Hydrogeology of Groundwater

Region 26

Bushmanland

J R Vegter

TT 285/06

Water Research Commission

HYDROGEOLOGY OF GROUNDWATER

REGION 26: BUSHMANLAND

Prepared for the Water Research Commission

by

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EXECUTIVE SUMMARY

This monograph is based on the digestion of data on governmental drilling and on geological / geophysical investigations by personnel attached to the Geological Survey and the Directorate of Geohydrology during the previous century. In addition, the Nuclear Energy Corporation of South Africa supplied Information that originated from investigations into the suitability of the Vaalputs site for radioactive waste disposal. This report covers the following aspects of Region 26 Bushmanland:

- Physiographic features (Figure 1)
- Tectono-stratigraphic subdivision (Figure 2) and lithostratigraphy
- Piezometric contours of four areas (Figures 4b, 5b and 6a)
- Division of Region on the basis of physiography and geology into 18 hydrogeological units (Figure 3)
- Statistical analysis per hydrogeological unit of borehole data contained in the National Groundwater Database (Figures 11 to 23d)
- Applicability of electrical resistivity and electromagnetic exploration methods and geophysical borehole logging.
- Groundwater recharge
- Hydrochemistry and water quality

Geology

The Region, which is 55000 km^2 in extent, is underlain by hard-rock formations - basically metasedimentary, metavolcanic and intrusive rock units of the Namaqua Metamorphic Province and minor lithostratigraphic units consisting of:

- volcano-sedimentary rocks and granite of Swazian-Randian age,
- unmetamorposed inorogenic volcano-sedimentary rocks of the Koras Group, and
- an interrupted thin cover of Dwyka Group shale, tillite / diamictite along the southern boundary of the Region

Primary aquifers

Cainozoic deposits that overlie the hard-rock formations consist over large areas of a thin cover of soil and calcrete and elsewhere of variable thicknesses of fluvial and aeolian deposits. In the palaeo-Kaboep (Coboop) Valley 76 m of sand has been encountered and in the palaeo-Koa Valley deposits exceed 100 m in thickness. The occurrence of water-bearing Cainozoic deposits is restricted to limited sections of the Koa and Kaboep (Coboop) Valleys and to parts of larger river valleys such as the Brabees, the Hartbees and tributaries. Information on the water-bearing properties of alluvial deposits along the Orange River is lacking. Except for Henkries spring in the lower Koa Valley, water-bearing Cainozoic deposits are not exploited on their own but generally in conjunction with underlying weathered and fractured bedrock e.g. Kenhardt's municipal supply is obtained from alluvium and weathered and fractured gneiss and schist in the valley of Driekop se Rivier.

Water in hard-rock formations

Drillers' logs do not differentiate between the large variety of metamorphic and intrusive rock types present. No attempt has therefore been made at distinguishing between their water-bearing properties. Analysis of borehole data yielded the following:

- In accordance with decreasing rainfall and an increase in the extent and thickness of superficial deposits there is a corresponding though not uniform deterioration in groundwater conditions from east to west.
- Percentage successful boreholes (yield ≥ 0.1 ℓs^{-1}) ranges from 51.8% in the hilly terrain built by Vaalkoppies and Brulpan quartzites in the east (hydrogeological subdivision 3) to 21.8% in the far west in the lower Koa catchment (hydrogeological subdivision 14) and to15.8% in hydrogeological subdivision 10 which drops steeply to the Orange River. The mean for the Region as a whole is 34%.
- According to drillers' logs of the Region as a whole, weathered and fractured hard-rock formation was encountered in no more than 26.8% of the 5000 boreholes recorded in the National Groundwater Database and exceeded 15 m in only about 5%.
- Sporadic weathering / fracturing to depths in excess of 100 metres is evidently limited to narrow linear structures
- Proper basins of weathering deeper than about 30 metres are far and few between or non-existent elsewhere.
- Weathering as agent in producing / enhancing secondary porosity is of importance only where water levels are less than about 30 metres deep
- Water is generally struck in fractured fresh rock below the weathered zone and not in the transition between weathered and fresh rock as is the case in the higher rainfall areas.
- The presence of weathered / fractured formation although not extending down to the water level resulted in slightly higher success rates; 5% and 8% respectively in subdivisions 4 and 5.
- Zones of intense jointing, fracturing, breciation, shearing are the loci for siting boreholes.
- Note however that silicification, epidotisation, chertification of mylonite reduce or may even destroy such secondary openings.
- Decrease or loss of fracture permeability is also caused by weathering of fracture surfaces, formation and deposition of clay minerals and calcite - seemingly a Region-wide phenomenon
- Major fault zones such as Brakbosch, Hartbees River consist mainly of impermeable rock with sparsely distributed water-bearing fractures. They are not as one might expect ideal drilling targets and perform no better than smaller structures.
- Most water strikes are made within 25 metres below water level. Optimum strike frequency is around 10 metres below water level.
- The Dwyka-Basement contact should not be regarded a target for striking water.
- No water was struck in contact zones between Dwyka sedimentary rocks and dolerite and dolerite and vice versa.

Geophysical exploration

- The usefulness of resistivity depth probing in the Bushmanland Groundwater Region is largely restricted to determining depths of weathering and thicknesses of alluvial deposits in areas with shallow water levels.
- The blanketing effect of a overlying low resistivity layer makes it impossible to distinguish under field conditions between unweathered but fractured and solid fresh rock. This applies to most of the Region.

- Chances of striking water may otherwise be enhanced somewhat by siting boreholes on the greatest depth of weathering / fracturing even though the interpreted depth falls short of the water level.
- Resistivity surveys e.g. rectangle profiling may be of assistance in locating narrow electrically conductive zones that potentially may be deeply weathered / fractured.
- Near-surface and lateral changes in resistivity present serious obstacles to depth probing. It is suggested that resistivity tomography may prove useful in tackling complex situations.
- Inductive electromagnetic surveys are useful and from a manpower and time point of view preferable to resistivity rectangle profiling in locating and tracing two-dimensional bodies of weathered or fractured rock.
- As electromagnetic anomalies are caused by the concentration of current in the near-surface weathered sections of fracture zones, anomalies as such are not indicative of deep fracturing.
- Not all fracture zones and lineaments produce EM anomalies. Lack of response does not necessarily entail lack of fracturing in depth. In some instances water has been struck in silicified breccia zones that appear tight on the surface.
- In addition to inspection and description of drill cuttings geophysical borehole logging is essential for a better understanding of the downhole physical state of the formation and the conditions under which water is struck.

<u>Recharge</u>

Piezometric contour maps, Figures 4b, 5b, 6a and 8, are cited as proof of:

- recharge, albeit at irregular intervals,
- groundwater flow, no matter how sluggish, and
- discharge chiefly through evapotranspiration, also effluent seepage and a few springs,

Evidence in support of evapotranspiration loss is provided by tree-lined ephemeral streambeds, pans with near-surface groundwater levels in the upper Koa valley, saline soils and efflorescence in laagtes and boreholes with water levels ranging between 1 and 6 metres in each of the 18 hydrogeological subdivisions.

Water level changes as large as 40 metres have been observed in boreholes on a major drainage divide. They are indicative of flow, of very limited storage and of occasional recharge events. No reliable estimates of recharge have as yet been made.

<u>Hydrochemistry and Water quality</u>

In broad outline, calcium and magnesium chloride and sulphate groundwater is characteristic of the Swazian-Randian Kaapvaal craton and Kheis Sub province formations. Sodium / potassium chloride and sulphate groundwater predominates over the rest of the Groundwater Region. Two-type dominance is found in the Upington-Kakamas area and south of Marydale. Total dissolved solids increase from east to west in unison with the change in chemical type.

According to the chemical criteria laid down in the manual “Quality of domestic water supplies, Vol. 1: Assessment Guide”, three-quarters of nearly 1000 water samples analysed were found not suitable for drinking. Harmful constituents in order of frequency of occurrence are fluoride, nitrate, chloride, sodium and sulphate.

Elevated levels of a combination of uranium and arsenic in groundwater around Pofadder correlated positively with the incidence of atypical lymphocyte counts (as a proxy of heamatological abnormality).

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The disbanded Steering Committee responsible for this project consisted of the following persons:

The late Mr. A.G. Reynders	Water Research Commission (Chairman 1995-1998)
The late Mr. H. Maaren	Water Research Commission (Member and Chairman 1998-1999)
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1. INTRODUCTION

1.1 LOCATION AND EXTENT

Region 26 (Figure 1 back of report) is approximately 55000 km^2 in extent and is located in the Northern Cape Province. The distance between its northwestern and southeastern extremities is about 540 km. It is about 180 km at its widest. The Region comprises principally the outcrop area on the Inland Plateau of rocks belonging to the Proterozoic Namaqua Metamorphic Province. It includes areas where these rocks are overlain by Cainozoic deposits and by a thin variable veneer of Dwyka Group rocks. Namibian-Mokolian intrusives, Koras Group volcanics and sediments as well as a narrow strip of Swazian Marydale Group rocks and intrusive Randian granite are also incorporated.

Commencing at Henkries Mouth on the Orange River a short distance downstream of Goodhouse, the western boundary is the divide between the Brak and the Oernoep (older literature / maps Uranoop) Rivers as far south as Kabinaberg. Both flow northwards towards the Orange River. The Brak joins the Koa Valley at Henkries the site of springs and a date plantation. The Koa debauches into the Orange River at Henkries Mouth. From Kabinaberg southeastwards the boundary is the divide between drainage regions D8 Koa Valley and F3 Buffels River. It passes about 10 km east of Steinkopf, directly west of Concordia, through Gamoep, Stofkloof, Vaalputs and Platbakkies to Banke 409 about 20 km northwest of Kliprand. The divide very roughly approximates the division between the ubiquitous sand cover in the east and the dissected hilly and mountainous terrain in the west (as shown on the 1:1 000 000 geological map 1997).

Headwaters of the southerly flowing Krom River determine the southwestern limit of the Region. The Koa Valley drainage is separated from that of the Krom River by a zone in which drainage is directed internally to Santab se Vloer, Groot Leeuvlei and Swabies se Pan.

The Orange River is the northern boundary from Henkries Mouth as far east as the 20^0 longitude line. After following this longitude line northwards for about 12 km, the boundary swings eastwards and follows the base of the Kuibis Formation as far as Droêhout 449. From here to the Rooidam farmsteads on Kurrees 369, 35 km north of Upington, the boundary is the edge of the overlying Dwyka Group. From Rooidam to the northwestern corner of Florida 295, the boundary is determined by the northernmost scattered exposures of Koras Group rocks, jutting through the Kalahari sand cover.

The northern extension of the Blauwbospan fault as indicated on geological sheet 2820 (Upington), is the boundary from Florida southwards to Lambrechtsdrif. From here the boundary runs southeastwards along the Orange River. About 35 km east of Groblershoop the boundary joins and follows the southwesterly striking Dabep fault to Kaboom 8, Prieska District.

From Kaboom 8 to Omdraai Vlei 94 Prieska District a distance of about 150 km, the Region's boundary is the contact between Marydale Group, Draghoender Gneiss and Skalkseput Granite on the one hand and strata of the younger Ventersdorp and Griqualand West Supergroups on the other. Faults belonging to the Doringberg set make up sections of the contact. South of Omdraai Vlei 94 and Nooitgedacht 95 Marydale Group rocks and the Skalkseput Granite disappear completely under cover of the Dwyka Group.

Inliers of the Uitdraai and Spioenkop Formations in the overlying Dwyka Formation are present as far southeastward as Roodevloer 123 which lies west of Nooitgedacht 95. Starting at Roodevloer 123 the southern limit of Region 26 is the edge of the main Karoo Basin. It is a tortuous line around the southeastern extremity of the Brakbospoort Hills, runs in a west-northwesterly direction, passes to the south of Copperton and Kenhardt to Yzer Vark Vlei 228 about 55 km south-southeast of Pofadder. The boundary has been drawn so as to incorporate a zone of thin Dwyka cover and inliers of the older rocks. Between Yzer Vark Vlei 228 and Consent Vley 3 the southerly trending boundary is the divide between the Koa Valley and head waters of the Krom River. On Consent Vley the divide splits to enclose a more or less rectangular shaped area of interior drainage separating the Koa, Krom and Buffels River catchments. The “corners” of the rectangular area are Consent Vley 3, Bloupan 175, Banke 409 and Vaalputs 369. From Vaalputs the boundary is the water divide between the Koa Valley drainage and the Buffels River as described above.

1.2 PHYSIOGRAPHY

The Orange River drains Groundwater Region 26. The Region comprises portions of the following secondary drainage regions (see 1:1 500 000 scale map “Drainage Regions of the Republic of South Africa” 1965):

- D 4 the lowermost part of the Molopo River
- D 7 comprising short tributaries north and south of the Orange River.
- the lower part of D 5 (Hartbees River)
- the eastern part of D 8 (mainly the Koa valley)
- the northwestern corner of drainage region D 6 (Ongers River)

A more detailed subdivision of catchments is shown in Figure 1 (back of report)

a) North of the Orange River:
   i. Bak River, Kourop River and few minor streams **(D 8)**
   ii. Molopo River **(D 4)**
   iii. Streams entering the Orange between the confluence of the Molopo and Lambrechtsdrif **(D 7)**

b) South of the Orange River:
   i. Koa Valley **(D 8)**
   ii. Streams entering the Orange between Henkries Mouth and Pelladrif **(D 8)**
   iii. Pella River or Goob se Laagte **(D 8)**
   iv. Kaboep (Coboop) River **(D 8)**
   v. Streams entering the Orange between Kaboep River and Hartbees River **(D 8)**
   vi. Left bank catchment of the Sak River between Knapsaklaagte and Hartbees River confluences **(D 5)**
   vii. Left bank catchment of the Hartbees River downstream of the Sak River confluence **(D 5)**: Main tributaries are Driekop se Rivier, Riefontein River, Tuins River, Sout River
   viii. Right bank catchment of Basterspût se Leegte and of the Hartbees River above the Sak River confluence **(D 5)**:
   ix. Right bank catchment of the Hartbees River downstream of the Sak River confluence. Main tributaries are the Mottels River, Rugseer River, Wolfkop se Loop, N’Rougas se Loop. **(D 5)**
   x. Streams entering the Orange between Hartbees River and Karosberg **(D 7)**
   xi. Streams entering the Orange between Karosberg and Buchuberg **(D 7)**
   xii. Northeasterly flowing streams between Ezels Klaauw 5 and Uitspanberg 52 **(D 7)**
   xiii. Area of closed / internal drainage **(D 6)**

Note that the divide between drainage regions D 6 and D 7 as shown in Figure 1 differs somewhat of that depicted on the official map. The modified D 6 area is characterized by pans and almost no surface outflow.

