Hydrogeology of Groundwater

Region 3

Limpopo Granulite-Gneiss Belt

TT 136/00

Water Research Commission

J R Vegter

HYDROGEOLOGY
OF GROUNDWATER

REGION 3:
LIMPOPO GRANULITE-GNEISS BELT

Prepared for the Water Research Commission

by

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EXECUTIVE SUMMARY

General features

Groundwater Region 3 - the Limpopo granulite-gneiss belt - is situated in the Northern Province. The belt is lenticular in shape and adjoins the Limpopo River for most of the way between longitudes 27^0 and 31^0. The Region is about 375 km long and measures 60 km at its widest. It consists of the lower portions of drainage regions:

- A 4 Mokolo River,
- A 5 the Lephalala River,
- A 6 the Mogalakwena River,
- A 7 the Sand River and
- A narrow strip along the Limpopo River that is part of the Nzhlele and Nwanedzi drainage regions A 8 and A 9.

There are, apart from Messina, an appreciable number of villages, small communities and informal rural settlements. Economic activities consist of cattle and game ranching, irrigation along the major rivers, copper and diamond mining.

West of Messina Region 3 is a monotonous flat to gently undulating bush-clad expanse, occasionally broken by hills consisting of metaquartzite and magnetite quartzite. The topography is more varied east of Messina where the country is characterised by rolling hills and ridges. The vegetation comprises several types of Bushveld. The climate is semi-arid subtropical. Rain, which falls during summer, tends to be erratic, varying from a mean of 425 mm in the west to about 300 mm in the extreme east.

Except for the larger rivers, which do not necessarily have year-round flows, water for household use, cattle and game ranching has to be tapped by means of boreholes. In places along the Mokolo, Lephalala and Limpopo Rivers, groundwater is withdrawn for irrigation by means of wellpoints.

Geology

Polymetamorphosed and highly deformed supracrustal and intrusive rocks of Swazian age and belonging to the Central Zone of the Limpopo Mobile Belt occupy most of Region 3. The supracrustal rocks consist of metaquartzite, magnetite quartzite, metapelite, granulite, leucogneiss, calc-silicate rock and marble. Intrusive rocks comprise biotite gneiss, meta-anorthosite, metagabbro, serpentinite, metapyroxenite and hornblendite.

Included in Region 3 are quartzites and conglomerates of the Koedoesrand Formation, granite, mylonite, ultramylonite and mylonitized gneisses of the Palala Shear Zone, Bushveld gabbro and granite and some outliers of Soutpansberg quartzitic sandstone and Karoo strata. As these younger rocks occupy a very subordinate part of Region 3 and because little is known about their water-bearing properties, they will receive no further attention.

With the exception of alluvium along the major rivers, other widespread surficial Tertiary and Quaternary deposits in the form of river terrace gravels, sand, calcrete and ferricrete, do not feature as water-bearing formations.

The Limpopo Mobile Belt has been intruded by east-west striking granite dykes, pegmatites and by diabase and dolerite dykes, generally striking east-northeast and west-northwest.

Major east-northeasterly trending zones of shearing, faulting and brecciation are present in the Limpopo Mobile Belt. Of them the Palala Shear Zone is the most notable. Horst and graben structures are present north of the Soutpansberg. Analysis of satellite imagery and aeromagnetic trends has led to the identification in the Swartwater area of a direction of normal faulting striking 10^0 east of north and of shearing 15^0 west of north.

Occurrence of groundwater

Beyond determining the extent of irrigation with groundwater along the main rivers, no hydrogeological investigation of the alluvial deposits has been undertaken. Past hydrogeological work has been restricted to the hard-rock formations. Drilling results in hard-rock formations are poor for most of Region 3. Of the NGWDB boreholes that have been drilled by government machines about 40% yield more than 0.1 $\ell\ s^{-1}$. The great majority of these holes were not sited by (hydro-) geologists or geophysicists. Although not analysed separately, borehole siting by the latter does not appear to have fared significantly better.

Data of boreholes drilled into rocks of the Limpopo Mobile Belt have been analysed statistically in terms of water level frequency, water strike frequency below surface and below water level, cumulative borehole depths, water level and water strike frequencies and yield - strike depth relationship. For this purpose ,the Region was divided into five Subregions. The Subregion underlain by younger formations south of the Palala Shear zone was excluded from the analysis. Depending on location, the maximum optimal strike depth ranges between 50 and 85 m below the surface and between 15 and 25 m below the water level. According to these analyses a substantial percentage of the NGWDB boreholes has been drilled considerably deeper than the optimal strike depths. This tendency to drill considerably deeper has to be ascribed to the fact that even optimal strike probabilities are poor. Generally speaking, better results could have been obtained if drilling had been suspended on reaching the maximum optimal strike depth (had it been known) and resumed at another site. Finally, higher yields do not go hand-in-hand with greater strike depth below water level.

West of the Lephalala River excluding the ambience of the Mokolo, Lephalala and Limpopo Rivers, water levels range between 30 and 70 m below surface. This is considerably deeper than elsewhere. From Swartwater eastwards, water levels range between 5 and 45 m. The piezometric configuration of the Beauty area also differs radically from that of the rest of the Region. Instead of following the topography, the piezometric surface drops below river level as one proceeds away from the Mokolo, Lephalala, and Limpopo Rivers. The depth of weathering is moreover greater than elsewhere in the Region - it may extend locally to as deep as 100 m. The deeper piezometric level of the Beauty area not only results from the greater depth and larger storage coefficient of weathered rock but also reflects the dynamic balance between groundwater recharge and loss. Loss is presumably almost totally through groundwater outflow to a low-lying area that is situated a considerable distance beyond the confines of the Beauty area. Here conceivably dispersed discharge through evapotranspiration would escape notice. The occurrence of thermal water at various places within the Region lends support to the idea of deeper and longer groundwater flow paths.

Barring the Beauty area, the piezometric surface manifestly mirrors that of the surface in the rest of the region. In contradistinction to the Beauty area, most of the groundwater flow here appears to be shallow and restricted to its surface catchment.

Brittle tectonic deformation, weathering and unloading are the agents responsible for the development of openings in rocks of the Limpopo Mobile Belt. Unless faults, dykes, dyke and formational contacts are weathered and/or fractured to below water level, they do not act *ipso facto* as aquifers. Although composition and texture determine the extent to which different rock types are affected by these processes, local variability and conditions do not allow a clear-cut lithological classification in terms of water-bearing properties. The supracrustal rocks of which metaquartzite perhaps should be singled out, seem more favourable targets, than the granite gneiss.

Borehole siting

Hydrogeological and geophysical siting of boreholes in the Beauty and Swartwater areas has shown that the probability of striking water is greatest :

- where weathering extends to below the piezometric level;
- where the depth of weathering and of the piezometric surface does not exceed 40 m; and
- in the first 10 m below the piezometric level.

The development of impermeable smectite instead of kaolinite and/or illuviation of fractures may be the reason for the poor results where weathering and piezometric levels are deeper than 40 m owing to a change with depth in the chemical composition of water and consequently of the hydrochemical reactions.

Evidence for the alleged successful application of neotectonic stress analysis in the Swartwater area for the siting of boreholes has been found unconvincing:

- Two lineament interpretations of the area are widely different.
- Successful boreholes up to 150 m distant from lineaments are assumed as proof. Boreholes plotted even much farther away on the map are cited in evidence.
- Inaccuracies in the location of lineaments and boreholes on the ground.

Favourably oriented lineaments that have been identified through stress analysis using satellite imagery and aerial photography have to be located accurately on the ground by means of geophysical techniques. At least several traverses should be run in order to confirm that lineament and geophysical indication coincide and have the same strike.

As depth of weathering and fracturing generally cannot be deduced from surface indications, the following geophysical techniques have to be employed:

- In the absence of exposures magnetometer traversing to establish the presence and position of dykes
- Electrical depth probing for locating and determining depths of basins and troughs of weathering. Constant electrode separation profiling is a reconnaissance technique that has to be followed by depth probing
- Frequency domain electromagnetic surveying for locating narrow linear zones of weathering/ fracturing.

  Its successful application by the Directorate of Geohydrology thus far has suffered from inadequate interpretation and an improper conception of the nature, form and depth extent of the bodies producing the EM anomalies.

Experimental seismic refraction work has not proven its superiority to geo-electrical methods as an exploration tool in Region 3. Its alleged capability of locating faults within bedrock coupled with the drilling of inclined boreholes has not been demonstrated. Although different properties of the subsurface are measured by the two methods, interpreted bedrock profiles resemble each other fairly closely. The high cost of the seismic refraction method and the transport, storage and handling of explosives count heavily against its use.

As dip, width and hydrogeological nature of two-dimensional electrical conductive features are generally unknown, especially its changing character with depth, drilling requires careful geological monitoring and geophysical borehole logging. Several closely spaced boreholes may have to be drilled in order to penetrate the structure at a depth below water level where it is sufficienly permeable to yield a usable supply of water.

Neglect to test pump boreholes after they have been subjected to hydrofracturing procedures have left a big question mark about the technique's worth as a tool for converting failures into successful boreholes. During hydrofracturing, pump-in pressures should be recorded continuously. Surging and chemical treatment should also be tested as a means of salvaging not only newly-drilled but also old weakened boreholes.

Groundwater levels, recharge and depletion

The limited volume of groundwater in storage that can be drawn on by a borehole and the irregularity of recharge recurrence are evident from:

- the weakening and drying-up of boreholes during droughts;
- rest level drops of up to 20 m and more that have been recorded in the vicinity of pumped holes.

Declining borehole yields and water levels do not necessarily indicate permanent and regional lowering of the water level. In the area west of the Lephalala River some water levels were several metres higher and others several metres lower in 1987/88 than during the early fifties. In two areas cleared of bush during the fifties, water levels were 5.6 to 17 m higher. On the other hand, the known cessation of spring flow on several farms, the non-existence of springs coupled with currently deep water levels on farms bearing names ending with the suffix "fontein" may be cited as evidence of gradual imperceptible environmental changes, perhaps through bush encroachment. Water levels rise significantly only during periods of high rainfall. Brief recharge periods are followed by lengthy periods of water level decline.

Groundwater quality

The total dissolved solids content of groundwater ranges between 500 and 2000 mg ℓ^{-1}. The main hydrochemical types are (Ca, Mg) $(HCO_3)_2$ and (Ca, Mg)Cl_2. More than 50% of groundwater samples analysed were found to be unsuitable for human consumption mainly as a result of high nitrate and fluoride concentrations.

Recommendations for further studies

1. In view of poor drilling results, especially in the Beauty area but also elsewhere in the Region, the methodology of siting boreholes and the hydrogeological control of drilling operations is in need of a thorough revision and overhaul. This applies particularly to the use and interpretation of geophysics. Unproductive deep drilling should be eliminated.
2. The role of surging, chemical treatment and hydrofracturing in the development and salvaging of boreholes.
3. Additional exploratory drilling at sites on Kaffersfontein and Wellust discussed in Chapter 4.
4. Hydrogeological study of alluvial deposits aimed at determining their extent, water-bearing properties, inter-relationship with riverflow , exploitability.
5. A study of the water-bearing properties of hard-rock as determined by:
   a) fracturing in relation to the neotectonic stress field and
   b) geochemical processes, hydrochemistry and products of weathering
6. Elucidate groundwater flow regime and discharge - what are the conduits, where and in what form is discharge.
7. Infiltration - modes of water movement through zone of aeration; moisture content and loss through evapotranspiration.
8. Water consumption by Bushveld vegetation; identification of facultative and obligate phreatophytes.
9. Recharge - its temporal and volumetric variability and its relation to rainfall.

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1. INTRODUCTION

1.1 LOCATION AND EXTENT

The Region - a lenticularly shaped, north-easterly trending belt, situated in the Northern Province - is about 375 km long, measures about 60 km at its widest and is about 13 910 km^2 in extent (see Figure 1, **back of report**). Its northern boundary is the Limpopo River, from Stockpoort 1 LQ in the west to Eendvogelpan 3 MS on the 29^{th} degree longitude in the east. Between Eendvogelpan and Overvlakte 125 MS, 29° 40' E (also situated on the Limpopo), the boundary swings away from the river and is formed by overlying Karoo strata (Region 4). From Overvlakte onwards, the Limpopo River is once more the boundary past 31° longitude, to just short of Mabiligwe.

The Region is bounded on the south between Stockpoort 1 LQ and Pretoria 483 LQ by the Waterberg Coal Basin (Region 2). The contact between the overlying Karoo rocks and the rocks comprising Region 3 runs east as far as Afgunst 143 LQ where it turns due south to Pretoria 483 LQ. From here the boundary again strikes east to just west of Marken where it swings northwards to the Melinda fault on Boekenhoutsfontein 108 LR, thus encircling rocks of the Bushveld Complex and the Palala Shear zone. Between Boekenhoutfontein and Leno 252 LR, which is situated north of Blouberg, the ENE trending Melinda Fault, is the boundary. Rocks belonging to the Waterberg Group (Region 6) lie south of the boundary between Pretoria 483 LQ and Leno 252 LR. From Leno the boundary swings sharply back in a WNW direction to Sofala 160 MR to encircle Karoo lava and sedimentary rocks of Region 5 before continuing in an east-north-easterly direction to the Limpopo River just past 31° longitude.

TABLE 1 FARMS AND THEIR NUMBERED LOCALITIES IN FIGURE 2 (back of report)

Farm name and number	Number on figure	Farm name and number	Number on figure
Afgunst 143 LQ	12	Longford 354 MS	29
Beck 568 MS	32	Manchester 244 MR	19
Beckman 139 MT	34	Oudenbosch 146 LQ	11
Bellevue 74 LQ	3	Overvlakte 125 MS	30
Boekenhoutfontein 108 LR	14	Pretoria 483 LQ	13
Breda 147 LQ	10	Retief 290 LR	23
Coila 58 MS	28	Richmond 492 MS	31
Dansfontein 40 LR	21	Riversdale 340 MS	27
Eendvogelpan 3 MS	24	Sofala 160 MR	20
Fairfield 154 LQ	9	Solitude 111 MT	33
Grootpan 90 LQ	7	Stockpoort 1 LQ	1
Grootvley 165 LQ	5	Taaiboschgroet 24 MR	25
Hardevlakte 152 MT	35	Theuniskloof 164 MR	16
Kaffersfontein 135 LQ	8	Umbilo 178 MR	17

TABLE 1 (continued)

Koperfontein 161 MR	15	Waterval 123 LQ	4
Kwarriepoort 226 LR	22	Wellust 73 LQ	2
Landsdown 227 MR	18	Witdrift 41 LQ	6
Leno 252 LR	26		

Over this distance the contact between the Swazian rocks of Region 3, and the Karoo rocks to the south is largely determined by faulting. It is however ill defined between Taaiboschgroet 24 MS and Riversdale 340 MS owing to a cover of sand (Taaibos fault). The Vetfontein fault is the boundary from Riversdale to the northern part of Harde Vlakte 152 MT. The Tshipise fault forms the boundary from the southern part of Harde Vlakte east-north-eastwards as far as the south-western portion of Solitude 111 MT. From here the boundary reverses west southwestwards along the contact with Karoo strata to Longford 354MS - a distance of about 90 km. From Longford the boundary swings northeastwards, following a fault which joins up with the east-north-easterly trending Bosbokpoort fault. The latter continues all the way to the Limpopo River.

1.2 PHYSIOGRAPHY

Region 3 is traversed from south to north by the lower reaches of the following major tributaries of the Limpopo River, from west to east: the Mokolo, Lephalala, Mogalakwena, Kolope, Sand and its tributary the Brak, the Nzhelele and the Nwanedzi Rivers. It consists accordingly of the lower portions of drainage regions A4, A5, A6, A7 and a narrow strip along the Limpopo River, part of drainage regions A8 and A9. From Stockpoort in the west to Mabiligwe in the east the Limpopo drops from about 800 to just less than 300 m above sea level.

The greater part of Region 3 lies at an elevation of between 850 and 600 m a.m.s.l. The main exceptions are:

- The watershed between the Lephalala and Mogalakwena Rivers which rises southwards from the Swartwater - Maasstroom road to over 950 m a.m.s.l.
- A strip about 20 km wide along the Limpopo River between Overvlakte and Messina, which lies below 600 m a.m.s.l.
- The valley of the Sand River which lies below 600 m a.m.s.l.
- That part of Region 3 east of Messina.

West of Messina Region 3 is a monotonous flat to gently undulating bush-clad expanse occasionally broken by hills consisting of Swazian metaquartzite and magnetite quartzite. The more important of these are:

- The Rustenburgkop between the Mokolo and Lephalala Rivers;
- The Vlieërante southeast of Swartwater;
- The Madiapala hills and the Dwarsberge respectively some 20 km north and south of the Maasstroom - Alldays road; and west of the Mogalakwena River;
- The Ga-Mogale hills north-northwest of Alldays.

Outliers of Soutpansberg quartzite build the Rooirant and hills on Dansfontein 40 LR, Kwarriepoort 226 LR and Retief 290 LR. Sheared quartzitic sandstone, shaly rocks, schist and conlomerate build the prominent Koedoesrand to the southwest of Baltimore. Partridge and Maud (1987) have classified the surface of this western half of Region 3 as undifferentiated Post-African.

Further eastwards the topography becomes more varied - the country being characterised by rolling hills and ridges such as Maselele, Kitchener and Bloukop respectively northwest, west and northeast of Mopane and those in the vicinity of Messina. Boulder-strewn ridges and dome-shaped hills around Messina are formed by Singelele granitoid gneiss. Marble stands out in hills along the Nzhelele on Beckman 139 MT. Partridge and Maud (1987) designate the surface of this part as dissected and of indefinite age.

As is evident from published geological maps, rock is poorly exposed west of 29° 10' except for a strip of variable width adjoining the Limpopo River. Although not shown on topocadastral maps, pans 50 to 200 m in diameter abound in the west (Visser 1952).

1.3 CLIMATE AND RAINFALL

The climate is semi-arid subtropical; the summers are very hot whilst the winters are mild. The Region enjoys summer rainfall that tends to be erratic. Mean annual rainfall varies from between 425 mm in the vicinity of Beauty in the west to about 300 mm in the east. According to the ACRU model (Schultze 1989), mean effective rainfall ranges from 360 to 260 mm per annum.

1.4 VEGETATION

The biome is Savanna according to Rutherford and Westfall (1986) and Low and Rebelo (1996). Mopane Bushveld is found east of a line joining Baines Drift on the Limpopo and Vetfontein to the southeast. To the west Arid Sweet Bushveld occupies the lower-lying ground bordering on the Limpopo and in the Lephalala and Mogalakwena River valleys, whilst Mixed Bushveld occurs on the higher-lying ground south of Swartwater between the latter two rivers (Acocks 1953; Low and Rebelo 1996).

1.5 ROLE OF GROUNDWATER IN THE REGION'S ECONOMY

Except for the larger rivers, which do not necessarily have year round flows, Region 3 is practically solely dependent on groundwater. In the absence of all but a few small springs, groundwater for urban and rural use has to be tapped by means of boreholes and in and along the rivers by wells or wellpoints.

- On farms, groundwater is required for household use and cattle and game ranching.
- Messina obtains its supply from wells in the sand of the Limpopo River and also from boreholes alongside the Limpopo River. The defunct Campbell Mine is used for storing river water when available.
- Villages in the Mokorong 1 District and the northern end of the Lebowa District, and small communities such as Mopane are dependent on groundwater.

Alldays, however, is supplied from boreholes drilled in Karoo lava and sedimentary rocks south of and outside the Region. This is also the case with Venetia Diamond mine which, obtains its supply from boreholes in alluvial deposits along the Limpopo River on Greefswald situated outside Region 3.

According to a survey conducted in 1969 by Rech (1970) about 670 ha were being irrigated from open water and wellpoints along the Mokolo River and just over a 1000 ha along the Lephalala River between Sarah Bell 174 LR and the confluence with the Limpopo River. Upstream from Sarah Bell 174 LR as far as Overyssel 512 LR over 500 ha were being irrigated. (Both not indicated on Figure 2. Sarah Bell is situated at the boundary between the Swazian and younger rocks to the south. Overyssel lies at the boundary of Region 3).

Prospects for abstraction by means of wellpoints exist on a number of farms along the Limpopo River. Irrigation along the stretch from Stockpoort 1 LQ to Kruidfontein 1 MR (not shown on Figure 2; adjoins Eendvogelpan 3 MS on the south) is, however, limited to a few farms. They are not indicated in Figure 2. They are, according to a survey conducted by the Directorate of Geohydrology in the late eighties, Charlestown 115 LQ (about 30 km downstream of Stockpoort), Klippan 25 LQ and adjoining Eersteling 138 MR just west of 28° longitude.

Some 180 ha on 10 farms centred on Bristol 17 LR about 20 km south of Swartwater are irrigated with groundwater (Blecher 1993).

2. GEOLOGY

Polymetamorphosed and highly deformed Archaean supracrustal and intrusive rocks occupy most of Region 3. The exceptions are:

- The Koedoesrand Formation north of the Abbots Poort fault
- Bushveld gabbro and granite south of Abbots Poort (on the Lephalala River)
- A few outliers of Soutpansberg quartzitic sandstone (e.g. the Rooirant)
- A strip of down-faulted Karoo strata northwest of Mopane
- Outliers of Karoo Sequence sedimentary rocks, 10 to 20 km west of Baltimore and directly north of the Melinda fault.
- Tertiary and Quaternary deposits in the form of river terrace gravels, sand, calcrete, ferricrete etc. With the exception of alluvium along certain river stretches, they do not feature as water-bearing formations.

As this paper is concerned with groundwater in rocks of the Limpopo Mobile Belt, further attention will not be given to them.

2.1 MESSINA SURROUNDINGS

The Archaean rocks are part of the Central Zone of the Limpopo Belt or Metamorphic Province which is situated between the Zimbabwean (Rhodesian) and Kaapvaal cratons and which straddles eastern Botswana, southern Zimbabwe and the Northern Province of South Africa.

TABLE 2 LITHOSTRATIGRAPHY OF THE MESSINA AREA

(Kent 1980; Brandl 1981)

	Lithostratigraphic unit	Lithology
	Bulai Gneiss	Grey porphyroblastic biotite gneiss of tonalitic composition
Beit Bridge Complex	Messina Suite	Meta-anorthosite and leucogabbro, metagabbro, serpentinite, metapyroxenite, hornblendite
	Gumbu Group	Marble, calc-silicate rock
	Malala Drift Group	Leucogneisses with intercalations of hornblende gneiss and metaquartzite
	Mount Dowe Group	Quartzo-felspathic gneiss, metapelite, amphibolite, mafic granulite, metaquartzite, magnetite quartzite, leucocratic gneiss

Sand River Gneiss		Migmatitic grey and leucocratic gneisses - hypersthene-bearing of grano-dioritic composition

Its lithostratigraphy as determined in the Messina area is given in Table 2. The table does not necessarily reflect the correct and latest age relationships.

According to Brandl (1981) the Sand River Gneiss was thought to be of sedimentary origin. Further, it was believed that this unit or part of it formed the basement on which the supracrustal rocks of the Beit Bridge Complex were deposited. The Beit Bridge Complex embraces a succession of supracrustal rocks into which the Messina Suite and Bulai Gneiss intruded. The order of succession of the supracrustal Groups is speculative.

Subsequent work on the field relationships of mid- and late Archaean high-grade gneisses of igneous and sedimentary parentage has shown that the supracrustal rocks of the Beit Bridge Complex are intruded by tonalitic to granodioritic protoliths of the Sand River Gneiss (Hofmann, Kroner and Brandl 1998).

2.2 KOEDOESRAND AREA

The Archaean lithologies in the Koedoesrand area south of 23° latitude (McCourt 1983) are given in Table 3. The Palala Shear Zone is assumed to mark the boundary between the Central and the Southern Marginal zones of the Limpopo Belt. The 10 km-wide shear zone consists of a northernmost sub-zone consisting of Palala granite, mylonite and ultramylonite, a central core of various mylonitized gneisses and a southern sub-zone of sheared and mylonitized Palala granite. The shear zone is exposed over a distance of about 30 km. Towards the east it is hidden under recent deposits of Waterberg rocks and towards the west by Karoo strata.

TABLE 3 ARCHAEAN LITHOSTRATIGRAPHY KOEDOESRAND

(McCourt 1983)

	Lithostratigraphic unit	**Lithology**
	Palala Shear Zone	Very fine-grained siliceous rocks containing amphibole and feldspar; hypersthene and garnetiferous gneisses; quartz-sericite and chlorite schists; sheared and mylonitised Palala granite
	Mogalakwena Gneiss	Grey biotite gneiss containing enclaves of amphibolite and paragneiss

Beit Bridge Complex	Messina Suite	Serpentinite, meta-pyroxenite, meta-anorthosite
	Gumbu Group	Marble and calc-silicate rocks subordinate amphibolite, meta-quartzite and paragneiss
	Mount Dowe Group	Meta-quartzite, magnetite quartzite and subordinate paragneiss, amphibolite and mafic granulite

Region 3 also includes quartzite and conglomerates, designated the Koedoesrand Formation (stratigraphic position unknown), the Villa Nora Gabbro and the Nebo Granite of the Bushveld Complex, all three of which occur south of the Palala Shear Zone.

2.3 BROMBEEK - LINTON AND MAASSTROOM AREAS

In the course of mapping an area around Brombeek and Linton west of 29° 30' and a second area around Maasstroom further west, Pretorius (1993) recognised three principal associations in the highly metamorphosed supracrustal rocks:

- a siliciclastic sedimentary sequence
- a mainly chemical precipitation sequence, and
- a chert-iron formation and mafic lava association.

Grey biotite gneiss of tonalitic composition, named the Alldays Gneiss was found to be intrusive, probably in *lit-par-lit* fashion, in the supracrustal rocks of the Beit Bridge Complex. Both the supracrustal rocks as well as the Alldays Gneiss have been intruded by anorthositic gneiss and ultramafic rocks which are taken to be part of the Messina Suite.

2.4 WEST OF LONGITUDE 28°

West of 28° longitude the supracrustal rocks have been subdivided into the same three Groups as around Messina (Brandl 1996). The field relationship between the supracrustal rocks and a dark grey migmatitic gneiss, termed Alldays Gneiss, of which only a few occurrences have been mapped, is not known, but it is assumed to be intrusive on the strength of evidence elsewhere. The Messina Suite consisting of metagabbro, meta-anorthosite, serpentinite and hornblendite is also present here.

In addition to these units, Brandl (1996) reports the existence of a variety of younger intrusive rocks in a 5 km wide zone mainly west of the Mokolo River. These rocks collectively termed the Constantia Suite consist of pyroxenite, leucocratic gneiss, syenite, augen gneiss, various granites, pegmatite and aplite.

2.5 DYKES

Younger intrusions in Region 3 are in the form of east-west striking granite dykes, pegmatites and diabase dykes that generally strike east-northeast and west to west-northwest. Post-Karoo dolerite dykes appear to be comparatively scarce, perhaps because they seldom produce positive relief features and are therefore not easily identified on aerial photographs.

2.6 METAMORPHISM AND DEFORMATION

Rocks of the Limpopo Belt have been subjected to granulite-grade metamorphism during an extended period of deep regional burial, followed by retrograde metamorphism as a result of regional uplift.

The history of ductile and brittle deformation is rather complex. In the Messina area four major tectonic events have resulted in a complex pattern of interference folds (Brandl 1981; Barton et al. 1979). McCourt (1983) recognised three deformational episodes in the Koedoesrand area. Refolding during the third event of the isoclinal folds that were produced during the first two, resulted in typical dome-and-basin structures. West of longitude 28° the Beit Bridge lithologies display linear easterly trends, tight isoclinal folds or oval-shaped closed structures. Gneisses of the Constantia Suite were deformed into open to isoclinal folds with east-west trending fold axis (Brandl 1996). In the Swartwater area Pretorius (1993) recognised three fold events. Elongated dome and basin interference structures were formed during the first two events about NW and NE trending axial planes. Open folds along NE trending planes were superimposed on the earlier two during the third event.

Major east-northeasterly trending zones of shearing, faulting and brecciation are present in the Limpopo Mobile Belt. Movement has been reactivated along them from the Archaean to post-Karoo times. Of them the Palala Shear Zone which is taken as the boundary between the Central and Southern Marginal Zones of the Limpopo Mobile Belt is perhaps the most notable. South and parallel to it are the 10 to 20 m wide Beaufort and Abbotts Poort Shear Zones. North and also paralleling the Palala Shear Zone is the Melinda fault. There is evidence south of Blouberg that movement along it commenced during deposition of Waterberg formations. The Waterberg rocks were down thrown to the south in Pre-Karoo times. North of the Soutpansberg the east-northeast trending faults delineate horst and graben structures. Karoo strata occupy the grabens. Main faults of this type have been named the Bosbokpoort, Tshipise and Klein Tshipise.

By analyzing satellite imagery of, and aeromagnetic trends in the Swartwater area (Figure 27), Andersen and Less (1992) identified a dominant direction of faulting with an orientation of 15° and a spread of 10° on either side of this mean. With the maximum horizontal stress oriented northeast, this direction is thought to be one of normal faulting. The next most prominent direction of faulting is 345°. This may be one of right lateral shear. Older strong breccia faulting strikes east-west. To the west on the quarter-million geological sheet Ellisras the trends of linear features inferred from aerial photographs vary from northwest to north.

2.7 TERTIARY AND QUATERNARY DEPOSITS

Tertiary gravel and sand deposits that are commonly calcified build prominent terraces along the Mokolo and Limpopo Rivers. Quaternary deposits consist of calcrete, ferricrete, terrace gravel, soil, red sand and alluvium. Soil and sand blanket the solid geology over large areas.

Data on the thickness, lateral extent and nature of alluvial deposits along the Mokolo, Lephalala and Mogalakwena Rivers are virtually lacking. Because of its clayey nature, alluvium flanking the lower stretch of the Mokolo River is not considered to be an important aquifer. Alluvial deposits along the

Sand, Nzhlele and Nwanedzi Rivers appear to be lacking where they traverse Region 3 (geological sheets 2228 Beit Bridge and 2230 Messina)

According to Brandl (1991), compiler of a map showing their area distribution along the Limpopo River, alluvial deposits are widespread from Stockpoort in the west to the confluence of the Motloutse River, opposite Ratho 1 MS (just east of longitude 29°). The alluvial fill is generally 5 - 6 m thick, but probably does not exceed 10 m. It is made up of dark brown silt with interlayered sand and gravel. In places calcrete bands are present.

Between Stockpoort in the west and Grootwater 29 LQ (a few kilometres downstream of the Lephalala confluence) the Limpopo has a very low gradient (approximately 1:3 500) and is characterised by large and small meanders. Downstream of Grootwater the river gradient increases considerably with concomitant narrowing of the alluvial strip.

3. OCCURRENCE OF GROUNDWATER

3.1 ALLUVIAL DEPOSITS

The main points have been discussed under sections 1,5 and 2.7. For more details De Villiers (1965), Rech (1970), Mulder (1973), Vipond (1980) and Orpen (1987) may be consulted.

3.2 HARD ROCK FORMATIONS

3.2.1. Drilling results

As indicated on the Borehole Prospects map (Sheet No 1 of the National Groundwater Maps) drilling results have been poor. The greater part of the Region has a success rate of less than 40%. The more favourable parts are situated:

a) between longitudes 27° 45' and 28° 40' and latitudes 22° 45' and 23° 15', and
b) south of Region 4, the Limpopo Karoo basin.

TABLE 4 BOREHOLE STATISTICS (NGWDB DATA)

(Region 3 as a whole)	No of holes	Mode	Lower Quartile	Upper Quartile
Borehole depth (m)	3 698	60	<33	>76
Yield $\ell\ s^{-1}$	710	0.12	<0.3	>1.6
Water level depth (m)	2 357	30	<12.5	>34.5

The best results have been recorded east of the Lephalala River, between Beauty and Tomburke – a success rate of greater than 60%. Between 30% to 40% of the successful holes yield more than 2 $\ell\ s^{-1}$. Table 4 is based on the National Groundwater Database as of 1994/95.

Because of its length and small width Region 3 has been divided into four Subregions A, B, C and D as depicted in Figure 3. The drilling success rates in these Subregions are given in Table 5. Figures 4 to 26 depict:

- the water level frequencies;
- the strike frequencies below the surface;
- the strike frequencies below the water level;
- the cumulative water level and strike frequencies and borehole depths;
- the yield - strike depth relationships in Subregions A, B, C and D.

