Hydrogeology of Groundwater

Region
1
Makoppa Dome

J R Vegter

TT 135/00
Water Research Commission

HYDROGEOLOGY

OF GROUNDWATER

REGION 1: MAKOPPA DOME

Prepared for the Water Research Commission

by

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EXECUTIVE SUMMARY

Region 1, the Makoppa Dome, is situated northwest of Thabazimbi and comprises the northwestern corner of the Northern Province as well as a small portion of the adjoining Northwestern Province. The Marico River constitutes part of its northern boundary and the lower Crocodile River crosses the Region in the east.

Region 1 is a bush-clad virtually level expanse except for some hilly ground in the extreme west and a few koppies in the east. By far the greater part is underlain by Swazian granite and granite-gneiss that contains scattered occurrences of Swazian metamorphosed metasediments and mafic intrusives. In the west there are two bodies of intrusive Gaborone Granite. Younger volcano-sedimentary formations fringe the Region's southern boundary. Cainozoic detrital deposits and calcrete extensively cover the Swazian rocks. Average annual summer rainfall ranges between 475 and 600 mm.

Groundwater is being exploited on a large scale along the Crocodile River for irrigation. Informal settlements, small communities and farms are dependent on groundwater for human consumption, household use, stock and game watering.

Alluvium along the Crocodile River consists typically of sandy clay or clay overlying sand, gravel and boulders. Weathered bedrock is usually present. The combined saturated thickness of alluvium and weathered bedrock ranges between 20 and 40 m. In 1985 the yields of boreholes that were used for irrigation averaged 7.9 $\ell\,s^{-1}$.

This report is concerned with the occurrence of groundwater in the hard-rock formations. Borehole data of the National Groundwater Database have been statistically analysed. The results have been produced in a number of figures and two tables. Drilling success rates are as follows:

Swazian rocks	35.9%
Gaborone Granite	25.4%
Volcano-sedimentary formations	28.9%

To be regarded successful a borehole must yield at least 0.1 $\ell\,s^{-1}$.

The occurrence of groundwater in hard-rock formations is determined by the extent of weathering and fracturing. Optimal strike depths are as follows:

Swazian rocks	30 - 85 m
Gaborone Granite	20 - 65 m
Volcano-sedimentary formations	35 - 55 m

Within these optimal strike zones the probability of striking water is still small. In the hope of striking water deeper down, unnecessary deep drilling has been undertaken in the past. It is more profitable to attempt a second borehole once the maximum optimal depth is reached. With the exception of known steeply dipping fracture zones, where second attempts to strike same shallower or deeper may be warranted, further drilling should not be undertaken in the immediate vicinity. There is no point in duplicating a borehole in basically the same formation. Water level depth plus a narrow optimal strike zone below water level should ideally determine drilling depth. This zone is generally 10 to 20 m thick.

Electrical depth probing and magnetic geophysical methods are indispensable tools in the siting of boreholes. Frequency domain electromagnetic techniques also may be employed to locate narrow linear conductive features such as fracture and fault zones. Geophysical work is generally guided by surface indications such as lineations on aerial photographs and satellite imagery, changes in soil and vegetation. To ensure optimal results, drilling, geological and geophysical borehole logging should go hand-in-hand. The most favourable orientation of structural elements may possibly be deduced from the orientation of the neotectonic strain ellipsoid. This has, however, not yet been proven in Region 1.

The presence of Cainozoic sediments and the possible existence of deep, infilled paleochannels appear to have escaped notice during previous groundwater investigations. The Council for Geoscience's (previously the Geological Survey) sedimentological and stratigraphic investigation of the Cainozoic sediments may have provided an explanation for the highly variable groundwater levels in an area virtually devoid of surface relief. Locating and tracing these paleochannels geophysically or alternatively the structural features that act as conduits, may help to resolve the deficiency in water. The distribution of deep and discordant water levels, which has been mapped on a farm-by-farm basis, serves as a starting point.

The Council for Geoscience's investigation has also highlighted the role of geochemical processes:

- The development of authigenic palygorskite from the probable precursor clay mineral montmorillonite in argillaceous strata of the Cenozoic Rooibokkraal Formation
- The calcification and ultimate replacement of palygorskite by calcrete. Swazian metamorphic and granitoid rocks, particularly in the south, were apparently also extensively calcretized.

The principal agent in these chemical processes is percolating water. Evidently there is a complex interaction between the occurrence and chemical character of the water, the chemical processes and products. The processes are governed by climatic and environmental conditions, rate of water movement and residence time. The question arises whether and to what extent these processes have produced or degraded the water-bearing properties of not only the Cainozoic deposits, but also of the underlying fractured metamorphic and granitoid rocks. The low success rate of holes sited geophysically on deep weathering may point to the formation of impermeable clay in the fractured transition zone at the base of the weathered zone.

Water level fluctuations and the presence of tritium in groundwater are proof of recharge albeit mainly at irregular intervals. Bush clearing enhances recharge through reduced tranpiration loss from the vadose zone and possibly also from the saturated zone.

In spite of, or rather because of its very scarce groundwater resources, Region 1 seems ideally suited for a holistic research approach into all aspects related to the occurrence, recharge, flow and discharge of groundwater, clay mineralogy and hydrochemistry. Suggested topics for research include:

- Locating and tracing paleochannels by means of geophysical methods and exploratory drilling, and test pumping with a view of determining the hydrogeological properties of their fill and their possible role as conduits;
- Alternatively, locating and tracing hard-rock geological structures that may act as conduits and be responsible for the discordant water level pattern;
- Water-bearing properties of hard-rock geological structures; of fracturing in relation to neotectonic stress field;
- The role of weathering in enhancing or degrading water-bearing properties - geochemical processes and weathering products in relation to hydrochemistry both within the zone of aeration and below groundwater level;
- Groundwater flow regime and discharge - what are the conduits, where and in what form is discharge occurring;
- Infiltration - modes of water movement through zone of aeration: moisture content and loss through evapotranspiration.

- Water consumption by Bushveld vegetation: detection and identification of phreatophytes; and
- Recharge - its temporal and volumetric variability and its relation to rainfall.

Much about the factors enumerated above may possibly be learnt from a comparative study of the Coetzersdam-Louwna area with similar hard rock geology, rainfall and vegetation where large-scale irrigation is practised with groundwater.

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REGION I - MAKOPPA DOME

1. INTRODUCTION

1.1 LOCATION AND EXTENT

The location of Region 1 is indicated on Figure 1 (**at back of report**). The Makoppa Region adjoins Botswana between Ramotswa in the west and Cumberland on the Limpopo River in the north-east. The base of the Transvaal Supergroup (Region 9) forms the southern and south-eastern boundary between the Botswana border and Groenvlei 87 KQ, which is situated about 28 km north of Thabazimbi. From this point northwards to the Limpopo River, Region I is bounded by the covering Aasvoëlkop Formation of the Waterberg Group and by diabase sills (Region 6). Except for a narrow strip in the west - a "panhandle" - which falls in the Northwest Province, the bulk of Region I lies in the western corner of the Northern Province. Its area is about 5 690 km^2. The localities of a selection of places and farms mentioned above and in the following text are shown in Figure 2 (**at back of report**).

1.2 PHYSIOGRAPHY

East and northeast of Derdepoort, Region I is a bush-clad, virtually featureless expanse at an elevation of between 850 and 1000 m a.m.s.l. Broad, generally south-north trending depressions are separated by gently undulating interfluves rising not more than 30 m above the drainage lines. The plain's monotony is broken by:

- isolated koppies rising a few tens of metres above the surrounding plain on Rustenburg 205 KP, on Zuid Brabant 262 KP (the Koringkoppies) and on Krugerspan 86 KQ;
- the Witfonteinrant, a series of hills with elevations of between 1200 to 1300 m a.m.s.l., along the region's southern boundary between Holland 237 KP in the west and Karoobult 126 KQ in the northeast; and
- *hilly terrain east of Derdepoort mainly* on Kameelhoek 174 KP, Portugal 198 KP, Napoleon 197 KP and Batavia 176 KP which adjoins Kameelhoek 174 KP on the east.

The topography in the panhandle west of Derdepoort is more varied. There are:

- the Seokangwana and Tshukudutshujwe hills near its western extremity;
- the Tshwene-Tshwene hills some 15 km southwest of Derdepoort, and
- several koppies on Turfsloot 79 KP.

The land surface according to Partridge and Maud (1987) is undifferentiated Post-African. The Region comprises a very small portion of drainage region A1 (Notwani) in the extreme west and lower portions of A2 (Crocodile) and A3 Marico). The Marico River enters the Region at Tweede Poort (elevation approximately 950 m.a.m.s.l) and forms the boundary with Botswana from Derdepoort to its confluence with the Crocodile. The latter enters Region I west of Thabazimbi at about 940 m a.m.s.l. and joins the Marico at about 855 m a.m.s.l. about 60 km to the north to form the Limpopo River. Except for the 'panhandle' and the Elandslaagte, the Lengope la Kgamanyane and Lenkwane Spruits in the Region east of Derdepoort, surface drainage is mostly poorly defined. East of Derdepoort the area is dotted with small pans ranging from a fraction of a hectare to several hectares.

1.3 CLIMATE AND RAINFALL

The climate is semi-arid and hot - daily maximum temperatures average about 32°C in January and 22°C in July. The corresponding daily minima are 18°C and 4°C. Rainfall is virtually limited to the October - April period, peaking during December - January. Average annual precipitation varies roughly between 525 mm in the west, to about 600 in the southeast, and to 475 mm in the northeast. According to the ACRU model, mean effective rainfall ranges between 375 and 450 mm per annum.

1.4 VEGETATION

The biome is savanna according to Rutherford and Westfall (1986) and Low and Rebelo (1996). According to Acocks (1953) the vegetation east of Derdepoort grades from Sour Bushveld on the Witfonteinrant northwards through Thornveld and Mixed Bushveld to Arid Sweet Bushveld along the Marico, Crocodile and Limpopo Rivers. Vegetation in the "panhandle" is designated Kalahari Thornveld and Shrub Bushveld. Low and Rebelo recognize the presence of three main vegetation types: Mixed Bushveld, Clay Thorn Bushveld and in the "panhandle" Kalahari Plains Thorn Bushveld.

1.5 ROLE OF GROUNDWATER IN THE REGION'S ECONOMY

Groundwater is being exploited on a large scale along the Crocodile River for irrigation. Rech (1970) found that in that year some 2000 ha along the river were irrigated from both surface and under-groundwater. He estimated that 8.8 million m^3 of groundwater and 2.1 million m^3 of surface water were abstracted for irrigation. No information is available about water-bearing alluvium and irrigation along the Marico River.

A comprehensive survey during 1985 (Hobbs and Chipps 1986) revealed that 2 605 ha was under irrigation from groundwater. The total volume of groundwater abstracted during the period April to October 1985 amounted to 23 million m^3. The figure is based on pumping rates and times and is probably an overestimate. Water was principally obtained from 264 boreholes tapping alluvial deposits. Some water was doubtlessly also obtained from boreholes tapping weathered/fresh bedrock.

There are no towns in Region 1. Informal settlements in the Supingstat-Kopfontein area (Supingstat is situated 10 km SSW of the Kopfontein border gate) in the extreme west and the small communities of Derdepoort, Dwaalboom and Makoppa are dependent on groundwater supplies.

On farms throughout the region, water for human consumption, stock and game is obtained from groundwater sources. Schumann (undated b) estimated that in the region east of the Marico River, annual consumption for these purposes amounted to about 1.7 million m^3. A significant increase in this figure which was recorded during the latter years appears to be unlikely.

2. GEOLOGY

The following summary was compiled from Jansen (1974); Schumann (undated a and b); Botha (1988); Walraven et al. (1994); Barton et al. (1995); Quarter Million Geological Sheet 2426 Thabazimbi; also the 1:1 000 000 Geological (1984 and 1998 editions) and Structure (1995) Maps of South Africa. Table 1 summarizes the evolution of the lithostratigraphic subdivision as featured on published geological maps. The lithologies are summarized in Table 2.

The greater part of the region is underlain by Swazian granite and granite-gneiss (ZA Figure 2) which contains scattered occurrences and inclusions of Swazian (para)-gneiss, granulite, schists, etc (Z). According to boreholes just over 60% of the area occupied by Swazian metamorphics and intrusives is underlain by granite- (gneiss). The granite varies from massive to foliated. These rocks are mostly concealed under an extensive cover of soil, calcrete, sand and alluvial deposits.

On Turfsloot 79 KP 20 km west of Derdepoort, gabbro known as the Modipe Gabbro Complex (Zmm), forms isolated hills. Another complex of basic to ultrabasic rocks along the Marico River, south of Derdepoort on Krokodildrift 87 KP, Nooitgedacht 90 KP, Mooiplaats 94 KP and Middelpoort 93 KP (adjoins Nooitgedacht 90 KP on the south), is tentatively correlated with the Modipe Gabbro.

Younger granite types, quartz porphyry and felsite belonging to the Gaborone Granite Complex (Rga Figure 2) are found in the west along the Zeerust-Gaborone road, on Kopfontein 78 KP (Kopfontein Gate is situated on this farm). Gaborone Granite also occurs southeast of Derdepoort on Nooitgedacht 90 KP, Port Elizabeth 199 KP, Stellenbosch 222 KP and adjoining farms according to the Thabazimbi sheet, the 1984 1:1 million Geological and the 1995 1:1 million Structure maps of South Africa. On the 1998 1:1 000 000 Geological Map this area is indicated as being occupied by Swazian granite-gneiss.

A succession of acid and intermediate lavas and clastic sediments build the northern flank of the Witfonteinrant (designated Rb in Figure 2). Presumably, older volcano-sedimentary successions underlie the hilly terrains of Seokangwana, of Tshwene-Tshwene, and between Derdepoort and Portugal 198 KP (designated Rky, Rk and Rp in Figure 2). Judging from Table 1 the ages of these rocks appear to be a matter of debate. Walraven et al. (1994) correlate the latter three occurrences with the Gaborone Granite Complex whilst the first, the Buffelfontein Group, is considered younger - proto-basinal Transvaal (SACS 1980). Barton et al. (1995) favour a correlation of the Group with the Kameeldoorns Formation and the Bothaville or Allanridge Formations of the Ventersdorp Supergroup.

Of these four occurrences of volcano-sedimentary rocks, the Buffelsfontein Group, which extends over a distance of 90 km and is up to 5 km wide, is the most extensive and best-developed succession. The strata comprise an arenaceous formation at the base, followed by basic and acid volcanic formations, in turn, overlain by a quartzitic formation (Tyler 1979).

The volcano-sedimentary succession (Rky and Rk) directly east of Derdepoort is fault-bounded on its southern side. A strip of down-faulted Black Reef quartzite (Vbr) is present along part of the fault line. In the extreme west, Gaborone granite is intrusive into a succession of mainly acid lavas (designated Rky Figure 2)

In the extreme east outcrops of Lebowa Suite Granite (Mle), surrounded by diabase of a post-Waterberg sill, have been included in Region 1 (not indicated on Figure 2).

Numerous WNW to NNW trending composite Pilanesberg dykes consisting of diabase and syenite traverse the Region. Along a road running more or less perpendicular to the strike of the dykes between Bloemhof 201 KP and Somerset 210 KP, a distance of about 30 km, 32 negative magnetic anomalies ascribable to Pilanesberg dykes have been located.

TABLE 1. EVOLUTION OF THE LITHOSTRATIGRAPHIC NOMENCLATURE

1970 1: million geological map of RSA	1974 1:250 000 geological sheet 2426 Thabazimbi		1984 1:1 000 000 geological map of RSA		1998 1:1 000 000 geological map of RSA	
Sedimentary volcanic and intrusive rocks	Sedimentary, volcanic and intrusive rocks (excl. dykes)		Sedimentary and volcanic rocks	Intrusive rocks excl. dykes	Sedimentary and volcanic rocks	Intrusive rocks excl. dykes
-	Tertiary to quaternary surficial deposits	no symbol	Tertiary to Quaternary Deposits (T-Qk & Q)	-	-	-
					Ecca Group (Pe)	
-	Diabase	Di	-	-		Diabase (Vdi)
T1 Black Reef Series	Black Reef Series	T1	-	-	Black Reef Formation (Vbr)	-
Dr Dominion Reef System	Ventersdorp	Vlf & VQ	Buffelsfontein Group (Vb)	-	Buffelsfontein Group (Rb)	-
V Ventersdorp System		VS & VR	Bothaville Formation (Vbt)	-	Platberg Group (Rp)	-
Dr Dominion Reef System	System	Vla	Allanridge Formation (Val)	-	Klipriviersberg Group (Rk)	-
		Vlf Intruded by 3G	Makwassie Formation (Rm)	Gaborone Granite (Rga)	Kanye Formation (Rky)	Gaborone Granite (Rga)
AG3 Gaborone Pluton	ARCHAEAN COMPLEX: Gaborone Granite	3G	-	Modipe Complex (Rmd)	-	Granite gneiss (ZA)
AN2 Basic Intrusive	Hyperite	2Ng				
AG2 N-Cape/ Transvaal Belt of metamorphism & granitization	Western Transvaal Belt of metamorphism & mobilization	2G		Granite gneiss (ZA)		
	Modipe Gabbro Complex	1Ng				Modipe Complex (Zmm)
S Swaziland System	Swaziland System & Jamestown Igneous Complex ?	Z	Basement Complex (Z)	-	Undiff. Basement Complex (Z)	-

TABLE 2. LITHOLOGY

Stratigraphic symbol on			Lithology
1:250 000 Sheet Thabazimbi	1:1 000 000 Geological Maps 1984	1998	
Mapped; no symbol	Q	not shown	Alluvium, soil, ferricrete, calcrete, surface limestone
Mapped; no Symbol	T-Qk	not shown	Kalahari sand
Not mapped	not mapped	Pe	Shale, sandstone
Di	not mapped	Vdi	Diabase
T1	not mapped	Vbr	Quartzite, grit, conglomerate, shale
Vlf &VQ	Vb	Rb	Arkose, shale, greywacke, conlomerate, basalt partly amygdaloidal, felsite, rhyolite, quartz and felspar porphyry, agglomerate
VS & VR	Vbt	Rp	Shale, conglomerate,grit, quartzite, sandstone graywacke, breccia, agglomerate, tuff
Vla	Val	Rk	Andesitic lava with acid lava, quartzite
Vlf	Rm	Rky	Rhyolite, dacite, andesite
2G	Rga	Rga	Rapakivi granite, granite, aplogranite, foliated granite, quartz porphyry, quartz felsite
1G	ZA	ZA	Granite and granite gneiss
1Ng & 2Ng	Rmd	Zmm	Gabbro, norite, hyperite, anorhosite, pyroxenite, werhlite, dunite, serpentinite, magnetite bands
No symbol	Z	Z	(Para)gneiss, granulite, schist, talc schist, quartz-sericite schist, quartzite, banded ironstone, amphibolite norite, serpentinite.

Another set of diabase dykes trend east to northeast e.g. on Engeland 183 KP and adjoining Zwartebosch 182 KP. According to the explanation on geological sheet 2426, the presumably accompanying aeromagnetic anomaly shown on the map, is one of a set, which probably is associated with Post-Karoo faulting (see below). East to northeasterly trending dykes on Laastepoort van Marico 86 KP, Klipdrift 85 KP, and Doornlaagte 151 KP are considered to be associated with the Gaborone Complex (Schumann undated a). Hobbs and Chipps (1986) mention exposures of dyke-like intrusions of syenite, of granophyre with a northerly strike, and of diabase striking east - west in the bed of the Crocodile River.