The Orange River, which flows through the northern part of the Region, is its most striking feature. The elevation of the Orange at Buchuberg Dam just before entering the Region is about 860 m.a.m.s.l. At the confluence of the Hartbees River the elevation is approximately 650 m, just above the Augrabies Falls 600 m and below Goodhouse where it exits the Region approximately 200 m.a.m.s.l. At the Augrabies Falls the river plunges about 150 metres.

Between Buchuberg Dam and the Augrabies Falls the river's gradient increases from a mean of 0.4 m.km^{-1} above Upington to an average of 1.6 m.km^{-1} below Upington. Rapids or small waterfalls at Keimoes, Friersdale and Neus are responsible for the steeper gradient. The aspect of the country that directly adjoins the river between Buchuberg Dam and the Augrabies Falls, likewise changes from a plain with moderate relief in the east to hilly ground down stream of Upingrton e.g. Neusberg, 967 m.a.m.s.l stretching obliquely across the Orange, Komsberg 982 m.a.m.s.l and Tierkoppe 851 m.a.m.s.l north of the river.

From below the Augrabies Falls to Henkries Mouth a distance along the river of about 330 km the gradient averages 0.75 m.km^{-1}. However between Uitdraai 82 and Kambreek en Zandfontein 38 a distance of approximately 100 km the gradient averages about 1.5 m.km^{-1}. Rapids and the Ritchie Falls situated just below Onseepkans are found in this section of the river.

All the way downstream of the Augrabies Falls the river is bordered by a tract of highly dissected ground mostly between 5 and 10 km wide. It widens to about 25 km on both sides of the tributary sand-filled valley of the Kaboep or Coboop River. On the left side of the valley the Mattheus Gat Mountains (1150 m) strike west-northwesterly from a farm of that name past Pofadder to Pelladrif on the Orange. The imposing Pellaberg (1180 m) lies north of Pella and west of that range. East of the Kaboep valley and an unnamed laagte, mountainous ground stretches from Scuit Klip 82 on the Kakamas - Onseepkans road to Warmbad Noord 1 on the river. The Riemvasmaak Settlement and the Augrabies Falls National Park occupy the dissected ground north of the river and east of the Namibian border.

The greater part of the Region south of the Orange River consists of plains with relief not exceeding 100 or so metres. Along the Hartbees River relief increases to almost hilly. Further east the northwesterly trending Brakbospoort hills between Copperton and Upington rise between 100 and 200 m above their surroundings of 1000 to 1100 m.a.m.s.l. This strip of hilly ground is more or less the watershed between drainage regions D7 and D5.

The elevation along the 500-km southern boundary of the Region decreases from about 1150 m in the east to around 1000 m.a.m.s.l in the west, except where the boundary crosses the upper reaches of the Sout River (elevation 900 m.a.m.s.l.), the Hartbees River and the Koa Valley at Swabies se Pan (both about 850 m.a.m.s.l.). On Uitval 171 north of Swabies se Pan from where the Koa commences its downward gradient to the Orange River the elevation is 897 m.a.m.s.l.

From the southern boundary the plains slope gently northwards to approximately the 900-m contour from where it commences dropping at an increasing rate towards the Orange River. In the far west the sand-filled Koa valley drops to about 400 m.a.m.s.l at Henkries. From here the drop down the 8 km gorge to the Orange River is approximately 190 metres. Elsewhere tributary streams west of the Augrabies Falls have gradients of up to 40 m/km over the last 5 or so kilometres. Contrariwise the gradient of the Hartbees River which joins the Orange upstream of the Falls, increases from about 1 m.km^{-1} in the vicinity of Kenhardt to only 1.5 m.km^{-1} at its confluence.

West of Pofadder the monotony of the plains and the wide sand-choked Koa valley, is broken by Goob se Berg, the Namiesberge, the Ghaamsberg, the Aggeneys and Black Mountain, the Haramoep mountains to the north of the last-named, Naib se Berg and other hills rising like inselbergs from the sand flats. All these including the northwesterly extension of the Mattheus Gat Mountains and Pellaberg attain elevations between 1100 and 1200 m.a.m.s.l. They rise over 200 metres above the surroundings.

The following cyclic land surfaces are present according to Partridge and Maud (1987):

- Undifferentiated Post-African Surface forming the southern and greater part of the Region.
- Two mountainous areas rising above the African Surface around Pofadder and north of Pella separated from each other by dissected ground.
- Two areas of African Surface:
  a) South of Pofadder forming the watershed between tributaries draining towards the Koa valley and those towards the Kaboep (or Coboop) and
  b) A short distance east of and parallel to the western boundary and stretching from the Pofadder-Springbok road southward as far as Platbakkies.
- Escarpment - a narrow strip adjoining the Orange River between Henkries and the Augrabies Falls.
- Dissected ground of undetermined age bordering on the Escarpment west of as well as upstream of the Augrabies Falls on both sides of the Orange and Hartbees Rivers.

1.3 CLIMATE AND RAINFALL

Information presented here is largely based on Schulze (1994). The climate varies in a west-east direction from desert to poor steppe. Average annual sunshine duration amounts to more than 80% of the possible. Temperatures are subject to great variation both seasonal and diurnal. The mean daily maximum and minimum temperatures in January are 35^0 and 20^0 C at Upington and 39^0 and 22^0C at Goodhouse (situated on the Orange River 5 km upstream of Henkries Mouth). Corresponding mean daily maximum and minimum temperatures in July are 20^0 and 5.5^0C at Upington and 23^0 and 6^0C at Goodhouse. Lower temperatures obtain on higher ground away from the Orange River valley. At O'Okiep just outside the western boundary the comparable Figures for January are 30.5^0 and 15.5^0C and for July 16.7^0 and 5.5^0C. At Pofadder the annual mean maximum and minimum temperatures are 25.9^0C and 10.9^0C compared to the 31.7^0C and the 14.9^0C at Goodhouse. Extreme daily summer maxima and minima can reach 46^0 and 32^0C whilst extreme daily winter maxima and minima may be as low as 5^0 and -10^0C. Frost is common during June, July and August.

Rainfall is highly unreliable. Only a narrow strip in the west falls within the winter rainfall region. The line that separates summer rainfall in the east from winter precipitation in the west runs roughly through Goodhouse and Bosluispan. Summer rainfall peaks in the late summer and is mainly due to convectional showers whilst winter precipitation is mainly cyclonic and orographic. Rainfall increases from west to east. As far east as 20^0 longitude the mean annual rainfall is less than 100 mm except in the far southwest near the edge of the interior plateau where it approaches a mean of 150 mm. Rainfall increases from 20^0 longitude eastwards to just over 200 mm in the extreme southeast. The mean annual effective rainfall (ACRU, Schultze 1989) varies likewise - from less than 50 to 150 mm per annum.

1.4 VEGETATION

The Biome is Nama-Karoo (Rutherford and Westfall 1986). False Succulent Karoo occurs along the western boundary in a zone varying in width in a north-south direction from 15 to 80 km and in a patch south of Pofadder. Two main veld types (Acocks 1953) are present over the rest of Region 26:

- Arid Blomkoolganna Veld in the southern half of the Region and in the Koa Valley.

- Orange River Broken Veld in the northeast grading into Namaqua Broken Veld (variation Rhigozum trichotomum Veld and Desert False Grass Veld) downstream of the Augrabies Falls.

1.5 GROUNDWATER IN THE REGION'S ECONOMY

The bulk of the Region's urban and rural population is concentrated along the Orange River and is dependent on river water for irrigation of crops and urban use – to name a few of the more important communities: Groblerhoop, Upington, Keimoes and Kakamas. Away from the Orange River surface water supplies are virtually lacking. The towns Kenhardt, Pofadder, Pella and Marydale however originated at the site of springs. Nowadays Pofadder and Pella including the Black Mountain Mine at Aggeneys are supplied from the river. Before water from the Orange River became available to the mine i.e. before 1980 about 1500 m^3d^{-1} was obtained from boreholes. Rooiberg Dam on the Hartbees River some 10 km upstream of Kenhardt is an intermittent source of water for irrigation.

Stock farming, which occupies more than 90% of the Region and its human population of around 7500 persons accordingly, is solely dependent on groundwater. This also applies to Kenhardt (population around 5000) and Marydale (population around 2500). According to Schumann (±1973 and ±1975) consumption of Marydale amounted to about 31 000 m^3 in 1969. Schumann also estimated that farmers in the 280 km^2 catchment in which Marydale is situated, were abstracting by means of windpumps 120 000 m^3 for stock and irrigation Kenhardt's consumption rose from 47 000 m^3 in 1964 (Nonner 1979) to 155 000 m^3 in 1985 and 233 000 m^3 in 1993 (van Dyk 1994). Consumption of groundwater in the Region is probably of the order of between one to two million m^3 per annum.

2. GEOLOGY

2.1 LITERATURE SURVEY

Published official sources of information about the geology of the Mokolian and older metasedimentary, metavolcanic and intrusive rock units of Bushmanland are:

1) The geological map Marydale (scale 1:238 000) published by the Geological Commission of the Cape of Good Hope in 1910.
2) A report by Rogers and Du Toit (1909) on the geology of parts of Kenhardt, Prieska and Carnarvon.
3) Geological Survey Memoir 53 by von Backström (1964) which deals with phacolith intrusions of charnockitic adamellite-porphyry, isoclinal and axial-plane folding and metamorphism in a portion of the area covered by sheets 2820D (Keimoes) and 2821C (Louisvale).
4) Geological sheets 2820D (Keimoes) and 2821C (Louisvale) scale 1:125 000 (1966).
5) Geological sheets 2818C and D (Goodhouse and Dabenoris) and 2819C (Onseepkans) scale1:125 000 with accompanying Explanation by von Backström and De Villiers (1972).
6) Geological Survey Handbook 8 Stratigraphy of South Africa; compiler L.E.Kent (1980).
7) Explanation of the 1984 edition of the 1:1 000 000 map of South Africa compiled by D.J.L. Visser (1989).
8) Quarter million geological sheets: Upington 2820 (1988), Prieska 2922 (1995) and Kenhardt 2920 (1998) which cover large portions of the Region as well as metallogenic sheets Upington 2820 and Kenhardt 2920 (1997).
9) Quarter million geological sheets: Postmasburg 2822 (1977), Britstown 3022 (1991), Springbok 2916 (2001) which cover small outskirts of Groundwater Region 26.
10) Explanation of geological sheet Britstown by Prinsloo (1989).
11) Bulletin 115 on the T'Oubep Suite of intrusives by Agenbacht (1992).
12) Explanation of metallogenic sheets Upington 2820 and Kenhardt 2920 by Du Toit (1998).
13) Explanation of geological sheet Kenhardt 2920 by Slabbert, Moen and Boelema (1999).
14) Explanation of geological sheet Springbok 2916 by Marais, Agenbacht, Prinsloo and Basson (2001).

Apart from the official publications the Namaqua Metamorphic Province has received a great deal of attention over the last 30 years or so. See for instance Joubert 1974, Botha *et al* 1977; Geringer 1979; Frick and Wheelock 1983; Stowe *et al* 1984; Hartnady Joubert and Stowe1985; Joubert 1986a and b; Geringer *et al* 1988; Schlegel 1988; Colliston *et al* 1989; Praekelt and Schoch 1997; Moen 1999; Colliston and Shoch 2002.

For Information on the younger Koras and Dwyka Groups consult respectively Du Toit (1965), Grobler *et al* (1977) and Visser (1985). McCarthy *et al* (1985), De Wit (1993 and 1999) and Brandt *et* al 2003 and 2005) write about Cainozoic deposits. Cornelissen and Verwoerd (1975) discuss the occurrence of pipe-like bodies whilst Scholtz (1985) and Smith (1986) provide descriptions of volcanic crater-lake deposits.

2.2 GEOLOGICAL SUBDIVISION OF GROUNDWATER REGION 26

Region 26 is composed basically of Mokolian metasedimentary, metavolcanic and intrusive rock units of the Namaqua Metamorphic Province. Additionally included in the Region are:

- a strip of volcano-sedimentary rocks and granite of Swazian-Randian age and part of the Kaapvaal craton In the Marydale - Omdraaisvlei area.
- the Koras Group of largely unmetamorphosed inorogenic volcano-sedimentary rocks east of Upington and Namibian-Mokolian intrusives.
- a thin cover of Dwyka Group tillite / diamictite and shale along the southern boundary.
- Tertiary and Quaternary fluvial and aeolian deposits and calcrete overlying Mokolian rocks.