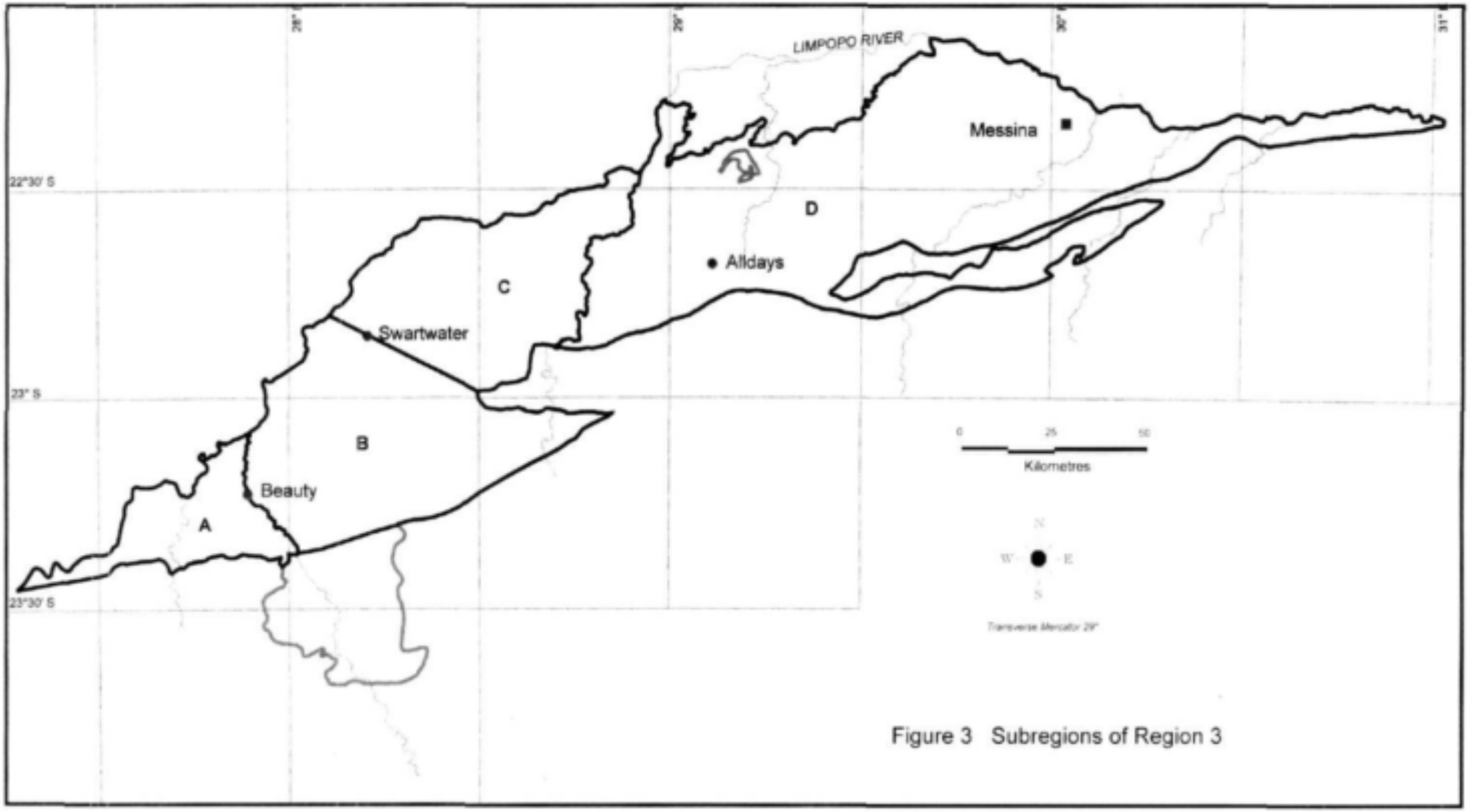


Figure 3 Subregions of Region 3

TABLE 5 DRILLING SUCCESS RATE (NGWDB DATA)

Subregion	Number of boreholes	Percentage of boreholes yielding		
		≥ 0.1 $\ell\,s^{-1}$	≥ 1.0 $\ell\,s^{-1}$	≥ 5.0 $\ell\,s^{-1}$
A water level ≥ 30 m	246	49.2	15.0	0.8
A water level <30 m	210	66.7	29.5	3.3
B	625	41.6	19.2	2.1
C	1227	36.7	15.0	2.4
D	1817	34.3	16.6	2.3

Borehole data of Subregion A has been split into two groups, namely holes with water levels of less than 30 m deep, situated mainly close to the Mokolo, Lephalala and Limpopo Rivers' and holes with water levels 30 m and deeper. These figures are discussed under section 3.2.3: Criteria for siting boreholes.

3.2.2 Hydrogeological investigations

Apart from *ad hoc* borehole siting by the Geological Survey and the Directorate of Geohydrology in the past, several investigations have been undertaken to obtain a better understanding of the occurrence of groundwater and to improve on borehole siting methodology. A considerable amount of work was also done to locate adequate supplies for Alldays and the Venetia diamond mine. This diverted attention away from the basement rocks to the Letaba lava and to alluvial deposits along the Limpopo River (Fayazi and Orpen 1989 and Orpen 1987).

Parts of the Region that received attention are delineated in Figure 27.

1) Farms in the Beauty area west and east of the Lephalala River (van Eeden and Steyn 1961 - the investigation was conducted mainly during the early fifties);
2) Farms situated between Tshipise - Mopane; Mopane - Pontdrif and Messina - Malala Drift (Fayazi et al. 1981);
3) Availability of groundwater around Alldays (Orpen et al. 1982)
4) Beauty (west of the Lephalala River only) and Swartwater areas (Bush 1989; Du Toit 1989 and 1990; Andersen and Less 1992)
5) De Villiers (1971) reported on recharge of groundwater by means of earth dams.
6) Vegter (1993 and 1995) discussed the effect of bush clearing in the vicinity of Beauty on groundwater recharge.

3.2.3 Criteria for siting boreholes

The problem of siting boreholes and establishing criteria for success may be looked at from different angles. Apart from statistical analyses of NGWDB data, information, data and findings of the above-mentioned reports have been recalculated reworked and processed. The results are summarized below.

3.2.3.1 Water level and strike statistics

Statistical data are presented in Figures 4 to 26 as follows:

FIGURE 4 WATER LEVEL FREQUENCY SUBREGION 3A-1
(water level deeper than 30 m)

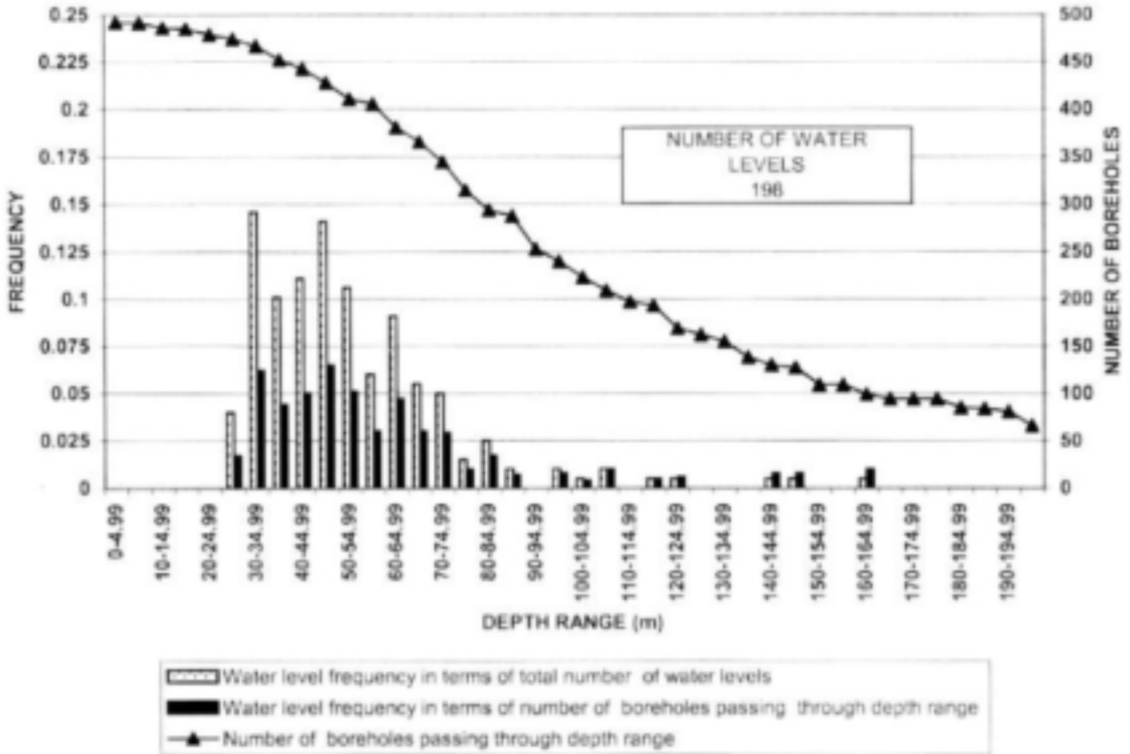


FIGURE 5 STRIKE FREQUENCY BELOW SURFACE
SUBREGION 3A-1 (water level deeper than 30m)

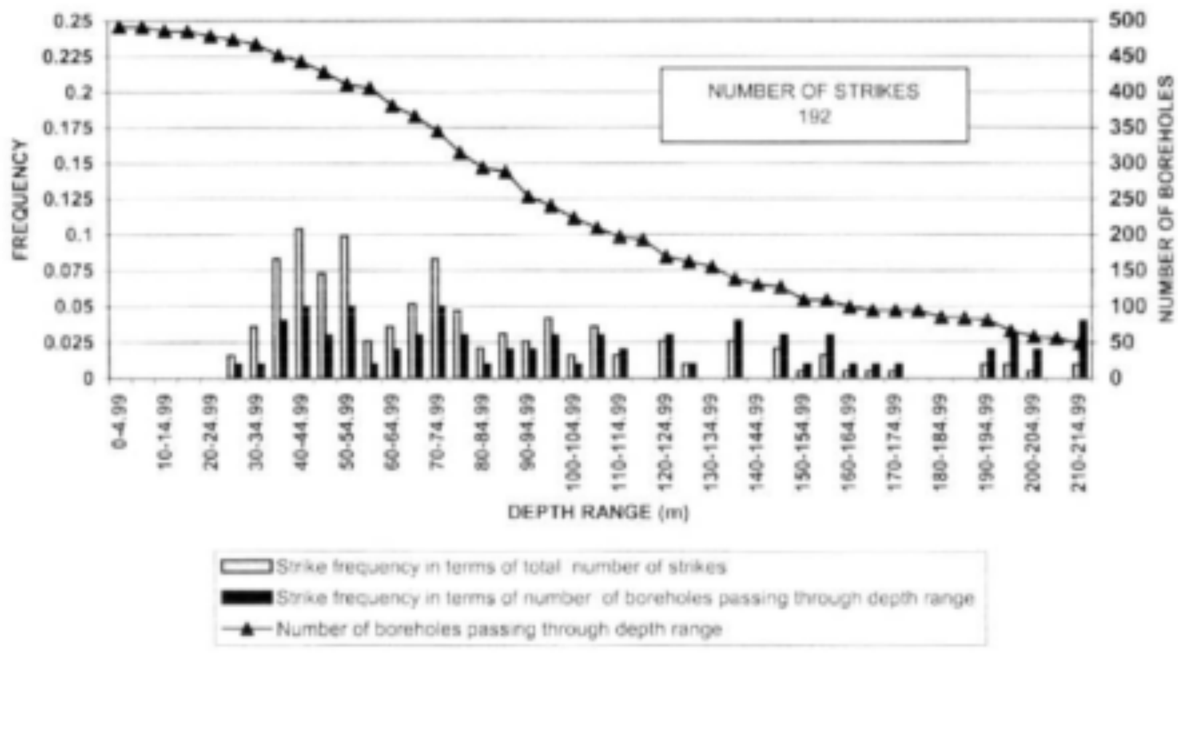


FIGURE 6 STRIKE FREQUENCY BELOW WATER LEVEL SUBREGION 3A-1
(water level deeper than 30 m)

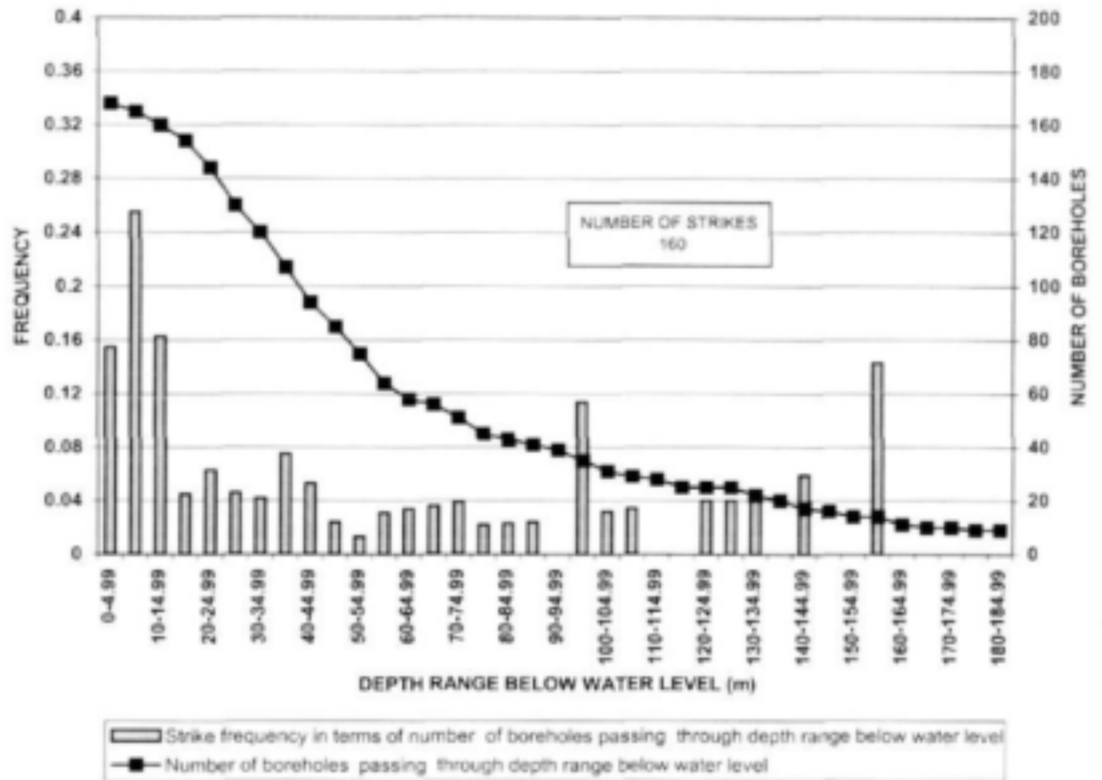


FIGURE 7 CUMULATIVE DISTRIBUTIONS OF WATER LEVELS, STRIKES AND METRES DRILLED
SUBREGION A-1 (water levels deeper than 30 m)

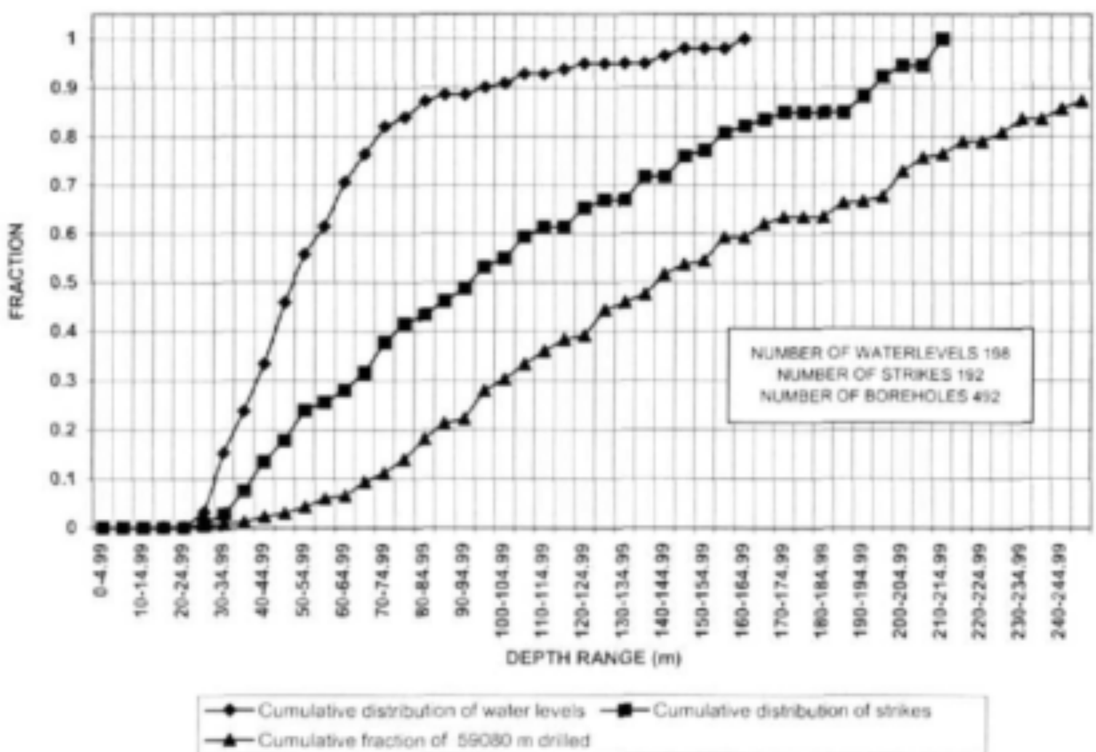


FIGURE 8 RELATIONSHIP: YIELD - STRIKE DEPTH BELOW WATER LEVEL SUBREGION 3A-1 (water level deeper than 30 m)

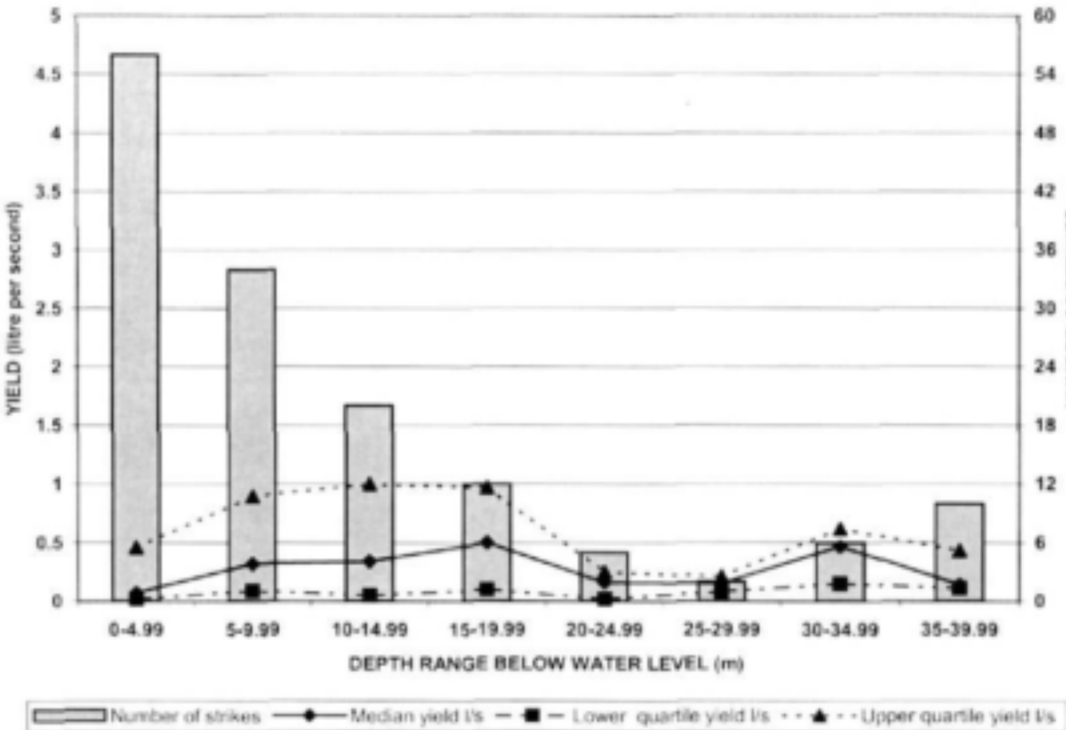


FIGURE 9 WATER LEVEL FREQUENCY SUBREGION A-2 (water level less than 30 m)

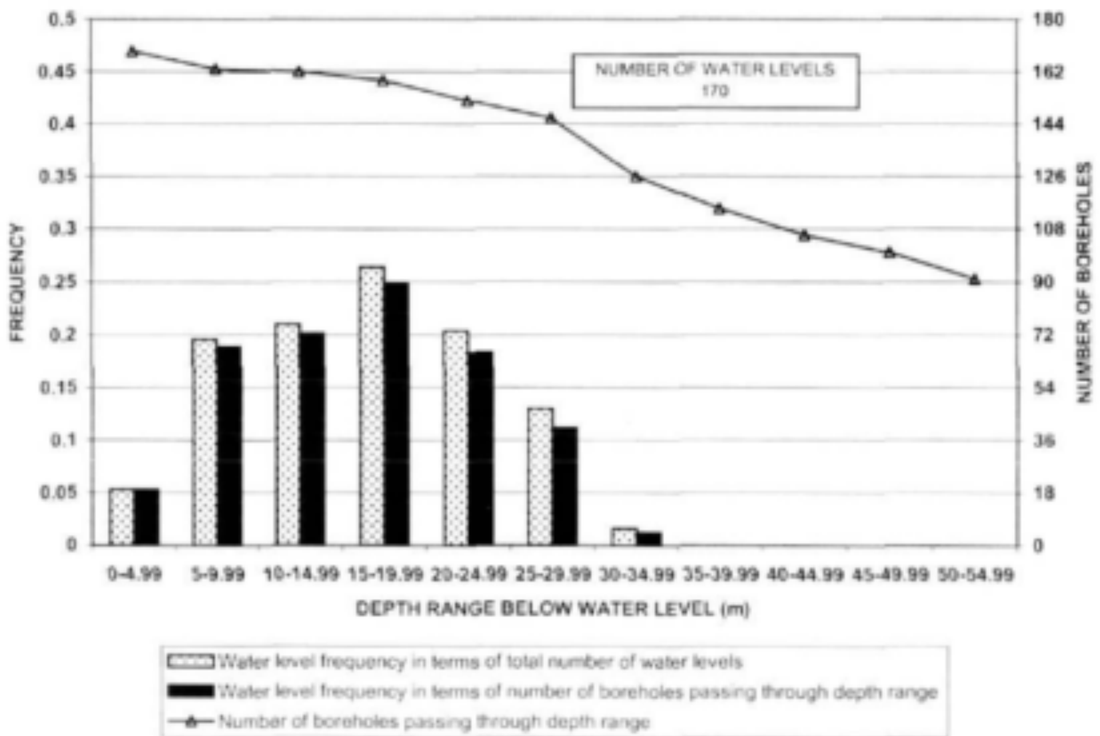


FIGURE 10 STRIKE FREQUENCY BELOW SURFACE SUBREGION A-2
(water level less than 30 m)

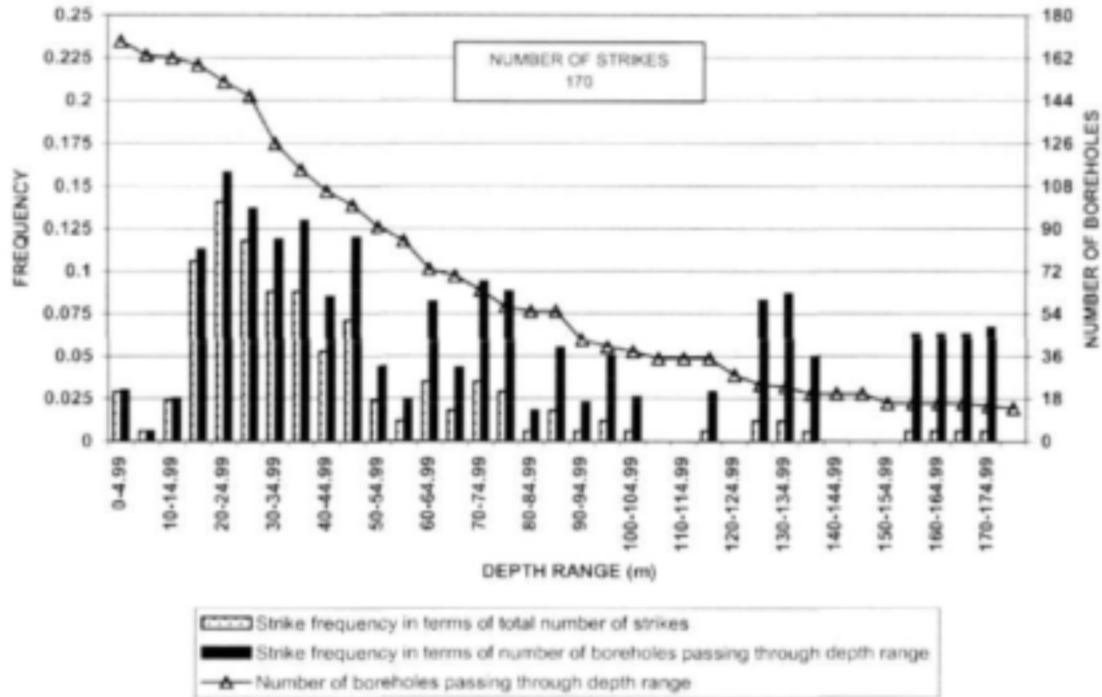


FIGURE 11 CUMULATIVE DISTRIBUTIONS OF WATER LEVELS, STRIKES AND METRES DRILLED
SUBREGION A-2 (water levels less than 30 m)