Aldiss (1989) reports the existence of a widespread set of lineaments on aerial photographs of southeastern Botswana. They mark a swarm of east-north-east trending deeply weathered hydrothermally altered dolerite dykes intrusive into Archaean Basement, Gaborone Granite and Kanye volcanics. Most of these dykes appear to be of pre-Transvaal age. Late or post-Karoo dolerite dyke swarms trending east-southeast are found to the north and south of this part of Botswana (Reeves 1979a and b). None are shown between the two swarms on his interpretation map based on aeromagnetic data.

The east-northeasterly striking Botswana dyke swarm extends most probably into Region 1. Although the northeasterly trending aeromagnetic lineations on geological sheet 2426 are believed to represent faults, some may well be associated with diabase or dolerite dykes of pre-Transvaal (or Karoo?) age.

Several dip faults have been mapped in the outcropping volcano-sedimentary successions in the south. Schumann (undated a) mentions the presence of silicified breccia zones striking east-west, northwest and west-southwest on several farms underlain by Swazian rocks.

In the Explanation on Geological Sheet 2426, the presence is mentioned of Karoo Beds 20 km north of Silent Valley. The farms involved are Marico Water 32 KP, Mouwplaats 33 KP (east of Marico Water), Mounthoop 42 KP (adjoins Mourplaats), Louisiana 43 KP adjoins Marico Water on the south), Zanddrift 44 KP (adjoins Louisiana 43 KP), Jakkalskraal 45 KP and Mowbray Park 48 KP (Figure 2). These beds are an extension of a down-faulted block of Karoo rocks west of the Marico River in Botswana. A number of probable dykes partly controlled by faulting are indicated in this area on geological sheet 2426.

According to Schumann (undated a) large parts of Region 1 are covered by red and black soils and by calcrete. Soils on the Swazian granite, granite-gneiss and metamorphic rocks generally vary in thickness from less than 1 to 15 m. The average is 3 - 4 m. On Donald 37 KP, Vanwykskraal 116 KQ and Noord Brabant 114 KQ soil and clay were found to depths of 34, 45 and 48 m respectively.

According to borehole logs calcrete or surface limestone from 1 to 50 m thick occurs over large areas (Figure 25). Surface limestone of proven economic importance (presumably at least several tens of metres thick) is found west of Dwaalboom on Bethanie 218 KP, Frankfort 219 KP, Winterveld 220 KP, Amsterdam 227 KP, Beaufort 228 KP, Jakkalskraal 239 KP and Schoongezicht 238 KP. On Graaff-Reinet 213 KP, east of Dwaalboom, 68 m of limestone was encountered in a borehole. Other farms where an appreciable thickness was found in boreholes are Stellenbosch 222 KP, Parys 226 KP, Langverwacht 235 KP and Welgewaagd 233 KP. These farms are all situated in the south. According to Schumann, ferricrete is found more commonly on Swazian granite in places east of the Crocodile River.

On the Thabazimbi sheet, aeolian sand is shown to cover large tracts in the northeast along the Crocodile, Marico and Limpopo Rivers. Kalahari sand is also present in the "panhandle" in the west according to the 1984 geological map. Alluvial deposits varying in width from 200 to 3 000 m border the Crocodile River (Hobbs 1983). On the 1:250 000 geological sheet (2426 Thabazimbi) a strip of alluvium averaging about 700 m wide is shown along the Marico River from Derdepoort to the Limpopo confluence. Alluvium has also been mapped along the Elandslaagte, Lengope lo Kgamanyane and Lenkwane spruits. At the junction of the latter two with the Marico River, the alluvial deposits fan out to form delta-like deposits. However nothing is known about the thickness and nature of these deposits.

Botha (1988) carried out a more detailed study of the surficial Cainozoic deposits because of the discovery and utilization of calcrete and palygorskite (attapulgite)-rich clays. He proposed the following Cainozoic stratigraphy:

TABLE 3. CAINOZOIC STRATIGRAPHY

Age	Stratigraphic unit	Lithology
Holocene	Alluvium	Alluvium deposited on flood plains
Late Upper Pleistocene?	Red sand	Red sand blanket
Early Upper Pleistocene?	Ferricrete	Ferricrete cementing regolith and reworked gravels
	Reworked gravels	Rounded clasts forming loose gravels
Late Middle Pleistocene?	Calcrete	Calcrete and authigenic palygorskite
Middle Miocene to Lower Pleistocene?	Rooibokkraal Formation	Sands, granule, pebble and cobble conglomerates with subordinate mudrock

The Rooibokkraal sediments as exposed in road quarries and mining trenches are seldom thicker than 6-10 m and occupy small channels eroded into the granitoid basement. Apart from the anomalously thick soil and clay on Donald 37 KP, Van Wykskraal 116 KQ and Noord Brabant 114 KQ mentioned above, Botha also refers to deposits on Geluk 38 KP and Beaufort 27 KP. The former adjoins Donald 37 KP on the south; the latter is situated alongside the Marico River 13 km northwest of Donald 37 KP (Figure 2). These deposits apparently fill narrow channels of the paleo Crocodile-Marico drainage system.

Unconfirmed borehole evidence on Elams-Hal 26 KP (10 km northwest of Donald 37 KP - Figure 2) suggests that up to 60 m of unconsolidated sediments are present. Borehole logs on Geluk 38 KP describe an upward fining succession of up to 60 m of gravel sand and clay. The base of the Cainozoic deposits is found in places more than 50 m below the present level of the Crocodile River. Botha thinks that the very poorly sorted calcified sands, gravels and palygorskite-rich clay deposits represent the distal facies of eroded alluvial fan remnants along the arcuate Witfonteinrant which forms the southern boundary.

The existence of a buried paleo-drainage system may have a bearing on the local widely divergent water level depths encountered in the Region. This aspect will be discussed in more detail in paragraph 5.2 (see also Figure 23).

3. OCCURRENCE OF GROUNDWATER

3.1 ALLUVIAL DEPOSITS ALONG THE CROCODILE RIVER

Hobbs (1983) and Hobbs and Chipps (1986) investigated the occurrence and exploitation of groundwater contained in alluvial deposits along a 65 km stretch of the Crocodile River from just north of Thabazimbi to its confluence with the Marico River. The deposits cover an area of about 97 km^2 and are estimated to contain 112 million m^3 of groundwater when fully recharged. The alluvial deposits and the Crocodile River are mutually interactive. During high river stages and low water tables, the river is recharging groundwater. Under opposite conditions, groundwater is discharged and contributes to river flow. Currently the latter appears to be ruled out by the heavy draft on groundwater for irrigation.

The alluvium consists typically of a layer of sandy clay to clay, 6 to 10 m thick overlying a deposit of sand, gravel and boulders varying in thickness between 5 and 30 m. Weathered bedrock from 2 to 20 m thick is normally present. The combined saturated thickness in boreholes specifically drilled for aquifer tests by Hobbs and Chipps ranged between 21 and 36 m. The maximum constant rates at which 9 boreholes were tested ranged from 5.2 to 27.6 $\ell\ s^{-1}$. Drawdown ranged from 5 to 41 m; transmissivity varies from 12 to 796 $m^2\ d^{-1}$ and specific yield averages 0.1. In 1982 the average yield of 118 boreholes which were used for irrigation and which tapped alluvial deposits was 13 $\ell\ s^{-1}$. In 1985 the number of holes had increased to 266 and the averaged yield had dropped to 7.9 $\ell\ s^{-1}$.

3.2 HARD ROCK FORMATIONS

3.2.1. Drilling results according to the National Groundwater Database

As shown on the Borehole Prospects map (Sheet No 1 of the National Groundwater Maps), drilling results are poor - less than 40% of the holes drilled, yielded more than 0.1 $\ell\ s^{-1}$. Over most of the region between 20 to 30% only of the successful holes, may be expected to yield more than 2 $\ell\ s^{-1}$. In an area roughly centered on Dwaalboom and more or less coincident with that underlain by thick deposits of calcrete, the probability is even less - between 10 and 20%.

The results of statistical analyses of borehole data contained in the 1998 NGWDB are presented in Table 4 and Figures 3 to 11. Note that in spite of the generally shallower water levels and strikes, success rates and borehole yields in Gaborone granite and the volcano-sedimentary formations are poorer than in the Swazian rocks. The deeper water levels and strike depths in the latter have to be ascribed to deeper and more advanced weathering.

Swazian rocks

It was found to be impracticable to divide NGWDB data into Swazian supracrustal metamorphic rocks and Swazian granite-(gneiss) categories. The data are therefore treated as a single entity in Table 4 and in Figures 3 to 7. The results may be summarised as follows:

- The optimal strike depth below water level as indicated in Figure 4 is between 0 and 15 m.
- The close relation between strike and water level is confirmed by the close relationship between cumulative water level and strike frequency curves (strike frequency in terms of total number of strikes; Figure 5). This relationship stems from the fact that water is generally struck in weathered and fractured rock near the base of the weathered zone and not far below the water level.

