Chemical composition of thermal springs in Limpopo (Olivier et al., 2008)

	SABS 1999	Warmbad*	Loubad	Buffelshoek*	Vischgat	Die Oog	Rhemardo	Libertas
pH	6 - 9	8.3	6.81	Not available	7.07	7.27	7.33	6.98
pH$_s$			7.79		7.82	8.01	7.96	8.00
SAR			0.34		2.39	1.72	1.62	1.13
TDS	<450	340	134.18		302.85	175.48	179.90	137.90
Conduct. (mS/m)	<150	69	25.00		52.00	32.00	34.00	25.00
CATIONS (mg/ℓ)								
Sodium	<200	132.5	7.87	151.6	55.95	34.21	32.72	21.98
Potassium	<50	2.9	2.90	5.7	6.13	3.62	3.58	3.57
Calcium	ns	13.0	30.92	27.1	36.13	24.80	25.57	23.02
Magnesium	ns	1.8	6.44	4.7	3.30	3.14	3.28	3.46
Boron	<1.5		0.04		0.06	0.05	0.05	0.05
ANIONS (mg/ℓ)								
Fluoride	1.5 (1*)	11.0	0.95	6.6	6.54	5.66	5.39	5.95
Nitrite	Ns	-	0.00	-	0.12	0.00	0.00	<0.1
Nitrate	Ns	0	0.59	0	0.68	0.60	0.88	0.41
Chloride	<200	85.2	2.21	138.5	31.70	28.31	28.64	7.24
Sulphate	<400	12.1	2.16	35.1	92.82	12.96	13.68	5.86
Phosphate	ns	< 0.2	0.00	-	0.00	0.00	0.00	<0.2
Carbonate	ns	-	0.00	-	0.00	0.00	0.00	0.00
Bicarb	ns	102.0	161.65	213.5	140.30	125.05	134.20	134.2
Classific. (Bond 1946)		D	E	D	E	E	E	E
Source: *Kent, 1949; Temperley, 1975 (as reported in Hoffmann, 1979 p8) ; **Hoffmann, 1979 p15 *DWAF, 1996; ns: not stipulated								

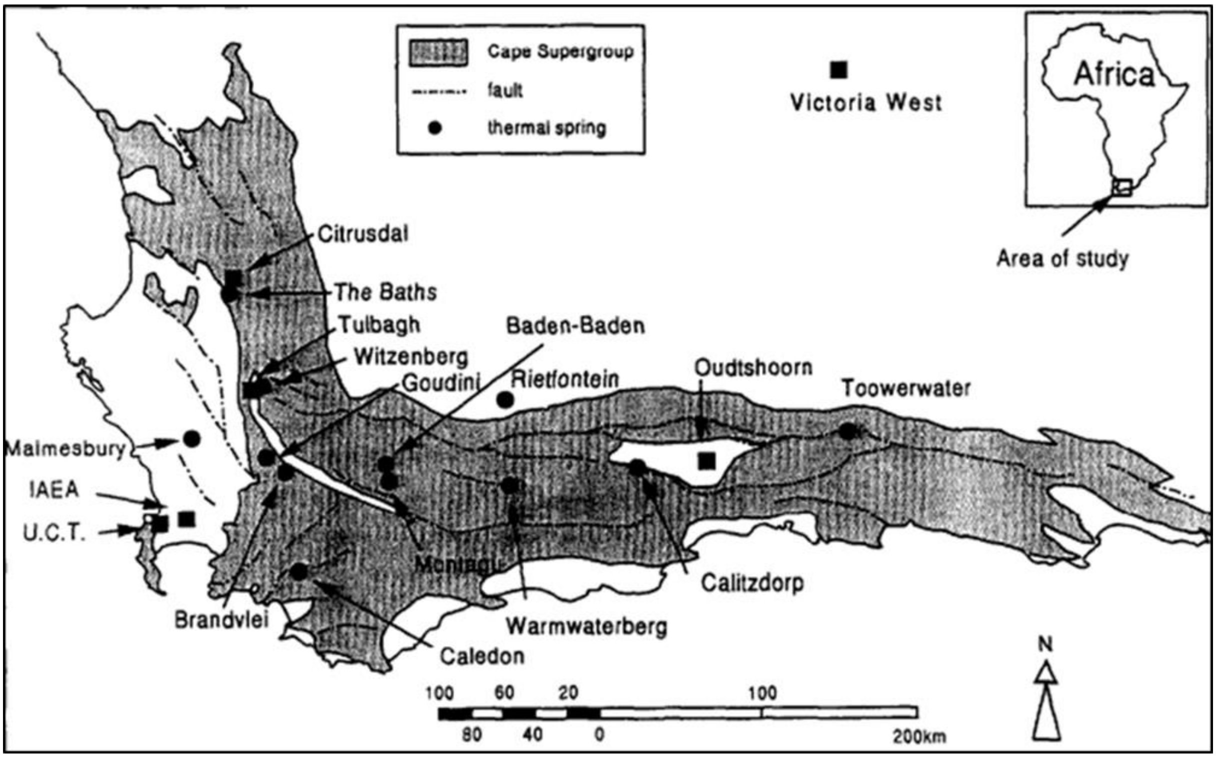
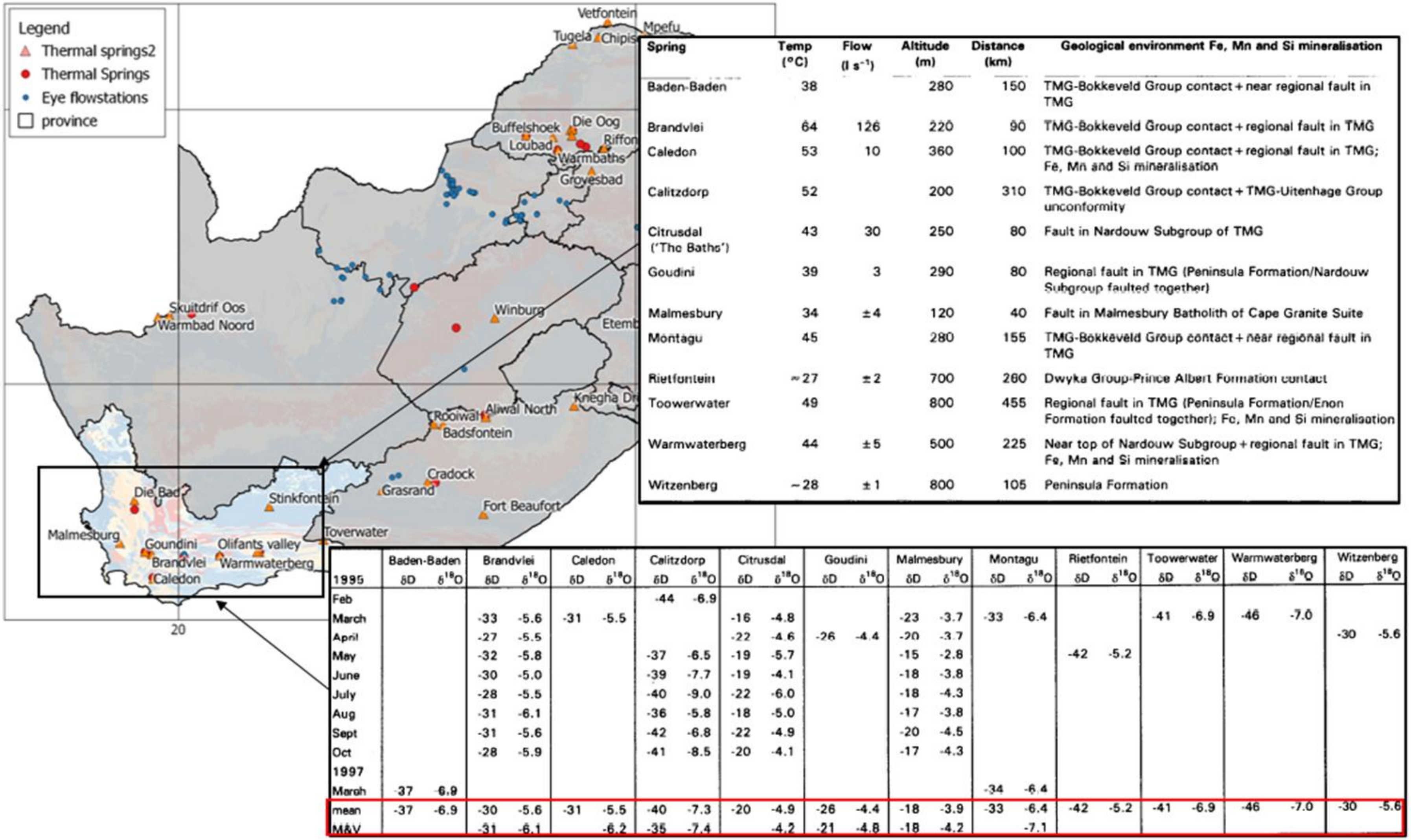


Figure 5-33: Location of the thermal springs investigated by Diamond and Harris (2000)



Spring	Temp (°C)	Flow (l s⁻¹)	Altitude (m)	Distance (km)	Geological environment Fe, Mn and Si mineralisation
Baden-Baden	38		280	150	TMG-Bokkeveld Group contact + near regional fault in TMG
Brandvlei	64	126	220	90	TMG-Bokkeveld Group contact + regional fault in TMG
Caledon	53	10	360	100	TMG-Bokkeveld Group contact + regional fault in TMG; Fe, Mn and Si mineralisation
Calitzdorp	52		200	310	TMG-Bokkeveld Group contact + TMG-Uitenhage Group unconformity
Citrusdal ('The Baths')	43	30	250	80	Fault in Nardouw Subgroup of TMG
Goudini	39	3	290	80	Regional fault in TMG (Peninsula Formation/Nardouw Subgroup faulted together)
Malmesbury	34	±4	120	40	Fault in Malmesbury Batholith of Cape Granite Suite
Montagu	45		280	155	TMG-Bokkeveld Group contact + near regional fault in TMG
Rietfontein	~27	±2	700	260	Dwyka Group-Prince Albert Formation contact
Toowerwater	49		800	455	Regional fault in TMG (Peninsula Formation/Enon Formation faulted together); Fe, Mn and Si mineralisation
Warmwaterberg	44	±5	500	225	Near top of Nardouw Subgroup + regional fault in TMG; Fe, Mn and Si mineralisation
Witzenberg	~28	±1	800	105	Peninsula Formation

	Baden-Baden		Brandvlei		Caledon		Calitzdorp		Citrusdal		Goudini	
1995	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O
Feb							-44	-6.9				
March			-33	-5.6	-31	-5.5			-16	-4.8		
April			-27	-5.5					-22	-4.6	-26	-4.4
May			-32	-5.8			-37	-6.5	-19	-5.7		
June			-30	-5.0			-39	-7.7	-19	-4.1		
July			-28	-5.5			-40	-9.0	-22	-6.0		
Aug			-31	-6.1			-36	-5.8	-18	-5.0		
Sept			-31	-5.6			-42	-6.8	-22	-4.9		
Oct			-28	-5.9			-41	-8.5	-20	-4.1		
1997												
March	-37	-6.9										
mean	-37	-6.9	-30	-5.6	-31	-5.5	-40	-7.3	-20	-4.9	-26	-4.4
M&V			-31	-6.1		-6.2	-35	-7.4		-4.2	-21	-4.8

	Malmesbury		Montagu		Rietfontein		Toowerwater		Warmwaterberg		Witzenberg	
1995	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O	δD	δ18O
Feb												
March	-23	-3.7	-33	-6.4			-41	-6.9	-46	-7.0		
April	-20	-3.7									-30	-5.6
May	-15	-2.8			-42	-5.2						
June	-18	-3.8										
July	-18	-4.3										
Aug	-17	-3.8										
Sept	-20	-4.5										
Oct	-17	-4.3										
1997												
March			-34	-6.4								
mean	-18	-3.9	-33	-6.4	-42	-5.2	-41	-6.9	-46	-7.0	-30	-5.6
M&V	-18	-4.2		-7.1								

Figure 5-34: Spring locations in South Africa, indicating the characterisation of the Western Cape thermal springs by Diamond and Harris (2000)

Geological cross-sections through the Citrusdale, Calitzdorp and Brandvlei springs were compiled by Diamond and Harris (2000) to characterise the structural features controlling the deep groundwater flow in these areas (Figure 5-35). Deep groundwater movement in the Table Mountain Group is through fractures, which are either horizontal bedding planes or vertical joints. Faults punctuate the stratigraphy and are present at nearly all the springs. It thus seems that faults are critical in providing preferential pathways through the normally impermeable Cedarberg Formation for heated water to percolate upwards (Diamond and Harris, 2000).

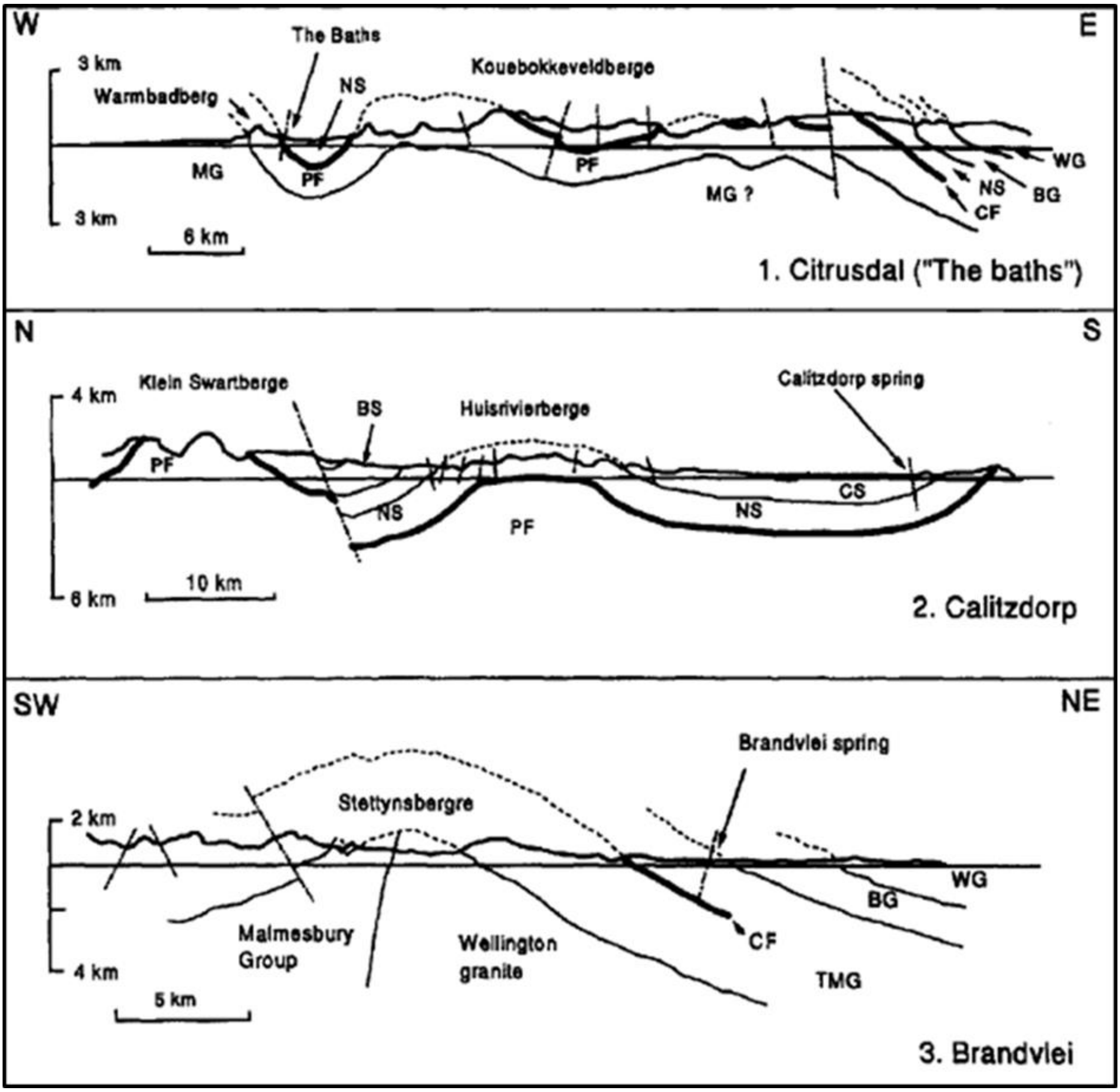


Figure 5-35: Geological cross-sections through the Citrusdale, Calitzdorp and Brandvlei spring areas

MG = Malmesburg Group	**NS = Nardouw Subgroup**	**CF = Cederberg Formation**
BG = Bokkeveld Group	**WG = Witteberg Group**	**PF = Peninsula Formation**
BS = Bidouw Subgroup	**CS = Ceres Subgroup**	**TMG = Table Mountain Group**

Miller et al. (2015) examined whether subthermal spring waters, defined as groundwater with a temperature >25 °C, are suitable proxies for deep Karoo groundwater. Temperature, major cations and anions, and ^{14}C were used to define three groups of groundwater: shallow (cold, young), deep (subthermal, old) and mixed (subthermal or cold, intermediate age). The three identified groups further showed that the isotope ratios of ^{14}C, $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C_{DIC}$, $\delta^{11}B$ and $^{87}Sr/^{86}Sr$ may be suitable indicators for deep groundwater (Miller et al., 2015). Sampling by Miller et al. (2015) included eight locations, widely dispersed throughout the Karoo Basin, where a subthermal spring or borehole was sampled along with a corresponding cold water (<25 °C) borehole site. It was concluded that the O and H isotopes were the most effective at differentiating the three groups; B isotopes differentiated the shallow from the deep group, but the deep group could not be differentiated from the mixed group; and the Sr and C isotopes did not differentiate any group (Miller et al., 2015).

Swana et al. (2015) made use of the complete set of ^{14}C, ^{3}H, ^{36}Cl and ^{4}He isotope data for a range of different groundwater types produced by Miller et al. (2015) to compare the effectiveness of these isotopes for evaluating the residence time of Karoo groundwater. Swana et al. (2015) found the shallow groundwater to be younger, while the subthermal spring water was generally older, with ^{14}C activity ranges and $^{3}He/^{4}He$ ratios indicating residence time ranges from modern to 20,000 years old. It was generally concluded that the subthermal groundwater was a reasonable proxy for deep groundwater in the Karoo, with subthermal groundwater showing longer residence times than shallow groundwater.

The deep groundwater indicators for subthermal springs or boreholes developed by Miller et al. (2015) and Swana et al. (2015) should be considered for application to future deep groundwater investigations where isotope sampling is performed.

Madi et al. (2014) conducted gamma ray measurements along the Tshisa, Aliwal North and Badfontein thermal springs, using a spectrometer to find the concentration (ppm) of U, Th and K for the chemical characterisation of the groundwater. The authors stated that hot springs might be indicative of possible neotectonics, i.e. young tectonic events.

Figure 5-36 shows the proposed neotectonic faults by Madi et al. (2014) related to thermal springs in South Africa, with the study site in the Eastern Cape indicated in blue and the chemical characterisation results. Murray et al. (2015) found that uranium indicators showed a concentration of less than 0.05 mg/ℓ for deep groundwater. However, the uranium concentrations measured by Madi et al. (2014) do not indicate deep groundwater according to this definition. The thermal nature of the springs does, however, suggest deep circulating groundwater. This disagreement could indicate that the findings of Murray et al. (2015) are not applicable in all areas of South Africa.

Statistical representation of potassium, uranium and thorium in the three hot springs

	Polile Tshisa			Aliwal North			Badfontein		
	K (ppm)	*U* (ppm)	Th (ppm)	*K* (ppm)	*U* (ppm)	Th (ppm)	*K* (ppm)	*U* (ppm)	Th (ppm)
Minimum	0.0	0.0	3.30	0.30	0.00	0.30	0.30	0.0	0.30
Maximum	1.8	11.4	21.10	1.70	3.20	12.60	1.70	3.2	12.60
Mean	0.6	2.3	8.96	0.95	1.16	5.44	0.95	1.2	5.44
Median	0.6	2.0	7.65	0.90	1.00	5.35	0.90	1.0	5.35
Standard deviation	0.4	2.1	4.17	0.29	0.86	2.28	0.29	0.9	2.28
Variation coefficient	0.6	0.9	0.47	0.30	0.74	0.42	0.30	0.7	0.42
Skewness	0.7	1.4	0.72	0.38	0.45	0.81	0.38	0.5	0.81
Kurtosis	0.2	3.1	−0.38	−0.24	−0.65	1.05	−0.24	−0.6	1.05

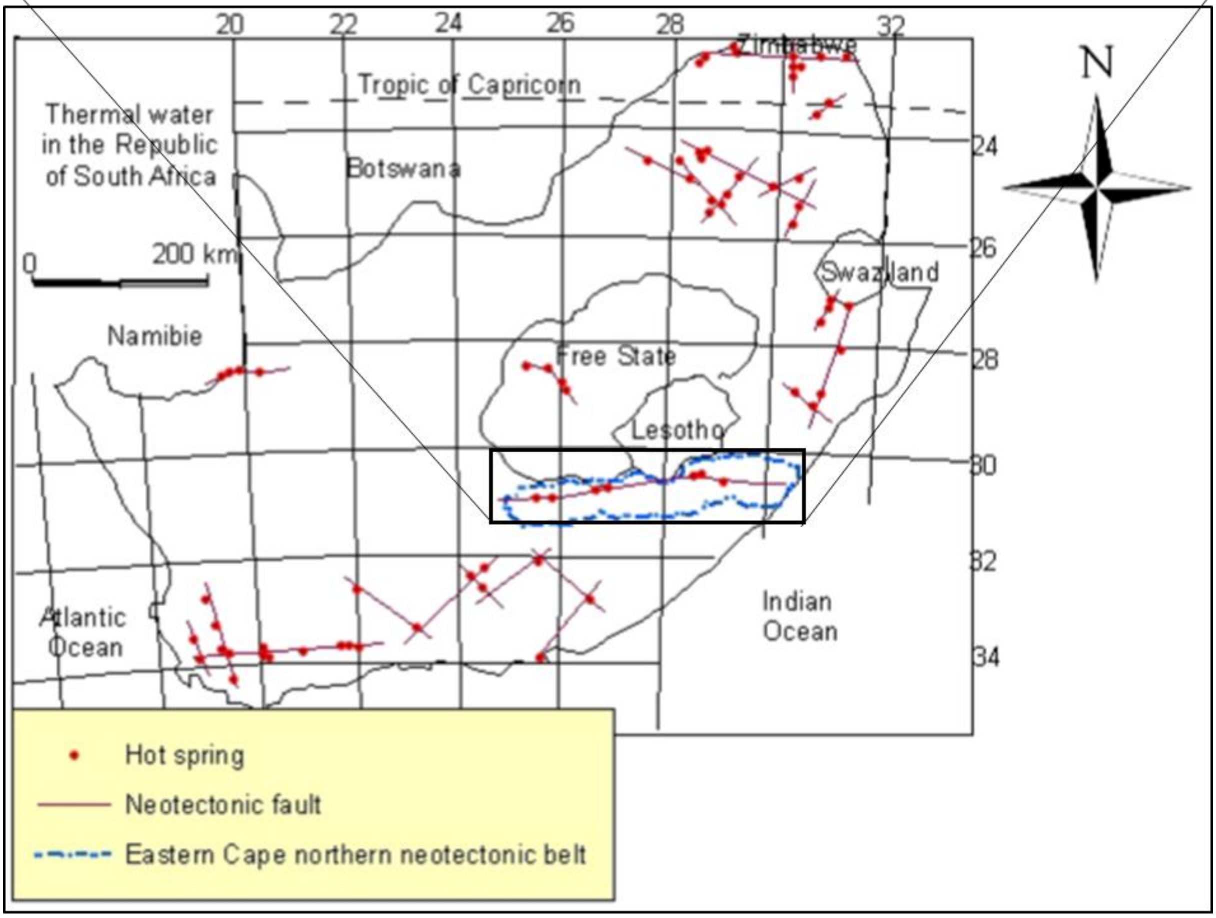


Figure 5-36: Hot springs in South Africa from Kent (1949), indicating the proposed neotectonic faults of Madi et al. (2014)

Shabalala et al. (2015) performed a chemical characterisation investigation of thermal spring water in the Soutpansberg Basin for the Sagole, Tshipise, Mphephu, Dopeni and Siloam thermal springs (Figure 5-37). Summer and winter sampling runs were performed, but seasonal variations in the chemical composition were found to be negligible; thus confirming that the source of the warm spring water is at depths not affected by seasonal recharge (Table 5-21 and Table 5-22). The thermal spring water samples were found to be rich in sodium, bicarbonate and chlorine, with very low concentrations of other element species. The chemical composition of the Sagole and Siloam thermal springs indicates the same origin of Na-Cl-HCO_3 waters, typical of deep circulating groundwater (Shabalala et al., 2015).

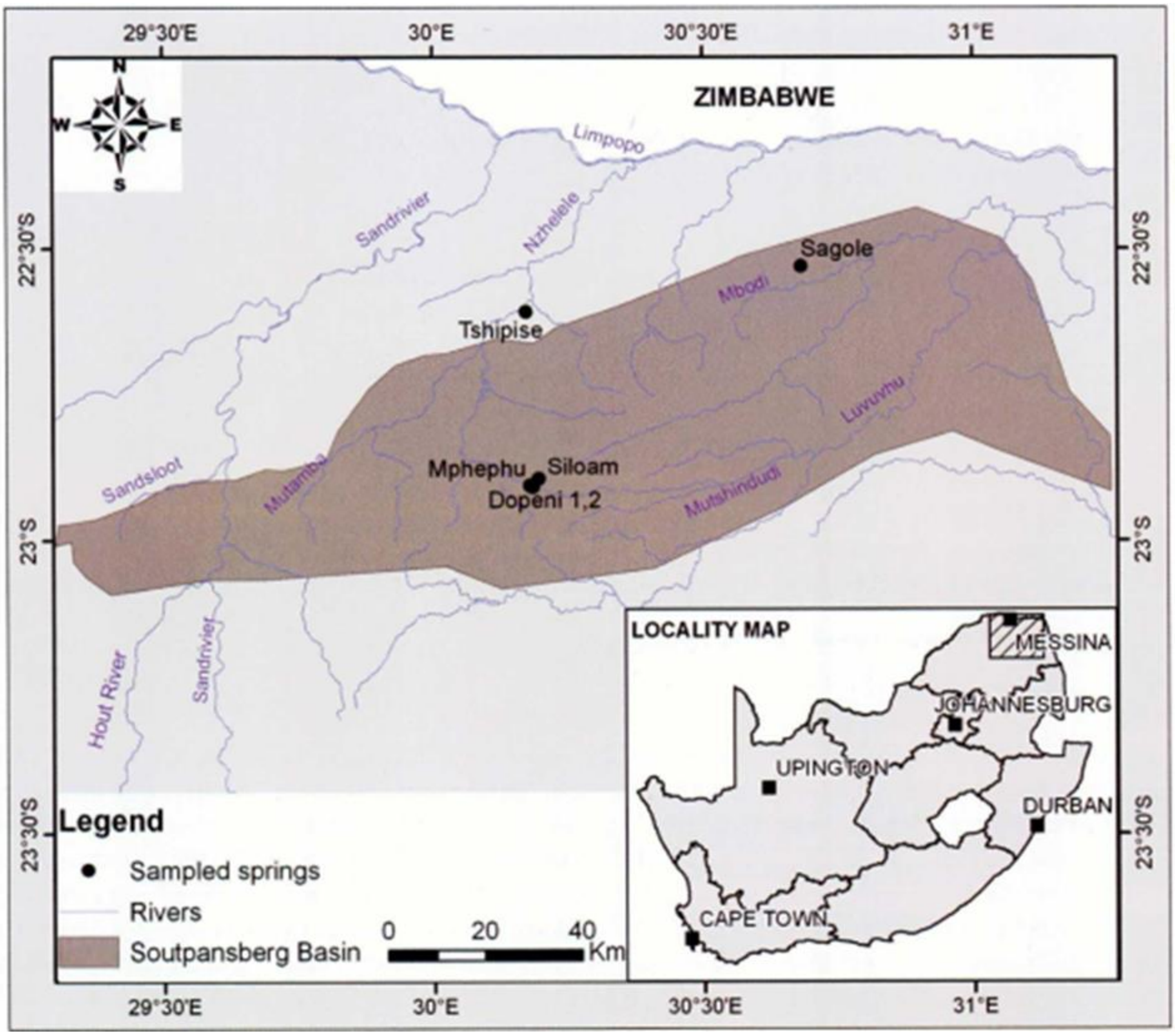


Figure 5-37: Location of the thermal springs used for the study of Shabalala et al. (2015)

Demlie and Watkeys (2011) conducted a characterisation study on the thermal springs in KwaZulu-Natal (Figure 5-38). The location, temperature, altitude, geological structures, circulation depths and chemical characteristics are described for the Black Mfolozi, Lilani, Natal Spa, Shushu and Warmbad springs. The KwaZulu-Natal thermal springs are situated within the Natal Structural and Metamorphic Complex, and the area is associated with numerous folds and faults, which are considered preferential flow paths for fluids. These fractures are known to originate at great depths beneath the earth's surface. According to Demlie and Watkeys (2011), a 3 °C change per 100 m depth is considered applicable for geothermal gradients in South Africa and can be used to approximate depth of origin, which when applied, gives circulation depths ranging from 1,235 to 1,700 m below the surface (Figure 5-38).

Table 5-21: Physical and chemical characteristics of thermal spring water in the Soutpansberg Basin in the winter of May 2013 (Shabalala et al., 2015)

Parameter	Dopeni 1	Dopeni 2	Siloam	Mphephu	Sagole	Tshipise	SANS 241-1 (2011) standards
Temp (°C)	40.7	46.5	59.0	38.2	41.5	51.2	–
pH (pH units)	6.89	7.05	8.82	7.14	9.3	8.43	≤5 – ≤9.7
EC (mS/m)	43.2	46.0	45.0	40.2	24.3	56.2	≤170
TDS (mg/L)	280	299	292	261	157	364	≤1200
Silicon (mg/L)	15.6	11.7	14.9	14.5	7.7	20.1	
Calcium (mg/L)	14.4	18.2	2.29	12.9	2.02	4.47	<150
Potassium (mg/L)	1.42	1.52	2.62	1.4	1.32	4.02	<50
Magnesium (mg/L)	11.5	14.0	<0.05	10.4	<0.05	0.12	<70
Sodium (mg/L)	41.7	43.9	66.2	40.6	64.5	155	≤200
Chloride (mg/L)	29.1	32.1	35.0	28.4	36.2	136	≤300
Nitrate (mg/L)	3.27	4.49	<0.3	2.81	<0.3	2.28	≤11
Sulphate (mg/L)	7.95	8.97	10.2	8.21	16.9	48.5	≤500
Total alkalinity (mg/L $CaC0_3$)	112	129	83.4	105	79.3	103	–

Table 5-22: Physical and chemical characteristics of thermal spring water in the Soutpansberg Basin in the summer of October 2013 (Shabalala et al., 2015)

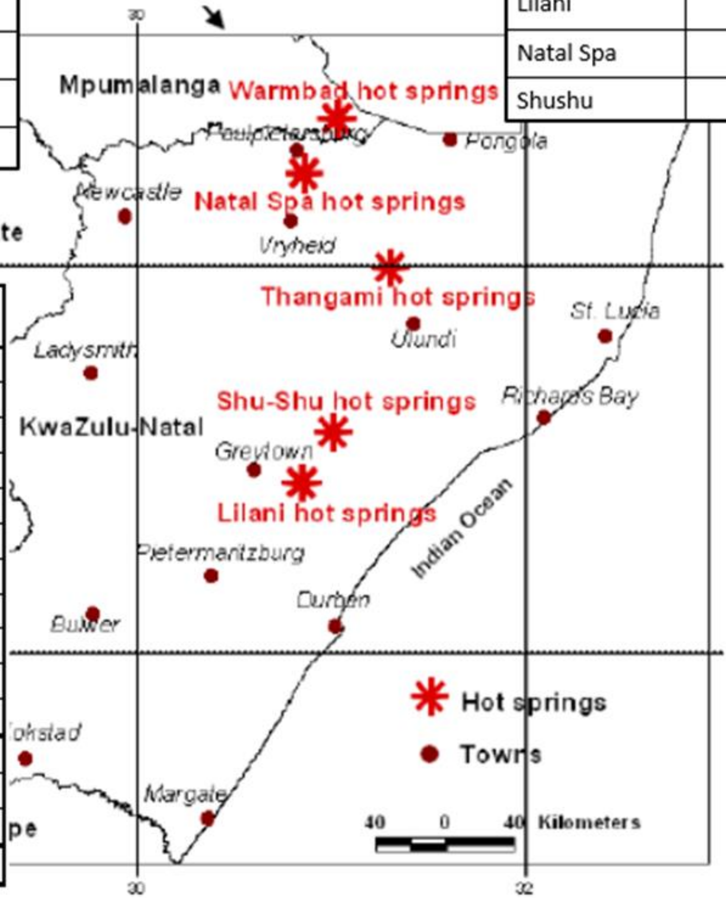
Parameter	Dopeni	Siloam	Mphephu	Sagole	Tshipise	SANS 241-1 (2011) standards
Temp (°C)	44.5	59.4	43.2	44.7	45.5	-
pH (pH units)	7.0	8.7	7.07	9.06	8.21	≥5 – ≤9.7
EC (mS/m)	47.1	44.6	40	48.1	117	≤170
TDS (mg/L)	306	293	259	312	760	≤1 200
Calcium (mg/L)	15.3	1.62	12.4	1.33	3.60	<150
Potassium (mg/L)	1.07	8.67	0.71	0.79	4.68	<50
Magnesium (mg/L)	10.1	<0.1	7.79	<0.1	<0.1	<70
Sodium (mg/L)	42.8	75.2	42.2	64.0	160.5	≤200
Chloride (mg/L)	31.3	42.8	32.9	43.0	142.6	≤300
Nitrate (mg/L)	3.60	0.24	2.34	2.88	0.13	≤11
Sulphate (mg/L)	7.34	9.45	8.06	16.6	47.2	≤500
Fluoride (mg/L)	1.95	4.83	2.30	0.62	4.87	≤1.5
Total alkalinity (mg/L $CaC0_3$)	124.9	81.8	111.1	75.66	104.1	-

5.3.8.3.4 Spring hydrographs for deep groundwater characterisation

The flow rate of thermal springs is determined by the size of the aquifer, the extent of recharge, the aquifer storage capacity, and the transmissivity and discharge capacity of both the aquifer and the conduit through which the water rises to the surface (LaMoreaux and Tanner, 2001). Considering this, measured spring discharges could potentially be used to determine the hydraulic characteristics of deep aquifers. This approach is commonly applied to karst environments, but could also be applied to fractured aquifers.

Spring Name	Location	Temperature (°C)	Altitude (mamsl)
Black Mfolozi	Ulundi	37	560
Lilani	Greytown	40	622
Natal Spa	Paulpietersburg	41	940
Shushu	Kranskop	51	217
Warmbad	Paulpietersburg	31	878

Spring	Temperature (°C)	Depth of Origin (mbgl)
Black Mfolozi	37	1235
Lilani	40	1335
Natal Spa	41	1370
Shushu	51	1700



Spring Name/ Sampling Point	Temperature (°C)	pH	TDS (mg/l)	EC (µS/cm)
Black Mfolozi 1	36.53	8.64	319	638
Black Mfolozi 2	34.05	8.67	317	635
Lilani 2	40.0	9.22	219	438
Lilani 3	38.70	9.18	218	436
Lilani River	17.63	7.80	82	163
Natal Spa	40.73	9.07	172	343
Natal Spa Borehole	22.01	6.41	120	240
Bivane River	18.16	8.06	48	95
Shu-Shu	51.0	7.7	789	1 554
Warmbad 1	30.10	9.67	139	278
Warmbad 2	31.20	9.56	141	278
Average	**32.74**	**8.54**	**233.09**	**463.45**
Minimum	**17.63**	**6.41**	**48**	**95**
Maximum	**51**	**9.67**	**789**	**1 554**
SANS 241 Standard		**5.5 - 9.5**	**1 200**	**1 700**

Figure 5-38: Locality plan of the thermal springs in KwaZulu-Natal, indicating the location, altitude, temperature, depth and chemistry measured for each spring (Demlie and Watkeys, 2011)

Taylor and Greene (2008) stated that spring discharge represents an integration of the various processes that govern recharge, storage and through-flow in a karst basin upstream from its outlet. The spring-discharge hydrograph and the applied analysis methods make it possible to obtain valuable information on the hydraulic stresses within the basin, evaluate basin flow characteristics, and estimate basin hydraulic properties (Taylor and Greene, 2008). Spring discharge hydrograph analysis methods include graphic, time-series and spectral analysis techniques (Taylor and Greene, 2008).

It is possible to estimate the average transmissivity of a karst basin by using spring discharge hydrograph analysis, following the methods of Rorabaugh (1964) and Milanović (1981), as cited by Taylor and Greene (2008):

$$\frac{T}{S_y} = \frac{\log\left[\frac{Q_1}{Q_2}\right]}{(t_1 - t_2)} \frac{L^2}{1.071}$$

where

T is aquifer transmissivity,

S_y is specific yield, Q is discharge,

t is time,

and

L is the effective karst basin length.

The storage (S_y) parameter could be obtained from aquifer test analysis, and it has been suggested that the effective length should be measured as the linear distance from the karst spring to the farthest basin drainage divide. The transmissivity estimated by this method should be validated by other methods, i.e. aquifer tests and quantitative dye-tracer tests (Taylor and Greene, 2008).

Rehrl and Birk (2010) stated that the tendency of karst aquifers to have a single spring, or limited group of springs, makes it possible to infer aquifer properties from observations made locally at the spring(s). Fractured aquifer springs that are generally found in South Africa have the same characteristic that could also facilitate the use of a spring hydrograph to determine the aquifer properties.

Useful characteristics of a spring hydrograph include the ratio of peak discharge to discharge, and the form and rate of the recession curve. High ratios of peak discharge to baseflow are commonly observed in karst catchments with point recharge into well-developed conduit systems, whereas more subdued responses are typical of less karstified systems with diffuse recharge and poorly developed conduits, i.e. fractured networks. The analysis of spring hydrographs can further be improved by an analysis of time-series physicochemical parameters (i.e. electrical conductivity, temperature) (Rehrl and Birk, 2010).

Rehrl and Birk (2010) highlighted the fact that the spring hydrograph methods are based on fairly simplistic conceptual aquifer models, and the assumptions made need careful consideration. In light of this and the complex nature of the subsurface, a more reliable basis for the analysis of spring responses is process-based modelling of flow and transport processes, e.g. using a hybrid model such as CAVE for karst environments, or potentially a fracture model such as Frac3D. Rehrl and Birk (2010) distinguish two fundamentally different approaches: forward modelling and inverse modelling (Figure 5-39).

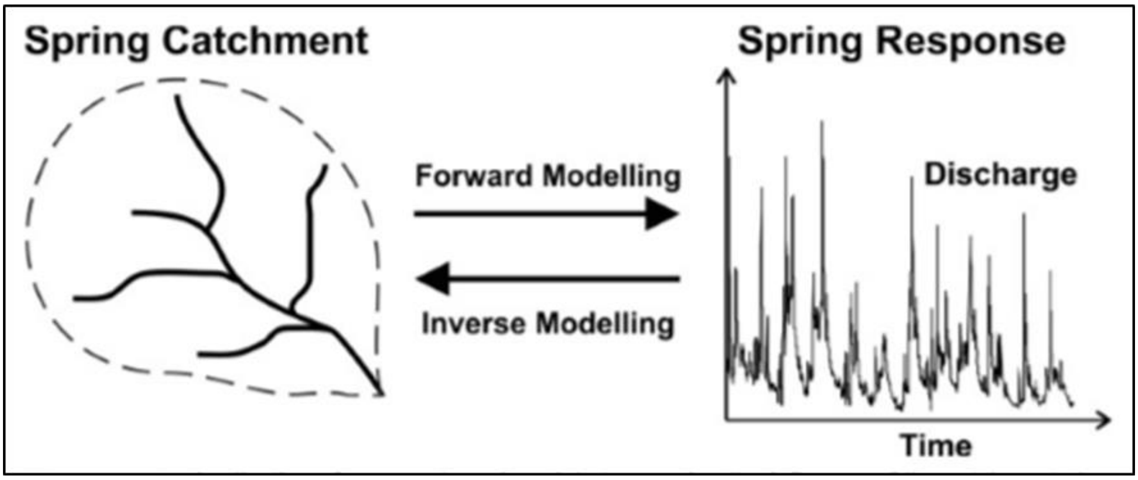


Figure 5-39: Application of process-based models to examine the influence of the catchment characteristics on spring responses (forward modelling) or to infer aquifer properties from spring responses (inverse modelling) (Rehrl and Birk, 2010)

Forward modelling uses hypothetical, but realistic model parameters to examine how spring responses depend on aquifer properties, such as conduit geometry. Forward modelling thus facilitates the identification of controlling processes and parameters. On the other hand, inverse modelling attempts to match measured spring responses by adjusting model parameters (model calibration). The resulting parameter values provide quantitative estimates of the corresponding aquifer properties (Rehrl and Birk, 2010).

Temporal spring discharge rates are not currently available for thermal springs in South Africa, yet this information might be held by the private owners of the springs. However, the DWS measures spring discharges from a number of cold springs, shown in Figure 5-29. Potentially, the currently available data could be used to gauge whether the spring hydrograph methods could be applied to South Africa's fractured aquifers. If the spring hydrographs are suitable for the fractured environment, temporal discharge rates from thermal springs could be collected fairly easily and used to characterise deep aquifers.

5.3.8.4 Summary

South Africa has a relatively large number of thermal springs, which currently form the most readily available source of information to characterise deep aquifer systems. Available physical and chemical information and characterisation are mostly found in individual, area-specific research papers. The thermal springs in South Africa have been analysed in most of the provinces, with limited information on the thermal springs of the Northern Cape.

Temporal spring discharge rates are not currently available for South Africa's thermal springs, but the DWS measures spring discharges from a number of cold springs. It was suggested that this information could be used to determine whether the spring hydrograph methods usually applied to karst environments would be applicable to South Africa's fractured aquifers.

Seeing that thermal springs are currently the most accessible means of characterising deep groundwater systems, these resources should be optimally utilised, starting with a national database and temporal discharge rates.

Based on the available information obtained from the literature study of South Africa's thermal springs, the characteristics of the deep aquifers from which the spring water originates are listed in Table 5-23.

5.4 CHARACTERISTICS OF DEEP AQUIFERS DERIVED FROM MINING

5.4.1 Introduction

The investigation of deep aquifers differs from the investigation of shallow aquifers in that access is more difficult and costly, especially in areas with no previous deep investigations. Using information from deep mines as a starting point to investigate deep aquifers is advantageous because direct access to the deep aquifers is provided by the shafts and exploration boreholes, while the costs are carried by the mines as part of their exploration and production programmes. Geohydrological information gathered at the mines may be extrapolated to characterise the deep aquifers in the unmined areas adjacent to the mine. A disadvantage of using geohydrological data from deep mines is the fact that the deep aquifers that are intersected by mining are likely to have been exposed to mining impacts. The observed aquifer conditions at the mine may therefore not be representative of the undisturbed aquifer conditions. However, the advantages of using mines to explore deep aquifers outweigh this disadvantage.

Table 5-23: Characterisation of the deep aquifer systems associated with thermal springs

Criteria	Description
Lithology	The rock units hosting the aquifers from which the thermal springs originate vary according to the location of the springs in South Africa. There is no single lithology associated with thermal spring occurrences, however the lithology would need to allow for fractures at depths. Competent lithologies tend to fault/fracture under stress and commonly form outcrops at the surface.
Occurrence	The thermal springs of South Africa are associated with deep geological structures, such as faults, folds and dykes. Thermal springs are found all over South Africa, but the majority are confined to a broad band (400 km wide) extending across more than half of the country: from Piketberg in the Western Cape through Kwa-Zulu-Natal, the Free State and Gauteng, up to the Soutpansberg in Limpopo Province. This belt is associated with areas of deformation, the Cape Fold Belt, Great Escarpment and the Limpopo Belt.
Physical dimensions	The physical dimensions of the aquifers, from which the thermal springs originate, vary according to the geomorphology of the area in which the springs occur, and the extent/connectedness of the fracture networks.
Aquifer type	Thermal springs in South Africa are associated with deep geological structures. The secondary aquifers are generally double porosity aquifers with fracture networks acting as the conduits of groundwater, while most of the storage occurs in the rock matrix.
Saturation level	The fact that thermal springs are associated with artesian aquifers implies that the aquifers are saturated and pressurised.
Heterogeneity and isotropy	No specific information on the heterogeneity and isotropy of the aquifer systems is available. However, all indications are that the aquifer systems are highly heterogeneous and anisotropic, which is characteristic of fractured systems.
Formation properties	The formation properties of the aquifers associated with thermal springs are expected to vary according to location in South Africa. Thermal springs in the Karoo Supergroup appear to originate from the more competent formations along deformation areas. The porosity of these formations is unlikely to exceed 5%, and could even be less at greater depths due to compaction.
Hydraulic parameters	Little information on the hydraulic properties of the aquifer systems associated with thermal springs is available. However, the observed flow rates at some of the springs suggest high permeabilities and transmissivities. Spring discharges could potentially be used to determine the hydraulic characteristics of deep aquifers.
Pressurisation	The aquifers from which thermal waters originate are by definition artesian, and hence under positive hydraulic pressure. These aquifers are confined.
Yield	Little information on the potential yield of the aquifer systems is available. However, some of the springs have flow rates in excess of 1 *l*/s and have been flowing since 1949 when first measured.
Groundwater quality	The quality of the groundwater from the thermal springs varies according to the geological formations forming the aquifers from which the thermal water originates. Generally, a Na-Cl-HCO_3 type of groundwater is associated with deep circulating groundwater.
Aquifer vulnerability and susceptibility	The great depths of the aquifers associated with thermal springs suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. Additionally, no seasonal variations in chemical composition are evident at select investigated thermal springs, which confirms that the source of the water is deep and unaffected by seasonal rainfall recharge.

There are more than 1,200 mines in South Africa. The most notable mines that are deeper than 300 m include the gold mines in the East, Central and West Rand, the platinum and chrome mines in the Bushveld Igneous Complex, the iron ore mines in the Northern Cape, the copper mines in Mpumalanga, the diamond mines in Limpopo, the Free State, Mpumalanga and the Northern Cape, base metals throughout the country, and the coal mines in the eastern provinces of the country. Groundwater inflows have been recorded at depths of approximately 1.6 km in some of the deep South African mines, confirming the presence of deep aquifer systems.

The mines themselves may be considered to be active, dynamic site investigations of the aquifers they penetrate. Dewatering operations at underground mines provide data on abstracted volumes of water and hydraulic head responses that may be used to estimate the hydraulic properties of the intersected aquifer systems. Mine dewatering may therefore be seen to be large pumping tests that are conducted over extended periods of time.

Apart from the geohydrological data that may be collected from deep mines, groundwater abstracted during dewatering, as well as groundwater that accumulates in the shafts of closed and abandoned mines, may in future augment the water supply to municipalities and communities. The groundwater from some closed mines is already being used for this purpose. Groundwater abstracted from the Musina Mine in Limpopo is used to supply water to the Musina Municipality, while groundwater from the Crocodile River Mine in the North West is used by market gardeners. As more mines close, the potential for using groundwater from the shafts for various applications, depending on groundwater quality, increases. Geohydrological data gathered at mines that are located close to points of water use will therefore contribute to an understanding of the deep aquifer systems that could have long-term benefits in terms of the sustainable use of groundwater for water supply.

5.4.2 Case studies

In this section, four deep mines in South Africa will be discussed as case studies to show examples of the geohydrological data on the deep aquifer systems that can be derived from deep mines. The investigations at these mines were conducted by KLM Consulting Services (KLM). KLM has obtained extensive experience over 27 years in the exploration, development and protection of deep sub-Saharan African aquifers, primarily for the mining industry, and has amassed detailed information on the deep aquifers. KLM interrogated its archives and selected five mines at which comprehensive data on deep aquifer systems is available. These are the following mines:

- The Finsch Mine in the Northern Cape
- The Orapa diamond mines in Botswana
- The Cullinan Mine near Pretoria
- The Palabora Mine in Mpumalanga

Only summaries of KLM’s investigations at these mines are given in this section (the complete KLM reports are available in electronic format).

5.4.2.1 Finsch Mine

Finsch Mine is located approximately 120 km northwest of Kimberley in the Northern Cape. The mine plant and headworks are located on top of the eastern escarpment of the Asbesberg Hills, which lies on the western edge of the Ghaap Plateau. The kimberlite pipe that was mined was discovered in the 1960s and mining began soon afterwards. South-north-west-east cross-sections through the Finsch Mine illustrate the topography of the area surrounding the mine (Figure 5-40). The mine is seen to occur near a local water divide with the topographic elevation decreasing to the south and north. Also shown in Figure 5-40 are the locations of the main dolerite dykes and the quarries relative to the mine. The kimberlite pipe that once formed a small pan is now a large open pit, 510 m deep, which is connected via old mining drifts to the underground tunnels that reach depths of 1.2 km below the surface. Further expansion of the underground workings to a depth of approximately 1.4 km is planned.

5.4.2.1.1 Geological setting

The Finsch kimberlite pipe intruded into the sedimentary succession of the Griqualand West Basin in the Precambrian sediments of the Ghaap Group, which dates back to approximately 2.5 billion years. The country rock comprises (from top to bottom) banded chert and ironstone, carbonaceous shale, limestone and dolomite. The banded ironstone is known to contain asbestos and tiger's eye. Passage beds form a transition between the banded ironstone and the dolomite. The country rock at the mine is a very thick sequence of massive dolomites, overlain by a thin sequence of passage beds and banded ironstone.

To the east of the mine on the Ghaap Plateau, the banded ironstone and passage beds have been eroded away. The exposed upper dolomite has developed into an elephant-skin karst pavement with numerous karstic features such as sinkholes, caves and grikes.

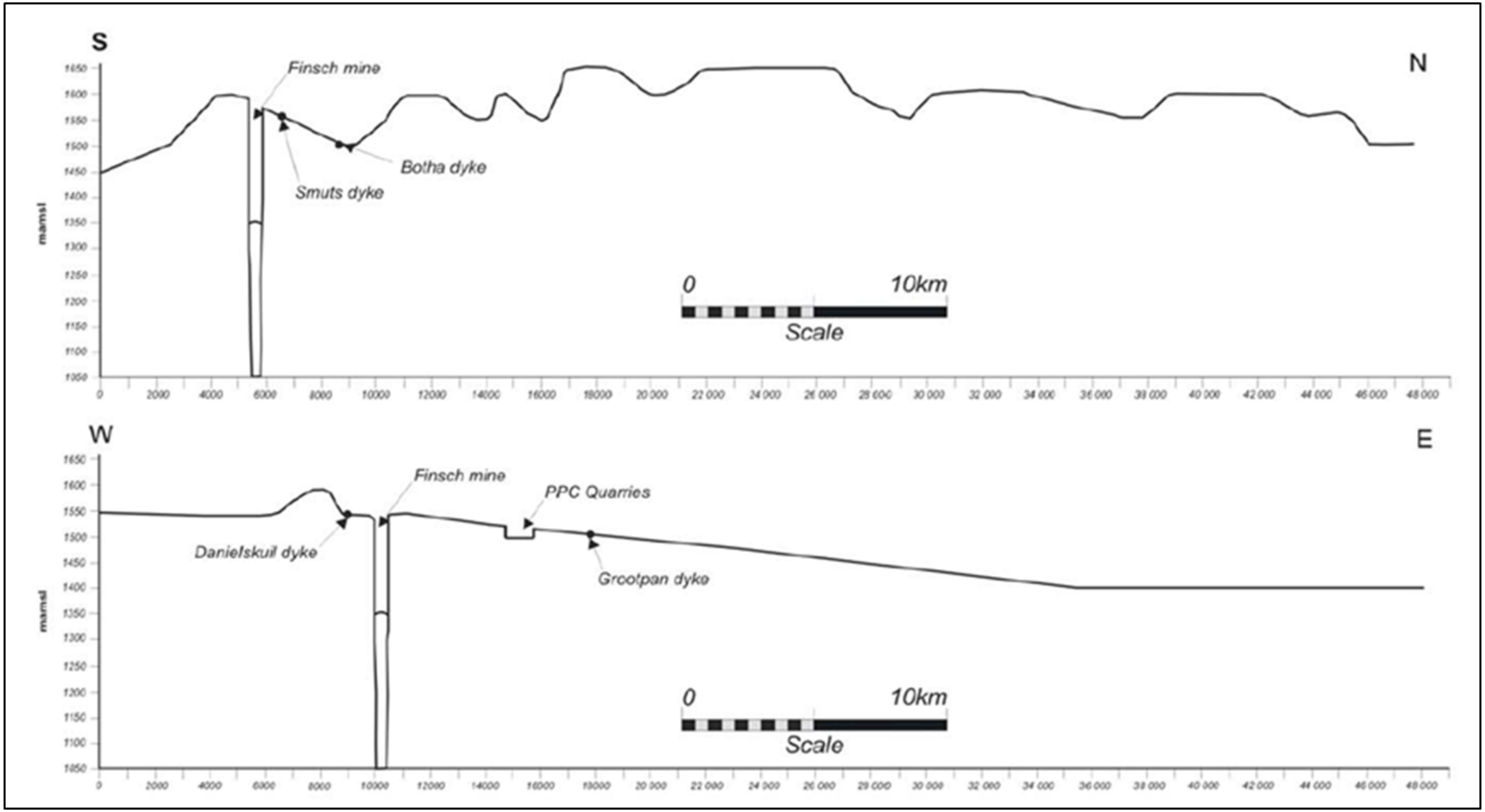


Figure 5-40: South-north and west-east cross-sections through the Finsch Mine, showing the topographical variations in the vicinity of the mine

The Wondergat, a very deep sinkhole of unknown depth, occurs some 60 km to the north of the mine. The Kuruman Eye, a permanent spring, occurs another 40 km to the north. This spring flows from the regional dolomite aquifer at a rate of approximately 7.3 million m^3 per annum (608 000 m^3 per month). The presence of cavities and voids as deep as 769 m, as well as the known springs, confirms that the mine is located within a regional aquifer. In the dolomite, groundwater is associated with bedding planes, chert- or silt-rich “dirty dolomite” and geological structures. The dolomite matrix itself has very low hydraulic conductivity. An understanding of the geohydrology of the dolomite aquifer therefore requires knowledge on the local and regional structures.

5.4.2.1.2 Geological structures

Structurally, Finsch Mine sits in the eastern limb of a north-northeast-trending synclinorium. In the plains below the Asbesberg Hills, the predominantly dolomitic strata of the Ghaap Group dip approximately 3° westwards towards the synclinal axis, but there is also a series of local fold structures with west-east-trending axes. The CGS estimated the thickness of the dolomites at 3,000 m. The primary dolomite is relatively impermeable, but deep, interconnected, water-bearing structures and near-surface karst development make the Ghaap dolomite a regionally significant aquifer.

Since groundwater flows more easily along tensional structures, the stress patterns for the region are of significance. Shearing is associated with compressional forces. Faults and fractures that are caused by shearing may give rise to zones of preferential flow and can influence the direction of groundwater flow. The *in-situ* stress measurements recorded in southern Africa up to depths of approximately 3,000 m show that the horizontal secondary principal stresses near the Finsch Mine trend approximately north-northwest-south-southeast (Figure 5-41). Based on the stress pattern, groundwater inflow to the Finsch Mine is expected to occur predominantly on north-northwest-south-southeast structures.

From a 1959 aerial photograph, three kimberlite dykes can be seen radiating outwards from the kimberlite pipe with strikes to the northeast, south-southwest and west. These dykes are referred to as the Smuts Dyke Group and have been mapped to depths greater than 1.3 km (Figure 5-42). The Danielskuil Dyke, striking south-southwest-north-northeast, is also prominent in the photograph. Two regional faults with south to north strikes are also visible (Rf2 and Rf3). Drainage from the Asbesberg occurs along deeply incised valleys.