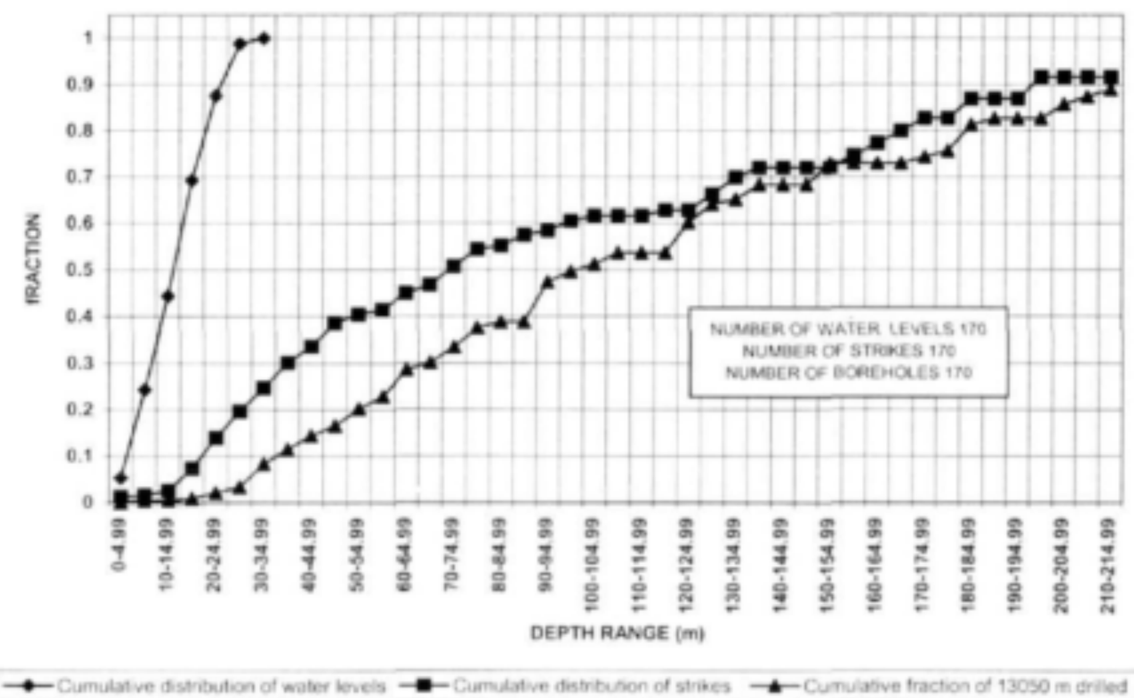


FIGURE 12 WATER LEVEL FREQUENCY SUBREGION 3B

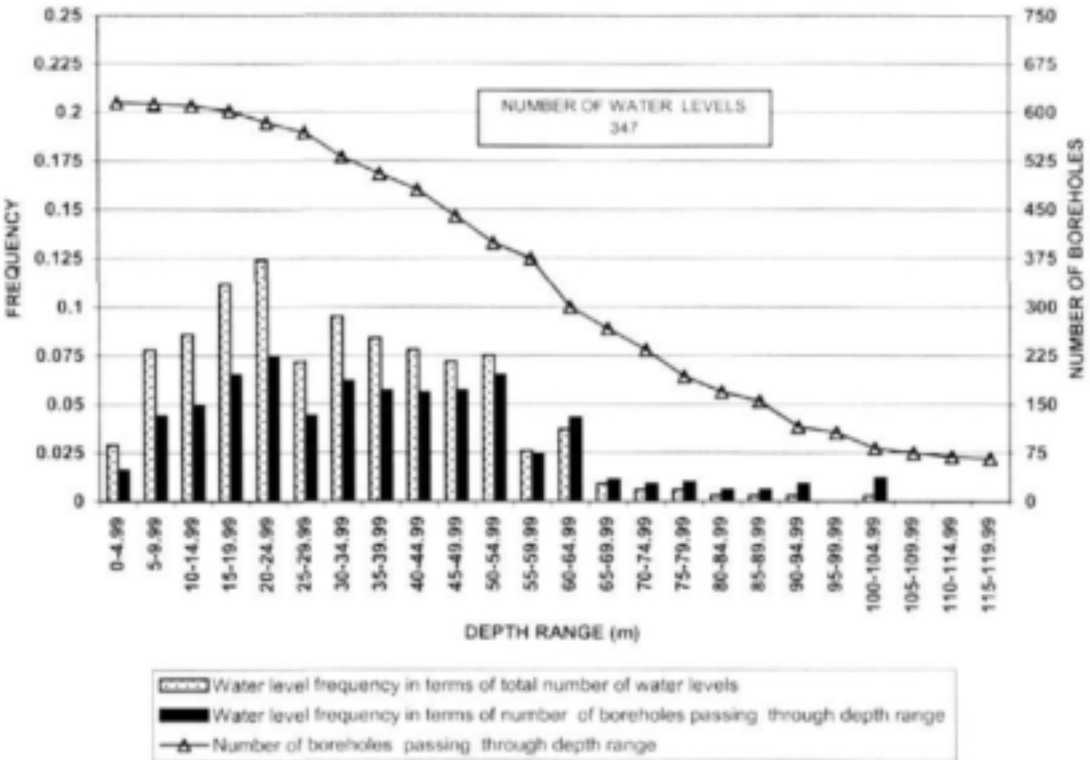


FIGURE 13 STRIKE FREQUENCY BELOW SURFACE SUBREGION 3B

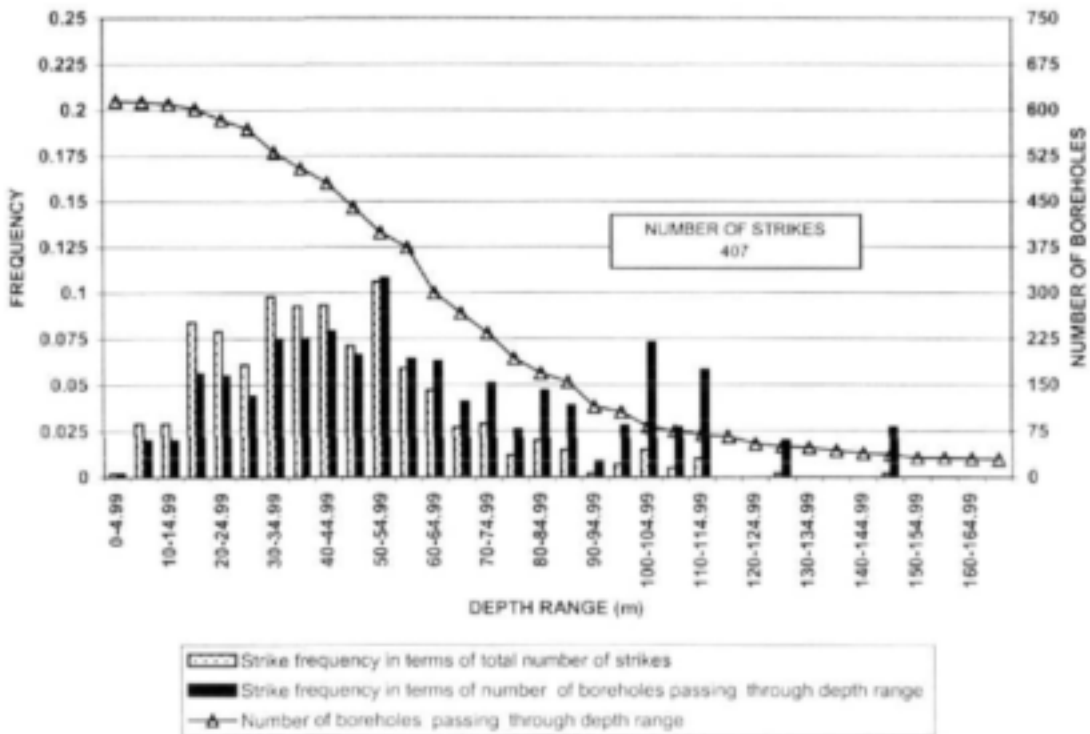


FIGURE 14 STRIKE FREQUENCY BELOW WATER LEVEL
SUBREGION 3B

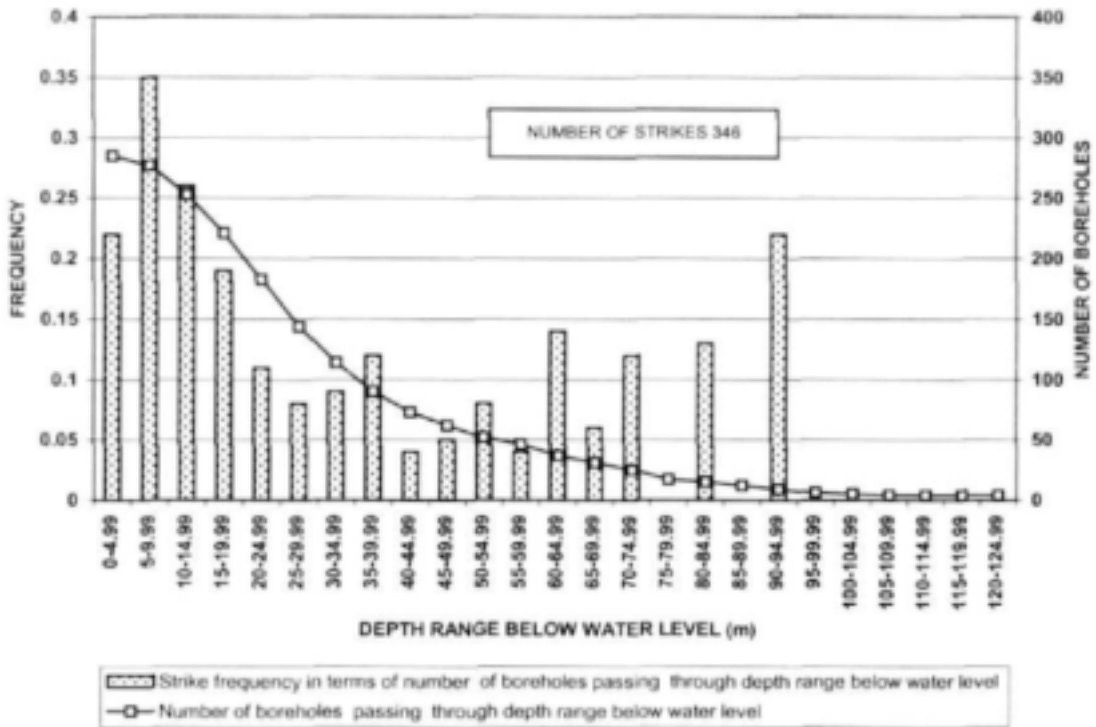


FIGURE 15 CUMULATIVE DISTRIBUTIONS OF WATERLEVELS, STRIKES AND METRES DRILLED
SUBREGION 3B

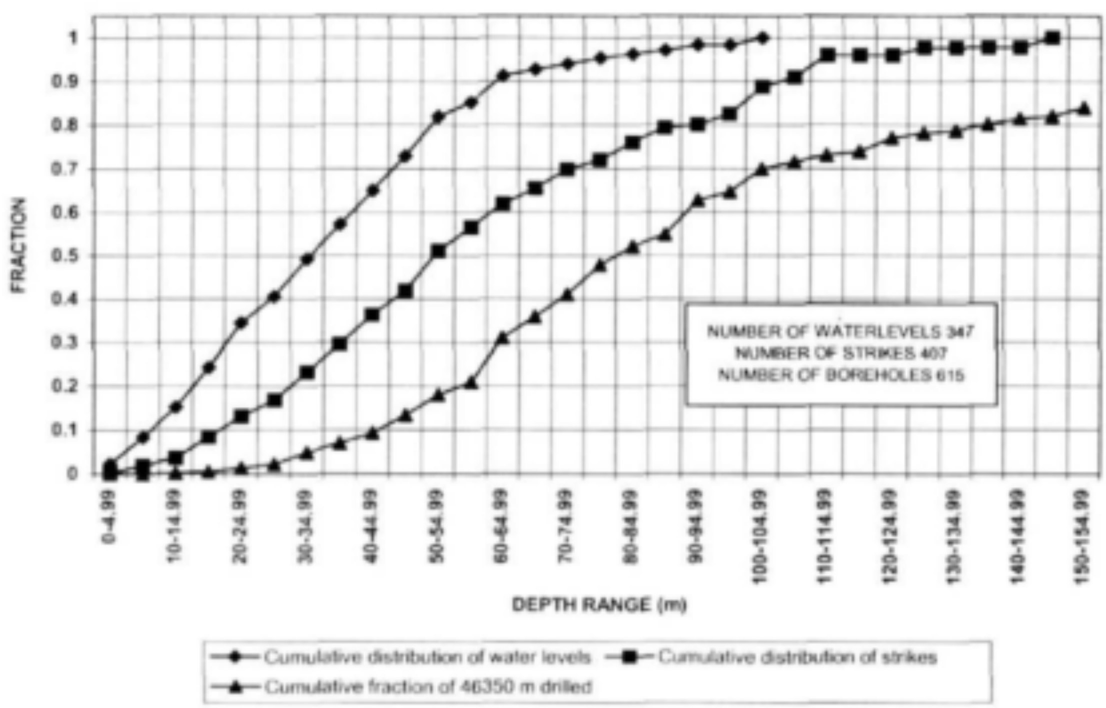


FIGURE 16 RLATIONSHIP YIELD - STRIKE DEPTH BELOW WATER LEVEL
SUBREGION 3B

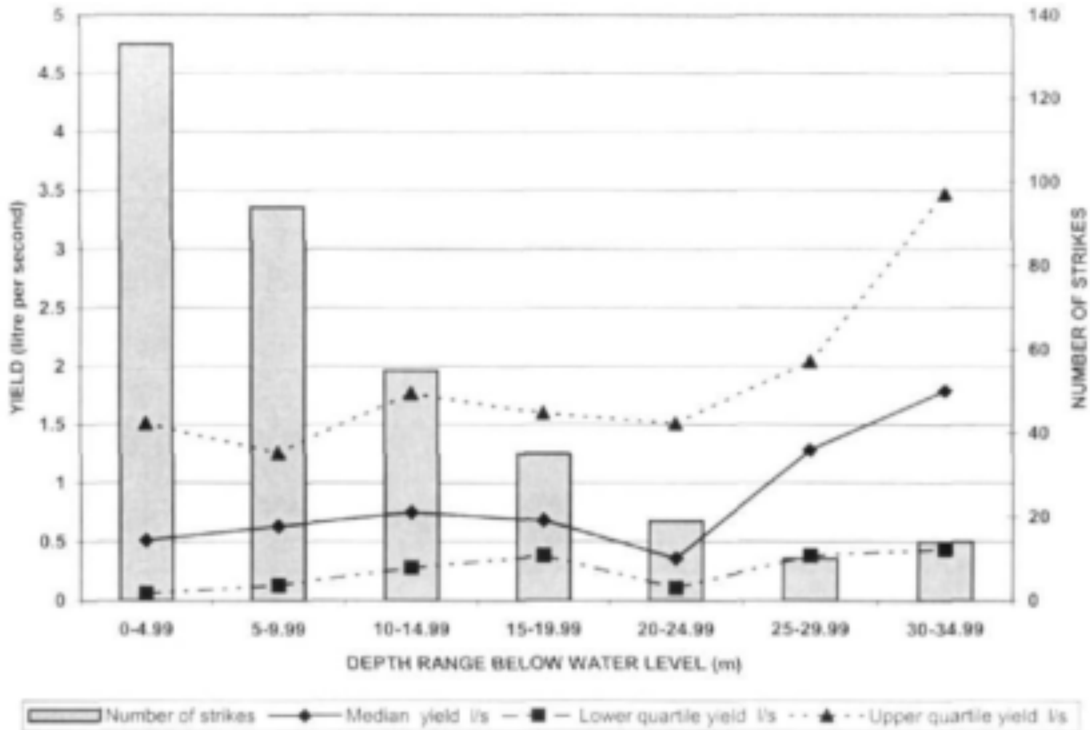


FIGURE 17 WATER LEVEL FREQUENCY SUBREGION 3C

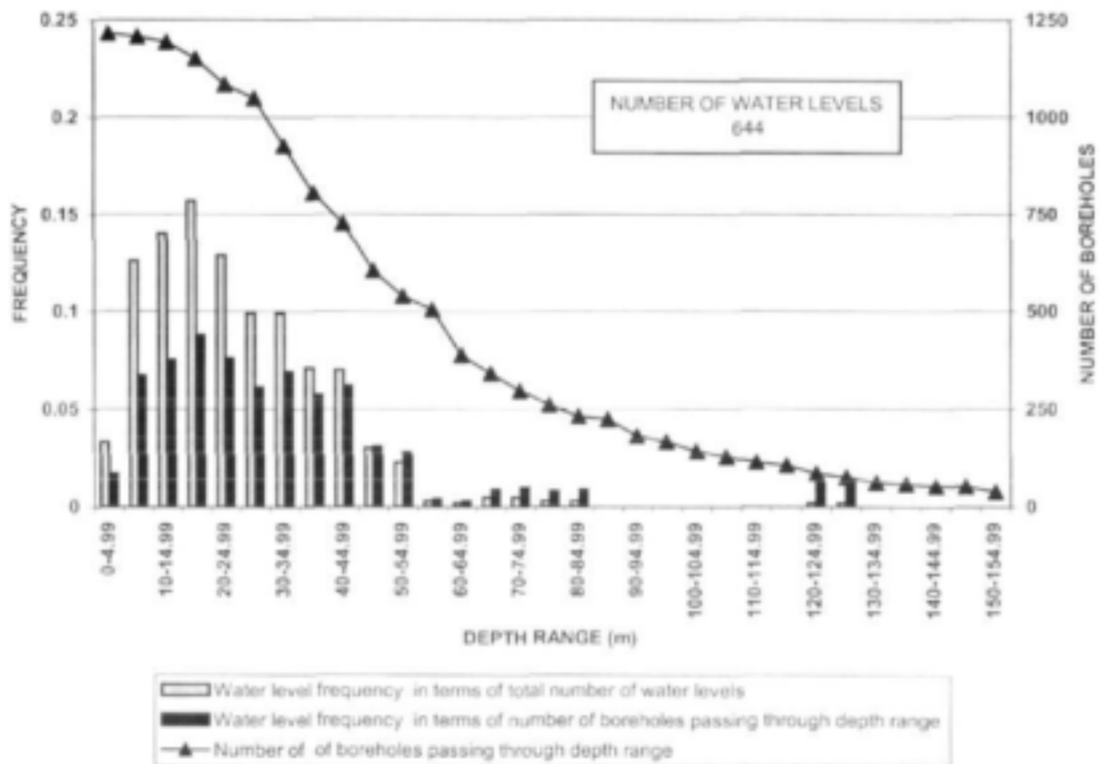


FIGURE 18 STRIKE FREQUENCY BELOW SURFACE SUBTEGION 3C

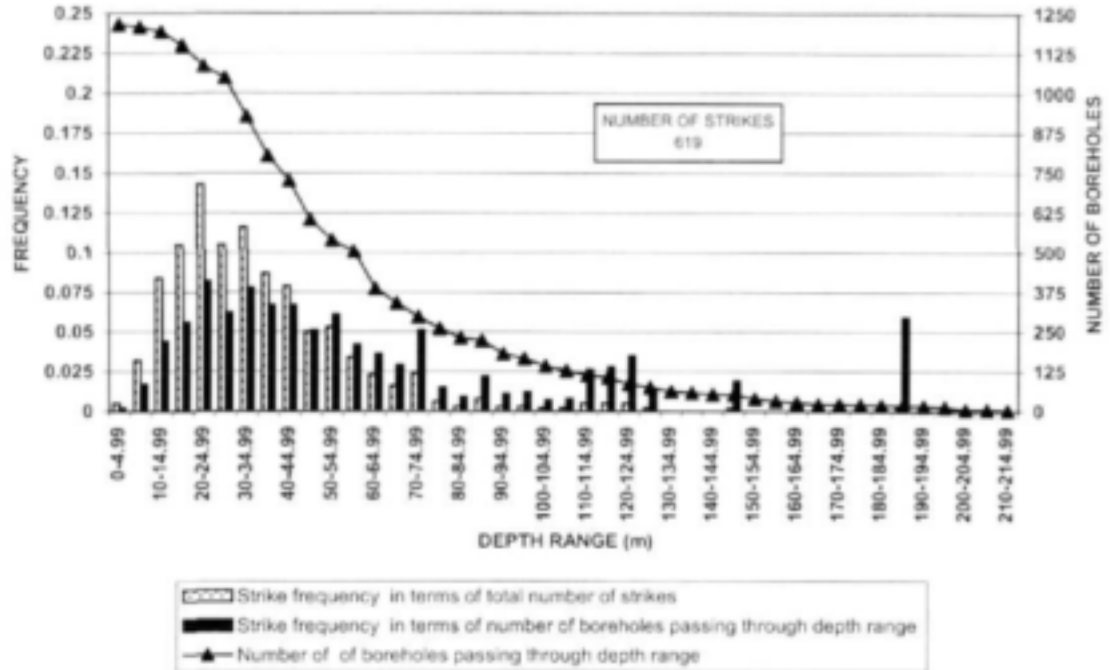


FIGURE 19 STRIKE FREQUENCY BELOW WATER LEVEL
SUBREGION 3C

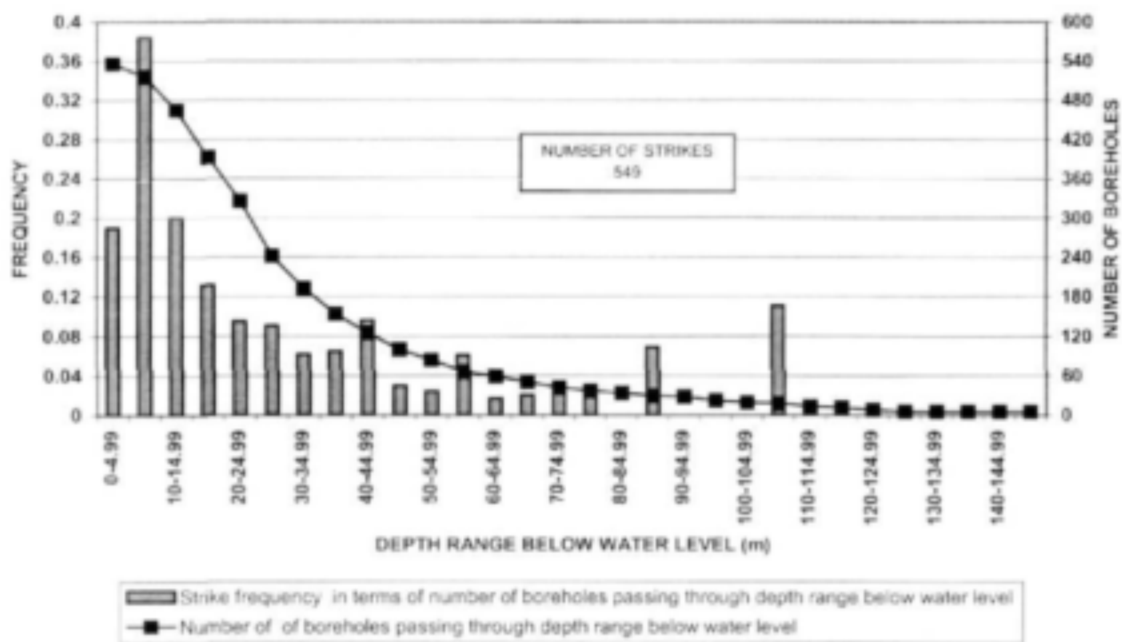


FIGURE 20 CUMULATIVE DISTRIBUTIONS OF WATER LEVELS, STRIKES AND METRES DRILLED SUBREGION 3C

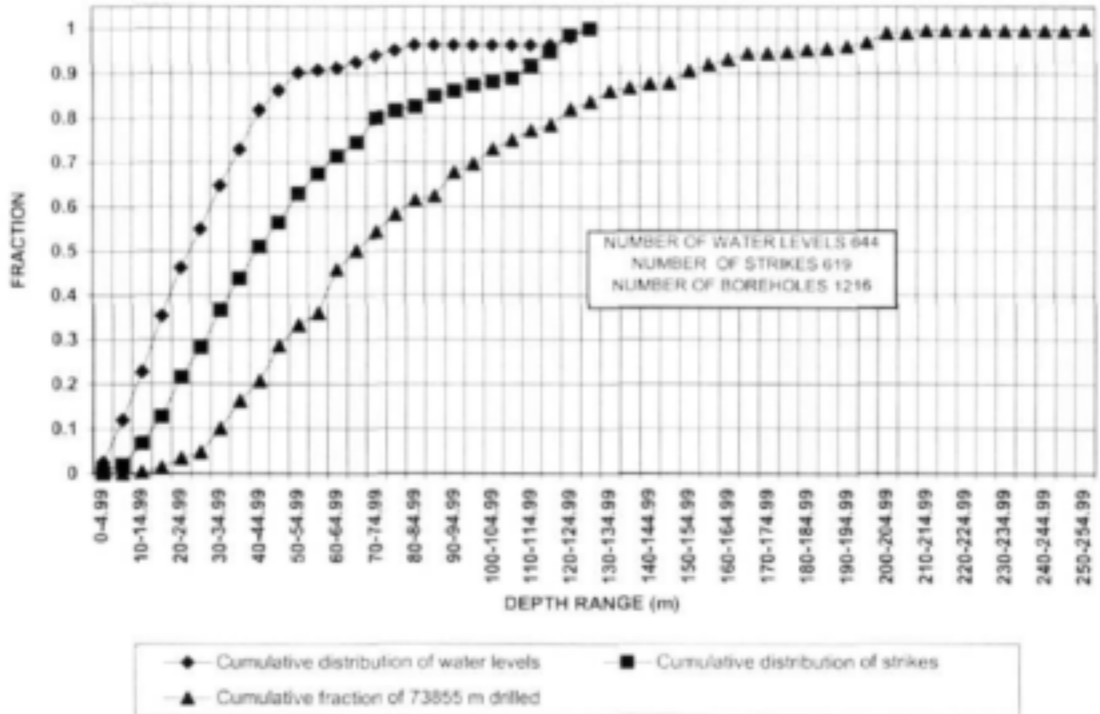


FIGURE 21 RELATIONSHIP YIELD - STRIKE BELOW WATER LEVEL SUBREGION 3C

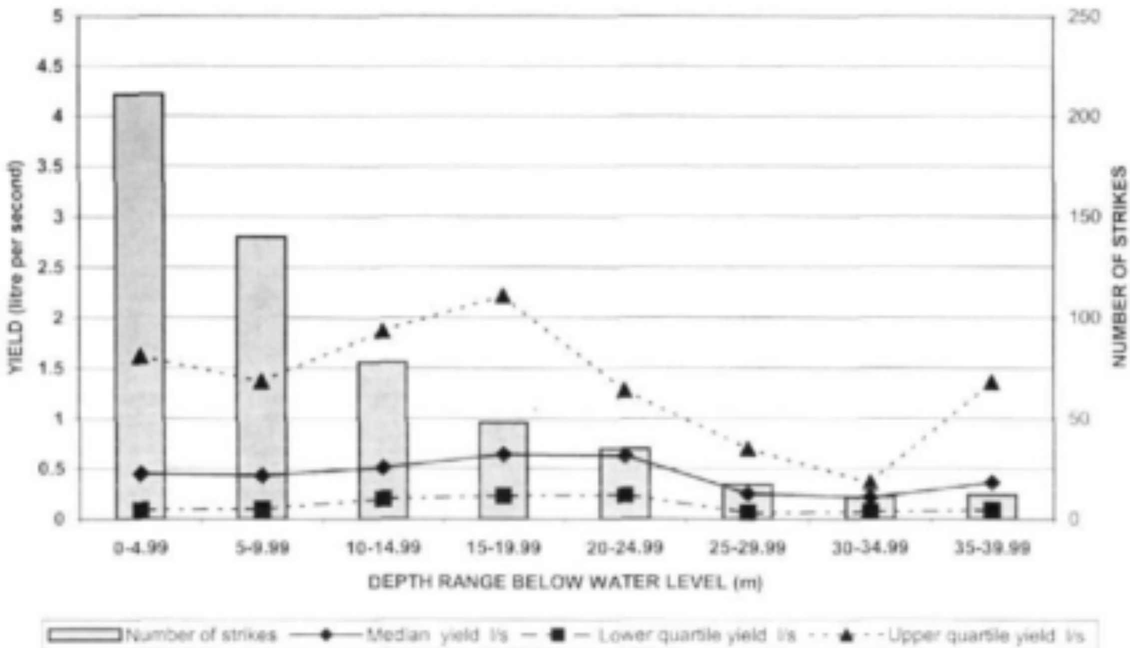


FIGURE 22 WATER LEVEL FREQUENCY SUBREGION 3D

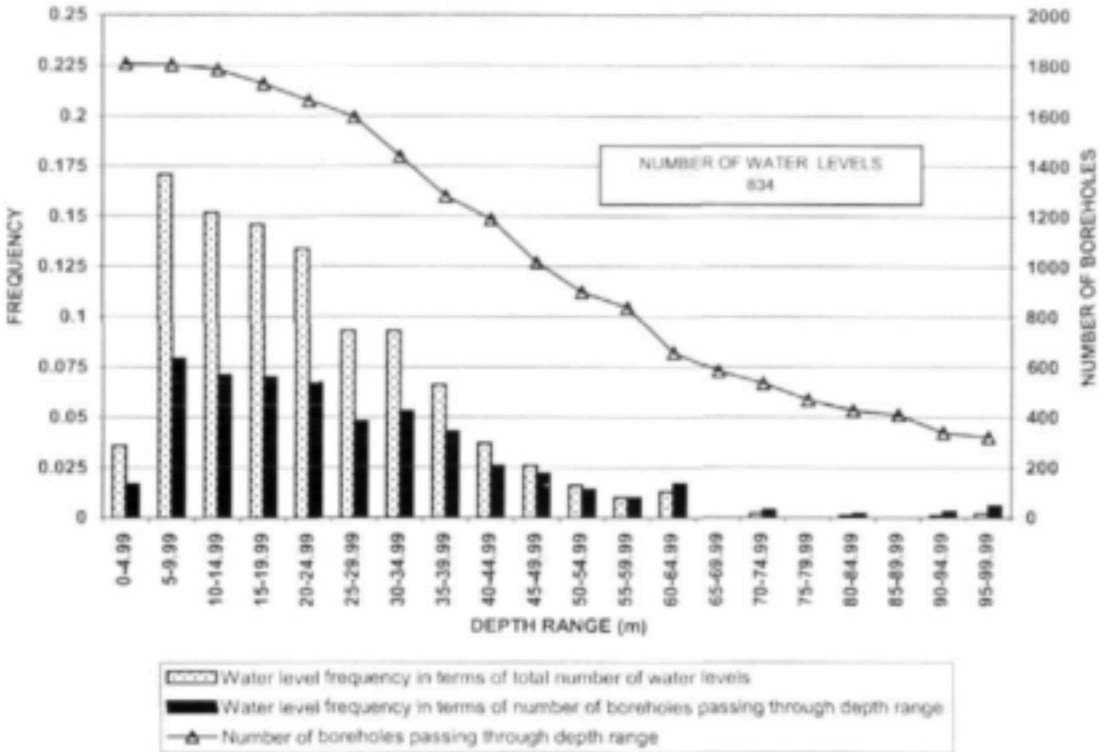


FIGURE 23 STRIKE FREQUENCY BELOW SURFACE SUBREGION 3D

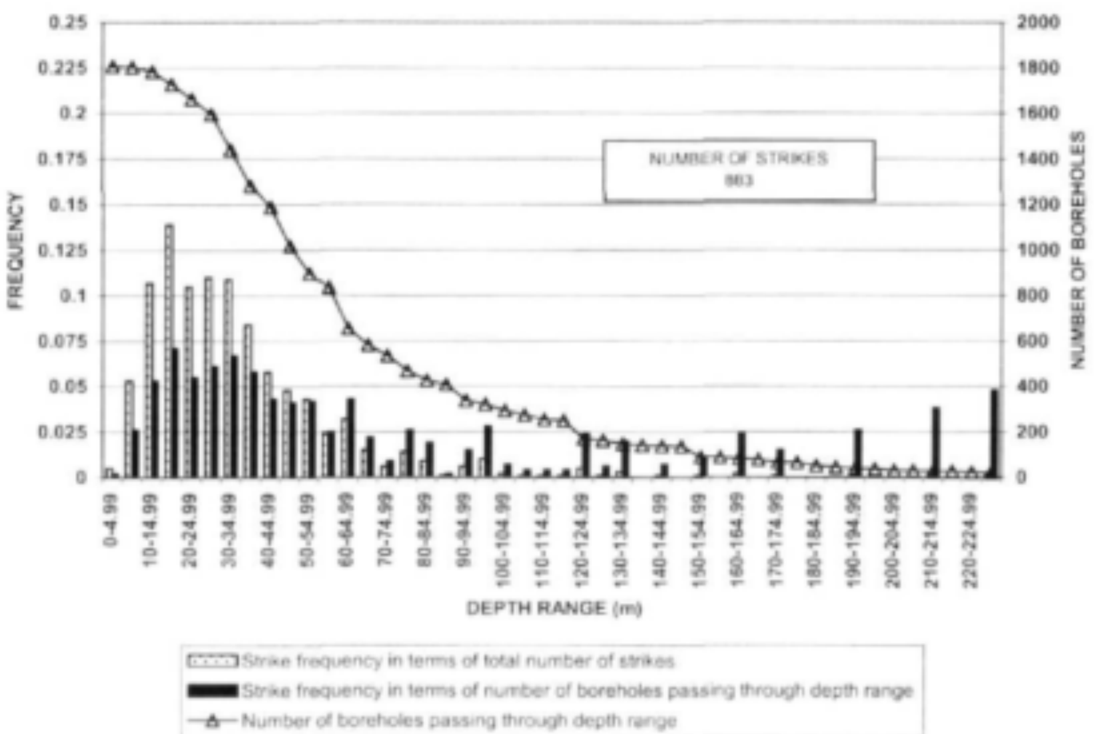


FIGURE 24 STRIKE FREQUENCY BELOW WATER LEVEL SUBREGION 3D

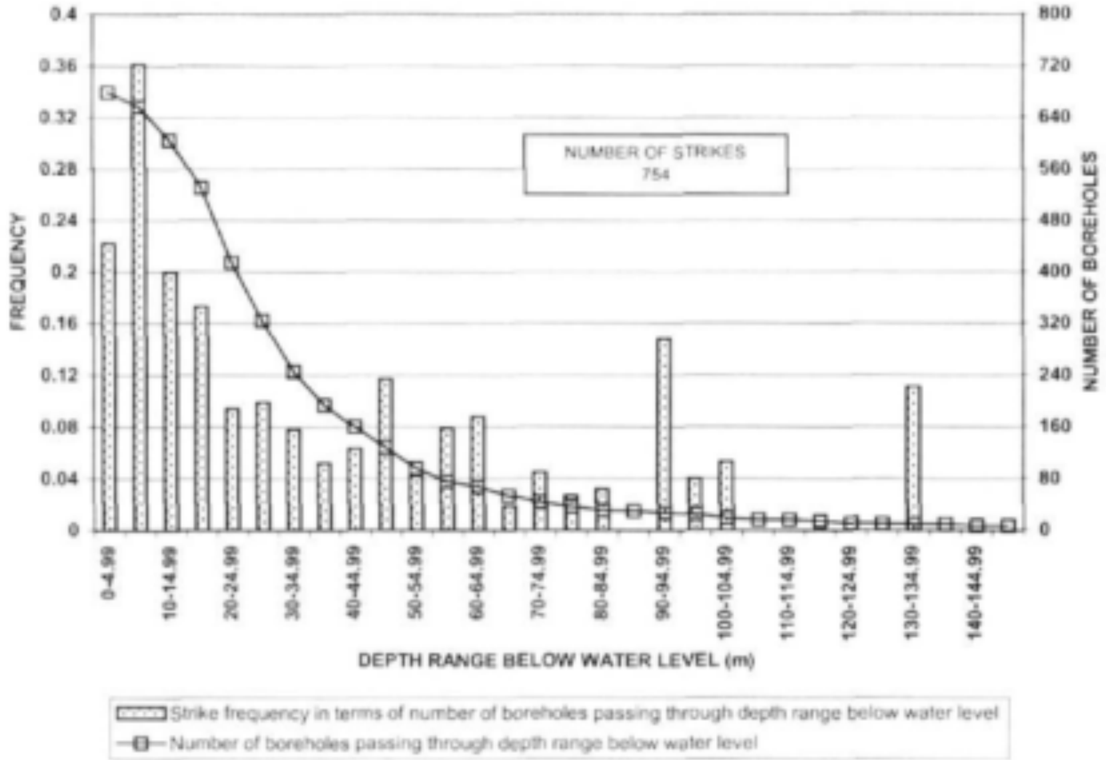


FIGURE 25 CUMULATIVE DISTRIBUTIONS OF WATER LEVELS, STRIKES AND METRES DRILLED SUBREGION 3D

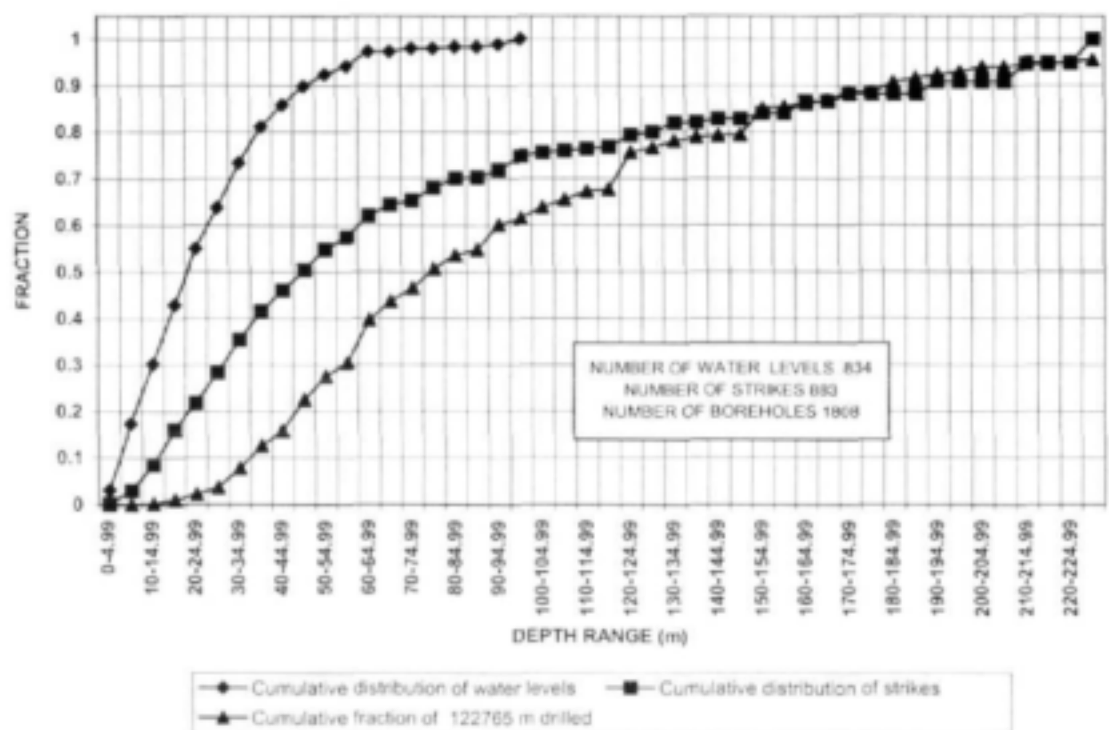
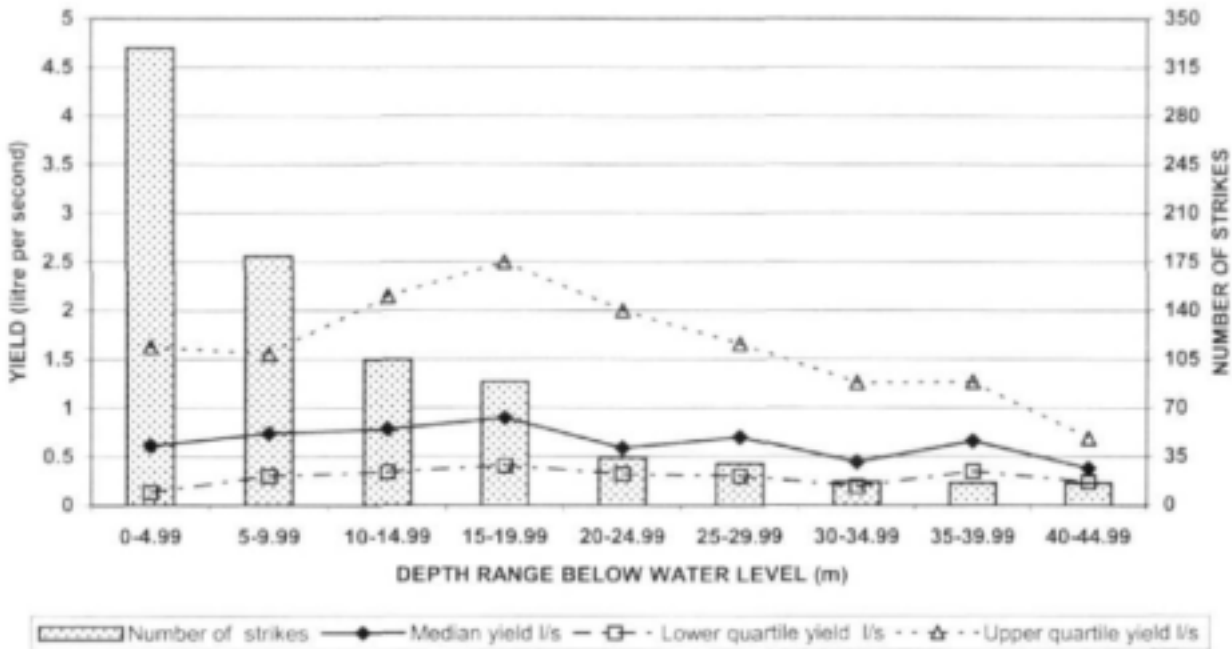


FIGURE 26 RELATIONSHIP: YIELD - STRIKE DEPTH
BELOW WATER LEVEL
SUBREGION 3D



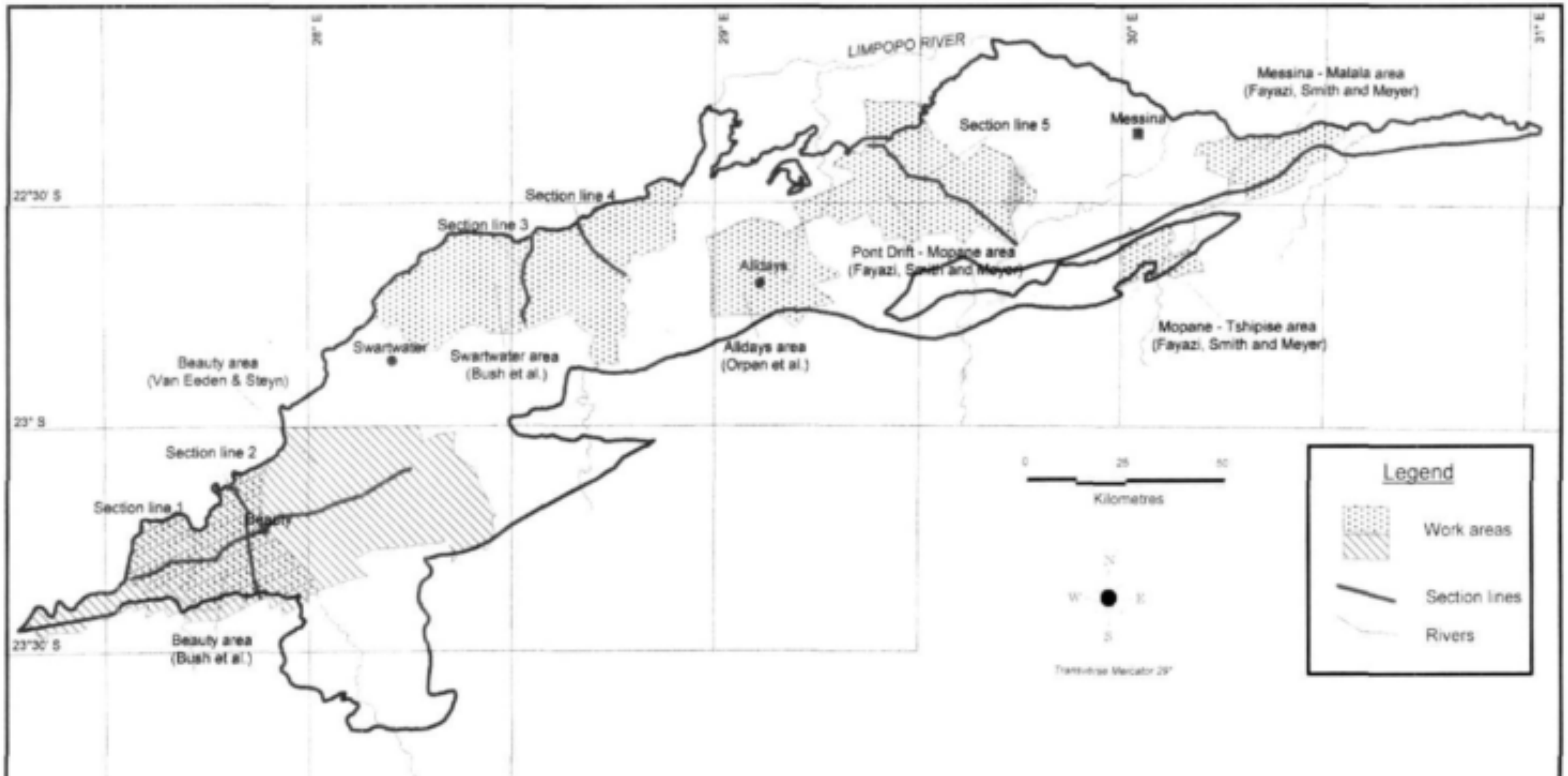


Figure 27 Past hydrogeological investigations

TABLE 6 CLASSIFICATION OF TEXT FIGURES DEPICTING STATISTICAL DATA

Item	Subregion				
	A- 1*	A- 2*	B	C	D
	Figure number				
Water level frequency	4	9	12	17	22
Strike frequency below surface	5	10	13	18	23
Strike frequency below water level	6		14	19	24
Cumulative distribution of water levels, strikes and borehole depths	7	11	15	20	25
Yield - strike depth relationship	8		16	21	26

*Subregion A-1 water levels ≥ 30m: Subregion A-2 water levels < 30 m

Table 7 summarizes information that may be gleaned from Figures 4, 6, 7, 9, 11, 12, 14, 15, 17, 19, 20, 22, 24 and 25. Because of insufficient data, the optimal strike frequency below water level was not determined for A 2. It is assumed to be similar to that of the other Subregions.