FIGURE 3. WATER LEVEL AND STRIKE FREQUENCY IN SWAZIAN ROCKS

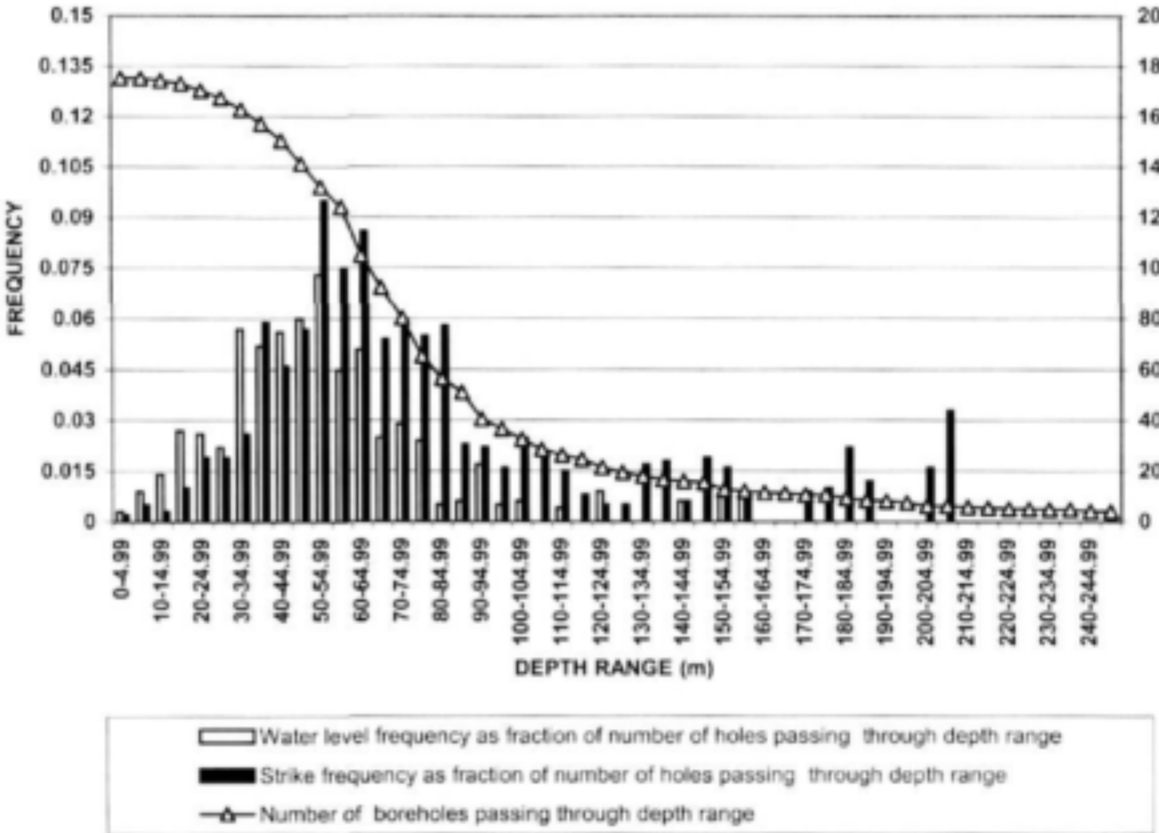


FIGURE 4. STRIKE FREQUENCY BELOW WATER LEVEL IN SWAZIAN ROCKS

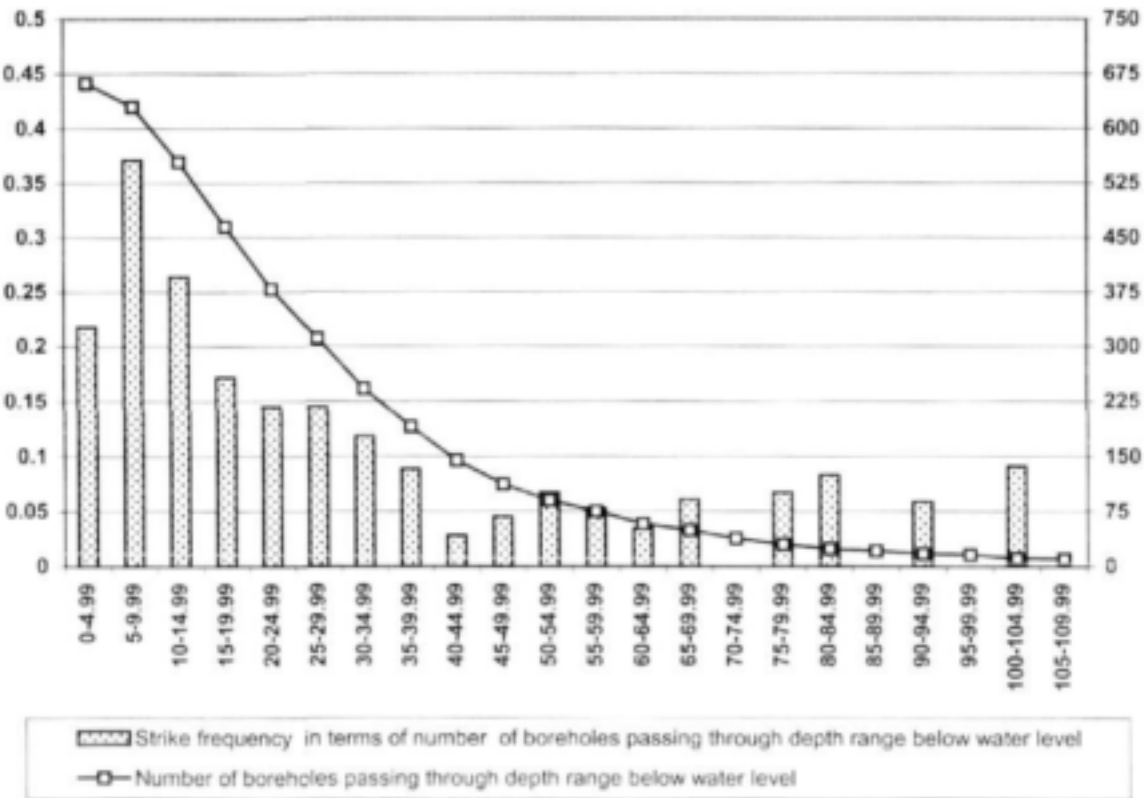


FIGURE 5. CUMULATIVE DISTRIBUTIONS OF WATER LEVELS, STRIKES AND METRES DRILLED IN SWAZIAN ROCKS

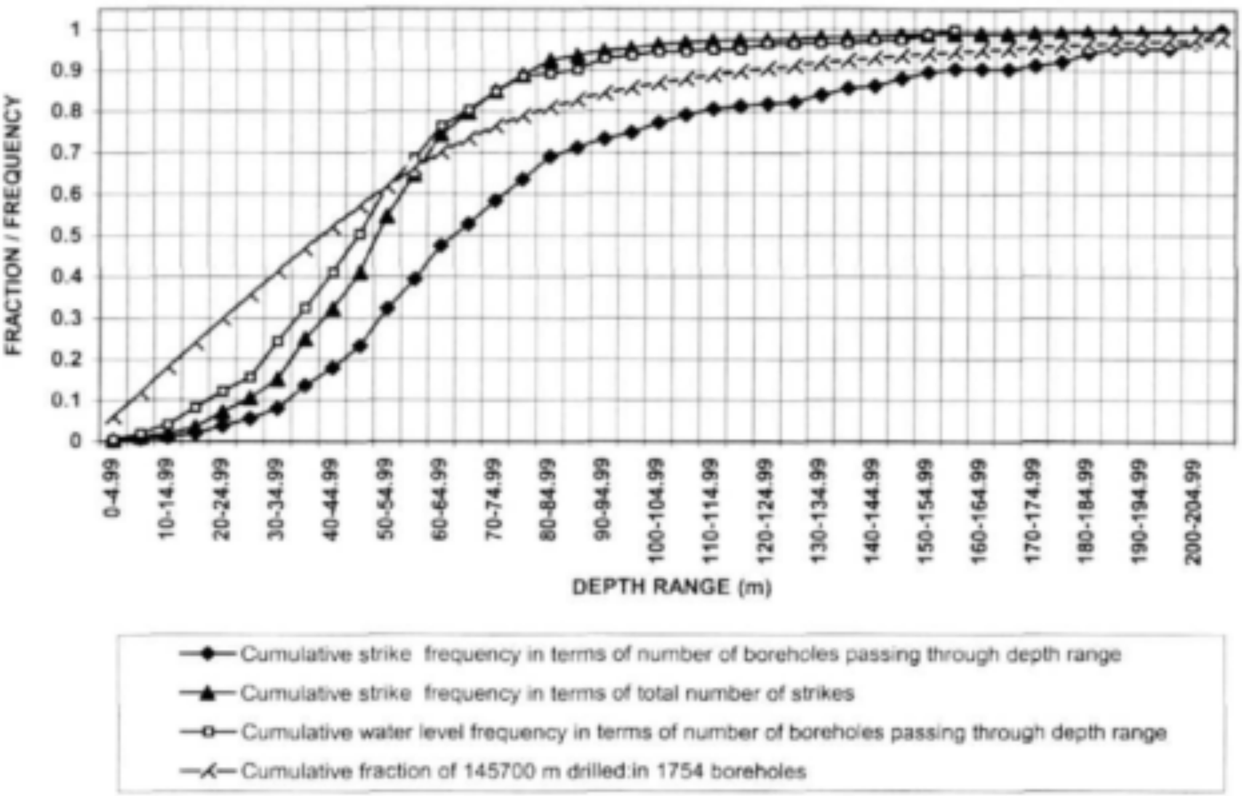


FIGURE 6. YIELD - STRIKE DEPTH RELATIONSHIP IN SWAZIAN ROCKS

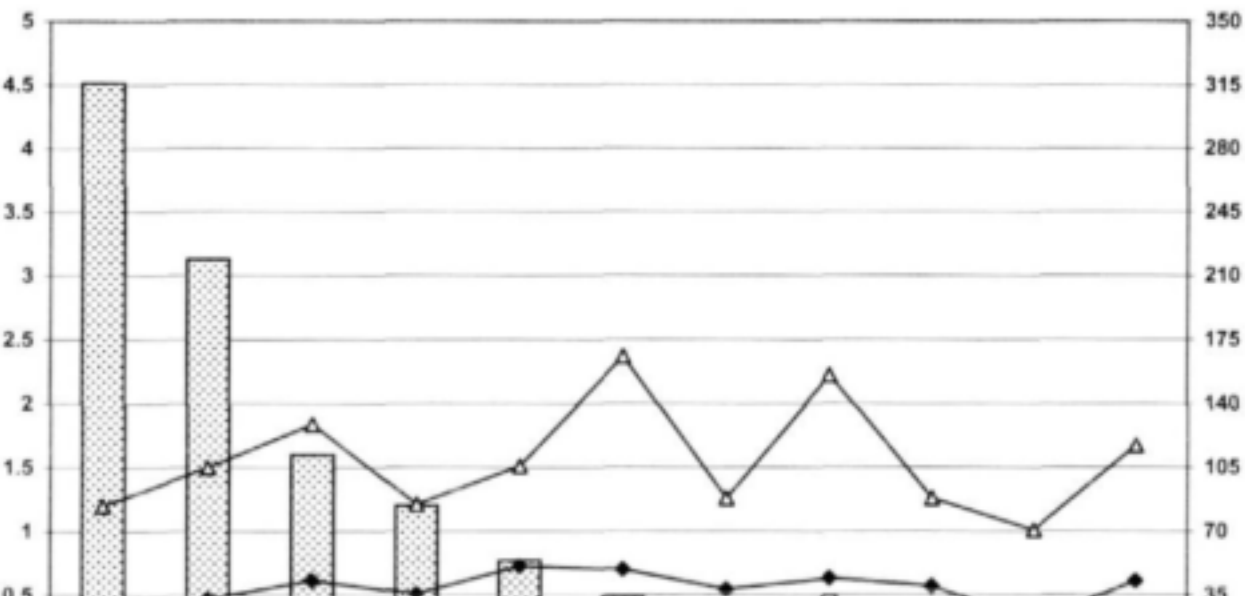


FIGURE 7. YIELD - WATER LEVEL RELATIONSHIP SWAZIAN ROCKS

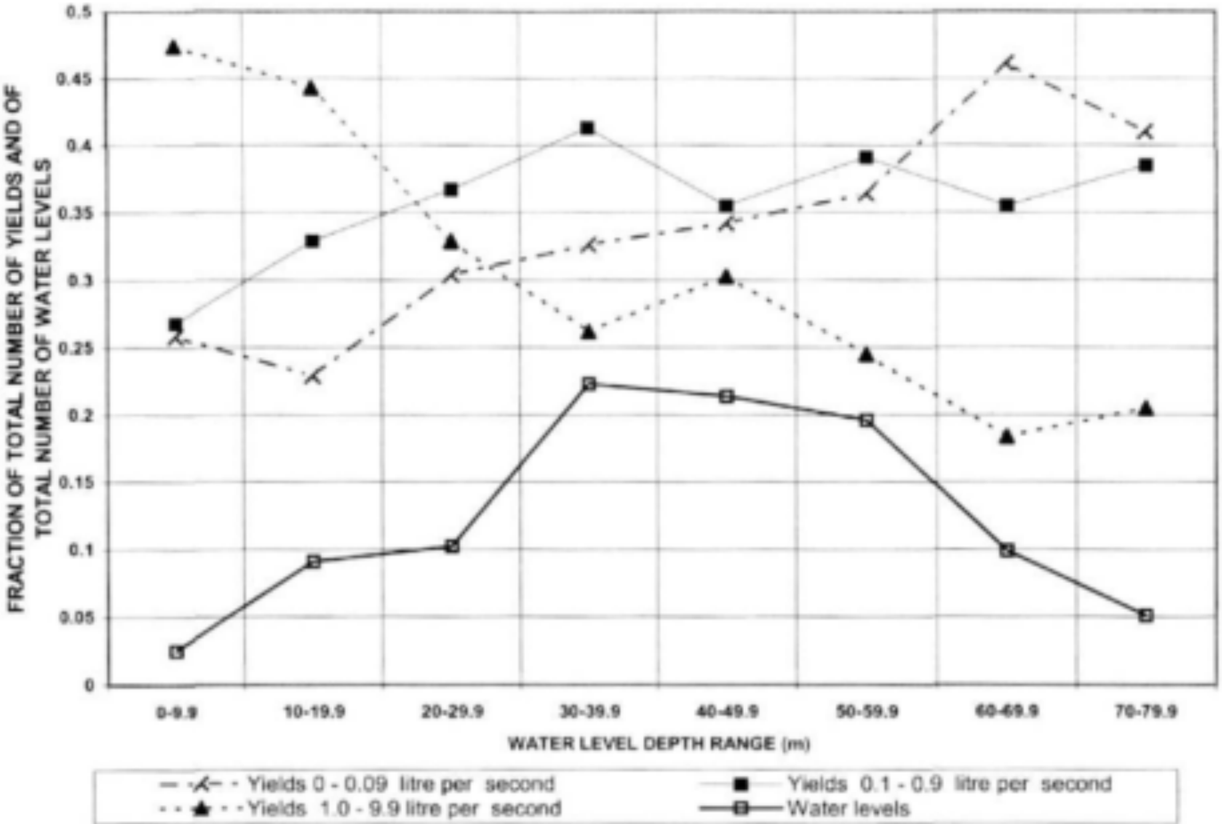


FIGURE 8. WATER LEVEL AND STRIKE FREQUENCY IN GABORONE GRANITE

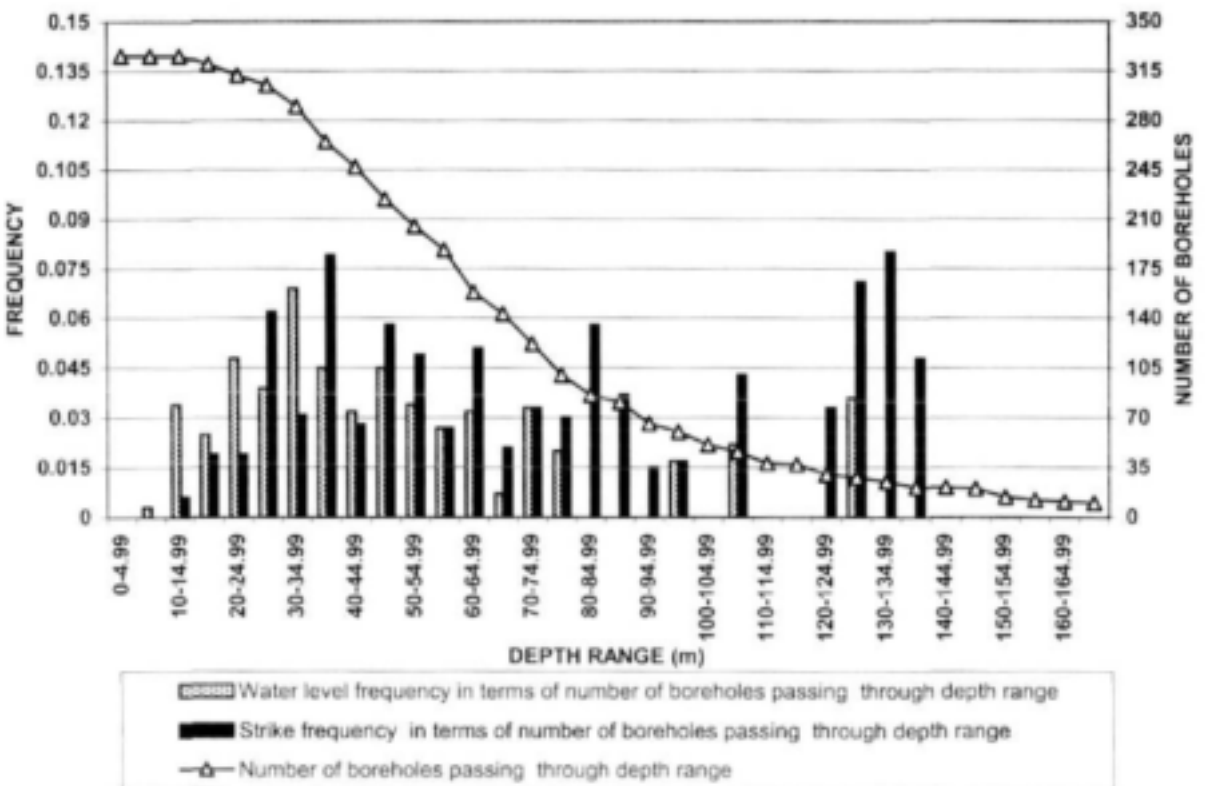


FIGURE 9. CUMULATIVE DISTRIBUTION OF WATER LEVELS, STRIKES AND METRES DRILLED IN GABORONE GRANITE

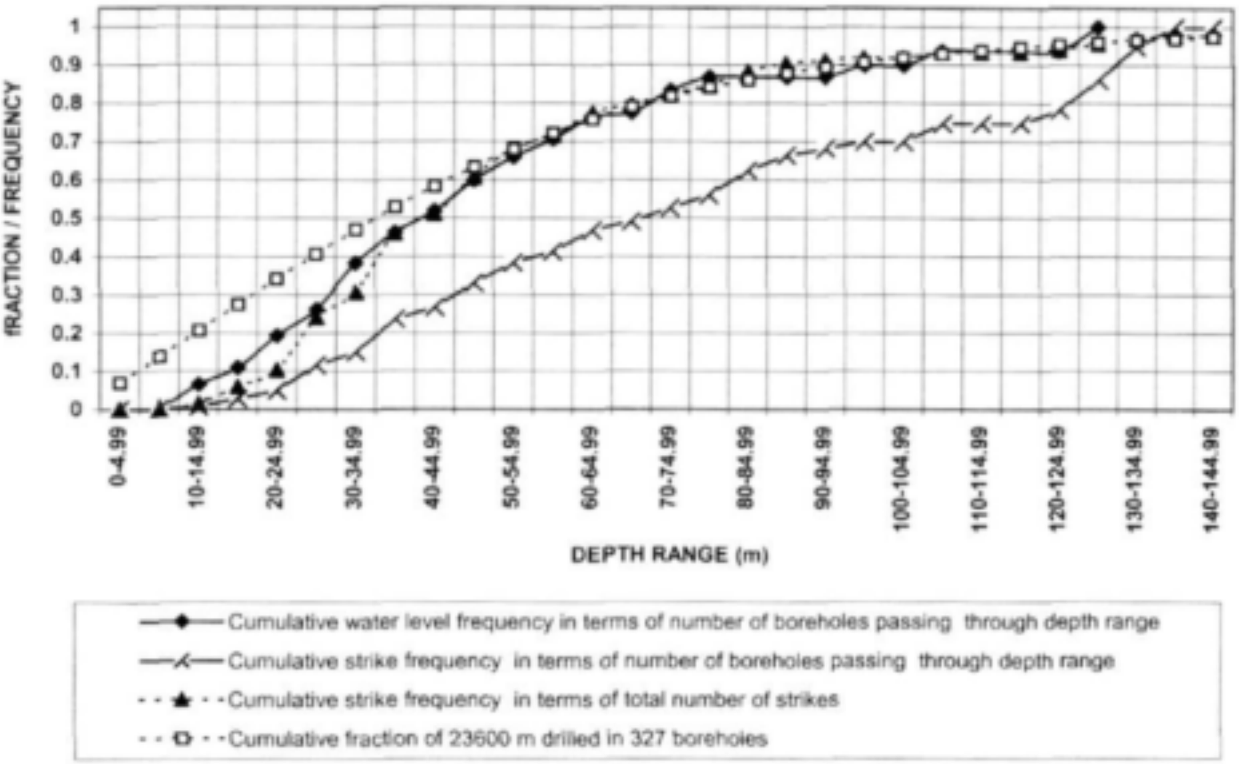


FIGURE 10. WATER LEVEL AND STRIKE FREQUENCY IN VOLCANO-SEDIMENTARY FORMATIONS

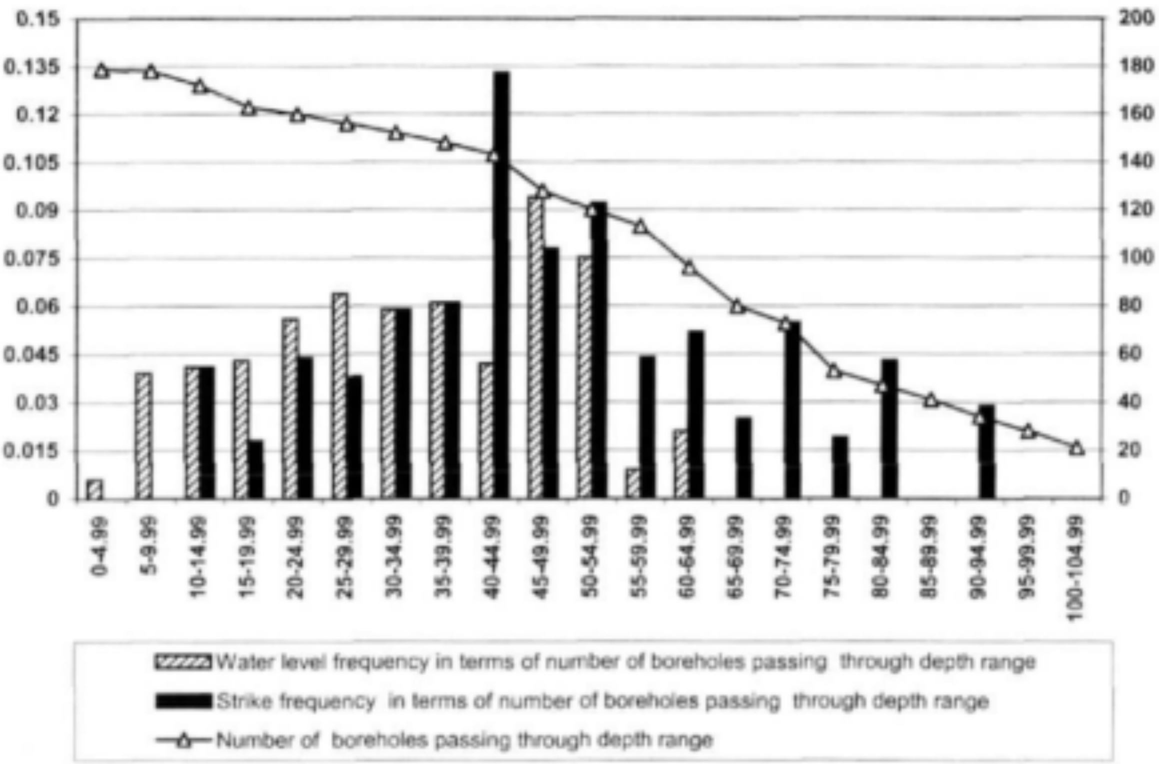


FIGURE 11. CUMULATIVE DISTRIBUTION OF WATER LEVELS, STRIKES AND METRES DRILLED IN VOLCANO-SEDIMENTARY FORMATIONS

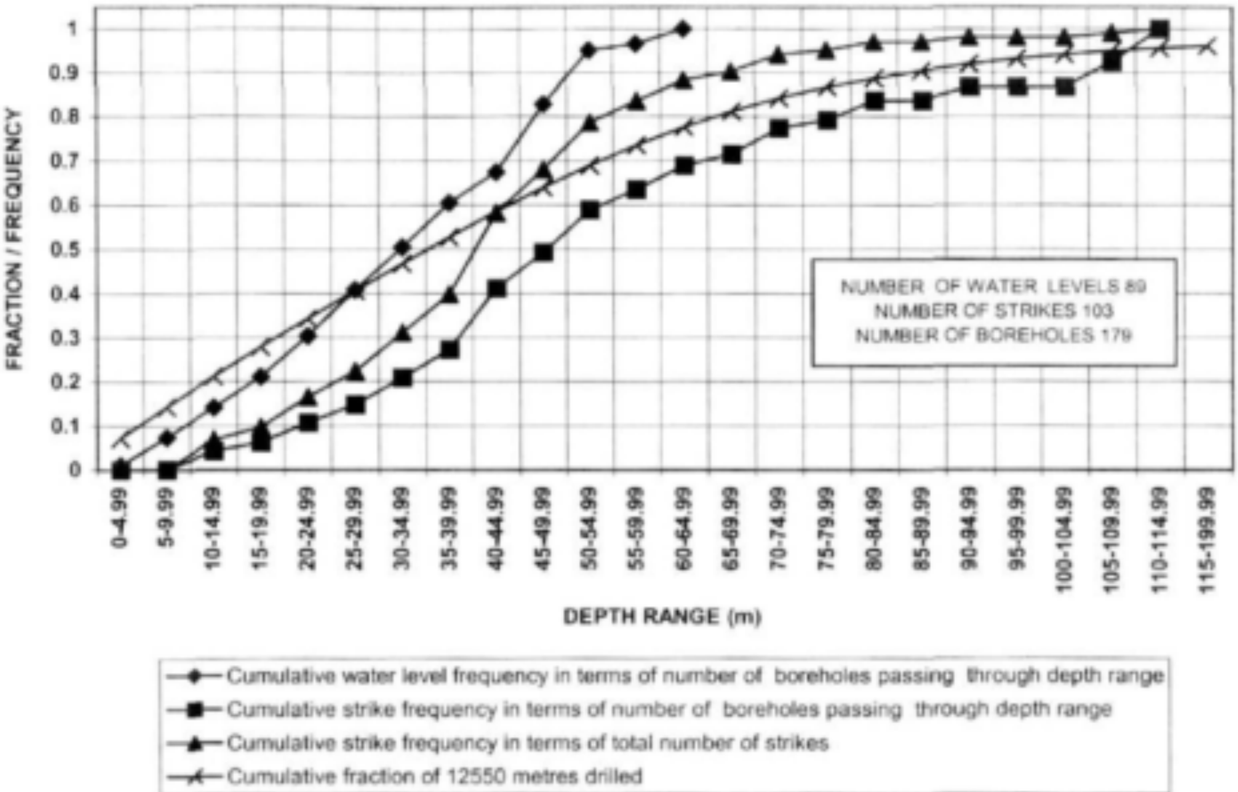


TABLE 4. STATISTICAL ANALYSIS OF NGWDB DATA

	Swazian supracrustal metamorphics and granite-(gneiss) Z and ZA	**Gaborone Granite (Rga)**	**Volcano-sedimentary rocks Rb, Rp, Rk and Rky**
Number of holes	1912	327	180
Yield	Percentage		
0 - 0.09 ℓs^{-1}	64.1	74.6	71.1
0.1 - 0.9 ℓs^{-1}	19.8	18.0	20.6
1.0 - 4.9 ℓs^{-1}	14.6	6.4	7.2
5.0 - 9.9 ℓs^{-1}	0.9	0.6	0.6
≥10 ℓs^{-1}	0.7	0.3	0.6
Number of holes yielding ≥0.1 ℓs^{-1}	687	83	52
Yield	Percentage		
0.1 - 0.9 ℓs^{-1}	55.0	71.1	71.1
1.0 - 4.9 ℓs^{-1}	40.6	25.3	25.0
5.0 - 9.9 ℓs^{-1}	2.5	2.5	1.9
≥10 ℓs^{-1}	1.9	1.2	1.9

TABLE 4 (continued)

Water levels range mainly between	25 - 65 m	15 - 50 m	20 - 55 m
Optimal strike and drilling depth ranges between	30 - 85 m	20 - 65 m	35 - 55 m
Mean strike probability per 5 m within the optimal range	0.061	0.053	0.1
% of total distance drilled had drilling been restricted to maximum optimal depth	81	78	67
90% of strikes shallower than	85 m	90 m	70 m
% of total distance drilled had drilling been restricted to accommodate 90% of strikes	69	88	81

- At depths of greater than 40 m below water level, the prospects of a water strike averages about one seventh of the average optimal strike frequency between 0 to 15 m.
- Water levels lie generally between 25 and 65 m; 90% of the water levels are shallower than 90 m (Figures 3 and 5)
- The optimal strike depth ranges between 30 and 85 m; 90% of the strikes are less than 85 m (Figures 3 and 5).
- Within this optimal range the probability of a strike is roughly 0.061 per 5 m.
- According to Figure 6, deeper strikes below water level are statistically not accompanied by higher yields. The upper quartile yields (and the maxima, in particular) fluctuate randomly and greatly.
- According to Figure 7, borehole yields in excess of 1 $\ell\, s^{-1}$ are generally associated with shallow water levels. Boreholes with deeper water levels have yields of less than 1 $\ell\, s^{-1}$
- There is no justification for drilling deeper than about 85 m in the majority of cases. The depth to be drilled should ideally be determined by the depth of the water level and the optimal strike zone of about 0 to 15 m below water level.
- Prospects of striking water drop sharply below 85 m (Figure 5). In fact, about 90% of the strikes occurred at shallower.
- Only 69% of the total distance of about 145 700 m drilled in NGWDB boreholes is required to account for 90% of the strikes.