Despite all the attention that the Namaqua Metamorphic Province has received, questions about its lithostratigraphy and tectonic history have been resolved only partially The Province according to Slabbert *et al* (1999) is characterized by an intricate pattern of folding and faulting additionally complicated by a large number of granite intrusions. Regional correlation of rock units is furthermore hampered through fragmentary exposures, variable strata successions and complex structure. The Metamorphic Province accordingly has been subdivided into a number of discrete tectono-stratigraphic fragments. These together with the Kaapvaal craton Marydale Group and granite, the graben-like Koras depository and the transitional zone of Dwyka cover are depicted in Figure 2 (at the back of the report).

On structural grounds the Metamorphic Province is divided into four subprovinces: Kheis, Gordonia, Bushmanland and Richtersveld. Du Toit (1998) and Slabbert *et al* (1999) describe the further subdivision of the subprovinces east of 20^0 longitude in the Explanations of the quarter million metallogenic and geological sheets Upington 2820 and Kenhardt 2920. The subdivision west of 20^0 longitude is based on the recently mapped but as yet unpublished sheets Onseepkans 2818 and Pofadder 2918. Messrs H.F.G.Moen and A.L.D. Agenbacht of the Upington office of the Council for Geoscience advised the author about the division shown in Figure 2. The Region encloses a small portion of the published sheet 2916 Springbok.

The Kheis Subprovince abuts against Kaapvaal craton rocks in the east and is bounded in the west by the Trooilapspan shear zone in the north and the Brakbosch fault in the south. The author divides the Subprovince further into two fragments:

- Fragment A (numbered II on Figure 2 and in Table 2a section 2.3) stretches from Gariep on the Orange River (28^0 36.5'S and 21^O 47.8"E) southeastwards to where its outcrop disappears under cover of the Dwyka Group. It is bounded on the east firstly by the Orange River and then between the Buchuberg Settlement and Kaboom 8 by the southwesterly striking Dabep fault. From Kaboom 8 southeastwards it abuts against the Swazian-Randian Kaapvaal Marydale Group, the Draghoender Granite-gneiss and the Skalkseput Granite. The fragment's western boundary is the Brakbosch fault between Boks Puts 118 (28^0 56.6' S and 21^0 45.1' E) and Grenaat Kop 120, (30^0 6.1'S and 22^0 26.6'E). Closure between Boks Puts 118 and Gariep is provided by the Blauwbospan fault.
- Fragment B (consisting of three parts numbered III, XIVa and XIVb on Figure 2 and in Table 2a section 2.3) extends from north of the Orange River southwards in the form of an irregularly tapering wedge. Its northern boundary is determined by the northernmost scattered exposures of Koras Group rocks, jutting through the Kalahari sand cover. An E-W line joining Kurrees 369, 35 km north of Upington, to the northwestern corner of Florida 295 is taken as the northern boundary. The eastern boundary is made up of:

i) The N-S striking fault (western branch of the Blauwbospan fault) between Florida 295 and Lambrechtsdrif.
ii) The Orange River between Lambrechtsdrif and Gariep
iii) The Blauwbospan fault (eastern branch) between Gariep and Boks Puts
iv) The Brakbosch fault between Boks Puts and Brierspan (7 km south of Putsonderwater).

In emulation of Du Toit (1998) the Trooilapspan / Koegrabe shear zone is taken as the western boundary of the Kheis subprovince. The westernmost outcrops of the Vaalkoppies Group are taken as the boundary where the Trooilapspan shear zone has not been mapped. Fragment B is composed of three parts: III comprises formations belonging to the Namaqualand Metamorphic Province whilst XIVa and XIVb consist of younger volcano-sedimentary rocks of the Koras Group.

The Gordonia Subprovince adjoins the Kheis Subprovince in the west and is divided into an eastern Boks Puts and western Hartbees River and Arribees fragments. The Boks Puts fragment is a southward-tapering wedge-shaped block located between the Trooilapspan and the Boven Rugzeer shear zones and the latter's prolongated linking up with the Cnydas shear zone. The Hartbees River fragment is bounded by the Boven Rugzeer / Cnydas shear zones in the east and in the west by the Hartbees River thrust and the Hollenbachskop shear zone. The Hartbees River thrust extends from De Boven End van Keelafsny Leegte 268 in the south (approx 29^0 38'S and 21^0 25'E) to just south of Augrabies in the north (approx 28^o 45' S and 19^o 19' E). From here the western boundary of the Gordonia Subprovince follows the Swartrand thrust up to Onseepkans in the northwest The Hartbees River fragment is separated from the Arribees fragment by the Hollenbachskop shear zone, a structure that is obliterated on Oup 80 by the younger Naros Granite.

The Hartbees River thrust separates the northwesterly trending tectonic fabric of the Kheis and Gordonia Subprovinces from the northeasterly trending tectonic fabric of the easternmost part of the Bushmanland Subprovince. Further to the west this fabric is oriented roughly east-west. That part of the Bushmanland Subprovince which lies within Groundwater Region 26 has been divided into six fragments namely Haakjes Doorn Kolk, De Kruis, Bry-Paal / Aggeneys, Drooge Grond, Khurisberg and T'Caimoeps Laagte / Kamiesberg. Whereas bounding shear zones between the different fragments could be mapped in the eastern part of the Subprovince, the wide-spread sand cover in the west allows fragment boundaries to be drawn by approximation only. Fragments are distinguished on the basis of differences in age, metamorphic grade or lithology.

The distinction between the Bushmanland and Richtersveld Subprovinces is age. The nature of the boundary between them is however heavily disputed and remains unresolved. The Groothoek thrust recognized west of the Groundwater Region by Theart (1980) has been interpreted as an oblique ramp dipping northward along which the Richtersveld Subprovince was transported southwards. This hypothesis has also been applied eastwards where the contact zone is concealed under an extensive sand cover. Marais et al (2001) however are of the opinion that the contact zone at Groothoek represents upward flexuring of the southern Bushmanland block.

The transition zones Z and Y between the Mokolian floor and overlying Dwyka glacial deposit are the 15th and 16th geological entities into which the Groundwater Region may be divided. Tertiary and Quaternary deposits occur throughout the Region and are not confined to a definable area.

2.3 LITHOSTRATIGRAPHY

Lithostratigraphy was compiled from published quarter million geological sheets and available Sheet Explanations mentioned under section 2.1. Messrs H.F.G. Moen and A.L.D. Agenbacht kindly supplied relevant information in respect of unpublished sheets 2818 Onseepkans and 2918 Pofadder.

2.3.1 SWAZIAN-RANDIAN KAAPVAAL CRATON ROCKS

TABLE 1 KAAPVAAL CRATON ROCKS

Fragment	Metamorphites			Intrusive Rocks
	Group	Formation	Lithology	
I Draghoender-Groveput				Skalkseput Granite
				Draghoender Gneiss
	Marydale: Subgroup Doornfontein	Uitzigt	Massive garnetiferous amphibolite, streaky amphibolite	
		Modderfontein	Banded iron formation, minor limestone / dolomite, amphibolite, greenstone, quartzite	
	Marydale: Subgroup Prieskapoort	Perdeput	Amygdaloidal basaltic lava, pillow lava, tuff, minor felspathic quartzite, minor ultramafic layers, amphibolite	
		Steenkop	Conglomerate, grit, subgraywacke, volcaniclastics, minor intercalated lava, acid lava, metaquartzite	

2.3.2 MOKOLIAN NAMAQUA METAMORPHIC PROVINCE

TABLE 2a KHEIS METAMORPHIC SUBPROVINCE

Fragment	Metamorphites			Intrusive Rocks
	Group	Formation	Lithology	
II Groblershoop				Plat Sambok and Waterkop Suites
				Unnamed grey augen gneiss
				Unnamed biotite and biotite-hornblende granite
				Kalkwerf Gneiss
				Stillerus Metagabbro
	Vaalkoppies?	Kaboom	Quartzite, minor sericitic schist	
		Spioenkop	Quartz-sericite schist, quartzite, paragneiss, amphibolite	
	Brulpan	Groblershoop	Micaceous schist, schistose quartzite	
		Uitdraai	Quartzite, subordinate quartz-sericite schist	
		Boegoeberg	Quartzite	
		Dabep	Quartz-sericite, quartz-chlorite-epidote and actinolite-chlorite schists, actinolite amphibolite	
III Sultanaoord				Swanartz Gneiss
				Kleinbegin Subsuite
				Mafic to ultramafic rocks
	Wilgenhoutsdrif	Leerkrans	Metabasalt, felsic lava, green schist, conglomerate, ferruginous chert	
		Zonderhuis	Phyllite, schist, carbonate rocks, conglomerate, serpentinite, quartzite	
	Vaalkoppies	Sultanaoord	Massive quartzite, interbedded phyllite	
		Dagbreek	Quartzite, schist, banded gneiss, migmatite, leucogneiss, amphibolite, serpentinite	

TABLE 2b GORDONIA METAMORPHIC SUBPROVINCE

Fragment	Metamorphites			Intrusive Rocks
	Group	Formation	Lithology	Hartbees Pan, Gemsbokbult, Skeerhok & Klipkoppies Granites
IV Boksput				Kleinbegin Subsuite
				Kraalkop Quartz-diorite
				Friersdale Charnockite
				Mafic and ultramafic rocks
	Areachap	Jannelsepan	Amphibolite, amphibolite gneiss, biotite gneiss, pelitic gneiss, cal-silicate rock	
		Sprigg	Schist, semi-pelitic gneiss, metaconglomerate, quartzite, amphibolite	
		Bethesda	Pelitic gneiss, biotite gneiss, amphibolite, calc-silicate rocks	
		Rateldraai	Kinzigite	
		Van Wykspan	Quartz-feldspar gneiss, lenses of amphibolite, calc-silicate rocks and metapelite	
V Hartbees River				**Granites:** Elsie se Gorra, Klein van Wykspan, Boven Rugzeer, Swartputs, Dwaalgees, Pypklip, Vaalputs, Louisvale, Keboes, Kanoneiland, Colston, Neilers Drif, Gouskop, Straussburg, Cnydas, Brussel, Rok Optel, N'Rougas, Liefdood, Gifberg and Donkieboud
				Granodiorites: Varsput, Daberas
				Enderbite Stolzenfels
				Tonalite; Nous West
				Gneisses: Smalhoek, Warmbad South, Schuitdrift, Yas, Stukkende Dam
				Mafic and Ultramafic rocks: Nouzees Suite, Biesiespoort metagabbro
	Group	Formation	Lithology	
	Biesje Poort	Goedehoop	Quartzite - sericitic and / or feldspathic, conglomerate lenses	
		Valsvlei	Medium-grained quartz-rich gneiss; calc-silicate and aluminous gneiss lenses	
		Ganzenmond	Quartz feldspar-gneiss; lenses of amphibolite, calc-silicate and pelitic gneiss	
		Rautenbach se Kop	Fine-grained pink-weathering gneiss	
		Puntsit	Quartz-rich and mafic calc-silicate rocks; lenses of wollastonite, marble, schist	
		Toeslaan	Kinzigite, pelitic gneiss, biotite gneiss, leucogneiss	
		Soutrivier	Banded biotite gneiss, muscovite gneiss, sillimanite-bearing gneiss	
		Sandputs	Quartzite, feldspathic and calc-silicate-bearing psammite, aluminous gneiss	
		Omdraai	Leucocratic quartz-microcline gneiss, amphibole gneiss, quartzite	
		Piet Rooisberg	Medium-grained pink-weathering gneiss	
	Koelmanskop Metamorphic Suite	Collinskop	Kinzigite	
		Bok-se-Puts	Gneiss with quartz-rich and pelitic zones	
		Kourop Migmatite	Migmatitic leucogneiss and biotite gneiss, garnetiferous in places	
		De Bomen Gneiss	Fine-grained grey to medium-grained reddish gneiss with garnet in places	
		Witwater Gneiss	Garnetiferous mica-poor gneiss	
		Twakputs Gneiss	Megablastic garnetiferous biotite gneiss	
		Narries Subsuite	Kinzigite, amphibolite, quartzite	
	Jacomyns Pan		Pelitic gneiss, quartzite, leucogneiss, amphibolite, calc-silicate rocks, marble	
		Sandnoute	Pelitic gneiss, quartzite, amphibolite, amphibole gneiss, calc-silicate rocks,	

TABLE 2b GORDONIA METAMORPHIC SUBPROVINCE (continued)

Fragment	Metamorphites			Intrusive Rocks
	Fragment	**Metamorphites**	**Intrusive Rocks**	
V Hartbees River	Vyfbeker Metamorphic Suite	Wolfkop	Marble; interbedded quartz-feldspar gneiss, quartzite, calc-silicate rocks, amphibolite	
		Hugosput	Garnetiferous pelitic gneiss; quartz-feldspar gneiss	
		Rozynen Bosch	Quartz-felspar gneiss, calc-silicate rocks, marble, amphibolite, biotite gneiss	
		Dreyer's Put	Granoblastic leucogneiss, quartzite and felspathic quartzite	
		Kenhardt Migmatite	Migmatitic biotite gneiss, amphibolite, leucogneiss, porphyroclastic biotite gneiss, marble, calc-silicate rocks Gneiss ±sillmanite nodules,quartz-biotite-sillimanite schist	
		Piet Rooi's Put s Gneiss	Leucocratic gneiss, minor quartzite	
		Mottels River	Aluminous gneiss, lenses of calc-silicate rocks amphibolite, marble	
		Putsies Gneiss	Biotite gneiss, migmatitic iin places, cala-silicate rocks, amphibolite	
		Driehoek	Amphibolite, amphibole and biotite gneiss, calc-silicate rocks marble	
VI Arribees				**Granites:** Naros, Konkonsies, Skuitklip
				Gneisses: Gemsbokvlakte, Bladgrond South, Poliisiehoek
	Arribees	Koenap	Kinzigite, calc-silicate rocks, marble	
		Bysteek	Calc-silicate rocks, marble	
		Oupvlakte	Two-pyroxene granulite: in places amygdaloidal or garnetiferous; metapelitic granulite, minor quartz-feldspar gneiss and calc-silicate rocks	