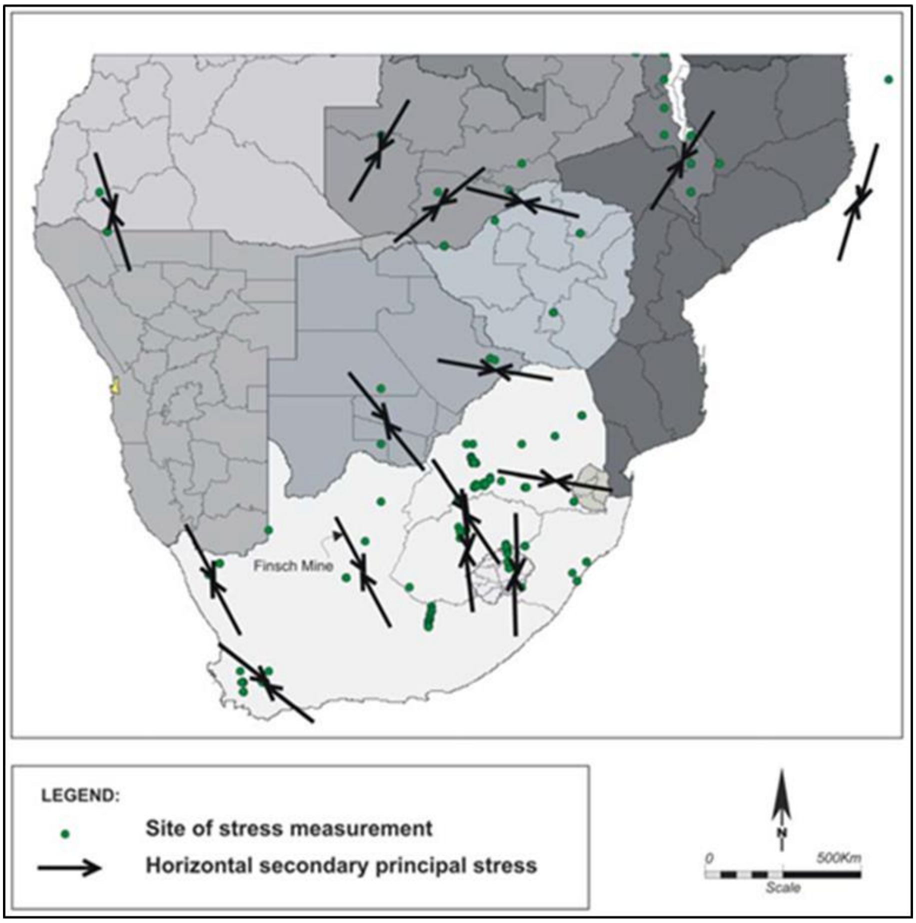


Figure 5-41: Orientation of the horizontal secondary principal stresses in southern Africa

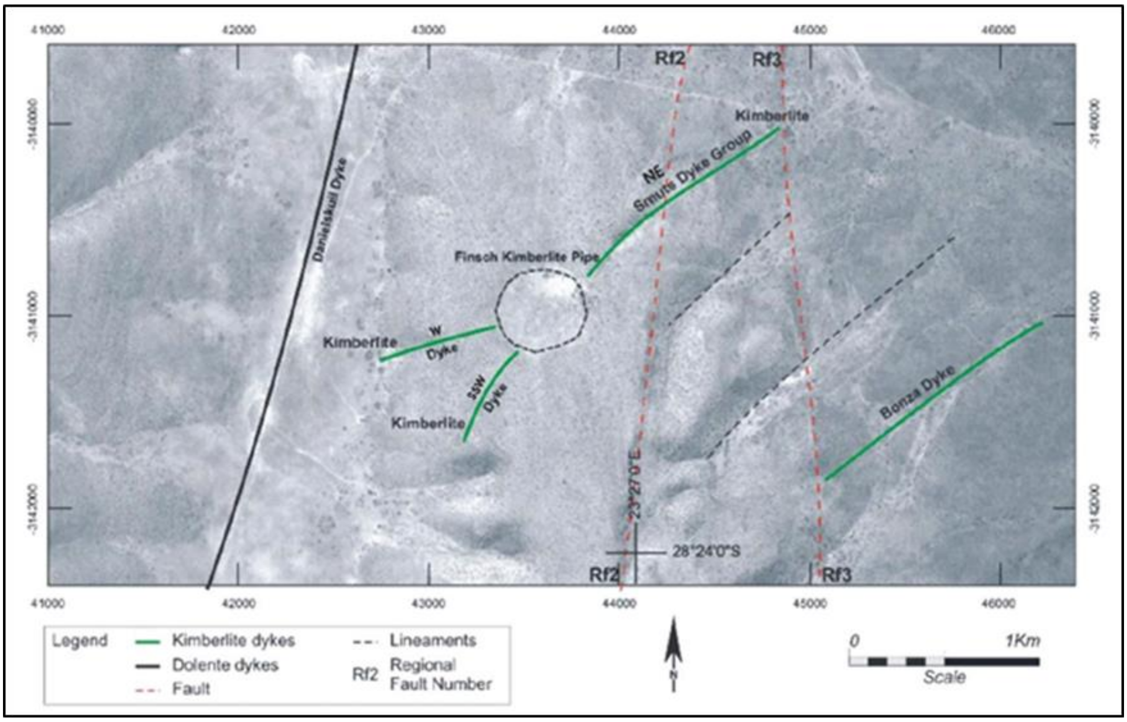


Figure 5-42: Aerial photograph (1959) of the area surrounding the Finsch Mine, showing the positions and orientations of prominent geological structures

The dominant structures are seen to be the regional faults and dolerite dykes that traverse the area in south-north to southwest-northeast directions and the kimberlite dykes that run southwest-northeast to west-southwest-east-northeast. The faults have normal throws that vary from a few metres to as much as 64 m. The southwest-northeast and west-southwest-east-northeast set of faults is intruded by the kimberlite pre-cursor dykes. The Danielskuil and Grootpan dolerite dykes are considered to be boundaries to the dolomite compartment, in which the Finsch Mine and PPC's limestone quarries are located. The two faults closest to the mine have south-southeast-north-northwest strikes. Because they are orthogonal to the principal horizontal stresses in the area, they may act as conduits for the preferential movement of groundwater. Figure 5-43 shows the structural interpretation against the surface geology in the vicinity of Finsch Mine.

The low intrinsic hydraulic conductivity of the Finsch dolomite and the high inflows to the mine indicate that groundwater movement is structurally controlled. Regional structures channel groundwater from the regional dolomitic aquifer towards the mine. Closer to the mine, the local structures and mining voids control the inflows to the mine. The structures in the open pit and underground workings were mapped and classified, and then examined to understand the relationship of the regional structures to groundwater movement. It is postulated that groundwater inflow to the Finsch Mine is controlled by both horizontal and vertical structures, forming a deep fractured and karst aquifer.

The horizontal and vertical water-bearing structures are linked by the kimberlite country rock contact, forming a lattice or scaffolding-type interconnection of conduits, all connected to a circular kimberlite contact drain. The mine workings (ramps and rim tunnels) also connect the horizontal and vertical water-bearing structures and facilitate drainage to the lowest points in the mine.

5.4.2.1.3 Geohydrological testing

Test pumping, packer testing and laboratory testing were performed as part of the geohydrological investigation at the Finsch Mine to calculate values for transmissivity (T), hydraulic conductivity (K) and storativity (S). Test pumping was conducted from two boreholes drilled from ground level and six boreholes drilled from 65 Level, 650 m below ground level. The results of the test pumping revealed both fracture flow and dual porosity flow. Although methods have been developed to analyse data from fractured and dual porosity aquifers, the data recorded at the Finch Mine was analysed using the Theis and Cooper-Jacob methods. The results of theses analyses are listed in Table 5-24.

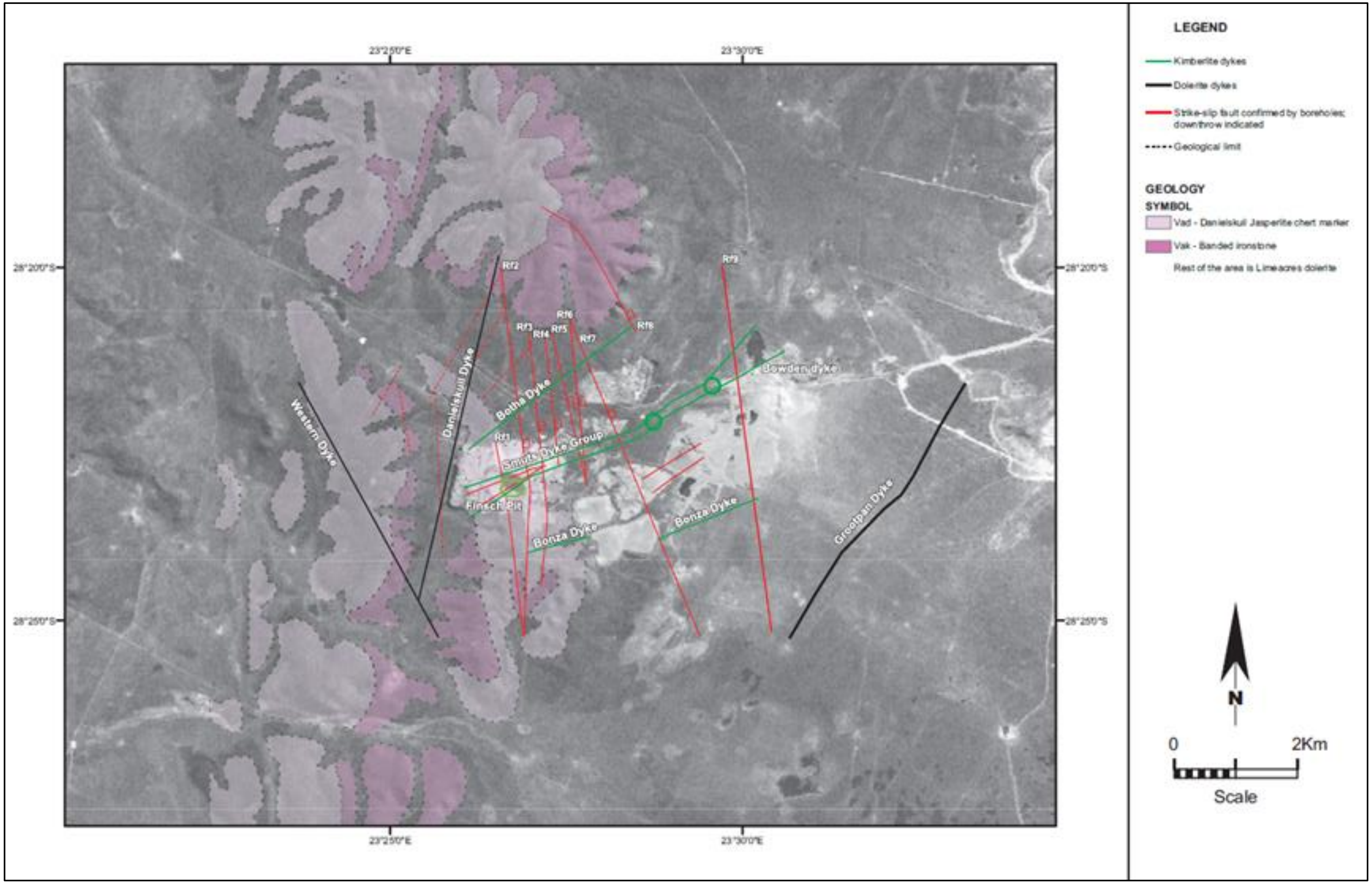


Figure 5-43: Surface geology and regional geological structures in the vicinity of the Finch Mine

Table 5-24: Results of the test pumping analysis boreholes at the Finsch Mine drilled from the 65 Level

#	Discharge rate (Q) (m^3/hr)	Drawdown (s) (m)	Transmissivity (T) (m^2/d)			Storativity (S)	Fracture depth (metres below 65 Level)	Aquifer response derivative
			Theis	Cooper-Jacob Drawdown	Cooper-Jacob Recovery			
65/173	28.8	163		1.4	1.3	$1x10^{-4}$	88.26-88.73 167-168	0.45
65/174	2.7	166	0.3	0.23	0.1	-	97.5-98.56 105.33-105.5	0.95
65/175	5.2	114	0.25	0.3	0.24	$6x10^{-7}$	108.25-135.3	0.29
65/176	43.2	65	5.5	5.6		$1x10^{-4}$ $5x10^{-4}$ $2x10^{-4}$ $1x10^{-4}$ $4x10^{-5}$ $8x10^{-4}$ $2x10^{-4}$ $8x10^{-4}$	64-65 86.1-89.1 113.8-125.8 129.1-135.6	0.95
65/177	4	178			0.3	-	128.1-133.2	>0.95
65/195	28.8	35	5.3	-	-	-	No core data	0.33

The transmissivities obtained from the analyses of the pumping tests performed on the boreholes intersecting the dolomite aquifer ranged from 0.1 to 5.6 m^2 per day. Two groups of transmissivities are evident: the low background transmissivity of the dolomite matrix and the higher transmissivity of the fractured dolomite. Two boreholes, 65/176 and 65/195, have the highest transmissivity values of 5.6 and 5.3 m^2 per day.

The low transmissivity values found for the other boreholes suggest that these boreholes intersect a very limited fracture system, with poor interconnection. However, all the boreholes on the western side of the rim tunnel, between 65/176 and 65/195, respond to the pumping of both boreholes 65/176 and 65/195. The radius of influence of the boreholes on the east and south of the rim tunnel is less than 25 m, indicating no interconnection and very low transmissivity. These boreholes are also located on the down-gradient side (in terms of the hydraulic head) of the pipe and are therefore in the hydraulic shadow.

The storativity of the dolomite below the 65 Level was calculated to be between 6×10^{-7} and 8×10^{-4} with an average of 1×10^{-4}, reflecting typically confined conditions. The confined status of the aquifer was confirmed by the sub-artesian hydraulic heads observed in all the boreholes. These results confirm the complexity of the dolomitic aquifer. High yields are only encountered where there is an intersection of vertical structures, where there is some connection with horizontal structures and on the up-gradient side of the pipe (in terms of the hydraulic head).

Following the test pumping of the boreholes drilled from the 65 Level, six deep exploration coreholes were drilled from the 65 Level to reach a depth of 1,000 m below ground level. These coreholes were packer tested and the results were used to identify water-bearing horizons and further characterise the hydraulic conductivity of the lower dolomite. Five horizontal coreholes were drilled and packer tested to define the extent of the zone of relaxation. Packer testing of the deep coreholes below the 65 Level gave a range hydraulic conductivity values from 1×10^{-5} to 2.28×10^{-1} m per day.

This shows that the five deep coreholes did not intersect any horizontal zones of increased hydraulic conductivity below the 65 Level. However, a black shale horizon within the Papkuil Formation may become a zone for water flow when overlying pressures are released.

The limited hydraulic tests performed on the kimberlite pipe itself suggest hydraulic conductivity below the 68 Level of 5.2×10^{-3} m per day. The heterogeneous nature of the kimberlite means that no single value obtained will be representative of the hydraulic conductivity of the pipe. Long-term test pumping with multiple observation piezometers would be required to obtain a defendable value for the hydraulic conductivity or to give a range of realistic values.

5.4.2.1.4 Hydrogeochemistry

A rigorous hydrogeochemical survey has not been conducted at Finsch Mine, but water samples have been collected for analysis by different departments at the mine since 1980. The samples that were analysed included water from surface pumping boreholes, water from underground seeps, flowing boreholes and pumped boreholes, as well as mine process water from the sumps. The sampling methods followed the recommended (unpreserved) procedure as outlined in the WRC's report TT54/92 (1992), and were analysed in laboratories in South Africa using methods recommended by SABS 11 to 1265 (SABS 241:1999).

The mine abstracts between 80,000 and 100,000 m^3 per month. The results of seepage mapping conducted in 2002 indicated that some 50% of the water seeping into the mine enters above the 51 Level, 510 m below ground level. The results of the geohydrochemical analyses conducted on groundwater samples from the mine showed that Finsch Mine has two main, but interconnected types of groundwater ingress. The first is from rainwater and near-surface groundwater, which flows in at approximately the 51 to 61 levels. Below the 62 Level, the inflow is predominantly upwelling from older water stored in the dolomite aquifer. Between these two zones, the mixing of groundwater occurs.

5.4.2.1.5 Discussion

The geohydrological data obtained from Finsch Mine confirmed that the dolomite on the Ghaap Plateau is a significant aquifer to a depth of at least 1.2 km. The values of the hydraulic parameters obtained from test pumping below 650 m below ground level (the 65 Level) are representative of deep aquifers. The rate of groundwater inflow (100,000 m^3 per month) measured since the 1980s is indicative of the long-term available yield from the deep aquifer system. However, exploitation of this aquifer will require accurate structural interpretation.

5.4.2.2 Orapa Diamond Mine, Botswana

From 1982 until recently, KLM was involved in groundwater exploration programmes to meet the water demands of the Orapa Diamond Mine in Central Botswana. This mine is located within the Kalahari Basin of the Karoo Supergroup. During the groundwater exploration programmes, boreholes were drilled to depths of 650 m below ground level. The aquifers that are intersected by these boreholes are also regionally significant in South Africa and the geohydrological information collected from these boreholes may provide insight into South Africa's deep Karoo aquifers. The distribution of the various Karoo basins that belong to the Karoo Supergroup in central and southern Africa is shown in Figure 5-44.

5.4.2.2.1 The Karoo Supergroup in Botswana

The Karoo Supergroup in Botswana has been divided into seven basins (Smith, 1984), as shown in Figure 5-45. The Orapa Mine is located within the Northern Belt of the Central Kalahari Sub-basin. The Karoo Supergroup covers approximately 80% of the country's surface area and is overlain by the Kalahari sediments that range in thickness from less than 1 m to as much as 200 m.

5.4.2.2.2 The Ntane Sandstone Aquifer

The Ntane Formation is the most productive aquifer in Botswana and has been exploited through several wellfields. This formation primarily comprises thick sequences of massive and bedded fine- to medium-grained sandstones (Modie, 2008). The Ntane Sandstone Aquifer also occurs at the Orapa Diamond Mine. Groundwater influx from this formation into the Orapa Diamond Mine and the nearby Letlhakane Diamond Mine amounts to approximately 38 000 m^3 per day. This volume of water has to be abstracted to allow mining to proceed.

There are currently six wellfields in the vicinity of the Orapa and Letlhakane diamond mines. These wellfields have 105 production boreholes. Analyses of pumping test data have indicated average transmissivities of 5 to 10 m^2 per day, while borehole yields range from 2 to 40 m^3 per hour (0.5 to 11 ℓ/s). However, in other wellfields that exploit the Ntane Sandstone Aquifer, yields in excess of 100 m^3 per day (28 ℓ/s) are not uncommon. The specific yield and specific storage of the aquifer has been estimated from numerical modelling at 0.001 and 5 x 10^{-5}, respectively. The water that is abstracted from wellfields is dominated by sodium and chloride, but bicarbonate is present in some waters.

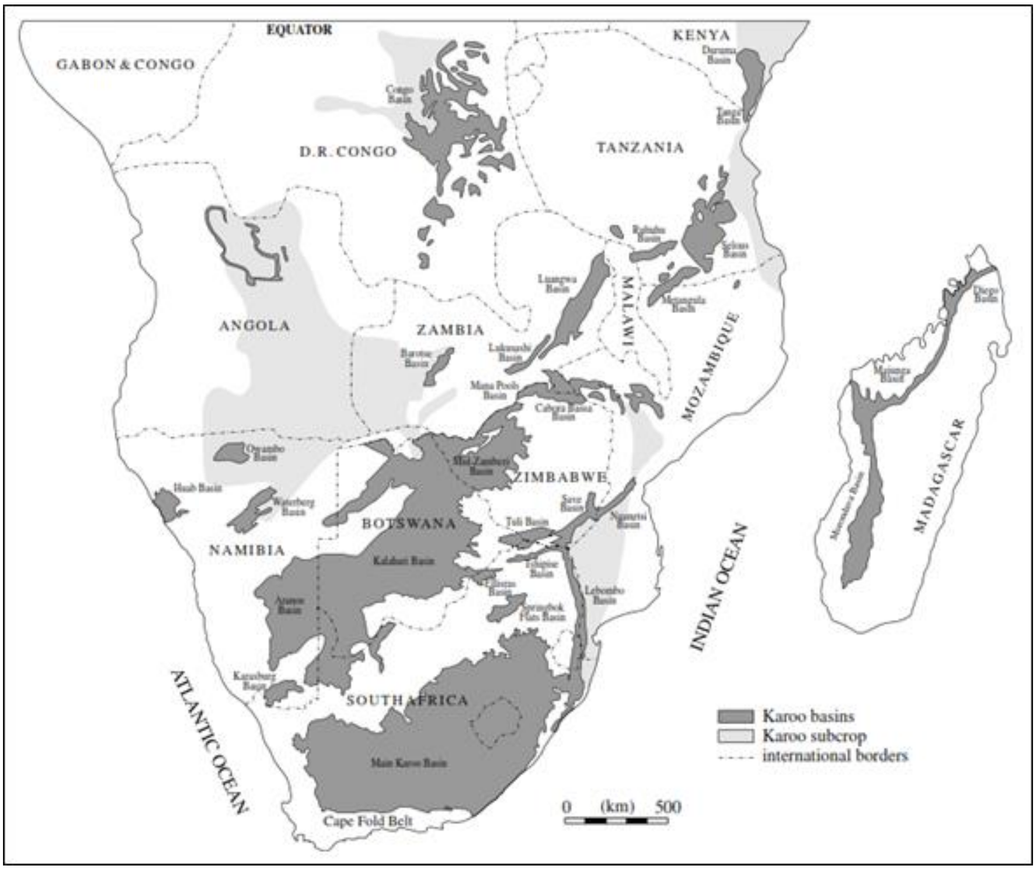


Figure 5-44: Distribution of the Karoo Supergroup in central and southern Africa (Catuneanu et al., 2005)

5.4.2.3 Cullinan Diamond Mine

The Cullinan Diamond Mine allows the study of deep aquifers since the underground mine reaches a maximum depth of approximately 1.2 km. This mine has had to deal with groundwater inflows for nearly 80 years. The mine is located east of Pretoria in metasediments. The proximity of the mine to densely populated areas means that water abstracted from the mine could be of importance for future water supply.

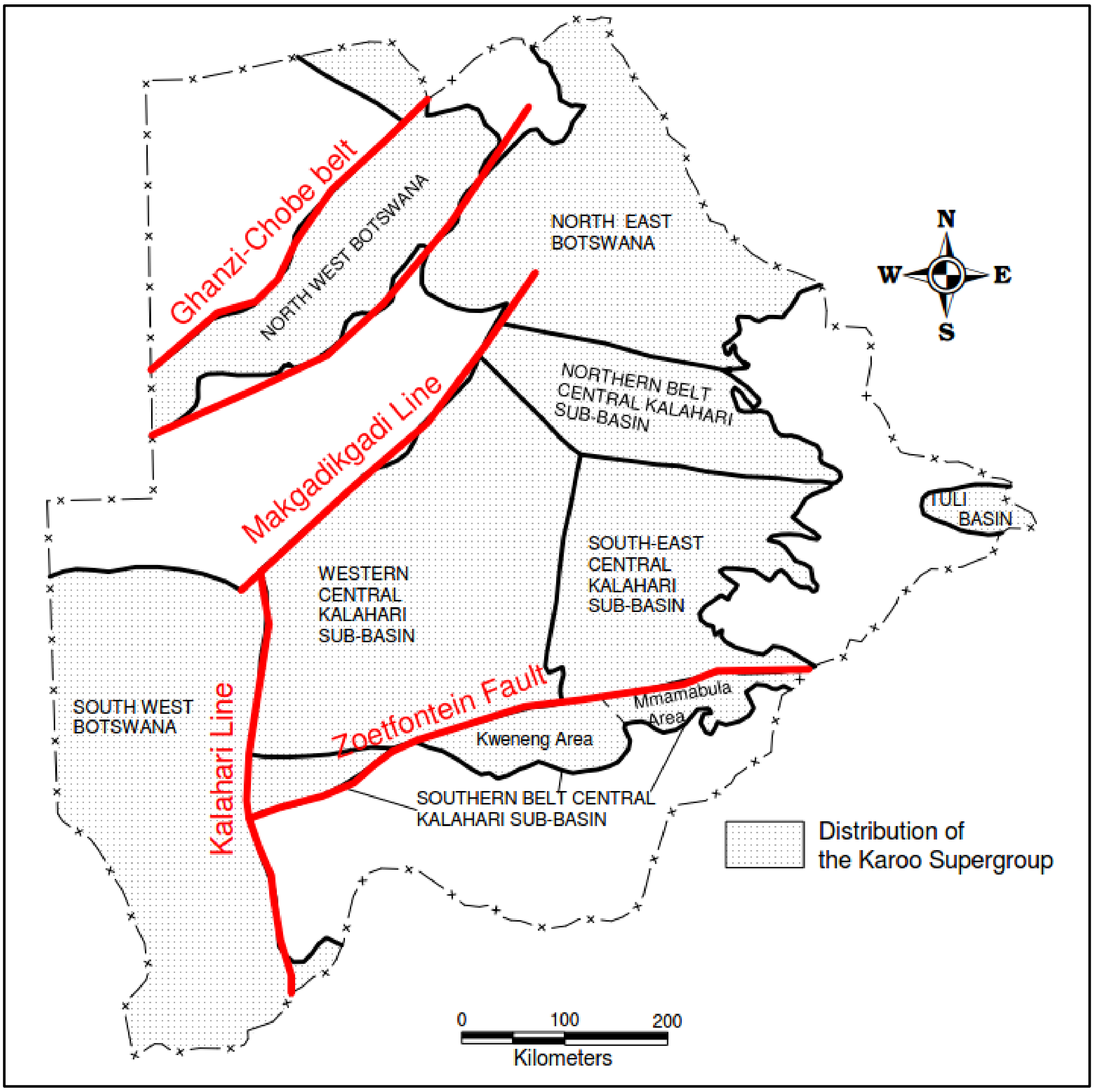


Figure 5-45: Distribution of the Karoo Supergroup in Botswana (Modie, 2008)

5.4.3.2.1 Geological setting

The surface geology in the vicinity of the Cullinan Diamond Mine is shown in Figure 5-46. The kimberlite pipe occurs in an area that is characterised by felsite and Waterberg quartzites. The felsite occurs in the form of a sill that has been tentatively correlated with the Rooiberg felsite, but could be a metasediment that has undergone felspathisation. The kimberlite pipe intruded approximatey 1,200 Ma ago and has been eroded by approximately 300 m.

A gabbro sill, with an average thickness of 71 m, intruded both the country rock and the kimberlite pipe. This sill has been dated at 1150 Ma. The upper contact of the sill is irregular and the kimberlite in contact with the sill has been metamorphosed in a zone with a thickness of 15 m. The sill has three well-defined joint sets, one sub-horizontal and two sub-vertical. The sill has been breached by mining.

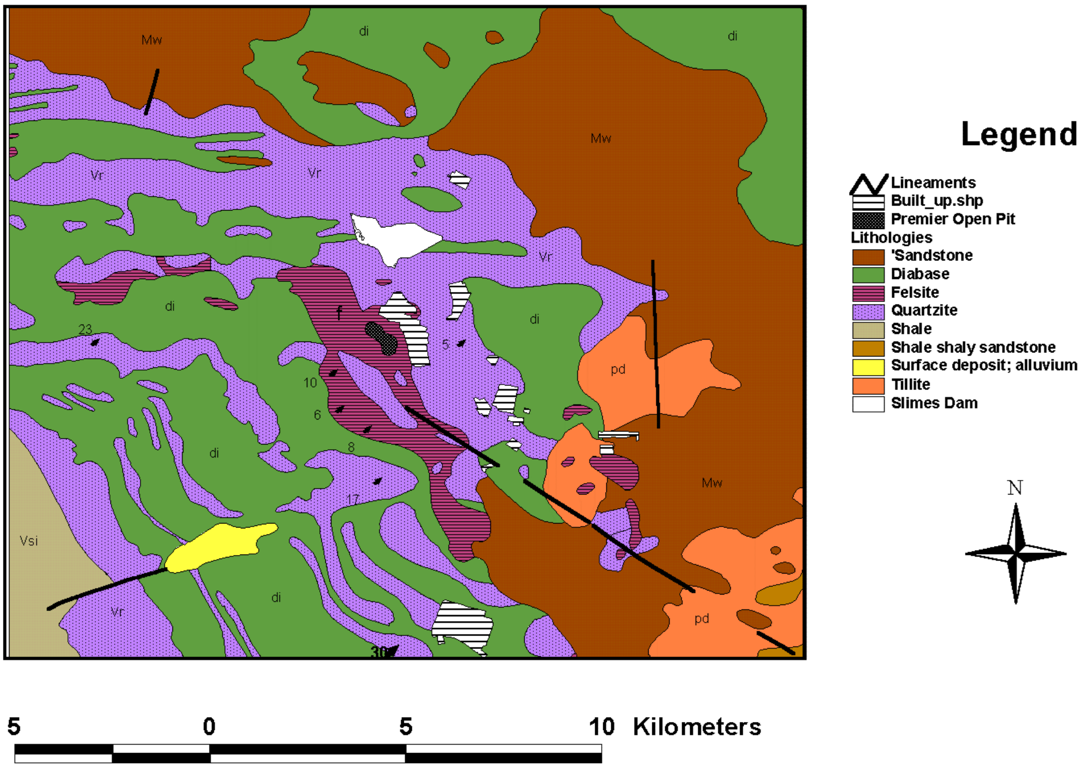


Figure 5-46: Geological setting of the Cullinan Diamond Mine

Below the gabbro sill, norites of the Main Zone of the Bushveld Igneous Complex are found. The norite unit is moderately to well jointed. Joints contain secondary minerals and are gouge-filled with soft to hard chlorite serpentine and tremolite.

Quartzites, shales and dolomites of the Transvaal Supergroup occur below the norites (below depths of approximately 670 m below ground level). The quartzite is fine to medium grained, white to pale-grey, very hard, fresh rock. The quartzite is generally very well jointed with joints being rough planar to rough undulating in nature. Joint surfaces generally contain no infilling, but chlorite infilling occasionally occurs. In places, the quartzite contains thin laminae of black quartzitic mudstone.

The meta-sediments consist of thinly interbedded hard, quartzite, quartzitic mudstone, dolomitic shale and medium-hard carbonate rocks such as calcite. The meta-sediments are very jointed, with serpentine and chlorite being the dominant joint infilling. The carbonate horizons are thinly interbedded with quartzitic mudstone.

On the surface, the kimberlite pipe has maximum dimensions of 860 x 400 m^2, giving a total area of 32 ha. Due to rim failure, the pit size is now 40 ha. The kimberlite contacts dip inward at about 85°. Exploration drilling suggests that the pipe bifurcates at approximately 1,000 m below ground level.

The contact zone between the kimberlite and country rock is well defined and poorly bonded. Movement on the contact has often been noted in tunnels.

5.4.2.3.2 Structural mapping and groundwater inflow

Five sub-vertical and two sub-horizontal joint sets have been identified at the Cullinan Mine, with the JS1, JS2 and JS6 sets being the most dominant. JS1 and JS6 trend south-north, while JS2 trends west-east. JS1 and JS2 can be traced into the kimberlite, suggesting that jointing took place after the emplacement of the kimberlite. The water inflow is not restricted to certain sets, indicating a highly interconnected network of joints. All shear zones and faults are associated with water seepage.

Jointing in the kimberlite is poorly developed and widely spaced. Persistent structural features control water seepage. Joints related to water inflow generally have a large aperture (average of approximately 2.4 cm) and have serpentine and chloride infill. The majority of inflows of water occurs at the roof zone directly above the rim tunnel intersections or from tunnel walls, 2 to 3 m from the corners.

The contact between the country rock and kimberlite acts as a conduit for water, particularly in mined-out areas and where collapse has taken place. Water ingress is found to decrease away from the kimberlite contact. Groundwater inflow decreases with depth and lower levels become progressively drier. In 1998, KLM examined wet ore passes and found that the wettest ore passes were those closest to the contact between the kimberlite and the country rock.

Level 568 is wet all around the ring tunnel, while the ring tunnel above is dry. This level could therefore represent the current position of the local water table (phreatic surface) in the country rock.

The current volume of groundwater inflow to the mine is approximately 39,900 m^3 per month. However, a numerical model has indicated that the groundwater inflow could increase to an average volume of 47,800 m^3 per month when mining reaches a depth of 1,080 m below ground level.

5.4.2.3.3 Packer test results

The contacts between the kimberlite pipe and the country rock act as significant conduits for groundwater flow. Packer tests were therefore performed on available underground boreholes to determine the hydraulic conductivities of these contacts. Since these boreholes were drilled to determine the position of the contact, they terminate shortly after penetrating the contact. The packer tests were performed at a depth of 763 m below ground level at five sites. The results of the packer tests are summarised in Table 5-25, while the results of the packer tests are presented in Table 5-26.

Table 5-25: Boreholes used for packer tests (all drilled from 763 m below ground level)

Borehole #	Depth (m)	Initial flow rate (L/min)	Test Target
Site 1 - 25 Bypass			
PM 458	397	40	Fracture Zones in country rock (meta-sediments)
PM 459	224	5	
PM 462	262	20	
Site 2 - Return Airways			
PM 460	119	1.2	Kimberlite / country rock (meta-sediments) contact and fractures; water intersected at 74 m in PM 460
PM 461	226	0	
Site 3 – NW			
PM 463	265	0.1	Kimberlite / country rock (meta-sediments) contact and fractures
PM 464	311.7	6.67	
Site 4 - NE			
468	359	0.37	Fractures Zones in country rock (meta-sediments), water intersected at 76m & 85m in PM 471 and 93m in PM 473.
469	399	2.73	
471	85	21.43	
473	374	17.64	
Site 5 - Central			
PM 465	Blocked at 1.5	Seepage	Fracture zones in country rock (meta-sediments)
PM 466	452	Seepage	

The results of the packer test analyses reveal K-values in the order of 10^{-4} to 10^{-6} m per day. However, many of these estimates are not considered accurate as some of the boreholes on which the tests were performed showed interconnectivity, while other boreholes were blocked at specific depths. The hydraulic conductivities listed in Table 5-26 therefore represent only first estimates of the hydraulic conductivities of the country rock and contact zones at depths greater than 763 m below ground level. These results represent the first tests of hydraulic conductivity at such large depths and allow insight into the hydraulic properties of the deeper aquifer systems at the mine. Groundwater influx into the mine from these deep fractured aquifers has been ongoing for more than 20 years.

Table 5-26: Results of the packer tests

Borehole #	Interval (m) (packer to hole bottom)	Geology	*K* (m/day)
Site 1 - 25 Bypass			
PM 458	95 - 397 200 - 397	Fractures in meta-sediments	1.59×10^{-4} 8.79×10^{-4}
Site 2 - Return Airways			
PM 461	148 - 232.10	Norite, shale, igneous rock and kimberlite contact	9.52×10^{-5}
Site 3 – NW			
PM 464	98 - 311.7 148 - 311.7 198 - 311.7	Norite, meta-sediments, dyke	2.93×10^{-5} 3.20×10^{-5} 4.15×10^{-5}
Site 4 - NE			
PM 463	98 - 265	Norite, kimberlite, dyke, shale	5.51×10^{-6}
Site 5 - Central			
PM 471	50 - 85 50 - 85	No log	6.97×10^{-4} 6.79×10^{-4}
PM 466	98 - 452 50 - 452	Norite, meta sediments	4.53×10^{-6} 2.61×10^{-6}
PM 473	60 - 374 50 - 374 50 - 374	No log	9.53×10^{-4} 5.94×10^{-5} 5.78×10^{-5}

5.4.2.3.4 Conceptual geohydrological model

From the available geological and geohydrological data, a conceptual geohydrological model of the Cullinan Mine was constructed. This conceptual model is shown in Figure 5-47. The conceptual model shows the possible movement of water into the mine and the different geologic units that are intersected by mining. Estimated hydraulic conductivities have been assigned to the geological units, but at this stage, there is insufficient knowledge to determine the vertical and horizontal hydraulic conductivities (K_v and K_h) of the different units.

Structural features, both natural and induced by mining, control the groundwater inflow to the mine. The contact between the country rock and the kimberlite pipe is water-bearing. Water ingress decreases with distance from the contact. All shear zones and east-west-trending faults are water bearing, and joints with apertures larger than 2.4 cm tend to be water bearing.

The mine appears to be drier with depth, although no flow measurements have been recorded for individual levels. The upper levels of the mine have been dewatered and the 568 m level appears to be the lowest level of the dewatered mine. Water intersected in fissures below the 568 m level appears to be confined. Water flowing through fissures above the 568 m level appears to be moving downwards through the formation.

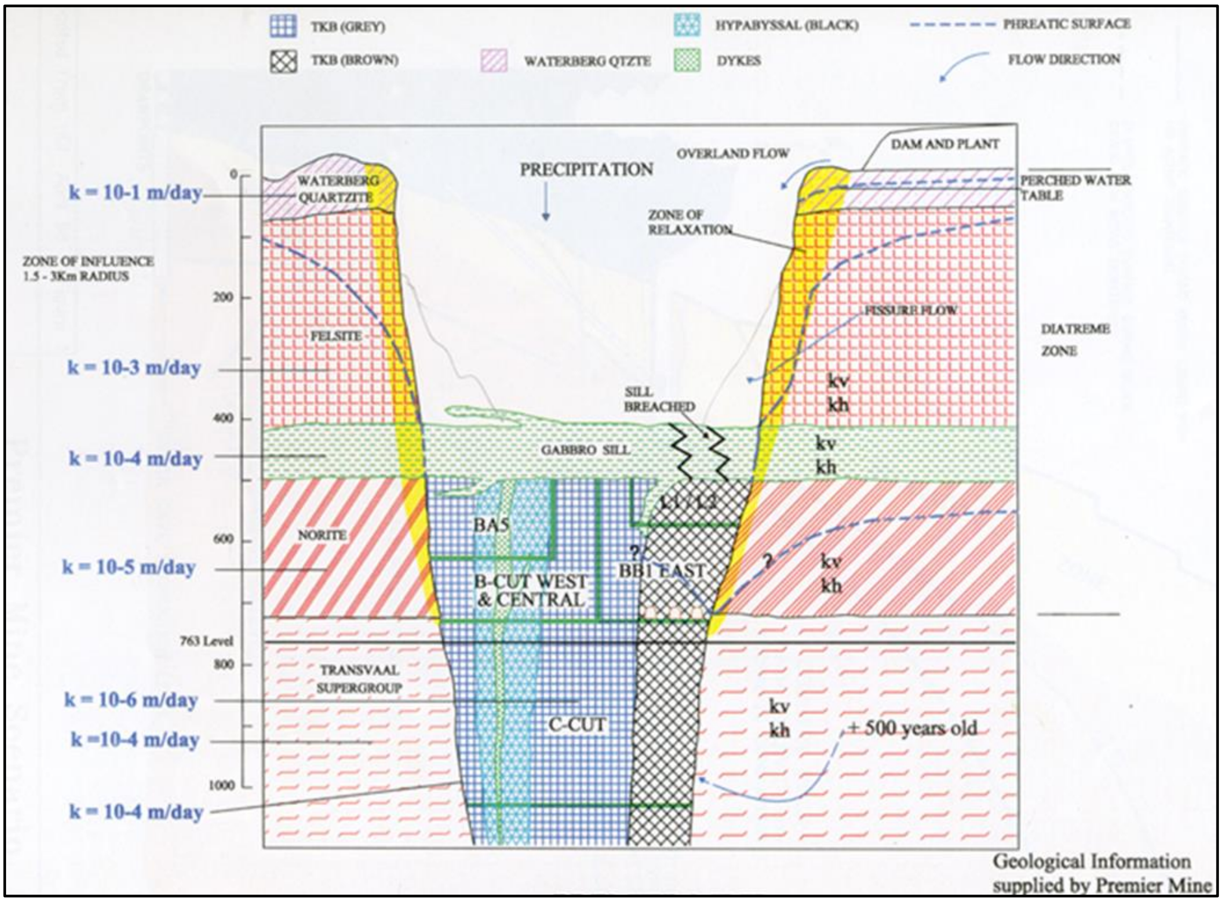


Figure 5-47: Conceptual geohydrological model of the Cullinan Diamond Mine

5.4.2.3.5 Discussion

The geohydrological investigations conducted at Cullinan Diamond Mine yielded information on the structures that control groundwater ingress to the mine. Furthermore, packer tests conducted at depths greater than 763 m below ground level allowed first estimates of the hydraulic properties of the deep fractured aquifer systems. This improved understanding of the deep aquifer system could, in future, be of great benefit for the sustainable use of groundwater abstracted from the mine for the municipal water supply.

5.4.2.4 Palabora Copper Mine

The Palabora Copper Mine, located in Mpumalanga, is another example of an open-pit mine that developed into an underground mine. The mine was started in the 1960s, reached its limit as an open-pit mine in the 1980s and was developed as a block cave mine to a depth of approximately 1.2 km below the surface. This mine has kept records of the aquifers intersected by both open-cast and underground mining.

5.4.2.4.1 Geological setting

The Palabora Copper Mine occurs within rocks of the Phalaborwa Igneous Complex, which was emplaced into the granite gneiss country rock approximately 2 billion years ago. The complex is concentrically zoned from carbonatite at the centre through foskorite and different phases of pyroxenite on the outer margins. Copper mineralisation predominantly occurs within the carbonatite, but extends into the foskorite. The carbonatite host rock is predominantly composed of calcite and magnetite with lesser apatite, while the foskorite host rock predominantly consists of olivine, magnetite and apatite with lesser calcite.

A number of unmineralised dolerite and other dykes cut through the igneous complex. These dykes predominantly have southwest-northeast strikes (Figure 5-48). Magnetic lineaments with a similar strike also occur in the vicinity of the complex and are in all likelihood due to the presence of dykes that occur at depth. No major fault zones in the immediate vicinity of the mine are indicated on the 1:250 000 geological maps. However, minor fault zones are known to occur near the mine.

5.4.2.4.2 Aquifers

Drilling and testing have confirmed a semi-confined aquifer system that can generally be divided into four aquifer zones:

- An upper weathered aquifer zone (0 to 15 m below ground level)
- A fractured permeable aquifer horizon (15 to 25 m below ground level)
- A fresh to slightly fractured aquifer zone (25 to 180 ms below ground level)
- An unweathered, slightly fractured zone that extends to a depth of approximately 1.2 km (granite gneiss)

These four aquifer zones are considered to be present in both host rock types, but with different weathering and fracturing depths. From the results of hydraulic tests performed on boreholes intersecting the different aquifer zones, estimates were obtained of the hydraulic parameters of the different units. The ranges of the hydraulic parameters for the aquifer zones are shown in Table 5-27. No estimates of the hydraulic parameters of the deep, unweathered fractured aquifer are currently available. Although it is known that very little groundwater flow occurs at depth, individual water-bearing fractures have been intersected at depth. One such fracture occurs at a depth of 1,350 m below ground level and has had a consistent flow of 2,000 ℓ per hour since March 2013. This fracture occurs in a corehole drilled to a depth of 1,600 m below ground level.

Table 5-27: Hydraulic parameters of the different aquifer zones at Palabora Copper Mine

Aquifer Zone	Granite Gneiss		Pyroxenite		Dolerite		Dolerite Contact Zone		Faults	
Hydraulic parameter	T (m^2/day)	S	T (m^2/day)	S	T (m^2/day)	S	T (m^2/day)	S	T (m^2/day)	S
Upper Weathered Aquifer	0.15-1.5	5.3×10^{-4}	1.5	5.3×10^{-4}	0.15	5.3×10^{-4}	3-60	5.3×10^{-4}	0.6-60	-
Fractured Permeable Aquifer	20	8×10^{-4}	75	8×10^{-4}	0.1	8×10^{-4}	2-40	8×10^{-4}	0.4-40	-
Fresh to Slightly Fractured Aquifer	0.03	5.2×10^{-5}	0.03	5.2×10^{-5}	0.02	5.2×10^{-5}	8	5.2×10^{-5}	6-600	-

5.4.2.4.3 Conceptual geohydrological model

The conceptual geohydrological model of Palabora Copper Mine is shown in Figure 5-48. The hydraulic parameters listed in Table 5-27 were assigned to the various geological units of the conceptual model. Sub-vertical dolerite dykes in both the pyroxenite and granite gneiss have very low hydraulic conductivities at depth, but are associated with higher hydraulic conductivities near the surface due to weathering.

5.4.2.4.4 Discussion

The Palabora Copper Mine is an example of well-documented geohydrological investigations at a mine, complete with drilling logs, information on groundwater strikes and flow rates that prove that there are water strikes in fractured metasedimentary rocks to depths of at least 1,350 m below ground level. The water-bearing fractures were intersected prior to mining and are therefore not man-made. Due to the relatively low observed flow rates from these fractures, it is unlikely that deep drilling from the surface would be used to target the deep aquifer systems. However, after mine closure, these types of inflows could be used as a permanent water supply that is accessed via the mine workings.

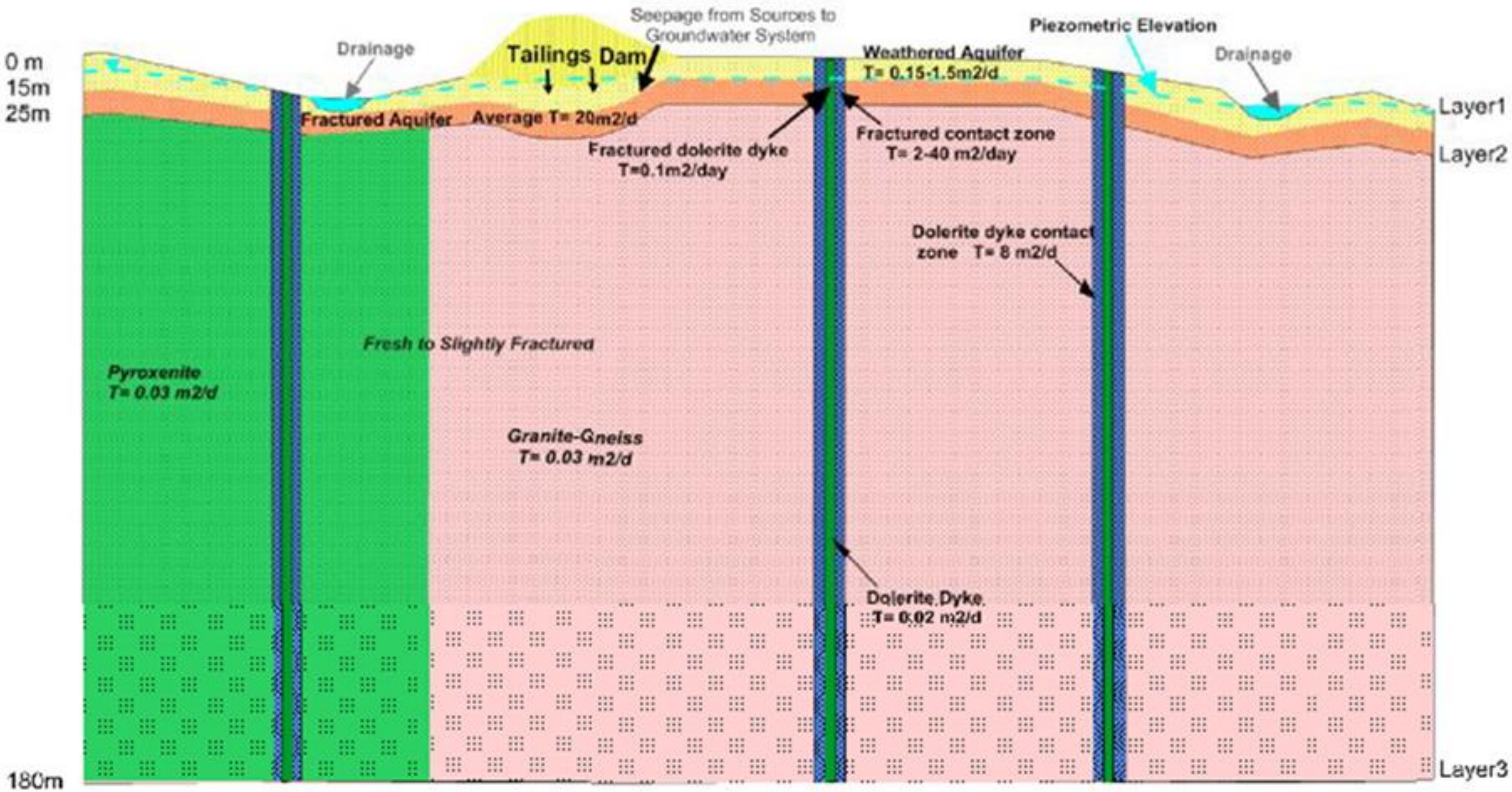


Figure 5-48: Schematic cross-section through the Palabora Copper Mine, illustrating the conceptual geohydrological model of the mine

5.5 CHARACTERISTICS OF DEEP AQUIFERS DERIVED FROM THE NATIONAL GROUNDWATER ARCHIVE

5.5.1 Introduction

The NGA is a web-enabled database that is managed by the DWS. It allows the capture, viewing, extraction and modification of groundwater-related data. The database was developed as part of the DWS's obligation to manage and develop South Africa's water resources (including groundwater) in a sustainable and equitable manner.

A number of data fields are available in the NGA to capture groundwater data. These fields include the following:

- Geosite information
- Lithology
- Water levels
- Discharge rate
- Field measurements
- Depth and diameter
- Water strike
- Downhole geophysics
- Yield tests

Many of the data fields allow the capture of data that may be used to gain insight into the characteristics of the aquifer systems that are intersected by these boreholes. Under these fields, different types of data may be captured. With the aim of characterising deep aquifer systems, the data fields and data types listed in Table 5-28 were considered relevant to the current study.

5.5.2 Data from the deep boreholes listed in the National Groundwater Archive

All the available data for the data fields and data types listed in Table 5-28 were extracted from the NGA for boreholes with depths exceeding 300 m. Table 5-29 lists the data extracted from the NGA for 31 deep boreholes (the location of these boreholes is shown in Figure 5-49). From Table 5-29, one can see that very limited information relevant to deep aquifer systems has been captured in the NGA.

Table 5-28: Fields and data types in the National Groundwater Archive deemed relevant for the characterisation of intersected aquifer systems

Field	Data Type	Field	Data Type
Geosite Information	Geomorphology	**Pumping Test Details**	Transmissivity
	Taste of Water		Storativity
Water levels	Water Levels		Hydraulic Conductivity
Abstraction	Quantity		Water Quality Class
Discharge Rate	Discharge Rate	**Yield Tests**	Test Type
	Discharge Type		Static Water Level
Field Measurements	Measurement Depth		Transmissivity
	Electrical Conductivity		Storativity
	pH		Hydraulic Conductivity
	Temperature	**Lithology**	Depth to Top
	HCO_3		Depth to Bottom
Depth and Diameter	Depth to Bottom		Formation Type
Piezometer	Depth to Top		Degree of Weathering
	Depth to Bottom		Degree of Fracturing
	Piezometer Height		
Water Strike	Water Strike Type		
	Depth to Top		
	Depth to Bottom		
	Total Blow Yield Value		

The electrical conductivity values are seen to range between 5 and 229 mS/m, indicating that salt concentrations in the deep groundwater are generally low enough not to be associated with health risks if ingested. Boreholes with electrical conductivity values higher than 70 mS/m may, however, have a salty taste. The pH values are seen to range between 4.6 and 9.66. Four boreholes (40142, 40147, 40148 and 40150) display acidic conditions with pH values ranging from 4.6 to 5.33. Since no information is available on the lithologies intersected by these boreholes or the history of the site where the boreholes are located, the reasons for the acidic conditions are currently unknown. The reason for the alkaline conditions at borehole 3325DC00052 is similarly unknown.

The water strikes in the deep boreholes occurred at depths ranging from 310 to 810 m below ground level in different lithologies. Some water strikes appear to be associated with igneous intrusions (diabase, dolerite), while others occurred in the absence of such intrusions. Blow yields ranging from 0.0002 to 34 ℓ/s were reported for the different boreholes. The highest blow yield was reported for a borehole drilled in dolomite that is intersected by diabase intrusions.

Table 5-29: Data relevant to the deep aquifer systems extracted from the National Groundwater Archive

Site identifier	Latitude (°S)	Longitude (°E)	Depth (m)	EC (mS/m)	pH	Temp (°C)	HCO_3 (mg/L)	Water strikes (mbgl)	Blow-yield (L/s)	Lithology
40142	-32.39523	18.95916	801	13	5.33	20.9				
40145	-32.14438	18.52958	800	186	6.71	21.2		480		
40147	-32.56589	19.06047	314	5	5.19	22.5				
40148	-32.55948	19.05910	350	8.5	5.3	21.4				
40150	-32.56328	19.05568	350	11	4.6	19.9				
037672A	-26.08444	28.54081	351					350	34	Dolomite, diabase
2327DC00073	-23.76831	27.50859	600					400	2.5	Sandstone
2327DD00071	-23.99213	27.98310	900					750	0.33	Quartzite
2623BC00011	-26.38793	23.66283	382.52					310.9	0.6	Sandstone, diabase
2627AB00087	-26.09915	27.37191	306.32					304.8	0.3	Chert, dolomite, shale
2628AA00176	-26.20611	28.04831	750					690	0.46	
2628AA00178	-26.20611	28.04830	900					810	1.32	
2721CB00005	-27.50871	21.26877	546					349.61 396 534	0.0003	Granite, limestone, quartzite, sandstone, shale, tillite
2721CD00021	-27.82594	21.33265	700					440		Granite, sandstone
2731DB00098	-27.71608	31.98313	480					360	0.5	Dolerite
2822BA00065	-28.07591	22.64159	999					730	0.18	Quartzite, shale
2830AA00011	-28.16790	30.24696	500					370	0.31	Dolerite, shale
2917CD00036	-29.85707	17.34914	353					310	0.0002	Granite
3119AB00025	-31.05030	19.29925	401					332		Dolerite, shale
3122AB00021	-31.07584	22.39940	600					330	0.57	Dolerite
3322AD00244	-33.45382	22.40917	420					350	1.3	
3325CD00138	-33.97740	25.36593	640					320	0.38	Sandstone
3325DB00030	-33.62878	25.77568	488					423.67	0.4	Sandstone, shale
3325DC00039	-33.77909	25.60275	373.93	229	6.35	28.9				Sandstone, shale
3325DC00052	-33.78563	25.62567	369	44	9.66	20.4			0.5	
BG00099	-33.81001	19.07955	305	7	6.6					
C1B3	-33.73433	22.27935	608	22.8	8.2					
GZ00029	-33.73441	22.27866	715	24.4		24.4				
GZ00417	-33.33242	22.53396	300	135						
H26-0439	-22.96032	29.78314	340			25.7				
QA2	-32.42630	22.57215	805	83.1	7.1		283.2			

Apart from the data listed in Table 5-29, data on the blow yields of another 519 deep boreholes are listed in the NGA. Unfortunately, no information is available on the depths at which water was struck in these boreholes. It is therefore possible that the reported blow yields relate to water strikes that occurred within the first 300 m of the boreholes. The number of boreholes with specific blow yields is listed in Table 5-30 (and shown graphically in Figure 5-50) against the depths of the boreholes. Some 61% of the boreholes have reported blow yields lower than 1 ℓ/s, while 79% have reported blow yields lower than 2 ℓ/s. Twenty-four of the 550 boreholes have blow yields greater than 5 ℓ/s.