Gaborone Granite and Volcano-sedimentary Formations

Figures 8 and 9 (Gaborone Granite) and 10 and 11 (Volcano-sedimentary Formations) are analogous to Figures 3 and 5 (Swazian rocks) respectively. Conclusions drawn from them are presented in Table 4. Owing to the relatively small number of boreholes, water levels and strikes:

- optimal strike depths below water level,
- yield - water level depth and
- yield - strike depth below water level relationships

could not be established for Gaborone Granite and the Volcano-sedimentary Formations. Their behaviour, most likely, resembles that of the Swazian rocks.

The cumulative water level and strike frequencies in Gaborone Granite are closely related as in the case of the Swazian rocks. They deviate in the case of the Volcano-sedimentary Formations. This may be ascribed to the absence of a properly developed zone of weathering, at least where the majority of holes have been drilled.

TABLE 5. METRES DRILLED PER WATER STRIKE

	Maximum optimal strike depth (m) (Table 4)	Congruent fraction of total depth drilled (Figures 5, 9 and 11)	Congruent fraction of total number of strikes (Figures 5, 9 and 11)	Average number of metres drilled per strike	
				Strike depths < optimal maximum	Strike depths >optimal maximum
Swazian Rocks	85	0.81 (Figure 5)	0.93 (Figure 5)	137	395 295/370*
Gaborone Granite	65	0.76 (Figure 9)	0.77 (Figure 9)	169	184 195/200*
Volcano-sedimentary Strata	55	0.69 (Figure 11)	0.79 (Figure 11)	107	177 115/200*

* First figure deepest strike; second figure deepest hole

Excessively deep drilling

The poor drilling success rates have resulted in deeper drilling. To what extent holes have been drilled deeper than necessary should be evident from Table 5. It appears profitable to cease drilling once the maximum optimal strike depth has been reached. If no water was struck, another site should be attempted rather than continuing deeper in the first.

3.2.2 Analysis and findings by Schumann (undated a and b)

Emanating from a spell of borehole siting during 1952 to 1957 Schumann also analyzed drilling results. His data, graphs and histograms were re-interpreted in a somewhat modified form and are summarized in Tables 6 and 7 below. As the area distribution of the boreholes on which his analysis is based, is not known, the results are perhaps not representative of the Region as a whole. Schumann dealt with the Buffelsfontein Group and the other volcano-sedimentary successions in the west under the name Dominion Reef System.

TABLE 6. SCHUMANN'S BOREHOLE STATISTICS

Formation	Number of holes	Percentage of holes yielding > 0.1 ℓ s^{-1}	Percentage of the successful holes yielding 2.0 ℓ s^{-1}
Swazian metamorphic rocks	549	33	23
Swazian granite/ granite-gneiss	730	40	15
Volcano-sedimentary successions	60	30	8
Gaborone Granite	61	51	3

The number of boreholes in volcano-sedimentary successions and Gaborone Granite are considerably less than in Table 4. More weight should be attached to the latter. The figures in the two tables for Swazian rocks compare quite well.

Outcrops of Swazian supracrustal metamorphic rocks are scarce. Owing to the ferruginous nature of some of the quartzites, the presence of Swazian metamorphic rocks may be deduced from an irregularly varying magnetic field in contrast to the relatively smooth field over granite and granite-gneiss.

The Swazian metamorphic rocks encountered in boreholes as identified from drilling chips are according to Schumann:

- quartzite - sericitised or chloritised, often ferruginous
- schists and phyllite derived from shale and argillaceous sandstones and arkoses
- limestone/marl altered to amphibole rock
- lava partly altered to amphibolite and granulite
- gabbroic rocks which could either be altered lavas or dyke rock.

Of the boreholes penetrating quartzitic rocks below the water level, 55% yielded water, whereas in schistose formations and in mafic igneous and crystalline metamorphic rocks, the success rates were only 14 and 20% respectively. Both convert to clay on weathering. In many cases there is, according to electrical borehole logs, a sudden change from clayey material to fresh rock - no gradual transition from highly decomposed through permeable fractured to fresh rock.

The Swazian granite-(gneiss) and metamorphic rocks are mostly deeply weathered as shown by an analysis of the depths of weathering in 460 holes. Weathering exceeded 15m in 74% and 30m in 48% of the holes. The majority, if not all, was sited without considering depth of weathering. Another feature evident from Table 7 is the considerable depth to the water level.

This is also illustrated on the Depth to Groundwater Level map (Sheet No 2 of the National Groundwater Maps). More detail about water levels follows in Chapter 5.

In more than 40% of the successful holes drilled in Swazian granite and granite-gneiss (20% and 23% in the case of Swazian metamorphic rocks and Gaborone granite), water was struck in fresh rocks only. Water was struck at depths as much as 90 m below the transition zone between weathered and fresh rock. Unfortunately, Schumann has provided no data on the relation between water level and the base of the weathered zone in granite and granite-gneiss. Fractured and weathered (?) zones have, however, been encountered in some boreholes to depths exceeding 200 m (see Chapter 4). Weathering and fracturing, as well as water levels, are generally deeper in the Swazian metamorphic rocks than in the granite and granite-gneiss rocks. That a usable supply will be struck in the saturated transition zone wherever it is present is by no means assured. In fact, the low success rate has to be ascribed partly at least to the fickle and unpredictable permeability or lack of it within this zone.

TABLE 7. RELATION BETWEEN SUCCESSFUL WATER STRIKES AND WATER LEVEL DEPTHS (after Schumann)

Formation	Distribution of borehole depths - (m) &%	Distribution of strike depths - (m) &%	Water level depth distribution (m) &%	Percentage (%) of all successful holes with strikes deeper than specified depth (m) below base of weathering
Swazian metamorphic rocks	40 - 80 67% > 80 17%	30 - 60 69% > 60 14%	30 - 60 68% > 60 4%	20% > 10m*
Swazian granite and Granite-gneiss	50 - 70 52% > 70 22%	30 -75 77% > 75 6%	15 - 45 55% 15 - 60 87% >60 8%	21% > 18m*
Volcano-Sedimentary successions	Not available	30 - 60 71% >60 m 10%	30 -60 65% > 60 6%	Not available
Gaborone Granite	Not available	30 - 60 93% > 60 3%	15 - 45 73% 15 - 60 95% > 60 5%	23% >12m*

* Distance below base of weathered zone in borehole.

The results in this table are in reasonable agreement with those of Table 4.

Drilling in dykes has proven fruitless unless they are weathered/fractured to below water level. The prerequisite for success alongside a dyke is likewise weathering and fracturing that extends to below the water level. Schumann (undated a) reports that 24 boreholes drilled in dykes struck solid rock above the groundwater level and were failures. Two were in dykes intrusive into Swazian metamorphic rocks and twenty-two on dykes intrusive into Swazian granite-(gneiss). Of the 41 holes drilled next to or near to dyke contacts in Swazian metamorphic rocks and granite-(gneiss), 21 were successful. In the successful boreholes that could be logged electrically, the depth of weathering/ fracturing was found to be favourable.

4. BOREHOLE SITING

4.1 CRITERIA FOR SITING BOREHOLES

Water-diviners, landowners, boring inspectors and drillers sited the overwhelming majority of holes that were drilled during the past 50 to 60 years. During this period some drilling sites were indicated by personnel of the Geological Survey and of the Directorate of Geohydrology (and no doubt by hydrogeologic consultants as well). It was, however, only between 1952 and 1957 and in the early sixties that serious attention was given to this Region by the Geological Survey's Groundwater Division (Schumann undated a and b; J.F. Gordon-Welsh 1960/61).

Prior to 1952 the results obtained by government and private geologists were, according to Schumann, no different from those of water diviners, etc. namely just over 30%. A borehole was deemed successful if it yielded at least 100 Imp. gallons per hour i.e. 0.125 $\ell\ s^{-1}$. Since 1961 the Geological Survey and the Directorate of Geohydrology as from 1977 sited boreholes on an *ad hoc* basis only. Except for experimental hydraulic fracturing in the early nineties, no further studies have been undertaken which were aimed at improving on borehole siting and at understanding the hard-rock hydrogeology of the Region.

TABLE 8. OPTIMAL BOREHOLE SITING CONDITIONS (Schumann undated b)

Criteria	**Swazian metamorphics**	**Swazian granite-gneiss**	**Gaborone granite**	**Volcano-sedimentary succession**
Drainage	Drainage line/pan	River/major drainage line	-	Rock is exposed on higher ground; siting inevitably restricted to valleys
Vegetation	Lush growth/lines of large trees indicative of deep weathering/linear structures	Dense growth, and tree lines somewhat more favourable than thinly vegetated areas	-	Denser growth/lines of trees indicative of weathering or formation contacts
Soil	Calcrete > 3 m thick under cover of soil	No clear indication found as to the more favourable soil type	-	-
Rock type/texture	Quartzitic types favourable; schists and meta-lavas unfavourable	No comment	-	-

Resistivity of weathered - fractured rock at the base of the weathered zone as deduced from depth soundings	Range not clearly definable; generally 40 to110 ohm.m; in quartzites higher. More favourable if these conditions found near a dyke	< 300 ohm.m. More favourable if this condition is found near a dyke. According to electrical borehole logging the zone in which water is struck generally has a resistivity < 500 ohm.m	20 to 90 ohm.m	20 to 120 ohm.m. Quartzite/ sandstone up to 180 ohm.m. Lava clayey below 40 ohm.m.

*No recommendations have been made about the depths to be drilled below the water level

During 1952-57 Schumann and associates (Schumann undated a) selected 140 sites of which 79 were drilled and 34 (43%) were successful. At the same time 197 holes were drilled on sites selected by water-diviners, drilling inspectors etc. Fifty holes (25%) were successful. Table 8 summarizes optimal borehole siting conditions as determined by Schumann (undated a).

4.2 EXAMPLES OF GEOPHYSICAL BOREHOLE SITING

The flat and featureless nature of most of the Region and the lack of rock exposures means that boreholes have to be sited virtually on geophysical indications only. The selection of where to conduct geophysical work is generally guided by indications such as lineations on aerial photographs and satellite imagery, changes in soil and vegetation, more luxurious vegetal growth, lines of denser vegetation, drainage lines and pans.

Past geophysical work consisted of electrical resistivity depth probing to determine depth of weathering and magnetometer traversing for locating and tracing dykes and magnetic Swazian metamorphic rocks. On the more problematic farms several hundred depth probes have had to be taken to locate deeply weathered formation which, ideally, should extend to below the expected water level. Even then the drilling results were disappointing. Experimental electromagnetic surveys were also conducted in an attempt to find and trace linear zones of fracturing and weathering. Where possible, electrical resistivity borehole logging was undertaken.

Examples of the use of geophysics and of the difficulties in obtaining a usable supply are shown in the following figures. With the exception of Figures 13 and 15, the rest are from a group of adjoining farms between 5 and 20 km northeast of Derdepoort. Note that by filling some boreholes with water electrical logs were recorded above the groundwater level.

Although weathering and fracturing extend in both cases to below 200 m (Figure 12), a negligible yield was obtained in borehole G15923, whereas hole G15908 proved to be a success, striking small supplies at 70 and 94.5 m, and the main supply at 205.4 m. Water levels were respectively 63.1 and 70.1 m deep.

FIGURE 12 ELECTRICAL RESISTIVITY LOGS OF BOREHOLES ON DOORNLAAGTE 151 KP AND BUFFELSDOORN 152 KP

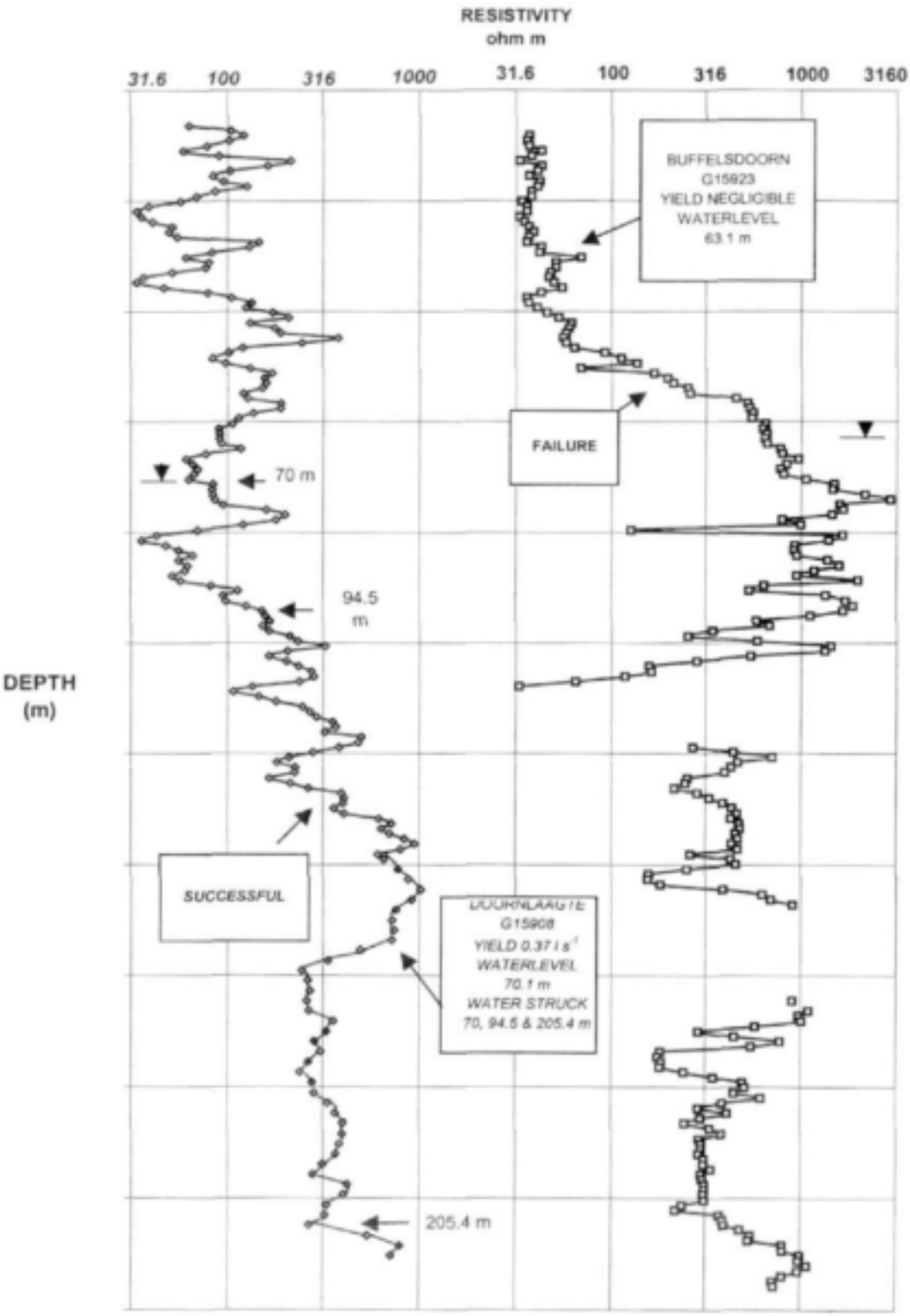


FIGURE 13 ELECTRICAL RESISTIVITY LOGS OF BOREHOLES WITH DISCORDANT RESULTS

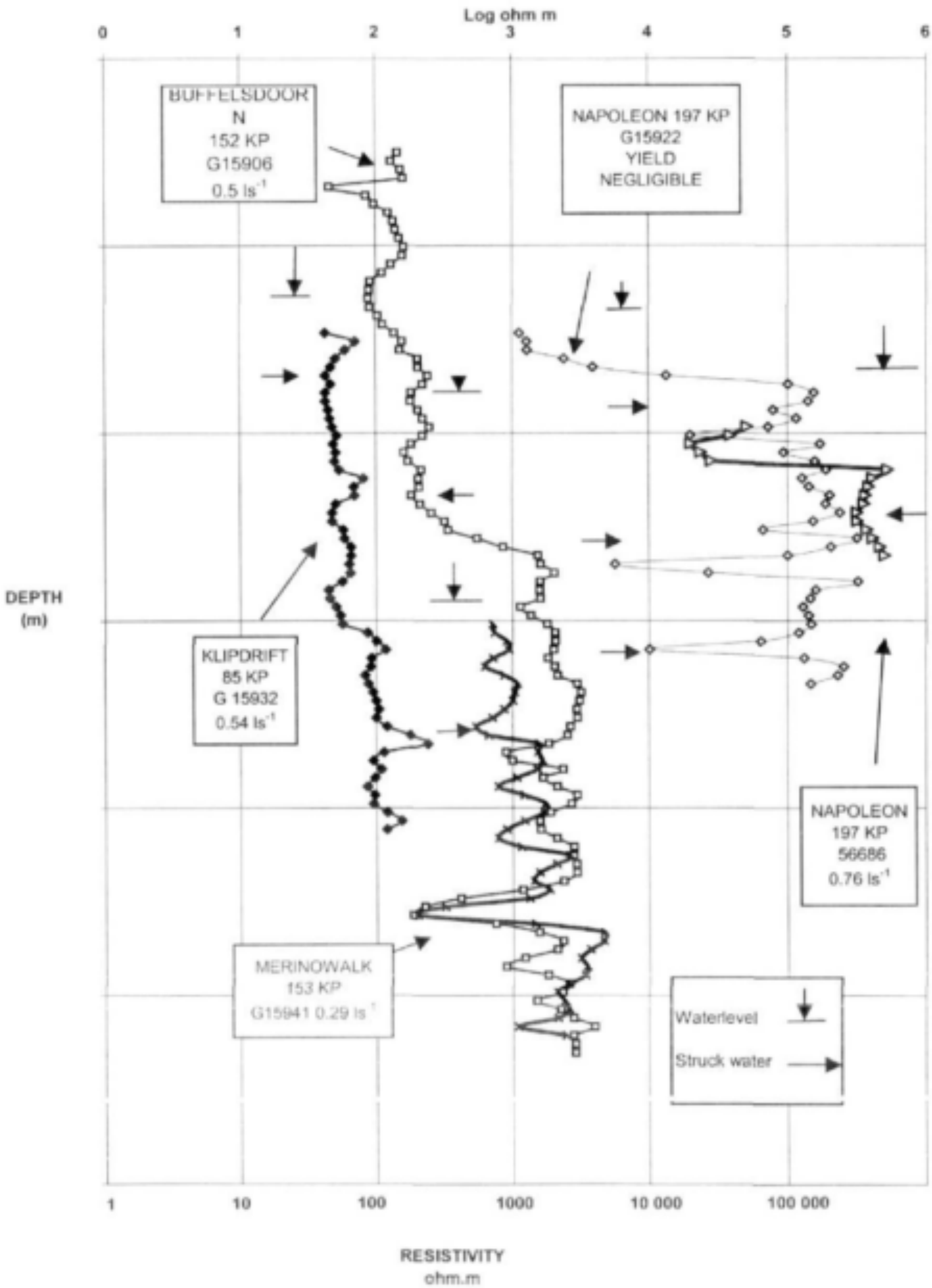


TABLE 9. CONTRASTING BOREHOLE RESULTS

Farm name & No	Borehole No	Depth of hole (m)	Water was struck at a depth of	Water level depth upon completion (m)	Yield $\ell\,s^{-1}$
Klipdrift 85 KP	G15932	86.9	32.9	24.2 (1961)	0.54
Buffelsdoorn 152 KP	G15906	109.1	46.3	36.6 (1961)	0.5
Merinowalk 153KP	G15941	103.9	72.5	54.9 (1961	0.29
Napoleon 197 KP	G 15922	69.8	35.7, 53.0 & 62.2?	29.2 (1961)	Negligible
Napoleon 197 KP	56686	61.2	32.2, 48.8	24.4(when drilled) 38.5 (1960)	0.76 negligible

Further contrasting results are illustrated in Figure 13. Details of the holes are given in Table 9. Borehole G15932 was selected on a decomposed wide diabase dyke. According to electrical depth probing weathering extends to 40 m, whereas it actually exceeds 80 m. Note the shallow depth at which water was struck. Boreholes G15906 and G15941 have similar electrical logs from 60 m down. They also compare well with those of Figure 12. Both proved successful. Although weathering in borehole G15922 extends to 33 m (according to electrical depth probing) i.e. to about 4 m below the water level and although several fractures were penetrated in fresh rock deeper down, the borehole failed to yield a meaningful supply. On the other hand, hole 56686 on the same farm, with only 15 m of weathering, yielded initially at least, a worthwhile supply.