Column 3 of Table 7 shows that by restricting drilling to depths listed in column 5, only a small percentage of deeper water levels will not be covered. With the exception of A1, the reality of these deeper water levels may even be open to question. If drilling of the NGWDB holes had been restricted to the listed depths, about 30% on average fewer metres would have been drilled. Moreover, as not all boreholes need to be drilled to maximum depth, the saving may even be as much as 40%. The saving on drilling depth would not have resulted in more successes. However, if this saving had been used for additional boreholes, between 35% and 50% more successful boreholes would most likely have resulted.

TABLE 7 WATER LEVEL STATISTICS

1. Subregion	2. Majority of water levels between	3. Percentage water levels deeper than column 2 and 5		4. Optimal strike zone below water level	5. Maximum optimal drilling depth according to column 4	6. % NGWDB a. boreholes b.strikes deeper than maximum optimal depth	
		2	5			A	B
A-1*	30 - (55)70 m	20	12	0 - 15 m	85	32	55
A-2*	0 - 30 m	0	0	0 - 20 m	50	88	60
B	5 - 60 m	12	4	0 - 25 m	85	26	23
C	5 - 45 m	16	8	0 - 20 m	65	37	27
D	5 - 45 m	12	3	0 - 20 m	65	42	37

*A-1 water level ≥ 30 m; A-2 water level < 30 m

Table 8 is based on Figures 5, 7, 10, 11, 13, 15, 18, 20, 23 and 25. There is, broadly speaking, good correspondence between optimal strike and water level depths below surface, as one would expect from the relationship between water level and optimal strike depths. The deduced minimum and maximum drilling depths based on strike frequency straddle those derived from water level statistics (column 5 Table 7). Strike frequencies at greater depths than the listed maxima are extremely low. The optimum strike frequencies, although on average about three times higher, are also low compared to other regions.

The low success rate (Table 5), the low strike frequency and, consequently, (unnecessary) deep drilling has to be ascribed to:

- mainly shallow weathering/fracturing - i.e. a dearth of structures sufficiently deeply weathered /fractured.
- deeply weathered and fractured zones lacking permeability as discussed below in section 3.2.3.3
- improper siting of boreholes.

Because of the sharp drop in the number of strikes with depth below water level - Figures 8, 16, 21 and 26 - firm conclusions about yield versus strike depth relationships cannot be drawn. The median yields of Subregion A are less than $0.5\ \ell\ s^{-1}$, those of C average around 0.6, B about 0.7 and D around $0.75\ \ell\ s^{-1}$.

TABLE 8 STRIKE STATISTICS

1. Subregion	2. Depth of optimum strike zone below surface	3. Transitional zone with poorer strike prospects	4. Maximum drilling depth according to 2 and 3		6. % NGWDB holes deeper than 4a and 4b		5. % strikes deeper than maximum depths 2 and 3	
			A	b	a	b	2	3
A-1*	30 - 55 m	55 - 115 m	60	120	84	40	76	36
A-2*	15 - 55 m	-	60	-	47	-	57	-
B	35 - 65 m	65 - 115 m	70	120	41	10	32	4
C	10 - 55 m	55 - 75 m	60	80	43	23	31	18
D	5 -45 m	45 - 65 m	50	70	62	34	43	35

* A-1 water level ≥ 30m; A-2 water level < 30 m

3.2.3.2 Lithology and structure

Fayazi et al. (1981) analyzed hydrocensus data of the Tshipise-Mopane, the Mopane-Pontdrif and the Messina-Malala areas (see Figure 27) in terms of lithology, contact between different formations and faulting. Their results are summarized below in Table 9. Drilling success rates cannot be gauged from this table. Only holes known to the occupant of the land at the time of the survey are listed. Most landowners/occupants do not possess information on drilling operations before their ownership/ occupancy and especially about failures and dried-up holes which previously fell into disuse. A reasonably reliable estimate of success rate is possible only from the Department of Water Affairs and Forestry's drilling records as has been done in the compilation of the National Groundwater maps. Some useful conclusions may nevertheless be drawn from the hydrocensus.

- **Lithology**

The relatively small number of holes located in supracrustal rocks reflects their limited extent in Fayazi et al.'s three study areas. Compared to granite-gneiss, smaller percentages of successful holes have fallen into disuse and dried-up. This may be an indication that the supracrustal rocks are more favourable drilling targets. In support of this deduction Fayazi et al. found that weathering in four holes in the Tshipise-Mopane area extends to below the water level, whereas it is generally shallower than the water level in successful boreholes drilled in granite-gneiss.

In their report on a structural analysis of the Swartwater area, Andersen and Less (1992) express the opinion that the chances of intersecting a strong water supply will be improved if faulting can be combined with marble, amphibolite, metaquartzite and calc-silcate rocks.

As marble and metaquartzite were encountered in only 9 of the 109 exploratory holes that were drilled, Bush (1989) has not commented on the relative merits of the different rock types in the Swartwater and Beauty areas.

- **Lithological contacts excluding dyke contacts**

Bush (1989) states that, as a consequence of metamorphism, lithological contacts are either welded or transitional in nature. Unless sheared or faulted (and weathered) to below the water level, they do not present favourable drilling targets. Fayazi et al. (1981) mention the existence of several successful holes on the contact between amphibolitic rocks and granite-gneiss in the Mopane-Tshipise area. Relatively high yields were struck in the Mopane-Pontdrif area in boreholes penetrating contacts between mafic Messina Suite intrusives, on the one hand, and leuco-gneisses and metaquartzite on the other; also between granitoid gneiss and meta-quartzite. The nature of the contact zones whether weathered, faulted or sheared is, however, not stated.

TABLE 9 BOREHOLE RESULTS IN TERMS OF LITHOLOGY AND STRUCTURE
(Tshipise - Mopane, Mopane - Pontdrif and Messina - Malala areas)

Principal rock type/ structural feature	Total number of holes found	Number of "dry" holes and those that yielded $< 0.13\ \ell\,s^{-1}$	Number of initially successful holes yielding $> 0.13\ \ell\,s^{-1}$	Number of successful holes in use during 1981 (percentage in brackets)	Number of successful holes not in use during 1981. (percentage in brackets)	Number of "dried-up" holes that were previously successful (percentage in brackets)
Granite-gneiss(a)	474	102	372	165 (44.4)	93 (25)	114 (30.6)
Supracrustal rocks* (b)	53	13	40	27 (67.5)	4 (10)	9 (22.5)
Contact zone between (a) & (b)	46	8	38	27 (71.1)	6 (15.8)	5 (13.2)
Dyke contact zones	41	16	25	18 (72)	3 (16.7)	4 (22.2)
Fault zones	9	1	8	4 (62.5)	2 (25)	1 (12.5)

* The supracrustal rocks consists of metaquartzite, magnetite quartzite, marble, calc-silicate rocks, amphibolite, metapelite, paragneisses.

- **Dykes**

Of the 15 holes, which were sited geophysically by Bush and co-workers in the Swartwater area and which penetrated diabase and dolerite dyke contacts, only one yielded more than 0.125 $\ell\ s^{-1}$. The success rate of holes not aimed at striking dyke contacts but drilled up to distances three dyke widths away, was better - 6 out of 18 yielded more than 0.125 $\ell\ s^{-1}$.

These findings appear to be corroborated by Fayazi et al. (1981) who found very little weathering along dykes in granite gneiss in the Mopane-Tshipise area - only one out of four holes on dyke contacts was successful. The situation appears to be somewhat different in the Mopane-Pontdrif area. With the borehole survey thirty holes were found drilled on dyke contacts. Of these, sixteen were equipped with diesel engines or windmills, four were open and cased but dried-up or filled-in, apparently initially successful, and ten were failures from the start. The type of dyke rock is not stated. The country rock with one exception, that of mafic Messina Suite, is granite gneiss. No information is provided on the state of fracturing and weathering of the contact zones. It appears that boreholes should not be sited on dyke contacts unless weathering and fracturing to below the water level has been established geophysically.

On the grounds that Karoo dolerite dykes are the southeastern extension of a dyke swarm which cuts across northern Botswana (Reeves 1979a and b) and were intruded into the failed arm of a triple junction. Andersen and Less (1992) have suggested that these dykes should be explored as potential aquifers. Proof is lacking.

- **Faults, shear and fracture zones**

The nine holes listed in the Table 9 lie along more or less prominent east - west striking faults. Five are situated along a fault, which cuts through rocks of the Limpopo Mobile Belt; three are situated on a boundary fault between rocks of the Malala Drift Group and the Stayt Formation of the Soutpansberg Group. One hole lies on the faulted contact between Karoo rocks and marble and calc-silicate rocks. Faults cutting through Karoo strata are not included (Fayazi et al. 1981).

Based on an analysis of borehole results in the Swartwater area, Andersen and Less (1992) identified as most favourable, faults with strike directions between 340° and 350°. The next favourable orientation is in the sector between 0 and 40° with a peak at 20°. Boreholes of which the mapped positions are shown to be within 150 m of fault lines, are assumed to have penetrated fault zones. Justification for such an assumption is lacking and deemed doubtful. The accuracy with which borehole positions and fault lines have been mapped is questionable. Hence, the reliability of the analysis is uncertain.

The value of fracture/shear zones in the Swartwater and Beauty areas cannot be gauged from the drilling results on sites selected by Bush and Field Party on lineaments and / or EM anomalies. Exploratory drilling was not conducted in a manner so as to disclose the nature of structures (other than dykes), which manifest themselves as lineaments. The nature of the conductors responsible for the EM anomalies is unknown for the same reason as well as for the lack of resistivity borehole logging. See chapter 4 particularly section 4.5 **Comments**.

3.2.3.3 Weathering and fracturing

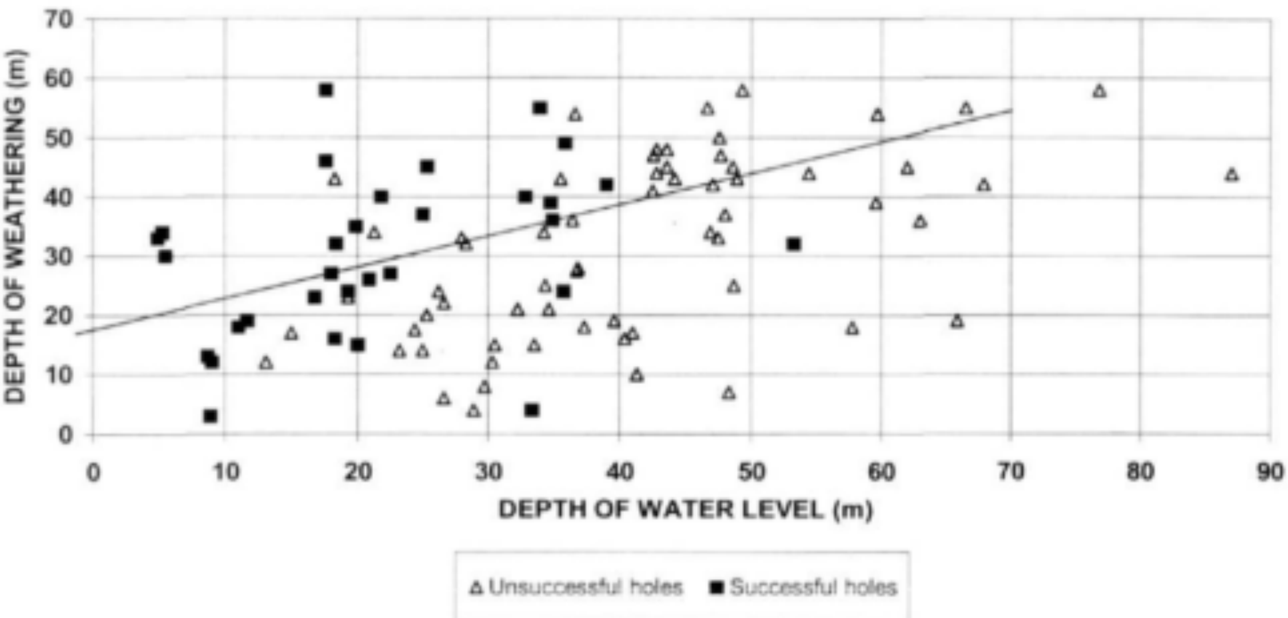
The water-bearing characteristics of the rocks comprising the Limpopo Mobile Belt depend on where and on the extent and depth to which openings have developed in these hard-rock formations through tectonic deformation, weathering, erosion and unloading.

The results of an analysis of 106 geologically/geophysically sited boreholes in the Beauty and Swartwater areas (Appendix 2 Volume 2 Bush 1989) are presented below.

Borehole results in terms of depth of weathering and water level

The importance of weathering in converting (fractured) hardrock into material capable of storing and transmitting groundwater is graphically illustrated in Figure 28. Whereas 15 out of 38 holes (39.5%) were successful in the weathering range 20 - 39.9 m, only 8 out of 35 boreholes (22.8%) yielded a usable supply where the depth of weathering exceeded 40 m - Table 10. This trend is also evident from the failures. In the depth range 20 - 39.9 m only four of 20 failures (20%) recorded weathering deeper than the water level. From 40 m down weathering deeper than the water level was recorded in 11 of 27 failures (40.7%).

FIGURE 28 RELATION BETWEEN SUCCESSFUL BOREHOLES AND DEPTHS OF WEATHERING AND THE WATER LEVEL BEAUTY AND SWARTWATER AREAS



In Table 11 five unsuccessful boreholes in which weathering extended less than 1.5 m below the groundwater level have been included in the second category (B). No water level was recorded in 10 unsuccessful holes. Note only one of 36 holes was successful where the depth of the water level exceeded 39.9 m. No useful supply was struck in any of the six holes in which weathering extended to below the water level.

With the exception of several boreholes in which marble, marble and associated biotite schist, marble and associated amphibolite, metapelite, calc-silicate rocks and metaquartzite were encountered and several instances of diabase and dolerite dykes, Bush has invariably described the rocks drilled as:

- gneiss - leucocratic or leuco-, pink, grey, hornblende, amphibolitic.
- alternating bands of leuco- and amphibolitic gneiss and
- amphibolite.

The presence of mica and pyrite is frequently mentioned. In a number of instances clay and calcium carbonate have been encountered in fractured rocks at depths ranging from near surface to about 70 m.

TABLE 10 BOREHOLE RESULTS IN TERMS OF DEPTH OF WEATHERING
(Beauty and Swartwater areas)

Weathering[1] depth range (m)	Number[2] of holes within depth range	Boreholes Yielding > 0.125 ℓ s^{-1} Total number successful (failures in brackets)	No. of successful (failed) holes with water level shallower than weathering		No. of successful (failed) holes with water level deeper than weathering		Percentage successful
0 - 9.9	8 (2)	2 (6)	0 (0)	-	2 (4)	33.3%	25
10 - 19.9	25 (4)	7 (18)	4 (1)	80%	3 (13)	18.8%	29.2
20 - 29.9	17 (1)	6 (11)	4 (1)	80%	1 (9)	10%	27.8
30 - 39.9	21 (2)	9 (12)	8 (3)	72.7	1 (7)	12.5%	45
40 - 49.9	25 (1)	6 (19)	6 (7)	46.2	0 (11)	0%	24
50 - 59.9	9 (0)	2 (7)	2 (4)	33.3	0 (3)	0%	22.2
60 - 69.9	1 (0)	0 (1)	0 (0)	-	0 (1)	0%	0
Totals	106	32 (74)	25 (16)		7 (48)		30.2
% successful		30.2	61		12.7		

[1] In his description of drill cuttings Bush (1989) distinguished between "weathered" (equivalent to saprolite), "weathered and / to fractured" (saprock), "fractured", "solid with occasional fracture" and "solid". The term "weathered" in this and the next table embraces the first two categories. The terms saprolite and saprock are terms used by the British Geological Survey (Wright in Wright and Burgess1992)

[2] The numbers in brackets are holes for which no water level data are available. They are included in the total number of holes.

Depth of water strikes

The frequency of water strikes below the surface and water level in boreholes sited by Bush and Field Party in the Beauty and Swartwater areas is given in Table 12. The strike percentages for the greater depth ranges are probably overestimated as drilling is normally continued only if conditions for striking water appear still favourable. In this regard, other analyses show that 70% of the water strikes in excess of 0.125 ℓ s^{-1} occurred between 10 m above and 20 m below the base of weathering and that 80% of the strikes were within the first 25 m below the water level.

Increases in the rate of which water is blown out of holes during the course of air drilling are recorded as water strikes. There may be some doubt about the reality of some of these strikes, especially if they occur in fresh hard rock and cannot be corroborated from drill cuttings, geophysical logging and/or drilling rate. Higher-lying water-bearing fractures may be opened up by the action of the drill and by the upward flow of water and suspended drill cuttings during the course of drilling.

TABLE 11 BOREHOLE RESULTS IN TERMS OF WATER LEVEL DEPTHS

(Beauty and Swartwater areas)

Water level depth range (m)	A. Depth of weathering* greater than water level depth			B. Depth of weathering* less than water level depth		
	Number of boreholes	Number of successful holes (yield > 0.125 $\ell\, s^{-1}$)	% success	Number of holes	Number of successful holes (yield > 0.125 $\ell\, s^{-1}$)	% success
0 - 9.9	5	5	100	1	1	100
10 - 19.9	12	9	75	2	1	50
20 - 29.9	8	6	75	10	1	10
30 - 39.9	8	6	75	14	2	14.3
40 - 49.9	6	0	0	17	0	0
50 - 59.9	-	-	-	5	1	20
60 - 69.9	-	-	-	6	0	0
70 - 79.9	-	-	-	1	0	0
80 - 89.9	-	-	-	1	0	0
Total	39	26	66.7	57	6	10.5

* Weathering as defined in footnote to table 10.

The possibility of a relationship between yield and depth of weathering/saturated regolith thickness has not been investigated owing to the small number of holes. That a correlation exists is doubted (see Wright 1992 in Wright and Burgess 1992).

TABLE 12 DEPTHS OF WATER STRIKES

(Beauty and Swartwater areas)

Depth range (m)	Number of holes passing through depth range		Number of strikes in depth range regardless of magnitude		Strike frequency in depth range	
	Below surface	Below water level	Below surface	Below water level	Below surface	Below water level
0 - 10	108	90	2	37	0.019	0.411
10.1 - 20	108	83	7	28	0.065	0.337
20.1 - 30	107	66	12	13	0.112	0.197
30.1 - 40	103	54	17	9	0.165	0.167
40.1 - 50	94	33	17	4	0.181	0.121
50.1 - 60	82	20	9	3	0.110	0.15
60.1 - 70	71	12	3	2	0.042	0,167
70.1 - 80	52	3	1	1	0.019	(0.333)
80.1 - 90	27	1	2	0	0.074	
90.1 - 100	21		1		0.048	
100.1 - 110	11		1		0.091	

The following conclusions may be drawn from the results presented above. The probability of striking water is greatest:

a. where weathering extends to below the piezometric level
b. where the depth of weathering and of the piezometric level does not exceed 40 m.
c. in the first 10 m below the piezometric level. This type of strike frequency probably reflects decompression (unloading) fractures (Wright in Wright and Burgess 1992).

Drilling deeper than about 20 m below the piezometric level does not appear to be warranted unless the existence and position of an open fracture or fracture zone can be established beforehand. This aspect will be discussed in Chapter 4 "Case histories of borehole siting and drilling".

Possible reasons for the poor results where weathering and piezometric levels are deeper than 40 m may be one or more of the following:

- Infilling of fractures. Wright (1992) mentions clay illuvation as the cause of decreased permeability of saprock.
- The formation of impermeable smectite. According to Drever (1988 p 145 - 151) the formation of clay minerals during weathering is in general agreement with thermodynamic predication. Gibbsite is formed where waters are extremely dilute, kaolinite is formed in dilute waters and smectites (swelling clays) are formed in more concentrated solutions. In examining the origin of dissolved constituents of some ephemeral and perennial springs issuing from granitic rock in the Sierra Nevada, Garrels and Mackenzie (quoted by Drever 1988) concluded that the composition of the ephemeral spring water could be accounted for by the weathering of plagioclase to kaolinite. The composition of the perennial spring water that has circulated deeper could be explained largely by the decomposition of plagioclase to smectite instead of kaolinite (see also McFarlane in Wright and Burgess 1992).
- The formation of interstital platelets of clay. Acworth (1987) quotes experimental evidence that the rate of removal of reaction products dictates whether clay minerals will form as pseudomorphs of the original mineral or as interstitial plates of new minerals. Low flow rates promote the formation of interstitial clay minerals whereas higher rates of flow lead to the formation of pseudomorphs. The latter will not change the texture and porosity as completely as the formation of platelets of clay between existing mineral grains.

Bush (1989) has reported the presence of grey clay in fractured amphibole gneiss at a depth of nearly 70 m in a borehole G38540 on Kaffersfontein 135 LQ. This is more than 20 m below the water level.

3.2.4 Water levels and piezometric profiles

Water levels range from 5 to 70 m below surface according to Table 7. The depth distribution is unfortunately not well depicted on Sheet 2 of the Groundwater Resources Map of South Africa because of its small scale. Water levels are generally shallower along all the rivers and not only along the Limpopo and Mogalakwena as shown on the map. Deeper water levels are also not restricted to the Baltimore - Tolwe area, but are found west of the Lephalala River (the so-called Beauty area) away from the immediate vicinity of the Limpopo, Mokolo and Lephalala Rivers.

Although not very obvious from the drilling success rates in Table 5, the region's worst groundwater conditions are found here as well as east of the Lephalala River up to about longitude 28° 15' and south of latitude 23° 15' (see Figure 2).

As illustrated in Figure 29 the piezometric profile west of the Lephalala River differs markedly from that east of the river and north of latitude 23° 15'. West of the river the piezometric profile does not mimic the surface. This is to a lesser degree also evident on the north-south section (Figure 30) where the piezometric gradient steepens or is interrupted by a step as the contact with the overlying

FIGURE 29 WSW-ENE SURFACE AND PIEZOMETRIC PROFILE CHARLESTOWN 115 LQ TO BALTIMORE 22 LR (SECTION LINE1 FIGURE 27)

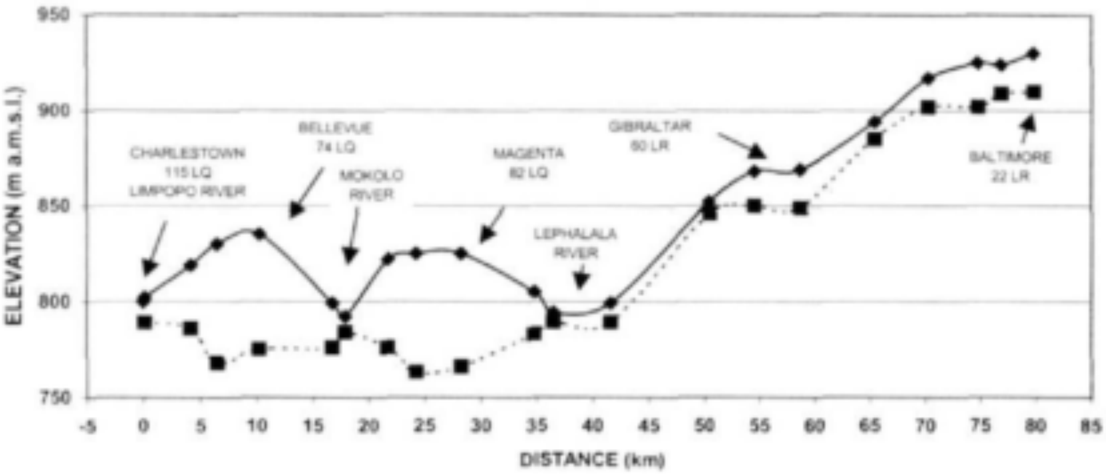
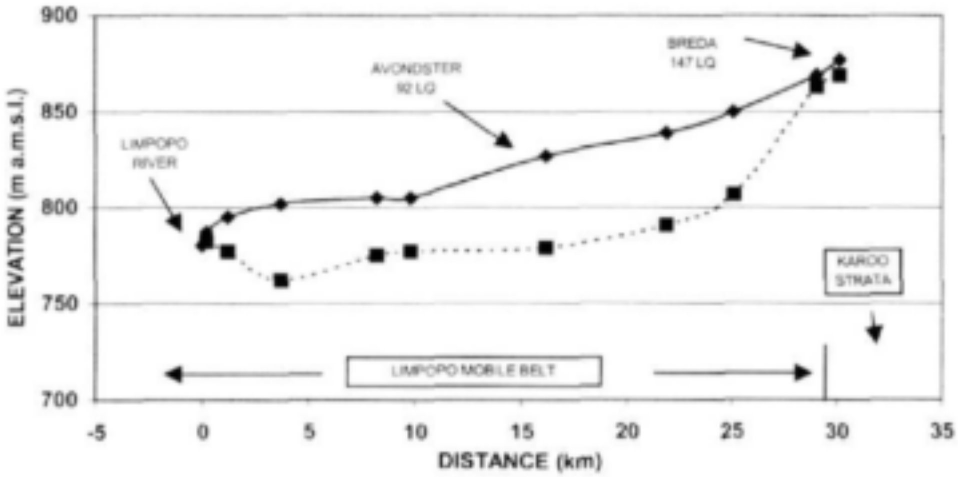


FIGURE 30 N - S SURFACE AND PIEZOMETRIC PROFILE GOEDEHOOP 39 LQ (LIMPOPO RIVER) TO BREDA 147 LQ (SECTION 2 FIGURE 27)



Karoo Beds is approached. The shallow water level in the Karoo rocks is the result of a small coefficient of storage.

Directly east of the Lephalala River and in the so-called Swartwater and Mopane - Pontdrif areas (Figures 31, 32 and 33) the piezometric profiles mostly parallel the surface (see Figure 27 for location of section lines). The parts with deeper piezometric levels (Figures 31 and 32) coincide with surface watersheds and with low groundwater potential areas according to Bush ((1989) - see enclosure 4.1 of report Gh 3577)). The chances of locating a meaningful supply here are poor. These areas appear to be remnants of an older weathered zone largely removed by younger erosion.

FIGURE 31 N - S SURFACE AND PIEZOMETRIC PROFILE, SWARTWATER AREA (SECTION LINE 3 FIGURE 27)

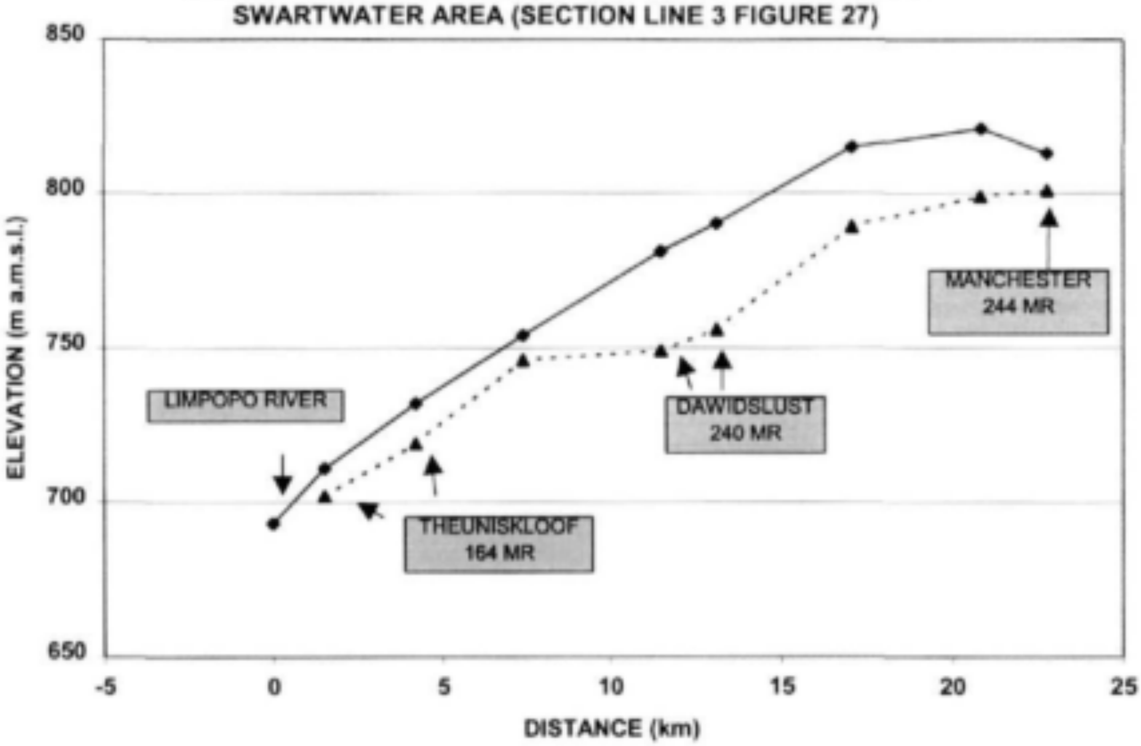


FIGURE 32 NW - SE SURFACE AND PIEZOMETRIC PROFILE SWARTWATER AREA (SECTION LINE 4 FIGURE 27)