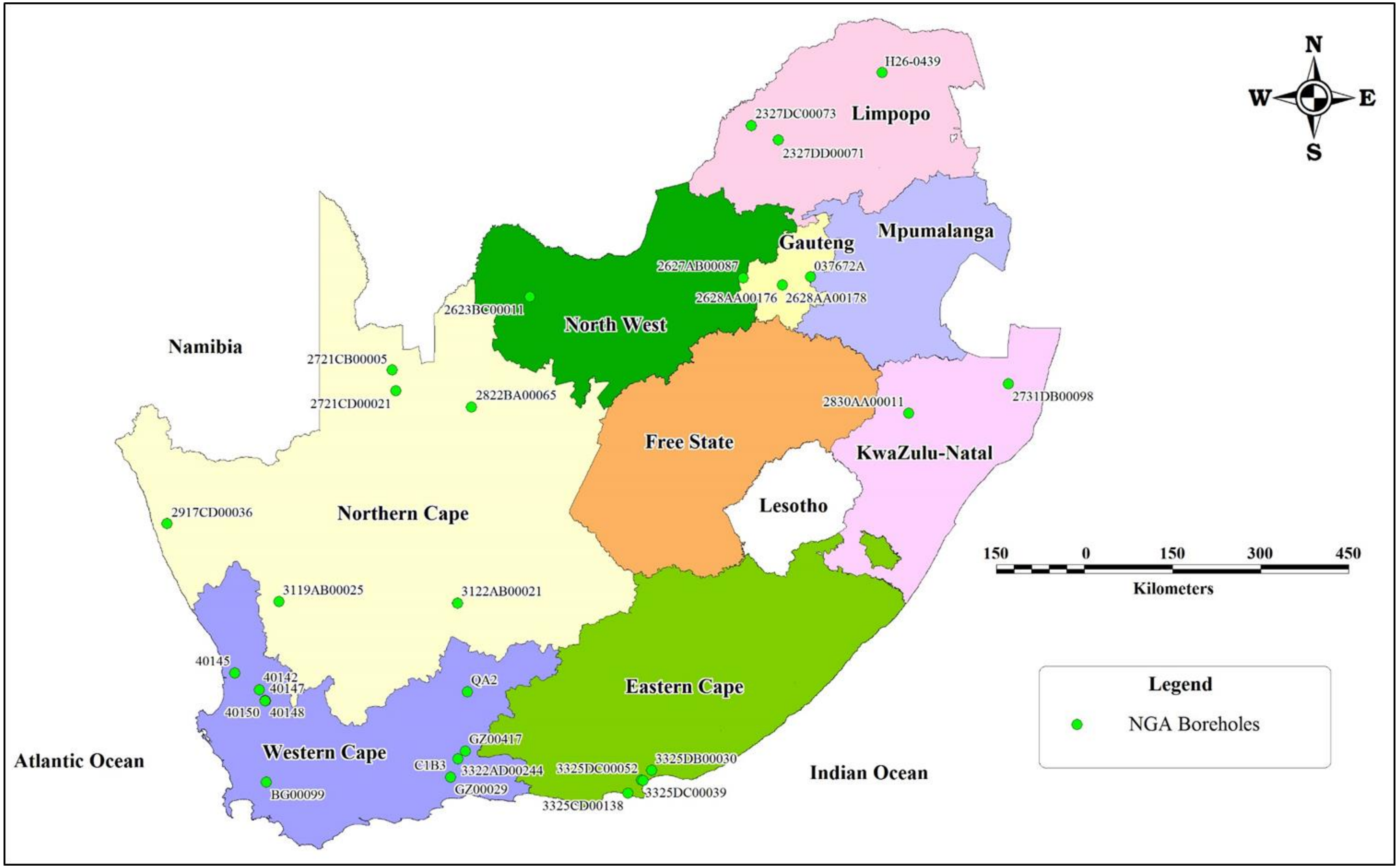


Figure 5-49: Location of the deep boreholes in the National Groundwater Archive for which information on deep aquifer conditions is available

Table 5-30: Number of boreholes with specific total blow yields

Borehole depth (m)	Total blow-yield (L/s)									Total
	0.00-0.99	1.00-1.99	2.00-2.99	3.00-3.99	4.00-4.99	5.00-9.99	10.00-19.99	20.00-29.99	30+	
300-399	75	20	5	3	0	1	2	0	1	**107**
400-499	57	11	7	5	3	1	1	1	1	**87**
500-599	28	12	6	7	0	1	1	0	1	**56**
600-699	41	13	7	4	2	3	1	0	1	**72**
700-799	41	9	8	8	0	0	0	0	0	**66**
800-899	42	25	5	7	2	2	0	1	1	**85**
900+	49	13	6	5	0	3	1	0	0	**77**
Total	**333**	**103**	**44**	**39**	**7**	**11**	**6**	**2**	**5**	**550**

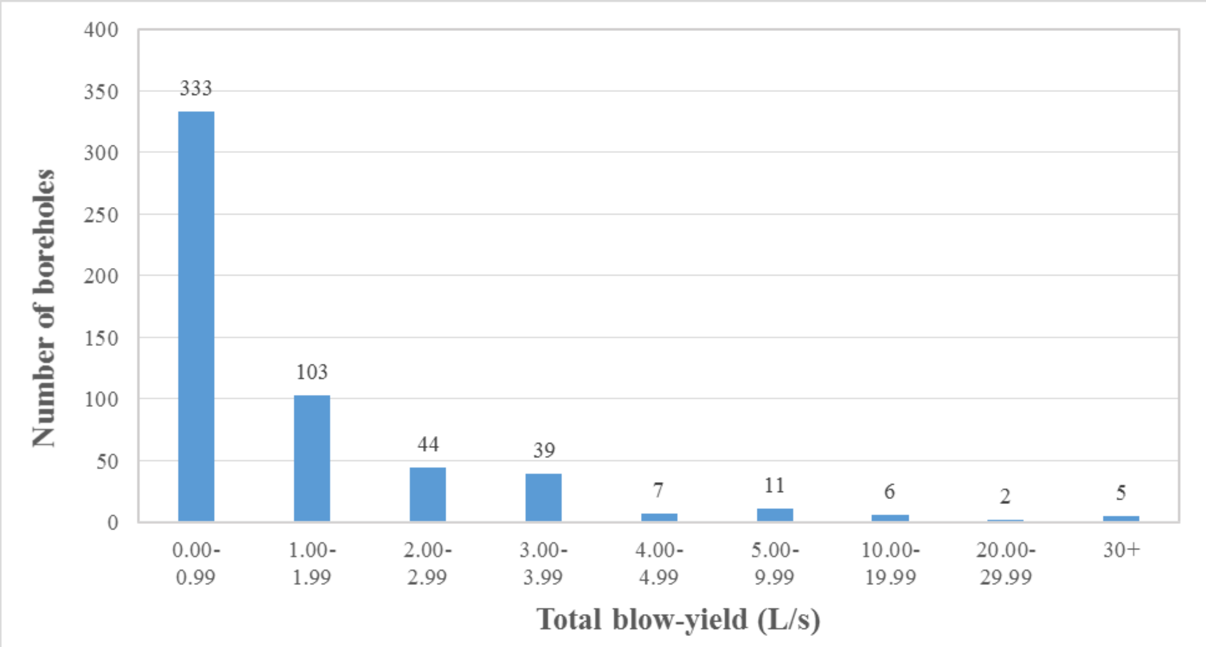


Figure 5-50: Distribution of the blow yields of the deep boreholes listed in the National Groundwater Archive

5.5.3 Summary

The NGA contains very little information on the geohydrological conditions of deep aquifer systems in South Africa. Of the 264,232 boreholes listed in the NGA, only 1,116 have depths equal to or in excess of 300 m. Of these 1,116 deep boreholes, only 550 have information on the blow yields encountered. Only 21 water strikes below depths of 300 m are listed (Table 5-29). The deep water strikes all occurred in hard rock environments and it can be assumed that these water strikes were associated with fracturing. Water quality information is limited to field measurements of electrical conductivity, pH level, temperature and HCO_3.

The characteristics of South Africa's deep aquifer systems, as derived from the data listed in the NGA, are summarised in Table 5-31.

Table 5-31: Characterisation of deep aquifer systems, as derived from the data listed in the National Groundwater Archive

Criteria	Description
Lithology	Water strikes occurred in various hard rock formations, including sandstone, shale, quartzite, dolomite, granite and tillite. These water strikes are likely to be associated with fractures in the hard rock formations. The water strikes in the dolomites may also have been associated with dissolution cavities.
Occurrence	The boreholes in which the deep water strikes occurred are widely distributed across South Africa. The fracture zones acting as conduits for water are expected to have very limited vertical extents. Most of the water coming from the fractures is likely to be stored in the matrix of the hard rock formations. The aquifer systems may therefore have significant vertical extents.
Physical dimensions	The vertical extents of the fracture zones encountered in the deep boreholes are expected to be very limited (a few metres at most). However, the sedimentary rocks hosting the fractures are likely to act as the main storage unit for the water. These sedimentary rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers systems intersected by the deep boreholes are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing (or dissolution in the dolomites).
Saturation level	Although no information is listed in the NGA, the fractures intersected in the deep boreholes are expected to be under positive pressure. Fully saturated conditions are therefore expected in the fractures.
Heterogeneity and isotropy	The aquifer systems are highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks.
Formation properties	The porosities of the sedimentary rocks forming part of the aquifer systems are likely to be very low, due to the large depths of burial. Despite the small porosties, the sedimentary rock matrices are expected to act as the main water storage units. The fractures, by contrast, are expected to create localised zones with very high porosities.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems are expected to be under positive pressure.
Yield	The blow-yields of the deep boreholes with water strikes varies significantly (0.0002 to 76 L/s). The potential yields of the aquifer systems are likely to be closely associated with the lithologies intersected (high-yielding aquifers are, for example, likely to occur in dolomitic rocks).
Groundwater quality	Very limited information on groundwater quality is available. However, field measurements of the EC and pH suggest that the groundwater at from many of the deep boreholes is of good quality.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be vulnerable to over-exploitation since little information is available on their rates of recharge and hence on the sustainable abstraction rates that can be employed.

5.6 CHARACTERISTICS OF DEEP AQUIFERS DERIVED FROM THE SOEKOR BOREHOLES

5.6.1 Introduction

Between 1965 and 1977, SOEKOR oversaw the drilling of several deep boreholes in the Karoo Basin as part of an oil and gas exploration programme. Although various authors have published information on these boreholes (e.g. Rowsell and De Swardt, 1976; Viljoen et al., 2010; Steyl et al., 2012; SRK, 2012; KGEG, 2013a; KGEG, 2013b; Talma and Esterhuyse, 2013; Van Tonder et al., 2013; Rosewarne, 2014a; Rosewarne, 2014b; Scheiber-Enslin, 2015; Scheiber-Enslin et al., 2015; Swana, 2016), the available data set contains many gaps and contradictory information. Information on the SOEKOR boreholes is presented in Table 5-32, while information on other deep boreholes that were used to assess the gas and petroleum reserves is listed in Table 5-33. The location of the SOEKOR boreholes is shown in Figure 5-51. The results of the drilling programme, as they relate to deep aquifer systems, are discussed in the sections below.

5.6.2 Lithologies intersected

Since the SOEKOR exploration programme aimed at investigating the potential gas and oil reserves of South Africa, the drilling programme focused on sedimentary rock successions, particularly the Karoo Supergroup with its strata rich in organic material. Many of the SOEKOR boreholes were drilled to depths where the basement rocks underlying the sedimentary units were encountered. Figure 5-52 is an example of the successions of sedimentary rocks encountered during the drilling of nine of the SOEKOR boreholes located at positions on either side of the dolerite line (refer to Figure 5-51 for the location of these boreholes).

5.6.3 Artesian water strikes

Since the SOEKOR boreholes were drilled using core drilling, only the free-flowing artesian water strikes (artesian water strikes for which the hydraulic heads exceed the surface elevation) were noted during drilling. The boreholes in which artesian water strikes were recorded are listed in Table 5-34. Water strikes are listed for 10 boreholes, with some boreholes exhibiting several artesian water strikes. It should be kept in mind that the primary purpose of the SOEKOR drilling programme was to explore for oil and gas. It is possible that artesian groundwater strikes occurred in other boreholes, but that such water strikes went unrecorded.

Table 5-32: Information on the SOEKOR boreholes

Borehole #	Company	Farm/Location	Nearby Town	Latitude (°S)	Longitude (°E)	Elevation (mamsl)	Depth (m)
AB1/65	Soekor	Abrahamskraal		-31.80161	22.61749	1 415	2 311
AD1/68	Soekor/Geological Survey	Addo		-33.58500	25.66472		
BE1/66	Soekor			-28.35045	32.09979		
BE1/67	Soekor			-28.67707	29.38693	1 151	
CK1/68	Soekor	Commandokraal		-33.52194	25.69667		2 115
CL4/68	Soekor/Sterrenberg Mynbou	Clocolan	Clocolan	-28.88788	27.55409		897
CO1/67	Soekor	Colchester		-33.68667	25.79222		>914
CR1/68	Soekor/Karroo Petroleum	Cranemere	Pearston	-32.48547 -32.48528	25.00871 25.00917	793	4 658
EL1/67	Soekor/Geological Survey	Elandsnek	Utrecht	-27.48056	30.45000	1 675	585
FI1/72	Soekor	Ficksburg Municipality	Ficksburg	-28.89371 -28.89333 -28.89385	27.84771 27.84806 27.84869	1 572	1 911
GL1/67 (GLEN1/67)	Soekor	Klipfontein	Bloemfontein	-28.95258 -28.95222	26.33377 26.33417	1 280	1 198
GSO1/67	Soekor/Geological Survey			-28.58278	29.38333		
GSO14	Soekor	Schietnek	Newcastle	-28.11000	29.69056	1 411	646
JA2/75	Soekor	Jackhalsdraai	Utrecht	-27.43472 -27.44816 -27.44770	30.18167 30.18347 30.18142	1 753	647
KA1/66	Soekor	Karreebosch		-32.01354	23.42586	1 036	2 469
KL1/65	Soekor	Klipdrift		-32.61688 -32.61861	20.45352 20.45383	729	3 370
KW1/67	Soekor	Klein Waterval		-32.98434	22.33611	969	
LA1/68	Soekor	Olney		-29.08564	27.48047	1 614	
MA1/69	Soekor	Matatiele		-30.32279	28.76773		
ME1/72	Soekor			-28.18750	29.27917		1 060
NA1/69	Soekor	Nanaga	Paterson	-33.55944	25.95167	1085?	2 063
OL1/69	Soekor	Olyvenbosch		-32.00024	19.86043	542	1 219
OM1/73	Soekor			-27.83333	29.51667		973
PA1/68	Soekor		Paterson	-33.47278	25.89222		
QU1/65	Soekor	Quaggafontein		-31.82662 -31.82792 -31.82639	21.43827 21.44253 21.43889	1 261	329
SA1/66	Soekor	Sambokkraal	Merweville	-32.66964 -32.65017 -32.66944	21.32856 21.33345 21.32917	741	4 169
SC3/67	Soekor	Schietfontein	Aberdeen	-32.77379 -32.77361	24.29952 24.30000	792	6 401
SP1/69	Soekor	Springfontein		-33.00433	27.76298	237	
SS1/73	Soekor	Sans Souci	Harrismith	-28.10417	29.44833	1 704	304
SW1/67	Soekor/Geological Survey	Swartberg		-30.15447	29.26635	1 682	
TK1/75	Soekor			-27.44306	30.31889		304
UV2/75	Soekor	Uitval	Utrecht	-27.51111 -27.51159	30.34444 30.34420	2 100	1 027
VR1/66 (VREDE1/66)	Soekor	Uitkomst	Vrede	-32.22441	24.21281	875	3 839
WE1/66	Soekor	Weltevrede		-30.89804 -30.89722	26.83988 26.84056	1 532	3 746
WI1/72	Soekor	Wittekrans		-28.70872	27.68854	1 695	1 520
ZE1/71	Soekor	Ntabankulu	Maputa	-27.07083	32.68583	73	1 900
ZF1/72	Soekor	Native Reserve		-27.21528 -27.21582	32.59694 32.59659	81	1 921
ZH1/74	Soekor	Nyalazi	Mtubatuba	-28.20722 -28.20716	32.40083 32.40063	34	973

Table 5-33: Information on deep boreholes used to assess the gas and oil potential of South Africa

Borehole #	Company	Farm/Location	Nearby Town	Latitude (°S)	Longitude (°E)	Elevation (mamsl)	Depth (m)
AM1/70	BJH du Preez Oil Exploration Company	Amandelboom		-31.37410 -31.38364	20.89330 20.88772	1 067	
AXT1	Anglo American			-30.61310	20.89330	1 218	
B3	?						
B390/1	Industrial Development Corporation						
B4	?						
BBF1	?						
BH1	?	Sambokkraal					
BH47	?						
BH6	?	Rietfontein					
BKP1	Anglo American						
CFK1	?						
D731/1	Industrial Development Corporation						
DA1-19 (D-A1)	?						
D-B/1 (D-B1)	?	Continental Shelve		-34.64162	20.91930		1 585
D-C1	?						
DD1/63 (D-D1)	Private						
DP1/78	Geological Survey						
Dubbelde Vlei	Northwest Prospecting Syndicate	Dubbelde Vlei					
E1288/1	Industrial Development Corporation						
E-B1	?						
EP1/78	Geological Survey						
G39974	DWA						
GP1/78	Geological Survey						
GSO15	Geological Survey	Dannhauser					0
HB-P 1	?						
HDA2	Anglo American						
HDA3	Anglo American						
HG1/84	Anglo American			-30.79640	20.29020	976	
HGK1 (HG1)	Anglo American						
HLP1	Anglo American						
HM1/78	Geological Survey						
KC1/70 (KC1/71)	BJH du Preez Oil Exploration Company	Leeuweriet		-31.35880 -31.38547	20.58210 20.58772	1 181	1 745
KD1/71	BJH du Preez Oil Exploration Company	Klipheuwels		-31.05470 -31.06625	21.81560 21.80044	1 315	1 771
KFN1	?						
KL1/78	Geological Survey						
OM1/73	?						
RM1/78	Geological Survey						
S1460/1	Industrial Development Corporation						
SO1/64	?						
TG1	?			-29.91599	25.67526	1 355	
TG2	?			-29.94730	25.63084	1 399	
TG3	?			-29.93694	25.61397	1 388	
TG4	?			-29.92342	25.59579	1 380	
TG5	?			-29.88919	25.59060	1 384	
TG6	?			-29.89685	25.60099	1 370	
TGX	?			-30.01081	25.75467	1 400	

Borehole #	Company	Farm/Location	Nearby Town	Latitude (°S)	Longitude (°E)	Elevation (mamsl)	Depth (m)
TU1/50	?						
VB122	Anglo American						
VB123	Anglo American						
VB124	Anglo American						
VFB1	?		Trompsburg				
VP1/78	Geological Survey						
XL1/65	?						
ZD1	?						
ZG1/72	?						
ZU1	?						
ZWT1	Anglo American					1 138	

Table 5-34: SOEKOR boreholes in which artesian water strikes were recorded

Borehole #	Artesian water strikes				
	Depth (mbgl)	Lithology	Flow rate	Temp (°C)	Hydrogeochemical information
CR1/68		Fractured Dwyka tillite			
GL1/67	752		270 - 320 L/hr		Water analyses done
KA1/66		Fractured Dwyka tillite			
KL1/65	936				
	983		0.15 L/s		TDS = 1 390 mg/L; pH = 8.9
	2 999				
	3 215	Fractured Table Mountain sedimentary rocks		50	NaCl = 900 mg/L
	3 228		1.9 L/s	49	
	3 347				
KW1/67		Fault zone in Dwyk tillite			TDS = 12 000 mg/L
SA1/66	2 975	Contact between shale and tillite	3.7 L/s	65	TDS = 6 460 mg/L
	3 029	Fractured Dwyka tillite	1.2 L/s	443	
	3 206	Fractured Dwyka tillite	3.0 L/s	46	TDS = 8 754 mg/L
SC3/67		Fractured Dwyka tillite			Almost fresh water
SP1/69	~4 180	Fractured Dwyka tillite			
VR1/66	654	Contact: Beaufort sedimentary rocks and dolerite	0.6 L/s		
	674	Fractured Beaufort sedimentary rocks	0.9 L/s		
	1 920	Fractured Ecca sedimentary rocks	~		
	2 195	Fractured Ecca sedimentary rocks	~		
	2 469	Fractured Ecca sedimentary rocks	0.5 L/s		
	2 743	Fractured Ecca sedimentary rocks	0.5 L/s		
	3 021	Fractured Ecca sedimentary rocks	0.5 L/s		
	3 200	Fractured Dwyka tillite	0.5 L/s	46	
WE1/66		Fractured rock	Considerable amounts of water		

Sources: Gibson et al.(1968), KGEG (2013b), Rosewarne (2014a, 2014b)

From the data listed in Table 5-34, one can see that artesian water strikes generally occurred within fractured sedimentary rocks, sometimes in the vicinity of doleritic intrusives. Most of the water strikes occurred in the fractured Dwyka tillites. However, the quality of the water from the various water strikes in the tillites varied significantly from “almost fresh” to having a TDS concentration of approximately 12,000 mg/ℓ. The depths of the water strikes ranged from 654 m to 3,347 m below ground level.

The flow rates of the various artesian water strikes were generally low, ranging from approximately 270 ℓ an hour (0.075 ℓ/s) to 3.7 ℓ/s. Only four of the water strikes had flow rates above 1 ℓ/s.

The temperatures of the deep artesian water strikes ranged from 44 to 65 °C. It is interesting to note that the shallowest water strike in borehole SA1/66 had the highest temperature, which was significantly higher than the two deeper water strikes. This suggests that the fracture networks are unconnected and complex, with deep circulating water emanating from the shallower fractures.

It is furthermore interesting to note that, of the 10 boreholes in which free-flowing artesian conditions were recorded, seven occur at surface elevations below 1,000 m above sea level (Table 5-32). This observation suggests that the deep aquifer systems are pressurised, but that the hydraulic heads are inadequate to give rise to free-flowing conditions for surface elevations above 1,000 m above sea level.

The geological borehole logs of three of the boreholes (KL1/68, SA1/66 and VR1/66), in which free-flowing artesian conditions occurred, are shown in Figure 5-53, Figure 5-54 and Figure 5-55, respectively. Also shown in these figures are the depths at which artesian water strikes occurred, as well as the field measurements that were taken during drilling.

5.6.4 Water quality

Apart from the field measurements of the TDS and Na-Cl concentrations, only limited information is available on the quality of the groundwater from the SOEKOR boreholes. Water samples were collected from artesian boreholes GL1/66 (GLEN1/66) during or shortly after drilling in 1966, while borehole SA1/66 was sampled during November 2012 and September 2013. The results of the chemical analyses performed on the water samples are listed in Table 5-35 and Table 5-36 for the macro and micro determinands, respectively.

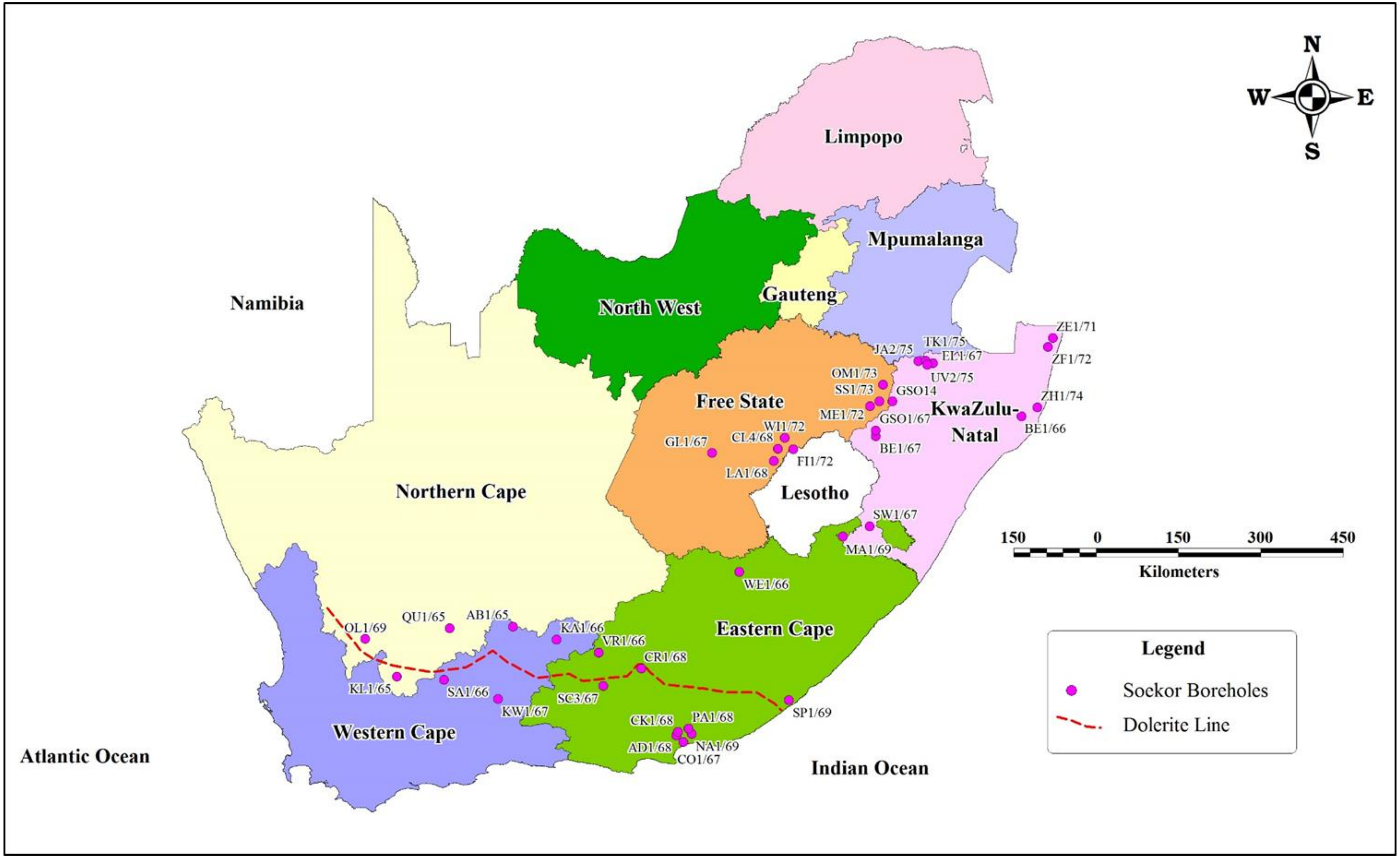


Figure 5-51: Location of the SOEKOR boreholes

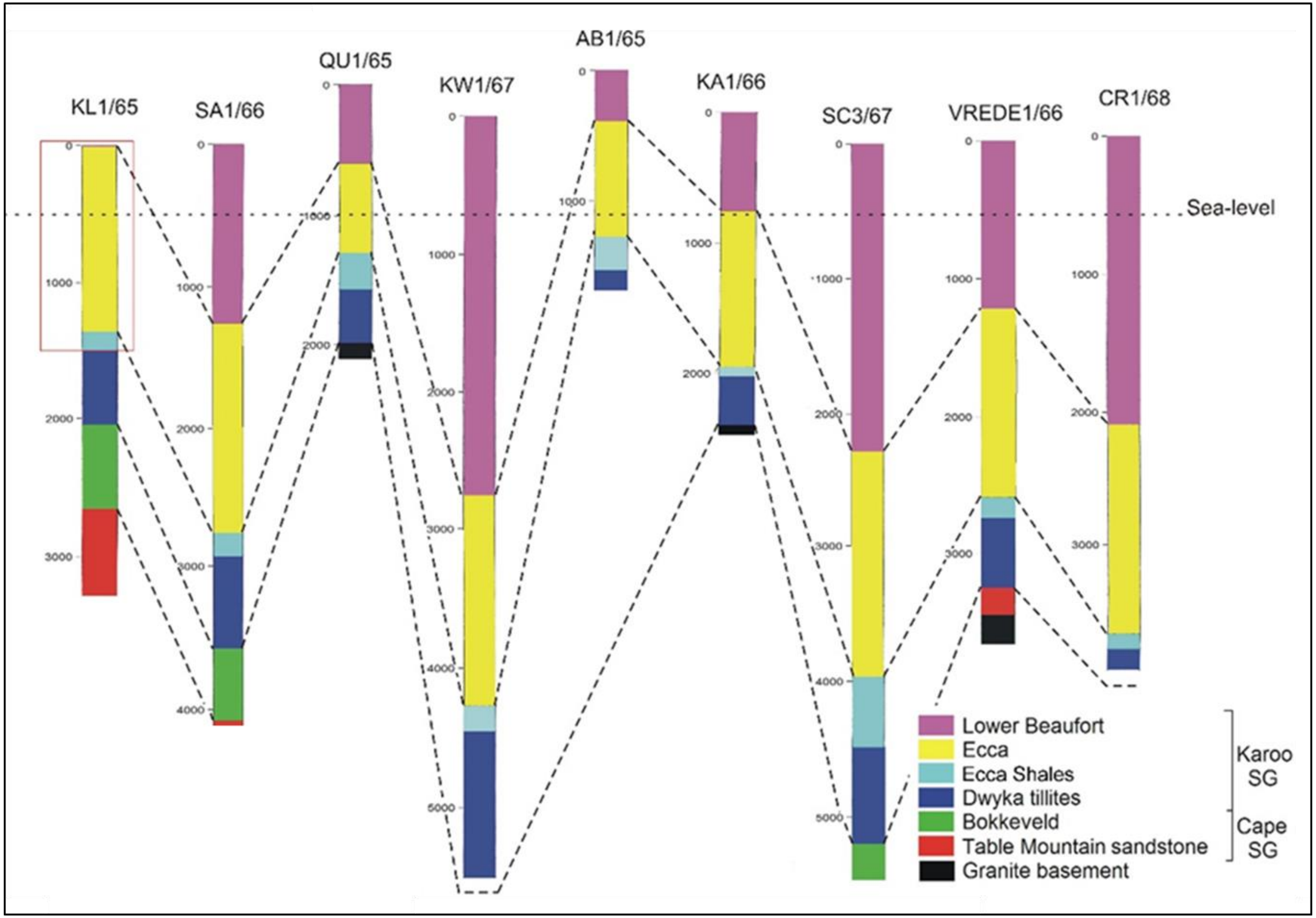


Figure 5-52: Stratigraphic succession of the main sedimentary units intersected by the SOEKOR boreholes on either side of the dolerite line

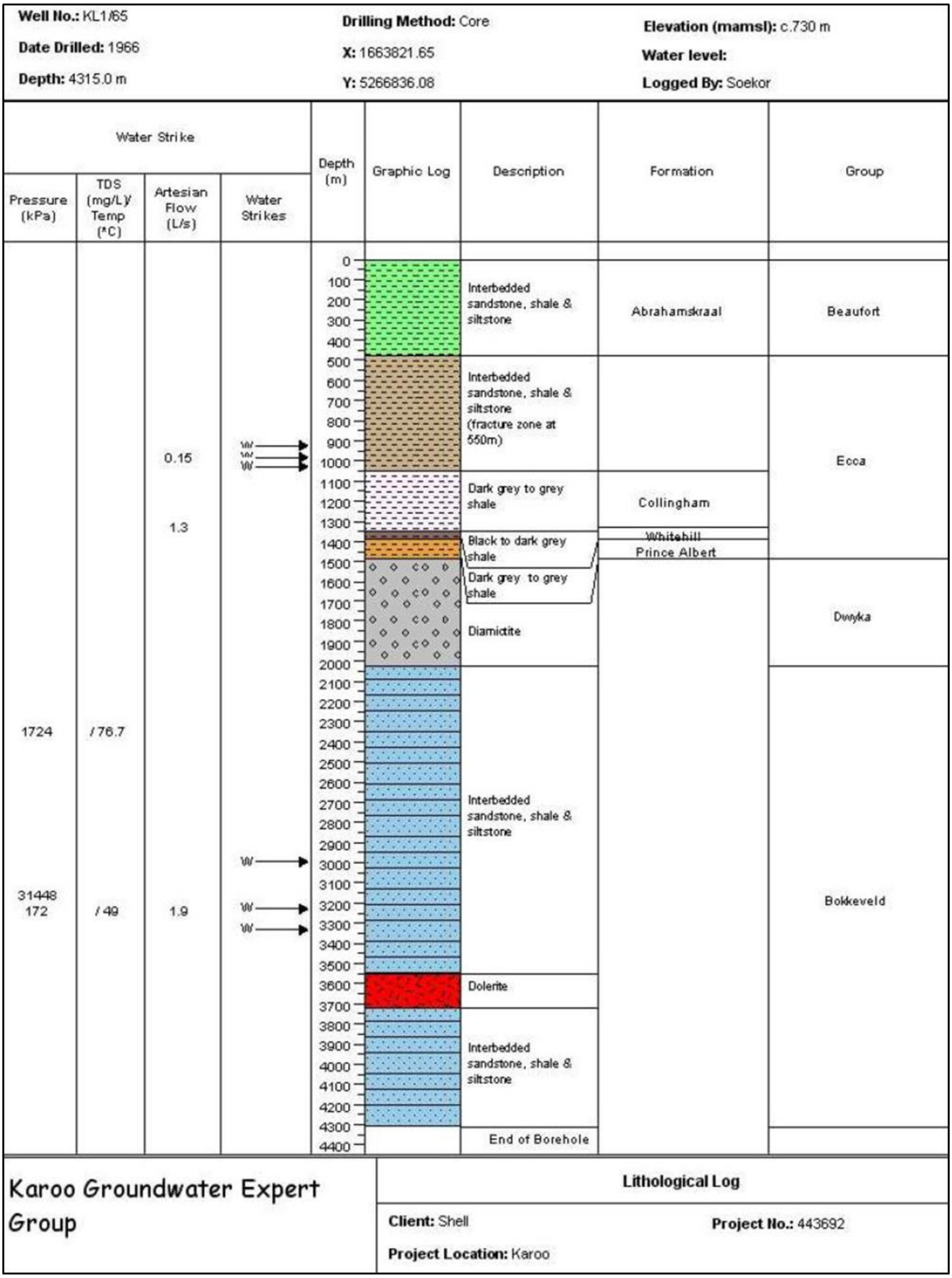


Figure 5-53: Geological log of borehole KL1/65 (KGEG, 2013b)

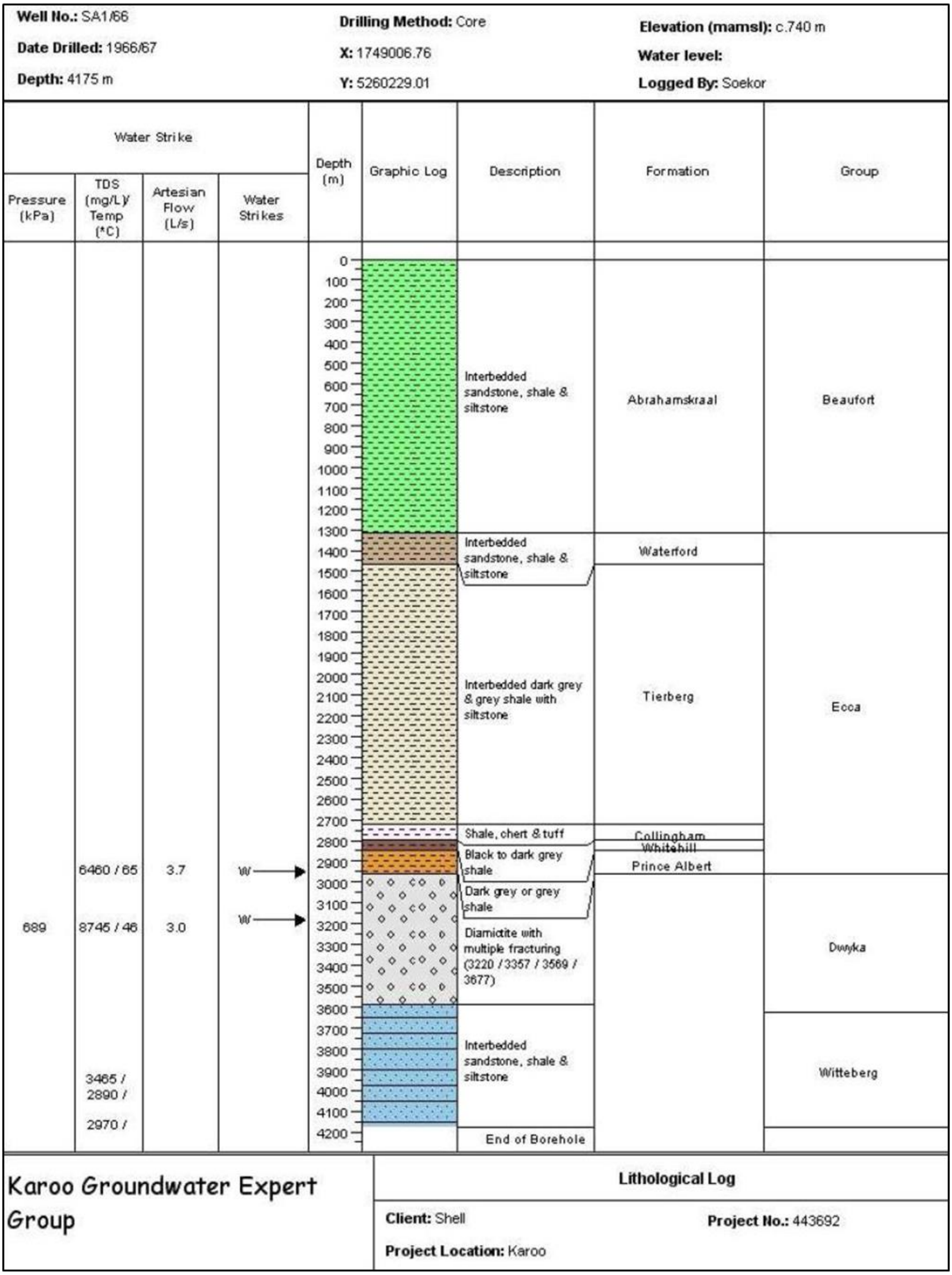


Figure 5-54: Geological log of borehole SA1/66 (KGEG, 2013b)

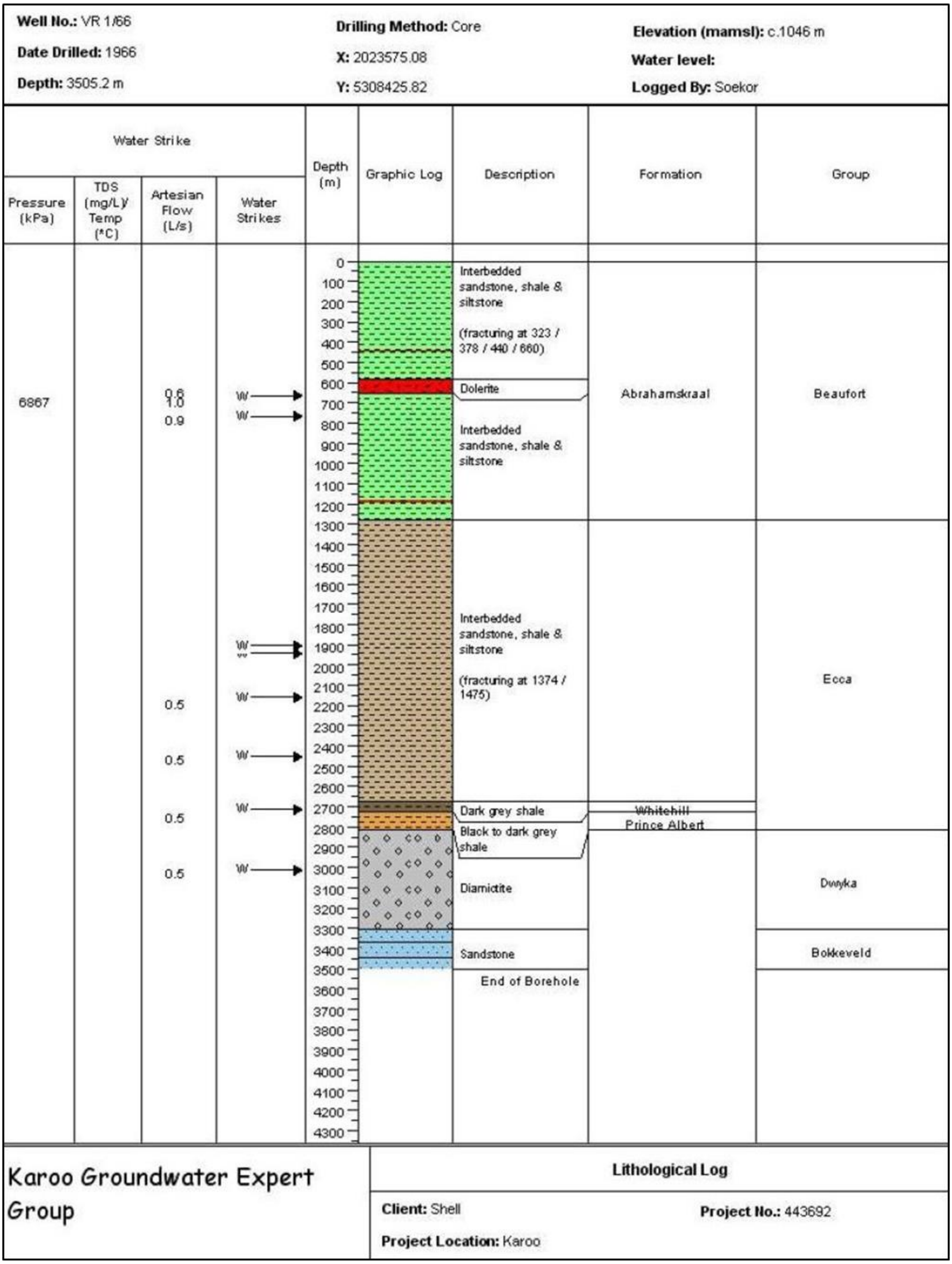


Figure 5-55: Geological log of borehole VR1/66 (KGEG, 2013b)

From the data listed in Table 5-35, one can see that very different water qualities were observed at boreholes GL1/66 and SA1/66. Very high sodium and chloride concentrations were recorded at borehole SA1/66. These concentrations are to be expected in deep, fairly stagnant (old) groundwater (Rosewarne, 2014b). The high concentrations of B, Br and F suggest that these ions could be used to "fingerprint" deep groundwater in the Karoo Supergroup (Rosewarne, 2014b).

Table 5-35: Results of the chemical analyses performed on water samples from boreholes GL1/66 and SA1/66 (macro determinands)

Borehole #	Date sampled	EC (mS/m)	TDS (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO_4 (mg/L)	NO_3 (mg/L)	T.Alk (mg/L)	CO_3 (mg/L)	HCO_3 (mg/L)
GL1/66	1966			713	12	46	5.0	1 132		12			73
SA1/66	Nov 2012	1 182	7 181	2 612	51	150	1.9	3 897	228		229		
SA1/66	Sep 2013	1 202	7 032	2 584	37	109	7.5	3 858	237		224		

Table 5-36: Results of the chemical analyses performed on water samples from boreholes GL1/66 and SA1/66 (micro determinands)

Borehole #	Date sampled	Sr (mS/m)	F (mg/L)	B (mg/L)	Br (mg/L)	Si (mg/L)	Fe (mg/L)	Mn (mg/L)
GL1/66	1966							
SA1/66	Nov 2012		4.7	18.5	3.7	25	0.05	0.26
SA1/66	Sep 2013	15.84		23.1	12	34	0.08	0.04

To examine the characteristics of the groundwater from borehole SA1/66, diagnostic plots may be used. In this section, three diagrams are used to compare the abundances of the major ion species in the groundwater samples taken from this borehole. These diagrams are the Piper, Expanded Durov and Sodium Adsorption Ratio (SAR) diagrams.

The Piper Diagram of the two samples from SA1/66 is shown in Figure 5-56. The chemical characteristics of the two water samples are so similar that they plot very close to one another. The samples plot to the far right of the diamond-shaped part of the Piper Diagram, showing that the water is of the sodium-chloride type, considered to be brackish or saline.

In Figure 5-57, the two water samples are seen to plot in the bottom right-hand square (field) of the Expanded Durov Diagram. Natural saline waters typically plot in this field. The SAR Diagram (Figure 5-58) shows that both the salinity hazard and the sodium hazard of the water samples are high, indicating that the water is not suitable for irrigation.

In terms of the groundwater quality, it should also be mentioned that some of the SOEKOR boreholes (e.g. SA1/66) are known to emit methane gas. The methane not only poses a health risk when ingested, but is also associated with risks due to the possibility of ignition.

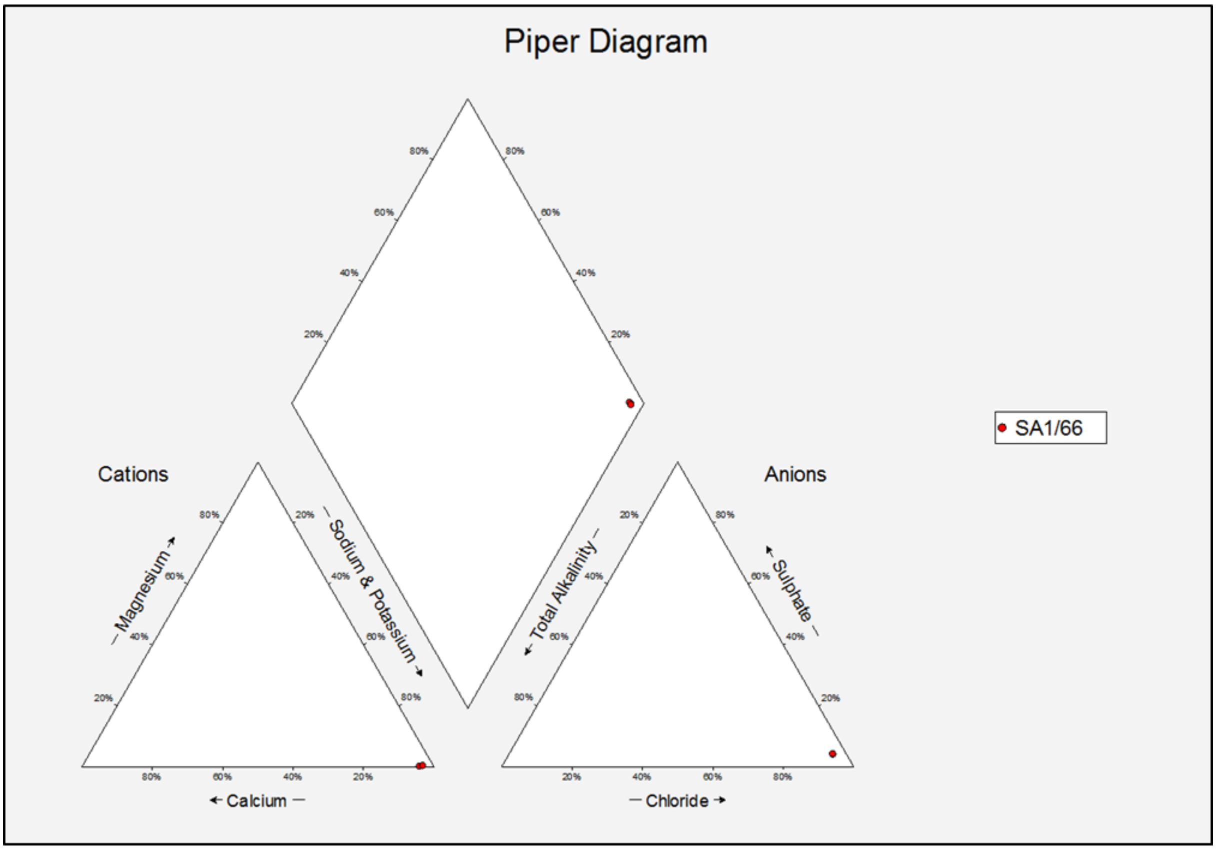


Figure 5-56: Piper Diagram of the water samples from borehole SA1/66

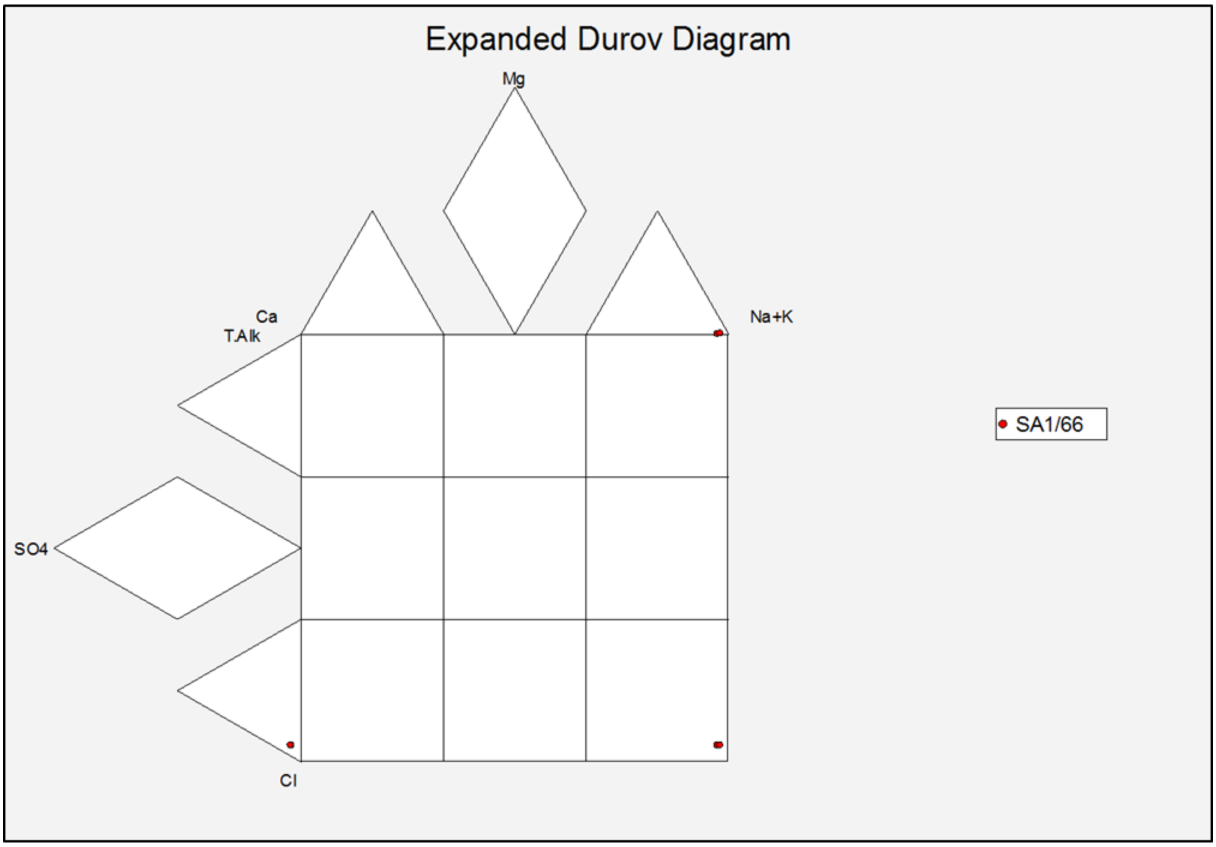


Figure 5-57: Expanded Durov Diagram of the water samples from borehole SA1/66

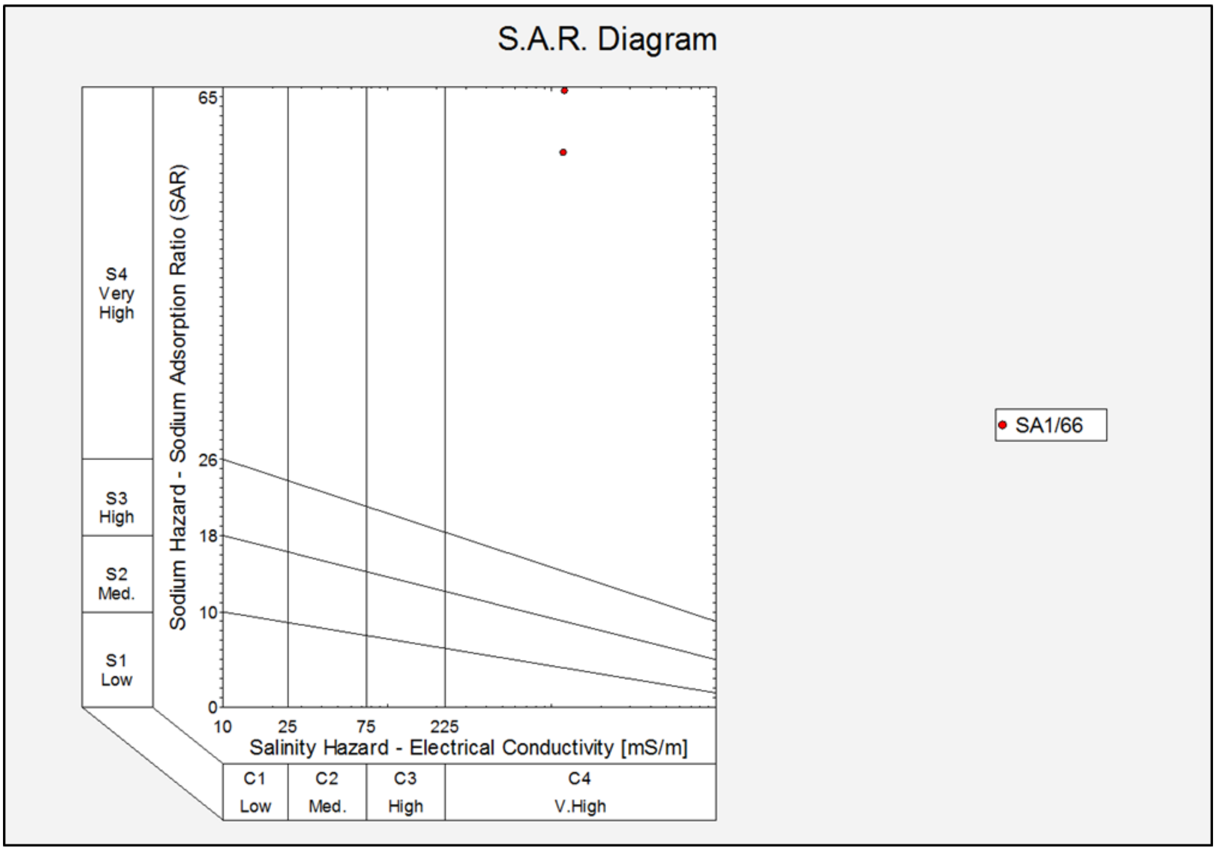


Figure 5-58: SAR Diagram of the water samples from borehole SA1/66

5.6.5 Geophysical logging

Geophysical logging was done on many, if not all, of the boreholes drilled as part of the SOEKOR exploration programme. The main purpose of the geophysical logging appears to have been to gain information to characterise the possible oil and gas reservoirs in terms of their potential to yield economic volumes of hydrocarbons. From the information gained during geophysical logging, the vertical extent of potential reservoirs could be determined. In addition, the geophysical logging was used to gain information on the porosities of the various rock units intersected during drilling. This information was also used to judge whether the different rock units had the storage potential required to be considered as a potential oil or gas reservoir.

The available information on the geophysical logging techniques applied to some of the SOEKOR boreholes is summarised in Table 5-37. Although the geophysical logging was not done with the aim of characterising the deep aquifer systems, it is possible that the recorded information may be re-evaluated and reinterpreted with a stronger focus on the deep groundwater conditions.

Table 5-37: Geophysical logging techniques applied to the SOEKOR boreholes

Borehole #	Geophysical logging technique									
	Electrical resistivity	SP	Radioactivity	Caliper	Temperature	Sonic	Acoustic	Formation density	Induction electrical	Gamma-Neutron
CR1/68	Yes	Yes	Yes	Yes	Yes	Yes	Yes			
EL1/67										
FI1/72	Yes	Yes		Yes		Yes		Yes		
JA2/75	Yes			Yes	Yes	Yes		Yes	Yes	Yes
KA1/66	Yes				Yes					Yes
KW1/67	Yes	Yes	Yes	Yes	Yes	Yes		Yes		
ME1/72	Yes	Yes				Yes		Yes		
OL1/69	Yes	Yes				Yes				
SP1/69	Yes		Yes	Yes	Yes	Yes		Yes		
SS1/73	Yes	Yes				Yes		Yes		Yes
TK1/75	Yes	Yes		Yes		Yes		Yes	Yes	Yes
WE1/66	Yes		Yes	Yes	Yes	Yes				
ZE1/71	Yes	Yes		Yes		Yes				Yes
ZF1/72	Yes	Yes		Yes		Yes				Yes
ZH1/74	Yes	Yes		Yes		Yes		Yes		Yes

5.6.6 Porosity

Since the porosity of the rock units intersected during drilling is a controlling factor that determines the potential of the unit to act as a reservoir for oil and gas, the SOEKOR exploration programme strived to determine the porosity distribution in the subsurface. However, there is an insufficient density of results to make a thorough assessment of the porosities of the various rock units (Gibson et al., 1968). Not only were cores submitted for laboratory analyses of porosity, but geophysical logging techniques were applied to obtain a more continuous profile of the porosity variations within the various lithological units (as discussed in Section 5.6.5).

The boreholes drilled in the Southern Karoo Basin revealed very low primary porosities (usually less than 2%) (Gibson et al., 1968). Secondary porosity due to jointing and fracturing was, however, observed in all the boreholes. In the Northern Karoo Basin, porosities in the Middle Ecca sand reached 15% (with occasional beds having porosities of up to 20%) (Gibson et al., 1968).

Information on the porosities observed in some of the SOEKOR boreholes is presented in Table 5-38. This information was taken from the individual borehole reports compiled after drilling.

Viljoen (2011) also summarised the porosities and permeabilities encountered in some of the SOEKOR boreholes. These values are listed in Table 5-39. One can see that the measured porosities ranged from 0 to 9.3%, but that, except for borehole OL1/69, the average porosities were well below 5%. Very low permeabilities were also measured in all the boreholes.