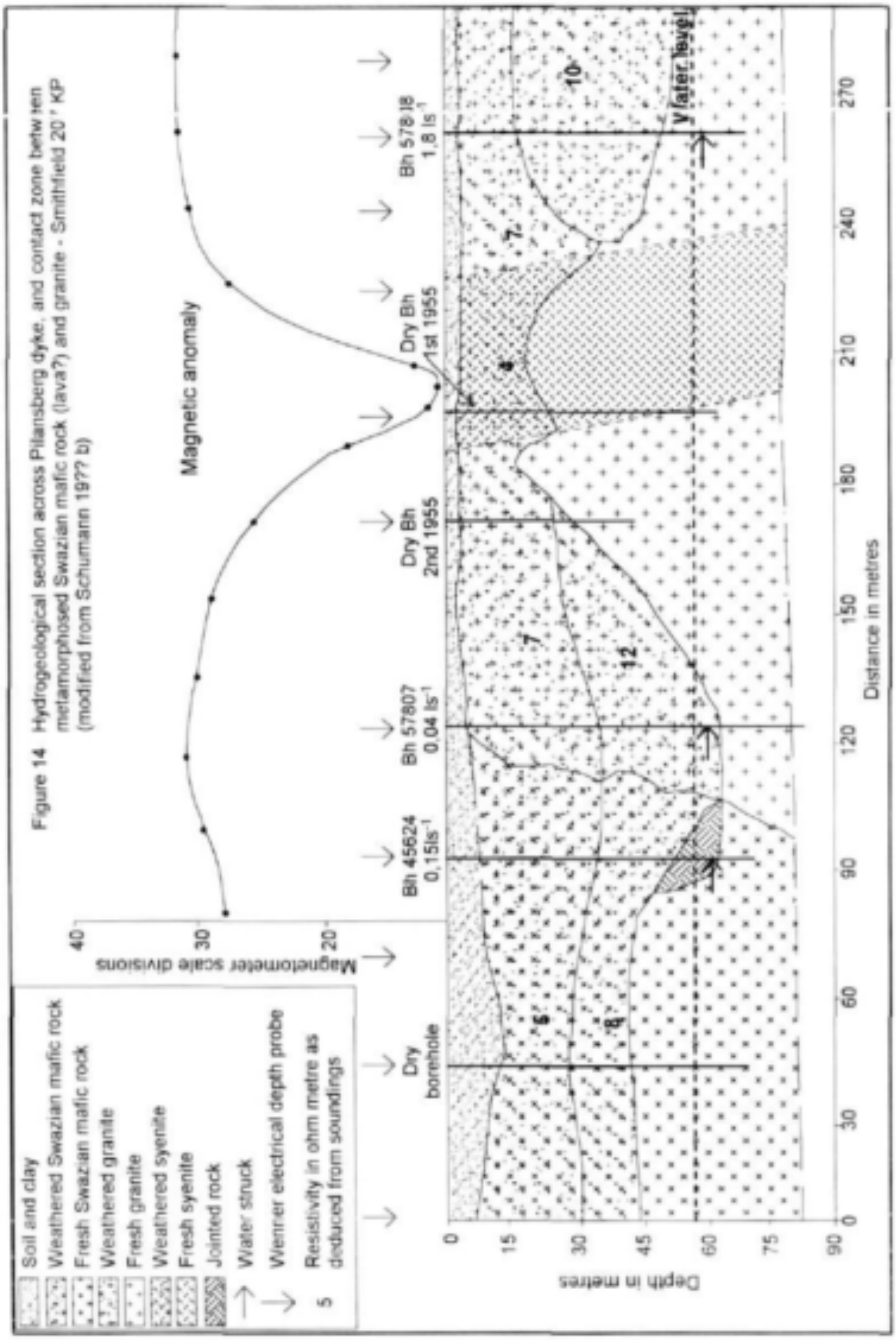


Figure 14 Hydrogeological section across Pilansberg dyke, and contact zone between metamorphosed Swazian mafic rock (lava?) and granite - Smithfield 20° KP (modified from Schumann 19?? b)

Note:

- The failure of borehole 57807 in spite of weathering extending to below the water level.
- Also the small yield of borehole 45624 in spite of striking fractured "diabase" according to the geological log.
- The highest yield was struck in fresh rock according to both the depth probe and geological log of hole 57808.
- Although weathering is much shallower over the dyke than in the adjoining granite, there is no difference in water levels on both sides of the dyke.
- Weathering exceeds 60 m in places.

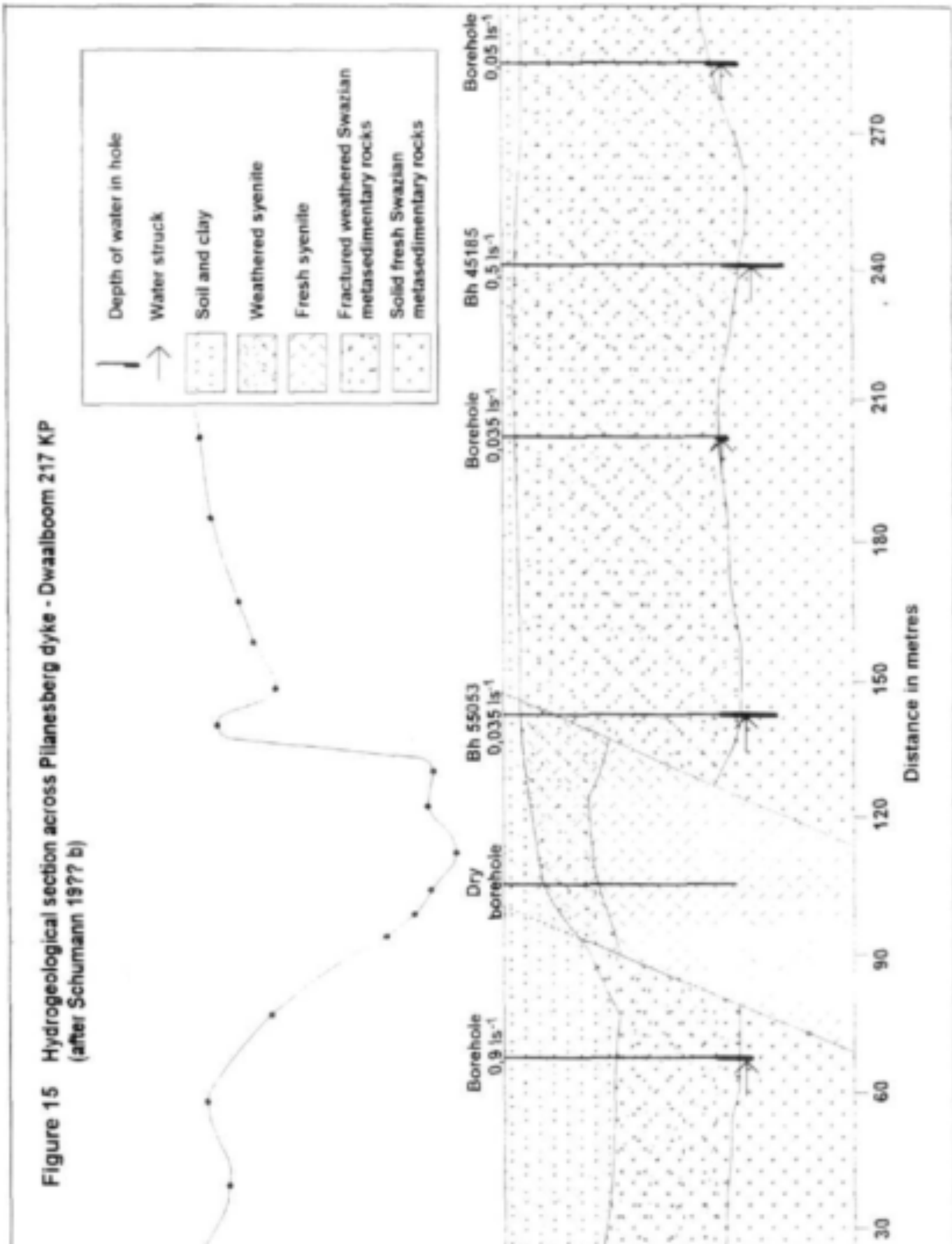


Figure 15 Hydrogeological section across Pilanesberg dyke - Dwaalboom 217 KP (after Schumann 1977 b)

Note:

- As in the previous figure the metasedimentary rocks near to and on both sides of the syenite dyke, are weathered deeper than the water level.
- The water level is the same on both sides of the dyke.
- Water was struck within 1 to 6 m below the base of weathering.
- The depth of weathering at the strongest borehole is 3 m shallower than at borehole 45185.

FIGURE 16 ELECTRICAL RESISTIVITY LOGS OF BOREHOLES DRILLED ACROSS A DIPPING DIABASE DYKE ON BUFFELSDOORNS 152 KP

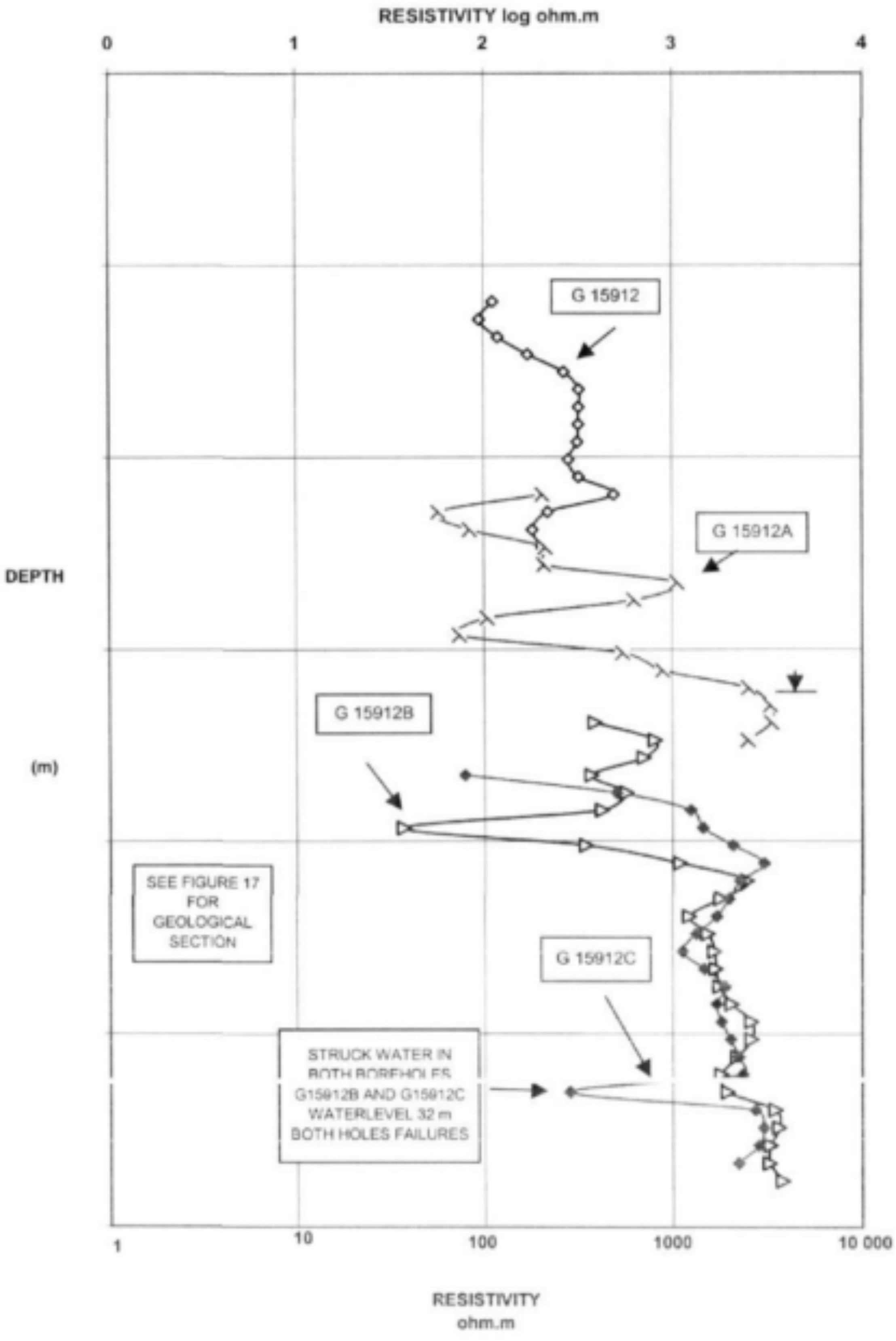
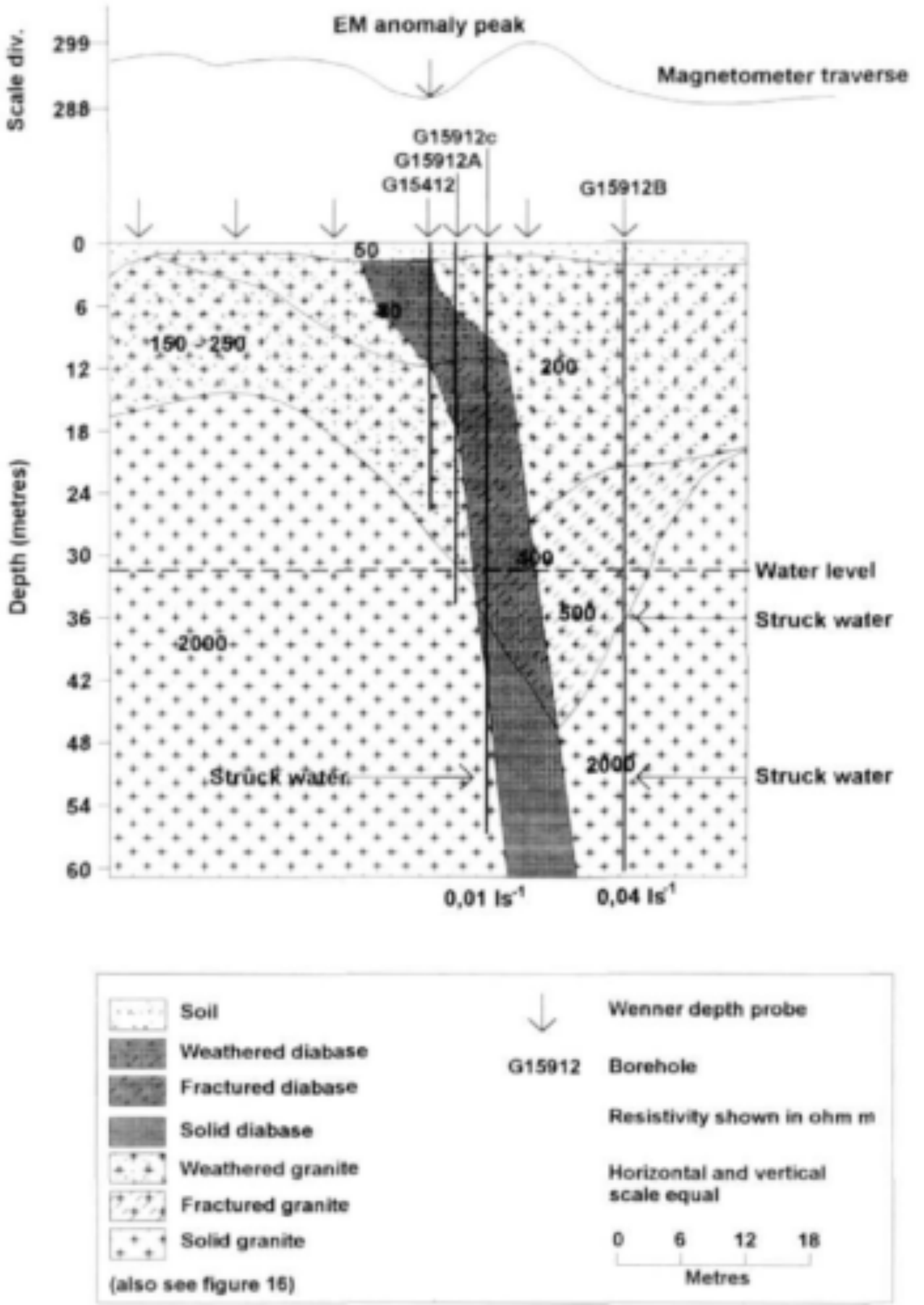


Figure 17 **Section across diabase dyke deduced from magnetic, electromagnetic, resistivity surveys, electrical borehole logging and geological borehole logs. Buffelsdoorn 152 KP**



This is another example of drilling close to and on a dyke that was located through galvanic electromagnetic (Enslin 1955) and magnetometer surveys followed by some electrical depth probing.