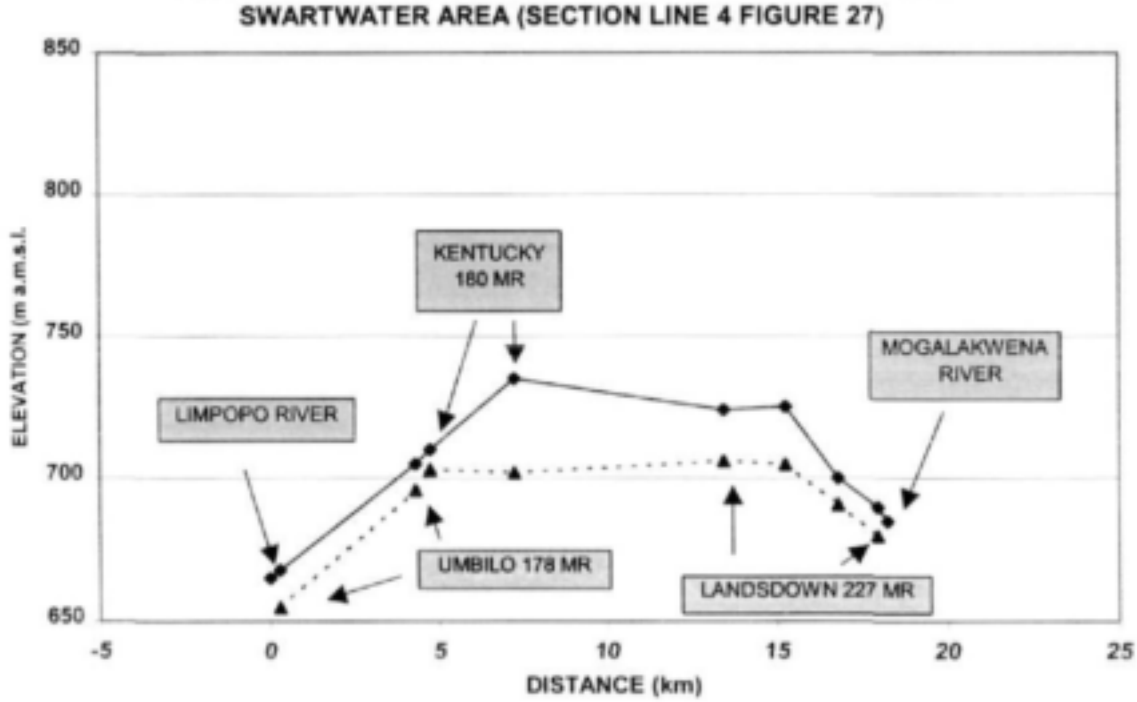
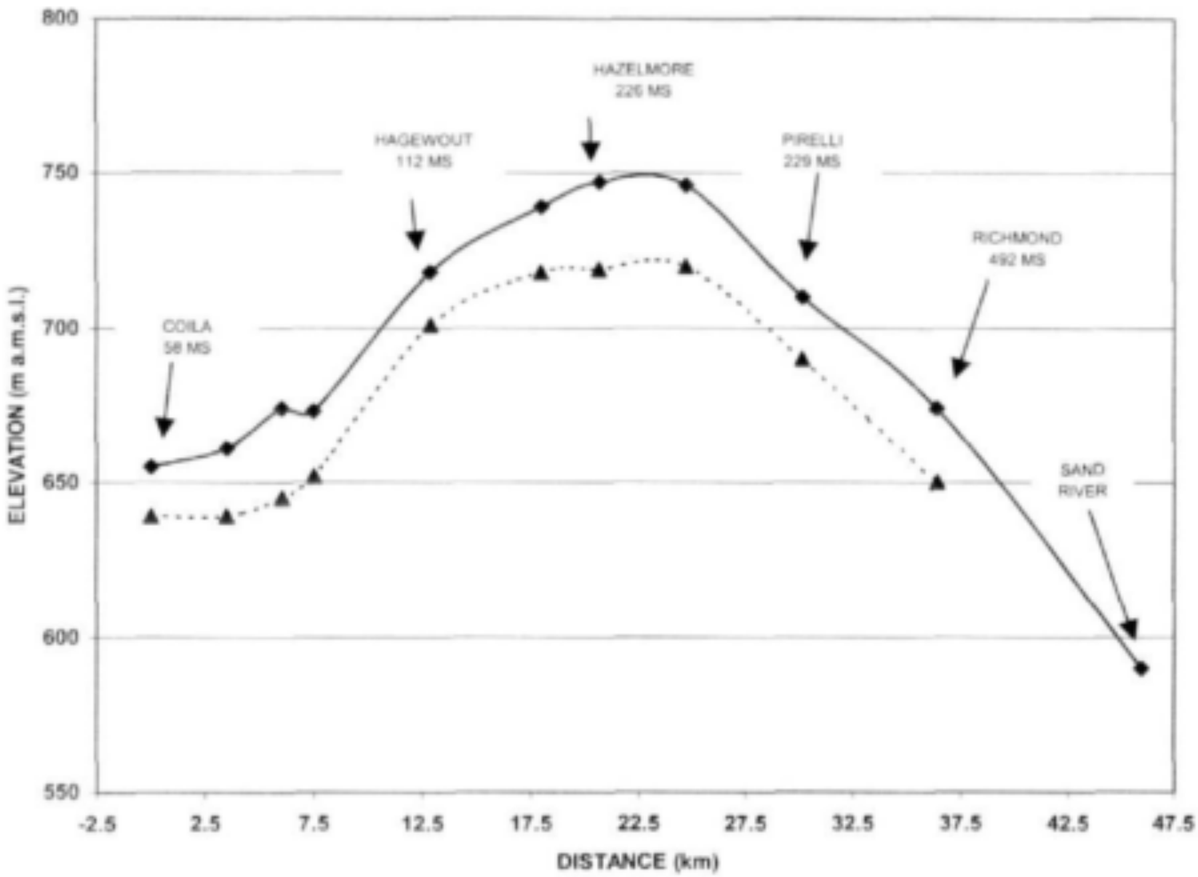


FIGURE 33 NW - SE SURFACE AND PIEZOMETRIC PROFILES PONT DRIFT - MOPANE AREA (SECTION LINE 5 FIGURE 27)



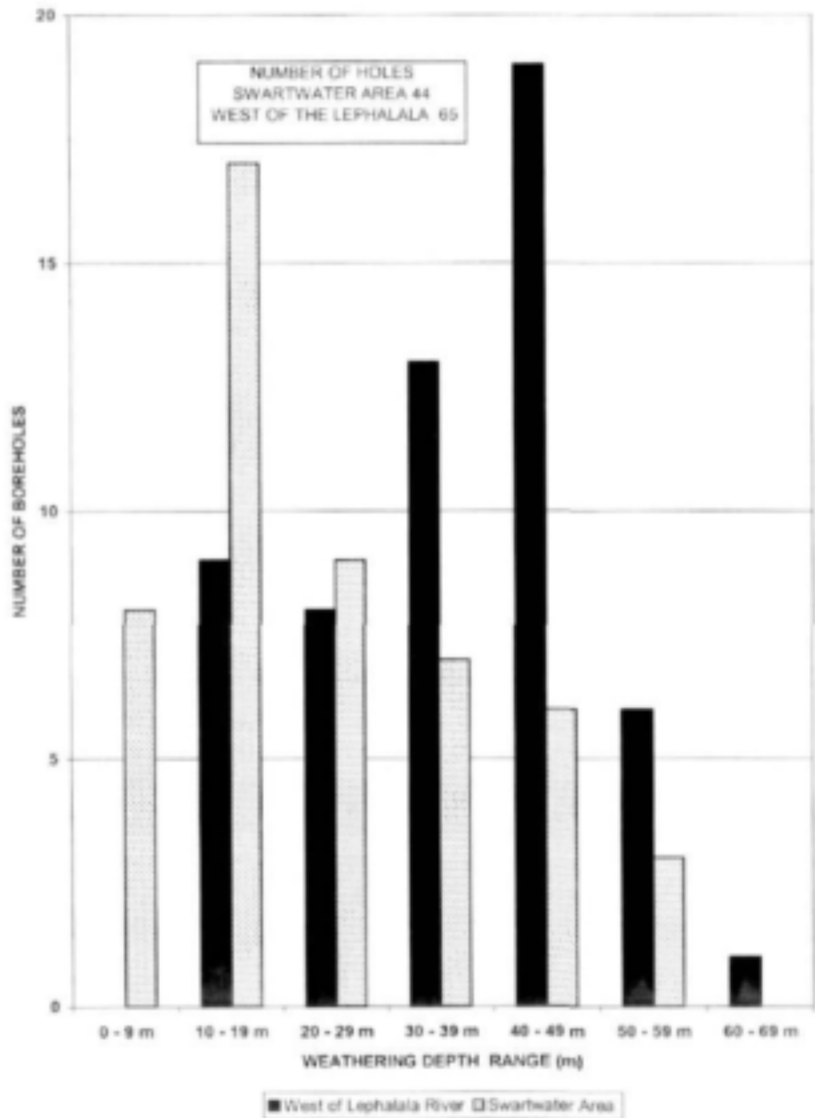
The difference between conditions in the Beauty and Swartwater areas is also evident from Figure 34, which shows that weathering is deeper in a larger percentage of Bush's exploratory holes west of the Lephalala River than in those drilled in the Swartwater area. The deeper piezometric level in the Beauty area results not only from deeply weathered rock and its relatively large coefficient of storage, but it also reflects a dynamic balance between recharge and loss. Assuming loss through groundwater flow as the most obvious, discharge has to take place at surface elevations of about 750 m a.m.s.l or less. The nearest locality with this elevation is on the Limpopo River some 50 km downstream of the confluence of the Lephalala. Whereas the rest of the Region appears to be characterised by mainly shallow and shorter flow paths, the Beauty area seems to be part of an extensive and deeper flow system formed possibly by the east-west trending fault system.

East of the Mogalakwena River the topography is more varied than in the Swartwater area. Depths of weathering are thought to be generally similar if not even shallower than in the Swartwater area. According to measurements by Fayazi et al. (1981) and Orpen et al. (1982) water levels are generally somewhat shallower east of the Mogalakwena River than in the Swartwater area.

3.2.5 Methodology for siting boreholes

Although aerial photography, satellite imagery and ground mapping are indispensable aids in the location of potentially water-bearing rock, they generally have to be supplemented by geophysical methods and techniques. Geophysics is employed not only in locating and pinpointing structures, but also in providing depth estimates of weathering and fracturing.

FIGURE 34 DEPTHS OF WEATHERING IN THE SWARTWATER AREA
AND WEST OF THE LEPHALALA RIVER (BEAUTY AREA)
(boreholes selected during 1987/88 investigation)



3.2.5.1 Satellite Imagery and aerial photography

According to Bush (1989) the various gneisses, anorthosite, and felsic rocks in the Swartwater and Beauty areas are clearly distinguishable from the metasediments on Landsat imagery in bands 4, 5 and 7. The former types are represented by light tonal shades of yellow, green, brown and grey; the latter by dark tones of grey, black or brown. Riverbeds, faults and shears are blue to black in colour. Bush produced lineament maps of the Swartwater and Beauty areas by combining the interpretation of satellite imagery with stereoscopic examination of aerial photography. Dominant strike directions, are northeast-southwest in the Swartwater and east-west in the Beauty area. The linear features represent according to Bush, fault and shear zones and four types of dykes: granophyre (least common), amphibolite (relicts of earlier basic intrusions), diabase and dolerite.

As discussed in section 2.6 Andersen and Less (1992) compiled a map of the Swartwater area showing faults as well as other clearly identifiable linear structures. The lineament maps of Bush and of

Andersen and Less differ greatly from each other. Whereas lineaments on the first are, broadly speaking, mainly east-west, those on the other are mainly north-south. Apart from the questionable accuracy of the maps, there are very few, if any features which are clearly common to both. Tugela 171 MR serves as an example of the discrepancies. Lineaments on Andersen and Less's map trend north-northeast; on Bush's map the pattern is different and strikes are northwest, north and east-west. The latter appears to be a dyke that is shown on the quarter-million geological sheet 2228 Beit Bridge. To be of use the two versions should be checked, corrected and brought into line.

3.2.5.2 Geophysical methods

The following geophysical methods have been applied:

•	Steyn during 1951- 1953	electrical depth probing - no formal report, field notes only	
•	Vegter and Steyn in 1951	electromagnetic Pari technique (Enslin 1952, 1955) - no formal report, field notes only (Pari = phase and amplitude ratio instrument	
•	Fayazi et al. (1981)	electrical depth probing and ground magnetics.	
•	Bush (1989) and Du Toit (1989)	ground magnetics	
		electrical resistivity	
		electromagnetic	Genie SE-88
			Geonics EM-34
			Omni-plus VLF
			Airborne Barringer INPUT
•	Geodass (1989) and Du Toit (1990)	seismic refraction	

A mining company conducted the airborne INPUT survey in the Swartwater area for mineral exploration. Follow-up Genie surveys over four major INPUT anomalies proved inconclusive in that no corresponding anomalies were found. The reason for the airborne anomalies is unknown. At this stage no conclusions about the value of airborne EM surveys - time as well as frequency domain - in groundwater exploration in Region 3 is possible. Results of the other, latest geophysical work, will however, be discussed below. An exposition of the fundamentals and physical interpretation of the various geophysical methods, their merits and limitations lies outside the scope of this monograph. Wiegmans (1990) has listed relevant references. For an evaluation of frequency-domain electromagnetic methods in groundwater exploration in South Africa the reader is also referred to Wiegmans (1990).

Magnetic and electrical methods

As weathering is nearly everywhere shallower than the water level, the premise has been mainly one of locating linear water-bearing features. Bush (1989) and Du Toit (1989) have both reported on the application of a combination of magnetic and electrical methods / techniques. A brief summary of their findings follows:

1. Magnetics should always be conducted preferably at the start of the investigation, to determine the possible presence of basic/mafic intrusions and to establish the magnetic properties of the country rocks. Great care has to be exercised however in the interpretation of magnetic anomalies. Andersen and Less (1992) state that magnetic anomalies represent mainly mineralogical variations in the crystalline basement as a result of granulite facies metamorphism

during the Limpopo orogeny. Magnetic overprinting is apparent on aeromagnetic images, which show dominant east-west magnetic trends cutting across geological ones.

2. As the Geonics EM-34 instrument is capable of operating in both low (less than 100 ohm.m) and high resistivity environments, its use as an alternative reconnaissance tool to resistivity profiling or depth probing is recommended.
3. To select the most appropriate electromagnetic technique for further detailed work, it is suggested that the average resistivity and thickness of the overburden be determined first, using either the Geonics EM-34 or the resistivity instrument.
4. The use of the Genie SE-88 for further definition of electrical conductivity anomalies is recommended only where the resistivity of weathered layer is less than 100 ohm m. See also section 4.5.2 under 4.5 Comments
5. The VLF technique in conjunction with Geonics EM-34 or resistivity profiling is the best choice for detail work where the thickness and resistivity of the weathered zone are respectively less than 30 m and 150 ohm m. A serious limitation of the VLF technique is the general weakness of the world-wide VLF transmissions in South Africa.
6. Useful detail data are also obtainable by the Geonics EM-34 instrument in conjunction with Wenner resistivity profiling where the resistivity of the overburden is greater than 100 ohm m and the depth of the water level is less than 40 m.
7. As Schlumberger soundings are less affected by lateral resistivity changes than those using the Wenner configuration, they are preferred for determining depth of weathering and fracturing across EM anomalies. Field curves are preferably interpreted by forward and inverse modelling by means of a microcomputer.
8. Being faster than Schlumberger sounding, Wenner depth probing coupled with empirical interpretation of sounding curves provide reasonable results where the depth of weathering does not exceed 35 m. The Schlumberger configuration should, in any case, be used for greater depths.

Seismic refraction

The following conclusions are based on the experimental seismic refraction survey (Du Toit 1990) that was conducted along three traverses previously covered by the different electrical exploration methods and by drilling:

1. Although there is a broad resemblance between the interpreted seismic refraction and electrical resistivity sections, layering and depths differ.
2. Sections derived from seismic and electrical methods portray different physical aspects of the substratum that cannot be directly correlated with water-bearing properties.
3. From a purely scientific point of view, seismic refraction instead of the electrical resistivity method can equally well be used for determining depth of weathering/weathering plus fracturing.
4. Calibration boreholes are required to correct for hidden (lower velocity) layers.
5. The alleged ability of locating fault zones in hard rock below the weathered zone and the water level was, however, not demonstrated on the three experimental lines. With possibly one exception, angle holes that were drilled to intercept seismically interpreted fault zones in bedrock, did not find fractured zones. The result is, however, not conclusive (see section 4.4.4).
6. There is little need to replace the electrical exploration methods with seismic refraction.
7. Its high cost and the logistics of having to use explosives, rule out seismic refraction surveys for the selection of borehole sites in all but areas of shallow weathering/fracturing where the weight drop technique may be used.

4. CASE HISTORIES OF BOREHOLE SITING AND DRILLING

The examples are from work done by Bush (Bush 1989 and Du Toit 1989 and 1990). The farms Koperfontein 161 MR, Witdrift 41 LQ, Kaffersfontein 135 LQ and Wellust 73 LQ are considered fairly representative of conditions and problems encountered in the Swartwater and Beauty areas. Unfortunately, no documentation is available in which the interpretation of the frequency-domain EM work and the reasoning behind the siting of the boreholes are set out.

Experimental seismic refraction surveys along Genie and Geonics traverses on three farms were conducted and interpreted by Geodass (Pty) Ltd. The seismic work was mainly aimed at locating steeply dipping structures within bedrock rather than determining weathering profiles. In keeping with the geophone spacing, Geodass estimates the location accuracy of such structures to be 5 m. Three types of steeply dipping interfaces have been distinguished by Geodass: probable fault, possible fault and lithological boundary. Why velocity discontinuities are interpreted as faults and on what grounds three types of structures may be distinguished, is not stated. Changes in bedrock velocity and slope appear to be the main criteria.

4.1 KOPERFONTEIN 161 MR (geophysical line1 and section see Figure 35)

Salient features are:

1. Situated in the Swartwater area
2. Very shallow weathering and water level
3. Omni-plus VLF and Genie SE-88 profiling across east-west striking dyke
4. Also magnetics and resistivity depth probing.

Magnetic, EM Genie and resistivity depth probing were done initially. The Genie response is weak. The positive peak over the dyke is the result of deeper weathering on both sides of the dyke. No anomaly/anomalies typical of a steeply dipping conductive sheet(s) i.e. fractured dyke contact zone(s) is/are evident. Boreholes G37755 and G37756, which were drilled on both sides of the dyke, were apparently not sited on the strength of the Genie response.

At a later stage, a prominent peak in the total field component was located with a VLF survey. The anomaly coincides with a shallow basin of weathering. Borehole G38544 which was drilled subsequently, passed through 8 m of fractured and highly weathered gneiss and struck a supply of 6.66 $\ell\ s^{-1}$ in fractured leuco-gneiss before passing into solid leuco-gneiss at a depth of 19 m. By comparison, the depth of weathering and of the base of the fractured zone in boreholes G37755 and G37756 are respectively 3 and 2.5, and 17 and 12 m. The water level is 9 m deep. Note that the VLF survey was not essential for siting hole G38544. It could just as well have been selected on the strength of the resistivity depth probing only.

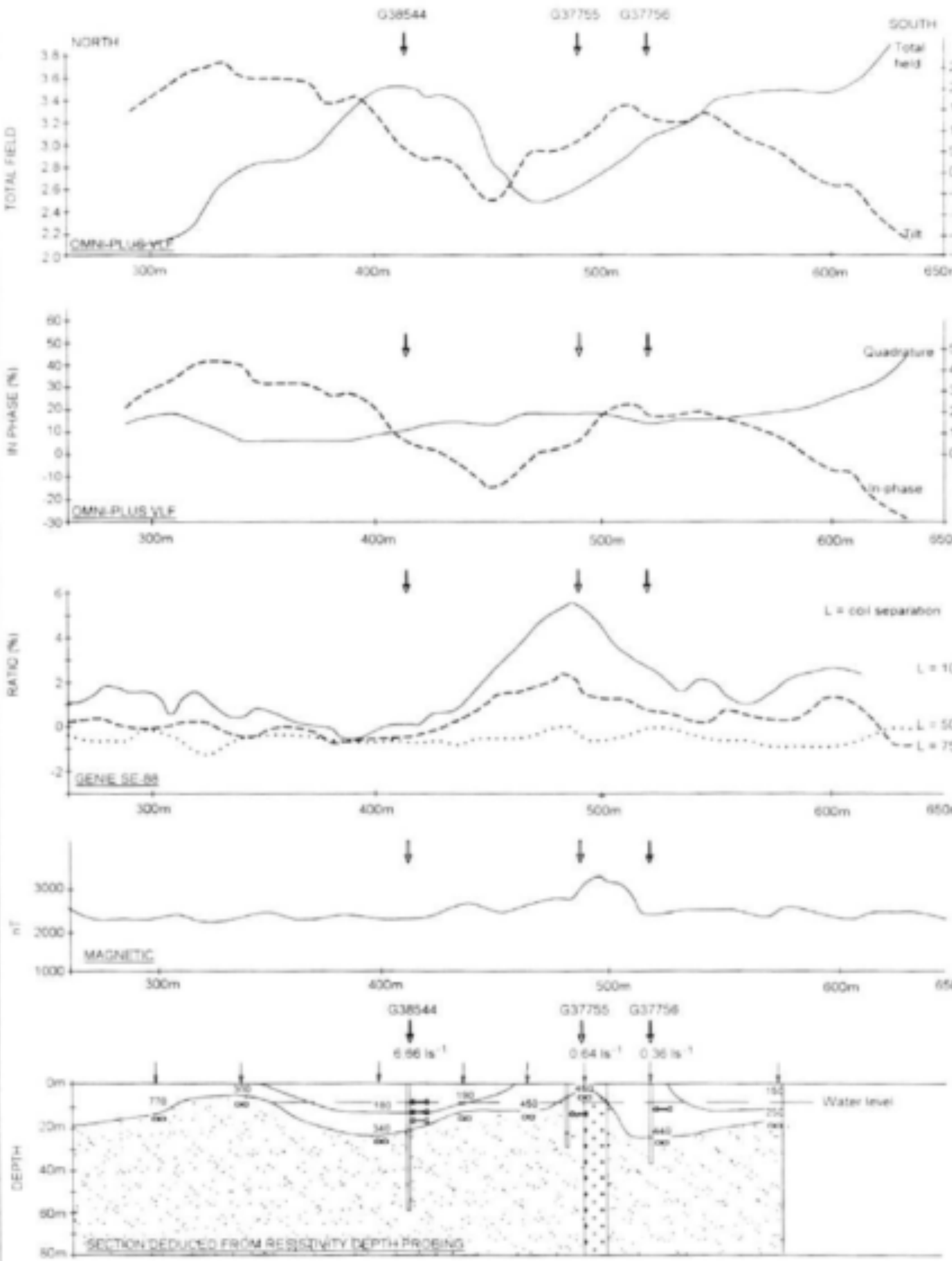


Figure 35 Geophysical traverses and interpreted geological section - Koperfontein 161 MR (after Bush 1989, Du Toit 1989)

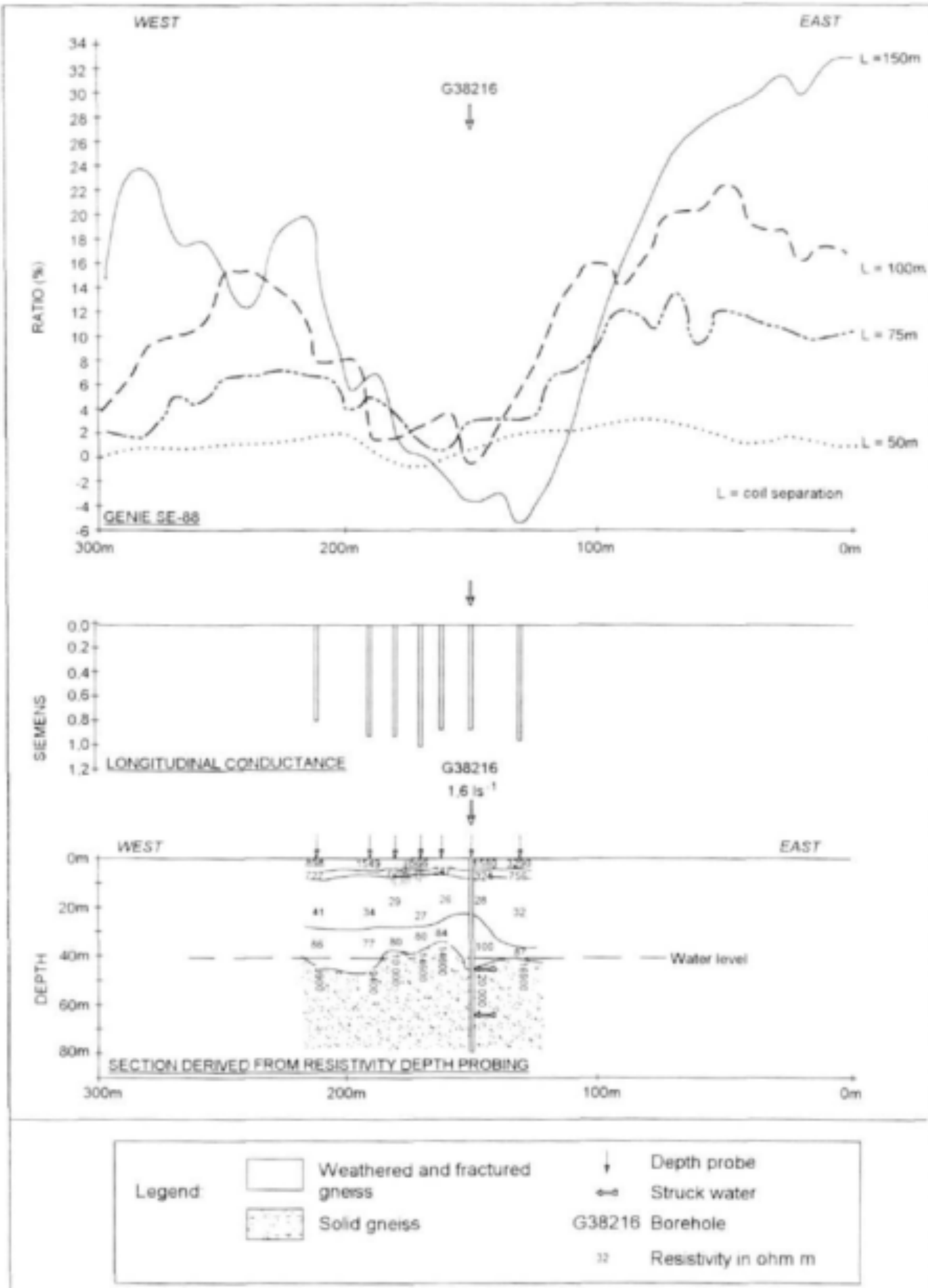


Figure 36 Geophysical traverses and interpreted geological section - Witdrift 41 LQ (after Bush 1989; Du Toit 1939)

4.2 WITDRIFT 41 LQ (geophysical line 3 and section, see Figure 36)

Salient features are:

1. Situated in the Beauty area
2. No lineament
3. Genie SE-88 profiling perpendicular to formational trend.
4. Magnetics (not shown in Figure 36), resistivity profiling and depth probing on Genie traverse
5. Presentation of longitudinal conductance value
6. Base of weathering and water level about 40 m deep.

Wiegmans (1990) states that the Genie anomaly is an example of the type where successful boreholes have been drilled elsewhere. According to him the anomaly is due to an easterly dipping conductive zone. Whether this explanation is correct remains unproven. The attitude of the fractures that yielded water (borehole G38216) and their relation to the overlying weathered rock is not obvious from the drilling result and the interpreted section.

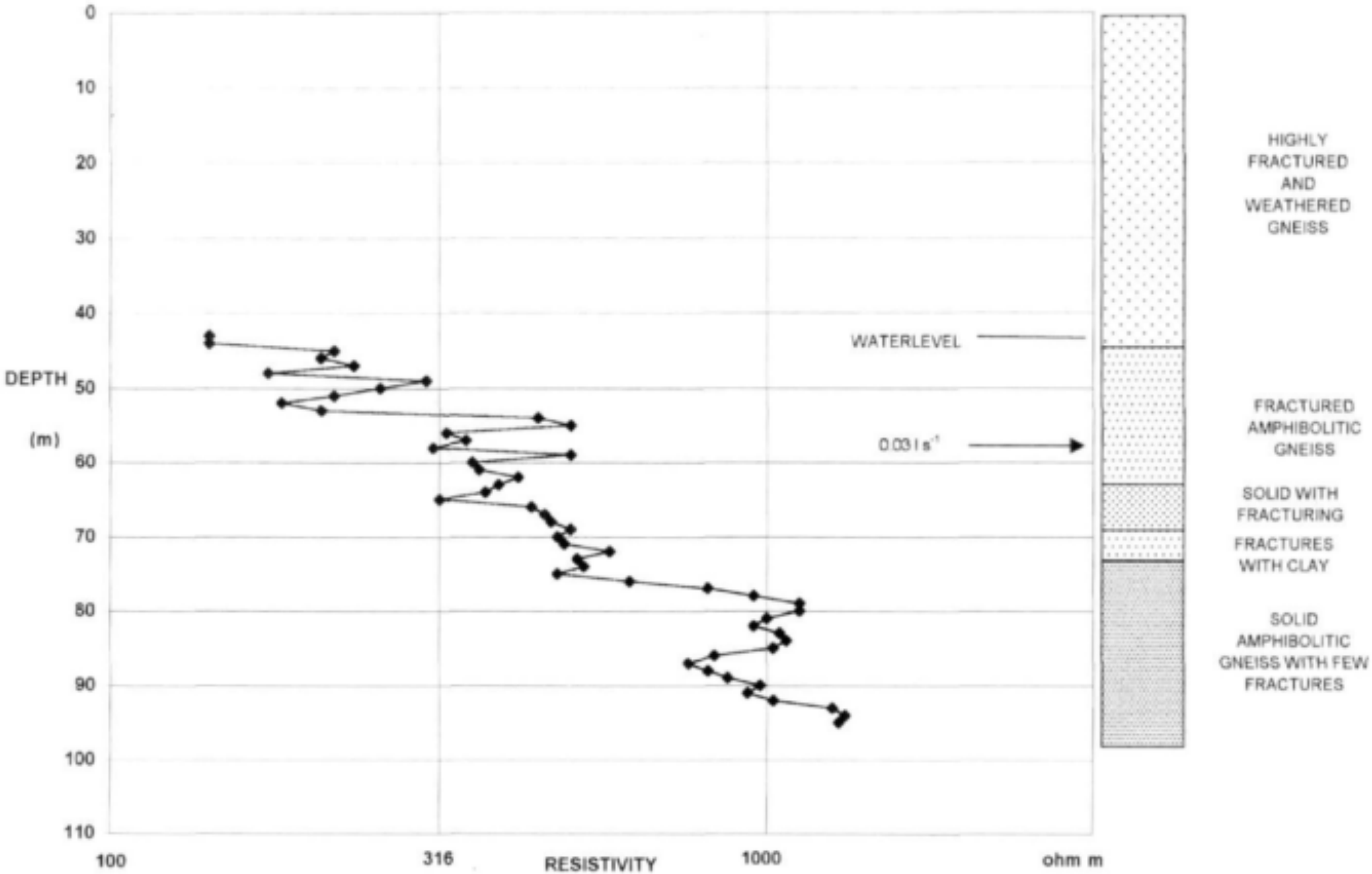
The Genie anomaly coincides with a resistivity profiling low. Unfortunately, electrical depth probing has not been extended far enough to establish whether depth of weathering and longitudinal conductance decreases sideways. As in the case of Koperfontein the possibility of siting a successful borehole within the 100 m wide weathered zone on resistivity depth probing only, cannot be ruled out.

4.3 KAFFERSFONTEIN 135 LQ (geophysical line 1 and sections; Figures 37, 38, 39, 40 and 41) (Figure 37 at back)

4.3.1 Salient features

1. Situated in that part of the Beauty area that is severely deficient in groundwater supplies.
2. Geonics EM-34, Genie SE-88 and Omni-plus VLF profiling across a NW to NNW curving lineament i.e. the most favourable orientation of faults according to Andersen and Less - see section 3.2.3.2 Faults, shears and fracture zones.
3. Magnetics (not shown in Figure 37) and resistivity depth probing.
4. Presentation of longitudinal conductance values.
5. Line of vertical boreholes across the lineament (Figure 37).
6. Base of weathered zone and of water level both exceed 40 m.
7. The water level lies within the weathered zone.
8. The transition zone between weathered and fresh rock is not permeable.
9. Clay-filled fractures were encountered in one borehole between 67 and 69 m in solid amphibole gneiss.
10. Seismic refraction was done after the initial vertical holes had been drilled.
11. One vertical and two angle holes were subsequently drilled in an attempt to intercept faults interpreted from the seismics (Figure 39).
12. Several holes were logged geophysically after having been filled up to the surface with water.

FIGURE 38 ELECTRICAL RESISTIVITY AND GEOLOGICAL LOGS OF BOREHOLE G38540
KAFFERSFONTEIN 135 LQ



4.3.2 Omni-plus VLF

As is to be expected from VLF profiling, the tilt and vertical in-phase component behave similarly. Whilst the tilt and in-phase responses near borehole G 38540 are apparently indicative of a vertical conductor, this is not confirmed by the vertical quadrature component. Borehole G38540 was drilled on the crossover point, which theoretically should lie directly above a vertical conductor. The geological and electrical logs of borehole G38540 are shown in Figure 38. Note that clay is present between 67 and 69 m depths in amphibolitic gneiss and that permeable fracturing is lacking well below the water level of 43 m.

Although the comparatively deeper weathering and fracturing may be indicative of a steeply dipping geological feature, the nature and form of the conductive material responsible for the VLF anomaly can not be determined from the available data. No anomalies were recorded in this position on the Genie and Geonics traverses. The second of the four positive VLF total field peaks on this traverse coincides roughly with a broad Genie positive (100 m coil separation) and with the main Geonics anomaly.

4.3.3 Genie SE-88

Negative Genie anomalies are not well defined. Correlation between the different coil separations is also uncertain. Wiegmans (1990) states that because the negative peak values are more positive with increasing coil separation, the anomalies have to be ascribed to conductivity variations in the overburden (= weathered zone?). They are due to current channeling rather than to toroidal induction.

Boreholes G38069, G38070, G38173 and G38174 have been drilled on the broad Genie and VLF total field positive referred to above. The positive anomalies presumably coincide with the previously mentioned lineament.

Hole G38539 has been drilled on what appears to be a southwest dipping conductive feature. On the seismic section (Figure 39) referred to below, an interpreted fault coincides with hole G38539. An alternating succession of weathered and fractured to highly fractured gneiss was encountered in this hole down to 58 m.

Borehole G38172 is situated on a Genie negative. The negative peaks of the different coil separations do not line-up well. A Geonics anomaly is associated with this negative. Whereas hole G38539 apparently has been drilled in or near to a dipping fracture zone, the same cannot be said about the geological log of G38172. As additional data/information are lacking, no further attention will be given to these two holes.

4.3.4 Geonics EM-34

The Geonics traverses were conducted with horizontal and vertical coil configurations and separations of 10, 20 and 40 m. The main anomaly consists of a positive peak, which broadens and flattens with larger vertical coil separation. It coincides with the positive VLF and Genie anomalies referred to above on which boreholes G38069, G38070, G38173 and G38174 have been drilled. With the horizontal coil configuration the anomaly changes from positive with the 10 m separation to negative with the 20 and 40 m separations. The anomaly, therefore, appears to be due to a 10 to 20 metre wide zone of more conductive weathered material. This zone is also evident from the higher longitudinal conductance and coincides with the deepest weathering as interpreted from resistivity depth probing. As mentioned above, it presumably coincides with the lineament.