Table 5-38: Information on porosities observed in some of the SOEKOR boreholes

Borehole #	Information on porosity
CO1/67	Primary porosity very low in the sandstones and siltstones. Secondary porosity due to jointing and fracturing
FI1/72	Geophysical logs indicate average porosities of 9 and 6% for the Beaufort and Middle Ecca Groups, respectively.
KA1/66	Low primary porosities observed along entire length of borehole, but secondary porosity due
KW1/67	Very little primary porosity. Secondary porosity (fractures, jointing) occurs at intervals
LA1/68	Porosity rarely exceeds 5%
ME1/72	Laboratory analyses of cores found porosity ranges of 9.1 - 12.8%, and 7.7 - 11.9%
OM1/73	Porosity logs show porosities that vary from 5 to 8%.
SP1/69	Primary porosity less than 1.5%. Secondary porosity in the upper portions of the Dwyka tillite.
SS1/73	Laboratory analyses of cores found porosity ranges of 13.9 - 23.2%, 8.2 - 24.1% and 14.5 -
TK1/75	Geophysical logging suggests average porosities of 12%. Confirmed by laboratory tests of core samples (average 14.8%).
WE1/66	Very little primary porosity. Secondary porosity along entire hole, often associated with upper contacts of dolerite intrusions.
ZE1/71	Porosities derived from the neutron log range between 1 and 19%.
ZF1/72	Laboratory analyses of cores found a porosity range of 4.65 - 22.8%
ZH1/74	Laboratory analyses of cores found porosity ranges of 29.9 - 36.7%, 8.0 - 36.8% and 12.3 -

Table 5-39: Porosity and permeability values for sandstone in some of the deep SOEKOR boreholes drilled in the Karoo (Viljoen, 2011)

Borehole #	Stratigraphic group	Depth interval (mbgl)	No. of samples	Porosity (%)		Permeability (mD)
				Range	Average	
KD1/71	Nama	1 478 - 1 486	3	1.8 - 2.4	2.1	<0.1
KL1/65	Bokkeveld	2 041 - 2 717	53	0 - 4.3	0.5	0 - 0.88
	Table Mountain	2 814 - 3 414	30	0 - 3.2	0.36	0
OL1/69	Table Mountain	1 068 - 1 173	5	2.7 - 9.3	6.3	0 - 0.16
SA1/66	Bokkeveld	3 596 - 3 947	9	0.23 - 4.19	0.96	0
SC3/67	Bokkeveld	5 334	1	1.02	1.02	0
VR1/66	Table Mountain	3 322 - 3 420	7	1.0 - 2.3	1.5	0

5.6.7 Summary

Although the SOEKOR exploration programme never intended to investigate deep aquifer systems, information obtained from the deep boreholes may be used to characterise these aquifer systems. The information relevant to the deep geohydrological conditions is summarised in Table 5-40.

Table 5-40: Characterisation of the deep aquifer systems from the results of the SOEKOR boreholes

Criteria	Description
Lithology	Water strikes occurred in various hard rock formations, including Dwyka tillite, TMG sandstone, Beaufort sedimentary rocks, and Ecca sedimentary rocks. All water strikes were associated with fractures in the hard rock formations.
Occurrence	The boreholes in which the deep water strikes occurred are widely distributed across South Africa. The fracture zones acting as conduits for water are expected to have very limited vertical extents. Most of the water coming from the fractures is likely to be stored in the matrix of the hard rock formations. The aquifer systems may therefore have significant vertical extents.
Physical dimensions	The vertical extents of the fracture zones encountered in the deep boreholes are expected to be very limited (a few metres at most). However, the sedimentary rocks hosting the fractures are likely to act as the main storage unit for the water. These sedimentary rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers systems intersected by the deep boreholes are likely of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing (or dissolution in the dolomites).
Saturation level	The Soekor boreholes were drilled using core drilling. Only free-flowing artesian water strikes were therefore detected. These water strikes are associated with positive pressure, and hence saturated conditions.
Heterogeneity and isotropy	The aquifer systems are highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks.
Formation properties	The primary porosities of the sedimentary rocks forming part of the aquifer systems are generally very low (well below 5%), but higher porosities are observed in some boreholes. Despite the small porosties, the sedimentary rock matrices are expected to act as the main water storage units. The fractures, by contrast, are expected to create localised zones with very high secondary porosities.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. A few permeability measurements confirm this observation. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.
Yield	The artesian flow rates of the deep boreholes are generally low (< 1 L/s). However, a few water strikes had flow rates higher than 3 L/s.
Groundwater quality	Very limited information on groundwater quality is available. Two samples from borehole SA1/66 reveal highly saline conditions. However, other deep water strikes were reported to yield "almost fresh" water. The quality of the groundwater seems to depend on the residence time and recharge rate of the aquifer systems. Low recharge rates may be linked to more saline conditions,
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be vulnerable to over-exploitation since little information is available on their rates of recharge and hence on the sustainable abstraction rates that can be employed.

5.7 CHARACTERISTICS OF DEEP AQUIFERS DERIVED FROM THE KARIN BOREHOLES

The Karoo Research Initiative is an academic contribution to geoscientific research in South Africa. The KARIN project entails the installation of two deep core boreholes in the southern parts of the Karoo Basin. The main aim of the project is to improve the understanding of the stratigraphy and basinal settings of potential shale gas reserves in the Karoo Basin south of the dolerite line. The project also had, as one of its objectives, the characterisation of the geohydrological conditions and water quality of the deep aquifer systems (De Kock et al., 2016a; De Kock et al., 2016b).

The two core boreholes were drilled by Geoserve Exploration Drilling (Pty) Ltd during the latter half of 2015. Borehole KFZ-01 was drilled on the farm Zandfontein, approximately 85 km northeast of Ceres in the Western Cape. This borehole was drilled to a depth of 671 m. Borehole KWV-01 is located approximately 10 km east of Willowvale in the Eastern Cape. This borehole was drilled to a depth of 2,353.5 m. The location of these two boreholes is shown in Figure 5-59. The information on the geological and geohydrological conditions gathered from the two boreholes is summarised in sections 5.7.1 and 5.7.2.

5.7.1 Borehole KZF-01

Borehole KZF-01 was drilled in the Tankwa Karoo, south of the Karoo Large Igneous Province, near Ceres. The borehole is located at a topographic elevation of 510 m above sea level and was drilled vertically to a final depth of 671 m. Core from the borehole was recovered with an average core recovery of 97.5%. Geophysical well logging was conducted after drilling. Groundwater samples were collected, both at the surface and at selected depths within the borehole. These samples were submitted for chemical analysis.

5.7.1.1 Stratigraphy and lithologies

The geological log of borehole KZF-01 is shown in Figure 5-60 (in the left-hand column). The borehole intersected the Tierberg, Collingham, Whitehill and Prince Albert formations of the Ecca Group, as well as the Dwyka Group near the bottom of the borehole (at a depth of 648 m below ground level). No dolerite was intersected in the borehole (Beukes et al., 2015). The geological log showed that the Tierberg Formation has a thickness of 341.05 m and consists of bedded to massive grey to black mudstone, siltstone and shale, while the Collingham Formation is 77.9 m thick and consists of interbedded tuffs, mudstone and minor siltstone. The Whitehill Formation is 19.5 m thick and consists of brecciated black shale. The Prince Albert Formation has a thickness of 180 m and consists of bedded grey mudstone and siltstone. Portions of the Whitehill and Prince Albert formations are duplicated in the geological log, possibly due to low-angle thrusting (De Kock et al., 2016a).

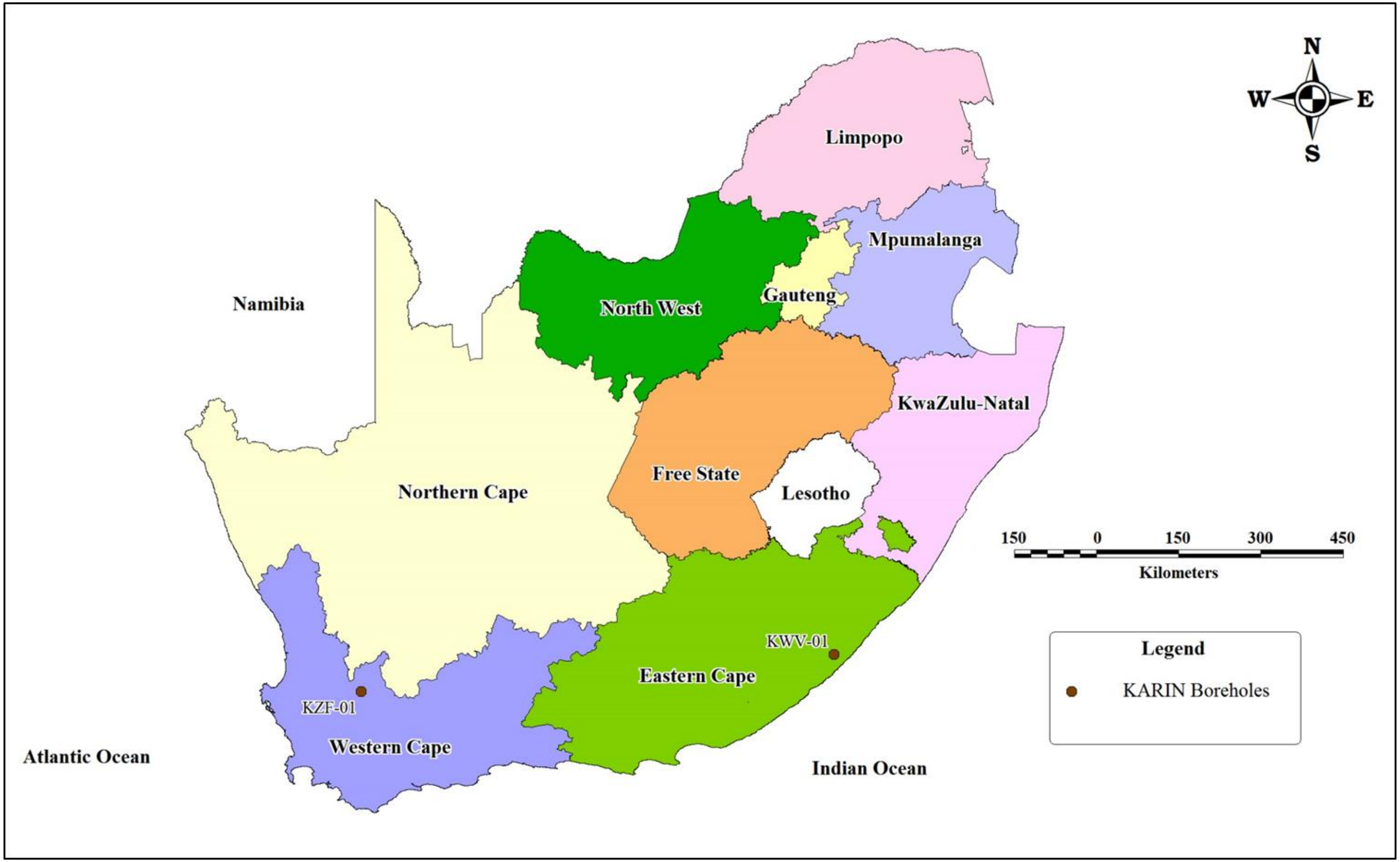


Figure 5-59: Location of the two KARIN boreholes

Fractures were observed at various depths within the first 100 m of the borehole. A fracture zone in the shale of the Tierberg Formation occurred at a depth of 82 to 83 m below ground level. This fracture zone resulted in some core loss

5.7.1.2 Water strikes

The shallow aquifer used by farmers for groundwater supply was intersected within the first 60 m of drilling. This aquifer was sealed off before drilling continued to greater depths (De Kock et al., 2016a). No water strikes occurred until a depth of 560 m below ground level was reached, where fresh artesian groundwater was struck. Another water strike occurred between 625 and 626 m below ground level, yielding slightly sulphurous, warm (24 °C) artesian water. A zone of near-vertical fractures (75°) between 668 and 671 m below ground level produced very strong (24,000 ℓ per minute), warm (43 °C) artesian water.

5.7.1.3 Geophysical logging

Weatherford Slimline Services Downhole conducted geophysical surveys on 29 August 2015. The following geophysical logs were obtained: caliper, resistivity, density, ATV, sonic, neutron, formation dipmeter, flowmeter and verticality. The borehole was logged with the aim of providing *in-situ* measurements of the physical rock properties and fracture orientations to supplement knowledge gained from drilled core analysis (Beukes et al., 2015). Some of the geophysical borehole logs are shown in Figure 5-60 (in the right-hand columns).

5.7.1.4 Groundwater sampling and analyses

Seventeen groundwater samples were collected from borehole KZF-01. Samples were collected both at the surface (five samples, corresponding to five different drilling depths) and at selected depths within the borehole (11 samples). (Information on sample TK3 is absent in De Kock et al. (2016a).) The samples were submitted to the laboratory of the IGS for chemical analyses. Information on the groundwater samples collected from KZF-01 is listed in Table 5-41.

The field measurements of the electrical conductivity values of the groundwater from borehole KZF-01 range between 468 and 731 µS/m (Table 5-41). These low electrical conductivity values show that the concentrations of the dissolved solids in the water are very low, indicating that the water is of a very good quality. The electrical conductivity values of the water samples from KZF-01 are significantly lower than the average electrical conductivity value (3 344 µS/m) recorded in 26 shallow boreholes that occur within a radius of 10 km from the drilling site.

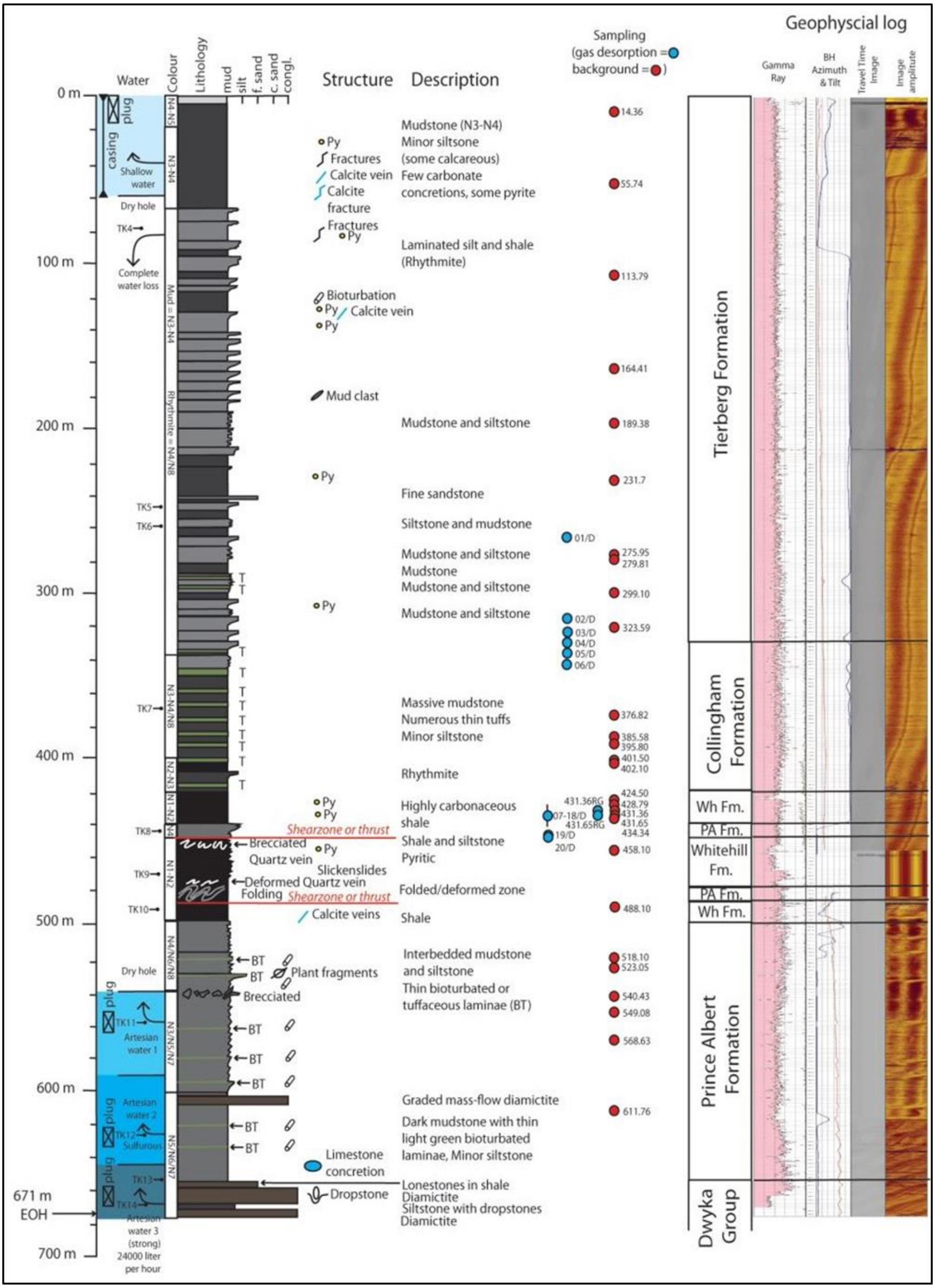


Figure 5-60: Geological and geophysical log of borehole KZF-01

The surprising observation that the deep aquifers contain groundwater of a much better quality than the shallow aquifers suggests that this water may be associated with aquifers of the Table Mountain Group that underlies the Karoo formations at the position of borehole KZF-01.

Table 5-41: Information on groundwater samples collected from borehole KZF-01

Sample #	Date sampled	Field pH	Field EC (µS/m)	Field Temperature (°C)	Sample depth (mbgl)
TK1	18/08/2015	9.2	626	20.0	Surface (from fracture at 559 mbgl)
TK2	19/08/2015	8.8	635	16.4	Surface (from fracture at 559 mbgl)
TK3	19/08/2015	-	-	-	-
TK4	20/08/2015	8.9	731	25.8	83.4
TK5	20/08/2015	8.4	666	26.4	249.5
TK6	21/08/2015	8.7	641	29.0	260.3
TK7	21/08/2015	8.8	654	29.7	369.0
TK8	21/08/2015	8.8	652	30.0	441.8
TK9	21/08/2015	8.9	662	31.0	470.3
TK10	21/08/2015	8.8	649	31.0	491.0
TK11	28/08/2015	8.4	496	33.7	559.7
TK12	28/08/2015	8.4	468	34.6	625.5
TK13	28/08/2015	8.3	467	36.6	654.4
TK14	28/08/2015	8.3	478	34.4	671.0
TK15	25/08/2015	-	-	-	Surface (drilling depth = 634.5 mbgl)
TK16	25/08/2015	-	-	-	Surface (drilling depth = 634.5 mbgl)
EOH	25/08/2015	-	-	-	Surface (drilling depth = 671 mbgl)

The field pH values of the water samples from KZF-01 show that alkaline conditions exist in the deep aquifers. These pH values are generally higher than the pH values of the groundwater samples from the shallow aquifer system.

The results of the chemical analyses performed on the water samples from borehole KZF-01 are listed in Table 5-42 (macro determinands) and Table 5-43 (micro determinands). These results confirm that the groundwater from the deep aquifer systems intersected by the borehole is of a very good quality.

5.7.1.5 Groundwater characteristics

To compare the characteristics of the groundwater from different sampling depths, diagnostic plots may be used. In this section, four diagrams are used to compare the abundances of the major ion species in the 11 groundwater samples taken at specific depths. These diagrams are the Piper Diagram, the Expanded Durov Diagram, the SAR Diagram and the Stiff Diagram.

The Piper Diagram of the depth-specific groundwater samples is shown in Figure 5-61. All 11 samples plot closely together near the bottom of the central diamond-shaped region of the diagram. This is due to the high sodium concentrations of the groundwater relative to the magnesium and calcium concentrations, and the high total alkalinities compared to the sulphate and chloride concentrations (Table 5-42).

Table 5-42: Results of the chemical analyses of water samples from borehole KZF-01 (macro determinands)

Sample #	pH	EC (mS/m)	Ca	Mg	Na	K	P. Alk	M. Alk	F	Cl	NO_2 as N	Br	NO_3 as N	PO_4	SO_4	CA Hard.	Mg Hard.	TDS
TK1	8.23	50.3	4.41	1.73	135	2.21	0	296	1.68	11.49	0.0056	BDL	BDL	BDL	0.76	11.03	7.09	452.95
TK2	8.11	50.4	4.92	2.07	144	2.58	0	298	1.25	12.61	BDL	0.0375	0.0637	BDL	1.20	12.30	8.49	466.80
TK3	7.70	51.0	5.96	2.47	143	4.04	0	299	1.25	14.48	0.0115	0.0658	0.0639	BDL	1.00	14.90	10.13	471.50
TK4	8.17	49.1	4.49	1.72	138	2.36	0	294	1.67	11.67	0.0051	0.1524	BDL	BDL	1.14	11.23	7.05	454.91
TK5	8.16	49.1	4.42	1.65	141	2.25	0	293	1.75	11.48	BDL	BDL	0.0461	BDL	0.78	11.05	6.77	456.35
TK6	8.19	49.1	4.49	1.67	138	2.18	0	294	1.68	11.42	BDL	BDL	BDL	BDL	0.88	11.23	6.85	453.92
TK7	8.20	47.9	4.94	1.85	146	2.25	0	293	1.65	11.33	BDL	0.0388	BDL	BDL	0.77	12.35	7.59	461.46
TK8	8.20	47.9	4.83	1.79	144	2.23	0	293	1.74	11.43	BDL	BDL	BDL	BDL	0.80	12.08	7.34	459.42
TK9	8.19	47.9	4.42	1.63	143	2.26	0	293	1.73	11.46	BDL	BDL	0.0479	BDL	0.75	11.05	6.68	458.27
TK10	8.16	47.9	5.36	2.04	141	2.35	0	295	1.67	11.43	BDL	BDL	0.049	BDL	0.75	13.40	8.36	459.63
TK11	7.79	36.1	8.27	1.76	99.5	3.73	0	218	0.71	12.35	BDL	0.0606	0.0483	BDL	0.77	20.69	7.20	345.26
TK12	7.72	35.0	8.93	1.90	98.3	3.96	0	210	0.71	12.54	BDL	0.0458	0.0474	BDL	0.92	22.32	7.79	337.33
TK13	7.60	35.0	9.10	1.75	89.1	3.82	0	208	0.63	12.47	BDL	BDL	0.0437	BDL	0.90	22.75	7.19	325.77
TK14	7.56	34.9	9.11	1.90	92.1	3.94	0	209	0.57	12.52	BDL	0.0369	0.0435	BDL	0.97	22.78	7.77	330.16
TK15	7.94	42.1	3.90	1.72	126	2.77	0	247	1.02	13.88	BDL	0.0477	0.0473	BDL	1.67	9.74	7.04	397.76
TK16	8.29	49.2	4.01	1.70	147	2.35	0	305	1.71	11.09	BDL	BDL	0.0423	BDL	1.06	10.01	6.98	474.26
EOH	7.50	34.9	8.37	2.36	98.2	5.73	0	211	0.70	13.60	BDL	BDL	0.0598	BDL	1.26	20.94	9.66	341.32

Concentrations expressed in mg/L
BDL = below detection limits

Table 5-43: Results of the chemical analyses of water samples from borehole KZF-01 (micro determinands)

Sample #	Al	As	B	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Si	Sr	V	Zn	Mo	Ni	Sb	Se	U
TK1	0.110	BDL	0.290	0.010	BDL	BDL	BDL	BDL	0.150	0.010	BDL	12.1	0.04	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK2	0.240	BDL	0.300	0.020	BDL	BDL	BDL	BDL	0.510	0.030	BDL	12.4	0.04	BDL	0.02	BDL	BDL	BDL	BDL	BDL
TK3	0.260	BDL	0.330	0.020	BDL	BDL	BDL	BDL	0.500	0.040	BDL	12.5	0.03	BDL	0.03	BDL	BDL	BDL	BDL	BDL
TK4	0.050	BDL	0.300	0.010	BDL	BDL	BDL	0.06	0.020	0.010	BDL	12.3	0.05	BDL	0.02	BDL	BDL	BDL	BDL	BDL
TK5	0.090	BDL	0.300	0.010	BDL	BDL	BDL	0.03	0.070	0.010	BDL	12.6	0.06	BDL	0.02	BDL	BDL	BDL	BDL	BDL
TK6	0.060	BDL	0.310	0.010	BDL	BDL	BDL	0.02	0.030	0.010	BDL	12.7	0.07	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK7	0.050	BDL	0.320	0.020	BDL	BDL	BDL	0.01	0.010	BDL	BDL	12.9	0.07	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK8	0.010	BDL	0.310	0.020	BDL	BDL	BDL	0.01	0.020	BDL	BDL	12.6	0.07	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK9	0.100	BDL	0.300	0.020	BDL	BDL	BDL	0.01	0.170	0.020	BDL	12.2	0.08	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK10	0.120	BDL	0.320	0.020	BDL	BDL	BDL	BDL	0.200	0.020	BDL	13.0	0.07	BDL	0.01	BDL	BDL	BDL	BDL	BDL
TK11	0.027	BDL	0.129	0.060	BDL	BDL	BDL	0.012	0.032	0.017	BDL	18.5	0.53	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK12	0.030	BDL	0.121	0.066	BDL	BDL	BDL	0.018	0.035	0.019	BDL	19.5	0.57	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK13	0.022	BDL	0.105	0.070	BDL	BDL	BDL	0.013	0.024	0.017	BDL	18.6	0.59	BDL	BDL	BDL	BDL	BDL	BDL	BDL
TK14	0.030	BDL	0.116	0.069	BDL	BDL	BDL	0.025	0.044	0.020	BDL	18.9	0.58	BDL	0.02	BDL	BDL	BDL	BDL	BDL
TK15	0.146	BDL	0.211	0.029	BDL	BDL	BDL	BDL	1.876	0.048	BDL	14.1	0.03	BDL	BDL	0.02	BDL	BDL	BDL	BDL
TK16	0.023	BDL	0.291	0.018	BDL	BDL	BDL	BDL	0.251	0.007	BDL	12.8	0.08	BDL	BDL	BDL	BDL	BDL	BDL	BDL
EOH	0.202	BDL	0.119	0.032	BDL	BDL	BDL	BDL	0.664	0.051	BDL	20.1	0.32	BDL	0.04	BDL	BDL	BDL	BDL	BDL

Concentrations expressed in mg/L
BDL = below detection limits

The Expanded Durov Diagram shown in Figure 5-62 again demonstrates that sodium is the major cation, while total alkalinity is the major anion. All 11 groundwater samples plot together in a cluster near the top right-hand corner of the central square of the diagram. Samples that plot in this region of the diagram are typical of wastewater. However, the groundwater samples from KZF-01 are evidently not affected by wastewater. The high sodium concentrations must therefore have a natural origin.

The SAR Diagram (Figure 5-63) shows two distinct water types in terms of salinity. The shallower samples (TK4 to TK10) cluster together in an area showing a medium to high sodium hazard, while the deeper samples (TK11 to TK14) cluster together in a region indicating a low to medium sodium hazard. It is interesting to note that the deeper water samples generally have lower salt concentrations.

The Stiff Diagram shown in Figure 5-64 shows that all the water samples have very similar relative abundances of the major cations and anions. However, the deeper samples (TK11 to TK14) clearly have fingerprints in the Stiff Diagram that differ from the fingerprints of the shallower samples. This observation again shows that two distinct water types may be identified in borehole KZF-01.

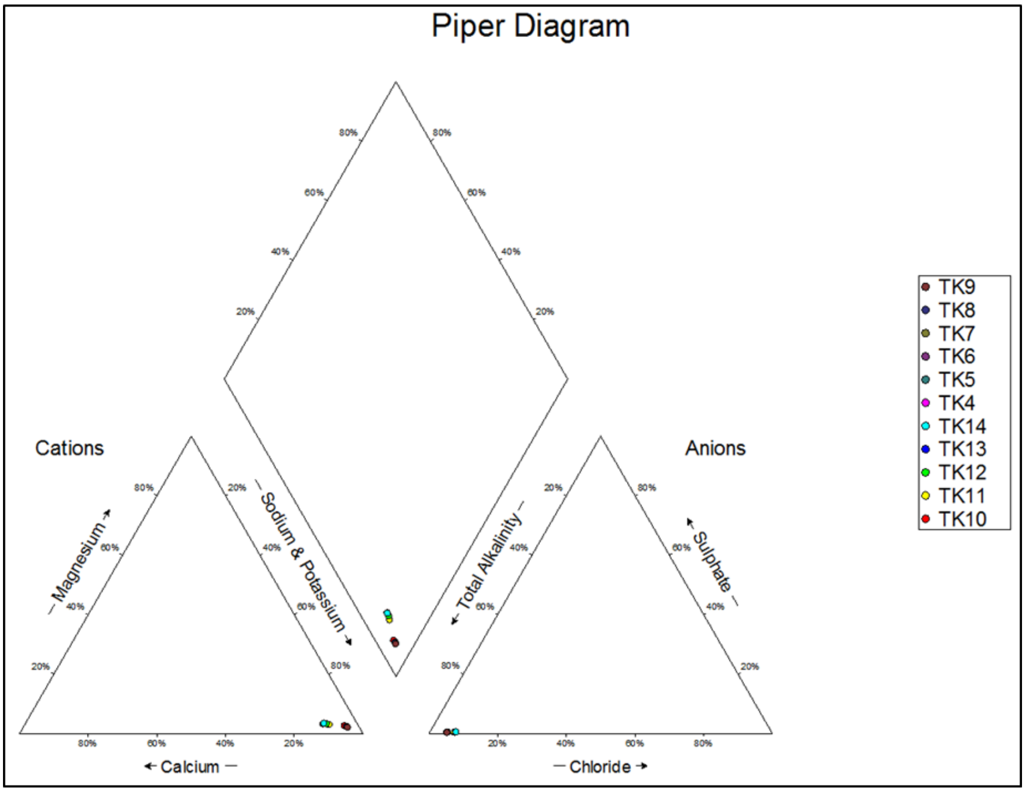


Figure 5-61: Piper Diagram of the groundwater samples from borehole KZF-01

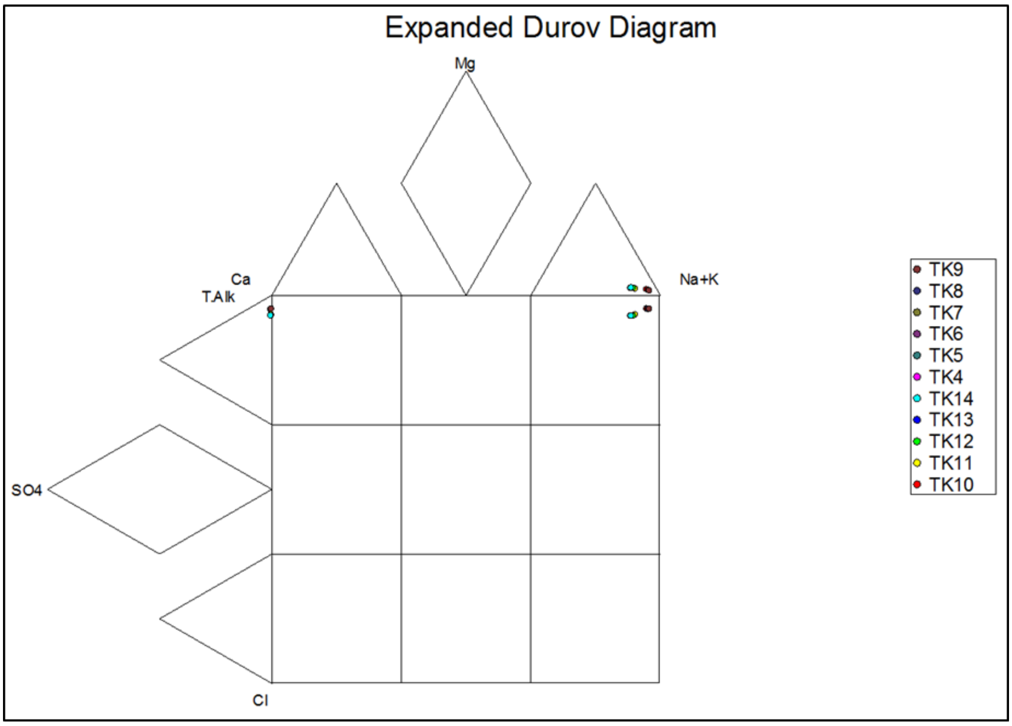


Figure 5-62: Expanded Diagram of the groundwater samples from borehole KZF-01

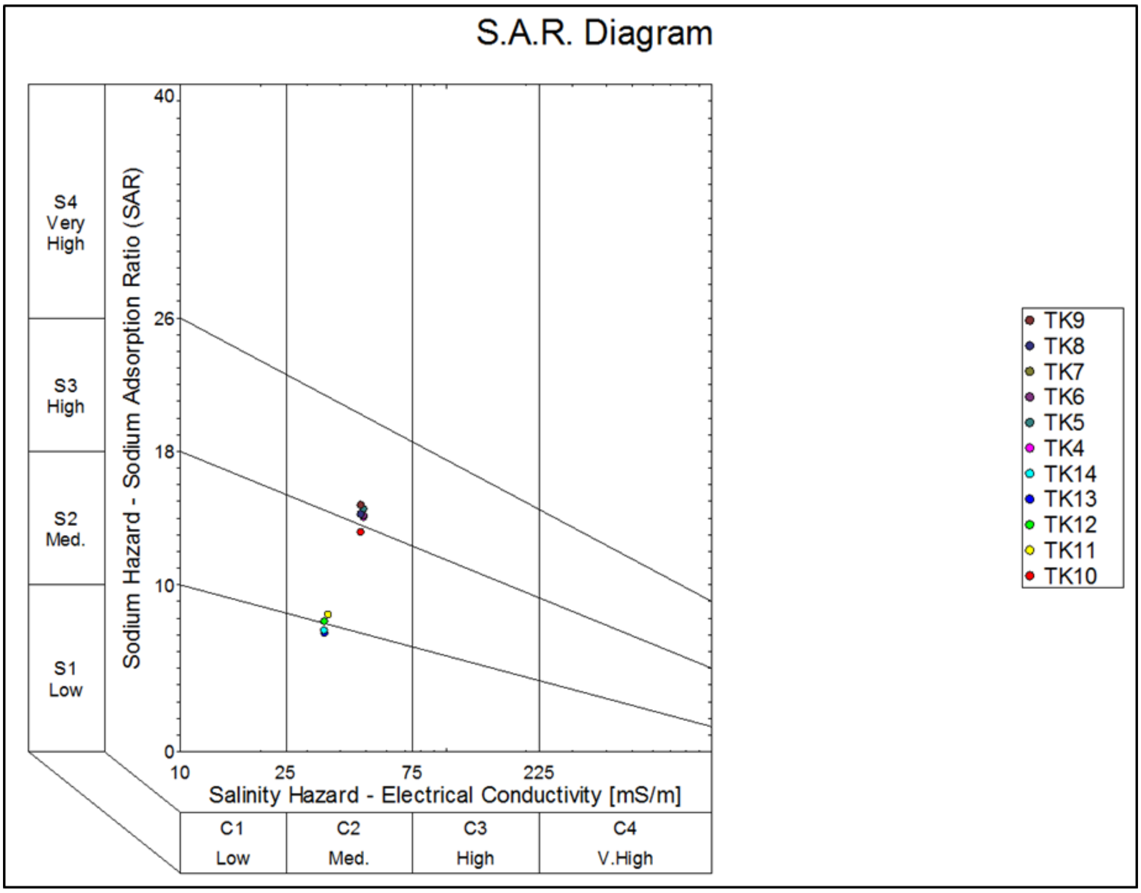


Figure 5-63: SAR Diagram of the groundwater samples from borehole KZF-01

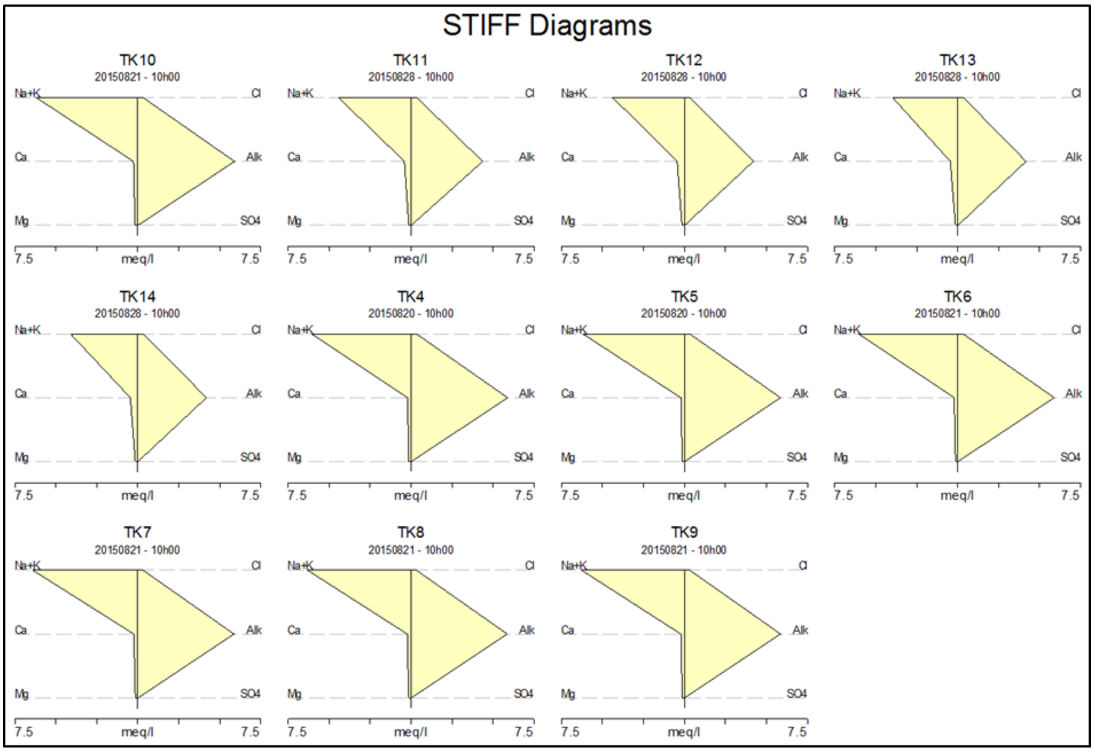


Figure 5-64: Stiff Diagram of the groundwater samples from borehole KZF-01

Although the relative abundances of the major cation and anion species suggest that only two distinct water types were encountered in borehole KZF-01, it should be noted that three distinct artesian water strikes occurred during drilling (refer to Section 5.7.2.2). It is quite possible that other non-artesian water strikes could have occurred, but went unnoticed in the core drilling process. It should also be kept in mind that mixing of the artesian waters is likely to have taken place as the water pushed up in the borehole from the different depths where water strikes had occurred. The depth-specific groundwater samples should therefore not be seen as representative of groundwater conditions at these specific depths.

5.7.2 Borehole KWV-01

Borehole KWV-01 was drilled near Willowvale in the Eastern Cape. The borehole was drilled in an area with abundant dolerite intrusives to allow comparison with the results of borehole KZF-01, drilled in a dolerite-free area. Borehole KWV-01 was drilled vertically to a depth of 2,353 m below ground level. Geophysical well logging was conducted after drilling.

5.7.2.1 Stratigraphy and lithologies

The lithological units intersected during the drilling of borehole KWV-01 are shown in Figure 5-65**Error! Reference source not found.**. The borehole intersected rocks that belong to the Beaufort and Ecca groups along most of its length. Rocks of the Dwyka Group were encountered at a depth of approximately 2,338 m below ground level.

The Beaufort Group is represented by the Balfour Formation, which mostly consists of interbedded mudstones and sandstones. A dolerite sill approximately 35 m thick was intersected in the Beaufort Group between depths of approximately 92 and 127 m below ground level.

Six formations of the Ecca Group were intersected by borehole KWV-01. These were the Waterford, Fort Brown, Ripon, Collingham, Whitehill and Prince Albert formations. Numerous dolerite sills were also encountered during drilling. The thickest dolerite sill had a thickness of almost 150 m. This sill was encountered in the Pluto's Vale Member of the Ripon Formation between depths of approximately 2,037 and 2,186 m below ground level.

Fault zones were intersected at depths of approximately 1,046, 1,122, 1,792 and 1,798 m below ground level. Fracturing was evident along much of the borehole length, particularly in the Waterford and Ford Brown formations, as well as in the Pluto's Vale Member.

5.7.2.2 Water strikes

Unlike in borehole KZF-01, no artesian water was intersected. It also appears that no non-artesian water strikes occurred during the drilling of borehole KWV-01, since attempts to sample the deep groundwater in the borehole yielded only drilling mud and diesel (De Kock et al., 2016b).

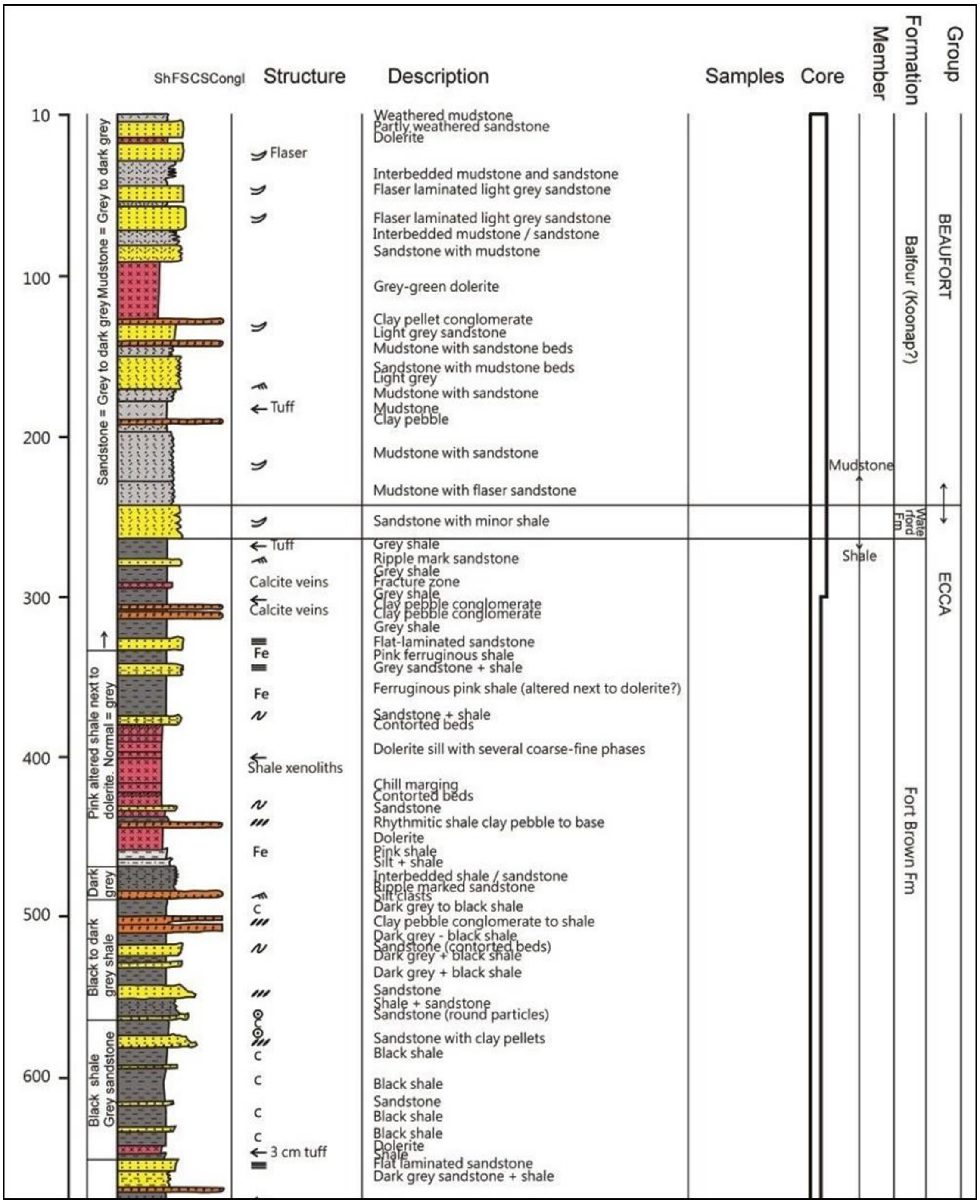
5.7.2.3 Geophysical logging

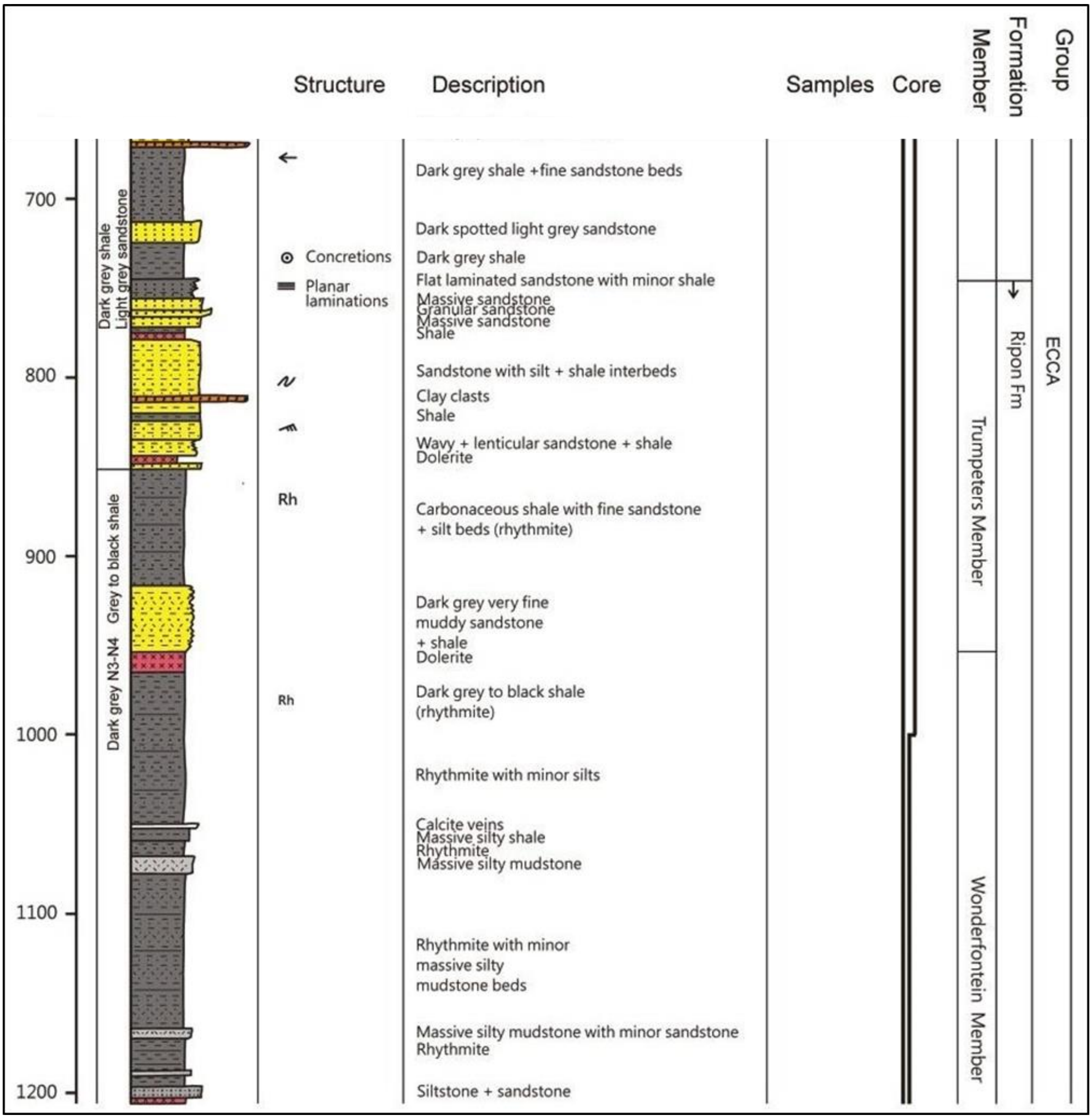
During January 2016, Weatherford Slimline Services conducted downhole geophysical surveys on borehole KWV-01 (De Kock et al., 2016b). The following geophysical logs were obtained: caliper, resistivity, density, ATV, sonic, neutron, formation dipmeter, flowmeter and verticality. The borehole was logged with the aim of providing *in-situ* measurements of the physical rock properties and fracture orientations to supplement knowledge gained from drilled core analysis.

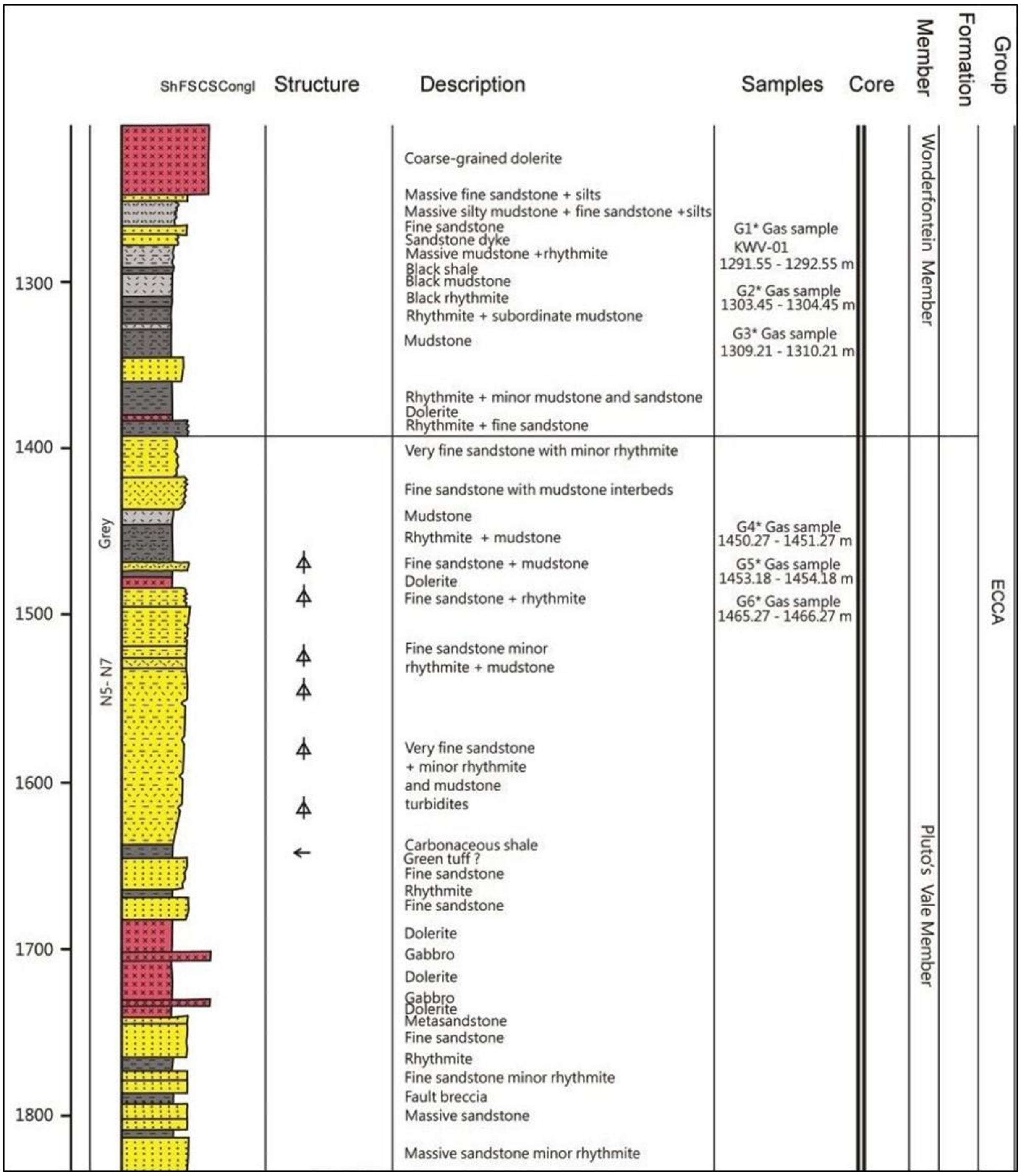
5.7.3 Summary

Comparison of the drilling results of boreholes KZF-01 and KWV-01 shows how varied the deep Karoo formations can be in terms of the occurrence of aquifers. Borehole KZF-01 was drilled at a position removed from dolerite intrusives and intersected both a shallow, non-artesian aquifer and deep artesian aquifers. Borehole KWV-01 was drilled in an area with abundant dolerite intrusions. Although faulting and fracturing of the geological formations were evident, no water strikes occurred in this borehole.

Since only two deep boreholes were drilled as part of the KARIN project, these results should not be seen as being representative of areas where dolerite intrusions occur and do not occur.


ShFSCSCongl
Structure
Description
Samples
Core
Member
Formation
Group
Weathered mudstone
Partly weathered sandstone
Dolerite
Flaser
Interbedded mudstone and sandstone
Flaser laminated light grey sandstone
Flaser laminated light grey sandstone
Interbedded mudstone / sandstone
Sandstone with mudstone
Grey-green dolerite
Clay pellet conglomerate
Light grey sandstone
Mudstone with sandstone beds
Sandstone with mudstone beds
Light grey
Mudstone with sandstone
Tuff
Mudstone
Clay pebble
Mudstone with sandstone
Mudstone with flaser sandstone
Sandstone with minor shale
Tuff
Grey shale
Ripple mark sandstone
Grey shale
Fracture zone
Calcite veins
Grey shale
Clay pebble conglomerate
Clay pebble conglomerate
Calcite veins
Grey shale
Flat-laminated sandstone
Fe
Pink ferruginous shale
Grey sandstone + shale
Fe
Ferruginous pink shale (altered next to dolerite?)
Sandstone + shale
Contorted beds
Dolerite sill with several coarse-fine phases
Shale xenoliths
Chill marging
Contorted beds
Sandstone
Rhythmitic shale clay pebble to base
Dolerite
Fe
Pink shale
Silt + shale
Interbedded shale / sandstone
Ripple marked sandstone
Silt clasts
Dark grey to black shale
Clay pebble conglomerate to shale
Dark grey - black shale
Sandstone (contorted beds)
Dark grey + black shale
Dark grey + black shale
Sandstone
Shale + sandstone
Sandstone (round particles)
Sandstone with clay pellets
Black shale
Black shale
Sandstone
Black shale
Black shale
3 cm tuff
Dolerite
Shale
Flat laminated sandstone
Dark grey sandstone + shale
10
100
200
300
400
500
600
Sandstone = Grey to dark grey Mudstone = Grey to dark grey
Pink altered shale next to dolerite. Normal = grey
Dark grey
Black to dark grey shale
Black shale Grey sandstone
Mudstone
Shale
Balfour (Koonap?)
Waterford Fm
Fort Brown Fm
BEAUFORT
ECCA


Structure
Description
Samples
Core
Member
Formation
Group
700
800
900
1000
1100
1200
Dark grey shale
Light grey sandstone
Dark grey N3-N4 Grey to black shale
Concretions
Planar laminations
Rh
Rh
Dark grey shale +fine sandstone beds
Dark spotted light grey sandstone
Dark grey shale
Flat laminated sandstone with minor shale
Massive sandstone
Granular sandstone
Massive sandstone
Shale
Sandstone with silt + shale interbeds
Clay clasts
Shale
Wavy + lenticular sandstone + shale
Dolerite
Carbonaceous shale with fine sandstone + silt beds (rhythmite)
Dark grey very fine muddy sandstone + shale
Dolerite
Dark grey to black shale (rhythmite)
Rhythmite with minor silts
Calcite veins
Massive silty shale
Rhythmite
Massive silty mudstone
Rhythmite with minor massive silty mudstone beds
Massive silty mudstone with minor sandstone
Rhythmite
Siltstone + sandstone
Trumpeters Member
Wonderfontein Member
Ripon Fm
ECCA


ShFSCSCongl
Structure
Description
Samples
Core
Member
Formation
Group
1300
1400
1500
1600
1700
1800
Grey
N5- N7
Coarse-grained dolerite
Massive fine sandstone + silts
Massive silty mudstone + fine sandstone +silts
Fine sandstone
Sandstone dyke
Massive mudstone +rhythmite
Black shale
Black mudstone
Black rhythmite
Rhythmite + subordinate mudstone
Mudstone
Rhythmite + minor mudstone and sandstone
Dolerite
Rhythmite + fine sandstone
Very fine sandstone with minor rhythmite
Fine sandstone with mudstone interbeds
Mudstone
Rhythmite + mudstone
Fine sandstone + mudstone
Dolerite
Fine sandstone + rhythmite
Fine sandstone minor
rhythmite + mudstone
Very fine sandstone
+ minor rhythmite
and mudstone
turbidites
Carbonaceous shale
Green tuff ?
Fine sandstone
Rhythmite
Fine sandstone
Dolerite
Gabbro
Dolerite
Gabbro
Dolerite
Metasandstone
Fine sandstone
Rhythmite
Fine sandstone minor rhythmite
Fault breccia
Massive sandstone
Massive sandstone minor rhythmite
G1* Gas sample
KWV-01
1291.55 - 1292.55 m
G2* Gas sample
1303.45 - 1304.45 m
G3* Gas sample
1309.21 - 1310.21 m
G4* Gas sample
1450.27 - 1451.27 m
G5* Gas sample
1453.18 - 1454.18 m
G6* Gas sample
1465.27 - 1466.27 m
Wonderfontein Member
Pluto's Vale Member
ECCA

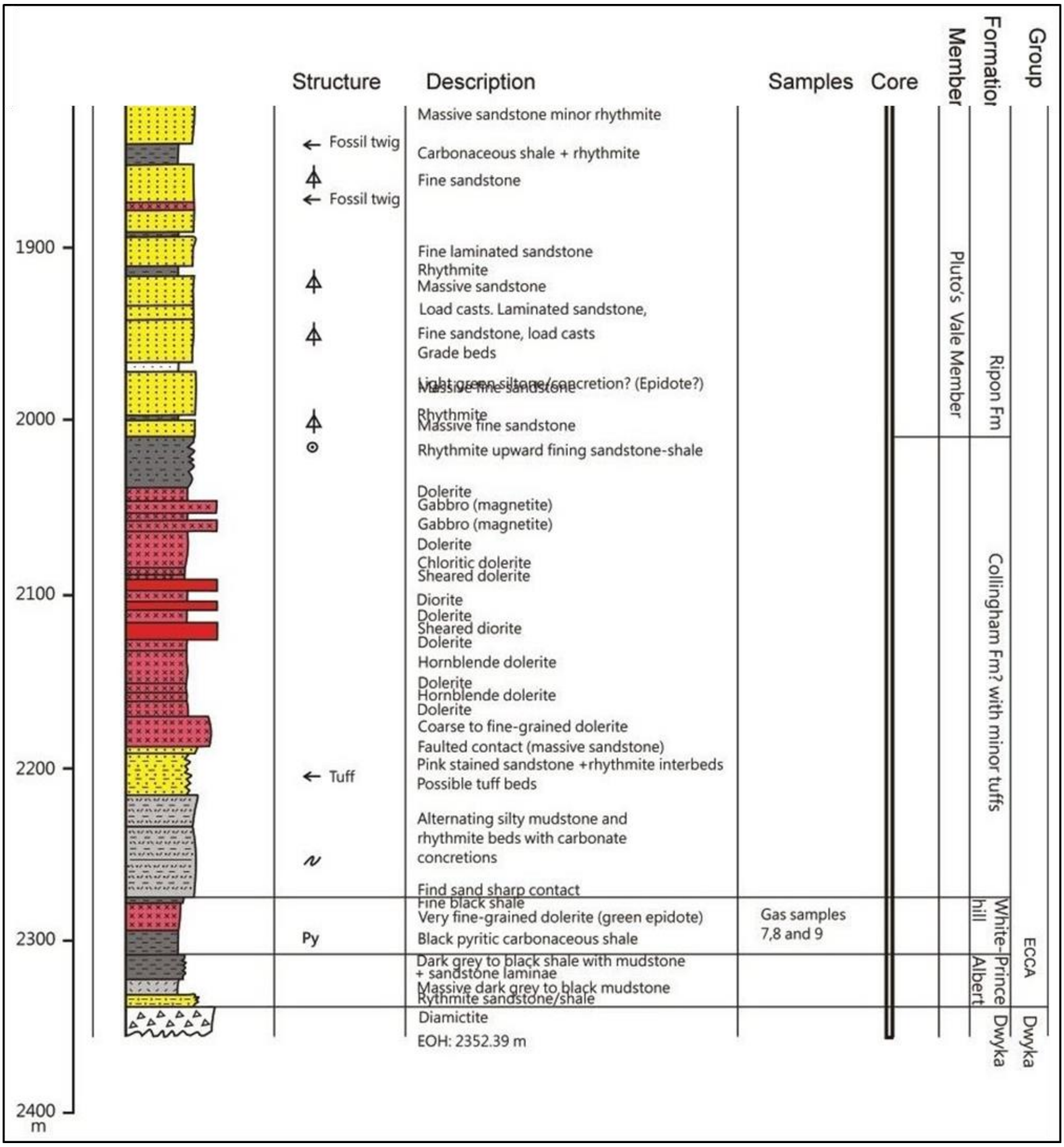


Figure 5-65 Error! Reference source not found.**:** **Geological log of borehole KWV-01**

A surprising result of the water analyses performed on the samples from borehole KZF-01 is the observation that the water quality of the deep aquifers is better than the shallow aquifer used by local farmers for groundwater supply. Although the groundwater from the deep aquifers may be associated with aquifer systems of the underlying Table Mountain Group, this observation shows the potential of exploiting the deep Karoo aquifers for water supply.