TABLE 2c BUSHMANLAND METAMORPHIC SUBPROVINCE

Fragment	Metamorhites			Intrusive Rocks
	Group	Formation	Lithology	
VII Drooge Grond				**Gneisses**: Noubestaan? Coboop, Noudap, Pipeline, Swartmodder, Banksvlei
	Droêboom	Longsiekvlei	Quartzite, calc-silicate rocks,amphibolite, conglomerate	
		Droêgrond	Quartz-feldspar gneiss	
		Klipvlei	Biotite gneiss	
		Pella Subgroup	Quartzite, quartz-biotite-muscovite-sillimanite schist, amphibolite, calc-silicate rock	
		Guadom	Biotite /hornblende gneiss, quartzose feldspathic gneiss	
		Onseepkans	Boitite-muscovite-sillimanite-cordierite schist	
		Noriseep	Amphibolite, calc-silicate rocks, gneiss	
VIII Brypaal / Aggeneys				**Granites:** Samoep & Kabis **Gneisses:** Namies South, Haramoep **Suites:** Nouzees: olivine gabbronorite and otho-amphibolite Gareskop:Pyroxenite, gabbro & norite dykes, Naab: Granite, granodiorite T'Oubep: Granite, granodiorite, tonalite, metabasite
	Bushmanland: Aggeneys Subgroup	Riet Put	Migmatised and crenulated cleaved biotite gneiss, amphibolite, marble, calc-silicate rocks, quartz-feldspar gneiss	
		Kameel Puts	Quartz-feldspar gneiss, banded biotite gneiss, amphibolite, biotite-quartz-feldspar gneiss	
		Brulkolk	Pegmatite-bearing quartz-feldspar gneiss, caldc-silicate rocks with lenses / layers of muscovite schist, marble, conglomerate,and amphibolite	
		Koeris	Psammitic schist, conglomerate, amphibolite, quartzite	
		Gams Member	Sulphide-bearing magnetite-grunerite-garnet-pyroxene rocks,cordierite fels, sillimanite schist, quartzite	
		Hotson	Rhythmically layered quartzite, quartz-feldspar-biotite gneiss ± sillimanite nodules, quartz-biotite-sillimanite schist	
		Wortel	Sequence of medium- to thick-bedded white quartzite with pelitic schist and interbedded sillimanite bodies	
		Koeipoort Gneiss	Medium- to coarse-grained leucogneiss in places biotite- and augen-rich	

TABLE 2c BUSHMANLAND METAMORPHIC SUBPROVINCE (continued)

Fragment	Metamorphytes			Intrusive Rocks
	Group	Formation	Lithology	
IX Haakjes Doorn Kolk				**Granites:** Krom Puts, Tuins, Lat River, Bakoondsvlei, Basjan
	Brakwater Metamorphic Suite	De Banken Gneiss	Variety of quartz-feldspar-biotite gneisses ranging from fine-grained to banded and medium grained augen gneisses	
		Sandkoppies	Fine-grained calc-silicate rocks	
		Haakdoorn	Quartz-feldspar gneiss amphibolite, calc-silicate rocks, aluminous and biotite gneiss, subordinate.quartzite	
		Poliesberg	Quartzose calc-silicate rocks intercalated lenses of quartz-felspar gneiss and marble	
		Slypsteenkrans	Amphibolite, subordinate calc-silicate rocks,quartz-feldspar and,quartz-feldspar biotite gneiss	
		Moddergat Gneiss	Fine and medium-grained banded biotite gneiss, coarse-grained biotite augen gneiss	
X De Kruis				De Bakken Granite
				Lange Kolk Suite: various granite-gneisses and diorite
		Kokerberg	Quartz-feldspar gneiss, pegmatitic zones	
		Zandbergshoop	Dark to grey-green calc-silicate rocks, quartz-feldspar-biotite gneiss	
XI T'Camoeps Laagte or Kamiesberg				**Granites:** Koos Vlei, Gabaip, Burton's, Vaalhoek Basjan Puts, Kalkvlei, Bantamberg
				Gneisses: Kraalbosch Vlei, Galputs, Mesklip
				Tonalite: Koesie se Dam
	Bushmanland: Kamiesberg Subgroup	Volmoed	Massive to poorly banded quartzite, interbedded felspathic quartzite, schist and iron formation.	
		Hytkoras	Pelitic and semi-pelitic biotite-garnet – sillimanite gneiss and cordierite gneiss, subordinate leucogneiss, biotite gneiss, amphibolite, calc-silicate rocks, and quartzite	
		Soutputs	Quartzose calc-silicate rocks with lenses / layers of amphibolite, conglomerate, quartzite	
		Kraandraai	Migmatised and epidotised calc-silicate rocks,calc-silicate rocks with quartz blasts	
		Steenkampsvlei Member	Fine to medium-grained amphibolite and biotite schist	
		Bossiekom	Quartz-feldspar gneiss with intercalted amphibolite,calc-silcate rocks,quartzite	
		Lekkerdrink Gneiss	Medium-grained leucogneiss	

XII Khurisberg				**Koperberg Suite:** Norite, diorite, Anorthosite, pyroxenite, serpentinised peridotite
				Granites: Kweekfontein, Concordia
				Gneisses: Areb, Konkyp, Modderfontein Mesklip, Nababeep
	Bushmanland: Khurisberg Subgroup	Springbok	Garnet-sillimanite schist, quartzite, minor calc-sikicate rocks and conglomerate	
	Gladkop Metamorphic Suite	Noenoemaasberg Gneiss	Pink-weathering fine equigranular gneiss - sillimanite-bearing in places	
		Brandewynsbank Gneiss	Fine-grained grey biotite gneiss – in places megacrystic	
		Steinkopf Gneiss	Fine-grained grey banded to massive biotite-hornblende gneiss	

TABLE 2d RICHTERSVELD METAMORPHIC SUBPROVINCE

Fragment	Metamorphites			Intrusive Rocks
	Group	Formation	Lithology	
XIII Dabenoris				**Hoogoor Suite:** leucocratic quartzo-felspathic (pink) gneisses
				Garekop Suite: Pyroxenite, gabbro & norite dykes
				Vioolsdrif Suite: Coarse-grained mafic and ultramafic rocks
	Orange River: Haib Subgroup	Hom	Biotite-hornblende schist, gneiss, quartzite	
	Droëboom	Guadom	Coarse-grained biotite-sillimanite biotite schist and biotite-hornblende gneiss	

2.3.3 MOKOLIAN UNMETAMORPHOSED INOROGENIC VOLCANO-SEDIMENTARY ROCKS

TABLE 3 KORAS GROUP

Fragment	Sedimentary and Volcanic Rocks			Intrusive Rocks
	Group	Formation	Lithology	
XiV a & b Koras				Blauwbos Granite
	Koras	Kalkpunt	Red sandstone, basal conglomerate, conglomerate lenses	
		Welgevind / Leeuwdraai	Quartz-feldspar porphyry, locally agglomerate	
		Lambrechtsdrif	Basaltic andesite lava, pyroclastics, lenses of conglomerate, grit, quartzite	
		Ezelfontein	Sandstone, conglomerate, grit, shale, mudstone, intercalated latite	
		Avondale	Quartz-feldspar porphyry, tuff	
		Christiana	Sericitic feldspathic sandstone, grit, conglomerate, quartzite, shale	

2.3.4 KAROO SUPERGROUP

TABLE 4 DWYKA GROUP

Trasitional zones	Sedimentary Rocks			Intrusive Rocks
	Group	Formation	Lithology	
Y & Z				Dolerite
	Dwyka		Clast-rich arenaceous and clast-poor argillaceous diamictite, bedded diamictite, massive carbonate-rich diamictite, basement-derived breccias, dropstone argillite and fine- to coarse-grained sandstone. overlying Mokolian, Randian and Swazian metamorphites and intrusive rocks	

2.3.5 CAINOZOIC ERA

Sand, scree, rubble, sandy soil.
Windblown sand and dunes.
Fluvial deposits.
Calcrete.
Kimberlite and olivine melilitite pipes and dykes.

2.4 STRUCTURAL GEOLOGY OF NAMAQUA METAMORPHIC PROVINCE

A desription of the complex structural features and history of the Namaqua Metamorphic Province falls outside the scope of this monograph. Discussion will be limited to a few general remarks. According to Joubert (1974) deformation in Namaqualand and the Pofadder area consisted of four, possibly five episodes. The second which gave rise to recumbent isoclinal folds and which was accompanied or followed by the highest degree of metamorphism, was the most important. Succeeding episodes of deformation were less intense and culminated in shear deformation.

Andreoli *et al* (1986) recognized five episodes of deformation in the Vaalputs area (extreme west) and state the dominant direction of faulting to be north-northwesterly. The most prominent, the Garing fault, is more than 30 km long. Faults are characterized by a narrow zone of reddened cataclastic granitic / gneissic rock rich in epidote and cored in places by mylonite. Reactivation of the north-northwesterly faults during the Cainozoic Era is indicated by the displacement of post-Cretaceous duricrusts and the association between lineaments and depressions in the Vaalputs Basin (Brandt *et a*l 2005).

East of the Pofadder area, in Sheet 2920 Kenhardt, Slabbert, Moen and Boelema (1999) also recognized four phases of folding not only in the Bushmanland Subprovince but also in the Kheis and Gordonia Subprovinces. The history of the prominent Brakbosch fault is complex. It experienced several episodes of activation. Displacements of 120 km horizontally and 2 km vertically seem to be indicated. In Sheet area 2920 shearing varies from local to regional. The Boven Rugzeer shear for example is characterized by intense shear foliation and retrogressive metamorphism. The Hartbees River Thrust consists of a wide zone of mylonisation and deformation.

2.5 BOUNDARY BETWEEN THE NAMAQUA METAMORPHIC PROVINCE AND KAROO BASIN

Owing to the flat topography, sparse exposures, the very low dip of the base of the Dwyka Group and unevenness of the glaciated floor, the southern boundary of the Region is not well defined but should rather be considered a transition zone. Visser (1985) describes the broad pre-Dwyka paleotopography as follows:

- Between Copperton in the southeast and the 21^{o} longitude west of Kenhardt the undulating southerly slope of the glaciated basement had relief differences of up to 100 metres as deduced from thickness variations in the diamictite and from basement rocks protruding through the Dwyka cover.
- Between Copperton and the Doringberg Range valleys and depressions trend north-northwest. Westward this direction changes to north-northeast and then to east near Kenhardt.
- West of 21^{o} longitude the Sout River valley represents a south-striking depression with a width of about 100 km and a depth relative to the surrounding basement in excess of 300 metres.
- The so-called Pofadder Ridge, which trends south, separates the Sout River depression from the Namaqua basin in the far west. The existence of the ridge is deduced from an increase in elevation of the Dwyka-basement contact and a corresponding overlap of the glacial beds by younger mudstone / shale of the Prince Albert Formation south of Pofadder as is shown on the 1:1000 000 geological map.

2.6 KIMBERLITE AND RELATED ROCKS

See Cornelissen and Verwoerd (1975) and Moore and Verwoerd (1985).
A swarm of some 270 pipe-like bodies are found between Aggeneys in the north and Platbakkies in the south. (Platbakkies is situated some 10 km south of Vaalputs). Three types are distinguished:

a) Olivine melilitite and olivine-nepheline melilitite pipes
b) Kimberlitic bodies some of which are dyke-like
c) A majority of sediment and breccia-filled diatremes ranging from 50 to 500 metres in diameter and filled by (carbonaceous) shale, dysodile, mudstone with calcareous intercalations, sandstone, grit, arkose, conglomerate and angular blocks of gneiss that collapsed into the crater.

$^{238}U/^{206}Pb$ determinations on zircon inclusions in kimberlitic material and K/Ar whole rock determinations on olivine melillitite yielded ages ranging from 77 ± 3 to 59.3 Ma. These Figures indicate that the pipes are late Cretaceous to early Tertiary in age (Moore and Verwoerd 1985). According to the palynological interpretation of Scholtz (1985) the age of sediments in the pipe on Banke 409 is Palaeocene. Smith (1986) has described the fossiliferous sedimentary succession overlying a kimberlite diatreme on the farm Stompoor 109 in the Prieska District. These sediments are interpreted as having accumulated within a crater-lake during the Late Cretaceous.

2.7 CAINOZOIC DEPOSITS

In addition to the pipe sediments superficial deposits i.e. alluvium, windblown sand and dunes, calcrete, surficial sand, scree and rubble ranging in age from Tertiary to Recent cover a considerable portion of the Region, particularly in the area west of Pofadder. They are of interest not only as potential aquifers but also by impeding groundwater recharge.

Relatively little is known about the extent and thickness of fluvial deposits that occur along rivers such as the Mottels and the Rugseer in the Kenhardt area, the Brabees which joins the Orange River at Augrabies, the Nous, Goob se Laagte and more. At Kenhardt alluvial deposits in the Hartbees River attain a thickness of 37 m downstream of the confluence of Driekop se Rivier. The bulk consists of fine-grained and clayey material (Van Dyk 1994). On Witvlei 203 fifty kilometers downstream a borehole penetrated 38 m of alluvium and on Omkyk 61 a further 20 kilometres downstream between 50 and 60 m of alluvium was reported in two boreholes. In Driekop se Rivier upstream of the Hartbees River confluence the reported maximum sand thickness is 11 metres.