- The upper weathered part of the dyke has apparently been displaced through soil creep.
- The position of the negative and positive magnetic peaks are more or less coincident with that of the edges of the fractured dyke at a depth of 12 m.
- Some water was struck at the same depth on both sides of the dyke, apparently in a horizontal fracture.
- The fracture prominently indicated on the resistivity log of hole G15912B at a depth of approximately 40 m, failed to yield water.

FIGURE 18 ELECTRICAL RESISTIVITY LOGS OF BOREHOLES DRILLED ACROSS A PRESUMED FAULT IN ANDESITIC LAVA NAPOLEON 197 KP

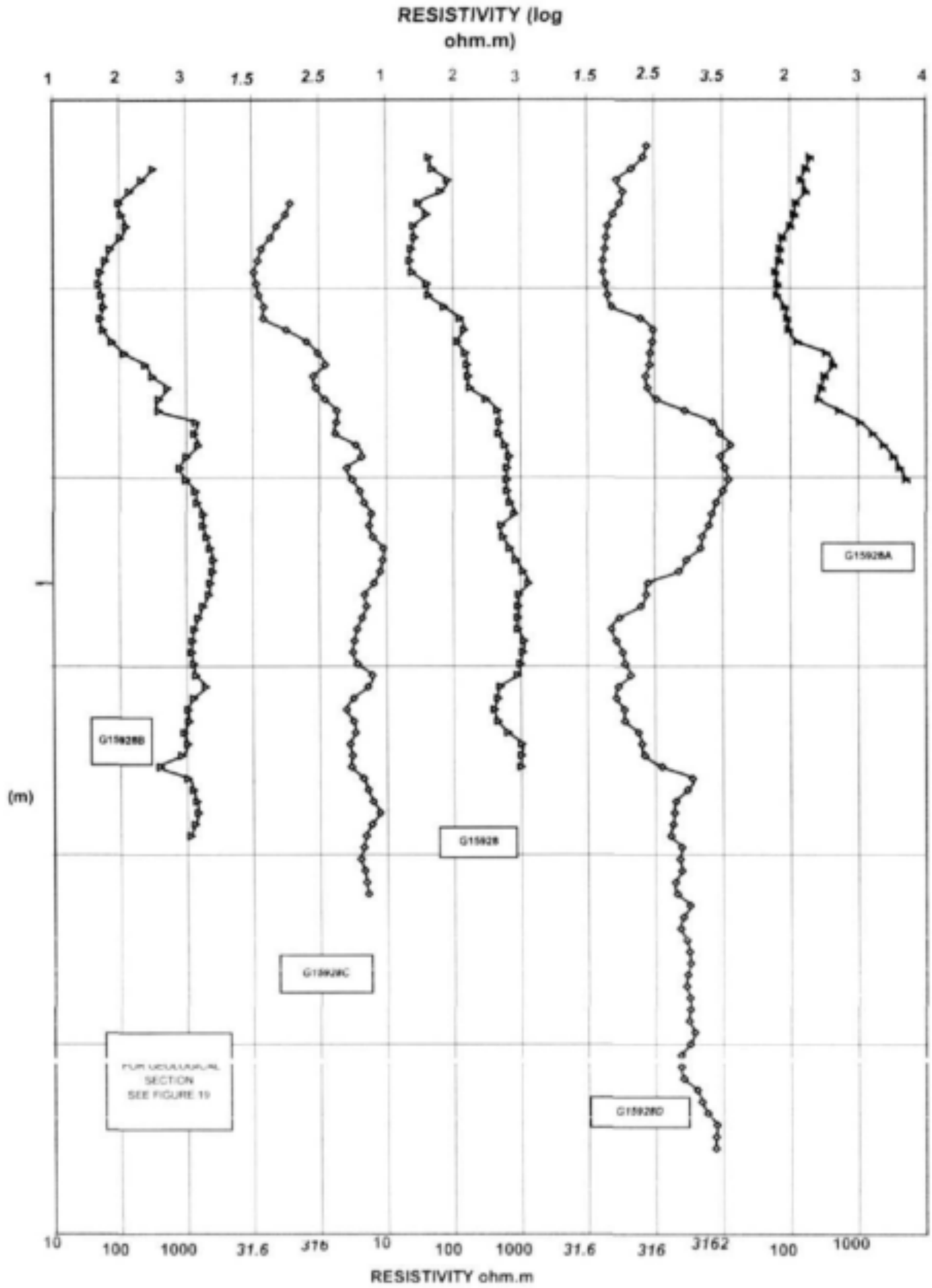
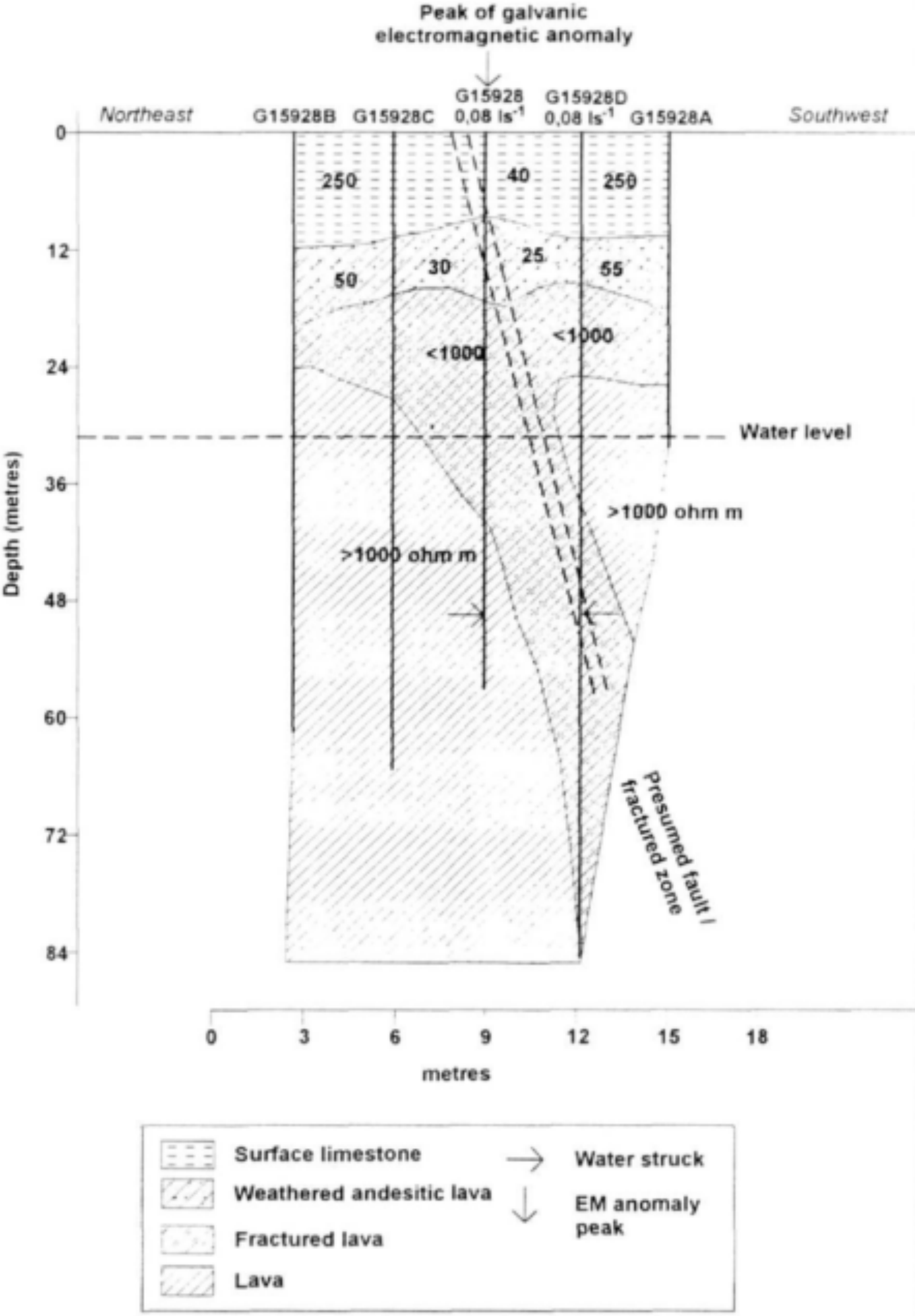


Figure 19 Section across presumed fault on Napoleon 197 KP (see also figure 18)



As illustrated in Figure 19, five closely spaced boreholes were drilled across the strike of an electromagnetic anomaly located by Enslin's galvanic technique (1956). Electrical resistivity logs of the five holes are shown in Figure 18.

- The anomaly apparently coincides with an aeromagnetic lineation, which subsequently has been interpreted and indicated on geological sheet 2426 that Thabazimbi is a probable fault.
- Borehole G 15928 was drilled on the peak of the electromagnetic anomaly. The resistivity of the near-surface weathered rock is the lowest in this hole.
- According to borehole G15928D that penetrated a low resistivity zone between 39 and 48 m, the fault dips apparently steeply to the southwest.
- In spite of penetrating the presumed fault zone considerably below the water level, borehole yield is very disappointing.

Conclusions

Depending on the local situation, one or more of the following factors count against obtaining better results with geophysical borehole siting:

- Groundwater storage is limited to fractured rock. Recharge is inadequate to saturate at least the lower section of the more porous weathered rock.
- Aquifers are localized and discontinuous.
- A permeable transition zone between decomposed and solid fresh rock is lacking. The transition is either sharp or fractures are tight or are filled with clay, calcite or other weathering products. The low hydraulic gradients as a consequence of the Region's flatness are not conducive to the removal of products originating from chemical weathering.

4.3 HYDROFRACTURING

Sixteen boreholes in this Region were subjected at an unknown date in the early nineties to hydrofracturing by C. Less of the Department of Water Affairs and Forestry. The results in the form of before and after pump test graphs, pressure breakdown curves and geophysical borehole logs presented by VSA Earth Science Consultants were re-examined and re-interpreted. Unfortunately, no written comments accompanied the data and no information is available on the strike depths and the nature of the water-bearing structures.

C. Less and VSA consultants determined the percentage of yield improvement from a comparison of the volumes of water pumped out for a specific drawdown before and after hydrofracturing. Neither the time taken nor the pumping rate to produce the set drawdown was taken into account in the Less' assessment.

In the re-assessment of the data, the volume of water in the hole was deducted from the volumes pumped out to obtain the inflow from the formation. This was necessary because in some cases that was virtually the only water drawn from the hole. The corrected volumes were divided by the times taken to require the set drawdowns, thus obtaining a figure for the mean rate of inflow from the formation.

The result was as follows:

1). Hydrofracturing had no effect in four holes; in three holes inflow rates dropped by as much as 60%.

2). After hydrofracturing inflow rates increased between 40 and 230% in nine holes. The average increase was 75%. The "before" inflow rates ranged between 0.1 and 1.2 $\ell\ s^{-1}$ and the "after" rates between 0.2 and 2.7 $\ell\ s^{-1}$. As these inflow rates were maintained for a brief spell only and because proper test pumping was not undertaken, proof is lacking that the boreholes are capable of providing significantly more water on a sustained basis than before hydrofracturing.

3). No information is available on the geological structures on which the holes are situated and the depths at which water was struck.

A proper evaluation of hydrofracturing is thus not possible.

5. WATER LEVELS

5.1 REGIONAL VARIATION OF WATER LEVEL DEPTHS

Water level depths that were measured during the past 90 years at the time when the boreholes were drilled vary considerably within individual farms. The variation ranges from 1 to 80 m. In view of the lack of relief over most of the region, the large variations in water level depths are puzzling. Part of the variation may doubtlessly be ascribed to recharge spells alternating with periods of natural discharge and, in some instances, to local depletion through pumping. Bush encroachment and bush clearing may also play a role.

It nevertheless seems doubtful that the very large water level differences (Figure 20) and their widespread occurrence can be ascribed solely to temporal variations. Water levels were measured on a few farms northeast of Derdepoort during a period of a few weeks at the turn of 1993/94. No significant temporal change of levels was expected during this period. Water level depths shown in Figure 21 nevertheless ranged from 13.1 to 71.8 m (the difference in elevation is approx. 30 m). The historical variation is even greater. The variability is much larger than one would expect from differences in surface elevations.

FIGURE 20 DISTRIBUTION OF WATER LEVEL VARIANCE IN TERMS OF NUMBER OF FARMS

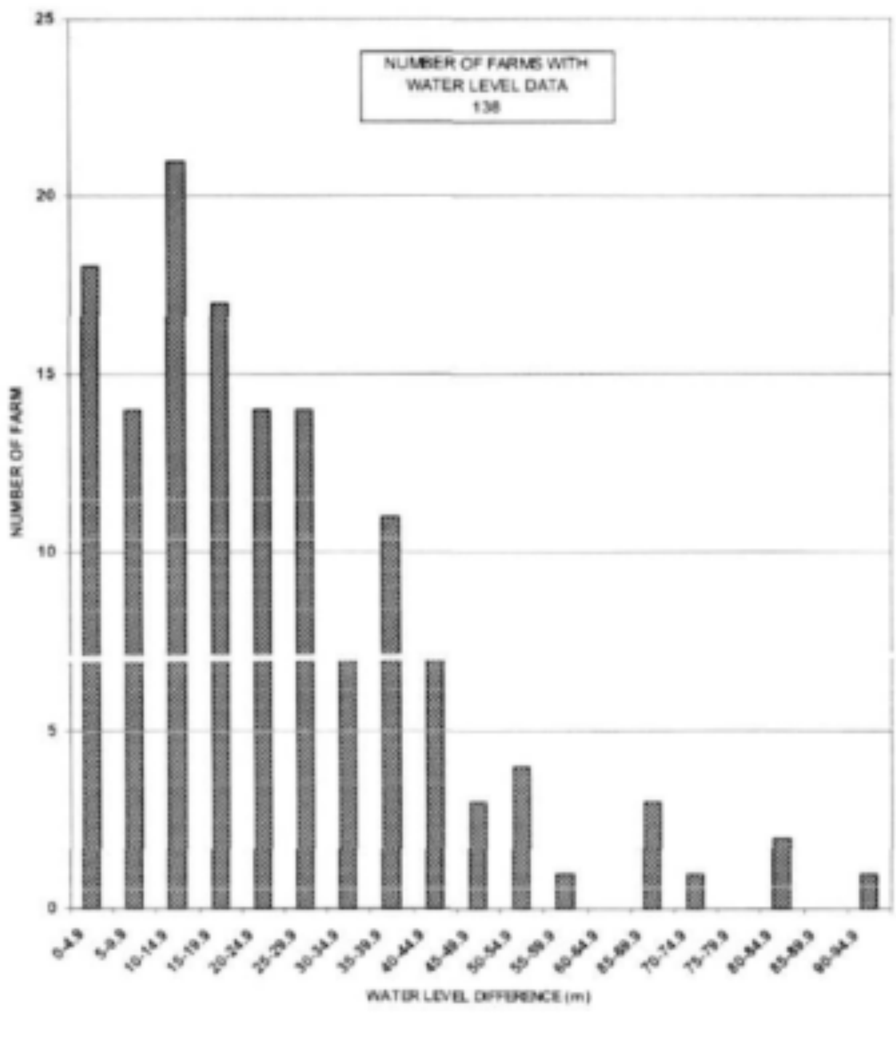
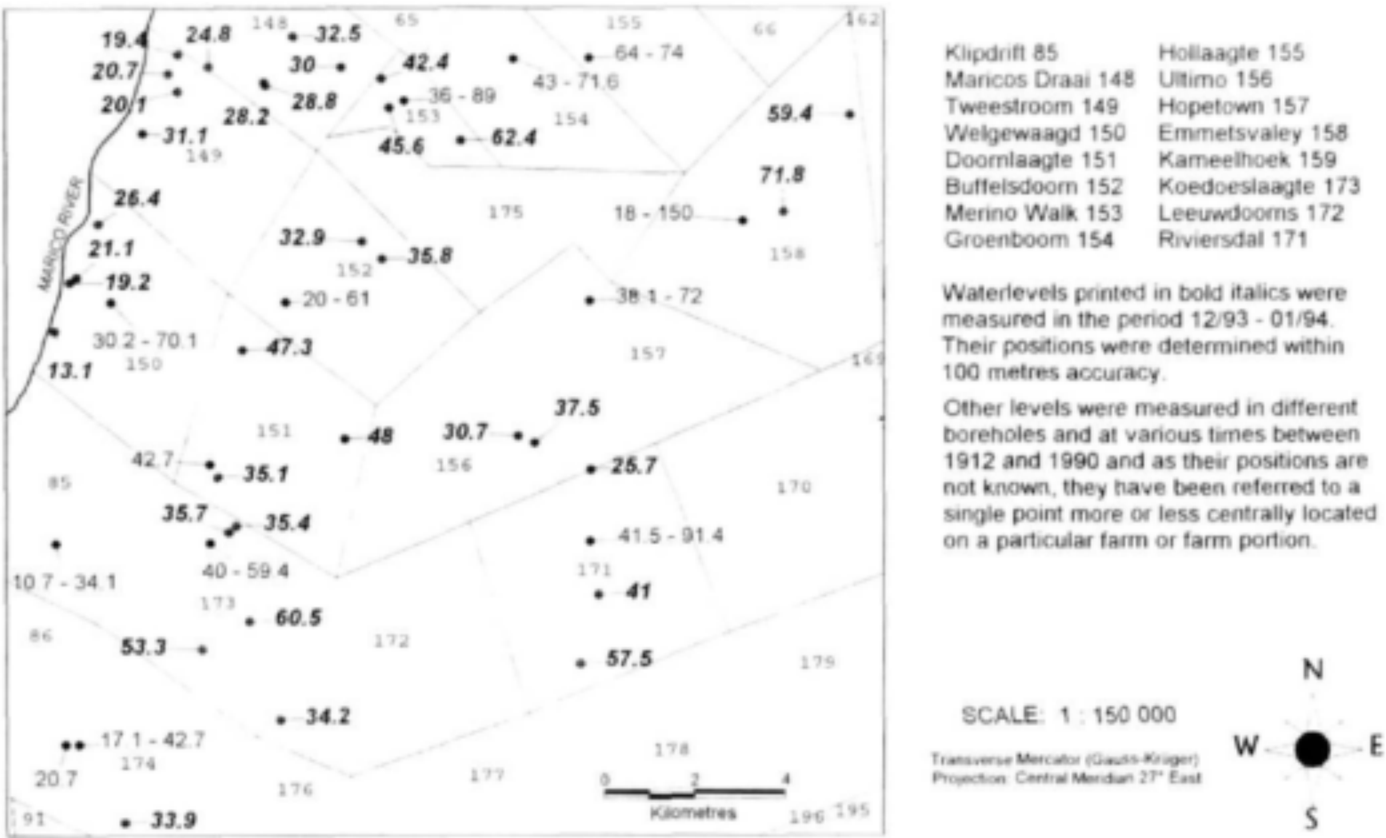


FIGURE 21 GROUNDWATER LEVELS NORTHEAST OF DERDEPOORT THABAZIMBI DISTRICT



In general, water levels closer to the Marico River are shallower than further east. The surface slopes downward towards the river.