From the results of the two deep KARIN boreholes, characteristics of the deep aquifer systems in the Karoo Supergroup may be derived. In Table 5-44, the deep Karoo aquifers are characterised using the aquifer classification criteria listed in Section 5.2.

Table 5-44: Characterisation of the deep Karoo aquifer systems from the results of the KARIN boreholes

Criteria	Description
Lithology	The deep artesian aquifers intersected by borehole KZF-01 are all associated with fracture zones in the rocks of the Ecca and Dwyka Groups. In the Ecca Group, the water-bearing fractrure zones occurred in mudstones of the Prince Albert Formation and siltstones of the Dwyka Group.
Occurrence	The fracture zones acting as conduits for groundwater occurred at specific depths (560, 626 668 mbgl) and had limited vertical extents (a few metres at most). However, most of the water coming from the fractures is likely to be stored in the matrix of the sedimentary rocks hosting the fractures. The aquifers may therefore have significant vertical extents.
Physical dimensions	The vertical extents of the fracture zones encountered in KZF-01 werevery limited (a few metres at most). However, the sedimentary rocks hosting the fractures are likely to act as the main storage unit for the water. These sedimentary rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock are therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.
Aquifer type	The aquifers intersected by borehole KZF-01 were all of the double-porosity type, consisting of rock matrix in which secondary porosity was developed through fracturing.
Saturation level	The fact that all the deep water strikes were artesian shows that the aquifer systems were pressurised above hydrostatic pressure. This implies that the aquifer systems are fully saturated systems.
Heterogeneity and isotropy	The aquifer systems are highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and the rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks.
Formation properties	The porosities of the sedimentary rocks forming part of the aquifer systems are likely to be very low, due to the large depths of burial. Despite the small porosties, the sedimentary rock matrices are expected to act as the main water storage units. The fractures, by contrast, are expected to create localised zones with very high porosities.
Hydraulic parameters	The hydraulic conductivities of the rock matrices of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.
Pressurisation	The aquifers systems intersected during the drilling of KZF01 were all artesian, indicating that they are under high pressure.
Yield	Only the free-flowing rate of the deepest water strike in the Dwyka Group was measured. This rate (24 000 L/min) was very high, showing that significant yields from the deep aquifer systems could occur.
Groundwater quality	The quality of the groundwater from borehole KZF-01 was surprisingly good, better than the quality of the shallow aquifers used by the farmers in the area.
Aquifer vulnerability and susceptibility	The large depths of the aquifers suggest that these aquifers have low vulnerabilities to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be vulnerable to over-exploitation since little information is available on their rates of recharge and hence on the sustainable abstraction rates that can be employed.

CHAPTER 6: PROTECTION OF DEEP GROUNDWATER

6.1 INTRODUCTION

This chapter investigates the risks posed to South Africa's deep aquifer systems by various activities, such as fossil fuel production, carbon capture and storage, mining and groundwater extraction. It describes approaches to protect the deep aquifer systems.

Specific objectives include the following:

- Identify and describe activities that may impact on the quality and quantity of groundwater in the deep aquifer systems of South Africa
- Describe various approaches to the protection of the deep groundwater resource, including available technologies, best practices, regulatory tools and management options
- Provide information on the legal framework for the protection of deep aquifer systems, including international law, relevant South African legislature and the National Groundwater Strategy
- Identify gaps and challenges in the legal framework that need to be resolved
- Propose a generalised framework for the protection of deep aquifer systems
- Propose future actions related to the protection of deep aquifer systems

6.2 ACTIVITIES THAT MAY IMPACT ON DEEP AQUIFERS

In this section, activities that may impact on deep aquifer systems in South Africa are identified and the potential impacts of these activities on the deep groundwater resources are described. The following activities that could potentially impact on the quality and quantity of our deep groundwater resources are discussed:

- Conventional deep mining
- Conventional deep fossil fuel production
- Unconventional deep fossil fuel production
- Carbon capture and storage
- Groundwater abstraction from deep aquifers for water provision
- Artificial recharge of deep aquifers

6.2.1 Conventional deep mining

Conventional deep underground mining activities in South Africa include the following:

- (Potential) deep coal mining in the Waterberg and Springbok Flats coalfields
- Mines extracting PGM, gold, cobalt, chrome, copper, nickel and silver from great depths (up to 3,585 m) in the Bushveld Igneous Complex
- Deep mines (some with depths in excess of 3,900 m) that extract gold and uranium from the various goldfields of South Africa
- Deep diamond mines (with depths up to 1,097 m) at various locations in the central and northern parts of South Africa

Although mining below depths of 300 m is usually done through underground mining, a few open-cast operations extract ore from depths in excess of 300 m. An example of deep open-cast mining is the deep open-cast pit of Phalaborwa Copper (898 m).

6.2.1.1 Potential impacts of mining on the deep aquifer system

Mining activities have the potential to negatively affect the environment during the exploration and operational phases, as well as during decommissioning and after mine closure (Bianchini, 2016). The exploration phase of mining usually impacts on the environment at shallow depths, although deep exploration drilling may also impact on the deep aquifer systems. During the operational phase of mining, large volumes of ore and host rock are typically removed from the subsurface. The ore is then processed to extract the minerals of interest, while the host rock is discarded as waste rock (spoils). Groundwater from the aquifers that are intersected by mining often seeps into the underground voids created by mining. This water usually has to be removed from the mines to allow the safe continuation of mining. This process is called mine dewatering.

Deep aquifers that are intersected by mining could potentially be impacted on both in terms of the quality and quantity of the groundwater in the aquifers. Some of the potential impacts are described below.

6.2.1.1.1 Aquifer dewatering

Due to the influx of water during the mining operation and the safety hazard associated with this influx, water has to be removed from the workings to create a safe working environment. This is usually done by installing submersible pumps into the mine and pumping the water to surface (Morton, 2009). In the process of dewatering the mine, the aquifer from which groundwater influx occurs may also be dewatered if the rate of mine dewatering exceeds the rate of groundwater recharge. Although deep aquifers may in some cases be recharged along preferential pathways extending to the surface (such as major faults, dykes and dissolution cavities), the recharge rate to deep aquifer systems is generally expected to be low. Deep aquifers that are intersected by mines are therefore likely to be particularly vulnerable to dewatering.

6.2.1.1.2 Impacts on groundwater quality

The extraction of ore and host rock from deep mines may impact on the quality of the groundwater in the intersected aquifers. Blasting activities may result in elevated nitrate concentrations in the groundwater. Increased salt loads in the groundwater are generally associated with mining activities. The specific salts that affect the quality of the groundwater depend on the chemical composition of the host rock and ore, but elevated sodium, calcium, magnesium, chloride and sulphate concentrations are common to most deep South African mines.

In addition, when sulphide-rich minerals (such as pyrite) come into contact with oxygenated water, acidic conditions may be created, leading to acid mine drainage (McCarthy, 2011). Acid mine drainage often leads to a serious degradation of the groundwater quality. The acidic conditions that are associated with acid mine drainage may, in turn, cause the mobilisation of trace metals in the groundwater. Trace metals that are typically associated with acid mine drainage include arsenic, barium, cadmium, lead, mercury and selenium.

Groundwater contamination may also be specific to the ore being mined in the deep mines. Radioactive contamination of groundwater is common at gold and uranium mines.

The groundwater quality of deep aquifer systems may furthermore be affected by contaminants associated with mining operations. Fuel and lubricants used by mining machinery, as well as sewerage from the workforce, are potential contaminants that impact on the groundwater quality of the deep aquifers.

6.2.2 Conventional deep oil and gas production

Natural oil and gas were formed when ancient marine organisms died and their bodies were buried beneath sediments. Over millions of years of intense pressure, the decomposed bodies of the organisms were transformed into oil and gas.

The conventional method of abstracting oil and gas is by drilling wells into the subsurface to intersect the oil and gas reservoirs. Sometimes gas is removed along with the oil that occurrs in a reservoir. This gas is referred to as associated gas. Conventional oil and gas production may be done on either onshore or offshore platforms.

6.2.2.1 Conventional oil and gas production in South Africa

The Geological Survey of South Africa conducted the first official exploration for hydrocarbons in the 1940s. The onshore areas of the Karoo, Algoa and Zululand basins were extensively explored by the government-formed SOEKOR (Pty) Ltd oil and gas exploration company, which was established in 1965 (PASA, 2013a; PASA, 2016). In 1967, the Mining Rights Act was passed, and offshore concessions were granted to a number of international companies. This allowed for the first offshore well to be drilled in 1969, and subsequently the discovery of gas and condensate by Superior in the Pletmos Basin. In 1987, a gas-to-liquid (GTL) project was initiated in Mossel Bay. In 1970, SOEKOR, along with Rand Mines, extended the exploration for hydrocarbons to offshore potential resources (PetroSA, 2016a).

The GTL Refinery started operations in 1992. At the time, the Mossel Bay refinery was the largest of its kind in the world (PetroSA, 2016a). In 2003, South Africa produced approximately 930,000 tonnes of natural gas and 104,860 tonnes of associated condensate at its Mossel Bay GTL Refinery (Department of Energy, 2016).

Crude oil has been extracted from the Oribi and Oryx oilfields off South Africa's southern coast since 1996. To date, more than 45 million barrels of crude oil have been produced from these fields. On average, Oribi and Oryx currently produce approximately 1,800 barrels of crude oil daily. Although the reserves in both fields are fast depleting, plans to further develop the Oribi field are at hand (PetroSA, 2016b).

Approximately 300 exploration wells are located over the entire offshore area of South Africa, with the most active period being between 1981 and 1991 when 181 exploration wells were drilled. These offshore exploration wells have led to the discovery of several small oil and gas fields, and the commercial production of oil and gas from the Bredasdorp Basin. There are two undeveloped gas fields and a further six gas discoveries in the Pletmos Basin. One oil and several gas discoveries have been made in the South African part of the Orange River Basin (PASA, 2013a; PASA, 2016).

6.2.2.2 Potential impacts of conventional oil and gas production on deep aquifer systems

Conventional oil and gas extraction processes may contaminate deep aquifer systems with a variety of pollutants, including petroleum hydrocarbons, salts, organic compounds and heavy metals (Allen et al., 2016). Oil fields usually contain large volumes of saline water. Water that has already been in contact with crude oil is typically contaminated with hydrocarbons, heavy metals, hydrogen sulphide and boron (Allen et al., 2016). Water-related impacts are governed by multiple factors, such as the amount and type of fossil fuel, the extraction methods used, the physical and geological conditions and the regulatory requirements.

Conventional oil and gas production may impact on the groundwater in the deep aquifers during the exploration, production, decommissioning and post-closure phases. During exploration drilling, formation water from the deep petroleum deposits and deeper fossil water aquifers could contaminate deep freshwater aquifers that are intersected by drilling. Fossil water can contain very high salt loads, naturally occurring radioactive material (NORM) and various heavy metals (USEPA, 2011; Clark and Veil, 2009). Furthermore, if well integrity is not maintained, fluids and wastewater generated during exploration drilling may migrate from the wellbore and enter the deep freshwater aquifer systems. Similarly, during the production phase, if well integrity is not maintained and leakages occur, the petroleum product that is pumped to the surface could impact on the deep aquifer systems.

Well integrity is also of prime importance during the production phase, since similar impacts on the deep aquifer systems as during the exploration phase could occur. Since large volumes of oil and gas will travel along the well to the surface over extended periods of time during production, failing well integrity could lead to severe impacts on the deep aquifer systems.

Deep aquifers that are contaminated by organics during the exploration and production phases may be impossible to rehabilitate, both from an economic and from a physical perspective. Certain organic contaminants act as long-term contamination agents, which adsorb to soil particles and can effectively not be removed from aquifer systems due to the fact that sorption processes are spatially heterogeneous, non-linear, and potentially limited by solute diffusion to sorbent material located within the interior of soil particles (GAO, 2010; NRC, 2012). Non-linear and/or rate-limited desorption can potentially contribute to plume persistence over decades.

The American National Research Council (NRC) (2012) stated that restoration of groundwater that has been contaminated by anthropogenic releases remains a significant technical and institutional challenge, and that, in at least 126,000 sites across the USA, contamination occured at such levels that closure of these sites could not be obtained. This estimate is a gross under-estimate according to the NRC (2012). Estimates on clean-up costs are in the region of $110 billion to $127 billion, which is also likely to be a gross under-estimate. Certain organic components are also very toxic to biologic life, even if they occur at parts per billion levels in groundwater (Mayer and Hassanizadeh, 2005).

6.2.3 Unconventional oil and gas production

Unconventional oil and gas production refers to fossil fuels that are extracted using techniques other than those that have been routinely used. The distinction between conventional and unconventional oil and gas changes over time as technologies that were once considered unconventional find broad application and become conventional technologies. The unconventional technologies described in this section should therefore be seen as unconventional only because they are relatively new at the present time.

In South Africa, unconventional oil and gas are produced at Sasol’s coal-to-liquid (CTL) plants, as well as at PetroSA’s GTL plant. However, since conventional methods are used to abstract the raw fossil fuels (conventional coal mining for CTL plants, and conventional gas production for the GTL plant), the impacts of these activities are considered under Section 6.2.2 (Conventional deep oil and gas production).

6.2.3.1 Unconventional oil

Unconventional oil is petroleum that is produced by methods other than the conventional oil well method. Some sources of unconventional oil are briefly described below.

6.2.3.1.1 Oil sands (tar sands)

Oil sands generally consist of extra heavy crude oil or crude bitumen that is trapped in unconsolidated sandstone. Due to the high viscosity of these oils, they cannot be produced by conventional methods, nor can they be transported without heating or dilution with lighter hydrocarbons, or refined by standard oil refineries without major modifications. Heavy crude oils often contain high concentrations of sulphur and heavy metals, particularly nickel and vanadium, which interfere with refining processes. These properties present significant environmental challenges to the growth of heavy oil production and use.

6.2.3.1.2 Tight oil

Tight oil is crude oil that is contained in petroleum-bearing formations of low permeability, often shale or tight sandstone. Economic production from tight oil formations requires the same hydraulic fracturing and often uses the same horizontal well technology as is used in the production of shale gas.

6.2.3.1.3 Oil shale

Oil shale is an organic-rich, fine-grained sedimentary rock that contains significant amounts of kerogen (a solid mixture of organic chemical compounds) from which technology can extract liquid hydrocarbons (shale oil) and combustible oil shale gas.

6.2.3.1.4 Coal and gas conversion

Using synthetic fuel processes, the conversion of coal and natural gas has the potential to yield great quantities of unconventional oil and/or refined products, albeit at a much lower net energy output than the historic average for conventional oil extraction.

6.2.3.2 Unconventional gas

Unconventional gas is natural gas obtained by technologies that are considered new and different to the standard technologies used in the gas industry. Some sources of unconventional gas are described below.

6.2.3.2.1 Shale gas

Shale gas is natural gas that is found trapped within shale formations of low permeability. To extract the natural gas from the shale, the permeability of the rock is usually increased through the process of hydraulic fracturing (fracking). Fracking involves the injection under high pressure of fracking fluid into the shale formations to cause fracturing and thus increase the permeability of the rock, thereby allowing natural gas to be released. Different fracking fluids are used by different companies, but usually it consists of water containing sand (or other proppants) and thickening agents. The purpose of the proppant is to keep the fractures created by fracking open when the hydraulic pressure is removed.

6.2.3.2.2 Coalbed methane

Coalbed methane is a source of natural gas that is generated and stored in coal beds. Coal therefore acts as both the source and reservoir rock, with the methane being produced by microbial (biogenic) or thermal (thermogenic) processes. Coal has a large surface area and can hold enormous quantities of methane. Since coal seams have large internal surfaces, they can store six to seven times more gas than the equivalent volume of rock in a conventional sandstone gas reservoir. Coalbed methane exists in coal in three basic states: as free gas, as gas dissolved in the water in coal, and as gas adsorbed onto the solid surface of the coal (PASA, 2013b). Since the adsorption capacity of coal increases with depth, deeper coal seams generally contain more methane than shallow seams (Xaba and Jeffrey, 2002). For coalbed methane production, coal beds should be buried at depths greater than 200 m, but preferably greater than 600 m (PASA, 2012a).

6.2.3.2.3 Methane hydrate

Methane hydrate is a solid compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice. Significant deposits of methane hydrate have been found under sediments on the ocean floors of the earth. Methane hydrates are believed to form by the migration of gas from deep along geological faults, followed by precipitation or crystallisation on contact of the rising gas stream with cold sea water. Although research has been conducted to investigate the possibility of extracting methane from hydrate deposits, no commercial production of gas from methane hydrate is currently taking place.

6.2.3.2.4 Synthetic natural gas

Synthetic natural gas is fuel gas produced from fossil fuels, such as coal and oil shale, or from organic plant matter.

6.2.3.2.5 Tight gas

Tight gas is similar to shale gas in that it occurs in rock materials of such low permeabilities that hydraulic fracturing is required to release the gas. However, tight gas is considered to be separate from shale gas since it does not occur in shale, but usually in sandstones and limestones of low permeability.

6.2.3.2.6 Underground coal gasification

Underground coal gasification is an *in-situ* combustion technique that converts coal underground into a combustible gas, thus providing a clean and convenient source of energy from coal seams where traditional extraction methods are economically, environmentally or technically inappropriate (e.g. in areas where coal seams occur at great depth) (Xaba and Jeffrey, 2002). The product gas is brought to the surface through production wells drilled from the surface.

6.2.3.2.7 Deep biogenic gas

Deep biogenic gas is an unconventional gas that is produced directly by microorganisms at great depth during respiratory and fermentative processes (microbial gas). Gas encountered is not generally contained in traps, but is continually generated at depth. The gas is composed predominantly of methane and other hydrocarbons, including helium. In South Africa, deep biogenic gas occurs in the deep mines in the Witwatersrand Basin, and has been noted in the Free State and Evander goldfields (PASA, 2012b).

6.2.3.2.8 Coalmine methane

Coalmine methane is produced as a result of the fracturing of coal during current and past mining operations. The fracturing causes the methane to be desorbed from the coal and released into the air. Because methane is explosive in air in concentrations ranging from 5 to 15%, safety procedures require the removal of the methane released during mining (Xaba and Jeffrey, 2002). There are currently no active coalmine methane recovery or end-use activities in South Africa.

6.2.3.3 Unconventional oil and gas production in South Africa

In South Africa, unconventional fuel is currently produced from the following sources:

- Coal conversion to liquid fuel at Sasol's CTL plants
- PetroSA's gas conversion to liquid fuel at the Mossel Bay GTL Plant
- Coalbed methane extraction
- Underground coal gasification

Apart from the above unconventional fuel production methods, the following sources of unconventional gas could potentially contribute to South Africa's energy mix:

- Shale gas
- Coalmine methane
- Methane hydrate
- Deep biogenic gas

6.2.3.4 Potential impacts of unconventional oil and gas production on deep aquifer systems

Of the unconventional sources of fuel listed in Section 6.2.3.3, deep biogenic gas, coalmine methane, the extraction of coalbed methane and shale gas, as well as underground coal gasification, could potentially impact on South Africa's deep aquifer systems.

6.2.3.4.1 Coalbed methane

Extraction of coalbed methane

The production of coalbed methane differs from conventional gas production. During conventional gas production, the pressure of the gas in the reservoir causes the gas to flow to the surface along the extraction well. However, coal beds are usually associated with groundwater, which holds the natural gas within the coal. As a result, gas production from coal beds requires the reduction of the water pressure by means of pumping (Fisher, 2003).

To extract the methane from coal beds, a steel-encased hole is drilled vertically into the coal seam and cemented into place. To increase the rate of gas extraction, the extraction hole may be deflected horizontally to run along the coal bed. If the coal bed is characterised by low permeabilities, hydraulic fracturing may be used to stimulate the release of natural gas (Fisher, 2003).

After the installation of the extraction well, water is pumped from the well to decrease the pressure within the coal seam and stimulate desorption on the methane (USGS, 2000). As a result of the pumping, both gas and produced water come to the surface through tubing. The produced water is reinjected into isolated formations, released into streams, used for irrigation or sent to evaporation ponds (Fisher, 2003). The water typically contains dissolved solids such as sodium, bicarbonate and chloride, but varies depending on the formation geology (USGS, 2000). The sulphate concentrations of coalbed methane waters are relatively low because the chemical conditions in coal beds favour the conversion of sulphate to sulphide, which is removed as a gas or as a precipitate. The TDS concentration of coalbed methane water may range from fresh (200 mg/ℓ) to saline (170,000 mg/ℓ) (USGS, 2000).

Potential impacts of coalbed methane extraction on deep aquifers

The extraction of coalbed methane may impact on both the quantity and quality of the groundwater in deep aquifer systems. In some areas, coal beds are known to act as regional or local aquifers (USGS, 2000). Since groundwater often has to be removed from the coal bed to reduce the pressure, dewatering of the deep aquifer may result. Contaminant impacts on the deep aquifer system may occur through several mechanisms, including seepage of gas and contaminated water through the fracture networks or along the annular space surrounding the well. Well integrity is therefore of prime importance to prevent contaminant impacts on the deep aquifer systems. If the produced water is disposed of in the subsurface through injection wells, direct impacts on the quality of the groundwater in the aquifer systems can be expected.

If hydraulic fracturing is used to increase the degree of fracturing on the coal seams, additional contaminants may be introduced into the deep aquifer systems in the form of fracking fluid. Fracking fluids often contain chemicals that are highly toxic, water soluble, volatile and highly mobile (MBM, 2010).

6.2.3.4.2 Shale gas

The shale gas reserves in South Africa have been estimated at 11 trillion cubic metres (tcm) (IEA, 2013). Although no shale gas extraction has taken place in South Africa, the possibility exists that future demands for energy may necessitate the exploitation of this resource. During 2009 and 2010, various multinational oil and gas corporations submitted applications for shale gas exploration permits to PASA (Bosman, 2011). The shale gas exploration rights awarded to these corporations are shown in Figure 6-1. The exploration areas cover approximately 150,000 ha (almost 40% of the surface area of South Africa).

The following Karoo rock formations are thought to be suitable for shale gas extraction (Steyl et al., 2012):

- The Whitehill Formation (Cape region)
- The Prince Albert Formation (Cape region)
- The Volksrust Formation (Free State and KwaZulu-Natal regions)

- The Vryheid Formation (Free State and KwaZulu-Natal regions)
- The Pietermaritzburg Formation (KwaZulu-Natal region)
- The Dwyka shales (all regions that are shallow enough)

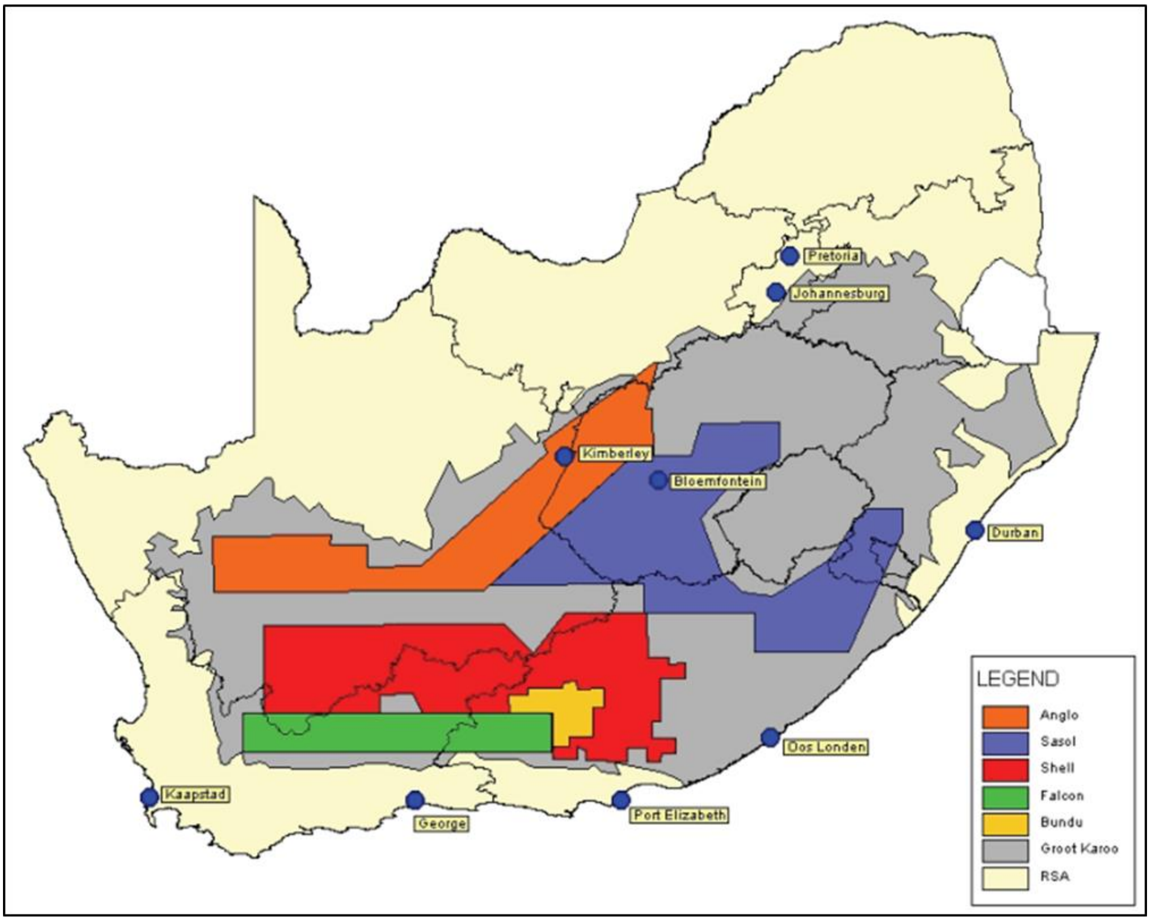


Figure 6-1: Shale gas exploration rights in South Africa (Steyl et al., 2012)

The formation of most interest in terms of shale gas development is the Permian-age Whitehill Formation of the lower Ecca Group, which contains an organic-rich, thermally mature black shale unit (Kuuskraa et al., 2013). The depth of the potential shale gas horizon in the Main Karoo Basin varies between approximately 1,000 m in the west and approximately 3,450 m in the east of the basin (KGEG, 2013).

Gas production through hydraulic fracturing

Hydraulic fracturing (fracking) is commonly used to enhance gas production from low permeability formations such as tight sands, coal beds and deep shales. During the hydraulic fracturing process, drilling is initially done vertically through the geological strata that overlies the horizon of interest for gas production. Casing is installed along the length of the borehole up to the depth where all viable aquifer systems have been sealed off to protect the groundwater resources from potential contaminants associated with the fracking process (Kotzé, 2012). As drilling proceeds deeper and deeper with the repeated addition of drilling pipes, different casing diameters are installed and cemented into the drilled holes, which become successively smaller in diameter with increased depth (USEPA, 2015).

At the depth of the gas-bearing shale layer, the borehole is deflected in a horizontal direction to run along the shale layer. Horizontal drilling may continue for up to 3 km. Once the horizontal borehole has reached its target extent, production casing is installed and cemented into place to prevent leaking.

The production casing is then punctured at selected points where fracturing fluid will be pumped through at a high pressure to fracture the shale, thereby increasing its permeability so that the shale gas can be released from the rock matrix (Kotzé, 2012). The chemical composition of the fracturing fluid, as well as the rate and pressure at which it is pumped into the shale, is tailored to the specific properties of each shale formation (Kotzé, 2012).

After hydraulic fracturing, the packers that isolate the segments from one another are drilled out, the pressure is reduced and some of the hydraulic fracturing fluid, together with naturally occurring fluids and gas from the production zone, returns to the surface (Mair et al., 2012). This fluid is known as flowback fluid or flowback water. After a few weeks, the water that returns to the surface is predominantly water from the fractured rock formation and is known as produced fluid or produced water. In general, 30 to 40% of the injected fluid will be recovered, but in some cases, this percentage can be much less (King, 2012; Rivard et al., 2012). The wastewater (flowback water and produced water) is kept on site in lined ponds or storage tanks. The water is generally moved off-site for disposal or treatment (CCA, 2014).

Potential impacts of shale gas extraction on deep aquifer systems

The major mechanisms whereby shale gas development through hydraulic fracturing can lead to the contamination of the deep groundwater resources are as follows (USEPA, 2006; Birol et al., 2012; Krupnick et al., 2014; Van Tonder et al., 2013):

- Deficiencies in the well casing or cement, which can lead to the unintended movement of liquids or gases along the outside of the production well or out of the production well into the deep aquifer systems.
- The movement of gases or liquids through the geological formation from the production zone.
- After production, the migration of contaminants associated with the hydraulic fracturing process along geological structures (faults and dykes) and along compromised casings due to the artesian and sub-artesian conditions in the Karoo.

Well integrity and the presence of geological structures that may act as preferential pathways for contaminant migration are therefore the main concerns when considering the potential impacts of hydraulic fracturing on the deep aquifer systems. It should, however, be taken into account that the deep aquifer systems in the Karoo Basin are expected to contain highly saline water. This water would likely require treatment prior to use. Contaminant impacts on the water quality may therefore be a lesser concern.

Apart from contaminant impacts on the quality of the deep groundwater resource, potential impacts may also occur on the quantity of water. The deep aquifer systems are known to be pressurised, with artesian or sub-artesian conditions reported at all deep boreholes that intersect these aquifer systems. Where artesian conditions occur, problems with well integrity may cause water from the deep aquifers to flow into the well or annulus and be released at the surface, thereby dewatering the aquifers.

6.2.3.4.3 Deep biogenic gas

Mining activities in South Africa have often been interrupted by safety concerns related to the presence of underground natural gas. For decades, this gas was considered to be a mine explosion hazard and was flared in large quantities without harnessing the energy (PASA, 2012b). With an increasing demand for energy, the deep biogenic gas (DBG) is now considered to be a potential source that could be exploited.

Although no DBG harvesting activities currently take place in South Africa, this natural gas resource could soon be included in the country's energy mix. The exact technologies that will be used are at present not known, but gas extraction would probably involve the installation of extraction wells in the rock face and pumping the gas to the surface through pipes running through the shafts.

The potential impact of the extraction of DBG on the deep aquifer systems is likely to be relatively small compared to the other impacts of deep mining operations (refer to Section 6.2.1.1). Since DBG has only been detected in deep mines in South Africa, its potential impacts on the deep aquifers may be considered a potential additional impact of mining.

6.2.3.4.4 Underground coal gasification

Eskom Resources and Strategy has estimated that South Africa has an estimated 45 billion tonnes of coal suitable for underground coal gasification (UCG), excluding the coalfields in KwaZulu-Natal, Ermelo and Witbank (Van der Riet, 2008). This coal was previously considered unminable. Furthermore, almost three quarters of South African coal resources (of which 70% is found in the northern Karoo basins of South Africa and 40% in the Ellisras Basin) are regarded as unminable when considering conventional coal-mining techniques (Van der Riet, 2008). These resources may, however, potentially be accessed through UCG.

Underground coal gasification may be used to harness energy from coal resources that cannot be conventionally mined through open-pit or long-wall mining, either because the coal is too deep to be mined economically or the geometry and physical conditions of the coal seams make it uneconomical or unsafe to mine conventionally (Van der Riet, 2008). Eskom has been running a UCG project in the Majuba Coalfield since January 2007. This is the longest-running UCG trial in the western world (Bhutto et al., 2013).

Gas production through underground coal gasification

Underground coal gasification is the process of gasifying coal *in situ* within the underground coal seam. The UCG process involves the installation of both injection wells and production wells in the coal seam. The coal is “mined” by igniting the underground coal in a cavity and injecting oxygen and water (steam) into the injection well to sustain the burning process. This is done to produce combustible synthetic gas (syngas), which is captured by the production wells.

The two most widely used UCG techniques in establishing a connection between the injection and production wells are the continuous retraction injection point (CRIP) process and the εUCG process. The linear CRIP method is the most efficient and successfully used method for UCG, while the εUCG process is a proprietary process with little published information on its workings (Burton et al., 2006).

Injection wells are usually drilled vertically into the coal seam, and then deflected horizontally to run along the coal seam for a distance of around 100 m. The purpose of the injection well is to introduce gasification agents, such as water and air or pure oxygen, to the coal seam and to introduce the ignition device at the coal seam to initiate the gasification process (Creedy et al., 2001). The injection well is cemented into place above the reaction zone to prevent gasses from escaping through the stainless steel well into the overlying formations and to facilitate the controlled introduction of air into the reaction zone (Burton et al., 2006). After the coal has been ignited, oxidant (air or pure oxygen) and steam are injected into the injection well to maintain the combustion of the coal, and to produce syngas. The steam is injected at a closely managed pressure to prevent an uncontrollable inrush of groundwater into the chamber, while also preventing gas loss and contaminant migration into the surrounding rock material.

Potential impacts of underground coal gasification on deep aquifer systems

Underground coal gasification may, in future, target those coal reserves in South Africa that are too deep to mine economically. It is therefore possible that UCG operations could, in future, impact on the subsurface at depths greater than 300 m and could therefore affect the deep aquifer systems.

Groundwater contamination is the most serious risk associated with UCG operations (Kapusta et al., 2013). During gasification, different gasification compounds, such as phenols and polycyclic aromatic hydrocarbons (PAHs) may migrate from the gasification zone and contaminate the groundwater resources (Burton et al., 2006).

The major mechanisms through which UCG operations could lead to groundwater contamination are as follows (Ahern and Frazier, 1982; Booth, 2002; Sury et al., 2004; Liu et al., 2006):

- Land subsidence due to the removal of material from the underground coal formation may cause pathways to form (such as induced fracture zones). The induced fractures in the overlying formations may also serve as preferential pathways for fluid and gas migration towards the shallow groundwater resources. However, this risk decreases with increasing depth of UCG.
- Contaminants from the coal seam disperse to and penetrate the surrounding rock layers and aquifers through diffusion.
- Contaminants leach from the underground residue by natural groundwater influx after the gasification process.

In addition, potential impacts related to the integrity of the injection and production wells include impacts related to poor well construction, gas migration along the annulus of the well, as well as unforeseen accidents during drilling.

Contaminants in both the aqueous and the gaseous phase may impact on the aquifer systems. Furthermore, during the gasification process, the host rock is also affected and may contribute to the salt loads, thereby affecting the groundwater quality.

6.2.4 Carbon capture and storage

Carbon capture and storage (CCS) is a process involving the separation of CO_2 from industrial and energy-related sources, transporting it to an appropriate storage location and storing it underground for long-term isolation from the atmosphere (IPCC, 2005). The purpose of CCS technology is to decrease the harmful impact of anthropogenic greenhouse gas emissions on the environment.

The world's first CCS project, Sleipner, started in Norway in 1996 and continues to operate today, storing approximately 1 million tonnes of CO_2 in the North Sea every year. Carbon capture and storage projects are entering operation, under construction or in advanced stages of planning in Australia, Canada, Saudi Arabia, the United Arab Emirates and the USA. The current world quantity of CCS is nearly 10 million tonnes of CO_2 captured and verified as stored every year (IEA, 2015).

Carbon capture and storage is achieved by geological storage of CO_2. The geological storage of CO_2 involves the injection of anthropogenic CO_2 into the underground formations, where it can be securely and permanently stored. Geological storage could target depleted oil and gas reservoirs, deep saline formations or unmineable coal seams. Carbon dioxide storage in depleted oil and gas reservoirs is analogous to how the original hydrocarbons were naturally trapped in the underground reservoirs. In deep saline aquifers, the CO_2 becomes trapped in the pore spaces between grains of sedimentary rock. For unmineable coal beds, the CO_2 displaces the coalbed methane adsorbed onto the coal surfaces (Viljoen et al., 2010).

The geological storage of CO_2 targets geological formations at depth, generally below 800 m for saline aquifers, and at a maximum of 300 m for coalbeds. Geological basins with deep, relatively slow, regional groundwater flow systems are preferrable to basins with shallow, short groundwater flow systems, which act negatively on the CO_2 storage potential of a basin. In terms of lithology, a large, deep, simple, undeformed and layered sedimentary basin with alternating sandstone and mudstone layers is preferrable. These CO_2 storage preferences seem to overlay those applied to locate potential deep groundwater (Viljoen et al., 2010).

Literature on the geological storage of CO_2 in saline aquifers has made the assumption that all groundwater in deep aquifers is saline, but this is not always the case. If the geological storage of CO_2 is limited to deep aquifers that are indeed saline and not fit for human consumption, the risk of impacting on a potential water source is reduced. Yet, if the storage of CO_2 further contaminates an already saline deep aquifer, which may be considered an unconventional water source in the future, it raises the question whether this consequence is acceptable compared to the benefits of CCS.

6.2.4.1 Carbon capture and storage in South Africa

Carbon capture and storage is not currently being implemented in South Africa, yet feasibility studies have been performed (Viljoen et al., 2010). It thus needs to be considered as an activity that could impact on deep aquifers in future.

The South African Centre for Carbon Capture and Storage (SACCCS) was launched in 2009 as a collaborative research organisation to further the technical understanding of the CCS potential in South Africa. The SACCCS has developed the South African Carbon Capture and Storage Roadmap, which was endorsed by Cabinet in May 2012. The roadmap for the commercial application of CCS in South Africa is summarised in Figure 6-2. The five phases of the roadmap are as follows:

- A preliminary potential investigation
- The compilation of a geological storage atlas
- The initiation of a pilot CO_2 storage project
- The development of a demonstration plant
- The commercial operation of a CO_2 storage project

The first two phases have already been completed and the pilot CO_2 storage project is expected to be realised in 2017.

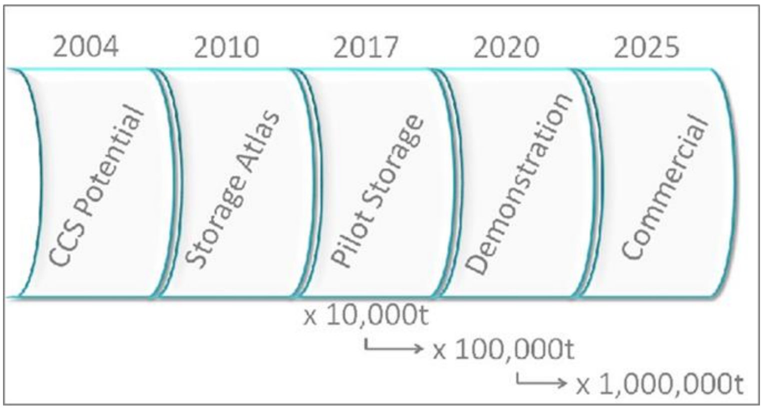


Figure 6-2: Illustration of the SACCCS roadmap for the commercial application of carbon capture and storage in South Africa (SACCCS, 2016)

6.2.4.2 Potential impacts of CCS on deep aquifer systems

The advantage and purpose of CCS technology is to decrease the harmful impact of anthropogenic greenhouse gas emission on the environment. However, the environmental benefits of CCS need to outweigh the potential environmental risks. The greatest environmental risk associated with CCS is linked to the long-term storage of the captured CO_2. The leakage of CO_2, either gradual or abrupt, could negate the initial environmental benefits of capturing and storing CO_2 emissions, and could even have harmful effects on human health (COA, 2007). The main potential impacts of CCS include local risks associated with CO_2 pipeline transport, local health, the safety and environmental risks of the underground or geological storage of CO_2, and the risks associated with chemical alterations or reactions in response to increased concentrations of CO_2 in the host rock and groundwater (IPCC, 2005).

The main focus of the environmental protection aspects related to CO_2 storage has traditionally been on shallow aquifers, and a plethora of information is available from this perspective. Some of the potential impacts on the shallow groundwater resources, in response to deep CO_2 storage, are illustrated in Figure 6-3. The greatest environmental risk for shallow groundwater is associated with the potential leaks of CO_2 (Figure 6-4).

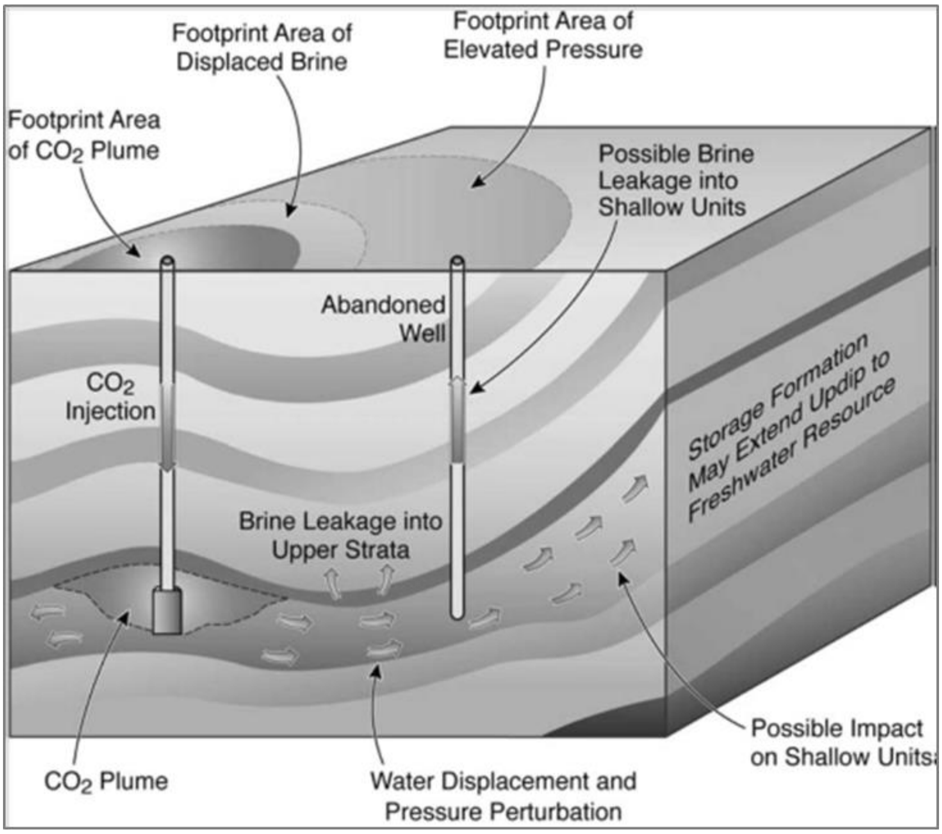


Figure 6-3: Schematic diagram of the potential impacts of CO_2 storage on shallow groundwater resources (IEAGHG, 2011)

From the perspective of protecting potential deep groundwater, the amount of research and literature is limited. The limited research conducted has shown that deep aquifers could potentially be vulnerable to contamination by geological CO_2 storage (Little and Jackson, 2010; Apps et al., 2010; Wang and Jaffe, 2004; Zheng et al., 2009). The main environmental concerns for deep groundwater that have been identified are the risks associated with chemical alterations or reactions in response to increased concentrations of CO_2 in the host rock and deep groundwater, and the displacement of deep groundwater in response to the injection of CO_2.

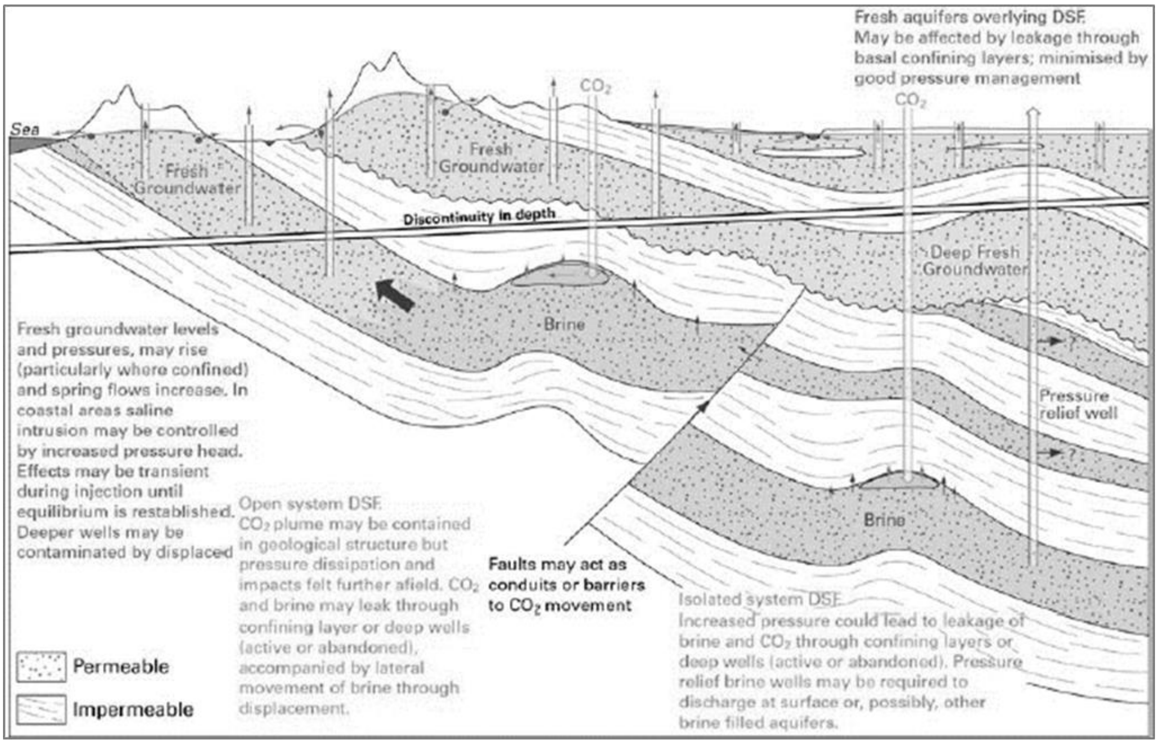


Figure 6-4: Schematic diagram to illustrate the potential leakage mechanisms of storage on fresh groundwater (IEAGHG, 2011)

6.2.4.2.1 Chemical alterations or reactions

The dissolution of CO_2 in a freshwater aquifer (potentially a deep aquifer) increases the total concentration of dissolved carbonate and thus increases acidity. The increased acidity can enhance the dissolution of minerals, including those containing hazardous trace elements such as arsenic, barium, cadmium, mercury, lead, antimony, selenium and uranium. The resulting increase in concentration of hazardous trace elements could detrimentally impact the quality of the groundwater (Apps et al., 2010).

6.2.4.2.2 Displacement of deep groundwater

By injecting CO_2 into deep storage formations, the original groundwater within these formations can be displaced. This displacement of groundwater, potentially saline or fresh, could have a number of impacts. If saline, the groundwater could have a negative effect on the surrounding aquifers as the saline groundwater is displaced into the surrounding aquifers (UKEA, 2002). This displacement could also result in a disruption of aquifer flow systems and groundwater discharge patterns (natural and artificial) by pressure perturbations due to geological storage.

6.2.5 Groundwater abstraction from deep aquifers for water provision

South Africa is a water-scarce country. Since the country's surface water resources cannot provide for the increasing demand for water, groundwater has become an integral part of the water supply to many urban and rural communities. Many of South Africa's towns are completely dependent on the groundwater resource for their supply. During periods of drought, when the surface water resources become more unreliable, the use of groundwater generally increases.

Boreholes used for groundwater abstraction are usually shallow (<100 m), although deeper abstraction boreholes occur. However, groundwater abstraction from aquifers that occur at depths greater than 300 m is very rare in South Africa. For this reason, not much is known about the deep aquifer systems and their potential to provide water.

Groundwater abstraction from the shallow aquifer system has increased significantly in recent years. Where the rate of groundwater abstraction has exceeded the rate of groundwater recharge, this has resulted in the over-exploitation of some of the shallow aquifer systems. These aquifer systems have effectively been mined for their water reserves. The dewatering of the aquifers has resulted in the lowering of the groundwater table, and possibly the closure of certain water-bearing fractures due to the reduction of water pressure in the fracture networks.

It is known that aquifers occur at depths much greater than 300 m. Many of these aquifers appear to be high yielding, although the salinity of the groundwater in the aquifers generally increases with depth. These deep aquifers may be considered a potential groundwater resource, to be used when the surface water sources and shallow groundwater sources are unable to meet the demands of the water users in an area.

6.2.5.1 Potential impacts of abstraction from deep aquifer systems

The abstraction of deep groundwater may impact on both the quality and quantity of the water that occurs in these aquifers. Due to their large depths of occurrence, the recharge rate to deep aquifers is expected to be much slower than that to the shallower aquifer systems. It may therefore take a long time to replenish the volumes of water abstracted from deep aquifers (Custodio et al., 2016). It may thus not be possible to abstract water from some of these aquifers in a sustainable manner. In such cases, the water stored in the deep aquifers should be seen as an emergency resource to be mined only when the water need is great.

The pressure release due to the abstraction of groundwater from the deep aquifers could furthermore cause permanent damage to the aquifers if the weight of the overlying rock units causes the fracture networks to close as compaction takes place. This observation again suggests that certain deep aquifers should only be seen as emergency resources from which water can only be extracted in times of severe shortages.

If compaction of the deep aquifer system occurs as a result of groundwater abstraction, this may be accompanied by seismic activity. The induced seismicity could potentially lead to the formation of fractures extending between aquifers that occur at different depths, thereby hydraulically connecting the aquifers. If the groundwater quality in one aquifer is poorer than that in another, the induced aquifer connectivity could lead to a deterioration in the water quality in the former aquifer. This is particularly true if the more saline aquifer is associated with a larger hydraulic head than the less saline aquifer.

The salinity of the groundwater in deep aquifers generally increases with the depth of the aquifers. If the integrity of the abstraction well is not maintained, it is possible that the more saline waters from deep aquifers could impact on the less saline groundwater that is found in aquifers at shallower depths. Fluid migration from fossil water aquifers may reach freshwater aquifers and cause irreversible loss of freshwater resources (Warner et al., 2012).

The abstraction of water from deep unconfined aquifers (such as dolomite aquifers in which the dissolution networks extend to the surface) may also lead to oxidising conditions in the aquifers as the groundwater level declines. These conditions may lead to the oxidation of some of the minerals found in the host rock. For example, lowering the water levels in the dolomite compartments of the East and West Rand could potentially expose the gold-bearing rocks of the Witwatersrand Supergroup to atmospheric conditions, which could, in turn, lead to the formation of acid mine drainage and the mobilisation of trace metals.

6.2.6 Artificial recharge

Water resources must be managed and used more efficiently and wisely if we are to meet the needs of a growing world population. Artificial recharge to groundwater aims at augmenting the groundwater stored in the aquifer systems by pumping surface water into the groundwater reservoir. Artificial recharge is usually done to address one or more of the following issues:

- Enhance the sustainable yield in areas where over-exploitation has depleted the aquifer
- Conserve and store excess surface water for future requirements, since these requirements often change over time
- Improve the quality of existing groundwater through dilution by introducing cleaner water to the aquifer system
- Remove bacteriological and other impurities from sewage and wastewater so that water becomes suitable for re-use

6.2.6.1 Artificial recharge in South Africa

The DWA and the WRC have supported the development of an Artificial Recharge Strategy, which was completed in 2007. The DWA published its artificial recharge strategy in June 2007, and began implementing it in November of that year. A nationwide assessment of potential artificial recharge areas was conducted as part of the rollout of the DWA's Artificial Recharge Strategy. Favourable artificial recharge areas were identified as those areas that have known high aquifer permeability. In this strategy, the DWA (2010a) describes the methodology that was followed, and provides detailed maps of the identified area that is suitable for artificial recharge.

The main reasons for the implementation of artificial recharge in South Africa are as follows:

- Artificial recharge is usually far cheaper than conventional surface water schemes.
- New surface water sources are not available.
- The aquifer offers storage opportunities where surface storage is not possible.
- Existing groundwater supplies are over-utilised.
- No further "natural" local groundwater sources are available.

Some existing examples where artificial recharge is being used effectively in South Africa include the following:

- Atlantis (Western Cape): recharge using stormwater and wastewater
- Polokwane (Limpopo): storage of treated wastewater
- Williston (Northern Cape): pumping across groundwater compartments
- Kharkams (Northern Cape): opportunistic recharge

Apart from these examples, artificial recharge activities are also planned at the following sites:

- **The Langebaan Road Aquifer for Saldanha Bay:** In this scheme, water is to be transferred from the Berg River during winter when demand is low and there is surplus surface water, and injected into the Langebaan Road Aquifer. A test has already injected 76,000 m^3 into the sandy confined aquifer.
- **Prince Albert:** The water demand in Prince Albert in the Karoo increases threefold over the summer months from approximately 1,000 to 3,000 m^3 per day. The current water sources for the town are a number of streams that originate in the nearby mountains and boreholes in a sandstone aquifer. The boreholes are used to capacity to bridge the summer months. The mountain water is supplied via a furrow and the idea is to divert this water into the aquifer during the winter when the furrow is being cleaned. This would add 120,000 m^3 to the aquifer for use in summer.
- **Plettenberg Bay:** Most of Plettenberg Bay's water comes from the Keurbooms River, but the town also relies on groundwater abstraction from the quartzite aquifer, especially during summer when requirements increase to over 300,000 m^3 per month and borehole water levels drop by tens of metres. Artificial recharge is considered for the town through ore treatment and the underground storage of seasonal water.
- **Calvinia:** This town in the western Karoo has the potential to store 100,000 m^3 as a back-up supply in a highly mineralised and permeable subsurface compartment, similar in shape to the kimberlite pipes. Treated surface water from the Karee Dam can be transferred to this compartment for safe storage.