Thick Cainozoic deposits occur in the palaeo-drainage channels of the Koa and Kaboep / Coboop valleys. Von Backstrom and De Villiers (1972) state that a well at the homestead on Wolftoon 48 in the Koa valley reached 64.5 m without striking bedrock. They quote Rogers (1915) who reported that a drill reached 120 m in the same valley between Wolftoon and Henkries. Frommurze (1937) mentions thicknesses of 45.7 and 106.7m respectively in a well on Bloemhoek 61 and a borehole on Nooisabes 51 in the Koa valley. The nature of these deposits may be gauged from data extracted from the National Groundwater Data base and Tabled below.

TABLE 5 KOA VALLEY DEPOSITS

Farm Name & No	**Borehole No**	**Lithology of Cainozoic deposits in the Koa Valley and immediate surroundings:** (Selected borehole logs of the Department of Water Affairs and Forestry)
Amam 46	136790	0 – 116 m Alluvium
	69316	0 – 3 m Sand; 3 – 33.5 m Gravel; 33.5 – 61 m Gravel and clay
	13344	0 -94 5 m Clay
Kabib 50	12396	0 – 39.6 m Sand and clay; 39.6 – 56.1 m Clay
	12230	0 – 102.7 m Sand and clay
	46333	0 – 167.9 m Sand
Nooisabes 51	110840	0 -131.7 m Sand; 131.7 -137.2 m Sandstone
Oenab 52	53354	0 - 42.7 m Sand
	150010	0 – 38 m Alluvium
Oenab-Noord 609	83643	0 – 78 m Clay; 78 – 80,5 m Gravel
Koeris 54	149441	0 – 60 m Alluvium
Naroep Restant	109302	0 – 54.9 m Clay; 54.9 – 145.1 m Sand
Heiorigas 49	12608	0 -3 m Sand; 3 – 61 m Clay; 61 – 92 m Limestone
Taaibosmond 66	71775	0 - 86.3 m Clay
Spioenkop 97	107143	0 – 28.7 m Sand; 28.7 – 123.1 Clay

On Gemsbok Vlakte 140 and Oupvlakte 90.in the Kaboep (Coboop) valley unconsolidated sediments respectively 55 and 75.6 m thick have been encountered.

In the far southwestern corner of the Region silicified and kaolinitised sandstone and conglomerate form the Kookoppe mesas and are preserved within the Daas Daap drainage on the farms Banke 409, Burtons Put 408 Plat Bakkies 388 and Daas Daap 378 (McCarthy *et al* 1985; Brandt *et al* 2003). A pebbly sandstone lying directly on a kaolinitised gneiss surface grades upwards into massive silicified sandstone. Immature cross-bedded arkosic grit is present locally. It appears that the arenaceous deposit is an alluvial fan in which the drainage was from west to east. Crater-fill dates and radiometric dating of nearby intrusives suggest a late Cretaceous to early Tertiary age for the fan accumulations.

On Vaal Puts 369 north of the Daas Daap area, kaolinitised gneiss and a small occurrence of Daas Daap beds are overlain by gritty sandy clay containing interrupted pebbly layers. The sediments which have undergone extensive bioturbation and pedogenesis were possibly deposited as unchannelized floodouts (Brandt *et al* 2005). They are influenced by north-northwesterly trending faults which also displace the underlying kaolinitised and silicified basement.

De Wit (1993) has made a detailed study of the Tertiary and Quaternary deposits at Bosluispan. The pan is located in the Koa valley about 90 km SSW of Pofadder. The study may serve as a model of the manner in which the Koa valley became sand-choked. The pan itself contains less than 0.5 m of sediment. Three quarries were excavated from the pan into the western side of the valley to access basal diamondiferous gravels. Mining exposed a complete vertical succession of the Tertiary sediments up to 9 metres thick. De Wit recognizes two lithofacies associations:

1) A lower fluvial and
2) An overlying one composed of lacustrine, terminal fan and fan sub-environments.

The fluvial unit which occupies depressions in a floor composed of gneiss or granodiorite and amphibolite grades upwards from a boulder-gravel into pebbly sands, sands, silts and muds. The overlying lacustrine sub-environment consists of massive and laminated silts, massive muds and marls. The terminal-fan sub-environment comprises coarse-grained sand with sparse and thin intercalations of laminated mud. Sand grains are sub-rounded in contrast to the angular to sub angular sand grains of the fluvial unit. An abundance of rhizoliths indicates that vegetation was plentiful. The fan sub-environment is made up of sand interrupted by a horizon of calcified soil and two of immature calcrete. Based on mammalian bones and teeth the age of the fluvial part of the deposit is estimated to be early Middle–Miocene. For a detailed discussion of the geomorphic history De Wit (1999) should be consulted. Hambleton-Jones *et al* (1986) describe several occurrences of uraniferous surficial deposits.

3. REVIEW OF GROUNDWATER INVESTIGATIONS AND REPORTS

A. The earliest scientific report on borehole siting appears to be that of Thomas Bain, Irrigation and Geological Surveyor in the Department of Agriculture of the Cape of Good Hope. His account "Report on the prospects of water boring on Government Ground in Bushmanland" was published in Appendix B of his Annual Report of 1892. Eight sites were selected along "a broad belt of red sand, evidently an ancient river-bed" (the Koa Valley) between Springbok and Pofadder. Drilling results are unfortunately not available.

B. Owing to the scarcity of water, the hardness of the rocks and the depths that have to be drilled, the Government has been assisting Bushmanland farmers for the greater part of the past century by drilling thousands of boreholes on a subsidy basis.
Frommurze (1937) analysed the results of governmental drilling in crystalline rocks of the Kenhardt, Namaqualand and Bushmanland Districts up to 1935. His results are listed below.

TABLE 6 BOREHOLE STATISTICS UP TO 1935

	Kenhardt District	Namaqualand and Bushmanland Districts
Number of boreholes	?	149
Average depth	50 m (164 ft)	49.4 m (162ft)
Average depth at which water was struck	41.1 m (135 ft)	37.2 m (122 ft))
Average depth of water level	28.3 m (93 ft)	24.7 m (81 ft)
Average yield	0.49 ℓs^{-1} (9270 Imp.gal diem^{-1})	1.1 ℓs^{-1} (21545 Imp gal diem^{-1})
Percentage successful (yield ≥ 0.038 ℓs^{-1} or ≥ 0.5 Imp gal min^{-1})	32	48

Except for summarizing data, the analysis has little use as a guide for the selection of borehole sites. Parameter variability is not addressed. The analysis combines hilly and mountainous Namaqualand terrain with the extensive sand-covered flats of Bushmanland. The former is characterized by shallow weathering and water levels; the latter by generally deeper water-levels.

C. Enslin (1943) demonstrated that basins of decomposition in crystalline rocks can be located with the electrical resistivity method. Amongst others a borehole was successfully sited by him in so-called weathered / decomposed Marydale lava on Jacomyns Pan 176, Kenhardt District. What was then considered Marydale lava is presumably presently called amphibolite of the Jacomyns Pan Group.

D. This successful demonstration ushered in a period of geophysical borehole siting. Geo-electrical selection of borehole sites on Bushmanland farms by personnel of the Geological Survey was virtually restricted to the period 1944 to 1970 and then on a part-time basis only. Persons involved were J.J.Taljaard 1944; F.W.Schumann 1945 to 1951 and again from the Prieska regional office during 1959 -70 (assisted by technicians A.C.W. Mew and J. Coetzer); J.R. Vegter 1946-48; C.V. Joubert 1948 and D.H. v.d. Merwe 1952-53. During the 1960's D. Pike, A.P.C. Nieuwoudt and G.J. Ellis of the Springbok regional office selected some borehole sites in far western Bushmanland. Reporting has been per individual investigation and farm.
During these years the hydrogeologist / geotechnician, with some exceptions, had little or no opportunity of exercising scientific control over the drilling operations or of logging

the boreholes. In the absence of the hydrogeologist boreholes were logged by the driller.

E. The status of groundwater investigations around 1950 may be gauged from Vegter (1953). He described the conditions under which groundwater occurs in the hard-rock formations and the use of electrical resistivity probing in locating basins or zones of weathering. A success rate of 57.5 % (yield ≥100 Imp.gallons hr^{-1} or 0.126 ℓs^{-1}) was obtained at sites where depth of weathering exceeded that of the water level. However, localities where weathering extends deeper than the water level are sparsely distributed, hard to find and in certain parts nonexistent. Attention had therefore to be directed to zones of fracturing, brecciation and mylonitisation. These are usually silicified and / or epidotised. Out of 35 boreholes selected on such zones only 14 (40%) were successful. The electrical resistivity method proved to be of little use either in locating them or in determining whether they contain potentially water-bearing openings at depth.

From 1910 to mid-century the Department of Irrigation had drilled 710 boreholes for farmers in the Kenhardt and Prieska districts. The success rate was 30.6% (yield ≥ 0.126 ℓ s^{-1}) and the average yield 900 Imp.gallons hr^{-1} or 1.135 ℓs^{-1}. Data about these boreholes are summarized in Table 7.

TABLE 7 GOVERNMENTAL DRILLING 1910 -1950
KENHARDT AND PRIESKA DISTRICTS

	1st Quartile (m)	Median (m)	3rd Quartile (m)	
Depth all boreholes	37	56	80	4 out of 710 holes > 152 m (500 ft)
Depth successful boreholes	37	53	72	1 out of 710 holes > 152 m (500 ft)
Strike depths	26	40	58	No strikes > 134 m (440 ft)
Water levels	19	28	40	4 out of 216 holes > 76 m (250 ft)

F. As a result of Vegter's findings some experimental electromagnetic surveys and drilling on fracture zones were undertaken in 1953. This work will be discussed in sections 7.3.3 and 7.3.4.

G. Enslin (1963) produced a preliminary report on the groundwater potential at Henkries and in the Koa valley. Enslin's investigation was only followed up around 2000 when a few gravity lines aimed at locating the sand-drowned Koa river were surveyed followed by the drilling of thirteen exploratory boreholes by the Department of Water Affairs and Forestry between February 2001 and July 2002 (see section 5.1 Koa Valley for more).

H. Schumann (±1975) compared the hydrogeology of the Makoppa Dome (Limpopo Province) with that of Bushmanland and eastern Namaqualand. At that time all the metamorphites of the Namaqua Metamorphic Province were considered to belong to the Kheis System of Du Toit (1954). Schumann based his statistical analyses of some 3800 boreholes, his description of the water-bearing properties, the siting of boreholes etc. accordingly. In addition to the intrusive Namaqua Granite-gneiss, the Grey Gneiss and the Geelbeksdam (Skalkseput) Granite, two categories of Kheis sedimentary and volcanic rocks were recognized:

- Metamorphic rocks of the Kheis type area (in the east): altered lavas (greenstones), tuffs, quartzite, quartz-sericite schists, banded ironstone, and limestone.

- Their reconstituted equivalents in the west: paragneiss, granulite, kingzigite, lime-silicate rocks and pink gneiss.

Borehole success rates (yields ≥ 0.126 ℓs^{-1} or 100 Imp.gallons per hour) ranged from 29% in the grey gneisses to 45% in rocks belonging to the Kheis System. The exception is adamellite with only 6%. In the majority of cases water is struck below the weathering base.

Zones of faulting and shearing were treated as a separate category. Out of a total of 157 boreholes drilled on silicified and epidotised zones of fracturing, brecciation and mylonisation in granite and gneiss 74 (47%) were successful.

I. Water for Kenhardt was the subject of investigations by Taljaard (1944); Nonner (1979 with resume by Mulder 1980), Van Dyk (1994), Van Dyk and Fourie (1999) and Fourie *et al* (1999). Nieuwoudt (1964) and Jackson (1982 with summary by Kok 1982) undertook investigations for the Pofadder Municipality. Aspects of these investigations and drilling are dealt with in sections 6.2.6 and 7.3.5.

J. The choice and development of Vaalputs as a suitable and safe repository for the disposal of low-level radioactive waste was based on a multidisciplinary investigation of which regional and detailed geological, geophysical and geohydrological studies formed the backbone (Andreoli *et al* 1986; Levin *et al* 1986; Anderson *et a*l 1986; De Beer and Blume 1984 and 1986; Levin 1988). Sandy and sandy gritty clay overlying kaolinised granite-gneiss was found to be a suitable storage medium.

Geological mapping of Vaalputs and adjacent farms on a scale of 1:10 000 was complemented by:

- A detailed airborne magnetic survey aimed at locating noritoid intrusives, kimberlitic pipes and faults;
- An INPUT survey; and
- Thermal infrared scanning.

Folow-up ground geophysical surveys comprised:

- Seismic refraction; and
- Schlumberger electrical sounding and rectangle profiling (De Beer and Blume 1984).

In an area of 1.6 km^2 selected for the proposed repository the uneven hard-rock surface was determined by means of Schlumberger soundings. The thickness of the overburden which consists of sand, calcrete, sandy gritty clay, sandy clay, calcareous clay, white kaolinitic clay and weathered basement, was found to vary from 6.6 to 36.5 m. The result compared well with that derived from continuous refraction profiling.

Most of the rectangle profiling was aimed at the Garing lineament or fault. It was found to be detectable electrically along two stretches whilst no low-resistivity anomalies were observed along an intermediate section. See chapter 7.2.3.and 7.2.6 for more information on soundings and profiling.

Drilling formed an essential component of the investigations. In the 1.6 km^2 area selected for the disposal site some 40 percussion boreholes were drilled:

- To determine the lithology and thickness of surficial sediments.
- To evaluate the stratigraphy at sites of geophysical anomalies.
- To determine the nature of aquifers.
- For geohydrological monitoring.