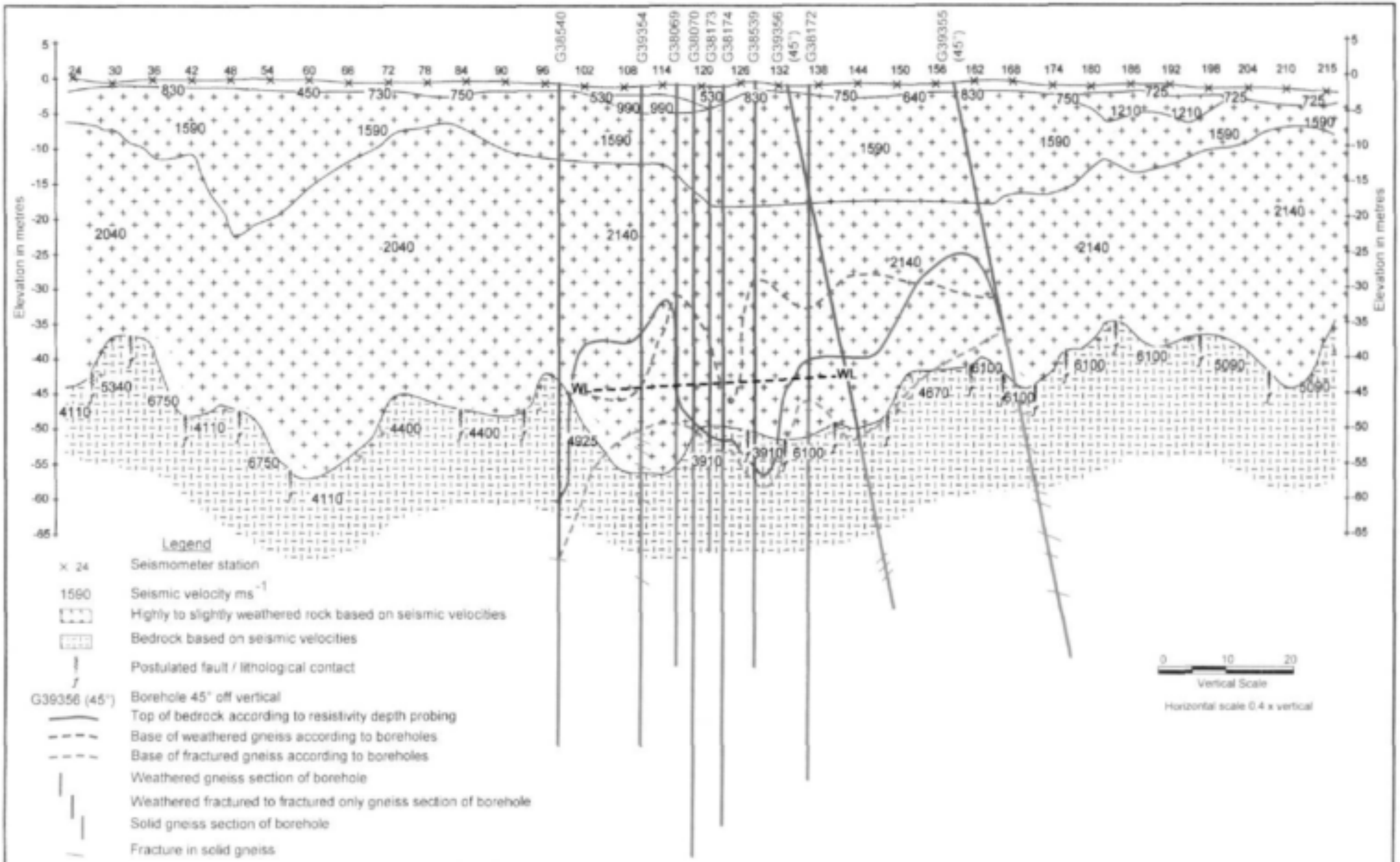


Figure 39 Exploratory boreholes superimposed on calibrated seismic section (according to Geodass (Pty) Ltd.) - Kaffersfontein 135 LQ (See figure 41 for detailed section across NW striking lineament - boreholes G38069 to G38174)

4.3.5 Seismic refraction

The Kaffersfontein seismic section is presented in Figure 39. To accentuate bedrock irregularity, Geodass has used a vertical scale 2.5 times the horizontal. Bedrock velocities vary from 2 590 to 6 750 m s^{-1}. Velocities of 2 500 to 4 000 m s^{-1} are probably representative of rock varying from somewhat weathered and fractured to fresh and fractured. Velocities exceeding 4 500 m s^{-1} may be taken as characteristic of solid rock. The zone of higher longitudinal conductance, into which boreholes G38069, G38070, G38173 and G38174 have been drilled, is underlain by bedrock having a seismic velocity of 3 910 m s^{-1}. It is also interesting to note that the superficial layer with a velocity of between 500 and 800 m s^{-1} is locally underlain within this zone by material with a velocity of 990 m s^{-1}. Elsewhere the superficial layer is directly followed by material with a velocity of 1 590 m s^{-1}. The velocity of 990 m s^{-1} is an indication of more thoroughly decomposed rock. The correlation between the different EM, resistivity and seismic results is quite good.

4.3.6 Electrical resistivity borehole logging and deduced geological section

Figure 40 depicts the electrical logs of boreholes G38540, G38069, G38070, G38173 and G38174 from near surface to the bottom. The geology and mean segmented resistivities as deduced from the electrical borehole logs are shown in Figure 41. Note the resistivity variations and lows recorded within the weathered zone as well as resistivities of less than 1 000 ohm m encountered in borehole sections which have been described as solid. It is postulated that the resistivity lows represent steeply dipping fractures and that the resistivities of less than 1 000 ohm m in solid rock are due to small offsets at depth between near-vertical fractures and boreholes. A possible fracture configuration is illustrated.

It is evident that if this concept is correct, the attitude of steeply dipping fractures has to be determined within the weathered zone by means of relatively shallow and closely spaced holes. Besides meticulous sampling and examination of drill cuttings, electrical logging from the surface is essential. Once the existence and attitude of fractures has been established, holes can be sited to strike fractures at greater depths.

Whether the postulated steeply dipping fractures are clay filled and if so whether they open up or simply change into tight fresh bedrock fractures deeper down will have to be established by drilling.

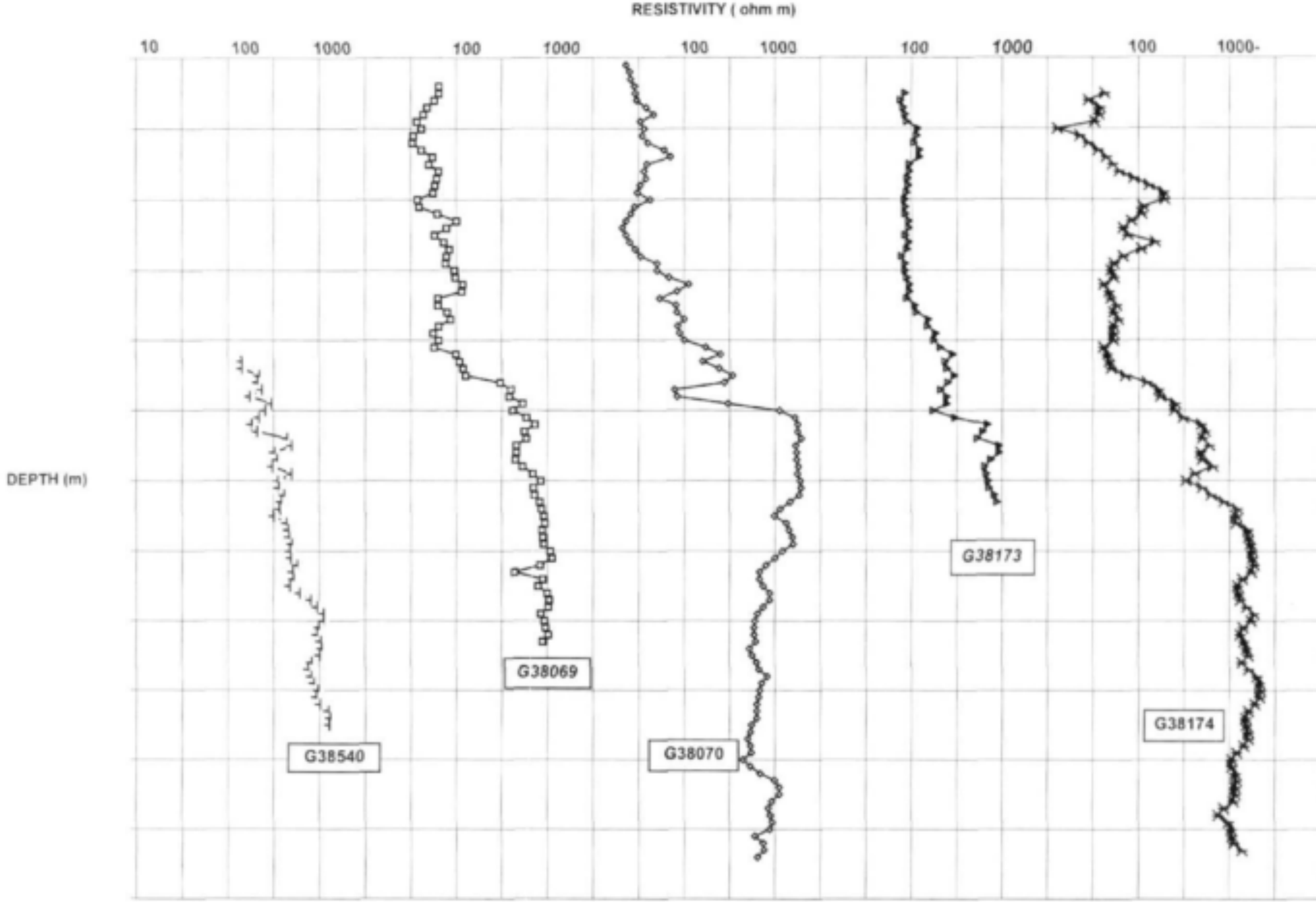
4.3.7 Depth of weathering

It is interesting to note that weathered granite, gneiss and schists have been encountered underneath appreciable thicknesses of Karoo Beds in coal prospecting holes on three farms situated near the northern edge of the adjoining Waterberg Karoo basin (Venter 1945). See Table 13 and Figure 2. The Fairfield borehole is situated about 9 km southwest of the exploratory drilling on Kaffersfontein; the other two are about 16 - 17 km south of the exploratory work on Wellust 73 LQ which is to be discussed below.

TABLE 13 WEATHERED BASEMENT BELOW KAROO BEDS

Farm name and No	Prospecting borehole No	Thickness of Karoo beds (m)	Thickness of weathered basement (m)	Depth to base of weathering (m)
Fairfield 154 LQ	18	72	28	100
Grootvley 165 LQ	12	187	21	198
Waterval 123 LQ	19	116	20	138

FIGURE 40 ELECTRICAL RESISTIVITY LOGS OF BOREHOLE DRILLED ACROSS LINEAMENT ON KAFFERSFONTEIN 135 LQ



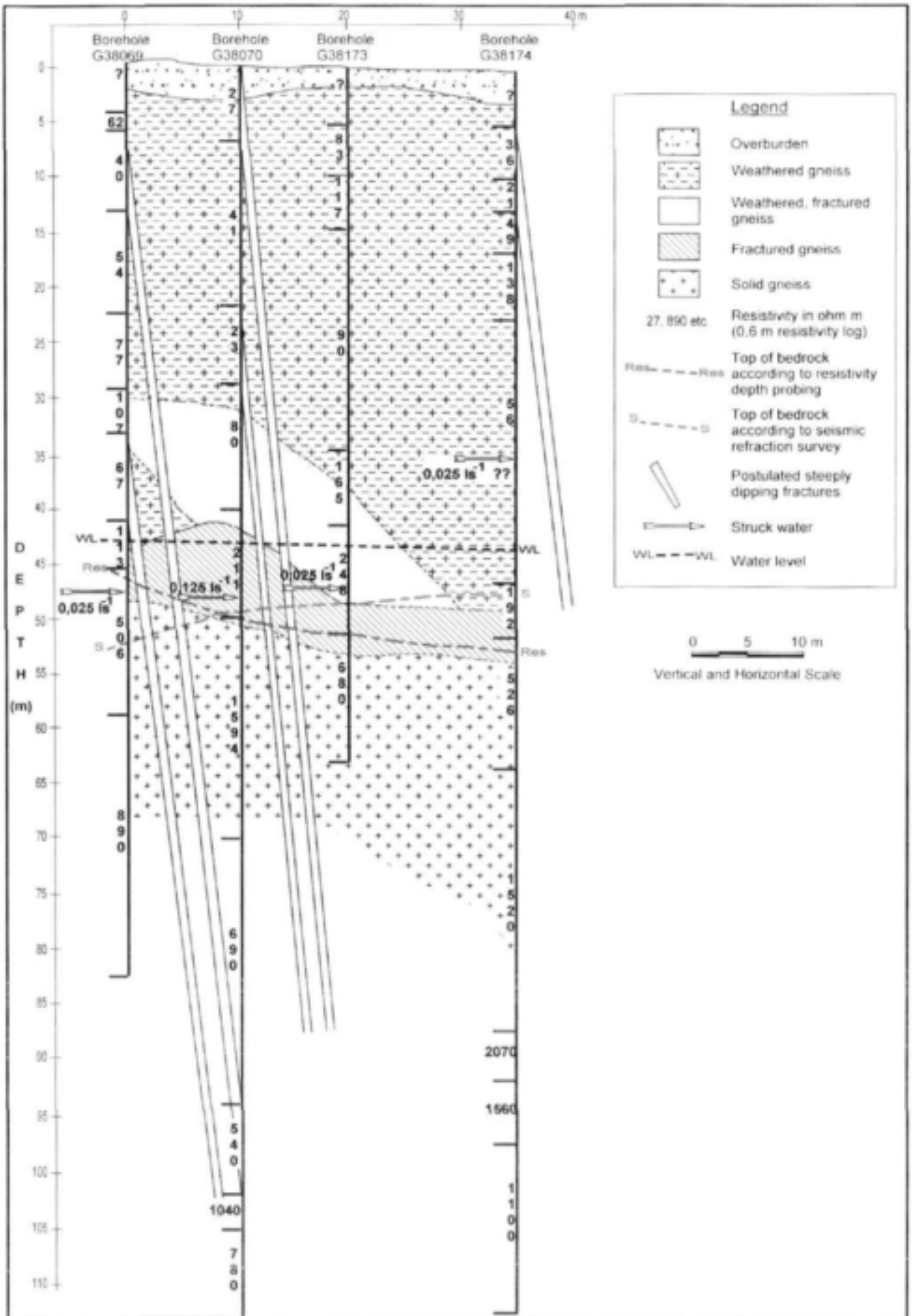


Figure 41 Resistivity lows on borehole logs postulated as indications of steeply dipping fractures - Kaffersfontein 135 LQ (see also figures 37, 39 and 40)

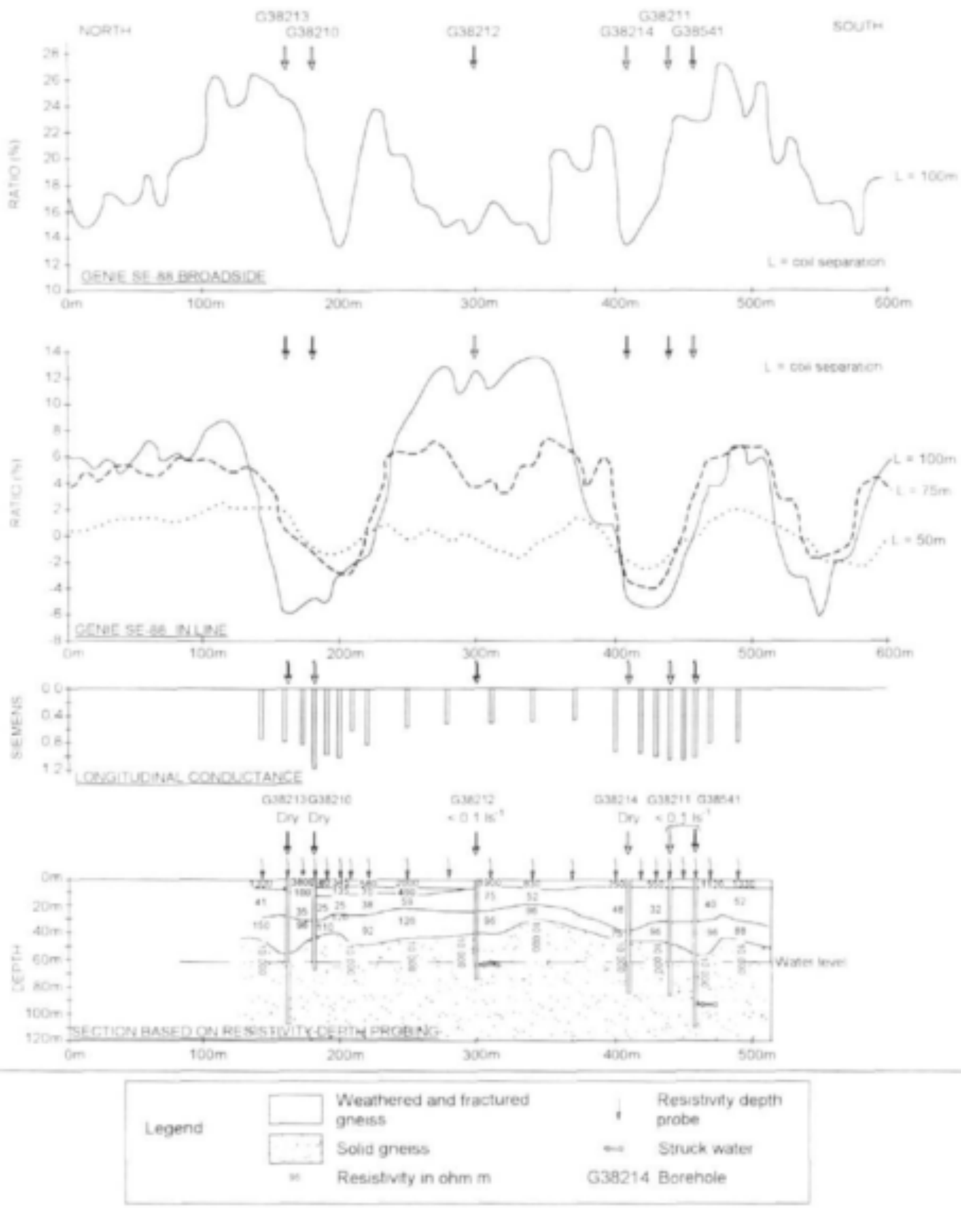


Figure 42 Geophysical traverses and interpreted geological section - Wellust 73 LQ (after Bush 1989; Du Toit 1989) (see also figures 43, 44, 45 and 46)

These farms lie at about the same elevation as Kaffersfontein i.e. at about 850 m a.m.s.l. The surface elevation on Wellust is about 830 m a.m.s.l. Weathering below the Karoo strata may be either of pre-Karoo age or the result of post-Karoo to Recent groundwater drainage along a fault zone that is present not far to the south of the coal prospecting holes.

The possibility that weathering may extend much deeper locally in this part of the Beauty area than has hitherto been found, should therefore be kept in mind. It may consequently be necessary to drill considerably deeper on well-defined fracture zones. The question whether water-bearing (permeable) fractured rock is present at depth still has to be resolved.

The existence of thermal springs lends support to the idea of deep groundwater circulation along fault zones in Region 3. Positions of the springs are shown in Figure 2 and some details are tabled below. Thermal water has also been struck at different levels between 488 and 945 m in the copper mines at Messina (Kent 1949). The geothermal step based on virgin rock temperatures in diamond holes in Harper mine works out at 41 m per °C. On this basis and a mean annual air temperature of 22°C, thermal water rises from depths ranging from 150 m in the case of Paddysland to 1 750 m at Tshipise. Discharges of thermal water need not be large, and mixing with shallow groundwater may take place, especially in sand-filled streambeds. It seems possible that small and dispersed discharges of thermal water may escape notice and that deep circulation may be more voluminous than is indicated by the few springs.

TABLE 14 THERMAL SPRINGS
(Kent 1949)

Name	Temperature °C	Flow $\ell\,s^{-1}$	Geological structure
Tugela 171 MR	42,8	0.14	Joints in gneiss
Paddysland 168 MR	26	?	?
Evangelina 71 MS	32.5	?	Diabase dyke in gneiss
Constantia 133 MT	37.7	0.1	Fault in gneiss
Vetfontein 360 MS	29.5	?	Letaba basalt faulted against Gneiss
Tshipise	65	9.5	Intersection of two post-Karoo faults

4.4 WELLUST 73 LQ (geophysical line 2 and sections see Figures 42, 43, 44, 45 and 46)

4.4.1 Main features

1. Situated in that part of the Beauty area that is severely deficient in groundwater supplies.
2. No mapped lineament; section perpendicular to east-west formation trend lines shown on geological sheet 2326 Ellisras.
3. In-line and broadside Genie SE-88 profiling across trend lines.
4. Magnetics, resistivity profiling and depth probing.
5. Presentation of longitudinal conductance values.
6. A line of boreholes was drilled across EM anomalies.
7. Base of weathered zone and of water level both exceed 40 m.
8. The transition zone between weathered and fresh rock is not permeable.
9. Seismic refraction was done after the initial vertical holes had been drilled.

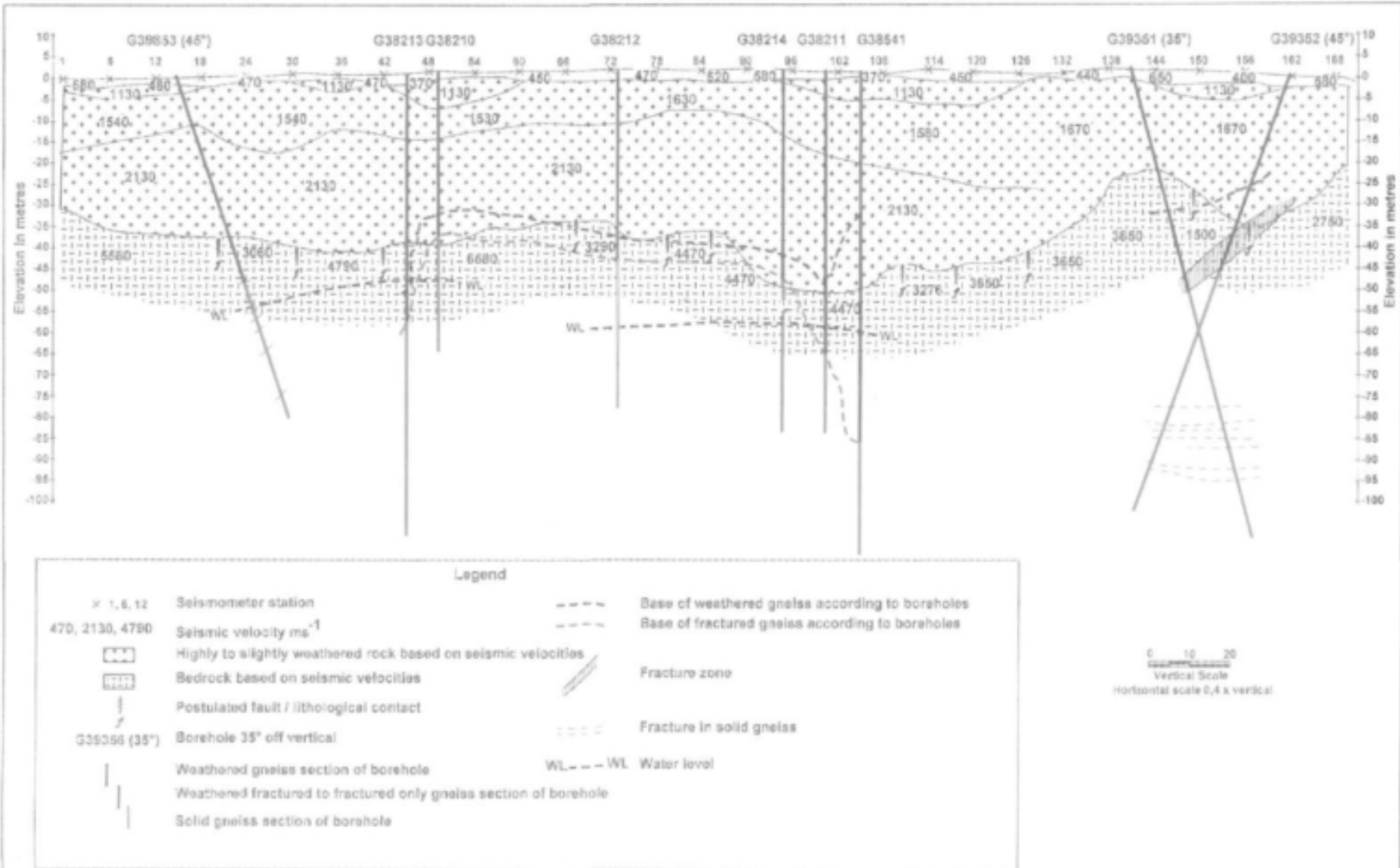


Figure 43 Exploratory boreholes superimposed on calibrated seismic section (according to Geodass (Pty) Ltd.) - Wellust 73 LQ
(See figure 46 for detailed section across NW striking lineament - boreholes G38214 to G38541)

10. Three angle holes were subsequently drilled in an attempt to intercept faults interpreted from the seismics.
11. Several holes were logged geophysically after having been filled up to the surface with water.

4.4.2 Genie SE-88

In-line as well as broadside Genie profiling located three well-defined negative anomalies. The anomalies are examples of the type where successful boreholes have been drilled elsewhere according to Wiegmans. Higher longitudinal conductance and deeper weathering according to resistivity depth probing characterize the two negative anomalies that were drilled (Figure 42).

4.4.3 Seismic refraction

As in the case of Kaffersfontein, Geodass has produced a seismic refraction section with vertical scale 2.5 times the horizontal (Figure 43). Bedrock velocities vary from 1 500 to 5 580 m s^{-1}. Velocities from 1 500 to 3 650 m s^{-1} are taken to represent rock ranging from weathered and fractured to fractured only. Velocities of 4 500 m s^{-1} and over presumably characterize solid rock. The seismic survey confirms that deeper weathering coincides with the Genie anomalies. However, contrary to the Kaffersfontein example, the bedrock velocity is that of solid not of fractured rock. As with Kaffersfontein, the Genie anomalies are associated with a second near-surface layer. Its velocity is intermediate between that of the superficial and the 1 590 m s^{-1} weathered rock layer, which elsewhere directly underlies the superficial layer.

4.4.4 Result of inclined drilling

As a result of the seismic survey further exploration drilling on the two Genie anomalies was apparently not considered justifiable. Instead, two other sites on the line were chosen. In the south two angle holes were drilled where a 1 500 m s^{-1} bedrock zone and depression is bounded by two postulated faults. The other feature on which one angle hole was drilled is a low-velocity bedrock zone of 3 090 m s^{-1} in the north which, according to the interpretation, is also bounded by faults. All three boreholes G39351, G39352 and G39353 failed to strike water.

Du Toit (1990) discussed the outcome of the three angle holes and questioned the existence of the faults. A re-evaluation of the data of holes G39351 and G39352 leads to a different picture. A northerly dipping fracture zone deduced from the geological logs and indicated in Figure 43 may be correlated with the southern fault flanking the 1 500 m s^{-1} zone. This fracture zone was penetrated by both angle holes well above the water level. On the other hand, the zones of small fractures which were penetrated between 70 m and 90 m in both angle holes, are seen as a more or less horizontal zone of fracturing rather than possible prolongation of the two faults deduced from the seismics.
The absence of a well-defined fracture zone(s) in borehole G39353 does not necessarily prove that the faults deduced from the seismics do not exist, or if they do, that they have no groundwater significance. A single hole may have missed them especially as the attitude of the faults or perhaps, more correctly, of the velocity discontinuities is unknown. A supposition that they are more or less vertical is not justified.

4.4.5 Electrical resistivity borehole logging and deduced geological section

Geological and electrical logs of boreholes G38213 and G38210, which were drilled on the northernmost Genie anomaly, are shown in Figure 44. Borehole G38210 failed because depth of weathering and fracturing falls short of the water level at 47.5 m. G38213 also failed in spite of weathered and fractured rock extending down to 54 m. Are the fractures clay-filled or tight? The reason

FIGURE 44 ELECTRICAL RESISTIVITY AND GEOLOGICAL LOGS OF BOREHOLES G38210 AND G38213 WELLUST 73 LQ

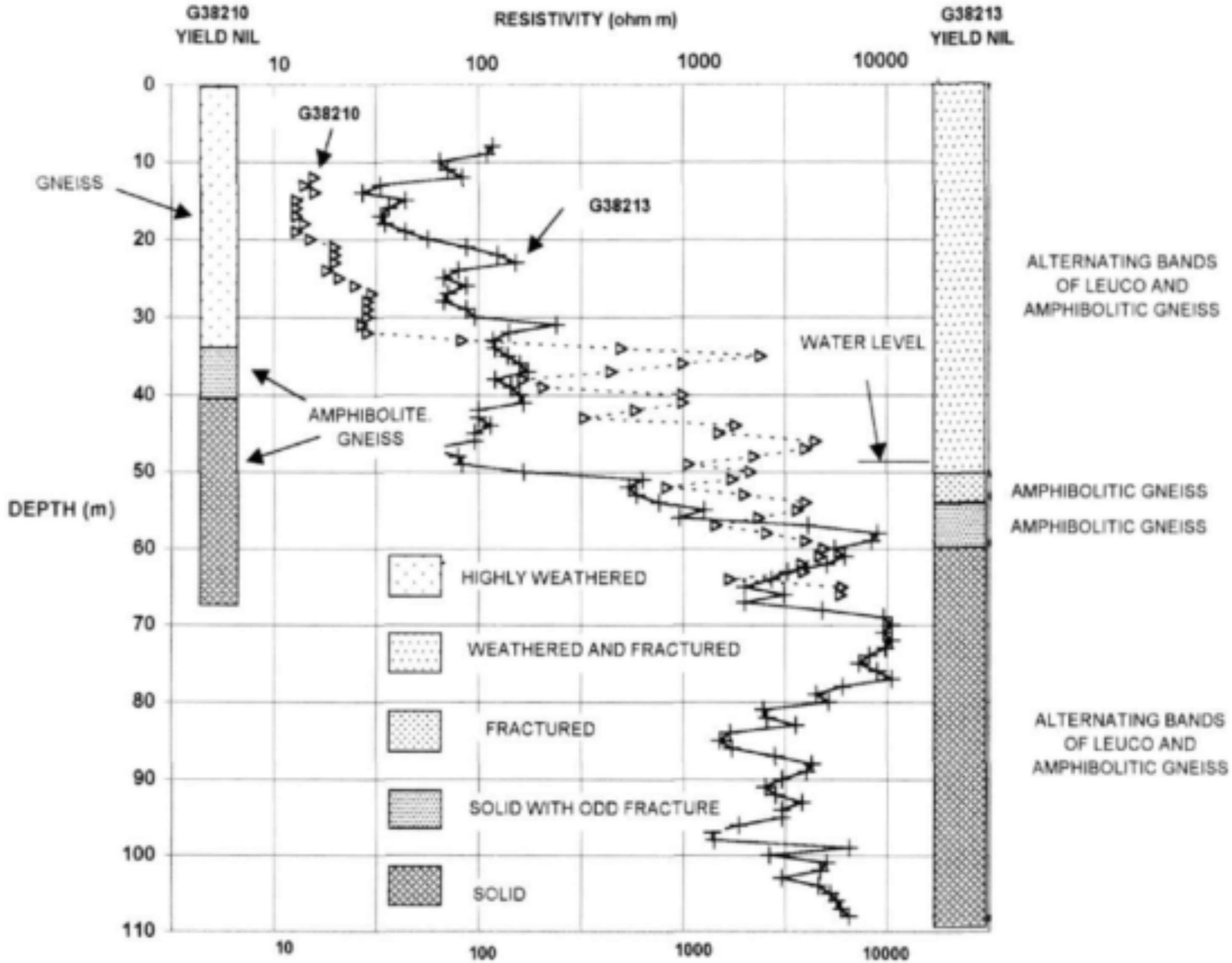
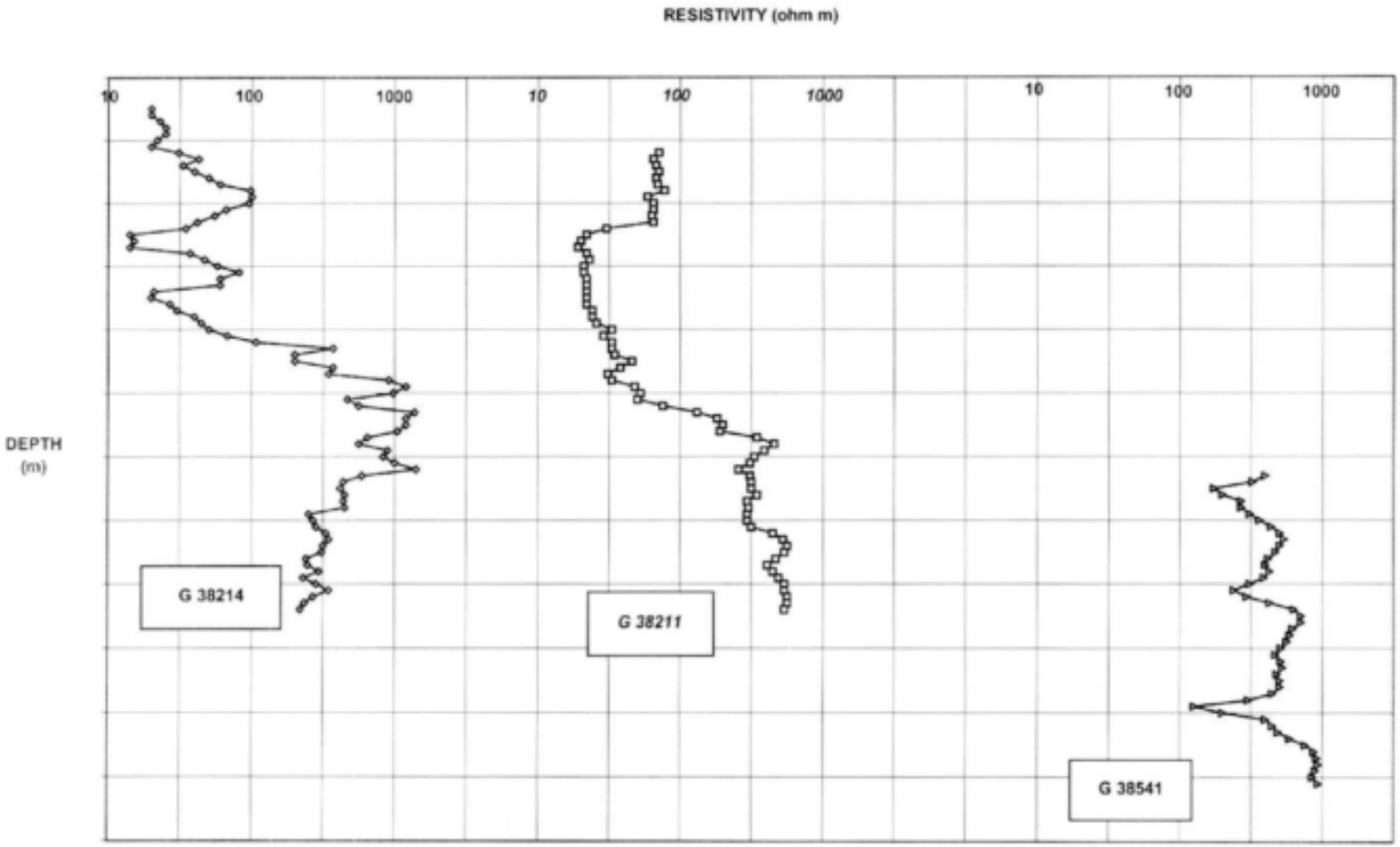


FIGURE 45 ELECTRICAL RESISTIVITY LOGS OF BOREHOLES G 38214, G 38211 AND G 38541 WELLUST 73 LQ



for the strongly fluctuating high resistivity values in the solid rock sections of the two boreholes is also not clear. They cannot be ascribed to fluctuations in borehole diameters.