The water cannot be lost, since the permeability of the surrounding formations is very low and only the municipality has an abstraction borehole within the compartment. Because of the mineralised nature of the host rock, the recharged and abstracted water is not suitable for human consumption and would need to be blended with the dam water prior to use. For this reason, the scheme, has not yet been implemented. Similar water quality problems could result from storing fresh water in disused mines.

6.2.6.2 Potential impacts of artificial recharge on deep aquifer systems

Artificial recharge in deep aquifers could potentially have a detrimental impact on these aquifers. The artificial recharge of deep aquifer systems takes place through boreholes that are installed in these aquifers. During drilling, different aquifer systems may be intersected at different depths. Shallower aquifers may be cased off to isolate the deeper aquifer system that is targeted for artificial recharge. If borehole integrity is not maintained, water migration between the different aquifer systems may take place along the annulus. Water of a poorer quality may therefore potentially impact on the water quality in the more pristine aquifers.

The quality of the water that is injected during artificial recharge will directly impact on the quality of the water in the deep aquifer system. If the quality of the injected water is poorer than the natural groundwater quality in the aquifer, detrimental impacts on the groundwater quality can be expected.

Clogging of the aquifer system may also occur during the implementation of artificial recharge schemes. Clogging can be caused by physical factors, such as air entrapment and suspended matter, as well as bacteriological and chemical factors (DWA, 2007). Artificial recharge could therefore impact on the hydraulic properties of the aquifers where they are intersected by the injection boreholes. However, where the borehole is used for both injection and recovery, clogging may be removed during recovery (Pyne, 1995; Pyne, 2005).

Deep aquifers may furthermore be damaged during artificial recharge through the dissolution of aquifer materials. The dissolution of arsenic has been observed in a number of artificial recharge projects (DWA, 2007, Murray, 2008). Over-abstraction during the recovery stage may also lead to compaction of the aquifers due to the weight of the overlying rock mass, thereby reducing the potential of the aquifer to store and transport water.

6.3 APPROACHES TO PROTECT DEEP AQUIFERS

In this section, various approaches to protect South Africa's deep aquifer systems are discussed. These approaches are the following:

- Establishing baseline conditions for deep aquifer systems prior to the commencement of activities that could impact on these aquifers
- Using available technologies to prevent or limit the impacts of activities on the aquifer systems
- Establishing and following best practice guidelines when performing activities that may impact on deep aquifer systems
- Using regulatory tools to enforce compliance of the activities with the existing laws that deal with, or are relevant to, the protection of deep aquifer systems
- Developing monitoring and adaptive management protocols to take changes in the aquifer conditions brought about by these activities into account and to adjust management procedures accordingly

6.3.1 Establishing baseline conditions

Understanding baseline conditions for aquifer systems is relevant for all types of activities that may impact on deep aquifer systems, i.e. conventional deep mining, conventional deep oil and gas production, unconventional deep oil and gas production, carbon capture and storage, groundwater abstraction from deep aquifers and the artificial recharge of deep aquifer systems.

Establishing baseline conditions includes gaining an understanding of deep aquifer systems that may be affected, and the baseline monitoring of the aquifer conditions prior to commencing with the activities.

6.3.1.1 Understanding deep aquifer systems

A proper understanding of the deep aquifer systems that may be affected by these activities is essential if these aquifers are to be protected from adverse impacts. Investigations should ideally be performed prior to the commencement of any activities. However, it should be appreciated that the large depths at which deep aquifer systems occur is a significant constraint to understanding these aquifers. The information used to establish the baseline conditions of deep aquifers may therefore be very limited.

To gain an understanding of deep aquifer systems, both a desktop study of the available information and additional field investigations may be required to gain further insight into these systems. The desktop study could include the following:

- The site geology and lithologies that are likely to be intersected by the activities
- The presence of geological structures (faults, shear zones, intrusives) that may be associated with deep aquifer systems or could influence the deep geohydrology
- The interpretation of existing geophysical data (seismic, electromagnetic, magnetotelluric) in terms of the deep structural geology and the presence of structures that may be associated with aquifer systems
- The presence of thermal springs mapped in the vicinity of the site
- Deep groundwater quality information from the analysis of water from thermal springs and/or existing deep boreholes (if available)
- Information on the hydraulic properties of deep aquifer systems (if available)
- Estimates of the recharge to deep aquifers based on an evaluation of the likely recharge areas and recharge rates

Since the available information on deep aquifer systems may be very limited in some cases, field investigations may be required to augment the existing information to gain an understanding of the deep aquifer systems. Field investigations could include the following:

- Hydro censuses to locate and map boreholes and springs near the site of the activity
- Sampling of all groundwater sites to establish the groundwater quality prior to the commencement of the activity
- Detailed mapping of the surface geology to detect and delineate structures (faults, intrusives) that have not already been identified
- Geophysical surveys to further investigate the deep structural geology and to identify geological structures of relevance to the deep aquifer systems
- Drilling of a number of deep investigative boreholes to depths equal to or greater than the expected depths of the activities. Geological logging of the boreholes should be done to record the lithologies intersected by drilling. The depths and yields of all water strikes should be noted.
- Downhole geophysical surveys in the deep investigative boreholes
- Sampling and chemical analysis of groundwater from the water strikes encountered in the deep boreholes
- Testing of the hydraulic properties of the deep aquifers by means of pumping and/or tracer tests

6.3.1.2 Baseline monitoring

Water resources monitoring is an important contributory measure to assist in the protection of water resources. For groundwater monitoring at sites where activities may impact on the deep aquifer system, a baseline study of the deep and shallow groundwater conditions is required before the activities begin.

The baseline groundwater quality conditions will then serve as a benchmark against which future groundwater qualities can be compared to detect contaminant impacts from the activities on deep and shallow aquifer systems, and to study temporal changes in groundwater quality due to these activities.

The Best Practice Guideline G3 (Water Monitoring Systems) of the DWA specifies the development of environmental and water management plans based on impact and incident monitoring, as well as the generation of baseline data before project implementation. Baseline data must, as a minimum, be relevant to the operation under consideration. Specific recommendations related to monitoring are discussed in Section 6.3.5.

6.3.2 Technologies and actions to minimise impacts

In this section, some of the technologies and actions that are available for the protection of South Africa's deep aquifer systems are described under separate headings for each of the activities that may impact on deep aquifers. Only a broad description of the more common technologies and actions is given in these sections. Furthermore, the technologies mentioned should not be seen as a comprehensive list of the available technologies, since many other technologies may be available to address specific deep groundwater problems.

6.3.2.1 Conventional deep mining

Underground and deep open-cast mining may impact on both the quality and quantity of the groundwater in deep aquifer systems. Mine dewatering impacts directly on the volumes of water stored in the aquifers, while ore extraction activities expose the groundwater to a variety of contaminants, as well as conditions that may lead to the deterioration of the quality of the groundwater.

Ideally, technologies that are aimed at protecting the deep aquifer systems should focus on putting measures in place to disturb the aquifer systems as little as possible. However, it should be appreciated that the invasive nature of mining implies that groundwater systems are very likely to be affected by mining activities.

The application of various methods of controlling groundwater flow into mine workings requires knowledge of the source and pathways of the portion of the aquifer that is hydraulically connected to the mine (USDA, 2003). A thorough understanding of the aquifer systems in the vicinity of the mine could therefore contribute to the minimisation of impacts on these aquifers. Mining activities can be planned to avoid geological structures (faults, fissures, dykes, dissolution cavities) that are likely to be associated with deep aquifer systems. Since a great deal of geological information is routinely gathered at mines, it is to be expected that an abundance of geological information will be available to assist in understanding the aquifer systems that could potentially be intersected. Pilot drilling ahead of the mining face could reveal the presence of water-bearing geological discontinuities (Cook, 1980). Underground mine geophysical surveys could further assist in detecting subsurface structures that could potentially be associated with deep aquifers.

Due to the large heterogeneity and anisotropy of the subsurface, groundwater inrushes into underground and deep open-cast mines are to be expected, even if steps are taken to avoid potential deep aquifers during mining. Large volumes of water may rush into the workings along single, isolated fractures that are intersected by mining. The occurrence of such fractures is very difficult to predict, even when using the most sophisticated geophysical techniques. Apart from the safety hazard posed by such groundwater inrushes and the costs associated with the removal of water from the workings, groundwater inrushes may also lead to the dewatering of deep aquifer systems.

Aquifer dewatering can be addressed by limiting the inrush of groundwater into the shafts and pits, and recharging the aquifers with the water abstracted from the mines. To reduce the influx of groundwater, it may be possible to seal off the major fractures along which groundwater migration takes place.

Modern grouting techniques may be applied to seal the fractures and reduce the inflow of groundwater (Daw and Pollard, 1986; Straskraba and Effner, 1998; USDA, 2003; Crenshaw et al., 2013). Grouting curtains may also be installed to locally reduce the average permeabilities of the rock formations from which groundwater influx takes place (Kipko, 1986; Kipko et al., 2001).

To combat aquifer dewatering, pumping strategies may be employed to replenish the aquifer at positions remote from the mine workings. Artificially recharging the aquifers in this way would imply that some circulation of the groundwater would take place through the system. The volumes of water that would have to be removed from the workings would therefore be larger than when no artificial recharge is done. In addition, the circulation of the groundwater would cause greater exposure to the contaminants associated with mining, as well as to oxidising conditions. Recirculated groundwater can therefore be expected to be of poorer and deteriorating quality than groundwater removed from the workings in the absence of artificial recharge.

Some *in-situ* treatment of the affected groundwater may be possible at certain mines. *In-situ* treatment techniques could potentially be used during the mining phase (Lottermoser, 2007). Groundwater that has become acidic under oxidising conditions may be treated *in situ* with alkaline substances prior to and during mine dewatering. This could limit acidification of the deep aquifer systems. *In-situ* treatment may also be done post-mining. For example, Canty and Everett (1998) describe the *in-situ* treatment of acidic conditions in an abandoned underground coal mine.

6.3.2.2 Conventional deep oil and gas production

Since the greatest risk of impacts on the deep aquifer system is associated with the installation and integrity of the wells, technologies that are focused on limiting the potential for such impacts are mostly related to well integrity. The factors that most influence well integrity are the type of casing and connectors, the cement and the drilling method selected for the well. Technologies that can be employed to additionally strengthen the integrity of the well include a corrosion-resistant lining or coating in the well interior (Bahadori, 2015). The selection of the above-mentioned casings, cement and linings or coatings is dependent on the following:

- The chemistry of the water associated with the resource
- The geological environment
- The pressure conditions
- The temperature conditions

Oil and gas resources almost always have associated connate water, which is also extracted from the well during production (Veil et al., 2004). This water is the main corrosive agent in oil and gas well production. The lining or coating, the cement and the casing that is selected for the well must be resistant to the water type. Continuous monitoring of the water is required to determine if the character of the water changes as extraction of the reservoir progresses, as well as post-production (Davies et al., 2014).

The monitoring of well conditions can also be performed in the reservoir itself as a permanent installation, allowing real-time responses to changes in reservoir and well conditions (Nyhavn et al., 2000; Algeroy et al., 2010). Synthesised epoxy or chitosan cement slurries have been tested to provide higher resistance to corrosion in acidic environments (Cestari et al., 2012).

Drilling-with-casing (DwC), an innovative drilling technique that is utilised in deep shale wells, has gained favour for the reduced time and cost associated with the drilling stages. Casings are, however, not intended for such use and often sustain damage in the process. If DwC is the preferred drilling method, it is suggested that large grained tube steels and premium connectors are utilised for increased resistance to the cyclic torque and compressive stresses (Cirimello et al., 2017).

The regular monitoring and sampling of regional groundwater systems is imperative to determine if well integrity is maintained. Regular analysis should be performed to determine if any leakage might occur from the operation (Davies et al., 2014). In situations where production wells are in close proximity to populated areas, the periodic analysis of domestic borehole chemistry can detect a failure in well integrity. Local authorities in certain countries have developed screening tests, which consist of a pre-drilling baseline, followed by regular monitoring (MDEQ, 2012).

Technologies to protect deep aquifer systems could include the following:

- Installing a remote-controlled downhole system of permanent monitors, packers and sealing elements, which are used to optimise the flow rates of hydrocarbons and wastewater. Such systems allow the dynamic adjustment of in-hole equipment.
- Burying corrosion-resistant lines and pipes for longer-term operations.
- Upgrading the cements used to hold the casings in place and seal the annuli around the wells. New cement technologies that are more durable and less prone to degradation could reduce the long-term risks to the deep aquifer systems.
- Using micro-seismic surveys to monitor fracture formation during the hydraulic fracturing process. Locating the subsurface positions of fracture development could assist in preventing fracturing networks from extending to deep aquifer systems.
- Monitoring the pressure in the wells to detect possible pressure drops due to failing well integrity.

6.3.2.3 Unconventional deep oil and gas production

6.3.2.3.1 Shale gas

The following technologies and approaches can prevent or limit the potential detrimental impacts of shale gas development on deep aquifer systems:

- Installing a remote-controlled downhole system of permanent monitors, packers and sealing elements, which are used to optimise the flow rates of hydrocarbons and wastewater.
- Transitioning to more environmentally benign fracturing fluids that would have lesser impacts on the water quality in deep aquifers.
- Making use of waterless hydraulic fracturing fluids, such as waterless liquid petroleum gas gels. This would reduce the amount of water used in the hydraulic fracturing process (Khuwaia et al., 2014), thereby limiting the potential for the transportation of contaminants to the deep aquifer systems.
- Including non-radioactive tracers in the proppant to allow the monitoring of fracture networks as they develop during hydraulic fracturing. These tracers would also allow the monitoring of fluid flow and the detection of communication between the deep aquifer systems.
- Conducting small-scale test runs of the hydraulic fracturing process to investigate the risk of casing and cement failure under fracturing pressures.
- Upgrading the cements used to hold the casings in place and seal the annuli around the wells. New cement technologies that are more durable and less prone to degradation could reduce the long-term risks to deep aquifer systems.
- Using micro-seismic surveys to monitor fracture formation during the hydraulic fracturing process. Locating the subsurface positions of fracture development could assist in preventing fracturing networks from extending to deep aquifer systems.
- Monitoring the pressure in the wells to detect possible pressure drops due to failing well integrity.

6.3.2.3.2 Coalbed methane

Little information is available on technologies to limit the environmental impact of CBM extraction. Most publications focus on technologies related to the treatment of the produced water, and do not consider the technologies available to protect the aquifer systems during the various phases of the extraction process.

However, since the extraction of CBM involves the installation of extraction wells and often the use of hydraulic fracturing, technologies that focus on improving well integrity could significantly reduce the risk of having detrimental impacts on deep aquifer systems. Similar technologies to those listed in Section 6.3.2.3.1 (dealing with shale gas extraction) are likely to find application in the extraction of CBM.

6.3.2.3.3 Underground coal gasification

Mitigation actions against impacts on deep aquifer systems may be applied during the operational and post-operational phases. Ensuring the integrity of the injection and production wells is of prime importance to avoid creating preferential pathways for contaminant migration. During the operational phase, certain actions can be taken to prevent or limit contaminant impacts:

- The pressure at the gasification cavity has to be maintained at a level close to, but slightly lower than the local hydrostatic pressure. Gas loss and contaminant migration into the local aquifer will thus be kept to a minimum. In addition, under such pressure conditions, small volumes of groundwater will move into the cavity. This water is necessary for the UCG process to continue. However, the ingress of water may cause slow dewatering of the deep aquifer system if the recharge rate is exceeded by the rate of groundwater flow into the gasification chamber.
- Efficient linkages between the injection well and the production well have to be established and maintained to avoid gas loss and contaminant migration into the surrounding rock material and deep aquifer systems.
- Groundwater quality monitoring needs to be done to detect any deterioration of the quality of the water of the deep aquifer systems related to UCG.

During the post-operational phase, a number of actions may be taken to prevent or limit impacts on the deep aquifer systems:

- Pressure in the gasification cavity has to be maintained at a level lower than the hydrostatic pressure.
- Residual contaminants within the gasification cavity have to be flushed out with steam.
- Contaminated groundwater should be removed from the gasification cavity.
- The interconnected injection and production wells should be properly ventilated to remove any remaining gases from the system.
- Groundwater monitoring should continue until contaminant levels have been reduced to acceptable levels.

6.3.2.4 Carbon capture and storage

Carbon capture and storage is implemented to reduce the impact of anthropogenic greenhouse gas emissions from industry and mining on the environment. These range from coal-fired power generation to the cement industry. However, CCS itself can potentially have a negative impact on the environment, and measures to prevent this need to be considered.

Very little information is available on technologies that can be used for the protection of deep aquifers when it comes to CCS. The main concern relates to the migration of the CO_2 into deep and/or shallow aquifers, and acidification of the groundwater with related heavy metal contamination (Little and Jackson, 2010; Apps et al., 2010; Wang and Jaffe, 2004; Zheng et al., 2009).

Technologies to minimise the impact of CCS, designed specifically for deep groundwater, are limited due to the fairly limited implementation of CCS, combined with a focus on shallow groundwater protection. However, well design and construction remain the most important aspects to consider in minimising the impacts of CCS on groundwater.

Some of the technologies that are available for the protection of deep aquifer systems during CCS include the following (Gibbins and Chalmers, 2008):

- Groundwater modelling to predict the displacement of groundwater in deep aquifers and the migration of CO_2 during and after the injection process
- The application of microseismic and other monitoring techniques to monitor the migration of CO_2 in the subsurface
- Borehole logging and smart monitoring technology to give early warning of leakages and seepages

O'Leary (2010) considered 10 categories for mitigation measures during CCS operations: construction, operation, decommissioning, the water environment, landscape, air environment, ecology, human environment, waste issues and reducing energy requirements. Interestingly, O'Leary (2010) did not identify mitigation measures specifically for groundwater, or more specifically for deep groundwater.

Some of the technologies described by O'Leary (2010) include the following:

- The development and use of environmentally benign chemicals
- Pipeline monitoring, including the use of internal smart pigging to perform magnetic flux leakage (MFL) tests and ultrasonic testing (UT)
- The monitoring of storage sites throughout the operation and post-closure. The techniques that are available include micro-seismic monitoring, side scan sonar monitoring and CO_2 detectors

The International Energy Agency's Greenhouse Gas R&D Programme (IEAGHG) (2011) conducted a comprehensive study specifically on the impacts of CCS on groundwater resources, and described mitigation and remediation strategies for the impacts of CCS on groundwater. Although the focus of the study was on impacts on the shallow aquifer systems, some of the strategies have application to deep aquifers. These technologies again focus on well integrity and monitoring.

6.3.2.5 Groundwater abstraction for water provision

A good understanding of preferential pathways and deep groundwater resources can come from building a tectonostratigraphic framework, or geofabric (Frogtech, 2013). The geofabric consists of the stratigraphy, lithology, facies architecture, fault geometry, basement structure and composition, and tectonics (Frogtech, 2013).

The use of general and smart monitoring technologies would also be advantageous in identifying possible changes in aquifer and geological structure during the abstraction of water resources from deep aquifer systems (Frogtech, 2013). Micro-seismic monitoring could assist in detecting changes in the aquifer and geological structure during abstraction from deep aquifers.

Numerical modelling of the response of the aquifer system could predict groundwater displacement and possibly changes in the groundwater chemistry as a result of abstraction (Gibbins and Chalmers, 2008; Frogtech, 2013).

6.3.2.6 Artificial recharge

Technologies for the protection of deep aquifer systems during artificial recharge are likely to focus on well integrity and monitoring. Some of the technologies that were developed for hydraulic fracturing may find application during artificial recharge, including the following:

- Including non-radioactive tracers in the injected water to allow the monitoring of fluid flow and the detection of communication between deep aquifer systems.
- Upgrading the cements used to hold the casings in place and seal the annuli around the wells. New cement technologies that are more durable and less prone to degradation could reduce the long-term risks to the deep aquifer systems.

- Using micro-seismic surveys to monitor fracture formation during the injection process. Locating the subsurface positions of fracture development could assist in preventing fracturing networks from connecting isolated aquifer systems.
- Monitoring of the pressure in the wells to detect possible pressure drops due to failing well integrity.

The use of geochemical modelling tools, such as speciation modelling, solute-transport modelling, mole-balance modelling, batch-reaction modelling and reactive-transport modelling, could furthermore assist in analysing aquifer storage recovery (Parkhurst and Petkewich, 2002).

6.3.3 Best practices

Best practice is a procedure that, through experience and research, has proven to reliably produce a specific result. A commitment to using best practices ensures that all the available knowledge and technology is used to confirm due diligence and thus prevent a tortious act. In South Africa, the DWS has developed a series of Best Practice Guidelines (BPGs), specifically for the mining industry. These are outlined below:

Hierarchy:

- H1. Integrated mine water management
- H2. Pollution prevention and minimisation of impacts
- H3. Water reuse and reclamation
- H4. Water treatment

General:

- G1. Stormwater management
- G2. Water and salt balances
- G3. Water monitoring systems
- G4. Impact prediction
- G5. Water management aspects for mine closure

Activities:

- A1. Small-scale mining
- A2. Water management for mine residue deposits
- A3. Water management in hydrometallurgical plants
- A4. Pollution control dams
- A5. Water management for surface mines
- A6. Water management for underground mines

Although the above BPGs were developed with the mining industry in mind, many may be applied to prevent or limit impacts from other activities that coud potentially impact on deep aquifer systems.

6.3.3.1 Conventional deep mining

The series of best practice guidelines for the mining industry that is described above considers all water management aspects, ranging from specific activities to surface operations. Mining in South Africa includes both open-cast and underground mines that would be considered deep (>300 m) in the current study. Conventional deep mining in South Africa could inherently reduce the impact on deep groundwater by following the general BPGs for mining. However, BPGs with a specific focus on deep groundwater are not currently available in South Africa.

By applying the existing BPGs, deep aquifers may be protected during deep conventional mining in the case where there are possible connections between shallow and deep aquifers, as shafts and other perforations represent linkages between the surface, shallow aquifer systems and the deep aquifer systems on which conventional mining may impact.

To protect the deep aquifers from impacts related specifically to deep mining activities, BPGs would need to be developed that consider aspects such as the following:

- Rising water levels in abandoned deep mines and the impact of this water on deep aquifers
- The structural integrity of geological formations
- The possible acidification of deep freshwater aquifers, if exposed to oxygen

Best practice guidelines for deep conventional mining would also involve designing the extraction process so as to avoid or minimise such impacts from the start of operations for new mining endeavours, and could include progressive controlled flooding or deep mine voids to avoid the generation of acid mine drainage, sealing off certain sections of mining operations where extraction has been finalised by using engineered plugs, monitoring deep aquifer water levels and water levels in the mining voids, monitoring seismic activity, etc. (Table 6-1). Such guidelines have not yet been developed in South Africa.

6.3.3.2 Conventional deep oil and gas production

The exploration and development of minerals and petroleum resources are legislated in the Mineral and Petroleum Resources Development Act, Act No. 28 of 2002 (MPRDA). In 2015, specific regulations to govern petroleum exploration and production were promulgated under the MPRDA – the Regulations for Petroleum Exploration and Production, 2015 (Government Notice R466). These petroleum exploration and production regulations prescribe standards and practices to ensure the safe exploration and production of oil (petroleum and other liquid hydrocarbons) and gas (coalbed methane and shale gas).

Under the environmental impact assessment of the MPRDA, the assessment of conditions below ground are required, including:

> "groundwater monitoring (area covered, duration of monitoring, watercourse) and deep groundwater investigation to be specified when independent preliminary research has been completed."

Table 6-1: Best practices for deep conventional mining

Best practice	Action	Reference
Identifying and characterising deep aquifer systems and target mining area	Identify potential deep freshwater aquifers in vicinity of mining target, delineate and understand mining target area – look at geological structures, aquifer characteristics etc.	Frogtech (2013)
Mapping out faults and fractures that may serve as preferential pathways	Faults and fractures serve as preferential pathways for fluid migration.	Gibbins and Chalmers (2008)
Monitor groundwater quality in the deep aquifer systems and mining basin	Monitor this information to generate additional information to confirm the geofabric model.	Frogtech (2013)
Building a geofabric model (a techtonostratigraphic model)	Build a geofabric model from aquifer characterization and building of geofabric model. Supplement the data from the geofabric with groundwater samples and monitoring data from deep aquifer systems.	Frogtech (2013)
Integrity of mining basin and associated deep aquifer	Continue monitoring the mining basin and deep aquifer(s) integrity via water levels, seismic activity.	Bildstein *et al.* (2010)
Shaft integrity	Monitoring shaft cement degradation and integrity, as well as plug integrity.	Bildstein et al. (2010); Bachu (2007); IEAGHG (2007a)
Modelling techniques	Predict deep groundwater displacement Describe geochemical processes to predict changes in deep aquifer water chemistry.	Gibbins and Chalmers (2008)

The MPRDA is the closest available resource to a BPG for conventional deep oil and gas production in South Africa. However, for a robust best practice consideration, international best practice guidelines are investigated.

According to Wawryk (2002), the guidelines and standards of the International Association of Oil and Gas Producers (OGP) and the American Petroleum Institute (API) are particularly influential. The OGP gives a summary of the International Organization for Standardization (ISO), which is available for use in the oil and gas industry (http://www.iogp.org/PapersPDF/Standards%20Issued%202017.pdf). Additionally, the API standards are available under the categories of natural resources damage assessment, pollution prevention, and soil and groundwater research (http://www.api.org/products-and-services/standards/standards-inquiries).

The Petroleum Services Association of Canada (PSAC) is the national trade association that represents the service, supply and manufacturing sectors within the upstream petroleum industry. The PSAC recommends technical industry-recommended practices (IRPs) developed by the Drilling and Completions Committee (DACC), which provide guidance or best practices to conduct operations in a safe and technically acceptable manner.

The appropriate IRPs for conventional oil and gas development include the following:

- IRP Volume 1 – Critical sour drilling
- IRP Volume 2 – Completing and servicing critical sour wells
- IRP Volume 3 – *In situ* heavy oil operations
- IRP Volume 4 – Well testing and fluid handling
- IRP Volume 5 – Minimum wellhead requirements
- IRP Volume 6 – Critical sour underbalanced drilling
- IRP Volume 7 – Standards for wellsite supervision of drilling, completion and workovers
- IRP Volume 8 – Pumping of flammable fluids
- IRP Volume 13 – Slickline operations
- IRP Volume 14 – Non-water-based drilling fluids
- IRP Volume 15 – Snubbing operations
- IRP Volume 20 – Wellsite design spacing recommendations
- IRP Volume 21 – Coiled tubing operations – draft
- IRP Volume 22 – Underbalanced and managed pressure drilling operations using jointed pipe
- Interim IRP Volume 24 – Fracture stimulation
- IRP Volume 25 – Primary cementing

These IRPs are available from http://www.psac.ca/leadership/health-safety/industry-recommended-practices-irps/. The listed IRPs are not directly related to the protection of deep groundwater resources, yet the implementation of these best practice guidelines in the development of oil wells will reduce the likelihood of contamination to the deep aquifers.

The Norwegian Oil and Gas Association (NOGA) has established a number of guidelines in the areas of environment, operations, integrated operations and industrial policy. The relevant guidelines include the following (available from https://www.norskoljeoggass.no/en/Publica/Guidelines/):

- 085 – Norwegian Oil and Gas recommended guidelines for sampling and analysis of produced water
- 093 – Recommended guidelines for waste management in the offshore industry
- 117 – Recommended guidelines for well integrity
- 135 – Recommended guidelines for classification and categorisation of well control incidents and well integrity incidents

The Ministry of Petroleum and Natural Gas of the Government of India developed the Good International Petroleum Industry Practices (GIPIP) in 2016. The GIPIP aims to provide guidelines for practices that are technically and contractually appropriate for different aspects of oil and gas exploration and production. The GIPIP covers exploration, discovery, appraisal, declaration of commerciality, field development, production, testing and analysis, health, safety and environmental, procurement procedure and other areas (MoPNG, 2016).

The Intermountain Oil and Gas Best Management Practices Project was initiated by the University of Colorado Law School's Getches-Wilkinson Center (formerly the Natural Resources Law Center), and provides a plethora of best management practices for the oil and gas development in the Intermountain West area. The free-access website (http://www.oilandgasbmps.org/) has a searchable database that addresses resources affected by oil and gas development. The database includes both mandatory and voluntary best management practices that are currently in use or recommended for responsible resource management in the states of Colorado, Montana, New Mexico, Utah and Wyoming in the USA.

There are numerous best practices and guidelines for the oil and gas industry on an international scale. This review of international BPGs is not exhaustive, but is sufficient for an overview of the available guidelines.

6.3.3.3 Unconventional deep oil and gas production

No documents to describe best practice guidelines for unconventional deep oil and gas production have been published in South Africa. The development of such guidelines should be based on international experience. Some of the guidelines to be considered include the following:

Hydraulic fracturing

- The best practice guidelines of the American Petroleum Industry (API, 2012)
- The guidelines for industry best practice of the United Kingdom Onshore Operators Group (UKOOG), the representative body for onshore oil and gas companies in the United Kingdom (UKOOG, 2013)
- The best practice guidelines set by the Government of New Zealand (Government of New Zealand, 2014)

Coalbed methane

- The technical development document of the United States Enivronmental Protection Agency (USEPA) for the coalbed methane extraction industry (USEPA, 2013)
- The handbook on best management practices for coalbed methane published by the Western Governors' Association (WGA, 2006)
- The local government guide compiled by the West Coast Environmental Law Research Foundation of Canada (WCELRF, 2006)
- The best management practices for natural gas in coal and coalbed methane of the Canadian Association of Petroleum Producers (CAPP, 2006)
- The handbook on best management practices and mitigation strategies for coalbed methane in the Montana portion of the Powder River Basin (USDE, 2002)

Underground coal gasification

- The best practices in underground coal gasification as described by the Lawrence Livermore National Laboratory (Burton et al., 2006)
- The best practices guide developed by WS Atkins Consultants for the United Kingdom Department of Trade and Industry (WSAC, 2004)
- The underground coal gasification report of the Queensland Ombudsman (2012)

6.3.3.4 Carbon capture and storage

The South African government has shown interest in exploring the CCS potential in South Africa and significant CCS activity has taken place. However, the SACCCS is still developing policy and regulations on CCS. Considering that South Africa has no specific policy or BPGs on CCS, international best practice should be considered in the interim (SACCCS, 2016).

The World Resources Institute (WRI) developed the Carbon Dioxide Capture and Storage Guidelines in 2008. This guideline effort was initiated to develop a set of preliminary guidelines and recommendations for the deployment of CCS technologies in the USA to ensure that CCS projects are conducted safely and effectively (WRI, 2008).

The following guidelines are available:

- Capture Guideline 1: Recommendation guidelines for CO_2 capture (Section 2.2)
- Capture Guideline 2: Recommended guidelines for ancillary environmental impacts from CO_2 capture (Section 2.3)
- Transport Guideline 1: Recommended guidelines for pipeline design and operation (Section 3.2)

- Transport Guideline 2: Recommended guidelines for pipeline safety and integrity (Section 3.3)
- Transport Guideline 3: Recommended guidelines for siting CO_2 pipelines (Section 3.4)
- Transport Guideline 4: Recommended guidelines for pipeline access and tariff regulation (Section 3.5)
- Storage Guideline 1: Recommended guidelines for measurement, monitoring and verification (MMV) (Section 4.3.1.1)
- Storage Guideline 2: Recommended guidelines for risk assessment (Section 4.3.1.2)
- Storage Guideline 3: Recommended guidelines for financial responsibility (Section 4.3.1.3)
- Storage Guideline 4: Recommended guidelines for property rights and ownership (Section 4.3.1.4)
- Storage Guideline 5: Recommended guidelines for site selection and characterisation (Section 4.3.2.1)
- Storage Guideline 6: Recommended guidelines for injection operations (Section 4.3.2.2)
- Storage Guideline 7: Recommended guidelines for site closure (Section 4.3.2.3)
- Storage Guideline 8: Recommended guidelines for post-closure (Section 4.3.2.3)

6.3.3.5 Groundwater abstraction for water provision

In 2008, the DWAF published clear guidelines on the assessment, planning and management of groundwater resources in South Africa (DWAF, 2008). These guidelines are consistent with the Integrated Water Resource Management (IWRM) principles (DWA, 2010c). Although the guidelines do not specifically consider groundwater abstraction from deep aquifers (at depths over 300 m), most of the proposed activities are relevant to both shallow and deep groundwater resources. However, some of the activities are likely to be much more challenging when applied to deep groundwater resources. For example, during the assessment of the groundwater resource, information of the geographic extent of the aquifer system(s) and the aquifer resource capability is required. The information that is typically considered includes the following:

- Geological and geohydrological maps
- Geohydrological reports
- Borehole logs
- Geophysical profiles of exploration and/or monitoring boreholes previously drilled in the area
- Test pumping results
- Groundwater quality data
- Monitoring data studied to gather direct geohydrological information across the area of investigation

The information on deep aquifer systems that is listed above is likely to be very limited if it exists at all. Obtaining this information would involve the installation of numerous deep boreholes on which the appropriate tests could be performed. This would pose a significant challenge, both practically and financially.

Despite the inherent challenges in applying the proposed guidelines to deep aquifer systems, these guidelines presently outline the best set of procedures to follow to protect deep aquifer systems from over-exploitation.

6.3.3.6 Artificial recharge

Although no best practice guidelines for artificial recharge have yet been published in South Africa, in 2007, the DWA released a document describing an artificial recharge strategy for South Africa (DWA, 2007). This document describes the vision (long-term goal), management objectives, strategic approach, tasks to be completed and the responsible organisations in the Artificial Recharge Strategy. Although the document makes no distinction between artificial recharge to shallow and deep aquifer systems, the proposed strategy is equally applicable to both systems. However, the application of some of the proposed actions will undoubtedly be more challenging when dealing with deep aquifer systems. For example, the quantification of the aquifer recharge potential is inherently a much more difficult endeavour when dealing with deep aquifers.

In 2009, the DWA published a checklist for implementing successful artificial recharge projects. Although this document did not make a distinction between artificial recharge to shallow and deep aquifers, many of the items on the checklist are equally applicable to shallow and deep groundwater systems (DWA, 2009).

Other international publications that describe guidelines to artificial recharge include the Central Ground Water Board (CGWB) (2000) and the American Society of Civil Engineers (ASCE) (2013). These guidelines could be considered when developing guidelines for aquifer recharge (both shallow and deep) in South Africa.

6.3.4 Regulatory tools

6.3.4.1 Conventional deep mining

The South African government extensively regulates conventional deep mining and its impacts on water resources. The most important regulations in terms of conventional mining and protecting water resources include the following:

- Regulation 704 (Government Notice R704) in Government Gazette 20119 of 4 June 1999 (Regulations in terms of section 26 of the National Water Act on the use of water for mining and related activities aimed at the protection of water resources)
- Government Notice 331 in Government Gazette 37603 of 2 May 2014 (National norms and standards for the remediation of contaminated land and soil quality in the Republic of South Africa)

These regulations are, however, focused on protecting shallower aquifer systems and surface water systems from the impacts of conventional mining. Regulations to protect deep aquifers from deep conventional mining should be developed, especially to manage the long-term liability to the state that is associated with now defunct mines. Aspects that must be addressed include the following:

- Managing rising water levels in deeper aquifer systems associated with the extraction areas of gold and platinum
- Managing water quality issues (such as acid mine drainage) associated with deep aquifer systems
- Managing seismic activity that may ensue from the filling up of mine voids with water and changes in the structure of deep aquifer systems

Since there may be connections between shallow and deep aquifer systems, it is imperative that possible quantity and quality issues, as well as issues with the structural integrity of the aquifers, be addressed in regulations. Financial provisions for any remedial action that must be taken in terms of current impacts on deep aquifer systems from defunct mines in South Africa would also have to be addressed.

6.3.4.2 Conventional deep oil and gas production

Regulatory tools allow the industry to internalise externalities. Regulatory tools, such as casing or cementing depth regulations, specified in Government Notice R466 on production wells, is an example of a “command-and-control” regulatory tool. Performance standards, on the other hand, may, for example, require that concentrations of specified pollutants in streams near drilling sites do not exceed a certain level or that a pressure test on casing cement does not exceed a given reading. Government Notice R466 specifies such boundaries for pressure test results. Case-by-case permits require operators to comply with regulator specifications per activity, similar to specifying licence conditions for a specific activity. The government may use a hybrid of all these approaches in managing oil and gas to minimise environmental impacts. According to Richardson et al. (2013), command-and-control is the predominant regulatory tool, and it is possible that this would also be the case in South Africa.

Setbacks would be a good control measure to establish sufficient distance between sources of impact associated with conventional oil and gas production activities to prevent contamination or other effects on sensitive deep aquifers. Setbacks from specific geological structures are recommended as these structures may represent a link between shallow and deep aquifers and may pose a contamination risk if fluids are able to migrate between these aquifers. Faults, shear zones, fold axes, dolerite dykes and sills, kimberlites and diatremes may represent structures of concern. Thermal springs should also be mapped as these represent a shallow-deep aquifer connection. These springs should be monitored using seismics and other geophysical techniques, as well as with water sampling. Specific setbacks are not recommended in this report, as more in-depth research is required to determine which setbacks for conventional oil and gas production are required.

6.3.4.3 Unconventional deep oil and gas production

As with conventional oil and gas production, regulatory tools allow the industry to internalise externalities. As with conventional oil and gas production, "command-and-control" regulatory tools could play an important role in regulating unconventional deep oil and gas production. Determining setbacks for production activities would help prevent contamination or other effects on sensitive deep aquifers. Setbacks from specific geological structures are recommended as these structures may represent a link between shallow and deep aquifers and may pose a contamination risk during unconventional oil and gas production. Recommended setbacks, based on the Strategic Environmental Assessment for Shale Gas, performed by the Council for Scientific and Industrial Research (CSIR) and a multi-author team of experts, can be found in Hobbs et al. (2016).

It is difficult to mitigate the failure of well integrity after well decommissioning. Although Government Notice R466 specifies that a well must have a decommissioning plan that must consider, among other factors, the current condition and design of the well, the difficulties of injecting cement into the annulus and the future monitoring of the integrity of the plug before being decommissioned, there are no guarantees that, over time (decades and longer), decommissioned wells would not leak. This is a serious concern to the authors and is also highlighted as a concern internationally (Davies et al., 2014; ANU, 2012; Bishop, 2011; DEP, 2009). This aspect underlines the importance of the precautionary approach and the application of stringent setback distances from valuable water resources and possible pathways.

6.3.4.4 Carbon capture and storage

In considering a CCS legal and regulatory regime, a key underlying feature is that South African mining law is in many ways pertinent to CCS (Glazewski et al., 2012), although the activity in question is the converse. Mining entails the extraction of a natural resource, whether it is solid, liquid or gaseous from underground, while CCS entails injecting or inserting a processed, highly dense gas with fluid properties into the ground. Glazewski et al. (2012) conducted a study titled "CCS: towards a regulatory and legal regime in South Africa". This report includes the following key and novel legal features (Glazewski et al., 2012):

- Questions around ownership of the "pore space" into which it is anticipated the CO_2 will be injected. Related to this is the question of ownership of the CO_2 itself in the event that these two notions are separated from one another.
- Whether the injection of a "supercritical" substance into the ground amounts to disposing of a "waste" or "hazardous waste", as defined in the National Environmental Management: Waste Act, Act No. 59 of 2008. The report concludes that, under current waste legislation, the substance in question indeed constitutes "waste" and is likely to also be considered "hazardous waste", because of the broad definitions of these terms in the Act. As such, the Waste Act will have to be complied with, among other environmental legislation.
- Potential long-term liability issues, including the required mechanisms to secure responsibility for the project over extended periods of time. Typical questions in this context are whether liability for the project, including the project site and the sequestered CO_2, should be transferred to the state on the understanding that it is likely still to be extant for many years, possibly hundreds of years, in contrast to private companies.

Such considerations around the transfer of liability to the state include site closure procedures and responsibility for ongoing monitoring, determining the point in time and the associated circumstances in which liability might be transferred to the state, and the types of financial and logistical preparations that may be required to be in place before transfer of liability can be effected.

- Possible conflicts around uses of the storage site, including potential conflicts between surface owners and CCS operators.
- Administrative and cooperative governance arrangements, including the respective roles of national, provincial and local tiers of government. The report has, as its point of departure, that the Department of Energy is the focal point for CCS-related activities. However, a number of other government departments will have an interest in CCS, including the departments of Environmental Affairs, Health, and Mineral Resources.
- Possible provincial or local government stumbling blocks. While the report does not identify major pitfalls under this heading, it identifies the necessity for compliance with provincial and local authority planning laws.
- Financial implications, including the state of play of incorporating CCS into the Clean Development Mechanism under the Kyoto Protocol and the financial implications, for CO_2 emitters, of the introduction of a carbon tax in South Africa – essentially, the cost-benefit dynamic between the cost of the carbon tax and the cost of sequestering CO_2 via a CCS project.

South Africa has numerous natural resource and pollution-related laws in place, including environmental laws that require a public policy process with interested and affected parties, as well as stakeholders. These laws will have a consequence in CCS-related activities. Glazewski et al. (2012) concluded that their study results would be adequate to proceed with a demonstration project, but cautioned that a dedicated CCS legal and regulatory regime needs to be put in place to govern this new and unique technology.

In the interim, international regulatory policy could be utilised for reference. The main piece of regulation for CCS across Europe is the European Union's CCS Directive on Geological Storage of Carbon Dioxide (Directive 2009/31/EC), which came into force on 25 June 2009 (CCSA, 2016). The directive describes a comprehensive legal framework for the environmentally safe geological storage of CO_2. However, it does not cover capture or transport in great detail. The International Energy Agency has developed a Policy Strategy for CCS (IEA, 2012a), and has conducted a legal and regulatory review (IEA, 2012b).

6.3.4.5 Groundwater abstraction for water provision

The National Water Act describes water use that requires a licence in section 21. Section 21(a) and 21(j) are relevant in the case of water abstraction from deep aquifers:

> Section 21(a) – taking water from a water resource
> Section 21(j) – removing, discharging or disposing of water found underground

Although licence conditions can be described for these uses, if water is to be abstracted from deep aquifers for water provisioning, regulations would have to be drafted for this activity. At present, little or no abstraction of groundwater from the deep aquifers (>300 m below ground level) of South Africa takes place. However, the possibility exists that the deep groundwater resource may, in future, contribute to the country's water supply in times of water shortages. Regulations therefore have to be drafted to do the following:

- Manage changes in the water levels or storage of these aquifer systems that relate to the abstraction of water
- Manage water quality issues that may ensue due to water abstraction from deep aquifer systems

- Manage seismic activity that may result from water abstraction and changes in the structure of deep aquifer systems
- Manage transboundary aquifers that underlie more than one country

6.3.4.6 Artificial recharge

Artificial recharge activities to the deep aquifer systems should be regulated to protect these groundwater resources from adverse impacts. Some of the actions that could be required for the implementation of artifial recharge activities include the following:

- Developing a conceptual geohydrological model of the deep aquifer system
- Estimating the storage capacity of the deep aquifer systems
- Assessing the quality of the groundwater in deep aquifers, as well as the quality of the water to be injected
- Determining the impact of artificial recharge on the quality of the groundwater in deep aquifers
- Using numerical models to assess the feasibility of the artificial recharge scheme
- Considering possible adverse geochemical reactions due to the injection of water into deep aquifers
- Considering the influence of high hydraulic pressures during injection on the deep aquifer systems

In South Africa, artificial recharge can be adequately addressed via the licensing procedure by attaching operational conditions and monitoring conditions to the licence. Specific regulations need not be drafted per se. Issues that must be taken into account include the monitoring of specifically the operations to avoid clogging the deep aquifer, possible seismicity, aquifer deformation and changes in the groundwater chemistry.

6.3.5 Monitoring and adaptive management

6.3.5.1 Introduction

The monitoring of water resources in deep aquifers is important to minimise, control and mitigate against the impacts that activities may have on these resources. A comprehensive understanding of groundwater conditions is required prior to the commencement of activities to ensure the proper interpretation of changes in the groundwater of deep aquifers over time. To assess the baseline conditions, the monitoring programme should be implemented prior to the commencement of the activity, and should continue during the active (production) and post-closure phases.

The monitoring programme serves to detect impacts on the deep groundwater resources and should therefore be developed by taking the specific impacts that a particular activity might have on the deep groundwater environment during the different phases of the activity into account. If impacts are detected, rehabilitation measures should be implemented. These measures should be linked to a management plan that is designed to address such impacts. Management practices should be flexible enough to adapt when the monitoring programme indicates that a particular activity is causing unplanned or undesired impacts on the aquifers.

The monitoring programme should be adapted during the life cycle of the activity to allow the monitoring of potential impacts that are particular to a specific phase of the life cycle. Monitoring data should also be used for the calibration and verification of the results of models used to predict and assess the impacts of the activities. Monitoring data should furthermore be used to evaluate and audit the success of management plans, and to assess the extent of compliance with prescribed standards and regulations.

Ideally, the monitoring programme should address the following:

- The density of the monitoring network
- The frequency of sampling
- The methods of sampling, collection and capturing the data

- The type of impact that could occur
- The parameters to be sampled during monitoring
- The methods for analysing the data
- The format for reporting the findings to the relevant authorities
- Mechanisms for auditing, and for recommending and implementing changes to the monitoring programme

The list of parameters to be sampled should be extensive enough that regulators can identify groundwater chemistry changes related to the particular activity. Quality assurance and control, the criteria used to evaluate the results of analyses, and data management are key components of the monitoring programme to be implemented.

6.3.5.1.1 Quality assurance and quality control during monitoring

Standardised monitoring requirements, similar in nature to the document series on "minimum requirements for waste handling", would have to be developed to ensure quality assurance and quality control.

These requirements include the following:

- Field sampling procedures should be robust, reproducible and reliable. A pilot sampling run may be required to serve as a reconnaissance exercise during which information on sampling points and data ranges are recorded, as well as logistical and technical constraints identified.
- The sampling should be undertaken by an accredited institution, and by accredited and appropriately trained individuals.
- The appointed institution needs to be unbiased and independent, and should not be connected to any of the interested parties.
- The sampling and handling methods that are used need to be clearly documented.
- Copies of the chain of custody (COC) forms must be kept. Sample results must be traceable through their collection, storage, handling, shipment and analysis, and information on persons handling the sample should be completed on the COC form.
- It is advised that two sets of duplicate samples are taken for analysis at the same laboratory and at a quality control laboratory, and that trip blanks or field blanks be employed.
- Laboratories must be accredited for the analysis of specified parameters via South African National Accreditation System (SANAS) accreditation and ISO certification. Where local laboratories cannot analyse samples, they must be sent to an internationally accredited laboratory.
- Water quality samples need to be sent to an accredited or unbiased laboratory for analysis. Samples should also be regularly sent to other accredited laboratories for verification.
- Good laboratory analysis practices must be ensured. This includes using calibration blanks to check for instrument drift, laboratory replicates to test the precision of laboratory measurements, spike samples, quality control samples of known constitution for comparison with analysis samples and sending duplicate samples for analysis at different laboratories.
- *In-situ* water quality samples must be taken using calibrated meters. *In-situ* water samples should be tested regularly by an accredited laboratory for verification to determine if the meters used are calibrated correctly.
- Results should be compared with the resource quality objectives, water quality standards and/or baseline data, if available.
- Reliable and tested methods, approved by the DWS (the legal custodian of South Africa's water resources), should be used to enable the comparison of data from repeated sampling.
- Data must be interpreted by individuals experienced in the particular field.

6.3.5.1.2 Laboratory and analytical criteria

As no single laboratory has the capability to conduct all analyses, it is recommended that the selection of the preferred laboratories be based on quality, detection limits and number of parameters that can be analysed so as to reduce the number of sample containers required and simplify the logistics of couriering the samples to several laboratories.

The quantification limits for all parameters must be based on the SANS 241:2015 drinking water standard and the South African Water Quality Guidelines for Agricultural Use (livestock watering) and Domestic Water Use. Where no guideline values are available, international guidelines must be consulted.

6.3.5.1.3 Data management

The efficient management and safe storage of data are essential prerequisites for a successful monitoring programme. The DWS keeps records of water quality, hydrology and river health under the Directorate: Resource Quality Services. The National Groundwater Archive can be viewed as the most up-to-date data archive on groundwater in South Africa. Options can be investigated to determine if this system can be efficiently adapted to manage information that is specific to deep aquifer systems in South Africa.

The following important aspects should be kept in mind in connection with monitoring data:

- A central database for all data should be curated by a reliable institution, and should be accessible to all stakeholders, including the public.
- Monitoring records kept by companies who partake in activities that may impact on the deep aquifer systems should be accessible to all.
- Good record keeping is an essential part of quality assurance. Original datasheets should be kept for as long as possible. It is also vital that the transcription of data from data sheets to electronic format is accurate and validated, and that this is done by a competent person who understands the data and who is capable of data interpretation.
- Data needs to be examined for irregularities immediately after collection and any identified impacts should be communicated to the relevant government department and to the company causing the impact as soon as possible.

Data requirements may differ during the different phases (exploration, production, post-closure) of the activities that could impact on the deep aquifer systems. This should be taken into consideration when prescribing monitoring requirements. Adequate data capture of drilling and extraction operations is a crucial part of proper monitoring and management. The development of a database system with a linked online mapping system would be ideal.

6.3.5.2 Conventional deep mining

Because of water quality concerns, surface and groundwater at mine sites is monitored before, during and after the operation of the mine. The information collected by water monitoring programmes is used to assess the effects of the mine on the surrounding environment and to develop appropriate water management plans.

The prevention of groundwater contamination is a key component of modern mine design, and a network of groundwater monitoring boreholes is usually installed to assess whether the preventative measures are successful. Most regulators and financial institutions worldwide now require mining companies to develop mine closure plans and make financial provisioning to cover all the costs of mine remediation and reclamation. Ongoing groundwater monitoring after closure is often a component of mine closure plans.

The groundwater monitoring programme of an underground or deep open-cast mine should be developed by taking the local geological conditions into account. The presence of geological structures (dykes or faults) that may be associated with deep aquifers needs to be taken into account when deciding on the positions of monitoring boreholes and the densities of the monitoring networks. Since the geology of the host rock and ore plays a major role in determining the type of contaminants that may impact on deep groundwater, the site-specific geological conditions should be considered when designing the monitoring programme and when deciding on which parameters to include in the analysis of samples. The frequency of monitoring should be high enough to allow the early detection of contaminant impacts on the deep groundwater system. When such impacts are observed, management decisions will be required.

6.3.5.3 Conventional deep oil and gas production

The monitoring of deep groundwater resources is important to minimise, control and mitigate the effects of possible conventional deep oil and gas production. A comprehensive understanding of groundwater conditions is required prior to the commencement of exploration to ensure the proper interpretation of changes in the groundwater of deep aquifers over time. Detailed monitoring plans should be developed for the different phases of conventional oil and gas extraction. Monitoring data would also be used for the calibration and verification of prediction and assessment models, for evaluating and auditing the success of management plans, and for assessing the extent of compliance with prescribed standards and regulations.

Monitoring should occur before, during and after conventional oil and gas development, and monitoring during well suspension and after well decommissioning is especially important to detect any failure in well construction with possible resultant leakages. It is important to note, however, that post-closure monitoring, in itself, does not constitute mitigation for the groundwater contamination of deep aquifers. It is a tool to detect groundwater contamination and initiate rehabilitation measures, and should be linked to a management plan to address detected pollution events.

Monitoring must be linked to a management plan to ensure that water resources are protected, and that action is taken when certain set thresholds are exceeded. Ideally, the monitoring plan should address the following:

- Design of the initial monitoring programme
- Methods of sampling, collecting and capturing the data
- Methods for analysing the data
- Format for reporting the findings to the relevant authorities
- Mechanisms for auditing, and for recommending and implementing changes to the monitoring programme

The determination of the baseline groundwater quality and quantity of deep aquifers must be performed. With regard to water chemistry, the concentrations of constituents naturally found in the water must be known. The list of constituents to be measured before conventional oil and gas extraction takes place should be extensive enough that regulators can identify groundwater chemistry changes related to oil and gas extraction.

After conventional oil and gas development has ceased in an area, the integrity of wells will need to be monitored. Decommissioned wells need to be monitored annually for well integrity going into the future, taking into account that well failure typically occurs over the long term (over 50 years).

6.3.5.4 Unconventional deep oil and gas production

The monitoring and management requirements for an unconventional oil and gas production project are very similar to those of conventional oil and gas production.

It is important to note that it would be difficult, if not impossible, to identify the effects of unconventional oil and gas production on deep groundwater systems without the baseline monitoring of such aquifer systems (GAO, 2012a; GAO, 2012b). In order to perform appropriate baseline monitoring, an understanding of the aquifer systems in an area (shallow and deep), as well as migration pathways for contaminants, is necessary. Baseline groundwater quality and quantity also need to be quantified. With regard to water chemistry, the concentrations of constituents naturally found in the water must be known, and monitored for deep aquifers.

For hydraulic fracturing operations, the type and concentration of the additives in the fracking fluids should be known. Government Notice R466 requires companies to report their frackwater additives, and some of these should be monitored as part of an early warning monitoring system for picking up contamination incidents. The list of constituents to be measured before the initiation of hydraulic fracturing should be extensive enough that regulators can identify which are suitable for detecting fracking-related changes. During exploration and development, operators should be required to monitor the quantity of water used and other technical aspects such as drilling rate, volumes of drilling and fracking fluids and their constituents, and micro-seismicity at exploration and production sites. Regulators would have to ensure that data dissemination from the operators occurs as required in accordance with the licence conditions. Similar to conventional oil and gas development, after unconventional oil and gas development has ceased in an area, the integrity of decommissioned wells will need to be monitored going into the future.

6.3.5.5 Carbon capture and storage

Measurement, monitoring and verification have been emphasised for successful CCS projects, where the amount of CO_2 stored at a specific site should be measured, the site should be monitored for leaks or any other deterioration of storage integrity over time, and it should be verified that the CO_2 is stored and unharmful to the ecosystem (Friedmann and Herzog, 2007).

Reliable and cost-effective monitoring and verification techniques are an important aspect of ensuring that geologic sequestration is a safe, effective and acceptable method for greenhouse gas control. The oil and gas industry has used a wide array of monitoring technologies to track fluid movement in the subsurface. These techniques are readily adaptable to CO_2 storage to monitor the behaviour of CO_2 underground. For example, seismic surveying provides an image of the subsurface, which often allows the behaviour of stored CO_2 to be mapped and predicted. Other monitoring technologies include down-hole and surface CO_2 sensors. New technologies, such as satellite imaging, which can detect movements of less than 1 mm in the earth's surface, are also being developed (CCP, 2015).

6.3.5.6 Groundwater abstraction for water provision

When groundwater is abstracted from deep aquifer systems, dewatering of the system is the main concern. Since the recharge rate of most deep aquifers is expected to be very slow, extracting water from the aquifer may effectively amount to mining the water resource. For such aquifers, it may be impossible to abstract water in a sustainable manner. These deep aquifers should therefore be seen as emergency water sources to be exploited at times when the country's water needs are high.

Since no sustainable abstraction rate exists for these aquifers, the rate of abstraction would depend on the water needs at the time of abstraction, but by taking into account that the future water needs of the country may require a reserve of groundwater to be left in the aquifer.

To monitor the impact of groundwater abstraction from the deep aquifers, the abstraction (pumping) rate from the aquifer and the hydraulic head (water level) in the borehole should be monitored over time. From the measured drawdown of the water level, it will be possible to determine whether the abstraction rate is causing the aquifer system to be dewatered too quickly for the planned period of abstraction. Based on the observed dewatering rate, the abstraction rate may have to be adjusted.

Since the salinity of aquifers generally increases with depth, many of the deep aquifers are expected to contain saline or brackish water. Depending on the level of salinity, the water may be extracted for different uses, which require different degrees of treatment. It may therefore also be necessary to monitor the water quality periodically during abstraction to verify that the water quality is still suitable for its intended use. The monitoring interval will depend on many factors, such as the abstraction rate, the planned period of extraction and the degree of salinity.

It is possible that groundwater abstraction from deep dolomite aquifers or deep aquifers in the Table Mountain Group may be done on a sustainable basis. These aquifers may be recharged at rates that are high enough to allow the sustainable abstraction of groundwater from the system. For these aquifers, hydraulic tests will need to be performed prior to the utilisation of the deep groundwater. From the results of the hydraulic tests, sustainable pumping rates should be determined that will protect the aquifer systems from dewatering. It will be necessary to monitor the abstraction rate and the response of the hydraulic head over time in order to ensure that the calculated, sustainable abstraction rate does not exceed the capacity of the aquifer to deliver water on a sustainable basis. Continuous management of the abstraction rate may be required since recharge rates are likely to be seasonal and may change over time as climate changes occur.