Groundwater was struck in a number of boreholes in fractured rock. No yield was recorded in others. In the vicinity of the disposal site the piezometric surface lies at a depth of 55 to 60 m.

The movement of water in both the unsaturated and saturated zones is a most important factor in characterizing a disposal site. For computer modeling of flow through the unsaturated zone soil moisture retention, coefficients of dispersion and distribution and hydraulic conductivity were determined. Natural isotopes in soil moisture and soil chemistry also received attention.

The suitability of the host material for disposal of radioactive waste from a geohydrological point of view is reflected by its low average saturated hydraulic conductivity of 10^{-8} $m.s^{-1}$. According to moisture measurements in auger holes water from rainfall of 126 mm over 4 days percolated down to only 3.5 m. Rapid movement to greater depths along preferential pathways such as desiccation cracks and root holes is however not ruled out (Levin 1988).

K. The spatial distribution of Borehole Prospects in Bushmanland can be read from Sheet 1 of the set of Groundwater Resources maps of South Africa (Water Research Commission and Department of Water Affairs and Forestry 1995). The probability of drilling a successful borehole (≥ 0.1 ℓs^{-1}), termed "Accessibility", is mostly less than 40%. It ranges between 40 and 60 % over limited areas. Exploitability i.e. the probability of a successful borehole yielding more than 2 ℓs^{-1} varies from less than 10% to 20%.

L. Groundwater Region Bushmanland is also covered on portions of the 1:500 000 Hydrogeo-logical maps published in 2001 namely 2714 Upington / Alexander Bay; 2916 Springbok and 2920 Prieska, Explanatory brochures have as yet not been published. This author is of the opinion that groundwater conditions are not portrayed correctly:

- According to these maps metamorphites are water-bearing by virtue of fractures whereas water is found in both fractured and weathered granitoids. The distinction in water-bearing character between metamorhites and granitoids is not supported by the present study.
- Water-bearing Cainozoic deposits at Henkries in the lower Koa valley are indicated on maps 2714 and 2916. On the other hand water-bearing fluvial deposits along rivers such as the Hartbees and Rugseer are not shown.
- The following remark occurs in the legends of all three maps: "unconsolidated sediments which are unsaturated have been omitted from the map". The meaning of this remark is obscure. Extensive tracts (dotted) of "unnamed sands Qz" are indicated on sheets 2916 and 2714 (Koa and Kaboep / Coboop valleys). These deposits are water-bearing over only small fractions of the areas indicated on the maps. Does the designation of the Qz areas as "intergranular and fractured" refer to the underlying bedrock? Many dry boreholes however have been sunk into the underlying bedrock in the indicated areas.
- The occurrence of groundwater is illustrated by means of sections. These are distorted in that they lack both horizontal and vertical scales and attempt to portray simultaneously broad geological structure as well as shallow small scale water-bearing features. The depth at which water may be struck and the probability of a strike is not stated.

On inset maps the distribution of borehole data, the elevation above sea level, mean annual precipitation and water quality (electrical conductivity) are shown.

4. PIEZOMETRIC CONTOUR MAPS

During the 1997/8 hydrocensus that was undertaken for the production of the 1:500 000 hydrogeological maps, the Directorate of Geohydrology kindly acceded to the author's request for more intensive data collection in three areas. Instead of merely sampling, information had to be collected as far as possible about every borehole whether successful or not. In addition to information provided by the landowner / occupant, position and elevation had to be determined, depth, water level and electrical conductivity of water had to be measured and where possible correlated with NGWDB records. Groundwater conditions in these three areas are thought to be a fair reflection of the Region as a whole. The large variety of Mokolian metamorphites and igneous rocks and their younger cover formations are represented; also the decrease in rainfall from around a mean of 150 mm per annum in the east to about 75 mm in the west. The three areas are situated:

- East of Kenhardt.
- Centered on the major drainage divide 60 km east of Pofadder.
- Between 30 and 70 km SW of Pofadder on both sides of the Koa Valley.

4.1 GEOLOGY

Simplified geology of the first two was copied from the 1:250 000 Kenhardt Metallogenic Map and unpublished field maps of the Council for Geoscience - Figures 4a and 5a (at the back of report). Lithology of the three areas is Tabled below.

TABLE 8 LITHOLOGY EAST OF KENHARDT

<table>
<tr><th colspan="4">SEDIMENTARY ROCKS</th></tr>
<tr><td>QUATERNARY</td><td colspan="2">KALAHARI SUPERGROUP</td><td>WINDBLOWN SAND</td></tr>
<tr><td>TERTIARY</td><td colspan="2"></td><td>CALCRETE</td></tr>
<tr><td>CARBONIFEROUS</td><td colspan="2">DWYKA GROUP</td><td>TILLITE, DIAMICTITE, SUBORDINATE SANDSTONE, MUDSTONE AND DOLOMITIC LIMESTONE</td></tr>
<tr><th colspan="4">METAMORPHIC ROCKS (MOKOLIAN OR OLDER)</th></tr>
<tr><td>FRAGMENT</td><td>GROUP</td><td>FORMATION</td><td>LITHOLOGY</td></tr>
<tr><td rowspan="5">HARTBEES RIVER</td><td>JACOMYNS PAN</td><td>(Mja)</td><td>PELITIC GNEISSES WITH QUARTZITE, LEUCOGNEISS AMPHIBOLITE AND CALC-SIILICATE ROCKS</td></tr>
<tr><td rowspan="4">VYFBEKER METAMORPHIC SUITE</td><td>KENHARDT MIGMATITE (Mke)</td><td>MIGMATITIC BIOTITE GNEISS, AMPHIBOLITE, LEUCOGNEISS, PORPHYROCLASTIC BIOTITE GNEISS, MARBLE AND CALC-SILICATE ROCKS</td></tr>
<tr><td>MOTTELS RIVER (Mm)</td><td>ALUMINOUS GNEISS, LENSES OF CALC-SILICATE ROCKS, AMPHIBOLITE, MARBLE</td></tr>
<tr><td>PUTSIES GNEISS (Mpt)</td><td>BIOTITE GNEISS, MIGMATITIC IN PLACES, CALC-SILICATE ROCKS, AMPHIBOLITE</td></tr>
<tr><td>DRIEHOEK (Mde)</td><td>AMPHIBOLITE, AMPHIBOLE AND BIOTITE GNEISS, CALC-SILICATE ROCKS AND MARBLE</td></tr>
<tr><td rowspan="2">HAAKJES DOORN KOLK</td><td rowspan="2">BRAKWATER METAMORPHIC SUITE</td><td>POLIESBERG (Mp)</td><td>FINELY BANDED SILICEOUS CALC-SILICATE GNEISS AND LENSES OF QUARTZ FELDSPAR AND MARBLE</td></tr>
<tr><td>MODDERGAT (Mmo)</td><td>BIOTITE GNEISS WITH STREAKY TEXTURE, AUGEN GNEISS, LENSES OF AMPHIBOLITE AND CALC-SILICATE ROCKS</td></tr>
<tr><td rowspan="2">DE KRUIS</td><td rowspan="2">DE KRUIS</td><td>KOKERBERG (Mko)</td><td>MEDIUM-GRAINED QUARTZ-FELDSPAR GNEISS, PEGMATITIC IN PLACES</td></tr>
<tr><td>ZANDBERGSHOOP (Mz)</td><td>CALC-SILICATE ROCKS WITH SUBORDINATE AMPHIBOLE AND BIOTITE GNEISS</td></tr>
</table>

TABLE 8 LITHOLOGY EAST OF KENHARDT (continued)

INTRUSIVE ROCKS

HARTBEES RIVER FRAGMENT	LIEFDOOD, ROK OPTEL, BRUSSEL, SWARTPUTS AND ELSIE SE GORRA GRANITES
HAAKJES DOORN KOLK FRAGMENT	LAT RIVER GRANITE
DE KRUIS FRAGMENT	DE BAKKEN GRANITE LANGE KOLK SUITE

TABLE 9 LITHOLOGY EAST OF POFADDER

METAMORPHIC ROCKS		
KOELMANSKOP METAMORPHIC SUITE	DE BOMEN GNEISS	FINE TO MEDIUM GRAINED GREY TO REDDISH GNEISS ± GARNET
	WITWATER GNEISS	GARNETIFEROUS ALASKITIC GNEISS
	TWAKPUTS GNEISS	GARNETIFEROUS MEGACRYSTIC BIOTITE GNEISS
	NARRIES SUBSUITE	KINZIGITE, AMPHIBOLITE, QUARTZITE
ARRIBEES GROUP	KOENAP FORMATION	KINZIGITE, CALC-SILICATE ROCKS, MARBLE
	OUPVLAKTE FORMATION	(a) TWO-PYROXENE GRANULITE IN PLACES AMYGDALOIDAL OR GARNETIFEROUS (b) METAPELITIC GRANULITE, MINOR QUARTZ-FELDSPAR AND CALC-SILICATE ROCKS
DROë BOOM GROUP	PELLA FORMATION	
	LONGSIEKVLEI FORMATION	QUARTZ-FELDSPAR GNEISS, CALC-SILICATE ROCKS, AMPHIBOLITE, CONGLOMERATE,
	DROëGROND FORMATION	QUARTZ-FELDSPAR GNEISS
	KLIPVLEI FORMATION	BIOTITE GNEISS
BRYPAAL GROUP	BRULKOLK FORMATION	QUARTZ-FELDSPAR GNEISS, CALC-SILICATE ROCKS, MUSCOVITE SCHIST, LIMESTONE, CONGLOMERATE, AMPHIBOLITE
	KAMEELPUTS FORMATION	QUARTZ-FELDSPAR GNEISS, BANDED BIOTITE GNEISS, AMPHIBOLITE, CONGLOMERATE
	RIET PUT FORMATION	BIOTITE GNEISS, AMPHIBOLITE, LIMESTONE, CALC-SILICATE ROCKS, QUARTZ-FELDSPAR GNEISS
BRAKWATER METAMORPHIC SUITE	DE BANKEN FORMATION	GREY MEDIUM-GRAINED BIOTITE GNEISS
	HAAKDOORN FORMATION	PSAMMITIC GNEISS, BIOTITE PARAGNEISS, AMPHIBOLITE, CALC-SILICATE ROCKS, ALUMINOUS GNEISS AND MINOR QUARTZITE
	SANDKOPPIES FORMATION	GREY CALC-SILICATE ROCKS AND QUARTZ-FELDSPAR GNEISS
	POLIESBERG FORMATION	FINELY BANDED SILICEOUS CALC-SILICATE GNEISS AND LENSES OF QUARTZ FELDSPAR AND MARBLE
	SLYPSTEENKRANS FORMATION	AMPHIBOLITE, SUBORDINATE CALC-SILICATE ROCKS, BIOTITE GNEISS
GRAPPIES GROUP	SOUTPUTS FORMATION	SILICEOUS CALC-SILICATE ROCKS, LENSES OF AMPHIBOLITE, CONGLOMERATE AND QUARTZITE
	KRAANDRAAI FORMATION	MIGMATISED SILICEOUS CALC-SILICATE ROCKS, AMPHIBOLITE
	BOSSIEKOM FORMATION	QUARTZ-FELDSPAR GNEISS, LENSES OF AMPHIBOLITE, CALC-SILICATE AND QUARTZITE
INTRUSIVE ROCKS		
TAFELKOP GNEISS		LEUCOCRATIC MEDIUM-GRAINEDTO AUGEN PINK GNEISS
BLADGROND SOUTH GNEISS		FINE-GRAINED LEUCOGNEISS
LUCAS VLEI GNEISS		MEDIUM-GRAINED GNEISS
SKUITKLIP GRANITE		COARSE GRANITE WITH RED AND GREY K FELDSPAR WITH CHARNOKITIC AND LEUCOCRATIC PHASES
KWESSIE GRANITE		GREY BIOTITE GRANITE
T'OUBEP SUITE		GRANITE, TONALITE AND GRANODIORITE

The hard-rock geology of the third area which is fairly extensively covered by sand is given in Table 10.

TABLE 10 LITHOLOGY SOUTHWEST OF POFADDER

FRAGMENT	FORMATION	LITHOLOGY
T'CAIMOEPS LAAGTE / KAMIESBERG	VOLMOED	QUARTZITE
	HYTKORAS	PELITIC GNEISS AND SCHIST
	KRAANDRAAIi	CALC-SILICATE LENSES, CONGLOMERATE, LIMESTONE, AMPHIBOLITE
	BOSSIEKOM	MEDIUM TO FINE-GRAINED QUARTZ-FELDSPAR GNEISS

4.2 PIEZOMETRIC CONTOURS

Piezometric contours are depicted in Figures 4b, 5b and 6a (at back of report). No correlation exists between piezometric surfaces and the large scale geological features of Figures 4a and 5a. In all three cases piezometric surfaces mirror surface topography. This is to be expected where water-bearing interstices decrease in number and aperture with increasing depth below surface. Deep circulation of groundwater in the Region is however not entirely ruled out as is evident from the existence of several thermal springs: Riemvasmaak (von Backström 1962), or Warmbad Noord 1 and Schuitdrift Oost 6 (Visser 1962).

A piezometric gradient is the integrated result of recharge, flow through a resistive medium and discharge. In the area east of Kenhardt piezometric gradients average about 3 m km^{-1} (Figure 4b). Groundwater is being discharged mainly, if not exclusively, through evapotranspiration. Evaporation from shallow groundwater is evident from saline soils and efflorescence found in drainage lines with pan-like surfaces such as Bastersput se Leegte and tributaries. In sand-filled and tree-lined riverbeds (so-called boomlope) such as the Mottels, Lat, Hartbees River, flood-recharged fresh alluvial water is gradually lost through evapotranspiration and is being replaced in time by subsurface saline seepage from the catchment.