The large difference in the resistivities and depths of weathered rock in holes a mere 20 m apart is noteworthy and may be taken as an indication:

- that the Genie anomaly is due to a narrow zone of highly weathered clayey and, therefore, more conductive rock;that the zone of highly weathered rock is the upper expression of a (steeply?) dipping fracture zone.

At least one borehole between G38210 and G38213 will be needed to prove or disprove this supposition. Should the supposition of a steeply dipping fracture zone prove to be correct, drilling should aim to establish whether fractures are:

- clay-lined directly below the water level;
- permeable or tight deeper down.

The orientation of the fractures with respect to the neotectonic stress field may prove to be decisive.

Electrical logs of boreholes G38214, G38211, G38541 have been reproduced in Figure 45. Unfortunately, hole G38541 was logged below the water level only.

Figure 46 depicts the geology and mean segmented resistivities as deduced from the electrical borehole logs. Note the resistivity variations and lows that were recorded within the weathered zone and the resistivities of less than 1 000 ohm m that were encountered in borehole sections which were described as being solid. As in the case of Kaffersfontein, it is postulated that the resistivity lows represent steeply dipping fractures and that the resistivities of less than 1 000 ohm m in solid rock are due to small offsets at depth between near-vertical fractures and boreholes. A possible fracture configuration is illustrated in Figure 46.

Whether the postulated steeply dipping fractures are clay filled or not or whether they open up or simply change into tight fresh bedrock fractures deeper down will have to be established by drilling.

4.5 COMMENTS

4.5.1 Electrical resistivity surveying

Electrical resistivity depth probing is well-suited for locating and determining depths of basins or troughs of weathering in Region 3. Provided the depth of weathering is deeper than the water level and that both are shallower than about 40 m, borehole siting should be about 75 % successful.

Owing to a misconception Du Toit (1989) has over-rated the value of resistivity profiling. Horizontal resistivity profiling does not portray resistivity variations at a specific depth e.g. at a depth equal to the electrode spacing.

Except for establishing depth of weathering, electrical depth probing is by itself inappropriate for the siting of boreholes where narrow zones of weathering and fracturing in bedrock have to be explored i.e. in the absence of:

a) basins/troughs of weathering,
b) permeable fracturing at the base of the zone of weathering as appears to be the case where weathering extends deeper than 40 m.

Under such circumstances frequency-domain electromagnetic surveys may provide the solution.

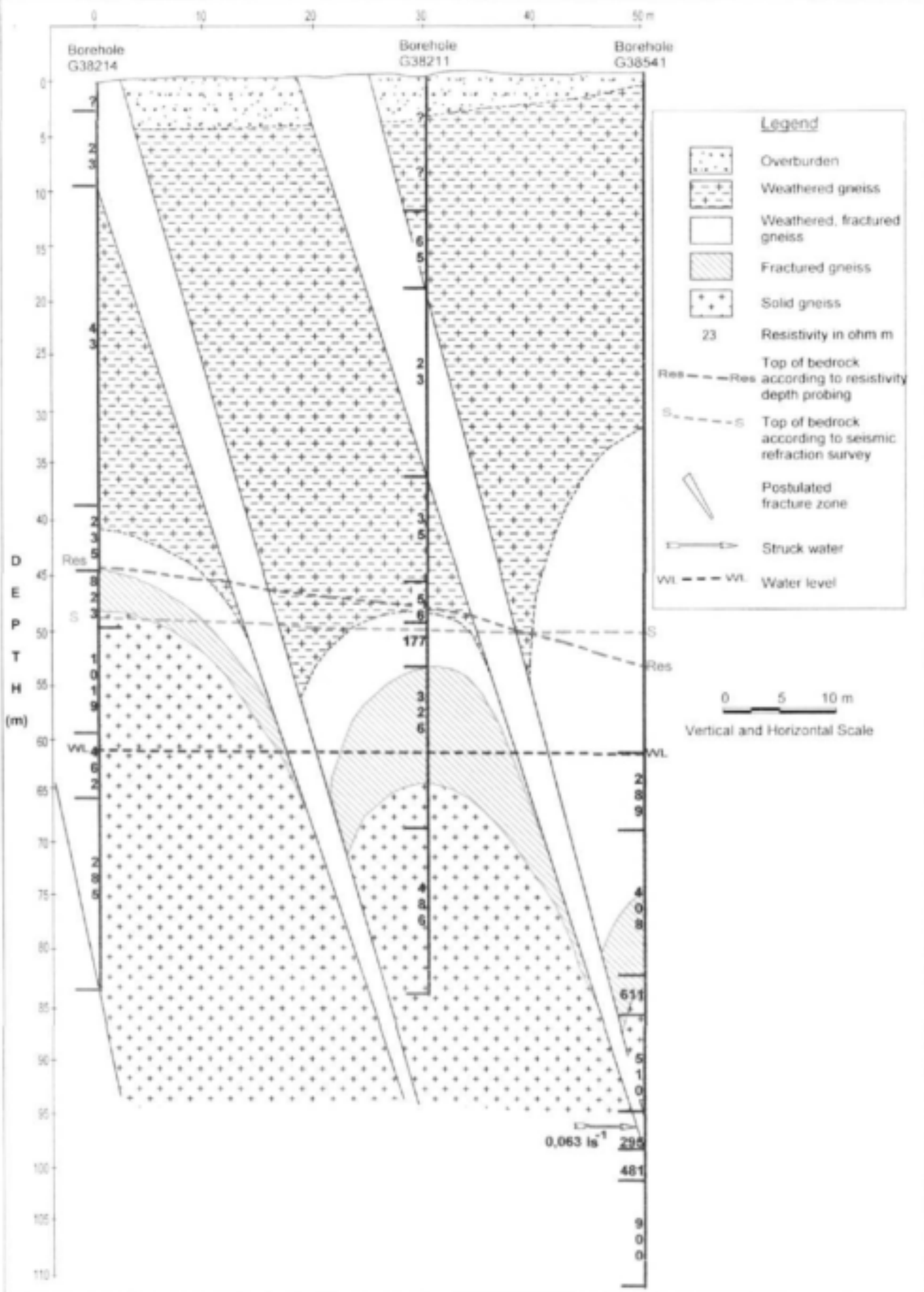


Figure 46 Resistivity lows on borehole logs postulated as indications of dipping fracture zones - Wellust 73 LQ (see also figures 42, 43 and 45)

4.5.2 Frequency domain electromagnetic surveying

Application of the various frequency domain EM methods is based on the assumption that:

1. Bedrock contains aquifers that are dipping two-dimensional (sheet-like) bodies e.g. single fractures or fracture zones.
2. Bedrock aquifers act as sheet-like electrical conductors capable of producing a measurable signal when excited electromagnetically.
3. Alternatively, the upward continuation of water-bearing fractures/fracture zones into the weathered unsaturated zone are EM-detectable and are distinguishable from the EM response of other conductors within the weathered zone.

The critical question is: "Are the Genie anomalies on which boreholes have been sited in the Swartwater and Beauty areas caused by bedrock conductors, that is by water-bearing fractures or fracture zones?".

Theoretical response profiles for dipping thin conductive plates in a non-conductive host have been reproduced in the interpretation manual of the Scintrex SE-88 Genie electromagnetic system (Lafleche and Johnson 1983). To produce a small negative ratio anomaly of 5% with a coil separation of 150 m and a frequency pair of 3037.5/112.5 herz, the physical properties of a vertical thin conductive sheet, theoretically have to be as follows:

- conductance of plate one Siemen,
- dimensions 400 m along strike and 200 m in depth
- situated 25 m below the surface of a non-conductive host.

An anomaly of this magnitude is comparable to or even smaller than those encountered in the course of the groundwater investigations. Although the dimensions and depths of water-bearing fractures (zones) may be comparable to those of the plate model, conductances are several orders smaller. For example, a fracture containing saline water with a conductivity of 300 $mS.m^{-1}$ would have to be 3.3 m wide to have a conductance of one Siemen. The cause of the Genie anomalies obviously lies just below the surface.

The finding of Bush and Du Toit that "the use of the Genie SE-88 for further definition of electrical conductivity anomalies is recommended only where the resistivity of the weathered layer is less than 100 ohm m." should not be construed as an instrumental limitation. It is the result of geological conditions. The improbability of clayey conductive bodies existing in areas of shallow weathering and fracturing - and consequently where resistivities are in excess of 100 ohm.m - explains the absence of Genie anomalies in such environments.

The cause of the 24 significant Genie anomalies located by Bush and Field Party has to be sought in near-surface conductivity contrasts, not in bedrock-seated water-bearing fractures. The six anomalies on farms in the Swartwater area and the eighteen in the Beauty area were found where the general depth of weathering and fracturing is 30 m or more. This is a clear indication that the Genie anomalies are caused by bodies of rock which are more decomposed - clayey - than the surrounding weathered material.

It should be evident that the presumable continuation in depth of an anomalous conductive body as a permeable water-bearing fracture zone can only be established by exploratory drilling. Shallow exploratory drilling, geological and resistivity or inductive logging above the water level, is required to determine the form and attitude of the conductive body before embarking on drilling progressively deeper holes.

Unfortunately, drilling was not carried out in a manner that would establish the nature, configuration and depth extent of conductors. In most instances, one hole only was drilled on an electromagnetic anomaly. Even where more than one hole was drilled, the conductive body could apparently not be identified from the drill cuttings. The borehole spacing was also too large for a start. Resistivity borehole logging could not be carried out above the water level at the time when exploratory drilling took place. The holes on Kaffersfontein and Wellust were logged electrically after completion of the drilling programme by filling-up the boreholes with water.

It is not surprising that only 9 of the 24 Genie anomalies drilled proved to be successful. In at least three of the nine cases, other holes drilled short distances away from the Genie anomaly were also successful. Boreholes could have been sited just as well on electrical resistivity depth probing where the piezometric level is shallower than the general depth of weathering and fracturing.

Another shortcoming of much of the geophysical work is the failure to determine the strike of a geophysical anomaly by at least two additional parallel traverses. The tacit assumption that an anomaly is caused by or associated with the feature - dyke, fault, lineament - in the vicinity of which it occurs, is not justified.

It is a pity that for reasons set out above, the application of frequency-domain electromagnetic surveying coupled with appropriate drilling and geophysical borehole logging has not been demonstrated.

5. INCLINED DRILLING AND HYDROFRACTURING

5.1 INCLINED DRILLING

The difficulty of locating and striking narrow steeply dipping water-bearing fissures by means of vertical holes is well-known. Formanek and Bezuidenhout (1988) successfully demonstrated the use of inclined drilling under such circumstances at the Eersteling Gold Mine near Pietersburg. This and the alleged capability of seismic refraction surveys to locate faults/fracture zones below the base of weathering in bedrock led to an experimental program of inclined drilling on three farms: Elandshoek 243 MR (10 km east of Maasstroom in the Swartwater area; Kaffersfontein 135 LQ and Wellust 73 LQ in the Beauty area (Du Toit 1990).

Only one of the seven angle holes drilled was successful. The successful hole on Elandshoek was drilled on a weathered wide shear zone where good yields were also struck in two vertical holes. Weathering and fracturing extends to well below the water level of about 22 m. According to Du Toit, nothing that resembles a fault zone was penetrated by the angle holes. The possibility that a fault/fracture zone was penetrated by hole G39352 on Wellust is demonstrated in Figure 43. Firm conclusions cannot be drawn from the seismic refraction and inclined drilling experiment for the following reasons:

- The grounds on which fault/formation boundaries have been interpreted have not been explained. The applicability of the interpretation methodology as far as bedrock conditions are concerned, needs to be critically evaluated.
- As the attitude of the alleged faults/formation boundaries is unknown, the possibility that they have been missed or have been passed through unnoticed within the transition from weathered/fractured cannot be completely ruled out (e.g. G39352 Wellust).
- Geological logging should have been supported by at least resistivity and, ideally, also sonic logging (correlation with seismic refraction).

Fracture/fault zones are not naturally permeable (water-bearing), regardless of depth below the water level nor are they universally vertical. The siting and angle at which inclined holes are drilled is critical. Generally speaking, more than one hole may be required to determine, firstly, the attitude of the fracture or fault and, secondly, to penetrate that section below water level which is permeable.

5.2 HYDROFRACTURING

5.2.1 General remarks

The high failure rate induced the Directorate of Geohydrology to investgate the possibility of converting dud holes into useable ones by means of hydrofracturing. The technique of hydrofracturing consists basically of sealing off a section of borehole below the water level and forcing water under high pressure into the sealed-off section in an attempt to open-up any fractures that are present. The results of hydrofracturing in Region 3 are contained in a report compiled by VSA Earth Science Consultants on behalf of the Department of Water Affairs and Forestry. The report comprises "before and after" water level drawdown and recovery graphs, pressure graphs and geophysical borehole logs.

As most of the boreholes that were subjected to hydrofracturing had very small yields, the before and after yield tests consisted of measuring the time taken and the volume of water pumped out to produce a particular drawdown. Pumping times lasted from a few minutes to several hours and the volumes of water pumped ranged from about 0.1 to 25 kℓ.

The VSA report, however, fails in its evaluation of the percentage improvement as no account was taken of:

a) The volume of water in the borehole, which in the case of weak holes comprises a considerable part of that, pumped out.
b) The different before and after pumping times to produce a specified drawdown.
c) Expressing improvement as a percentage is meaningless in the case of virtually dry holes

5.2.2 Data processing

For these reasons the data were re-evaluated. The determination consisted of calculating:

1. The volume of water stored in the hole between the static and drawdown levels
2. The before and after inflow volumes by deducting stored volume from the volumes pumped out before and after hydrofracturing
3. The mean before and after inflow rates by dividing inflow volume by the times taken to produce the same specified drawdown
4. The gain or loss of inflow rate.

Details about the holes subjected to hydrofracturing are summarised in Table 15. Results of the re-evaluation are given in Table 16.

5.2.3 Discussion of results

The results may be summarised in terms of inflow rate changes as follows:

- Inflow rates were improved in 9 out of 16 holes (range + 0.11 to +1.19 $\ell\ s^{-1}$)
- Inflow rates were virtually unaffected (changed by less than + or - 0.1 $\ell\ s^{-1}$) in 5 holes
- Inflow rates decreased in 2 holes (- 0.17 and - 0.46 $\ell\ s^{-1}$)

Note that an inflow rate of more than 0.1 $\ell\ s^{-1}$ during the brief duration of the drawdown test is not necessarily indicative of a successful borehole.

In terms of boreholes yielding more than 0.1 $\ell\ s^{-1}$ and less than 0.1 $\ell\ s^{-1}$ before hydrofracturing, the results may be summarised as follows:

- Inflow rates improved in 4 out of 5 successful holes (range 0.19 to 1.19 $\ell\ s^{-1}$). In one hole, inflow rate decreased by 0.46 $\ell\ s^{-1}$.
- Out of 11 dud holes 5 had increased inflow rates (range 0.11 to 0.58 $\ell\ s^{-1}$). In 5 holes hydro-fracturing had virtually no effect; while in one hole inflow rate dropped by 0.17 $\ell\ s^{-1}$.

As the nine holes with increased inflow rates were not test pumped after hydrofracturing, the value of hydrofracturing cannot be assessed properly.

Examining the results in terms of depths of weathering and water level yields the following:

- Inflow rates increased by more than 0.1 $\ell\, s^{-1}$ where:

Depth of water level is less than 30 m	6 out of 8 boreholes
Depth of water level is between 30 and 40 m	3 out of 8 boreholes
Depth of water level is greater than 40 m	0 out of 3 boreholes

- Inflow rates increased by more than 0.1 $\ell\, s^{-1}$ where:

Depth of weathering is less than 25 m	4 out of 6 boreholes
Depth of weathering is between 30 and 40 m	4 out of 5 boreholes
Depth of weathering is greater than 40 m	0 out of 3 boreholes

As pressure and pump rpm were not recorded continuously, the pressure response that was recorded during the hydrofracturing process is difficult to interpret. In several instances the pressure remained steady throughout the pump-in period. Pressure drops were mostly gradual, happening over periods varying from several to ten and more minutes. In some cases the pressure built-up again after the initial gradual drop. Whether sharp pressure drops occurred in two or three instances cannot be inferred with any degree of certainty. The time interval between readings was too long.

There is no clear relation between pressure response and success/failure of the hydrofracturing treatment. Opening-up of plugged fractures/fissures appears to be the reason for effected improvements. The question arises whether the same effect could not have been produced by surging and/or chemical deflocculation of clay.

TABLE 15 DETAILS OF HOLES SUBJECTED TO HYDROFRACTURING

Farm name & No Borehole No Borehole depth (m) Water level depth (m)	Yield (ℓs^{-1})	Geological notes	Resistivity log	Caliper log
Bambata 33 MR BA8 99 14.17	0.08	Borehole in amphibolite and ? supercrustal rocks; 500 m west of NE striking fault (Landsat lineament).Nearby NNE fault not mapped	Except for lows at 40m and 99 m; resistivity varies between 3000 ohm m and 5000 ohm m	Smooth below 52 m
Benedict 27 MR BT3 169 21.17	dry*	Amphibolite in vicinity of hole; hole 600 m west of NE striking fault	Weathered to 41 m. Resistivity decreases gradually from 5000 ohm m at 60 m to 2000 ohm m at 100 m and remains steady tobottom except for a low at 153 m	Smooth from 41 down
Daantjieslaagte 200 MR DL 7 48 23.42		Banded metasedimentary rocks: metapelite, lava ? and amphibolite near small fault. No Landsat lineament in vicinity	Weathered to 37 m; resistivity 200 ohm m; resistivity of section below 37 m rises to 2000 ohm m.	Caving between 34.5 and 36 m; fracture at 38.5 and 42.5m
De Hoek 226 MR DH 9 41 16.94	0.38	Interbanded granulitic gneiss and amphibolite. Hole about midway between two NE trending Landsat lineaments - faults - 600 m apart	Weathered to 27 m; resistivity 400 to 500 ohm m. Bottom section 3000 ohm m.	Caving between 25 and 27m
Holdrift 81 MR G37770 84 36.65	0.071	Weathered diabase to 27 m; solid from 35 m; marble to 57 m; marble and amphobolite alternating to 84 m. Water struck at 70 m; 300 m north of a ENE trending lineament	No log	No log
Holdrift 81 MR G38067 83.8 35.67	0.19	Metasedimentary rocks: gneiss, marble and amphibolite. Weathered to 25 m; fractured to 60 m; water struck at 48 m in gneiss - marble contact; 75 m north of lineament	Resistivity 200 ohm m to 60 m; resistivity high between 53 to 57 m; from 60 m down resistivity increases gradually to >3000 ohm m at 84 m. Small low at 71 m	Caving at 45 m. Wall rough to about 73 m
Isipingo 37 MR IP 2 42.1? 40.67	0.063	No data	Resistivity log problematic	Fracturing 30.5 to 34 m?
Kaffersfontein 135 LQ G38173 66 42.84	0.025	Weathered leucocratic gneiss to 37 m, fractured to 49 m and solid to 66 m; 0.025 ℓs^{-1} struck at 47 m; Situated on NNW trending lineation	Resistivity 100 ohm m from 5 to 35 m; increases to 200 ohm m between 35 and 51m; 900 ohm m to bottom of hole with a resistivity a low – fracture - at 53.5 m	Wall rough from top to bottom

TABLE 15 DETAILS OF HOLES SUBJECTED TO HYDROFRACTURING (CONTINUED)

Farm name & No Borehole No Borehole depth (m) Water level depth (m)	Yield (ℓs^{-1})	Geological notes	Resistivity log	Caliper log
Melkbosch 49 MR G37768 84 34.6	0.087	Leuco and amphibolitic gneiss - fractured to poorly-fractured and weathered in places to 62 m. Water struck at 54 m. Situated 500 m north of ENE trending dolerite dyke.	Resistivity from water level to bottom 2000 ohm m with indications of fractures at 52, 58, 73 and 77 m nothing noteworthy	Fractures at 52, 58, 78, 80 m
Oxton 31 MR ON 1 60 33.85	"dry"	On metasedimentary contact; no fault	Resistivity from water level to 50 m 900 ohm m; below 50 m to bottom 1500 ohm m	Smooth from 24 m down
Paddysland 168 MR PD 9 55 31.88	?	About 400 m east of NNW striking fault (Landsat lineament)	Resistivity from water level at 31m to 35.4m 500 ohm m; from 35.4 - 46.5 varies between 500 - 1200 ohm m; to bottom at 54m 2000 ohm m; resistivity low at 52m	Fractures at 37.5 and 43.5 m
Selous 80 MR SL 13 63 4	1.33	250 m south of ENE trending lineation (fault) near amphibolite outcrop	Resistivity 2000 ohm m down to 12 m; thereafter to bottom of hole 1000 ohm m with a low at 23.3m	Fractures at 8.5, 15, 17.5 and prominent from 22.5 to 25 m; borehole wall rough between 40 to 50 m
Snydersfontein 130 LQ G38200 96 47.65	"dry"	Weathered gneiss to 47.5 m; fractured amphibolitic gneiss between 47.5 and 56 m; Solid amphibolitic gneiss to 96 m. No lineation present	Resistivity down to 32 m 90 - 100 ohm m; 32 to 60 m 350 ohm m; 60 to bottom 1000 ohm m Resistivity lows at 52 and 80 m	Wall rough to 67 m and between 80 m and bottom
TIN Base A 47 5	?	No data	Resistivity 700 to 1000 ohm m down to 7.5 m; increases gradually to approx 7000 ohm m at the bottom of the hole	Fractures at 5 - 7 m, 13.5, 17.5, 34.5 and 38.5 to 40 m
IN Base TB1 47 5	"weak"	No data	As for TIN Base A	Hole wall rough to 8m. Fracture at 17.5
Unitas School US ! 31 10.7	?	Hole drilled on resistivity low; no log available	From water level to 21.3 m resistivity 500– 800 ohm m; rises to 5000 ohm m from 21.3 to bottom of hole	Very fractured down to 23.6 m; caving between 16.8 and 18.9 m

TABLE 16 HYDROFRACTURING RESULTS

Farm name & No and (borehole No see report Gh 3577)	Single packer settings at depth(s) (m)	Single packer depth(s) and recorded pressure drop from/to (see note below)	Draw down (m)	Inflow rate prior to hydro-frac (ℓs^{-1})	Inflow rate after hydro-frac (ℓs^{-1})	Inflow rate gain (ℓs^{-1})
Bambata 33 MR (BA6)	37.4, 58, 59.9, 69, 79.4, 84, 88.9 and 97.1	59,9 m; 1300 / 800 psi	78	0.04	0.62	0.58
Benedict 27 MR (BT3)	79, 88, 102.5, 41.5,44.5 and 110.5	102.5 m; 1150 / 800 psi; 110.5m; 1400 / 1200 psi	98	0.21	0.34	0.13
Daantjieslaagte 200 MR (DL 7)	31.75 and 40.75	40.75 m; 1400 / 800 psi,	20	0.73	0.92	0.19
De Hoek 226 MR (DH9)	34.5, 36 and 23.5	34.5 m; 1200 / 800 psi.	5.5	0.32	1.08	0.76
Holdrift 81 MR (G37770)	42, 54 and 69	54 m; 1200 / 600 psi	19	0	0.11	0.11
Holdrift 81 MR (G38067)	*55.5 and 73.5*	*73.5 m;1300 / 1000 psi*	*26*	*0.63*	*0.17*	*- 0.46*
Isipingo 37 MR (IP 2)	no data	No data	10.35	0.59	0.64	0.05
Kafferfontein135 LQ (G38173)	no data	No data	19	0.36	0.36	0
Melkbosch 49 MR (G37768)	*51.15, 55.65, 69 and 75*	*no drop recorded*	*48*	*0.07*	*0.04*	*- 0.03*
Oxton 31 MR (ON1)	47 and 55	no drop recorded	24	0	0.11	0.11
Paddysland 168 MR (PD9)	37.5 and 43.5	no drop recorded	20	0.04	0.39	0.35
Selous 80 MR (SL13)	27.2 and 50.5	no drop recorded	14	0.67	1.86	1.19
Snydersfontein 130 LQ (G38200)	63	63m; 1400 / 1200 psi	39	0.38	0.21	- 0.17
TIN Base(A)	30, 37.07 and 13.5	Incomplete data	41.2	0.21	0.23	0.02
TIN Base (TB1)	30, 37.07 and 13.5	As for TIN Base A	41.2	0.39	0.3	- 0.09
Unitas School (US1)	12 (2x) and 18	18 m 1300 / 700 psi	1.65	1.24	1.8	0.56

Note: Only those results with packer settings have been recorded above where pressure drops occurred.

6. WATER LEVEL FLUCTUATIONS AND GROUNDWATER RECHARGE

6.1 EARLY VIEWS ABOUT RECHARGE

Van Eeden and Steyn (1961) have suggested that the chances of striking water in boreholes east of the Lephalala River and north of latitude 23° 15' are better than in the Beauty area, because of:

- the widespread occurrence of surface limestone east of the river which allegedly transmits infiltrating water more readily out of reach of evapotranspiration than (deep) soil, and
- the shallower and more variable depth of weathering in the east.

They draw attention to the fact that in spite of a thick sand-cover and denser vegetation, no particular difficulty is experienced in finding groundwater in the Karoo strata of the adjoining Waterberg Coal Basin. They express the opinion that the conditions controlling infiltration of rainwater in the area underlain by Karoo rocks conform more to that of surface limestone than to the soil-covered and deeply weathered crystalline rocks (in this connection refer to the piezometric profile Figure 30). Van Eeden and Steyn contend further that after bush-clearing, replenishment of groundwater in the deeply weathered crystalline rocks is possible only after the unsaturated zone as a whole has been brought to field capacity. This implies that recharge does not take place in bush-clad areas underlain by weathered crystalline rocks.

Bush (1989) looked at borehole yields and water level depths in the Swartwater area i.e. east of the Lephalala, in terms of the presence/absence of calcrete deposits. He found that the average yield of boreholes in a calcrete environment ($3.03\ \ell\ s^{-1}$; 89 boreholes) was more than double that of holes where no calcrete was observed ($1.36\ \ell\ s^{-1}$; 310 holes). However, no meaningful difference in water level distribution between calcrete and non-calcrete areas was found. Bush offers the following explanation: Calcrete is deposited in:

- zones of fracturing where greater groundwater mobility is possible and, therefore, average higher yields
- areas where carbonate rocks are more abundant and solution features result in more favourable water-bearing properties.

No conclusion regarding the effect of calcrete on recharge can be drawn from these findings.

6.2 VARYING WATER LEVELS AND DRYING-UP OF BOREHOLES

Very little is known about historical water level fluctuations. Information available to Fayazi et al. (1981) suggests that in 1980/81 water levels in the Mopane-Tshipise area were between 8 to 18 m deeper than when the holes were drilled. In one specific case, on Beck 568 MS, the water level was 25 m lower than in 1928. The water level measurements were presumably mostly made by Fayazi et al. in the vicinity of groundwater abstraction points. In other words, this drop does not necessarily entail a general lowering of such magnitude over the whole Mopane-Tshipise area. They also found that in the three areas investigated by them (Figure 27), 133 out of a total of 483 originally successful holes had "dried-up".

De Villiers (1972) states that on a group of farms east of Alldays boreholes dried up within a few years or even months after they had been brought into use. This was especially notable towards the end of the 1963 - 66 period of sub-normal rainfall. At that time water levels had dropped by between 2 and 12 m. Blecher (1993) found that in 1991- 92 water levels on a group of farms 20 km south of Swartwater were as much as 20 m deeper in places than in 1972.

Bush (1989) compared water levels measured by Steyn of the Geological Survey in the early 1950s in the Beauty area with measurements made during 1987/88. As there was no means of identifying the 1950's boreholes, the comparison is based on levels measured on 12 farms in proximity of the old positions. In 5 instances, levels were shallower by 0.5 to 4.2 m; levels were deeper by 1.2 to 3.2 m in 3 cases, whilst no change was recorded in one instance. Large rises of respectively 17, 5.6 and 13.2 m were found on Oudenbosch 146 LQ, Klipplaat 134 LQ (adjoining Kafferfontein 135 LQ on the west) and Snydersfontein 130 LQ (10 km west of Kaffersfontein 135 LQ) where areas had been cleared of bush.

Bush (1989) also reported that yields had diminished in 62 out of 100 boreholes in the Swartwater area. He stated that spring flow had ceased on Selous 60 MR (on the Limpopo River due north of Swartwater), Jakkalsfontein 54 MR (20 km northeast of Swartwater), Paddysland 168 MR and Tugela 171 MR.

On Kaffersfontein_135 LQ and on Snydersfontein 130 LQ (10 km west of Kaffersfontein 135 LQ) situated in the Beauty area, water levels recorded by Bush (1989) lie between 42 and 48 m below the surface. It seems likely that the extinct springs, after which the farms were named, were ephemeral in the past and that they were fed after good rains from temporally perched groundwater bodies. Support for this opinion is provided by small water strikes that were recorded 3.8, 38 and 8 m above the water level in boreholes on Kaffersfontein 135 LQ, Wellust 73 LQ and Witdrift 41 LQ, all situated in the Beauty area.

Declining borehole yields and water levels as experienced by the farming community do not necessarily signify a regional lowering of the piezometric level but are, according to Bush (1989), indications of site-specific dewatering, owing to the limited extent of aquifers and groundwater storage.

6.3 WATER LEVEL OBSERVATIONS IN THE BEAUTY AND SWARTWATER AREAS

In the course of Bush and Field Party's investigations during 1987/88, water levels were measured on three occasions in a number of boreholes in the Beauty and on two occasions in the Swartwater area.

Beauty Area

Water levels were measured in 137 holes on 56 farms during September 1987 and again during April and June 1988. With the exception of 14 holes in which April water levels were down by 0.02 to 1.07 m and four holes in which there was virtually no change, April levels were up by 0.02 to 8.28 m in the remaining 119 holes. The average rise was 1.07 m. Rainfall during the summer of 1987/88 was well above the mean (Vegter 1993). By June 1988 water levels were still rising in 50 holes while they had started to decline in the rest.

Swartwater Area

Water levels were measured in 33 holes on 19 farms during March 1988 and again during June 1988. With the exception of 8 holes in which rises ranging from 0.12 to 2.38 m (mean 0.86 m) were recorded and four holes in which there was virtually no change, June levels were down 0.09 to 3.16 m in the remaining 21 holes. The average drop was 0.52 m. Imbibition by the matrix of a double porosity medium is probably largely responsible for the initial drop after the rainy season. It is a pity that subsequent measurements were not made. These may have proved/disproved this supposition.

The water level changes that have been observed during 1987/88 in both the Beauty and Swartwater areas indicate that recharge occurs in shallow as well as in deeply weathered areas and in the presence as well as the absence of surface limestone. Recharge takes place preferentially through so-called "macro-pores" rather than through the matrix of the material comprising the unsaturated zone.

6.4 CONTINUOUS MONITORING 1989-1997 AND THE EFFECT OF CLEARING BUSHVELD VEGETATION

An investigation into the effect of bush clearing on recharge was initiated during the 1987/88 investigations. On Oudenbosch 146 LQ and the adjoining farm Welgelegen 142 LQ 160 ha of land was cleared of bush during the 1950's. More or less at the same time, about 110 ha was also cleared on Grootpan 90 LQ. Boreholes for water level recording/regular observation were drilled in 1988 on Oudenbosch 146 LQ and on Grootpan 90 LQ/Ongerep 674 LQ.

Oudenbosch

The water level in the cleared field is depicted by graph A5N001 (borehole G38545) in Figure 47 and in the bush 1000 m west of the cleared field by graph A5N004 (borehole G38542). Note:

- The higher elevation (A5N001) in the cleared field
- The receding A5N001 water level whilst the A5N004 level is slowly rising
- Small upward deviations from the downward trend of A5N001 seem to coincide with step-like rises of A5N004 during the first quarter of 1991, the last quarter of 1992 and during the summer of 1993/94.