6.3.5.7 Artificial recharge

The DWA (2009; 2010b) provided a checklist for the implementation of successful artificial recharge projects. Groundwater monitoring was included as a required action during the feasibility, implementation and operation, and maintenance stages of the projects.

When investigating the feasibility of an artificial recharge project, the conditions of the deep aquifer systems should be known. Information on the baseline groundwater quality should therefore be obtained. This may require the installation of a number of boreholes into the aquifer system to allow the sampling and hydraulic testing of the aquifer (Murray, 2008). Background groundwater monitoring should therefore form an integral part of the monitoring programme to be implemented.

During the implementation stage, the groundwater and recharge monitoring system should be set up, and monitoring procedures should be compiled. During this stage, decisions on the numbers and positions of observation boreholes will need to be made. Criteria for the desired water quality in the deep aquifer should be set at this stage.

During the operation and maintenance stage, monitoring of both the groundwater quality and the hydraulic head in the aquifer will be required to evaluate the impacts of the artificial recharge on the deep aquifers. Groundwater quality monitoring will be of particular importance if the quality of the recharged water is poorer than the quality of the groundwater in the aquifer. Monitoring results should be evaluated against the desired water quality criteria. Management decisions should be taken if the desired criteria are not met.

6.4 LEGISLATION AND REGULATIONS RELEVANT TO DEEP AQUIFERS

This section discusses legislation and regulations relevant to the protection of deep aquifers, and covers all related activities that may impact on deep aquifers, without specifically differentiating between the different types of activities.

6.4.1 International law

Sources of international law with relevance to the protection of deep aquifer systems include the following (Birnie and Boyle, 2002):

- International custom or customary law
- Treaty law, e.g. treaties, conventions, protocols and pacts

- General principles of international law
- Secondary sources of international law, including, but not limited to expert teachings and judicial decisions

South Africa is a signatory to various treaties. To give effect to these treaties, section 231(4) of the Constitution provides that:

> "...any international agreement becomes law in the Republic when it is enacted into law by national legislation...".

Thus, South Africa's international obligations only become applicable in a domestic sense when the obligation is enacted as national legislation. This means that obligations of international agreements are not binding on South African citizens until they are enacted as domestic legislation.

Customary international law is relevant in terms of environmental liability and general obligations at an international level. These commonly adopted legal principles are integrated in various agreements, such as the Rio Declaration of 1992 and the Declaration of the United Nations Conference on the Human Environment of 1972 (the Stockholm Declaration).

These principles include integrated environmental management, inter-generational equity, the precautionary principle, the polluter-pays principle, the equitable utilisation of shared resources, and sustainable development. International customary law and international conventions and treaties are thus important to South Africa. International customary law principles such as the polluter-pays principle, the precautionary principle and the preventive principle are discussed in section 2 of the National Environmental Management Act, Act No. 107 of 1998 (NEMA). All these principles are relevant for the protection of both shallow and deep aquifer systems.

6.4.2 One Environmental System in South Africa

The establishment of the One Environmental System (OES) was a watershed moment in the history of environmental assessment in South Africa. The legal architecture underpinning the OES has largely been put in place, but there are still some significant gaps and conflicts, particularly as far as petroleum resources are concerned (Humby, 2015).

The assessment of all listed and specified activities is dealt with in terms of the OES, which became effective on 14 December 2014. The relevant principal features of the OES with respect to exploration and mining are as follows:

- All environment-related aspects are to be regulated through one environmental system under NEMA and all environmental provisions are to be repealed from the MPRDA
- the Minister of Mineral Resources will issue environmental authorisations under NEMA

Prior to the establishment of the OES, the environmental provisions of both the MPRDA and NEMA would have been invoked to assess and manage the environmental impacts of petroleum reconnaissance, exploration or production. Now, in terms of the OES, the environmental aspects associated with activities that may impact on deep groundwater resources (mining, oil and gas production) will be dealt with in terms of the provisions of NEMA, with the DMR being the competent authority. The MPRDA remains relevant, however, to the extent that no reconnaissance permit, or exploration or production right, may be granted by the Minister of Mineral Resources if the application does not meet the specified environmental criteria.

The OES also requires the Minister of Mineral Resources, the Minister of Environmental Affairs and the Minister of Water Affairs to agree on fixed timeframes for the consideration and issuing of authorisations under their respective legislations, and that they would agree to synchronise such time frames.

6.4.3 Relevant South African legislature

The South African legislature relevant to the protection of deep groundwater resources includes the Constitution, the National Water Act, the National Environmental Management Act and the Mineral and Petroleum Resources Development Act.

6.4.3.1 The Constitution

The Constitution of the Republic of South Africa, Act No. 108 of 1996, is the supreme law of South Africa and contains the Bill of Rights. The Constitution, with its environmental right, is a crucial enactment, as are a number of other acts, which regulate the inter-related areas of environmental concern.

6.4.3.2 The National Water Act

The Water Act of 1956 was replaced by the National Water Act of 1998, which is considered worldwide to be the best water legislation as it was acknowledged with an international prize. The National Water Act is the principal legal instrument governing all water resources in South Africa, and is based on the principles of equity, efficiency and sustainability. This Act is the best legal instrument to ensure good governance of groundwater resources.

The following reasons are given for this statement:

- Groundwater became public water with the promulgation of the National Water Act in 1998.
- Water use and protection are addressed in an integrated way through IWRM with the DWS as the custodian of all water resources.
- Institutional development ensures the management of water at the regional (catchment) and at the local level. The relevant institutions for these two levels of management are the catchment management agencies and the water user associations. The umbrella framework, under which the use and protection of water resources are controlled and managed, is the IWRM Framework. The two sets of complementary strategies used to manage water in South Africa to achieve a balance between the use and protection of water resources within the IWRM Framework are resource-directed measures (RDM) and source-directed control (SDC).

The IWRM Framework and strategies are summarised in Figure 6-5. The framework is well developed for surface water, but for groundwater it remains a challenge. It is, however, essential that groundwater also has to be regulated under this framework. The institutional dispensation is of the utmost importance to the effective management of water.

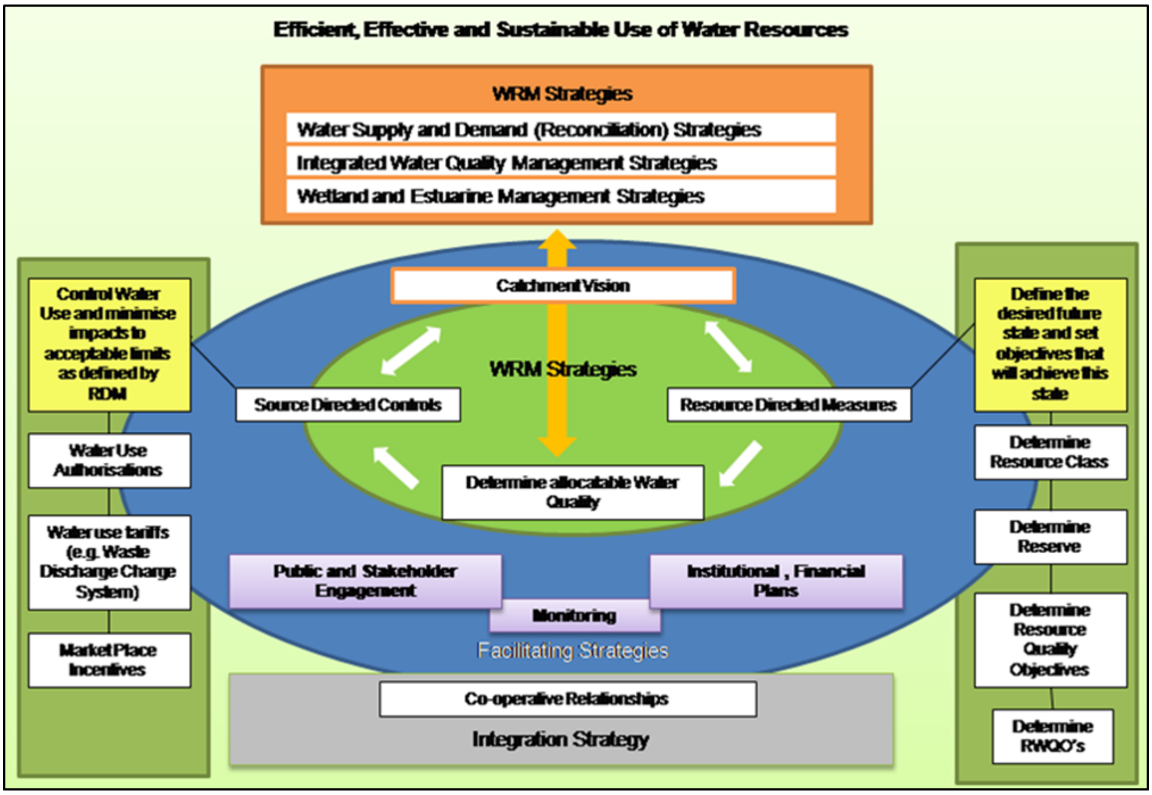


Figure 6-5: The IWRM Framework and strategies (adapted from Braune et al., 2014)

Despite the developed guidelines for groundwater resource management, which provide clear instructions for incorporating groundwater management into the IWRM Framework, groundwater resources are still undervalued, and legislation, regulations and guidelines are neither enforced nor implemented (Knüppe, 2011). For the effective governance of deep groundwater, this needs to be addressed.

The above challenge is, however, a global challenge as well, and has led to the development of a global framework of action with a shared global vision for 2030 to ensure sound groundwater governance. This was also addressed locally by Braune and Adams (2013) for the sub-Saharan Africa region.

The development of the National Groundwater Strategy, which the DWS published for comment, should also give direction on the regulation of deep groundwater resources.

6.4.3.2.1 Regulation of deep aquifers using the National Water Act

The National Water Act is the logical legislation, with DWS as the leading agent, to regulate deep aquifers. It is necessary to also regulate these aquifers within the IWRM Framework and the institutional framework. Whether the RDM strategy or the SDC strategy will be the leading strategy to use will depend on the water quality of the specific deep aquifer. This is also a dependent factor for managing deep aquifers in many other countries worldwide.

As an example, consider the Table Mountain Group aquifers, with their good quality water. Water use will be the driving principle with SDC the leading strategy in cooperation with section 21 authorisation and in more detail in terms of section 21(a) (taking of water) and section 21(b) (storing of water). The protection of this resource is of importance, but the RDM strategy for groundwater protection is not as clear as it is for surface water. The strategy for deep groundwater is a debatable issue at this stage. By contrast, when considering the deep aquifers within the Karoo Supergroup, and specifically with reference to unconventional gas extraction through hydraulic fracturing, the protection strategy (RDM) may be the leading strategy.

The DWS has already identified section 21(e) of the National Water Act as the relevant section to be used to regulate hydraulic fracturing (SDC). This section is for controlled activities as identified by the DWS. The RDM strategy for deep aquifers needs attention, though.

The institutional arrangements are also very important in the regulation and governance of deep aquifers. The roles of catchment management agencies, water user associations and aquifer management committees should be evaluated. The assessment of deep aquifers in relation to boundaries also has to be considered, and the establishment of Aquifer Boundary committees should be considered. Planning will be the responsibility of the appropriate institutions.

The National Water Act ensures that the nation's water resources are protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all persons and in accordance with its constitutional mandate. Sections 2(g) and 2(h) of the Act specify the "protection of the aquatic and associated ecosystems and their biological diversity" and "reducing and preventing pollution and degradation of water resources", respectively.

Water resources are managed and protected in the National Water Act by the need to obtain a licence for permissible "water use", except in cases where a licence is not required, for example where a "general authorisation" or "Schedule 1 use" has been issued. Water use is defined in section 21 of the National Water Act and includes:

a) taking water from a water resource;
b) storing water;
c) impeding or diverting the flow of water in a watercourse;
d) engaging in a stream flow reduction activity contemplated in section 36;
e) engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1);
f) discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;
g) disposing of waste in a manner which may detrimentally impact on a water resource;
h) disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process;
i) altering the bed, banks, course or characteristics of a watercourse;
j) removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people; and
k) using water for recreational purposes.

Once an applicant falls into any one or more of the items listed above, the Minister of Water and Sanitation may issue conditions for the granting of a licence. Section 29 of the National Water Act sets out conditions that can be attached to general authorisations and licences, which relate to the protection of the water resource, to water management and to return flow, and to discharge or the disposal of waste, which is relevant in the case of a controlled activity, in the case of the taking or storage of water and in the case of a licence.

The DWS is in the process of formulating its own regulations regarding unconventional oil and gas production. It has invoked section 38 of the National Water Act to declare "the exploration and/or production of onshore, naturally occurring hydrocarbons that require stimulation, including but not limited to hydraulic fracturing and/or underground gasification, to extract, and any activity incidental thereto that may impact detrimentally on the water resource" as a controlled activity. This was published in General Notice No. 999 as section 37(e) of the National Water Act. The declaration of unconventional oil and gas extraction as a controlled activity means that water use licences will be required for unconventional oil and gas production.

It is important to note that Part 3 of Chapter 3 of the National Water Act provides for the determination of a reserve and related matters (sections 16 to 18) before issuing a licence.

This means that reserve determinations on groundwater and surface water resources are required for any water use that requires a licence, be it conventional mining, unconventional oil and gas production, water abstraction from deep auifers or artificial recharge.

Lastly, Chapter 14 of the National Water Act (sections 137 to 145), titled "Monitoring, assessment and information", is particularly relevant to all activities that impact on deep aquifers (conventional deep mining, unconventional oil and gas production, carbon capture and storage, water abstraction from deep aquifers, as well as aritifical recharge). Monitoring, recording, assessing and disseminating information on water resources are critically important for achieving the objectives of the Act. The Minister of Water and Sanitation must establish national monitoring systems and national information systems, each covering a different aspect of water resources, such as a national register of water use authorisations, or an information system on the quantity and quality of all water resources. The Minister must also establish mechanisms and procedures to coordinate the monitoring of water resources after consultation with the relevant organs of state, including water management institutions and existing and potential users of water.

Key regulations on the use of water that are important for unconventional deep oil and gas production, as well as conventional mining under the National Water Act, includes Government Notice 704. The regulations on the use of water for mining and related activities aimed at the protection of water resources (Government Notice 704/1999 in the Government Gazette of 4 June 1999) are aimed at protecting water resources. Other relevant regulations for conventional mining, as well as unconventional oil and gas production, are stipulated in Government Notice 1199 (18 December 2009), which specifies conditions for impeding or diverting flow or altering the bed, banks, course or characteristics of a watercourse to persons using water under sections 21(c) and 21(i) of the National Water Act. In these regulations, no water use is allowed within a 500 m radius from the boundary of a wetland. Also, altering the bed, banks, course or characteristics of a watercourse is not allowed within the 1:100-year floodline or within the riparian habitat, whichever is the greatest. Regarding these regulations, the protection of shallow aquifer systems would, by default, mean the protection of deep aquifer systems, since communication between shallow and deep aquifer systems via failed casings of deep wells or via fractures in geological structures (for unconventional oil and gas production) or via deep shafts (for conventional mining) could mean a risk to deep aquifer systems, which would be reduced by these protection measures.

6.4.3.3 The National Environmental Management Act

The requirements for environmental impact assessments (EIAs) under NEMA are applicable in a water context. The principles in section 2 of NEMA apply to both the MPRDA and the National Water Act. An important principle is the precautionary ("risk-averse and cautious") approach, which specifies that a risk-averse and cautious approach is applied to development. This takes into account the limits of current knowledge about the consequences of decisions and actions.

Another important principle is that the costs for remedying pollution, environmental degradation and consequent adverse health effects must be paid for by those responsible for harming the environment. Chapter 3 of NEMA requires cooperative governance, which would be important if activities that may impact on deep aquifers, and the related protection of deep aquifers, are to be managed effectively between different spheres of government.

6.4.3.4 The Mineral Resources and Petroleum Development Act

The exploration and development of mineral and petroleum resources are legislated for in the MPRDA. Conventional mining is extensively covered under the MPRDA.

In terms of unconventional petroleum production, oil and gas companies in South Africa submitted their applications for exploration rights in terms of the MPRDA in 2011. At the time, section 39 of the MPRDA required that an Environmental Management Plan (EMP) be submitted as part of an application for a gas exploration right.

These EMPs were submitted in 2011 as part of the applications for exploration rights. The applications are still pending, and even though section 39 of the MPRDA was repealed, all pending applications must be finalised as if section 39 had not been repealed. Subsequently, in 2015, the DMR requested the applicant companies to carry out a review of their EMP reports to determine whether they comply with the requirements set out in section 39(3) of the MPRDA.

Section 2(h) of the MPRDA seeks to ensure "…that the nation's mineral and petroleum resources are developed in an orderly and ecologically sustainable manner while promoting justifiable social and economic development" in accordance with section 24 of the Constitution. Environmental management is addressed in section 39, and sets out in section 39(3) the requirements attendant on an environmental management programme or an environmental management plan. It is important to note that the mining industry is a long-established industry in South Africa, while the petroleum resources industry, particularly land-based extraction, is still in its infancy. As a result, while the MPRDA tackles both, much associated regulation, particularly that which covers environmental matters and water, tends to focus on mining activities and is silent on petroleum production activities.

Environmental authorisations are the key features of both the mining and petroleum regulatory regimes. Section 37 of the MPRDA states that all prospecting and mining operations must adhere to the environmental management principles of NEMA, while section 38 states that any operator has a responsibility to manage environmental impacts and must, as far as possible, rehabilitate the environment affected by these operations. Section 39 calls for operators to conduct an EIA and submit an EMP where baseline information of the affected environment, to determine protection and remedial measures, must be established. Section 41 calls for operators to make financial provision for the remediation of environmental damage. An operator remains responsible for any environmental liability, pollution or ecological degradation and its management until the Minister of Mineral Resources has issued a closure certificate. No closure certificate may be issued until the Minister of Water and Sanitation has confirmed, in writing, that the provisions relating to health and safety, and the management of potential pollution to water resources, have been addressed (section 43).

In 2015, specific regulations to govern petroleum exploration and production were promulgated under the MPRDA: the Regulations for Petroleum Exploration and Production, 2015 (Government Notice R466). These petroleum exploration and production regulations prescribe standards and practices to ensure the safe exploration and production of oil (petroleum and other liquid hydrocarbons) and gas (coalbed methane and shale gas).

6.4.4 The National Groundwater Strategy

The National Groundwater Strategy (NGS) has, as one of its goals, the improved recognition of the strategic value of groundwater, and the importance of its efficient use and protection (NGS, 2016). The National Groundwater Strategy adjustment was executed to be inclusively considered in the National Water Resource Strategy (NWRS 2) of June 2013, and increased participation and consultation between affected parties. The NGS (2016) therefore focuses on achieving stakeholder input by consultation with the different mining, agriculture, local government and catchment management agency sectors. The NGS (2016) is a worthy and long-awaited effort to get groundwater management and regulation to be part of the DWS's well-established IWRM Framework. It also recognises the principle of the consideration of the hydrological cycle as an entity in effective water law development and implementation.

6.4.4.1 Objectives of the National Groundwater Strategy

The objectives of the National Groundwater Strategy are as follows:

- Achieve improved rural supplies for basic and livelihood needs from groundwater and other local sources.

- Achieve sustainable small town or village supplies from groundwater, practicing integrated water resource management at a local scale.
- Improve water security for urban development from groundwater to the range of conjunctive use options, integrated with wastewater management.
- Expand irrigated agriculture, especially for small-scale and supplementary irrigation, from groundwater, with the focus on sustainability and the appropriateness and cost-effectiveness of technology.
- Develop new groundwater sources in increasing complex locations, including brackish water for industrial or mining supply in situations of increasing water scarcity. Special or complex aquifers fall in this category and may require special institutions to be established to govern these aquifers. Deep aquifer development is very relevant to this objective.
- Achieve appropriate groundwater resource governance and sustainable resource utilisation at all levels through national or regional facilitation (resource assessment and planning, setting up norms, regulations, user empowerment and institutional development) of local participation actions (joint use, management and the protection of common resources).

6.4.4.2 Themes of the National Groundwater Strategy

The mission of the NGS is to ensure sustainability, accessibility and cost-effective groundwater supplies for human survival and socio-economic development, while maintaining the environment supported by groundwater. The NGS supports the IWRM Framework of the DWS, the custodian of all water in South Africa. The themes of the NGS (2016) are as follows:

- **Stakeholder-driven development and implementation.** Continuously improve stakeholder understanding and collectively agree on and work within an expanding framework of local participative management and “good groundwater governance”.
- **National groundwater leadership.** Develop and maintain the national groundwater champion that must hold the overall groundwater governance framework together and facilitate and support its roll-out, smooth functioning and growth.
- **Responsive groundwater regulatory framework.** Anchor the shared understanding of groundwater governance in appropriate policy and regulations that will enhance the sustainable and efficient use of groundwater resources.
- **Groundwater resource protection.** Develop and maintain approaches for the proactive protection of groundwater resources and aquifer-dependent ecosystems to secure a sustainable supply of water for human survival and socio-economic development, while maintaining essential groundwater environmental services.
- **Sustainable groundwater resource utilisation.** Translate a practical understanding of groundwater resources into appropriate guidance material to fully capacitate those responsible at all levels for sustainable groundwater resource utilisation. This should cover planning, development, management and protection.
- **Appropriate institutional development.** Develop, facilitate, capacitate and support appropriate institutions that will allow the effective local participative management of groundwater resources.
- **Redirecting finances.** Redirect incentive policies and public expenditure that impacts on groundwater by and within different sectors to achieve a combined, much stronger focus on sustainable and efficient groundwater management.
- **Groundwater resource planning and development.** Achieve integrated groundwater resource planning at the national, regional and local levels that will fully and sustainably establish the unique potential of groundwater for socio-economic development.
- **Information management.** Grow and maintain the groundwater resource knowledge base, focusing on the resource itself, its socio-economic role and its appropriate management. Develop and maintain effective and efficient information and information systems, as a shared national objective and as an integral part of water management strategies, in support of groundwater development and management at all levels.

- **Regional and international partnerships.** Actively participate in and grow appropriate regional and international partnerships towards groundwater resource understanding and optimal utilisation, including transboundary resource management.
- **Water sector skills and capacity.** Develop and maintain skills and capacity for the sustainable development and management of groundwater resources at all management levels and with the participation of all stakeholders as part of a long-term, ongoing process.
- **Local actions.** Manage and maintain actions on all strategy fronts in a concerted effort from government at different levels, from municipalities and utilities, the private sector, civil society, educational institutions, the media and professional associations to achieve essential local actions for sustainably managing shared groundwater resources.

The governance of deep aquifers is important and relevant to some of, if not all the themes of the NGS.

6.4.5 Challenges and gaps to be addressed

Challenges with regard to the governance of groundwater has been absorbed locally in South Africa, as well as globally, and many, if not all problems do and will influence the effective governance of deep aquifers. The major problem is the lack of human resource capacity and funding to implement the National Water Act and the groundwater governance framework (Pietersen et al., 2011). The incorporation of groundwater management in the IWRM Framework is lacking and is compulsory within the principle of the governance of all components of the hydrological cycle.

Knüppe (2011) interviewed 18 groundwater governance experts on groundwater management tools available in South Africa and their importance. The tools, relevant to the management of deep aquifers, are as follows (Kotzé, 2015):

- Implementation of existing groundwater legislation and regulation
- Improved cooperation structures between different administration levels
- The development of a nationwide information management system
- Monitoring pollution sources
- Developing an aquifer monitoring system and national database to store pertinent data such as recharge, discharge, stream flow, etc.
- Developing economic instruments
- The conjunctive use of surface water and groundwater resources

The strengthening of policies, legislation, institutional reform and the proper recognition of groundwater resource management and groundwater governance will contribute valuably to the effective implementation of water legislation and groundwater regulations in South Africa.

Regulations must be specifically drafted for the protection of deep aquifers, which are related to activities that could potentially impact on these aquifers. Current regulations available at the DWS extensively cover conventional mining in South Africa, but the DWS still has to draft regulations for unconventional oil and gas production. In addition, if South Africa is going to undertake CCS, as is currently being investigated by the SACCCS, regulations for this will also have to be drafted to protect deep aquifer systems. An analysis of the regulatory choices for CCS has already been done as part of a project for the World Bank (2013).

6.5 PROPOSED GENERALISED FRAMEWORK TO PROTECT DEEP AQUIFERS

The generalised framework proposed for the protection of South Africa's deep aquifer systems incorporates the following actions:

- The determination of baseline conditions prior to the commencement of any activity that could impact on the deep aquifer system.
- The structural and geohydrological characterisation of the area to be impacted on by the activity.

- The development of a conceptual geohydrological model of the aquifer systems that may be impacted on by the activity.
- The identification of all possible impacts of the activity on the deep groundwater resources.
- The simulation of the potential impacts of the activity on the deep groundwater system through numerical modelling.
- The consideration of available technologies to avoid or reduce impacts on the deep aquifers.
- The consideration and implementation of national and international best practice guidelines for the particular activity.
- The application of existing laws and regulations to regulate the activity so as to protect the deep groundwater resources.
- The development of new laws and regulations where existing laws and regulations are deemed inappropriate or inadequate to protect deep aquifers.
- The implementation of a monitoring programme specifically designed to monitor potential impacts on the deep groundwater system by the activity.
- The application of adaptive management strategies to deal with unforeseen situations arising from the implementation of the activity.

CHAPTER 7: DEEP GROUNDWATER DATABASE

This section deals with the development of a database for information relevant to the deep aquifer systems in South Africa. The aim is to collate all the available information on deep aquifers in South Africa into a user-friendly database that can continually be updated when new information becomes available.

Specific objectives are as follows:

- Organise all the information and data gathered during previous phases of the WRC project so that the information can be consolidated in the database
- Capture all the available data in the database.

7.1 DESCRIPTION OF THE DATABASE

7.1.1 Introduction

The database on the deep aquifer systems in South Africa was compiled in an Excel file, accessed through the software package WISH (Windows Interpretation System for Hydrogeologists), developed by the IGS. The data captured in the database includes all the data gathered during the investigations into the sources of data on South Africa's deep aquifer systems (refer to Chapter 4). Data relevant to deep aquifers to be captured in the database includes the following:

- Site name or ID
- Site coordinates
- Site type
- Geological borehole logs
- Data on borehole construction
- Data on depths of water strikes
- Data on yields of water strikes
- Data on groundwater quality
- Data on groundwater levels
- Geohydrological borehole logging data

Since the available data on South Africa's deep aquifer systems is sparse and incomplete, many of the above types of data could not be captured for all sites in the database. Many data gaps therefore occur in the database. Some of these gaps could potentially be filled in future as more data on the sites becomes available.

7.1.2 Description of WISH

7.1.2.1 Introduction

WISH is a software package that is capable of displaying thematic maps with data and graphs that depict the data in specialised ways (Lukas, 2012). The software package consists of a mapping and graphing facility, linked to a database. The database could be in one of the following formats:

- An Excel file
- An Access database
- A Hydrobase database
- An Aquabase database
- A Muniwater database

Of the above five formats, the Excel file format is the most commonly used.

7.1.2.2 Data captured

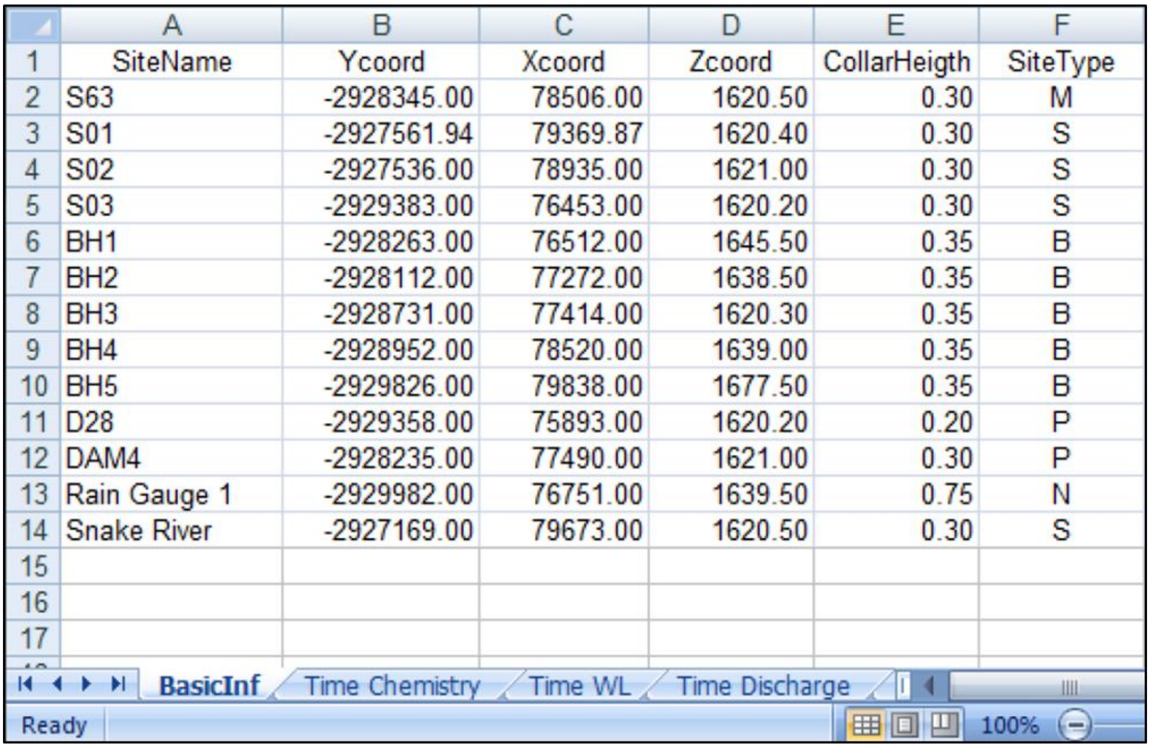
When an Excel files is used as a database, different data fields are captured as separate Excel sheets. These fields and the relevant data are described below:

7.1.2.2.1 Basic information

The basic information (*BasicInf*) sheet is the most important sheet in the database (Lukas, 2012). All sites are defined within this sheet. The *BasicInf* sheet contains five required data fields:

- *SiteName*
- *Xcoord*
- *Ycoord*
- *Zcoord*
- *SiteType*

The *Xcoord* and *Ycoord* fields contain the coordinates of the sites, while the *Zcoord* contains the surface elevations. The *SiteType* field defines the site in terms of its type by using different alphabetic characters. For example, single borehole sites, multiple borehole sites, fountains and springs, pans and dams, and meteorological stations are identified by the characters B, M, S, P and N, respectively (Figure 7-1). Apart from the above mandatory fields, any additional static data that is relevant to the sites may be captured in the *BasicInf* sheet (such as CollarHeight in the example in Figure 7-1).



	A	B	C	D	E	F
1	SiteName	Ycoord	Xcoord	Zcoord	CollarHeigth	SiteType
2	S63	-2928345.00	78506.00	1620.50	0.30	M
3	S01	-2927561.94	79369.87	1620.40	0.30	S
4	S02	-2927536.00	78935.00	1621.00	0.30	S
5	S03	-2929383.00	76453.00	1620.20	0.30	S
6	BH1	-2928263.00	76512.00	1645.50	0.35	B
7	BH2	-2928112.00	77272.00	1638.50	0.35	B
8	BH3	-2928731.00	77414.00	1620.30	0.35	B
9	BH4	-2928952.00	78520.00	1639.00	0.35	B
10	BH5	-2929826.00	79838.00	1677.50	0.35	B
11	D28	-2929358.00	75893.00	1620.20	0.20	P
12	DAM4	-2928235.00	77490.00	1621.00	0.30	P
13	Rain Gauge 1	-2929982.00	76751.00	1639.50	0.75	N
14	Snake River	-2927169.00	79673.00	1620.50	0.30	S
15						
16						
17						

Figure 7-1: Example of a *BasicInf* sheet in an Excel file acting as a database

7.1.2.2.2 Time-related data

Different types of time-related data can be captured in the database. These data types include the following:

- *Time Chemistry*, which contains data on the water quality of samples taken on particular dates at particular times
- *Time WL*, which contains data on water levels as measured on particular dates at particular times

- *Time Rainfall*, which contains data on rainfall figures measured on particular days at particular times
- *Time Photo*, which allows the capture of information relevant to photographs taken of the sites
- *Time Discharge*, which contains data on discharge rates from sites as measured on particular dates at particular times

Apart from the above data types, user-defined temporal data may also be captured in the database. Sheets that store time-related data have to start with the word “Time”, and have to contain the following data columns:

- *SiteName*
- *DateTimeMeas* (the date and time of measurement)
- The values of the parameter measured

The *SiteName* data column forms the link between the basic information (in the *BasicInf* sheet) and the time-related data. The *SiteName* field in both the time-related data sheet and the basic information sheet must be identical to allow these fields to be linked.

7.1.2.2.3 Borehole data

Data that is relevant to borehole sites is captured in the sheets with names starting with “BH” (Lukas, 2012). The following sheets are typically included:

- *BH Geology*, in which the geological borehole log data is captured
- *BH Construction*, which contains data on the construction of the borehole (drilling diameter, casing material, casing thickness)
- *BH Fill*, which contains data on the fill material used around the annulus of the borehole
- *BH Parameters*, which contains data on physical and chemical parameters (e.g. pH level, temperature, dissolved oxygen, electrical conductivity) measured in the borehole
- *BH Yield*, which contains data on the yields measured in the borehole

7.1.2.2.4 Pumping test data

Pumping test data may be captured in an Excel sheet named *PumpTest*. The following data fields can be captured in the *PumpTest* sheet:

- *SiteName*, which contains the name of the borehole site from which water was abstracted during the pumping tests
- *ObsSiteName*, which contains the name of the borehole site in which groundwater levels were measured during the pumping tests (this name will be the same as the SiteName if water level measurements were taken in the abstraction borehole)
- *PumpMethod*, which describes whether measurements were taken during the pumping (P) or recover (R) phases of the pumping test
- *DateTimeStart*, which gives the date and time when the pumping test was started
- *DateTimeMeas*, which gives the date and time of the water level measurement
- *WaterLevel*, which lists the water levels measured on the specific dates and times
- *PumpRate*, which describes the pumping rates used on the specific dates and times

7.1.2.3 Time series analysis

Temporal data may be plotted as time graphs to investigate the trend in the data. Three graph types are available:

- Linear graphs, which plot straight lines that connect the measured parameter values on the y-axis against the time of measurement on the x-axis (Figure 7-2)

- Scatter plots, which plot the measured parameter values as dots on the y-axis against the time of measurement on the x-axis (Figure 7-3)
- Bar plots, which plot the measured parameter values as vertical on the y-axis against the time of measurement on the x-axis (Figure 7-4)

Statistical operations may be applied to the time series data. Time series data may be presented in box-and-whisker plots simultaneously, which indicate the minimum and maximum parameter values measured at the site during a selected time interval, the standard deviation around the mean of the parameter values measured during a selected time interval, and the value of the parameter during the latest monitoring event (Figure 7-5). Different sets of time series data may also be correlated against one another to investigate whether changes in the values of one parameter correlate with changes in another parameter.

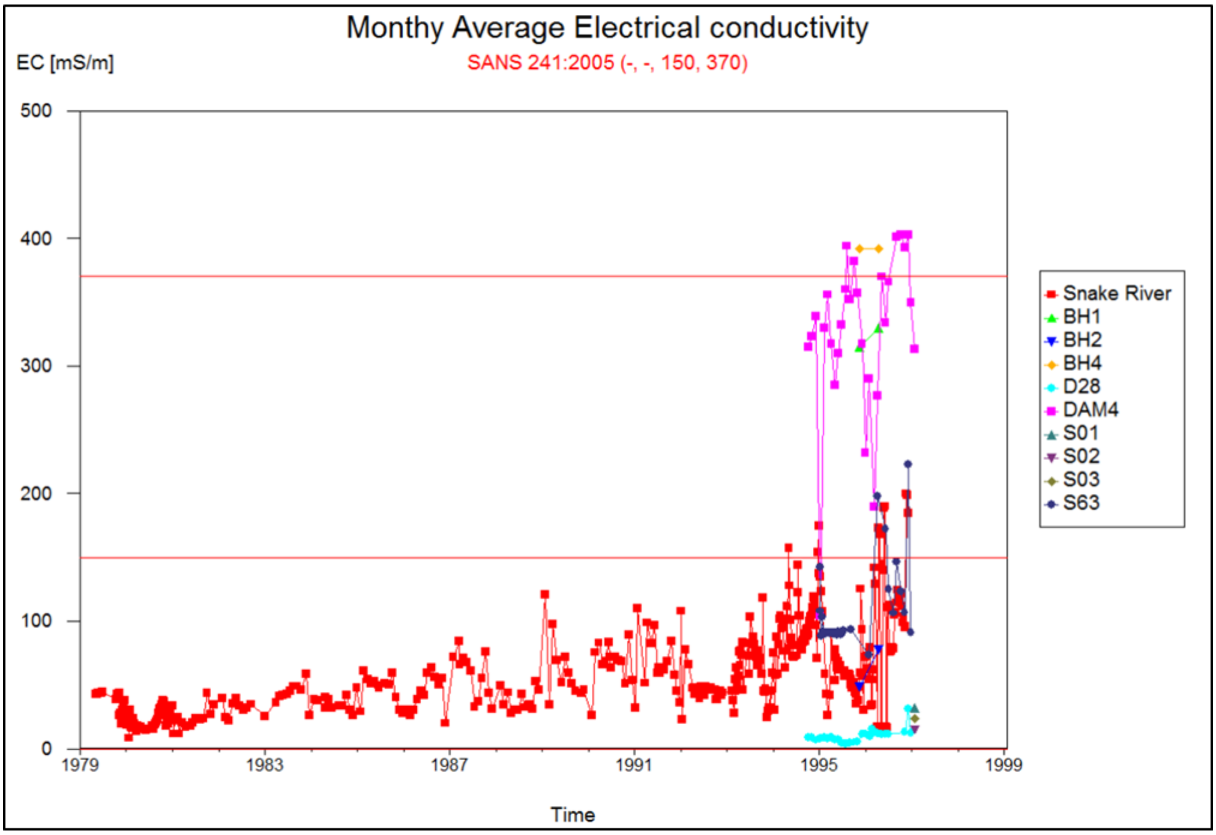


Figure 7-2: Time-based line graph

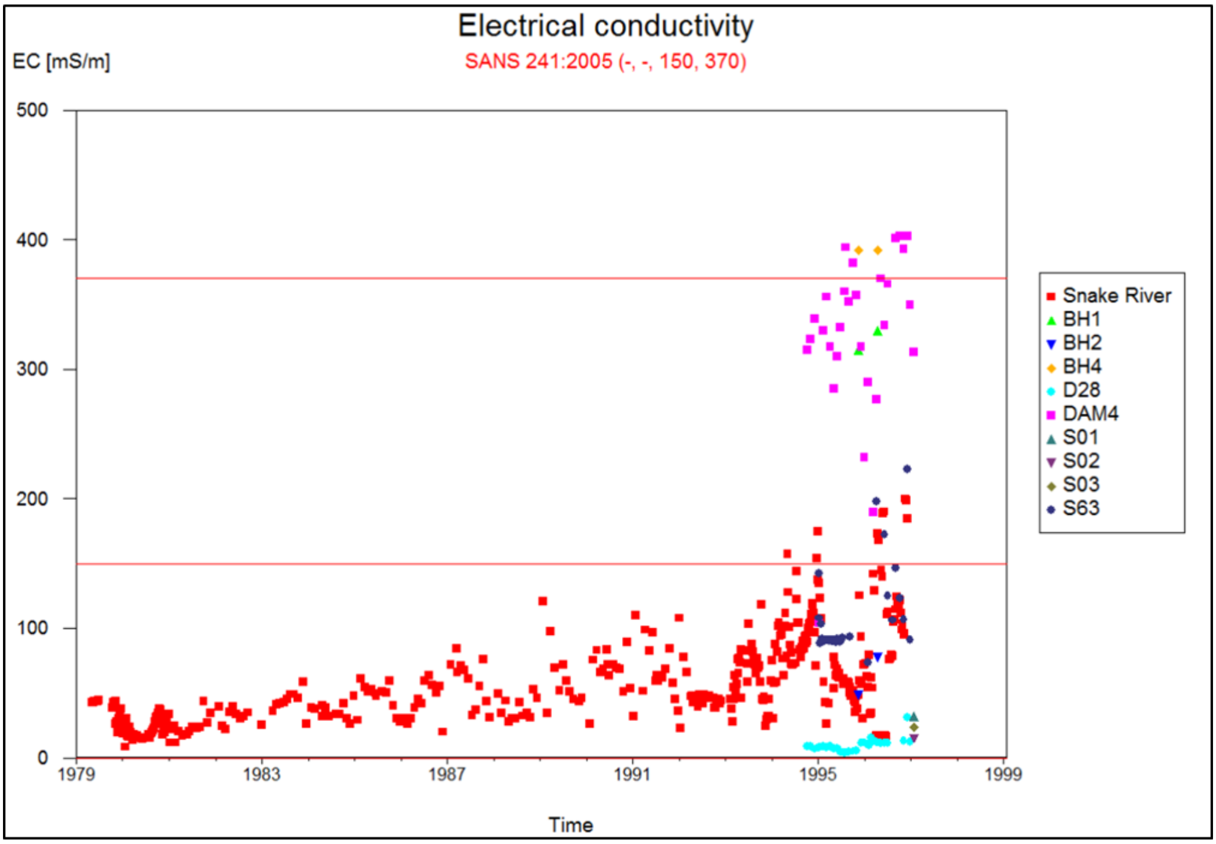


Figure 7-3: Time-based scatter plot

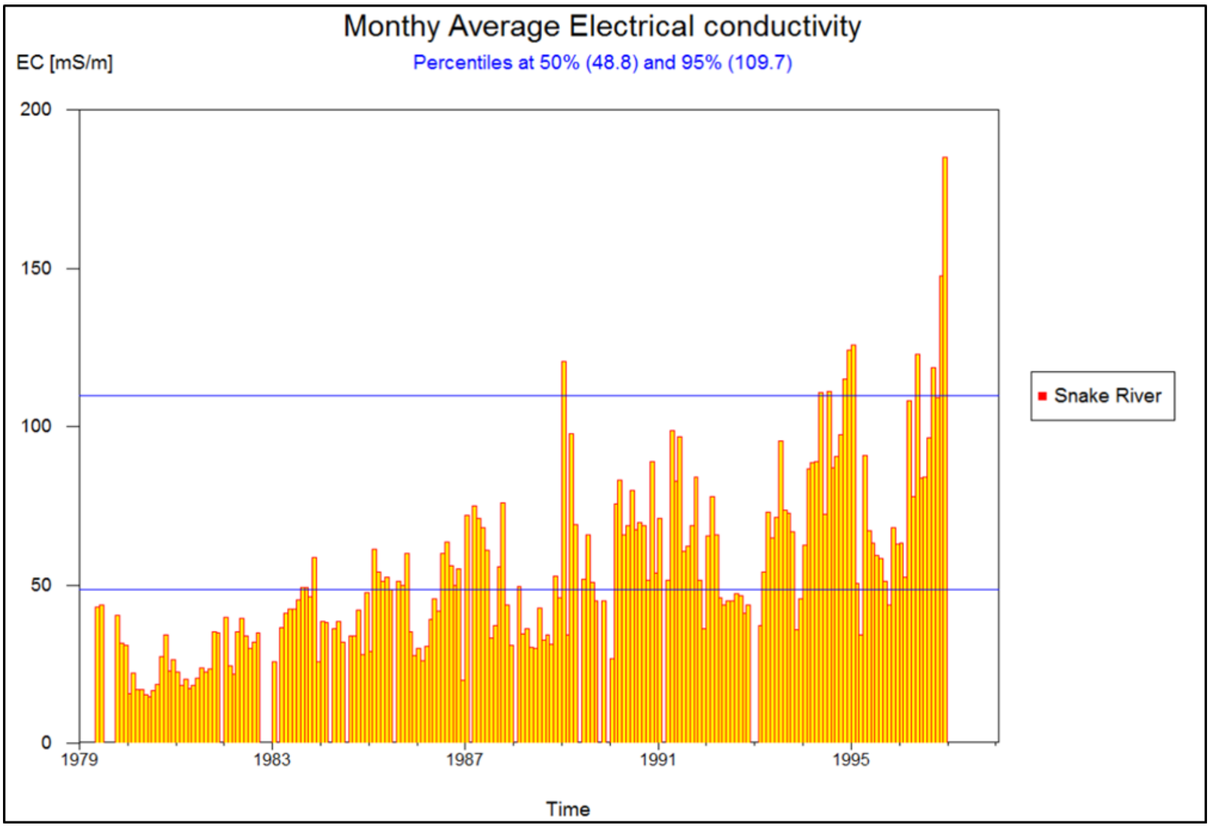


Figure 7-4: Time-based bar graph

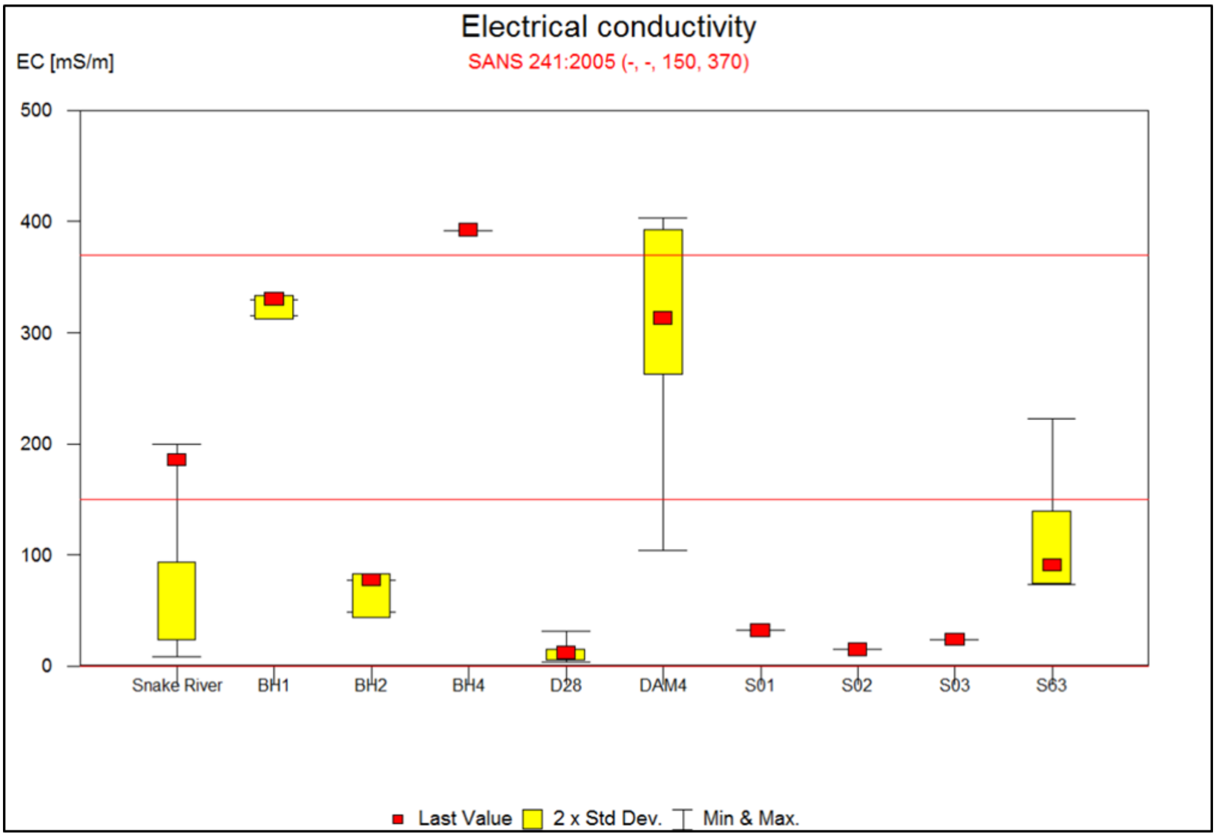


Figure 7-5: Box-and-whisker plot

7.1.2.4 Specialised chemical diagrams

WISH allows chemical data to be plotted in six specialised chemical diagrams (Lukas, 2012):

- Piper Diagram (Figure 7-6)
- Durov Diagram (Figure 7-7)
- Expanded Durov Diagram (Figure 7-8)
- SAR Diagram (Figure 7-9)
- STIFF Diagram (Figure 7-)
- Schoeller Diagram (Figure 7-)

The first three diagrams are mainly used for correlation between waters sampled at different sites and for water classification. The SAR Diagram is used to determine if water is suitable for irrigation. STIFF diagrams display the major ion composition of a water sample and are used for "fingerprinting". The shape of the diagrams represents the ratios between the different parameters. Similar water chemistries result in similar shapes on the STIFF diagrams. The Schoeller Diagram allows different chemical parameter values to be plotted on different vertical axes in the same graph. The linear lines that connect the parameter values characterise the chemistry of the water sample from a particular site, allowing comparison with chemistries from other sites.