Dense growths of the alien Prosopis fodder tree have invaded sandy riverbeds with their shallow water levels such as Driekop se Rivier and Rugseer River. To combat transpiration loss from the aquifer of the lower Driekop se Rivier, source of Kenhardt's municipal supply, an eradication programme was instituted in 1997 (Van Dyk 1999). Nearly 150 000 Prosopis trees were cut down in an area of 549 ha. A study has been undertaken to determine the effect of Prosopis eradication on the Rugseer aquifer (Fourie *et al* 1999). Results of this study have not yet come to hand.

East of Pofadder (Figure 5b) in the upper reaches of the Sout and Kaboep / Coboop Rivers, respectively southeast and southwest of the major drainage divide, piezometric gradients are about 2.5 and 3 m km^{-1}. North of the divide along Kantorogas se Laagte and tributaries, the gradient is 8 m km^{-1}. Here on the Hellum 1 and 2 portions of Lucas Vlei 93 meaningful groundwater supplies are virtually non-existent.

Southwest of Pofadder and east of the Koa Valley (Figure 6a) the piezometric gradient is roughly 4 m km^{-1}. It steepens to around 10 m km^{-1} within some 5 km of the Koa. A similar steep gradient is found on the western side. It continues further away from the Koa. The hydraulic gradient along the Koa between Bosluis and Galputs pans is about 1.2 m km^{-1}. It steepens "downstream" to Zuurwater, a distance of about 65 -70 km along the valley, to 2.6 m km^{-1} and between Zuurwater and Henkries, a distance of about 80 km to 3.2 m km^{-1}.

4.3 ELECTRICAL CONDUCTIVITY OF GROUNDWATER

In all three areas (Figures 4c, 5c and 6b at the back of the report) there is no obvious electrical conductivity trend. Large differences in EC are found between closely situated boreholes. This state of affairs may be ascribed to different depths at which water is struck and to differences in transmissivity and interconnectivity of fractures / fracture sets.

As no information is available on the depths at which water with differing EC was struck, correlation between EC and water level depth was attempted. The largest number of EC measurements has been made east of Kenhardt. Figure 7 is accordingly a plot of EC against water level depth in the catchments of the Mottels River and part of Basterspput se Leegte. It is evident from Figure 7 that on the whole water in the catchment of Basterspput se Leegte is more saline than that of the Mottels River. The fit of a second order polynomial curve to the Mottels River data appears acceptable. The validity of that fitted to data of Basterspput se Leegte may be questionable. The polynomial trends may be interpreted as indicative of EC increasing with water level depth as well as downstream towards the discharge area i.e. shallower water levels. Better quality water is found in parts with intermediate water level depths, more favourable recharge areas?

The variation in electrical conductivity in the catchments east of Kenhardt is examined in greater detail in Table 11 a, b and c. Only the lower portion of Driekop se Rivier southwest of Kenhardt is shown on Figure 4 a, b and c. Kenhardt derives its water supply from this catchment. The Mottels River and Lat River catchments are underlain by metamorphytes of the Jacomyns Pan Group, the Vyfbeker Metamorphic Suite and intrusive granites. According to the 1:250 000 geological map 2920 (Kenhardt) Dwyka Group is lacking in these two catchments. The catchment of Driekop se Rivier is split between the De Kruis and Haakjes Doorn Kolk fragments. Dwyka rocks are present only in the uppermost part of the catchment some 25 km south of Kenhardt.

FIGURE 7 RELATIONSHIP BETWEEN PIEZOMETRIC LEVEL AND GROUNDWATER EC MOTTELS RIVER AND BASTERS PUT LEEGTE CATCHMENTS

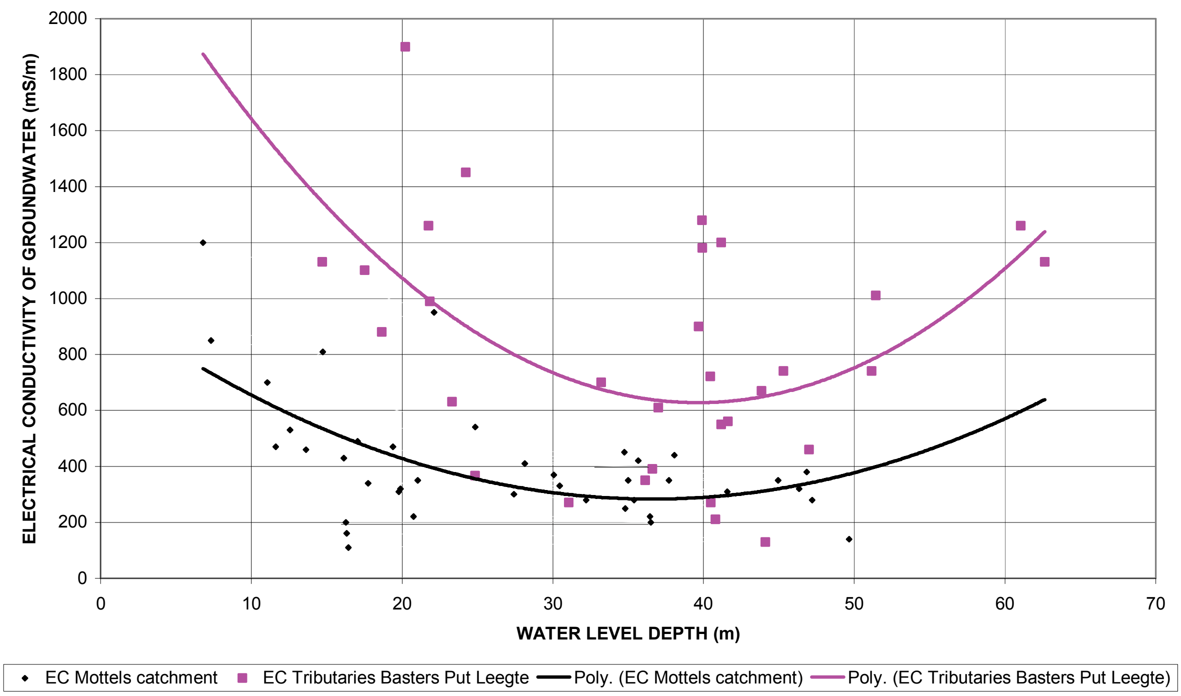

TABLE 11a EC RANGE IN CATCHMENTS EAST OF KENHARDT

Catchment name	From	To	Electrical conductivity range (mSm^{-1})	
			Minimum	Maximum
Mottels River	Hartebeest Pan 175	Steynsput 178.-	140	2000
Unnamed	Jagt Bult 262	Bosch Bult 311	129	1260
Keelafsnyleegte	Bastards Pan 259	Klaarpraat 267	210	1900
Brand holte	Witkopjes 258	Klaarpraat 267	120	840
Lat River	Witkopjes 258	Groot Lat Rivier 382	153	320
Driekop se Rivier	De Bakken 186	Kenhardt Townlands	22	1031

TABLE 11b MEAN, MEDIAN AND QUARTILE EC VALUES IN CATCHMENTS EAST OF KENHARDT

Catchment name	Surface gradient m km^{-1}	Electrical conductivity mSm^{-1}			
		Mean	Median	1st Quartile	3rd Quartile
Mottels River	3.1	447	350	284	425
Unnamed	4	853	1000	558	1130
Keelafsnyleegte	3.1	824	810	362	1120
Brand holte	3.7	507	580	295	685
Lat River	5	210	188	161	233
Driekop se Rivier	7.1	241	121	70	317

TABLE 11c MEAN, MEDIAN AND QUARTILE PIEZOMETRIC LEVELS IN CATCHMENTS EAST OF KENHARDT

Depth of Piezometric level	Catchment			
	Mottels River	Three tributaries of Basterputs se Leegte combined*	Lat River	Driekop se rivier
Mean	24	35.6	11.8	15.1
Median	19.9	37	8.5	13.7
1st Quartile	13.6	23.5	7	9.3
3rd Quartile	34.8	41.4	17.1	18
Range	3.4 - 52.7	8.5 - 63.1	5.7- 21.9	3.8 - 32.2

* Unnamed, Keelafsnyleegte and Brandholte catchments

Erratic strewn surfaces are found over large portions of the Jagt Bult – Bosch Bult, Keelasnyleegte and Brandholte drainage areas. Here as is shown in Figure 4a Dwyka Group strata overlie rocks of the Vyfbeker Metamorphic Suite. According to borehole logs the cover varies in thickness and nature. It is mostly less than 10 metres thick and comprises soil, calcrete, clay (weathered shale?), gravel and boulders (diamictite residuum). On Witkopjes 268 shale was encountered down to 25.2 and 22 m and on Klaarpraat 267 down to 23.5 m. On Boxch Bult 311 a borehole penetrated 34 m of limestone - probably calcretised Dwyka shale. Sandstone respectively 10 and 17 m thick, probably of fluvio-glacial origin, was found in two boreholes on Klaarpraat 267. Owing to the thinness of the cover and deeper piezometric level the occurrence of groundwater is practically limited to the Basement rocks.

From the foregoing and Tables 11 a, b and c it appears that:

- The better quality water is found in the catchments with steeper gradients and devoid or largely devoid of a Dwyka cover and characterized by shallower water levels.
- The poorer quality water is found in catchments with flatter gradients, with extensive Dwyka cover and characterized by deeper piezometric levels.

EC determinations though small in number around the major divide east of Pofadder appear to corroborate the above deductions - see Table 12.

TABLE 12 EC VALUES IN CATCHMENTS EAST OF POFADDER
(See Figure 5b)

<table>
<tr><td rowspan="3"></td><td colspan="3">Upper Catchment of</td></tr>
<tr><td>I and II</td><td>III</td><td>V</td></tr>
<tr><td>Samoep / Kotie se Laagte and Nous R.</td><td>Kaboep River</td><td>Sout River</td></tr>
<tr><td>No of EC determinations</td><td>6</td><td>6</td><td>7</td></tr>
<tr><td>Range of EC's (mSm^{-1})</td><td>161 – 1000</td><td>291 – 1540</td><td>220 –1187</td></tr>
<tr><td>Mean EC (mSm^{-1})</td><td>491</td><td>682</td><td>648</td></tr>
<tr><td>Piezometric gradient m km^{-1}</td><td>8</td><td>3</td><td>2.5</td></tr>
</table>

Electrical conductivities southwest of Pofadder and east of the Koa Valley (Table 13) compare well with those of catchments I and II (Table 12) and that of the Mottels River (Table 11a). West of the Koa EC values are about twice as high.

The reason for this sudden jump may be ascribable to:

- The presence of Dwyka Group rocks.
  On Koumis 599 shale presumably Dwyka, was reported in a few boreholes and in one borehole clay (weathered Dwyka shale?) was encountered down to 56 m.
- The area lies in the transition between winter and summer rainfall. A thicker sand cover coupled with low intensity (winter) downpours would lead to fewer infrequent recharge events.
- Groundwater is discharged through evaporation from low-lying pan areas in the Koa valley Bosluis, Bitterputs and Galputs pans.

TABLE 13 EC VALUES SOUTHWEST OF POFADDER

<table>
<tr><td rowspan="3"></td><td colspan="2">East of Koa Valley</td><td>West of Koa Valley</td></tr>
<tr><td>Upper (eastern) farms</td><td>Lower (western farms)</td><td rowspan="2">Struisbult 94 Koumis 599</td></tr>
<tr><td>Luttigshoop 214:Yzer-Vark-Vlei :228; Middel-Deur-Vlei 216: Neels-Vlei 215; Van-Tittensville 208</td><td>Dirk's Kop 597; Kalk Vlei 628; Narugas 227; Heuning- Vlei 229</td></tr>
<tr><td>No of EC determinations</td><td>20</td><td>16</td><td>7</td></tr>
<tr><td>Range of EC's (mSm^{-1})</td><td>167 – 935</td><td>196 – 1003</td><td>681 – 1656</td></tr>
<tr><td>Mean EC (mSm^{-1})</td><td>490</td><td>531</td><td>1139</td></tr>
<tr><td>Median (mSm^{-1})</td><td>447</td><td>459</td><td>1187</td></tr>
<tr><td>Piezometric gradient (mkm^{-1})</td><td>4</td><td>4 to 10</td><td>10</td></tr>
</table>

5. PRIMARY / COMPOSITE AQUIFERS

Cainozoic deposits are the only formations in Bushmanland that possess meaningful primary porosity. The occurrence of water-bearing Cainozoic deposits is restricted to the Koa and Kaboep / Coboop Valleys and to the larger rivers. Information on the water-bearing properties of alluvial deposits along the Orange River is lacking. Except for the lower Koa Valley Cainozoic deposits are as far as the writer is aware, not exploited on their own but always in conjunction with underlying weathered and fractured bedrock i.e. as part of a composite aquifer. Owing to a lack of information an overview is not possible of all the instances where composite aquifers are being exploited.

5.1 KOA VALLEY

The Koa valley lies in Hydrogeological Subdivisions 14 and 16 (see sections 6.2.14 and 6.2.16). Henkries spring is situated at the bottom end of the 11500 km^2 Koa catchment and at the upper end of the Henkries River valley where it enters the mountainous tract that borders on the Orange River. The spring issues from calcified sand.

Above Henkries spring the valley widens into the Henkrieslaagte a 30 km wide sand-filled depression between Jakkalswater 25 in the west, Koisabes 47 in the east and the Een Riet and Geselskapbank hills in the south (Gevers *et al.* 1937). Isolated hogbacks representing the summits of irregularities of the drowned valley floor project above the sand flats. Southeastwards in an upstream direction Henkrieslaagte narrows somewhat and forms the sand-filled Koa Valley. The valley stretches southeastwards for about 60 km before swinging south for another 70 - 80 km to embrace the Galputs, Bitterputs and Bosluis pans and beyond.