5.2 PALEOCHANNELS

Evidence for the existence of deep paleochannels (Botha 1988) prompted an examination of the distribution of deep and discordant water levels and of the occurrence of thick detrital and calcrete deposits reported in drillers' logs. According to Botha (1988) the detrital sediments (Rooibokkraal Formation) as well as (weathered) granitoids and metamorphic rocks were widely calcretized. Thick sections of calcrete found in boreholes may thus be indicative of either paleochannels or of deeply weathered basement rocks adjacent to paleochannels or of deeply weathered fracture zones.

The spread of maximum thicknesses of detrital and calcrete deposits is depicted in Figure 22 in terms of the number of farms on which they were encountered. Thicknesses of less than 15 m were disregarded.

The area distribution of the deepest water levels and of the water level variance on a farm-by-farm basis is depicted together with the thicknesses of detrital and calcrete deposits in Figures 23 and 24 (**at back of report**). Water levels of successful holes (yielding $\geq 0.1\ \ell\ s^{-1}$) only were used in the compilation.

The outcome is somewhat disappointing. A clearly recognisable pattern of paleochannels or structural features has not emerged. A broad rather vague correlation between deep water levels and thick detrital and calcrete deposits is evident in Figure 25. Because borehole positions are known by farm name and number only and as holes were obviously not sited to locate and trace paleochannels or deeply weathered fracture zones, a clearer pattern cannot be expected.

FIGURE 22. MAXIMUM THICKNESS OF CAINOZOIC DETRITAL DEPOSITS AND CALCRETE IN TERMS OF NUMBER OF FARMS WHERE RECORDED

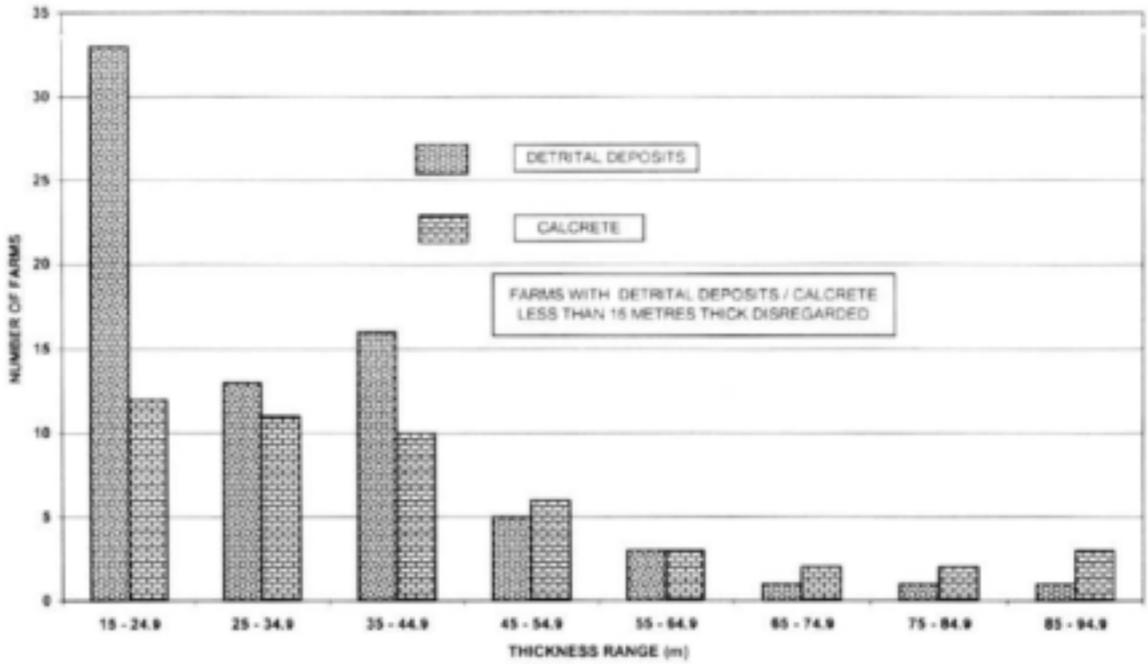
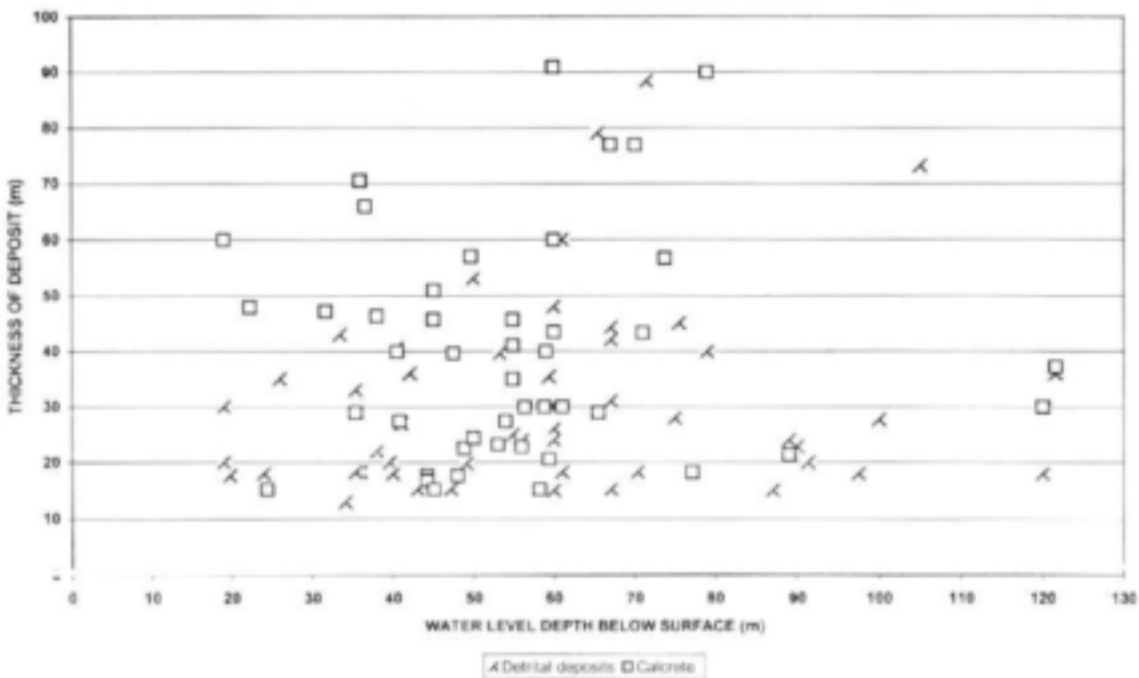


FIGURE 25. DEEPEST WATER LEVELS VERSUS GREATEST THICKNESS OF CAINOZOIC DETRITAL AND CALCRETE DEPOSITS PER FARM



According to crude estimates of surface elevations from 1:50 000 maps, the deeper water levels lie well below Crocodile and Marico riverbed level, on farms 39 KP, 53 KP, 55 KP and 53 KP, even below the elevation at the their confluence.

The explanation for this phenomenon is obscure. The fact that groundwater is being recharged albeit considerably only at irregularly and widely spaced intervals, means that groundwater is being discharged apparently in lower-lying area(s) outside the region. The hydraulic gradients along such flow lines would appear to be very low and the volumes are probably small.

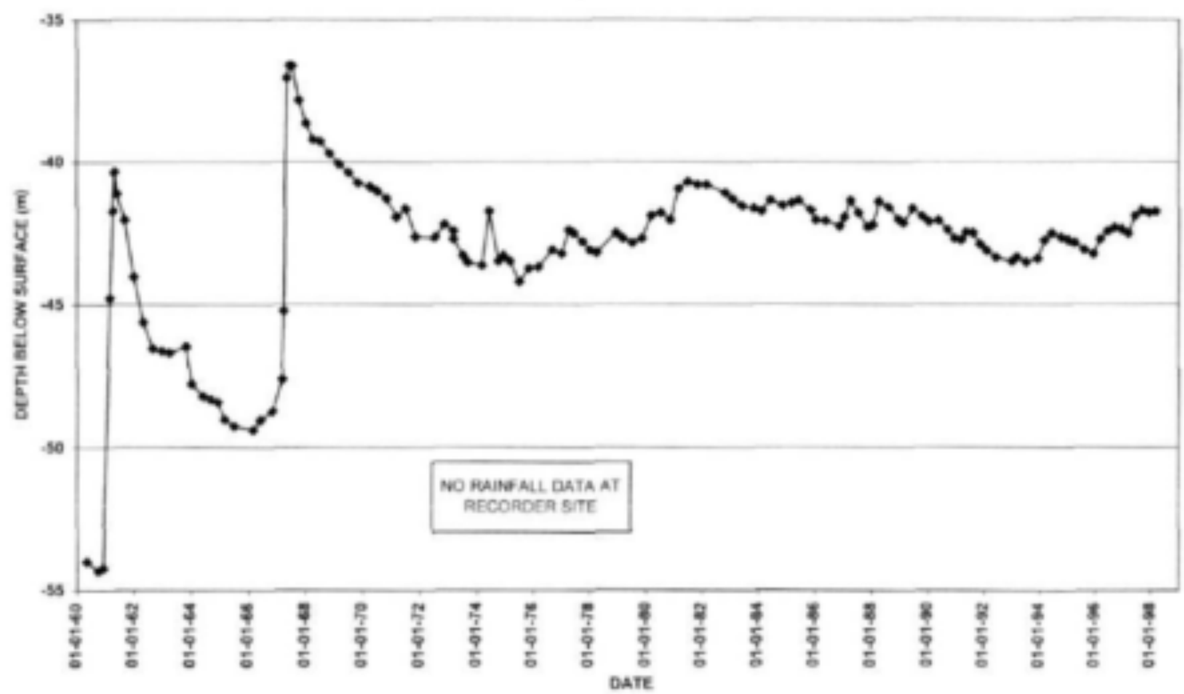
5.3 TEMPORAL VARIATION

The following observations prove that groundwater recharge takes place:

1. In 1960 the Division of Hydrological Research of the then Department of Water Affairs erected a water level recorder on Merinowalk 153 KP. Figure 26 depicts the water level fluctuation over the period 1960 to 1998. Unfortunately, rainfall has not been recorded here. Rainfall recorded on five farms between 20 and 35 km away averaged 74% higher in 1960/1 than the 38-year mean of 510 mm per annum. In 1966/7 the mean of the five stations was 100% higher. In 1967 the wide flat valley in which the water level recording borehole is situated was flooded for weeks (verbal communication of farm owner).

   These two seasons – the highest in the period 1955/92 – are reflected by sharp water level rises of 14 and 12 m respectively. As the two subsequent relatively rapid declines of the water level cannot be ascribed to large-scale abstraction by pumping, the phenomenon is postulated to be the response of a double porosity medium to recharge. Permeable fractures with little capacity for storage fill-up rapidly while high porosity semi-permeable rock material imbibes water slowly from the fractures. The double porosity system apparently needs several years to adjust.

FIGURE 26. WATER LEVEL FLUCTUATION ON WELGEMOED 175 KP
(RECORDER STATION A2NO1O)



The gradual water level rise between 1976 and 1982 coincides partly with a wet period between 1973 and 1978. During this period each season's rainfall was about 40% above the average. That only a gradual water level rise was observed during this period may be ascribed to one or more of the following:

a) Total seasonal rainfall though above mean, was less than in the 1960/61 and 1966/67 seasons.
b) The intensities and temporal distributions of rainstorms during the 1973-1978 period were different to those of 1960/61 and 1966/67.
c) Infiltration conditions were different – as a result of earlier light rainfall during the 1973-1978 seasons, macropore openings had become sealed before the onset of heavier rainstorms which otherwise may have been recharge effective.
d) At shallower depths decomposed granite not only has a higher storage coefficient but also does not exhibit a double porosity character. This may be linked to the presence at shallower depth of kaolinite as weathering product, which presumably is more permeable than smectite deeper down (see Vegter 2000a Section 3.2.3 and 2000b Section 5.1).
e) The assumption that Merinowalk also received above normal rainfall as indicated by distant rainfall stations may not be true.

It is of interest to note that a sharp water level rise was recorded around 1977 in boreholes on Frankfort 69 KP situated 18 km east of Merinowalk153 KP – see next paragraph 5.4. This rise was not followed by a sharp decline. Although sufficient observations are lacking it would appear that on Frankfort water levels declined considerably after the 1966/67 high rainfall season.

2. Schumann (undated b) recorded the following water level fluctuations:

a) In the autumn of 1955 the water level rose by 3.7 m in hole 57642 on Doornlaagte 151 KP.
b) In 1954 the water level in hole 10570 on Noord Brabant 114 KQ stood at 67.1 m, compared to 51.8 m in 1925.
c) In hole 26699 on the same farm the water level was 22.6 m lower in 1954 than at the time of drilling in 1940.

5.4 BUSH CLEARING

The effect of clearing bushveld vegetation on groundwater has been monitored on Frankfort 69 KP. The year 1960 saw the clearing of 400 hectares of Arid Sweet Bushveld vegetation on this farm. The clearing led, over a period of 18 years to a rise in water level underneath the cleared field from a depth of about 70 to less than 50 m - hydrographs of boreholes A2N100 and A2N102 (Figure 27). Since then the water level under the cleared field has more or less stabilised. Spreading of the water level mound into the surrounding bush-clad area is illustrated by the hydrograph of borehole A2N099. For further details see Vegter (1993 and 1995).

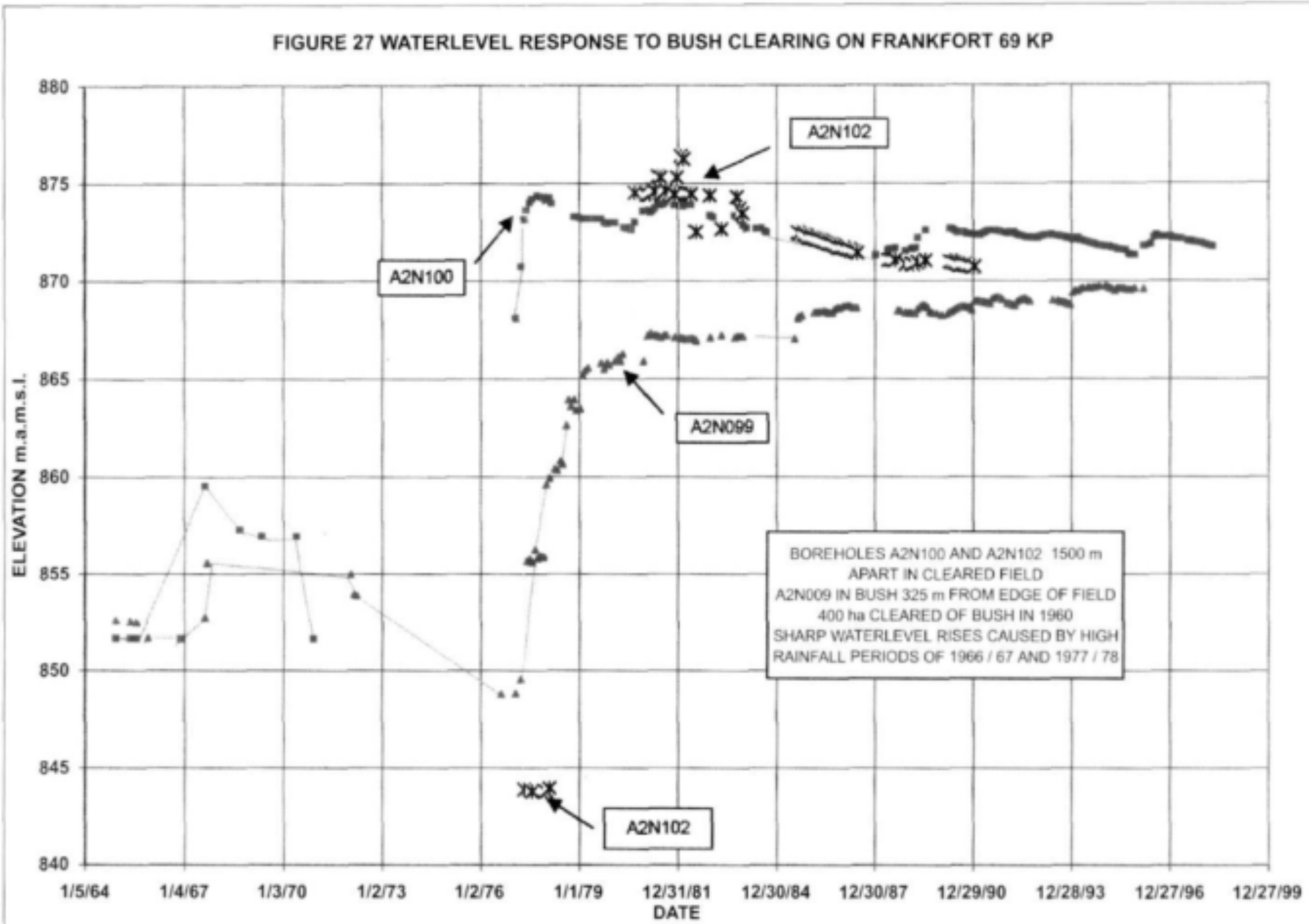


FIGURE 27 WATERLEVEL RESPONSE TO BUSH CLEARING ON FRANKFORT 69 KP
ELEVATION m.a.m.s.l.
880
875
870
865
860
855
850
845
840
1/5/64
1/4/67
1/3/70
1/2/73
1/2/76
1/1/79
12/31/81
12/30/84
12/30/87
12/29/90
12/28/93
12/27/96
12/27/99
DATE
A2N102
A2N100
A2N099
A2N102
BOREHOLES A2N100 AND A2N102 1500 m APART IN CLEARED FIELD
A2N009 IN BUSH 325 m FROM EDGE OF FIELD
400 ha CLEARED OF BUSH IN 1960
SHARP WATERLEVEL RISES CAUSED BY HIGH RAINFALL PERIODS OF 1966 / 67 AND 1977 / 78

6. GROUNDWATER QUALITY AND HYDROCHEMISTRY

According to Sheet No 2 of the national Groundwater Resources maps, total dissolved solids range between 500 and 2000 mg ℓ^{-1}. Simonic of Hydromedia Solutions (Pty) Ltd. classified the overall potability of 277 analyses of water samples as follows:

TABLE 10 POTABILITY CLASSIFICATION

Class	1	2	3	4	5
Description	Ideal	Good	Marginal	Poor	Unacceptable
No of analyses	27	73	85	53	39
% of analyses	9.7	26.4	30.7	19.1	14.1

The distribution of the samples is far from ideal as shown in Figure 28. Of the 122 samples collected along the Crocodile River 25 are from the alluvium, 82 from granite and 15 from quartzite and lava. Potability of water from the alluvium is generally ideal or good.

TABLE 11 DISTRIBUTION OF HARMFUL ION CONCENTRATIONS IN POOR AND UNACCEPTABLE POTABILITY CLASSES

Ion	**Ca**	**Mg**	**Na**	**K**	**Cl**	**SO_4**	**NO_3**	**F**	**EC**
No of analyses containing harmful concentration	5	7	11	0	16	4	57	29	11
% of analyses	1.8	2.5	4.0	0	5.8	1.4	20.6	10.5	4.0

Nitrate and fluoride are the main hazards. Although not evident from the analyses plotted in Figure 28, the fluoride content of groundwater from the Gaborone Granite is unacceptably high.