7.1.2.5 Pumping test analyses

WISH allows analysis of the pumping test data captured in the *PumpTest* sheet to estimate the hydraulic parameters of the aquifer systems intersected by the boreholes. Analyses can be done using the following methods:

- The Theis Method
- The Cooper-Jacob Method

- The Hantush Method
- The Step-drawdown Method
- The Recovery Method

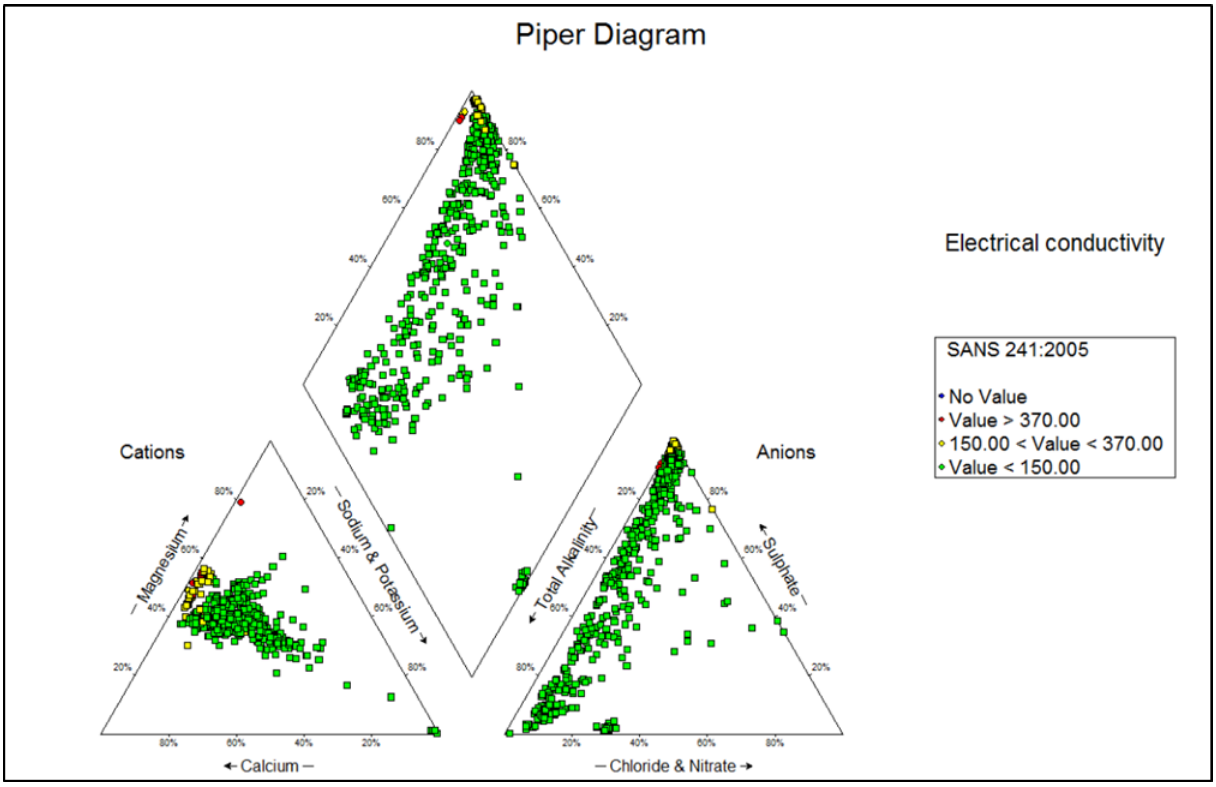


Figure 7-6: Example of a Piper Diagram

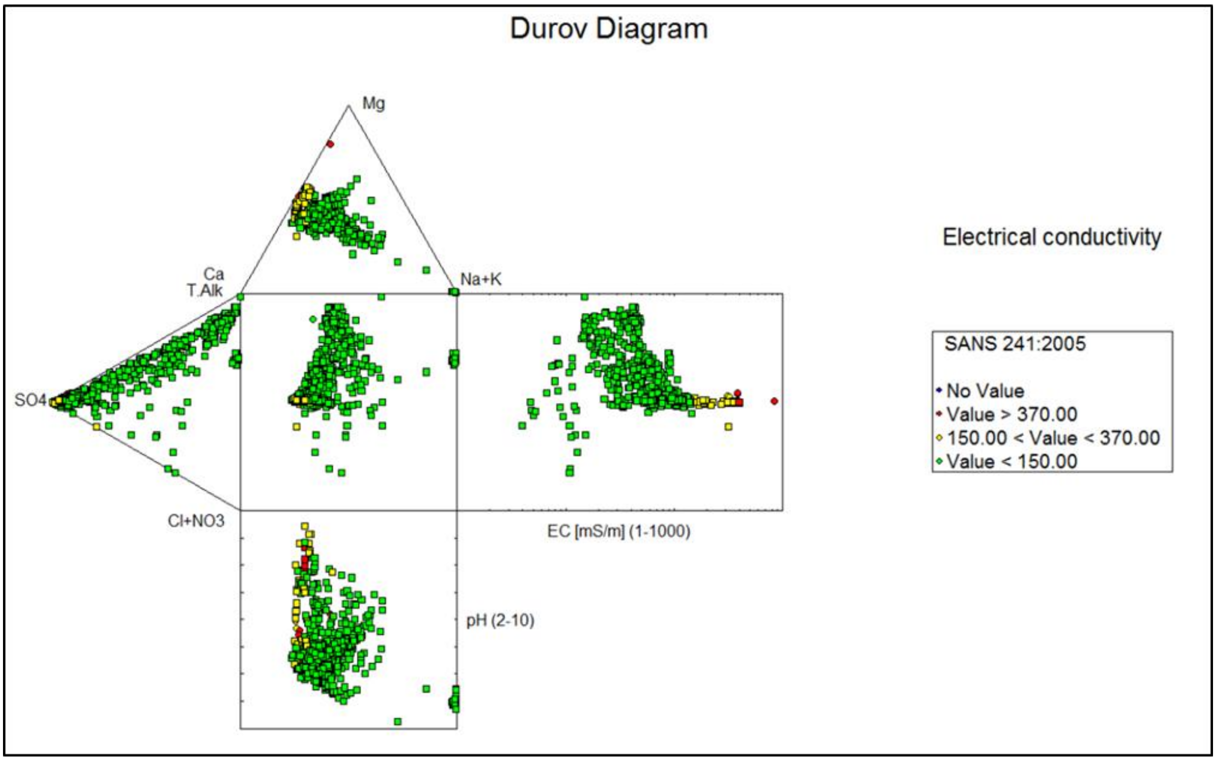


Figure 7-7: Example of a Durov Diagram

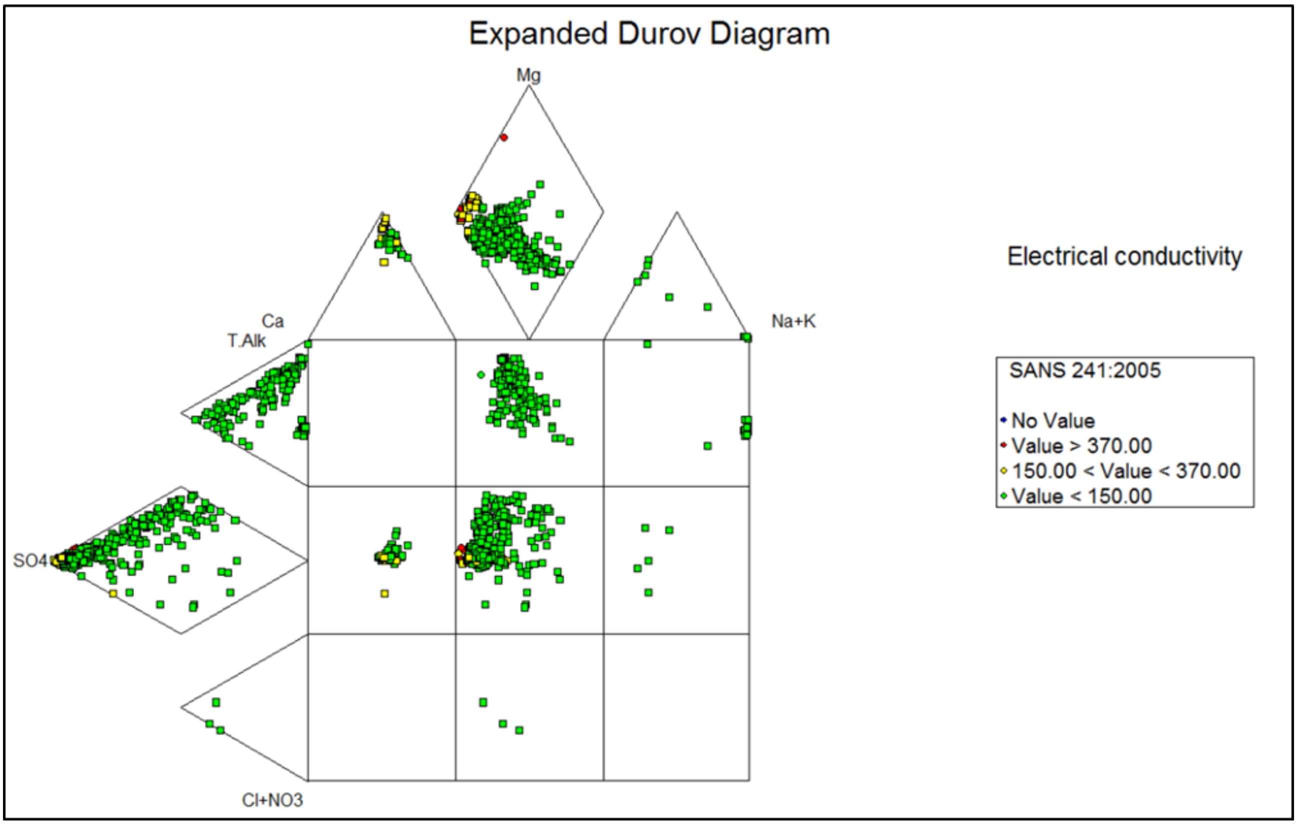


Figure 7-8: Example of an Expanded Durov Diagram

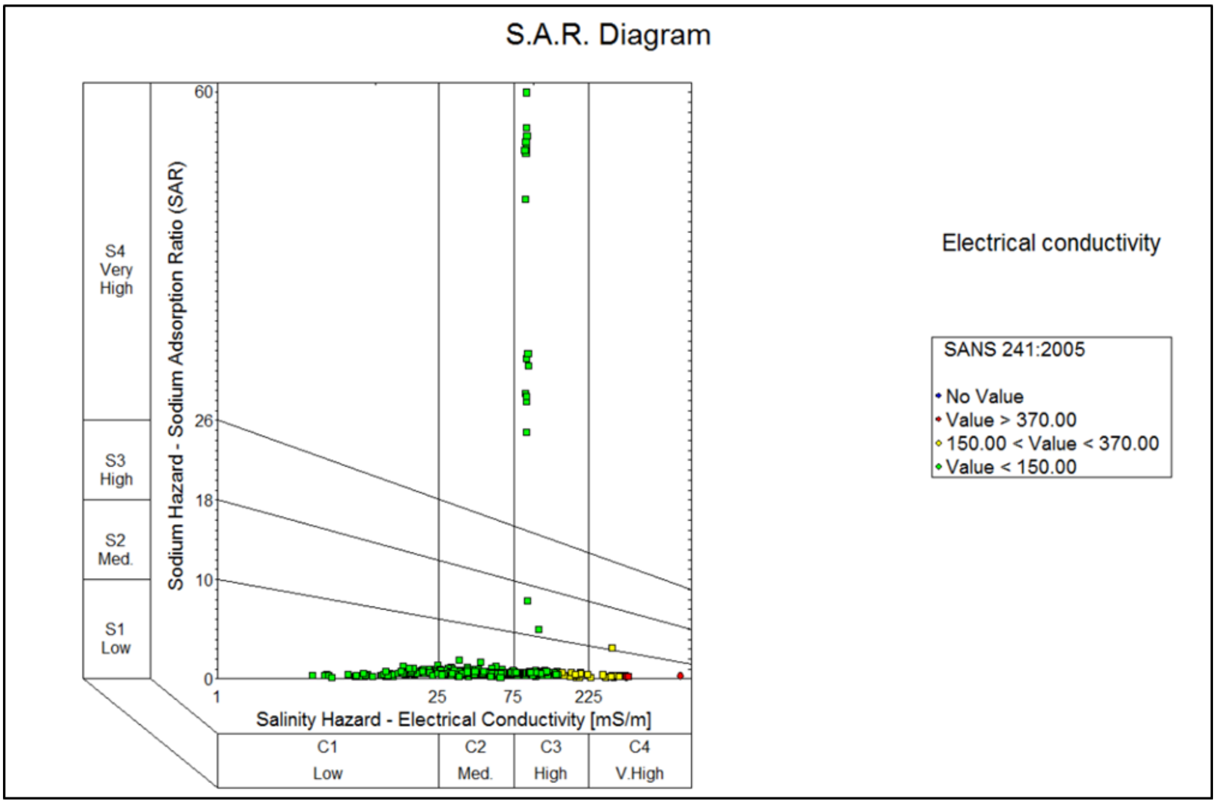


Figure 7-9: Example of an SAR Diagram

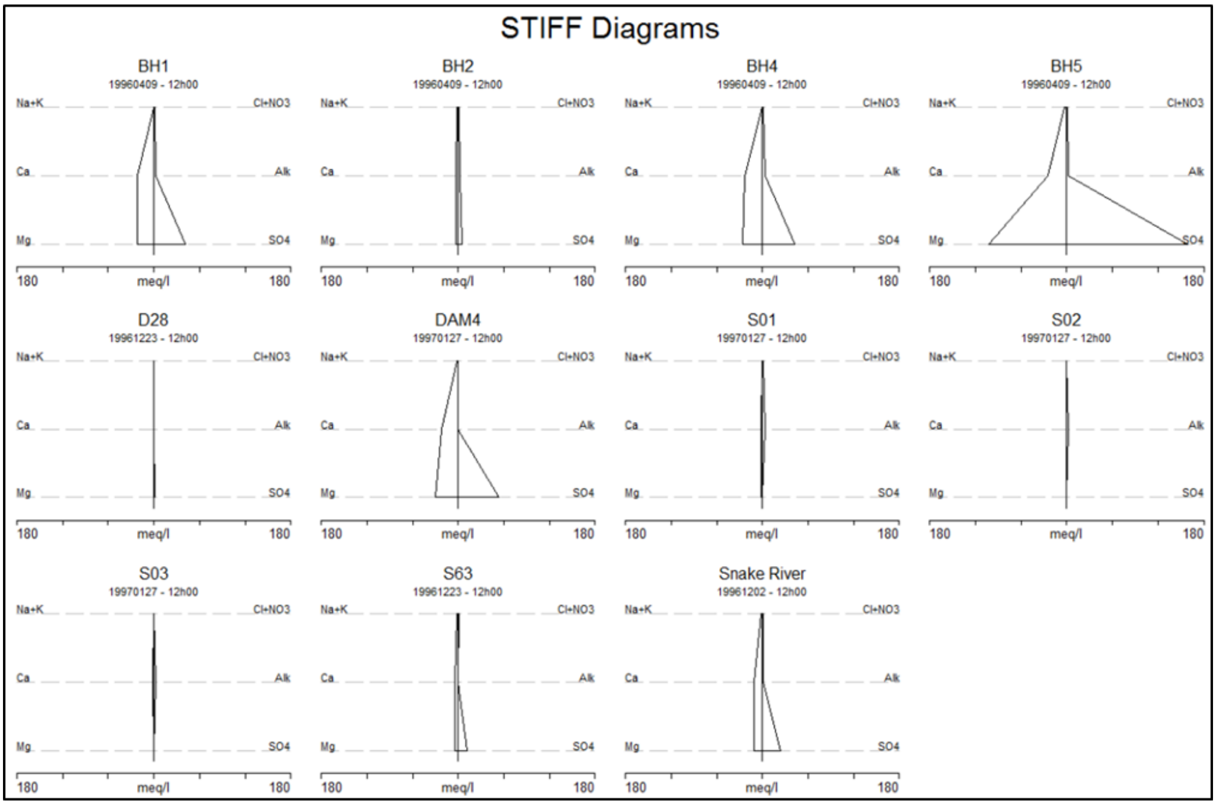


Figure 7-10: Example of a STIFF Diagram

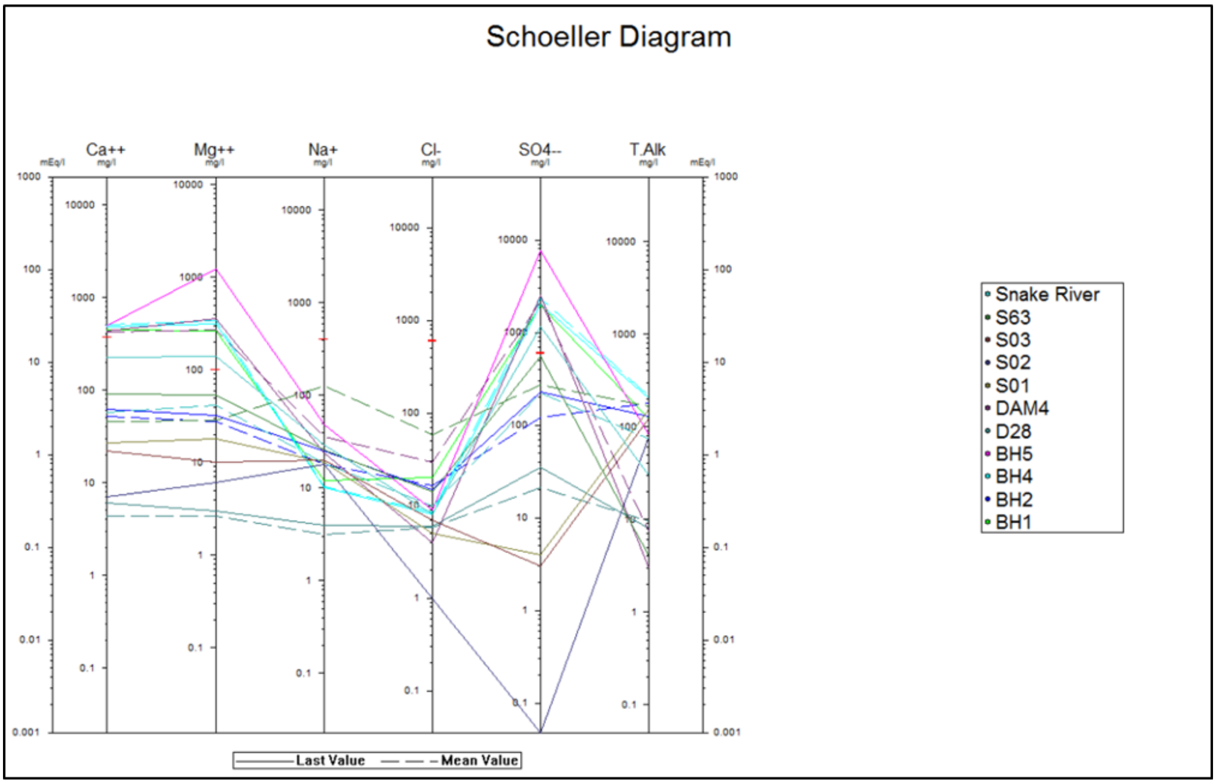


Figure 7-11: Example of a Schoeller Diagram

7.1.2.6 Geohydrological borehole logs

The lithology information entered in the BH Geology sheet, together with the borehole information entered in BH Construction, BH Yield and BH Parameters, may be displayed graphically as geohydrological borehole logs. Very detailed logs (or very long ones) can be generated over multiple pages (Lukas, 2012). An example of a geohydrological borehole log generated by WISH is shown in Figure 7-.

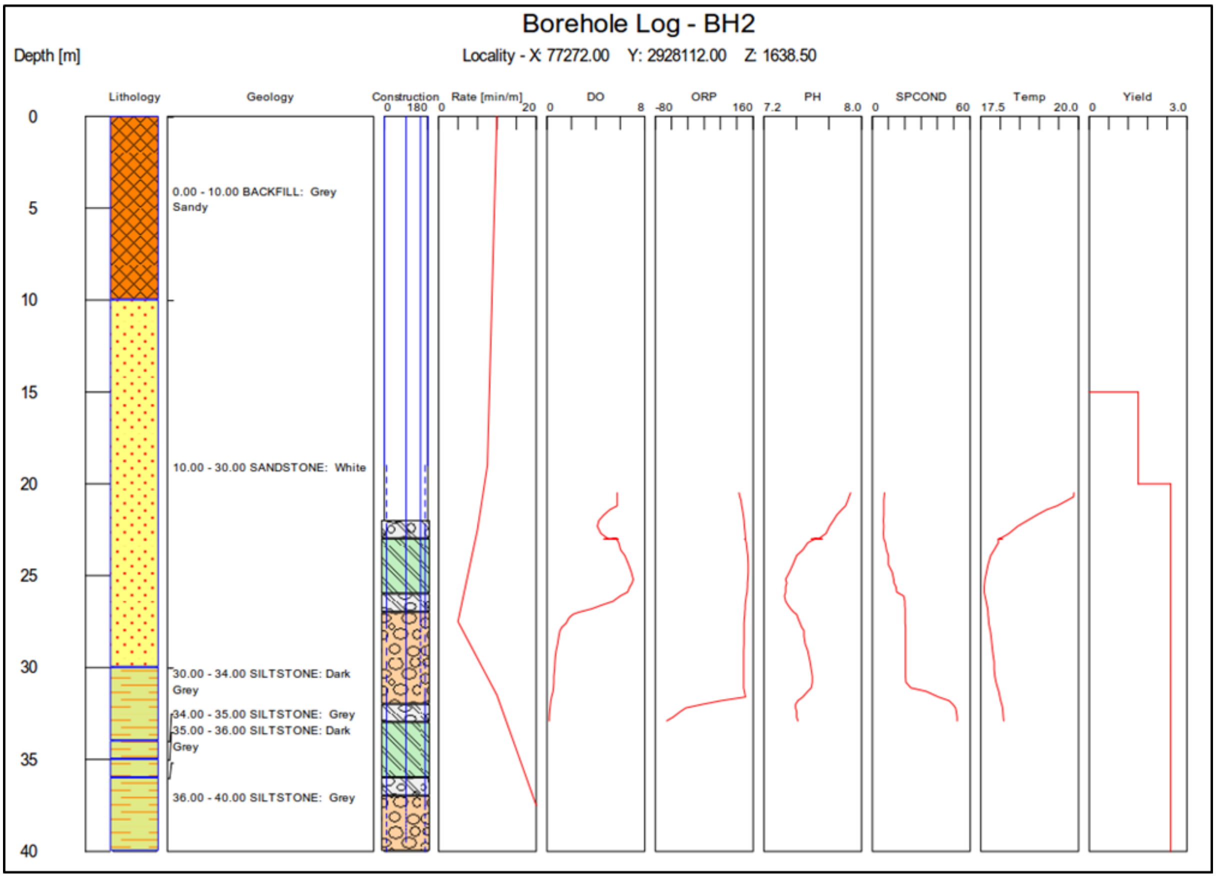


Figure 7-12: Example of a geohydrological borehole log

7.1.2.7 Graphical user interface

7.1.2.7.1 Graphical user interface

The graphical user interface (GUI) is that part of WISH that allows the user to visually interact with the data in the database. By using the *Xcoord* and *Ycoord* data stored in the *BasicInf* sheet, the GUI allows the positions of the sites to be plotted against background maps. The GUI allows the importation of geo-referenced raster images, as well as the most commonly used GIS file formats (.dgn, .dxf, .shp, .map).

Different data sets are managed as different layers in the GUI. These layers can be turned on or off as desired, and moved upwards and downwards to show certain data sets above others in the GUI. The GUI is interactive and allows sites to be selected so that data can be viewed or extracted from these sites.

The GUI furthermore allows certain operations to be performed on data. For example, the gridding and contouring of spatially distributed data can be done to create a contour map of the data. This contour map can also be displayed as a layer in the GUI. An example of the GUI is shown in Figure 7-.

7.1.3 Data captured in the database on deep aquifers

7.1.3.1 Introduction

During the investigations, the following confirmed and potential sources of data on deep aquifers and groundwater conditions were identified:

- Boreholes of the IHFC. The IHFC database indicates the location of 39 deep boreholes that range in depth from 300 to 800 m, with an average depth of 535 m
- The Pangea database of the ICSU. The Pangea database has information on 119 boreholes in South Africa, of which 116 are deeper than 300 m
- A CGS's database on deep boreholes. This database contains information on 5,221 boreholes with depths exceeding 300 m
- The SOEKOR boreholes
- Boreholes drilled as part of KARIN
- Information on deep boreholes from PASA.
- The National Groundwater Archive of the DWS.
- Information on the occurrence of thermal springs in South Africa as obtained from publications (articles, papers, reports)
- Information on the locations and depths of underground mines in South Africa. Information on the occurrence of deep groundwater could potentially be obtained from these mines.

These sources of data were interrogated to extract all data relevant to the deep aquifer systems. This data was included in the database that was compiled as part of the current deliverable.

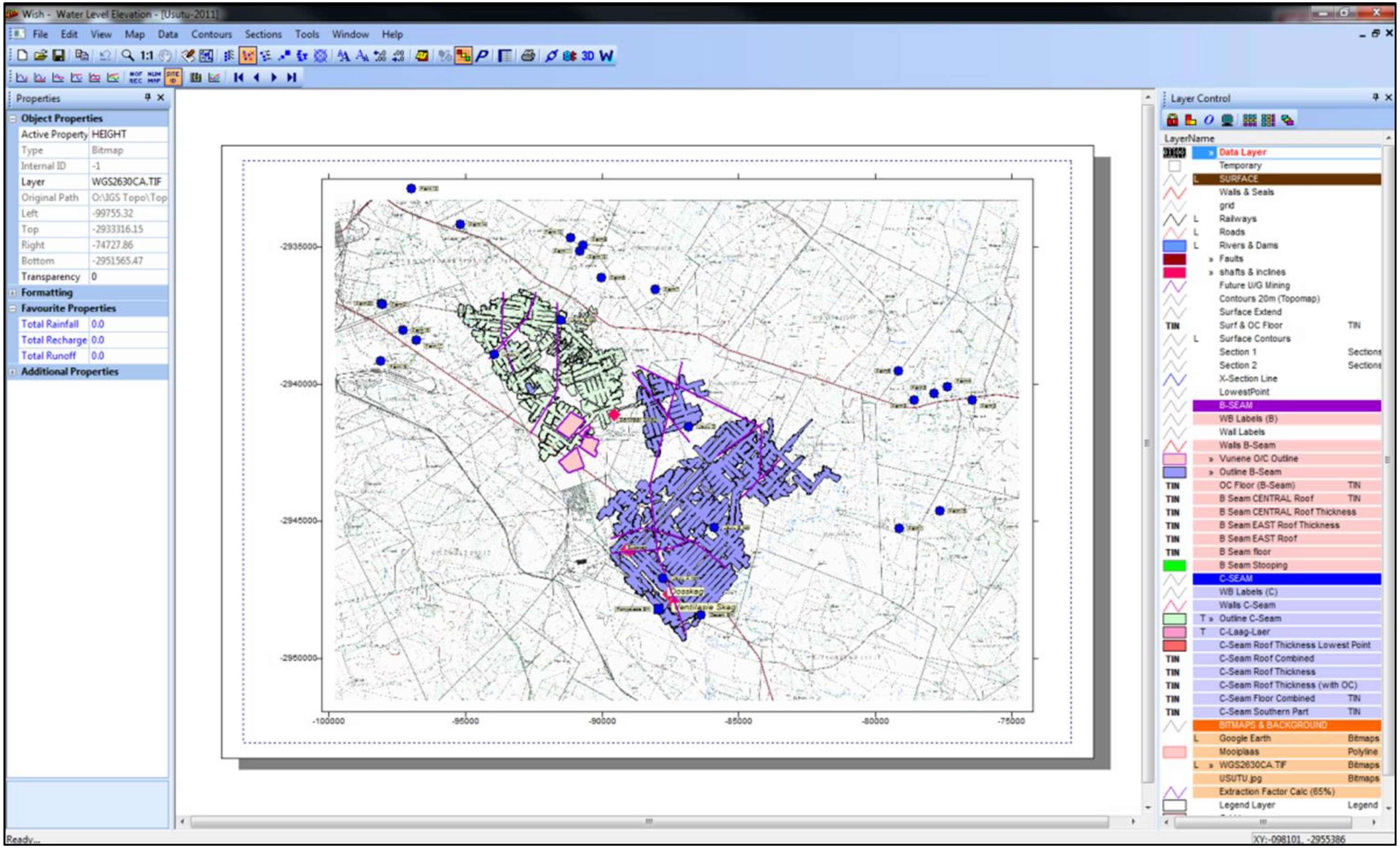


Figure 7-13: Example of the WISH's graphical user interface

7.1.3.2 Basic information

The *BasicInf* sheet of the database on deep aquifers lists 6,635 sites. These sites include the following:

- 5,221 borehole sites from the CGS's database
- 1,116 borehole sites from the NGA
- 123 boreholes sites from the Pangaea database
- 71 thermal springs
- 49 borehole sites from the IHFC database
- 38 SOEKOR boreholes
- 13 borehole sites from the database of PASA
- Two KARIN boreholes

The distribution of the sites across South Africa is shown in Figure 7-. Borehole sites are indicated by circles, while spring sites are shown as squares.

7.1.3.3 Time-related data

Time-related data captured in the database includes data on groundwater chemistry, groundwater temperature and discharge rates from groundwater sites.

7.1.3.3.1 Groundwater chemistry

The *Time Chemistry* sheet lists chemistry data from the analysis of 355 groundwater samples taken on specific dates and times. Some sites were sampled multiple times, while data is available for only a single sampling event for other sites. Some analyses are comprehensive, and include all major and minor determinands of groundwater analyses, while other analyses are limited to a single parameter, such as pH or electrical conductivity.

The temporal changes in the sodium concentrations at the thermal springs of South Africa are shown in Figure 7-5. Similar time graphs can be extracted for the other chemical or physical parameters that are included in the analyses and for other selections of sites. Piper, Durov, Expanded Durov, SAR and Schoeller diagrams for the analysis of water samples from the thermal springs are shown in Figure 7-16, Figure 7-17, Figure 7-18, Figure 7-19 and Figure 7-20, respectively. A box-and-whisker plot of the nitrate concentrations at the thermal springs is shown in Figure 7-1.

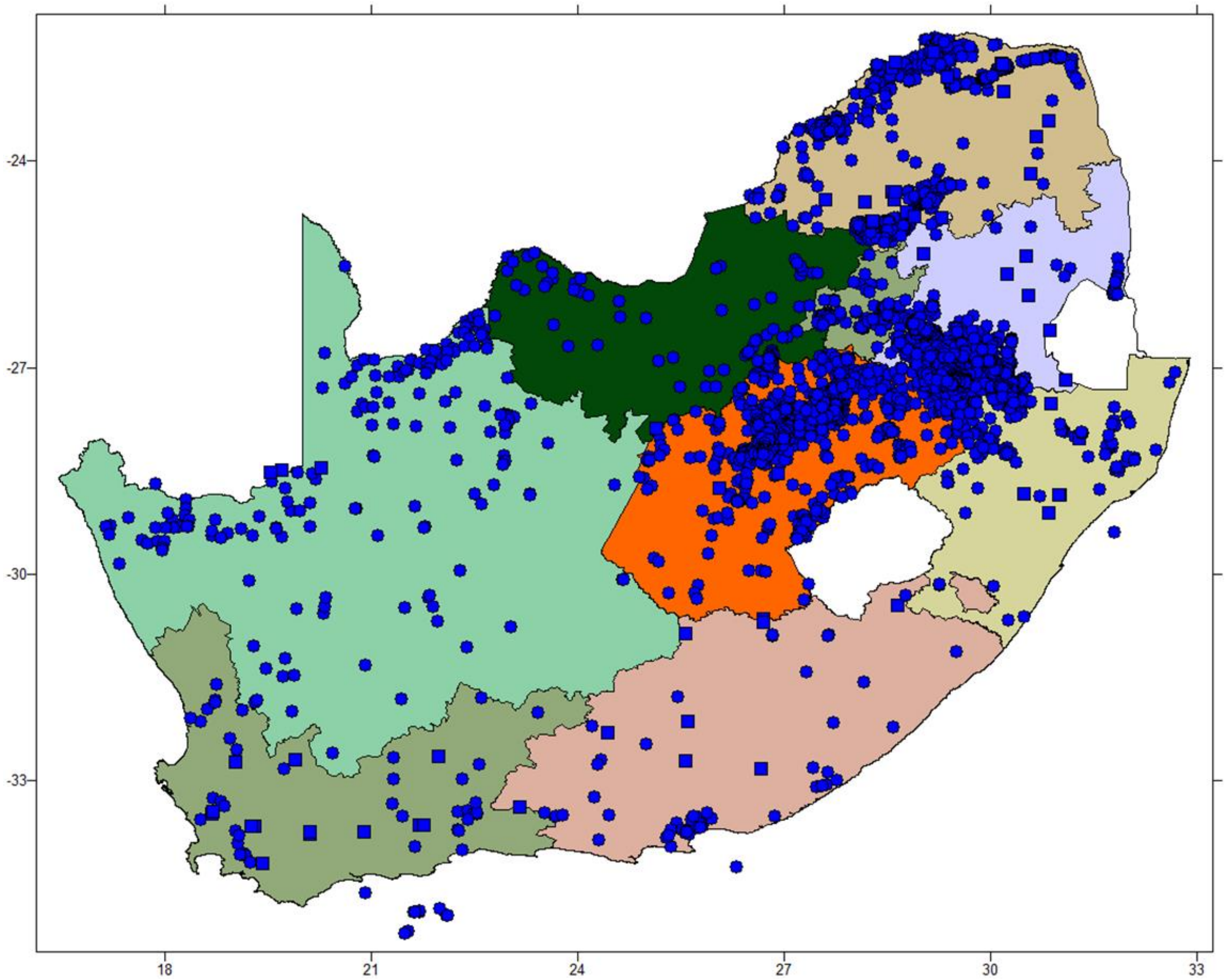


Figure 7-14: Sites in the database on the deep aquifer systems of South Africa

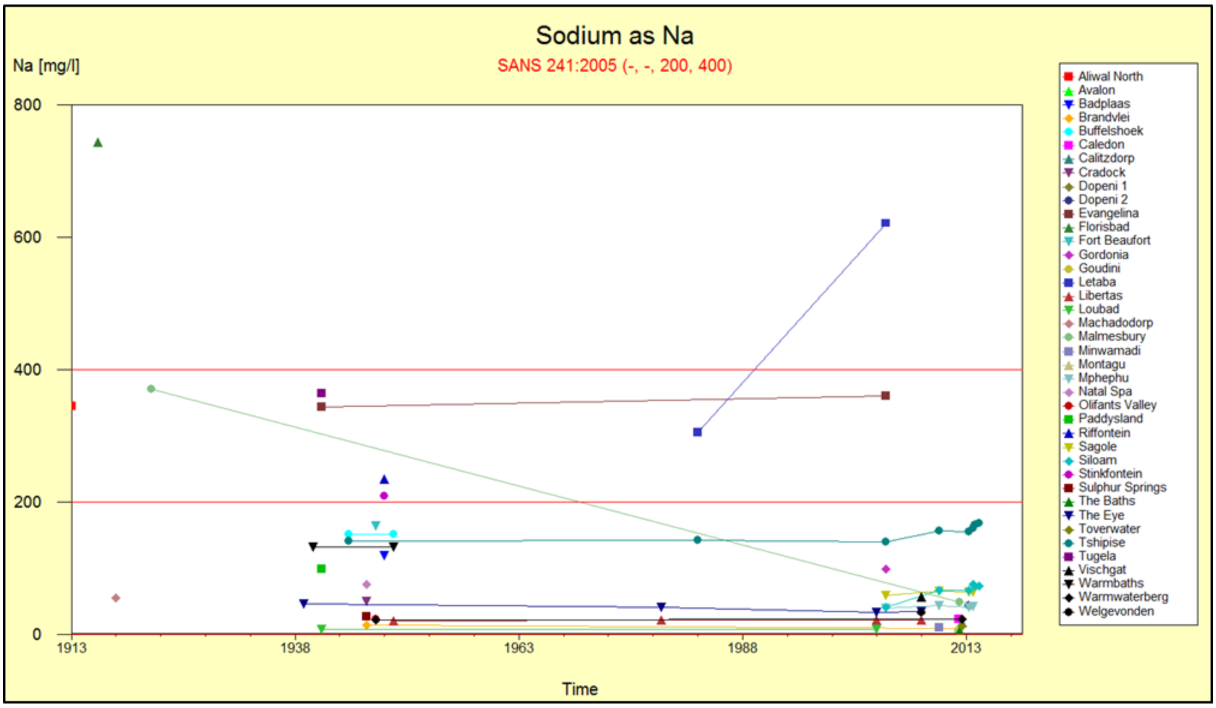


Figure 7-5: Temporal changes in the Na concentrations at the thermal springs listed in the database

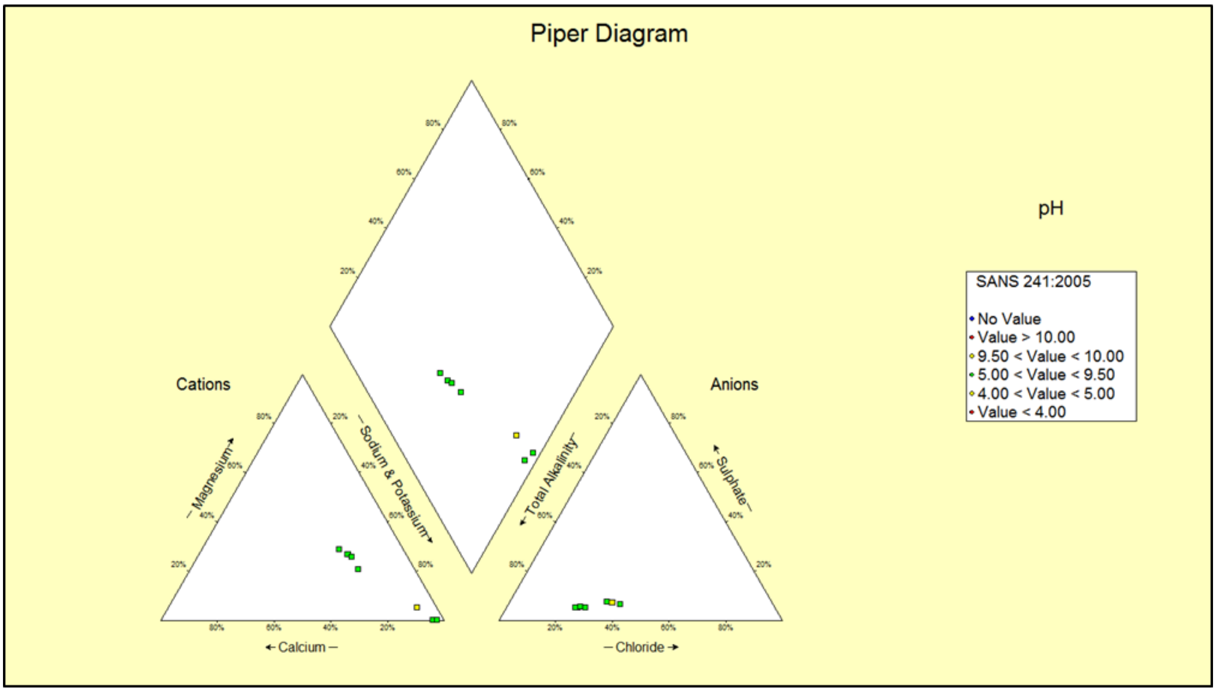


Figure 7-16: Piper Diagram for the water samples from the thermal springs in South Africa

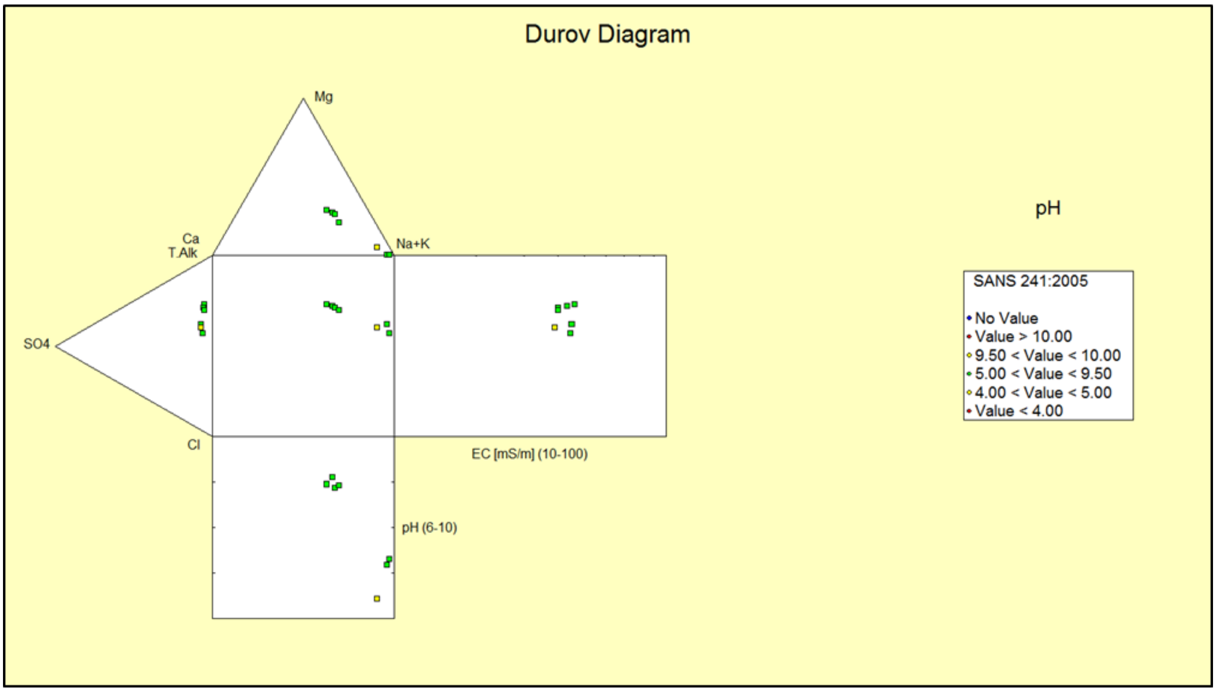


Figure 7-17: Durov Diagram for the water samples from the thermal springs in South Africa

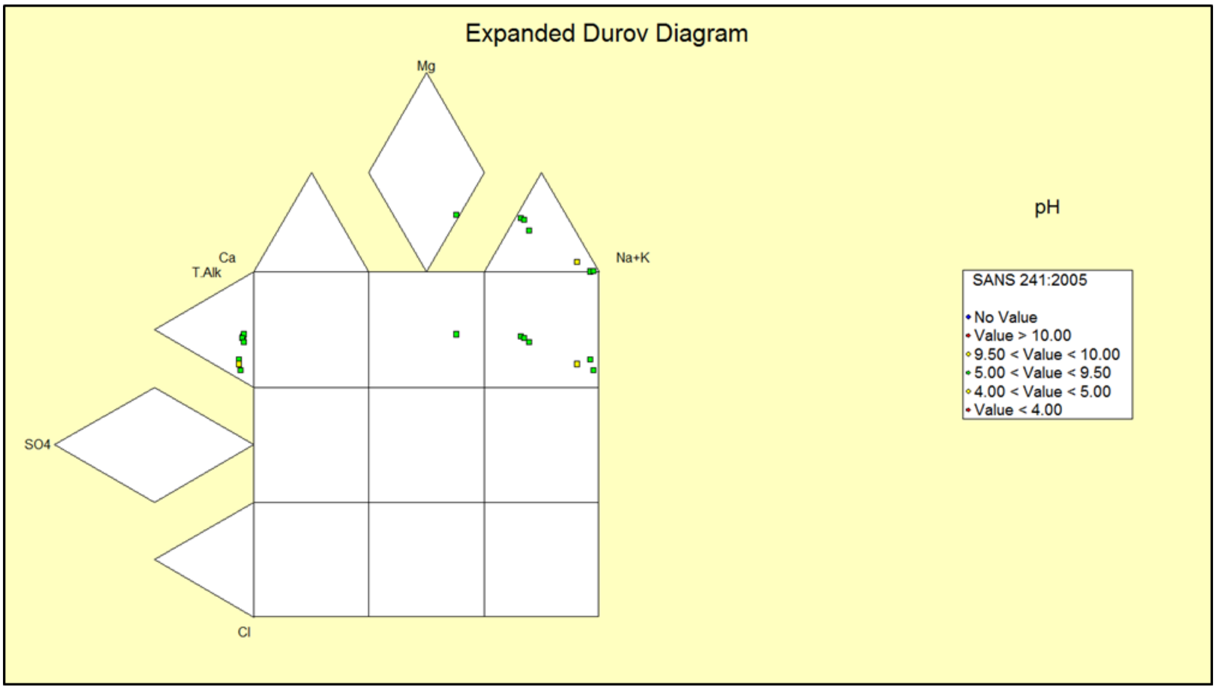


Figure 7-18: Expanded Durov Diagram for the water samples from the thermal springs in South Africa

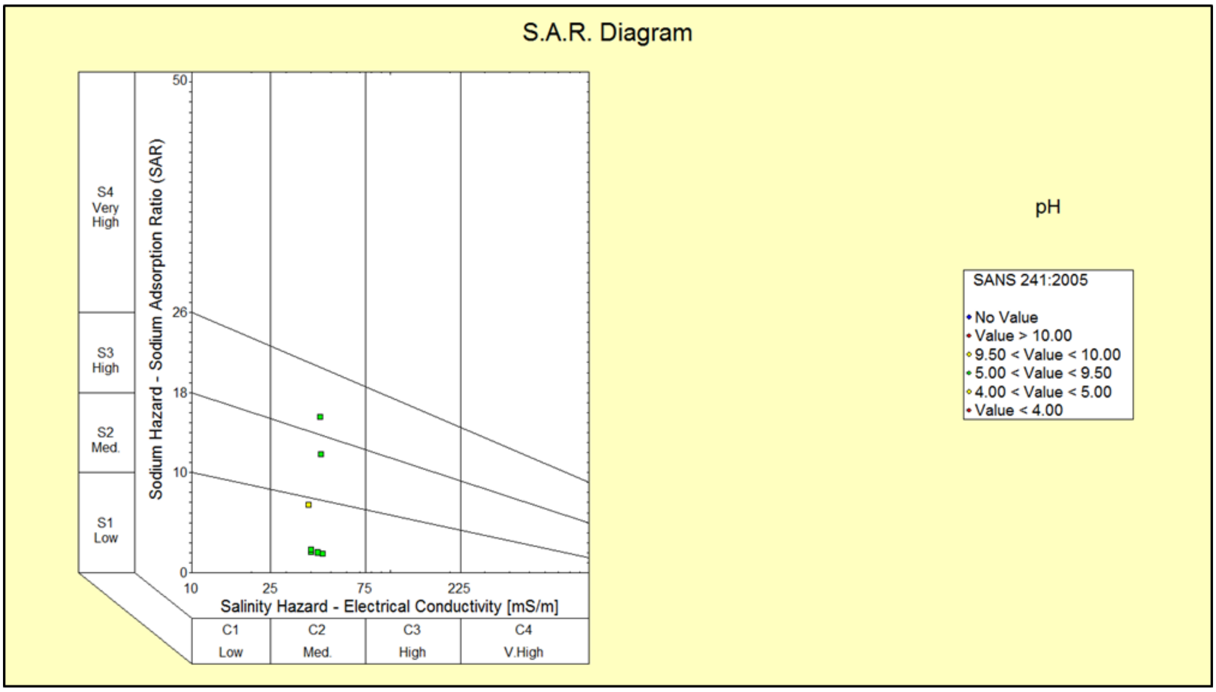


Figure 7-19: SAR Diagram for the water samples from the thermal springs in South Africa

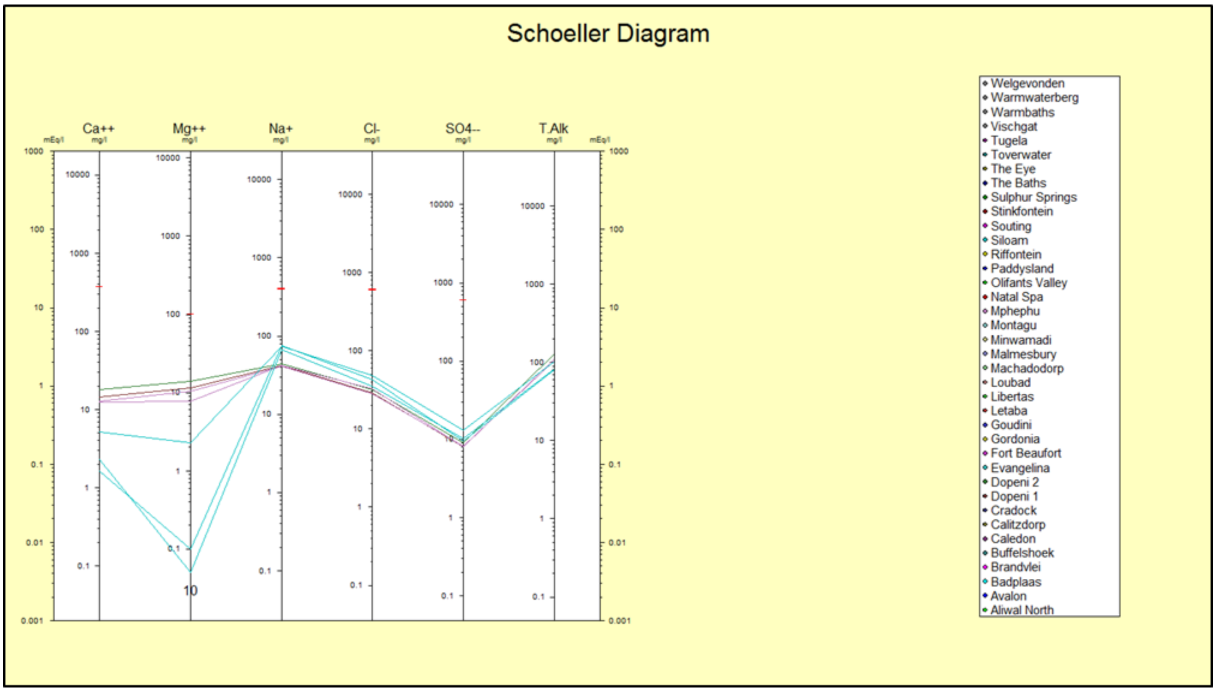


Figure 7-20: Schoeller Diagram for the water samples from the thermal springs in South Africa

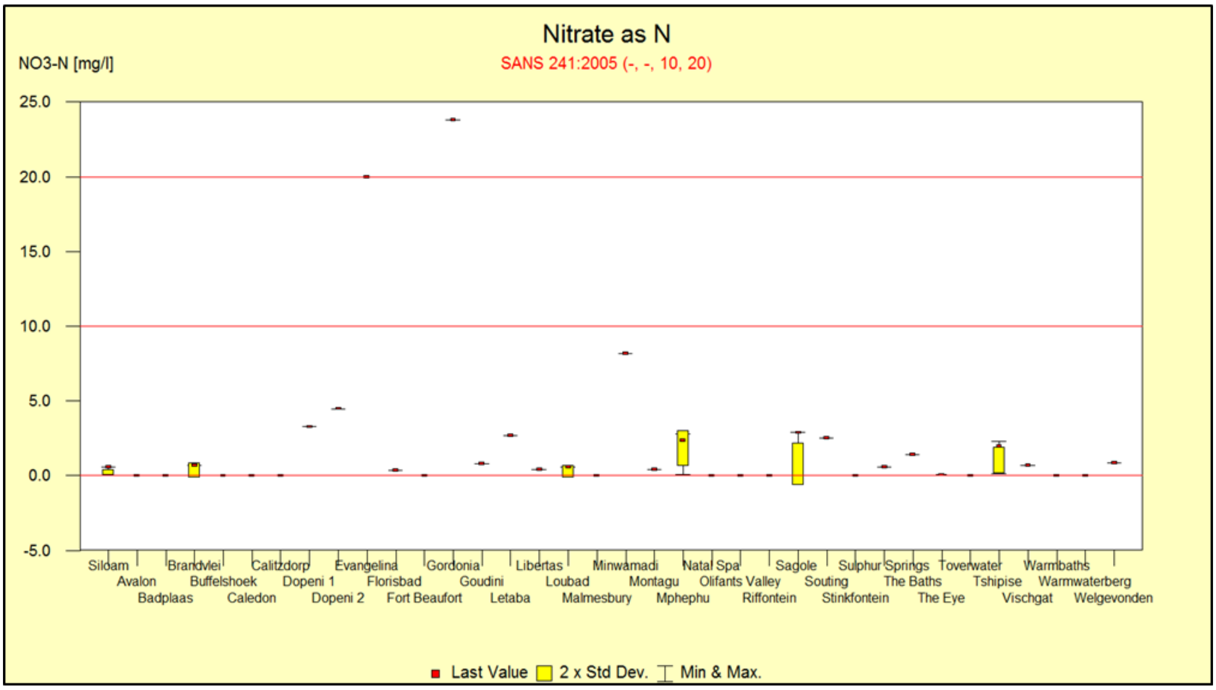


Figure 7-21: Box-and-whisker plot for the nitrate concentrations at the thermal springs in South Africa

7.1.3.3.2 Groundwater temperature

Data on 184 groundwater temperature measurements is included in the database. Data on the temperatures at some sites is restricted to single measurements, while multiple measurements were done at other sites. As an example, the temporal changes in the temperatures measured at the thermal springs of South Africa are shown in Figure 7-622.

7.1.3.3.3 Discharge rates

Data for 38 measurements of the discharge rates from the groundwater sites is included in the database. The discharge rates measured at the thermal springs of South Africa are shown in Figure 7-23723.

7.1.3.4 Borehole data

Borehole data in the database is currently limited to water temperature measurements taken at different depths within borehole KZF-01 (KARIN). However, hard copies of the geological logs of many of the SOEKOR boreholes are available. The information contained in these hard copies could be incorporated into the database by creating electronic versions of the logs. Considering the large depths of the boreholes and the detail contained in the logs, this will be an arduous and time-consuming endeavour. Similar remarks can be made about the borehole logs of the two KARIN boreholes.

7.1.3.5 Pumping test data

No pumping test data on the deep aquifer systems was found during the investigations. No pumping test data has therefore been captured in the database.

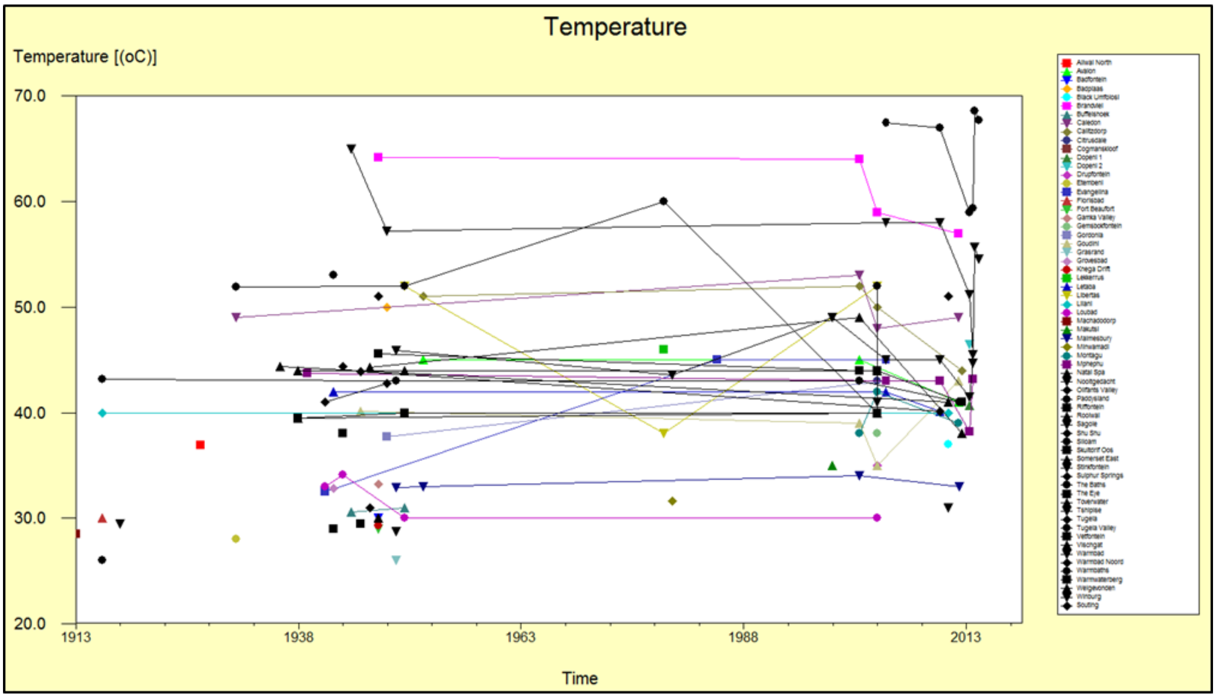


Figure 7-6: Temporal changes in the temperatures at the thermal springs listed in the database

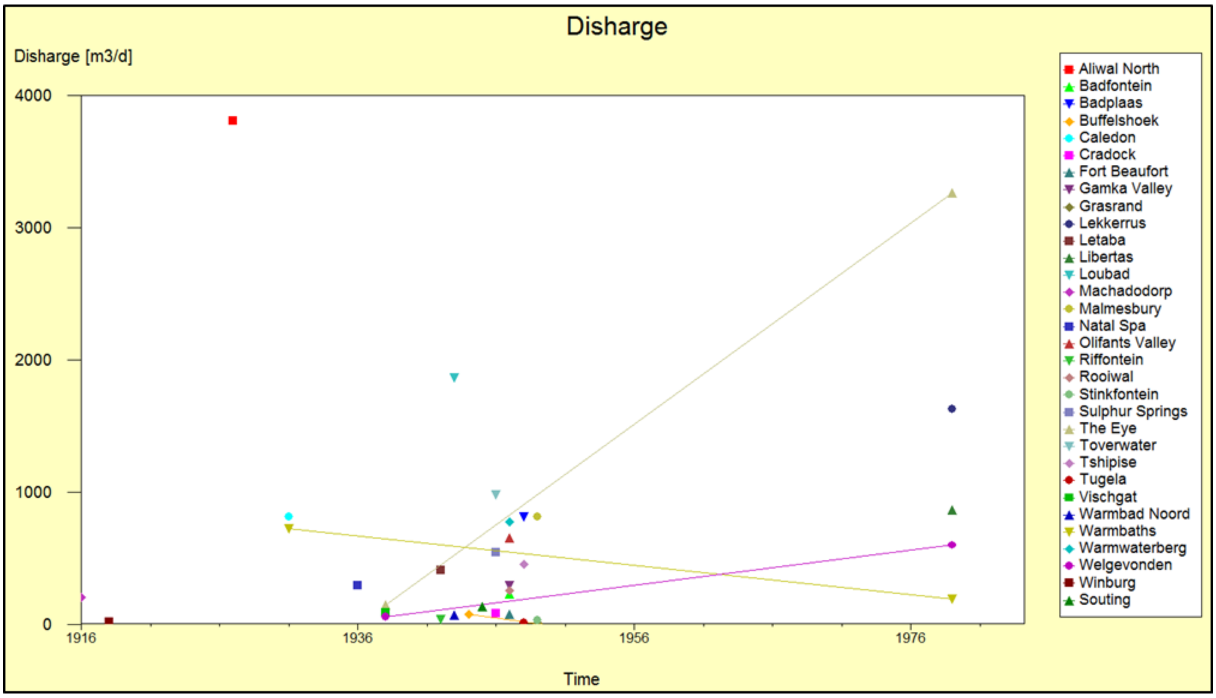


Figure 7-237: Temporal changes in the discharge rates measured at the thermal springs listed in the database

7.2 CONCLUSIONS AND RECOMMENDATIONS

The deep aquifer database currently contains data on the deep boreholes and thermal springs that was gathered during the investigation. The data was compiled by accessing various databases (CGS, IHFC, Pangaea), the NGA, published literature and unpublished reports. Some of the reports date from the 1960s and only scanned copies of very low quality are available for some reports. The data on the deep aquifers is generally sparse and incomplete at most sites. There are also inconsistencies and contradictions in the data.

The database compiled during this study should be managed as a work in progress and should be continually updated as more data becomes available and as inconsistencies are resolved. It is recommended that an organisation be appointed to manage the database to keep it updated as new data becomes available. This will avoid the creation of several dissimilar versions of the database.

CHAPTER 8: RECOMMENDATIONS

Based on the results of this project, a number of actions are recommended to improve our understanding of South Africa's deep aquifer systems and ensure their protection:

1. Although information on a vast number of deep boreholes is listed in the various databases that were consulted during the investigations, the data relevant to the geohydrological conditions was found to be very sparse for most boreholes. For example, only borehole depth and temperature data was available for the boreholes listed in the IHFC database. However, the original drilling reports for these boreholes are likely to still exist, although these reports have probably been filed away in an archive. Locating, retrieving and studying these reports will likely be a challenging and time-consuming endeavour, but attempts should be made to acquire these reports. Similar comments are valid for the reports on the boreholes listed in the databases of Pangaea and PASA.

2. There is currently large confusion about the boreholes drilled as part of the SOEKOR exploration programme. The various databases and reports on these boreholes are contradictory concerning the number of boreholes drilled, the borehole numbers assigned to these boreholes, the coordinates of the boreholes and the depths of the boreholes. The borehole reports that are available are typically electronic versions of scanned documents. Some of these reports contain detailed handwritten geological borehole logs. It may be worthwhile to consolidate all the information on the SOEKOR boreholes in a single database. This would require a desktop study of the available report and capturing the data in electronic format. Furthermore, field investigations will be needed to locate the boreholes and to verify the available information on these boreholes. Additional investigations, such as geophysical logging and packer tests, should be performed on the boreholes to gain insight into the deep aquifer conditions.

3. As with the SOEKOR boreholes, there is currently incomplete and often contradictory information on the thermal springs of South Africa. It is recommended that all the information on the thermal springs is also consolidated into a single database. This will again require both a desktop study and time-consuming field investigations.

4. Deep mining in South Africa involves activities (e.g. installing shafts, drilling exploration boreholes) that allow direct insight into the deep geohydrological conditions. However, since the deep groundwater conditions are of less concern to the mining companies than the presence of ore, geohydrological information has not been routinely collected at the mines. In addition, information gathered by the mines has often been treated as proprietory or confidential. There is a need for a paradigm shift that would allow the bridging of the perceived divides between the mining industry and the groundwater industry. Through the collection of information on the deep aquifer systems at mines, the current state of knowledge on the deep groundwater system will be improved. This will likely be to the ultimate benefit, not only of the groundwater community, but also of the mining companies, since a better understanding of the deep aquifers will, for example, allow more efficient management of groundwater influx into the mines.

5. For the protection of the deep aquifer systems from impacts from various activities, it is recommended that the general framework proposed in this report be used. This framework includes actions such as baseline investigations, the geohydrological characterisation of the affected area, the development of a conceptual geohydrological model of aquifer systems, the identification of all possible impacts of the activity on the deep groundwater resources, the simulation of the potential impacts of the activity on the deep groundwater system through numerical modelling, the consideration of technologies available to avoid or reduce impacts on the deep aquifers, the consideration and implementation of national and international best practice guidelines, the application of existing laws and regulations to protect the deep groundwater resources, the development of new laws and regulations where existing

laws and regulations are deemed inappropriate or inadequate, the implementation of a monitoring programme specifically designed to monitor potential impacts on the deep groundwater system by the activity, and the application of adaptive management strategies to deal with unforeseen situations arising from the implementation of the activity.

6. During the current project, a database on South Africa's deep groundwater systems was developed. This database should be managed as a work in progress and should be continually updated as more data become available and as inconsistencies are resolved. It is recommended that an organisation (possibly the CGS) be appointed to manage the database and keep it updated as new data becomes available. This will avoid the creation of several dissimilar versions of the database.

7. Close cooperation should be established with those organisations involved in the drilling of deep boreholes (KARIN, the Bushveld Igneous Complex Drilling Project, the carbon capture and storage industry, the coalbed methane industry) to allow deep geohydrological data to be recorded as a matter of routine during the drilling of deep boreholes.

8. To allow the geohydrological characterisation of South Africa's deep aquifer systems, it is recommended that deep boreholes, designed by geohydrologists and dedicated to geohydrological investigations, be installed at selected locations. The construction of these boreholes should be such that geohydrologists will be able to collect comprehensive datasets on the aquifer parameters and groundwater conditions. These boreholes could potentially allow for the development of new technologies to characterise deep aquifer systems.

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