Grootpan/Ongerep

Graphs A5N005 (borehole No G38549) and A2N006 (borehole G38550) in Figure 48 depict water levels in the cleared field on Grootpan. They are about 380 m apart. Hole A2N006 is situated north of A5N005 and is sited on an east-west striking fracture zone that was located geophysically. Borehole G38552 (A5N008) was drilled on the eastern extension of the fracture zone about 950 m away. It is situated in bush on Ongerep. Borehole G38551 (A5N007) is also located in bush about 300 m south of G38552.

Note:

FIGURE 47 GROUNDWATER LEVELS ON OUDENBOSCH 146 LQ

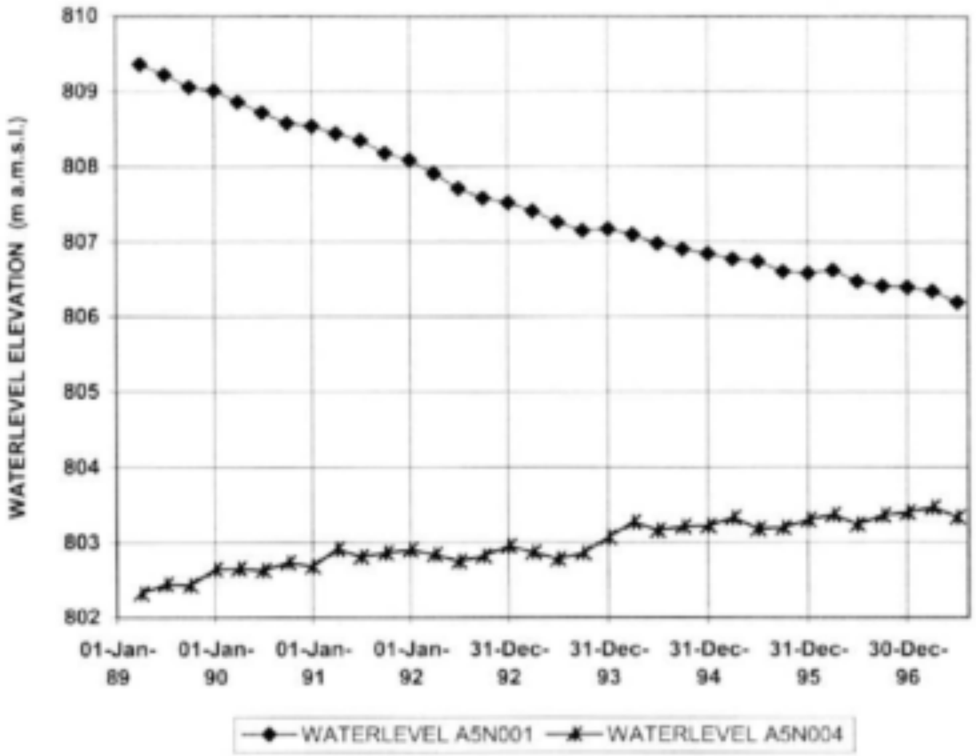
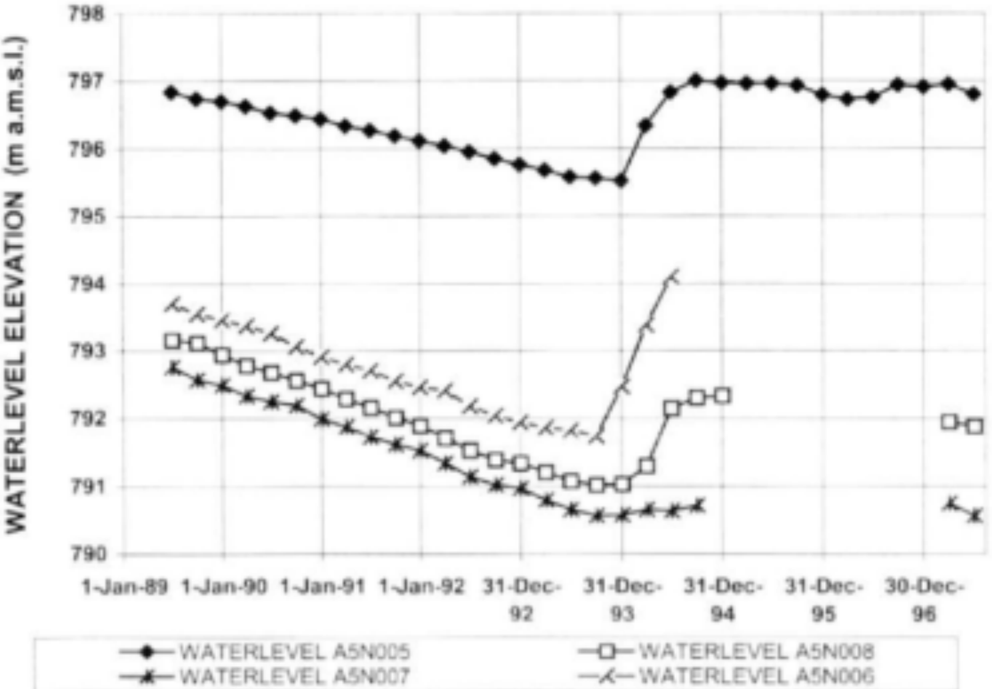


FIGURE 48 GROUNDWATER LEVELS ON GROOTPAN 90 LQ AND ONGEREP 674 LQ



- The higher elevations in the cleared field.
- The downward trend of the water level in all four boreholes - recession following the 1987/88 recharge even.
- The water level rise (also recorded on Oudenbosch) of 1.4 m (A5N005), 2.3 m (A5N006), 0.25 m (A5N007) and 1.3 m (A5N008) during the 1993/94 season.
- The water level difference between A5N005 and A5N006 and the hydraulic gradient towards A5N008 - an indication of flow towards and along the fracture zone.
- In contrast with Oudenbosch, the water level in borehole G38549 in the cleared field was relatively stable at about 797m over the period 1994 - 97. That below the cleared field on Oudenbosch continued to drop during this period though at a somewhat slower rate.

From an examination of old water level data pre-dating bush-clearing Vegter (1993) concluded that water levels appeared to have risen by about 10 m below the cleared lands on Oudenbosch and Grootpan as a result of bush clearing.

The higher water levels may be ascribed to:

i. enhanced recharge through less water loss from the unsaturated zone, or
ii. the elimination of groundwater loss through transpiration by Bushveld vegetation (phteatophytes), or
iii. a combination of i. and ii.

The water level response observed in boreholes is determined not only by rainfall, but by pattern and depth of weathering and fracturing, storage coefficient, transmissivity, infitration and recharge and the placement of observation holes. The water level behaviour on Oudenbosch and Grootpan/Ongerep below and outside the cleared field is notwithstanding explainable in terms of the concept of a groundwater mound below the cleared lands and outward flow towards the bush covered areas.

Significant recharge occurs seemingly at irregular intervals – see, for instance, figures 26 and 27. To obtain an idea of the possible duration between major recharge events rainfall records of eight widely spaced stations in the Beauty area were examined. Annual seasonal rainfall for the area was estimated by averaging rainfall at the eight stations. The mean seasonal rainfall for the area over the period 1945 - 46 to 1991 - 92 is 420 mm. The requirements to qualify as major recharge seasons were postulated to be seasonal rainfall greater than 500 mm of which at least either 300mm must fall within a period of 2 months or 400 mm within a period of 3 months. The results are tabled below.

TABLE 17 POSTULATED MAJOR RECHARGE SEASONS IN THE BEAUTY AREA 1945/46 T0 1991/92

Rainfall season	Estimated area seasonal rainfall (mm)	Period of concentrated rainfall (months)	Estimated amount of concentrated rainfall (mm)
1947/48	560	4	400
1952/53	640	2	295
1954/55	565	2	310
1966/67	605	4	500
1970/71	495	2	330
1971/72	604	3	415
1974/75	615	2	300
1975/76	560	3	410
1977/78	510	3	420
1979/80	550	2	350
1980/81	595	3	390
1987/88	580	4	475

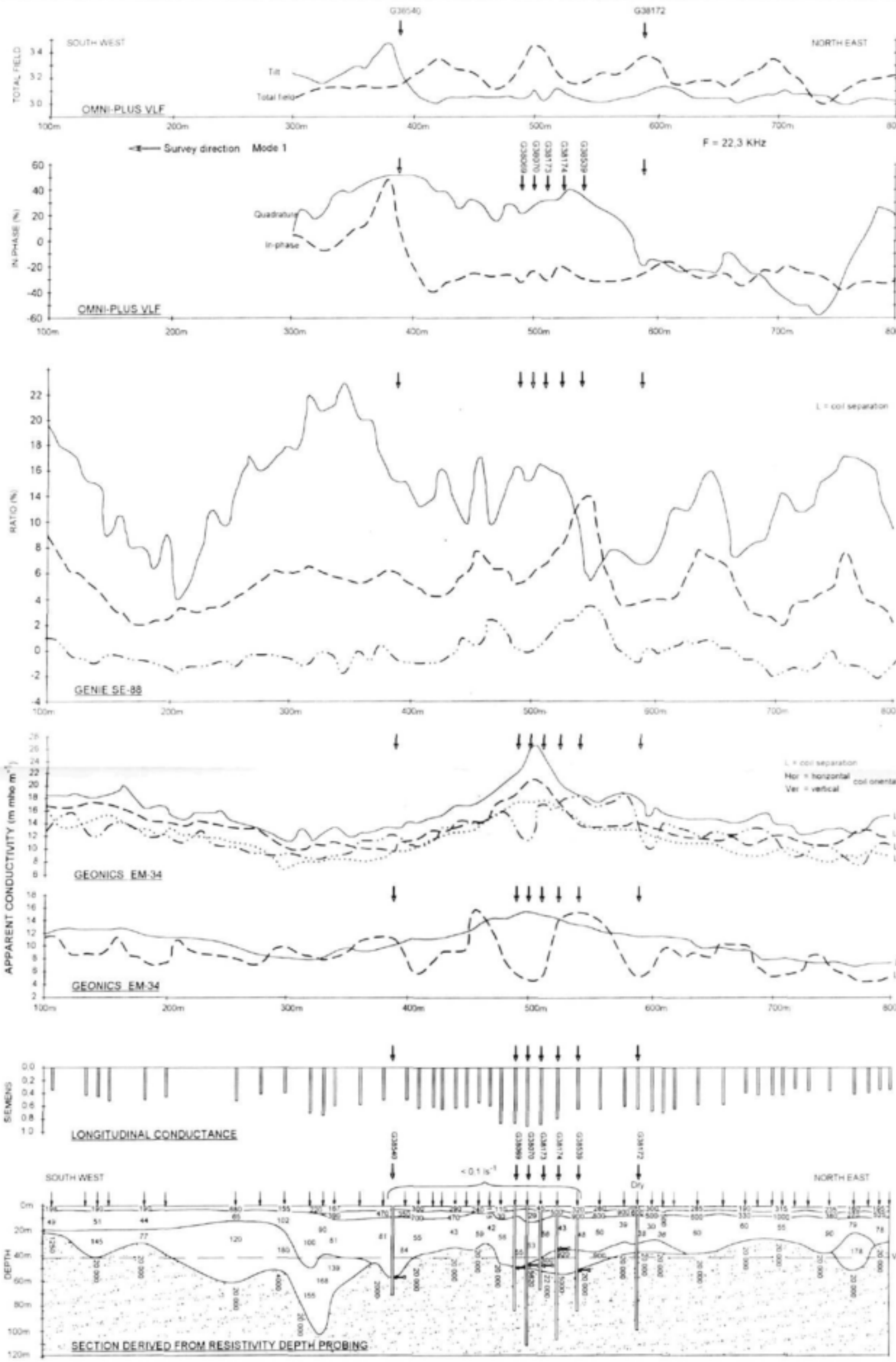


Fig. 37 The geophysical traverses and interpreted geological section - Kaffersfontein 135 LQ (after Bush 1989; Du Toit 1989) (see also figures 38, 39, 40 and 41)

There is, unfortunately, very little field evidence whereby the postulated requirements for major recharge may be checked. Recharge was recorded during 1966/67 on Frankfort 69 KP situated approximately 200 km southwest of the Beauty area in Region 1 (Figure 27 Vegter 2000). The postulated recharge during the 1987/88 season after six seasons of below average rainfall is confirmed by water level measurements mentioned in paragraph 6.3.

6.5 ISOTOPE DETERMINATIONS

The Schonland Research Centre for Nuclear Sciences conducted the following isotope determinations: ^{3}H, ^{14}C, $\delta^{13}C$, $\delta^{18}O$. Four groundwater samples were collected in the late 1980's from the cleared fields on Oudenbosch and Grootpan and seven from bush-clad areas on the two and three other farms in the vicinity. There is no clear distinction in isotope contents between cleared and bush-clad areas.

That recharge is taking place in cleared as well as in bush-clad areas is confirmed by the tritium values. Compared to the relatively low tritium values, ^{14}C is abnormally high.

TABLE 18 ISOTOPE DETERMINATIONS
(Schonland Research Centre for Nuclear Sciences)

Isotope	Cleared field	Bush-clad area
^{3}H (TU)	0.8 ± 0.3 to 3.4 ± 0.4	0.0 ± 0.2 to 2.2 ± 0.3
^{14}C (pmc)	52.5 ± 0.5 to 99.1 ± 0.7	96.1 ±1.1 to 111.3 ± 0.6
$\delta^{13}C$ (%)	- 7.8 to -11.5	-7.8 to - 14.2
$\delta^{18}O$ (%)	-3.4 to - 4.3	-4.1 to – 4.9

Two explanations may be offered for this:

- a recharge event before a higher level of tritium was introduced into the atmosphere by nuclear explosions.
- ^{14}C entering the groundwater through root decay that releases "young" CO_2.

Further work is needed to clarify the reason for the high ^{14}C values.

The use of isotopes in fractured formations is, unfortunately, seriously hampered by uncertainty about the location and derivation of the sample within a heterogeneous medium. Samples probably are mixtures of older (bottom) and younger (top) waters.

6.6 QUANTITATIVE ESTIMATE OF RECHARGE

No studies aimed at determining recharge quantitatively have been undertaken in Region 3. According to Sheet 2 of the map set "Groundwater Resources of the Republic of South Africa", mean annual recharge is estimated to vary over different parts of the region from between 1mm and 5 mm to between 10mm to 15 mm. The basis on which these estimates have been derived are set out in the Explanation to the set of maps and will not be repeated here (Vegter 1995).

6.7 ENHANCING GROUNDWATER AVAILABILITY

Apart from the effect of bush clearing on groundwater availability, impounding storm runoff and allowing it to infiltrate may enhance recharge. De Villiers (1972) reported on the beneficial effect of 13 earth dams on farms east of Alldays. The dams are situated in wide watercourses and have capacities ranging from 1000 m^3 to 25 000 m^3. Most of them were constructed in the period 1966 - 69. Yields of boreholes in their immediate vicinity increased from as little as 0.125 $\ell\ s^{-1}$ to as much as 1.25 $\ell\ s^{-1}$. In 1971 water levels stood from 7 to more than 20 m higher than before the dams were built. To enhance infiltration it is important that the soil layer in dam basins is removed and that the underlying fractured and partly decomposed rock is exposed. Accumulated silt should be removed from time to time.

Bush (1989) came to similar conclusions regarding the effect of earth dams across ephemeral streams on 15 farms in the Swartwater and Beauty areas:

- higher water levels,
- higher yields than before dam construction; alternatively yields of weakened boreholes recovered to what they were initially and
- period of useful supply extended in those instances where boreholes are incapable of a perennial yield.

7. HYDROCHEMISTRY AND WATER QUALITY

According to Sheet 2 of the "Groundwater Resources of the Republic of South Africa" map set, total dissolved solids vary between 500 and 2000 mg ℓ^{-1}. The main hydrochemical types are (Ca, Mg) $(HCO_3)_2$ and (Ca, Mg) Cl_2.

M. Simonic of Hydromedia Solutions (Pty) Ltd. classified the overall potability of 750 analyses of water samples. The chemical criteria are laid down in the manual "Quality of domestic water supplies Volume1 Assessment Guide" of the Department of Water Affairs and Forestry, the Department of Health and the Water Research Commission (1998). The result is produced in Table 18.

TABLE 19 POTABILITY CLASSIFICATION

Class	1-blue	2-green	3-yellow	4-red	5-purple
Description	Ideal	Good	Marginal	Poor	Unacceptable
No of samples	29	100	231	245	145
% of samples	3.9	13.3	30.8	32.7	19.3

More than 50% of the water samples are not suitable for drinking. The spatial distribution of the samples is shown in Figure 49. According to Table 19, nitrate and fluoride are the main harmful constituents.

TABLE 20 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 samples containing harmful ion	22	27	41	0	61	14	236	132	48
% of samples	3.4	4.1	6.0	0	9.4	2.1	35.4	20.2	7.4

Fayazi et al. (1981) and Bush (1989) have sampled the areas investigated by them. The data fields are presented in three Piper diagrams (Figure 50). Groundwater of the Swartwater and three areas further east is almost exclusively of calcium-magnesium bicarbonate or calcium-magnesium chloride type. A wider hydrochemical variation is found in the Beauty area. The Swartwater diagram was copied directly from Bush (1989). As individual points were not shown on the original, the field with the greatest concentration of points, unfortunately, cannot be shown. The majority of Swartwater samples are probably also of the calcium-magnesium carbonate-bicarbonate type. The greater range of the Beauty area appears to be related to the deeper water levels and the greater depth of weathering.

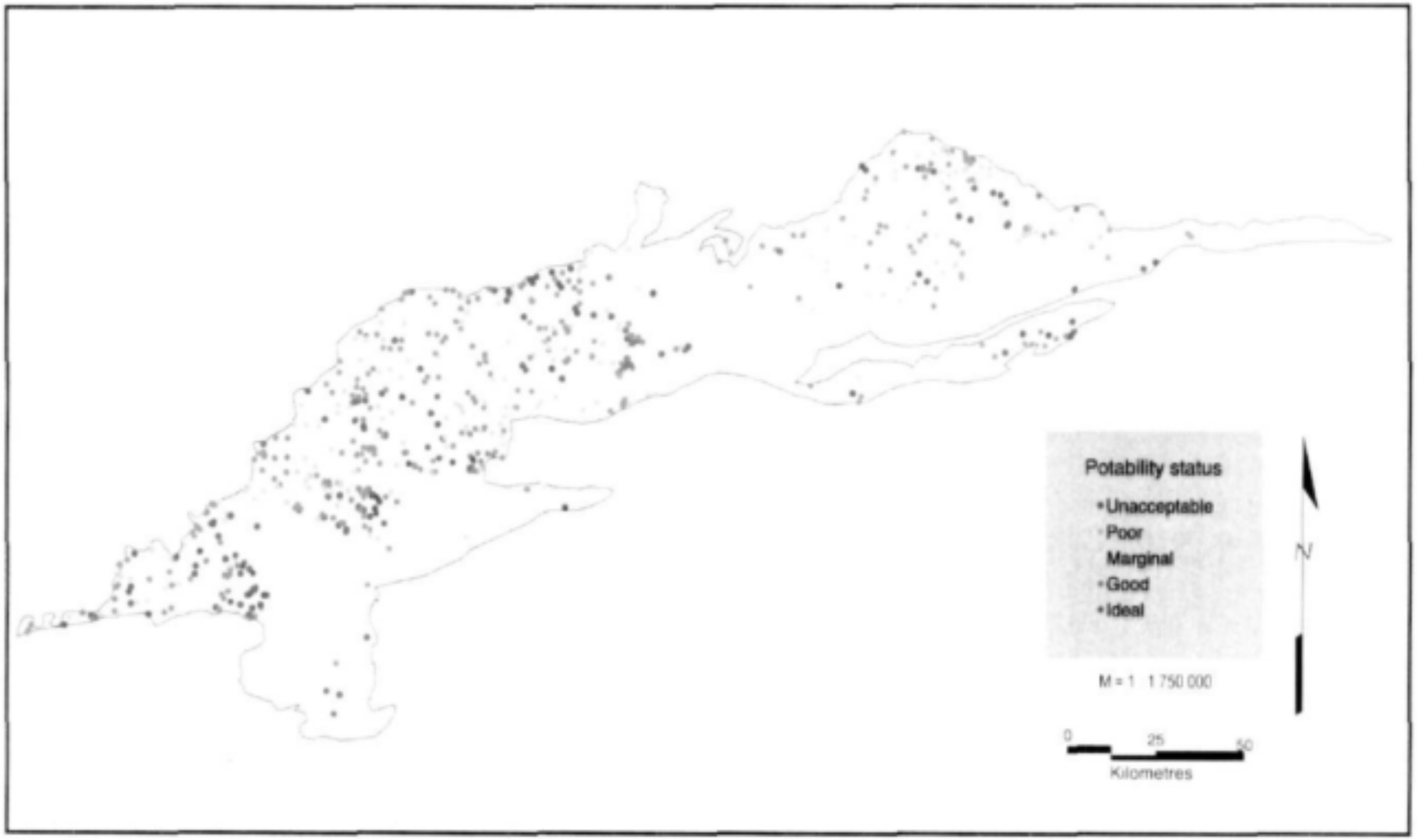


Figure 49: Distribution of water sampling points and potability status - Region 3

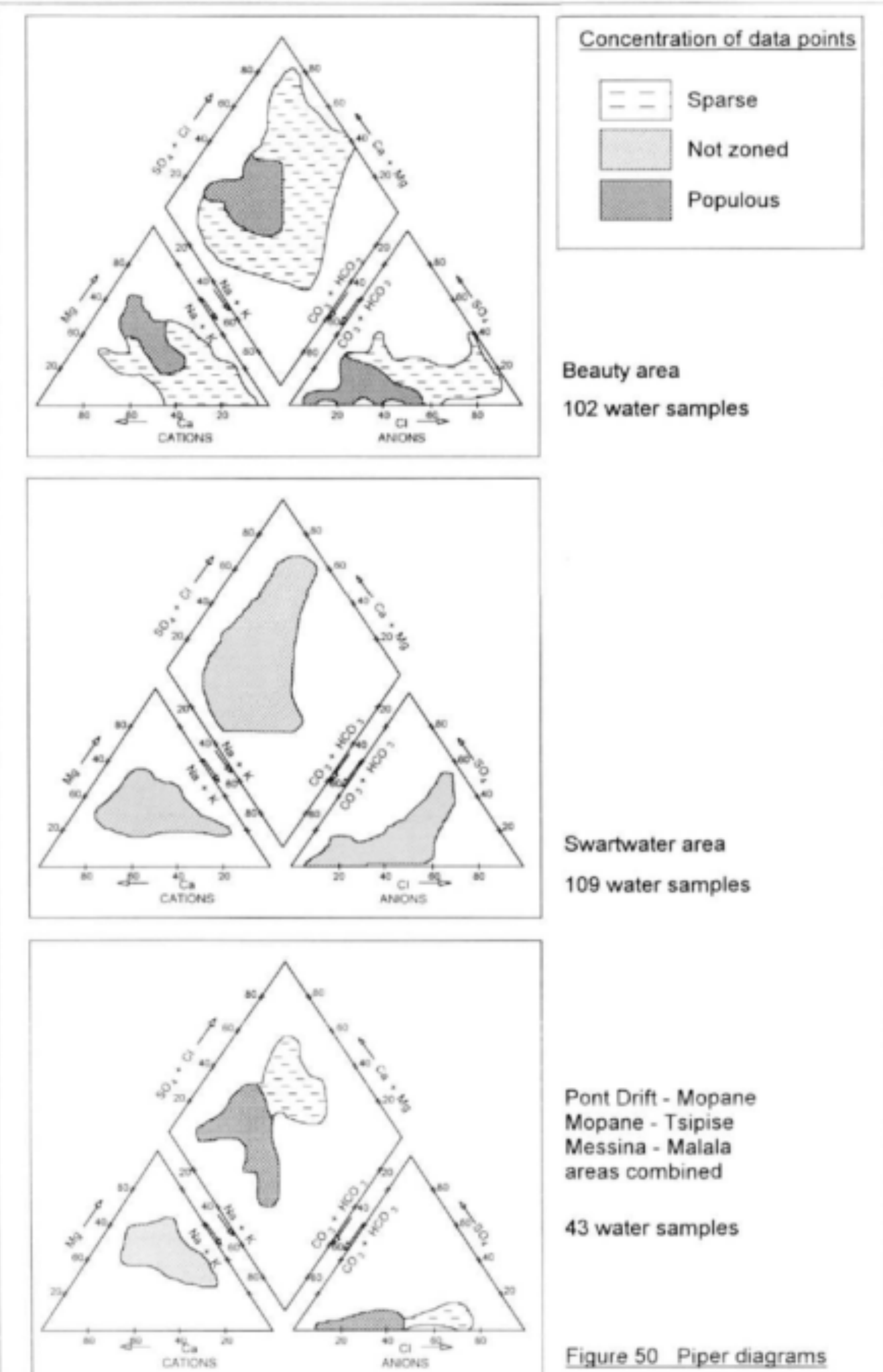


Figure 50 Piper diagrams

8. CONCLUSION AND RECOMMENDATIONS FOR FURTHER WORK

1. In view of poor drilling results, especially in the Beauty area but also elsewhere in the Region, the methodology of siting boreholes and of the hydrogeological control of drilling operations is in need of a thorough revision and overhaul. This applies particularly to
   a) The use and interpretation of geophysics.
   b) The effective integration of geophysical borehole logging with hydrogeological control of drilling operations especially where sites are located on two-dimensional geological features.
   c) Restricting drilling to optimal strike depths - eliminate deep drilling which is considerably less productive.
2. Additional exploratory drilling at sites on Kaffersfontein 135 LQ and Wellust 73 LQ (discussed in chapter 4) to establish if and at what depth deeply weathered fracture zones are capable of yielding a usable supply.
3. A hydrogeological study of alluvial deposits aimed at determining their extent, water-bearing properties, inter-relationship with river flow and their exploitability.
4. A study of the water-bearing properties of hard-rock formations as determined by
   a) fracturing in relation to structure and the neotectonic stress field;
   b) role of unloading;
   c) hydrochemistry, geochemical processes and products of weathering.
5. Determine and analyze the contrasting groundwater flow and discharge regimes of the Beauty area and the rest of the Region - what are the conduits, where and in what form is discharge.
6. Infiltration - modes of water movement through zone of aeration; moisture content and loss through evapotranspiration
7. Water consumption by Bushveld vegetation: identification if present of facultative and obligate phreatophytes.
8. Recharge - its temporal and volumetric variability and its relation to rainfall.
9. Borehole development - role which surging, chemical treatment and hydrofracturing should play in borehole construction and in the salvaging of previously productive holes.

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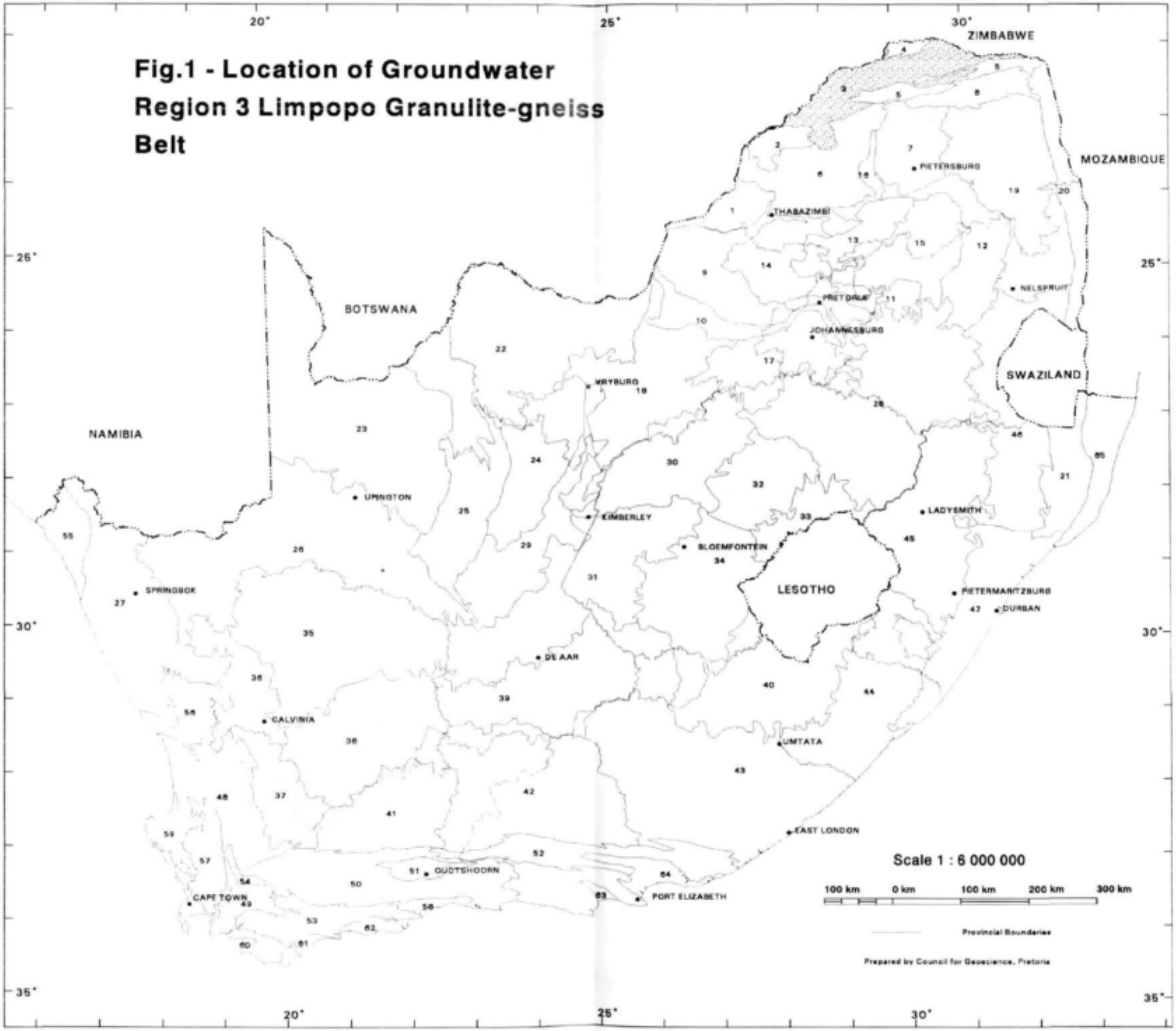

Fig.1 - Location of Groundwater Region 3 Limpopo Granulite-gneiss Belt

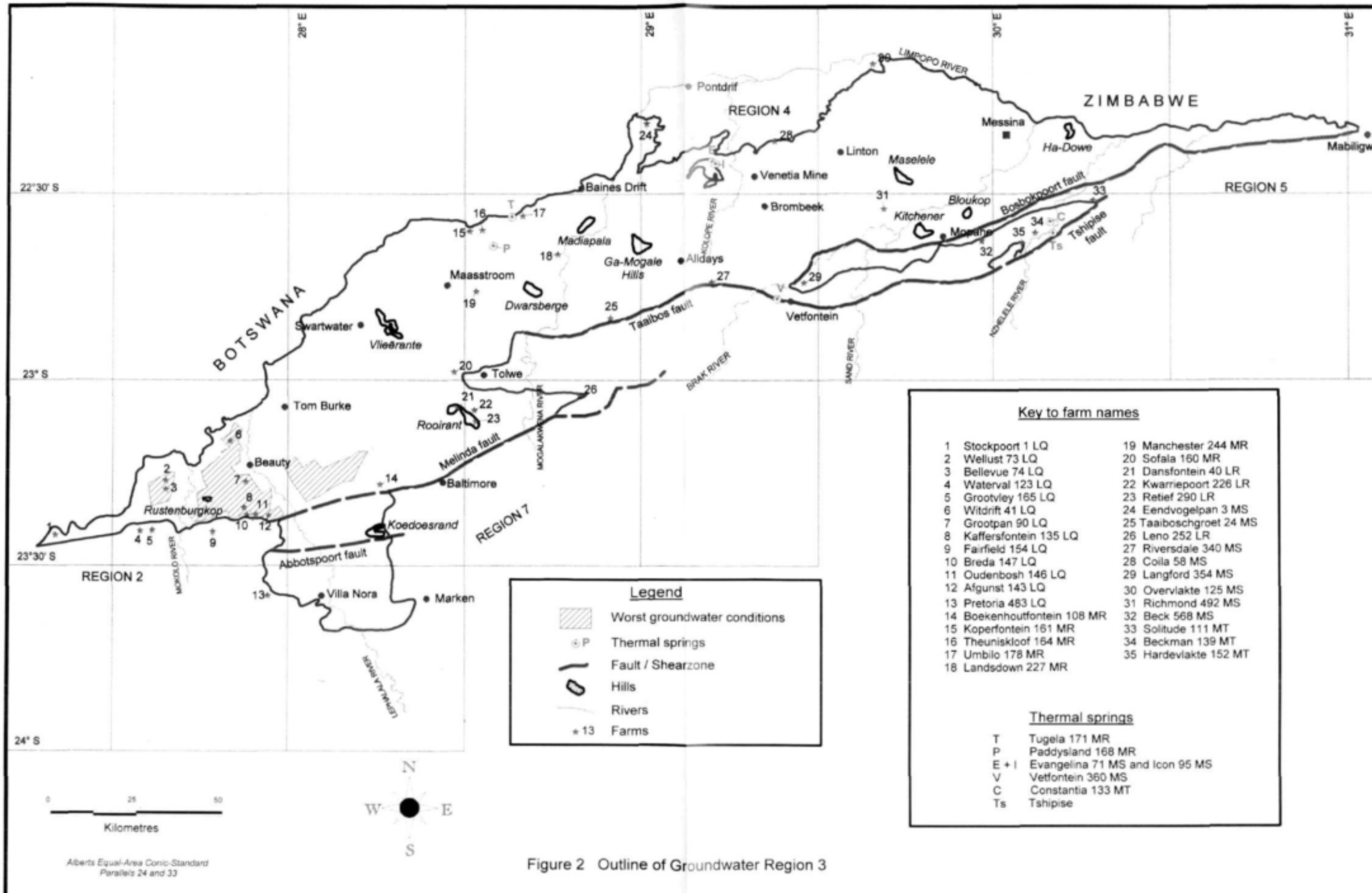

Figure 2 Outline of Groundwater Region 3