Two main hydrochemical types of water are present: calcium-magnesium bicarbonate water, presumably of shallower origin, and calcium-magnesium chloride-sulphate water presumably of deeper origin.

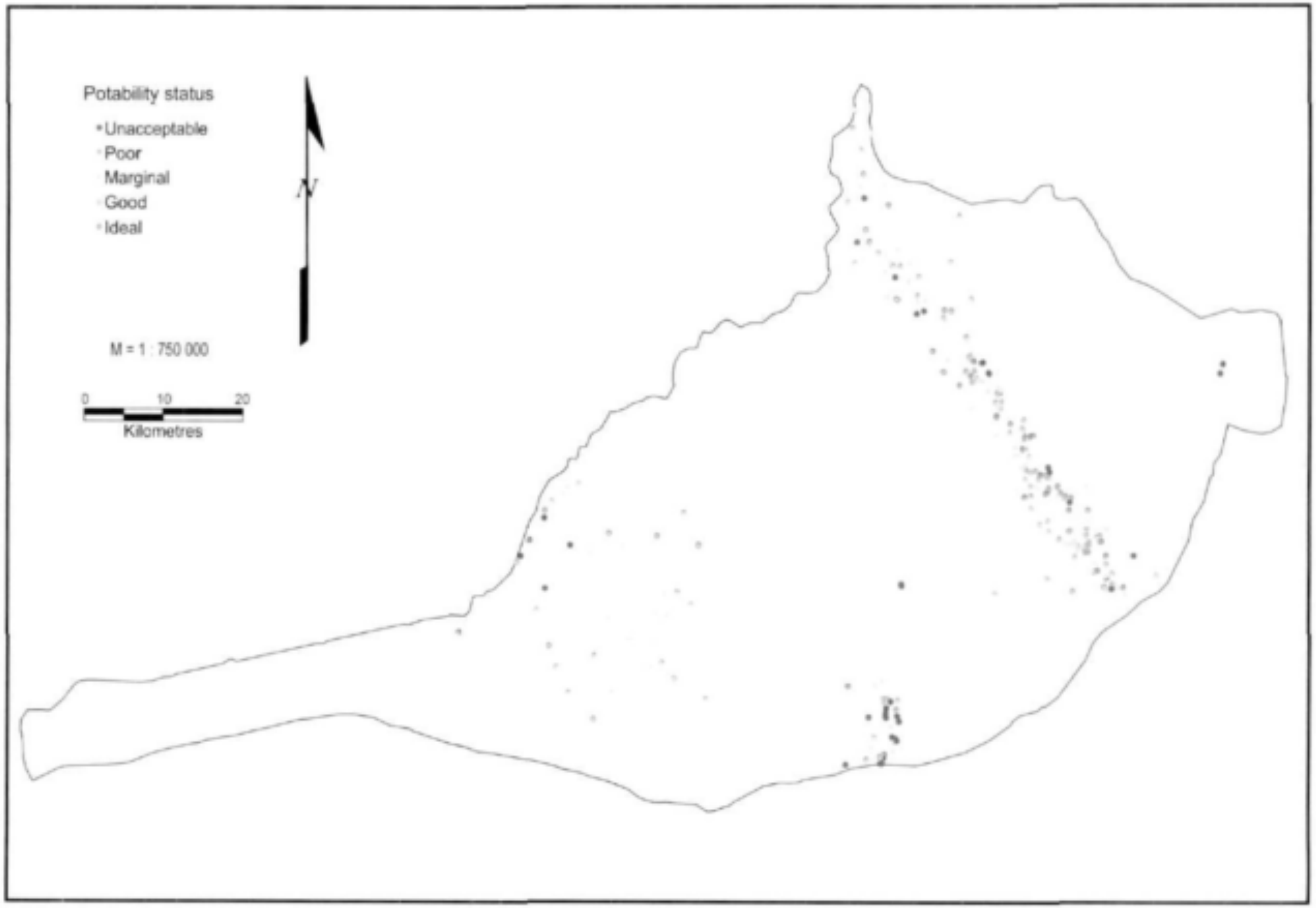


Figure 28: Distribution of water sampling points and quality status - Region 1

7. CONCLUSIONS AND RECOMMENDATIONS

Except for the proximity of the Crocodile and presumably the Marico Rivers, Region 1 is poorly endowed with groundwater. The reason(s) for this state of affairs is not clear, especially when compared to the Coetzersdam-Louwna area some 60 km west of Vryburg. The Coetzersdam-Louwna area is also situated on extensively and deeply weathered granite. Rainfall is somewhat lower; vegetation is savanna. Large volumes of water are abstracted here for irrigation.

Region 1 seems ideally suited for a holistic research approach into all aspects related to the occurrence, recharge, flow and discharge of groundwater, clay mineralogy and hydrochemistry, in particular with respect to:

- Locating and tracing paleochannels by means of geophysical methods, exploratory drilling; and test pumping with a view of determining the hydrogeological properties of their fill and their possible role as conduits.
- Alternatively, locating and tracing geological structures that, by acting as conduits, may be responsible for the discordant water level pattern.
- Water-bearing properties of hard-rock geological structures; of fracturing in relation to neotectonic stress field (Andersen and Ainslee 1993).
- The role of weathering in enhancing or degrading water-bearing properties, geochemical processes and weathering products in relation to hydrochemistry both within the zone of aeration and below groundwater level.
- Groundwater flow regime and discharge - what are the conduits, where and in what form is discharge.
- Infiltration - modes of water movement through zone of aeration; moisture content and loss through evapotranspiration.
- Water consumption by Bushveld vegetation; detection and identification of phreatophytes if present.
- Recharge - its temporal and volumetric variability and its relation to rainfall.

Much about the factors enumerated above may possibly be learnt from a comparative study of the Coetzersdam-Louwna area with similar hard rock geology, rainfall and vegetation where large-scale irrigation is practised with groundwater.

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MAPS CONSULTED

Topocadastral Map Sheet 2426 1990 scale 1:250 000. Dir. Surveys and Mapping Mowbray.

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Fig. 2 - Region 1 Makoppa Dome

Adapted from Geological sheet Thabazimbi 2426
and RSA 1:1000 000 Map (1998)

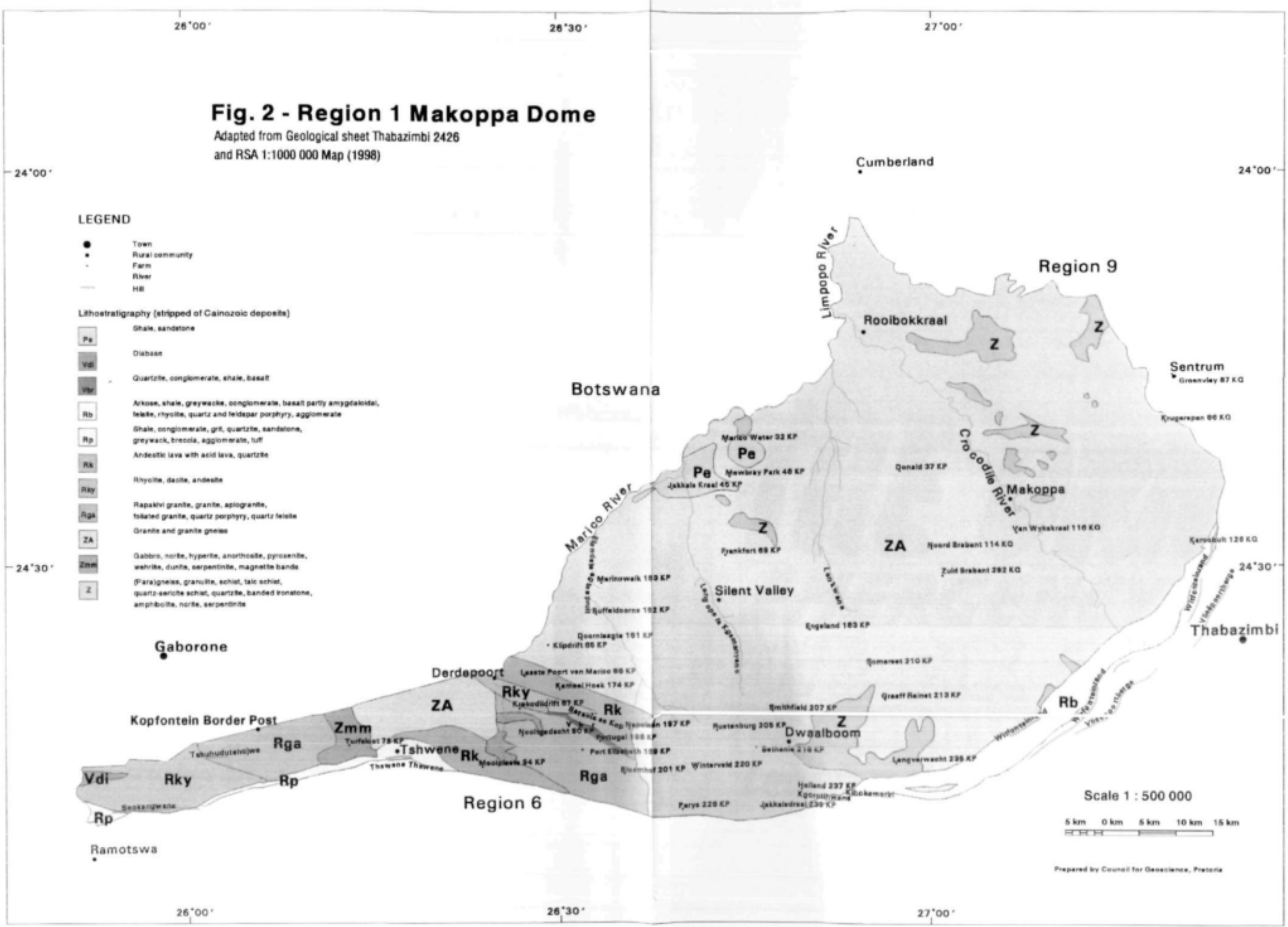

Fig.1 - Location of Groundwater Region 1 Makoppa Dome

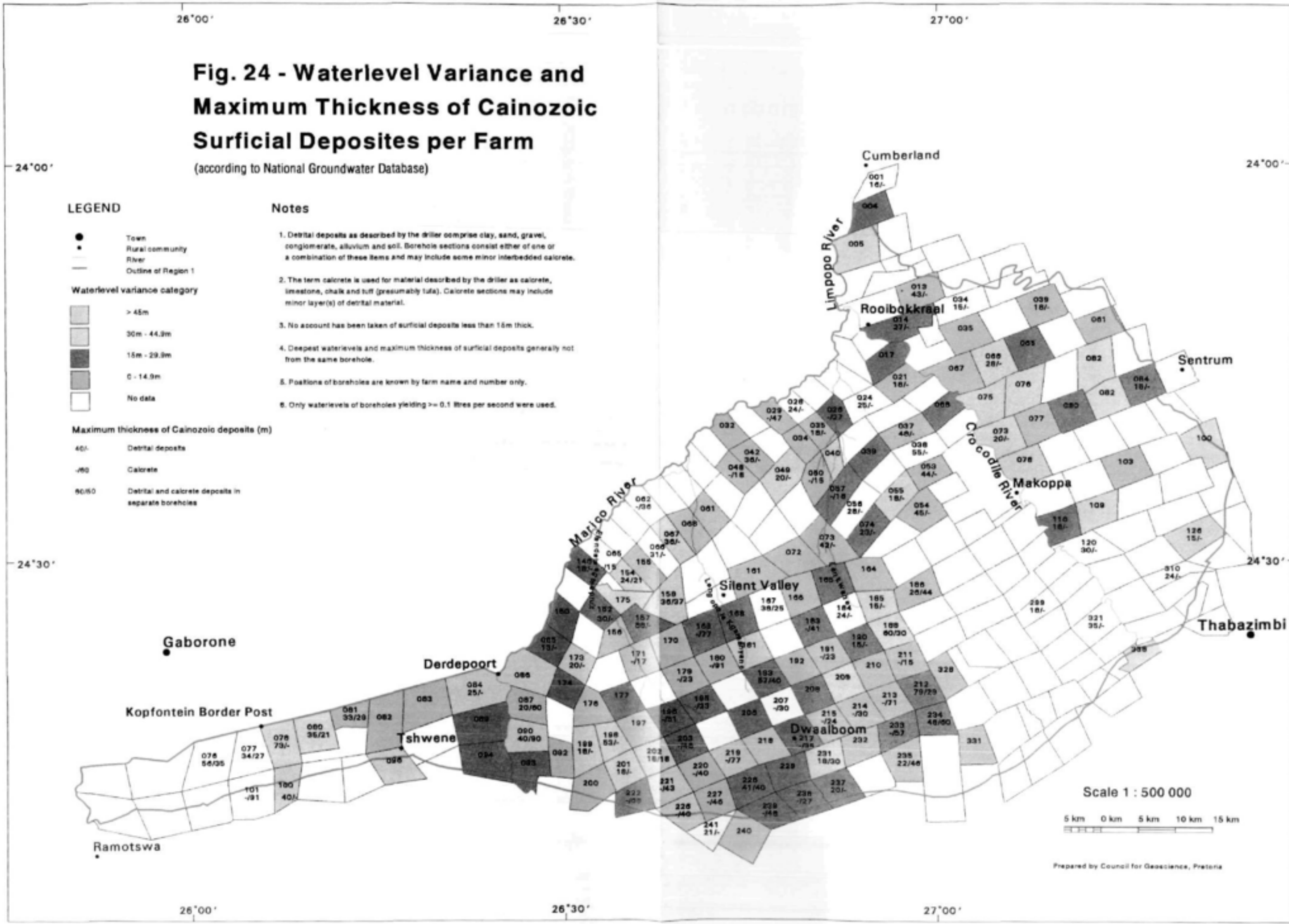

Fig. 24 - Waterlevel Variance and Maximum Thickness of Cainozoic Surficial Deposites per Farm

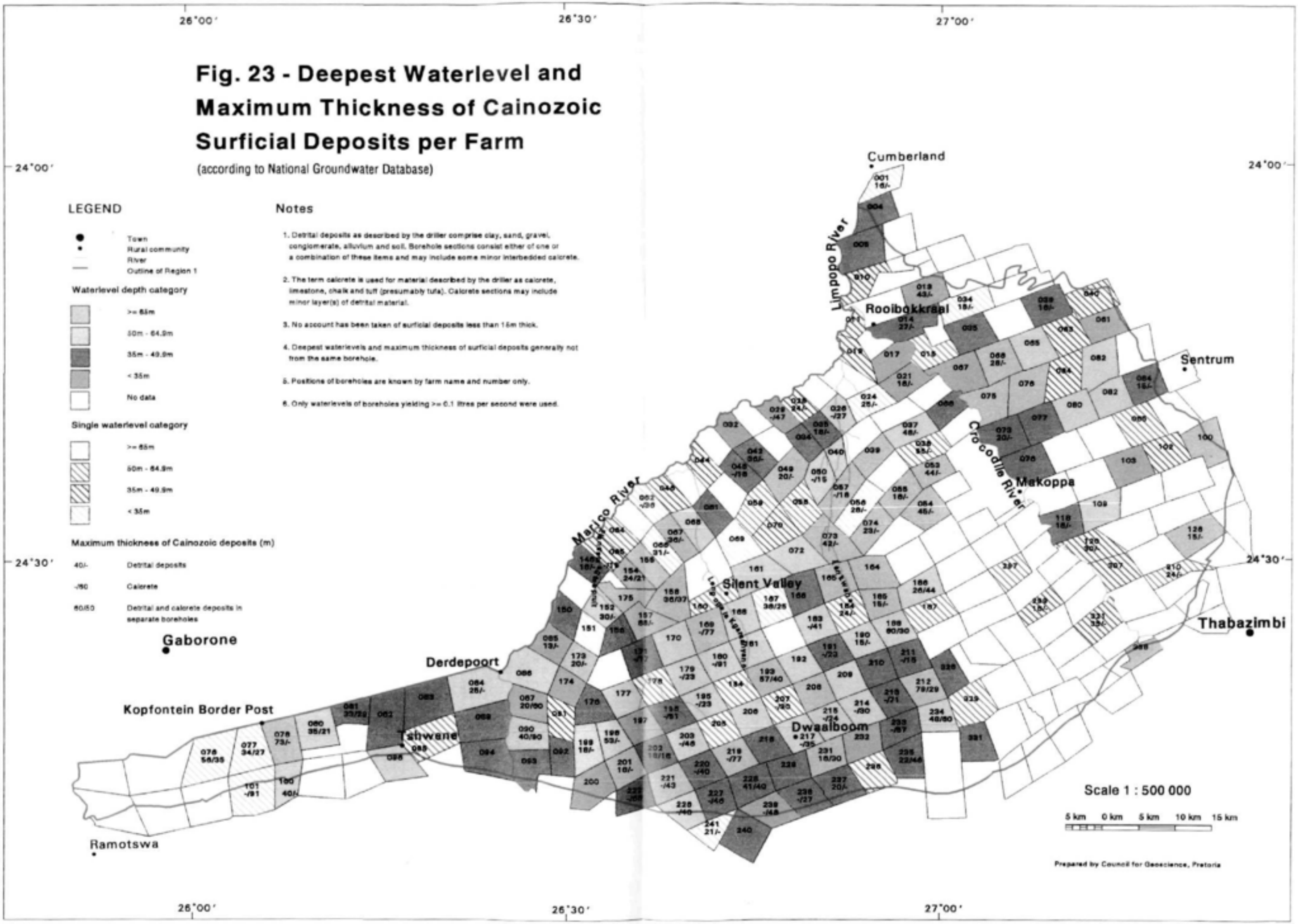
Fig. 23 - Deepest Waterlevel and Maximum Thickness of Cainozoic Surficial Deposits per Farm
(according to National Groundwater Database)
LEGEND
Town
Rural community
River
Outline of Region 1
Waterlevel depth category
>= 65m
50m - 64.9m
35m - 49.9m
< 35m
No data
Single waterlevel category
>= 65m
50m - 64.9m
35m - 49.9m
< 35m
Maximum thickness of Cainozoic deposits (m)
40/- Detrital deposits
-/50 Calcrete
Detrital and calcrete deposits in separate boreholes
Notes
1. Detrital deposits as described by the driller comprise clay, sand, gravel, conglomerate, alluvium and soil. Borehole sections consist either of one or a combination of these items and may include some minor interbedded calcrete.
2. The term calcrete is used for material described by the driller as calcrete, limestone, chalk and tuff (presumably tufa). Calcrete sections may include minor layer(s) of detrital material.
3. No account has been taken of surficial deposits less than 15m thick.
4. Deepest waterlevels and maximum thickness of surficial deposits generally not from the same borehole.
5. Positions of boreholes are known by farm name and number only.
6. Only waterlevels of boreholes yielding >= 0.1 litres per second were used.
26°00'
26°30'
27°00'
24°00'
24°30'
Cumberland
Limpopo River
Rooibokkraal
Sentrum
Crocodile River
Mekoppa
Marico River
Silent Valley
Thabazimbi
Gaborone
Derdepoort
Kopfontein Border Post
Tshwane
Dwaalboom
Ramotswa
Scale 1 : 500 000
5 km 0 km 5 km 10 km 15 km
Prepared by Council for Geoscience, Pretoria