The Koa never flows along its entire length. Streams that run into the Henkrieslaagte (such as the Gari / Brak and Sabies from the south and southwest and the Beenbreekspruit further to the east) possess well-marked courses only in their upper reaches. Lower down, they become shallow depressions in the sand, indistinct, even obliterated. Sand dunes also block flow from tributary streams that at times may reach the valley bottom. Thus pans such as Marthas are formed. Below Henkries spring the rapidly dropping floor of the Henkries valley is terraced. Four terraces are clearly distinguishable (see Mabbutt 1951 and Enslin 1963). The valley drops about 170 m over the distance of 7.5 km to the Orange River. In the terrace faces layers of sandy limestone are exposed.

At the request of the then Department of Coloured Affairs which was interested in expanding the production of dates at Henkries spring, Enslin (1963) undertook a reconnaissance investigation. He determined collar and water level elevations of boreholes in the catchment above Henkries and concluded that Henkries spring owes its existence to groundwater percolating down the sand-drowned riverbeds of the Koa and tributaries.

Henkries spring and seepages rise from the upper terrace in the Henkries valley. About 12 km upstream of the spring the sand fill is up to 130 m thick and the water level depth about 60 m (Table 14). The spring owes its origin to constriction of the flow field and to thinning of the sand fill in the downstream direction. In April 1963 the flow used for irrigating the date plantation was gauged at 1.4 ℓs^{-1}. Terrace faces lower down the valley also coincide with constrictions in the aquifer and are thus also zones of effluent seepage. Seepage from the third terrace from the top amounted to 3.25 ℓs^{-1} in 1963 (1176 mSm^{-1} or 8000 $mg\ell^{-1}$). The seepage waters become increasingly saline downstream owing to repeated infiltration, emergence and evaporation.

Rainfall averages about 90 mm per annum over most of the spring's catchment except for the mountainous southwest where mean annual rainfall is about 150 mm. Enslin concluded that groundwater in the Koa valley is replenished by:

- Lateral inflow of groundwater from adjoining higher-lying rock-exposed ground where rainfall would not be completely absorbed by a sand cover and be lost through evaporation.
- Infiltration of flood water in the sandy beds of tributary streams.

Based on flow measurements and the increase in salinity down Henkries valley, Enslin thought that the total subterranean flow above Henkries may be more than 12 ℓs^{-1}. This statement should not be taken seriously as boreholes above the spring yield water that is also more saline than the spring (see Table 14 and 15). To determine the development potential Enslin recommended that a borehole survey, geoelectrical depth probing, exploratory drilling and test-pumping be undertaken. These recommendations were however never put into effect.

In 2001/2 the Department of Water Affairs and Forestry drilled 13 exploratory boreholes along lines respectively 2750 and 2400 m long and about 3 and 12 km upstream of the spring (see Figure 8 at the back of the report). The drilling was preceded by gravity observations. The two lines are oriented more or less perpendicular to the direction of groundwater flow. Data supplied by the Geohydrology Office Upington are summarized in Table 14.

Note the large variation in elevation of bedrock of 61 m (or 67? m) on line 1 and 127 m on line 2 (see also Figures 9 and 10) The mean drop in water level between line 2 and 1 is about 19.2 m whilst the lowest bedrock elevations on the two lines differ by 32 m. The water level in borehole No 83034 at the spring 3 km down from line 1, stood at approx. 371 m.a.m.s.l. (April 1963) - about 30 m lower than Line 1. Bedrock on the other hand lies at approximately 351 m in borehole 83034 i.e. 33 m higher than the lowest bedrock level on line 1. It thus appears that east of borehole 83034 bedrock should drop sharply to well below 300 m. A narrow ravine must exist below the terraced infill of the Henkries River valley.

TABLE 14 EXPLORATORY BOREHOLES HENKRIES- WOLFTOON AREA

Line	Bh. No	Longitude	Latitude	Surface Elevation (m)	Depth (m)	Bedrock depth (m) (elevation) (m.am.s.l.)	Water level (elevation) (m.a.m.s.l)	Yield ℓs^{-1}	EC mSm^{-1}
1	G47232	18.1047222	28.9825	419.42	102	101 (318)	18.8 (400.6)	20	285-347
	G47233	18.1102778	28.9811111	420.38	43	42 (378)	-	>12.1	450-379
	G47234	18.1163889	28.9797223	420.86	84	81(341)	16.81(404.1)	>12	430
	G47235	18.1233334	28.9783334	420.58	48	42 (379)	-	4.21	628
	G47242	18.0988889	28.9827778	429.97	90	89 (341)	28.8(401.2)	5	150
	G47243	18.0994444	28.9825	429.97	89	89 (341)	25.6(404.4)	-	-
	G47244	18.1258334	28.9786111	420.58	36	36? (385)	25.2(395.4)	-	-
2	G47236	18.1805556	29.0330556	495.952	24	18 (477)	-	-	-
	G47237	18.1796445	29.0355555	483.579	114	113 (371)	61.2 (422.4)	5.5	115-460
	G47238	18.1763889	29.0358333	479.674	136	130 (350)	59.3 (420.4)	5.5	220-470
	G47239	18.1661111	29.0422222	478.892	113	112 (366)	-	5.5	130-150
	G47241	18.1663888.	29.0419444	479?	-	-	-	-	-
	G47240	18.1597222	29.0438889	477.250	96	92 (385)	58.2 (419.1)	2.55	150

The Cainozoic deposits encountered in the 13 Water Affairs boreholes consist of a variety of sands with some intercalated layers of clay and in one borehole of silt. The different layers of sand are described as coarse, medium fine, gravelly, clayey, and calcareous; in some cases with boulders, or gravel, or pebbles, or clay. Colours of the sands vary from white, grey, grey-brown, brown, yellow, red-brown to red. The clays are in some instances sandy or sandy and gravelly or with boulders. Clay colours vary from grey, grey-brown, grey-green, green, yellow-green, yellow, yellow-brown, brown to red. The electrical conductivity of water struck in the boreholes varies from 130 to 628 mSm^{-1}.

Borehole SK94/118 was drilled for the Department of Housing, Local Government and Planning of the Provincial Administration of the Northern Cape (Toens *et al* 1995). Its position is 29.0508^0 S and 18.1376^0 E i.e. about 2.5 km southeast or upstream from the line of boreholes No's G 47236 to G47241; its collar elevation is 487 m.a.m.s.l. Red-brown alluvial and aeolian sand was encountered to a depth of 70 m (419 m.a.m.s.l). The hole was drilled to a depth of 119 m in fault breccia. Water was struck at 68 m below surface and tested at 5 ℓs^{-1}; EC 680 mSm^{-1} (Toens *et al* 1995).

FIGURE 9 SECTION THROUGH CAINOZOIC DEPOSITS 3 km UPSTREAM FROM HENKRIES SPRING

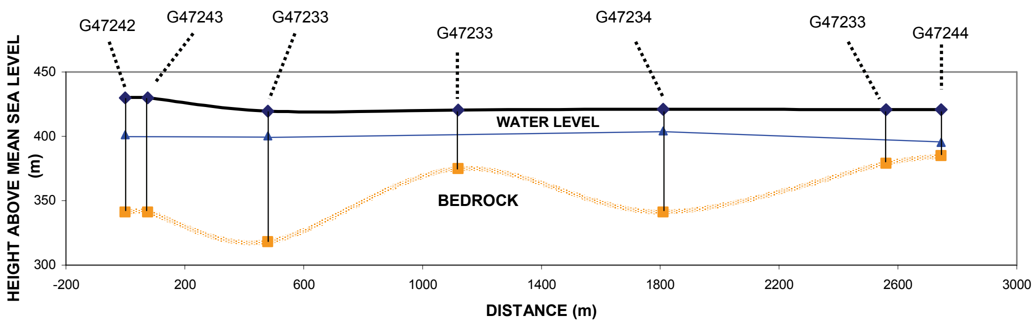

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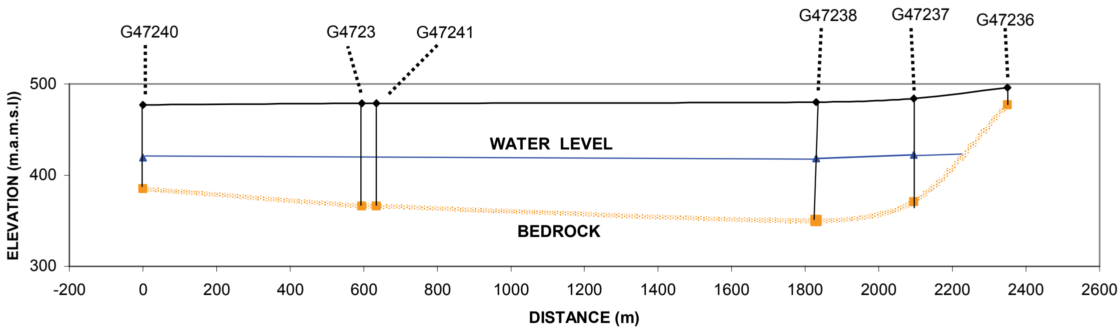
FIGURE 10 SECTION THROUGH CAINOZOIC DEPOSITS ALONG STEINKOPF - GOODHOUSE ROAD 13 KM UPSTREAM OF HENKRIES SPRING



Additional quality data abstracted from Enslin's 1963 report follow below:

TABLE 15 EC VALUES KOA VALLEY (ENSLIN 1963)

Farm	Borehole No	EC mSm^{-1}	TDS $mg\ell^{-1}$
Henkries Steinkopf 22	Spring	211	1320
Stofbakkies Steinkopf 22	Well	183	1150
Wolftoon 48	70317	215	1400
On Steinkopf 22 - Gezelschapbank 71 boundary	49828	73	450
Kabib 50	83457	934	5600
Nooisabes 51	10597	238	1480
Zuurwater 62	39065	1515	10200

The quality of the groundwater contained in the Cainozoic deposits and bedrock formations thus ranges from 73 to 1515 mSm^{-1}. The equivalent total dissolved solids range is from about 450 to 10200 $mg\ell^{-1}$. The large variation in water quality may be ascribed to:

a) The two modes of recharge:
- Better quality (younger) water from recharge by infiltration of flood water.
- Poor quality from lateral inflow of groundwater.

b) Rapid vertical and lateral facies changes in the deposition of the fluvial, lacustrine and aeolian Cainozoic sediments that prevent mixing.

Apart from the two lines of exploratory boreholes drilled during 2000/1 the National Groundwater Data Base contains only seven records of boreholes with piezometric levels within the Cainozoic deposits. These are listed in the Table below. In two boreholes water was struck in basement rocks and not in the Cainozoic deposits. Through the years more than 100 boreholes have been drilled on these farms. Most of them failed to strike water.

TABLE 16 BOREHOLES WITH WATER- BEARING CAINOZOIC DEPOSITS

Farm Name and Number	NGWD Borehole I D Number	Thickness (m) Cainozoic deposits	Depth water was struck (m)	Water level (m)	Yield ℓs^{-1}	Nature of saturated deposit
Steinkopf 22	2918AA00034	64.9 (+?)	57.9	51.8	0.68	sand
Amam 46	2918AB00005	116 (+?)	115	108	0.4	alluvium
Wolftoon 49	2918AA00052	82 (+?)	70	60	1.28	sand
Heiorigas 49	2918AA00009	92.1	94.5	83.8	0.63	limestone
Kabib 50	2918AB00056	121.9 (+?)	?	109.7	?	sand
Nooisabes 51	2918AB00064	137.2	106.7	103.6	0.81	sand
Naip 68 portion 4	2918AD00047	54	67	23	0.5	clay

TABLE 17 BOREHOLES WITH NON WATER-BEARING CAINOZOIC DEPOSITS THICKNESS > 100 m

Farm Name and Number	NGWD Borehole I D Number	Thickness (m) Cainozoic deposits	Depth water was struck (m)	Water level (m)	Yield ℓs^{-1}
Kabib 50	2918AB00048	102.7	-	-	-
Kabib 50	2918AB00057	167.9	-	-	-
Kabib 50	2918AB00058	119.8	181.1	175.9	0.64
Kabib 50	2918AB00082	136	-	-	-
Kabib 50	2918AB00083	139	231	185	0.38
Naroep	2918AB00038	145.1	161.5	161.5	1.35

The areal extent of water-bearing Cainozoic deposits can unfortunately not be determined. A piezometric contour map, Figure 8 (at the back of the report), was compiled from rather sparse and widely scattered data that was extracted from Enslin's report, the Directorate of Geohydrology's hydrocensus during 1999 by S.A. Fourie, the exploratory drilling of 2001/2 and the National Groundwater Data Base. The latter contains data on many boreholes that were drilled in and along the valley by the Department of Water Affairs and its predecessor. It is very unfortunate that with a few exceptions borehole positions are not known. It is however clear that the "sand-drowned" Koa River and tributaries tap groundwater from bordering higher-lying hard-rock formations. Note that water levels in bedrock on adjoining higher ground vary from 100 to 185 metres below surface.

Hills such as Lemoenpoortberg and Langeberg on Ou Taaibosmond 66 and the Hoedberg, Windhoekse Berg and Bobbejaangat on Zuurwater 52 straddle the course of the Koa. The limited gaps between them indicate that the palaeo Koa River probably flowed in a narrow gorge down stream of Aggeneys. Groundwater exploitation would doubtlessly benefit if the courses of the palaeo Koa River and major tributaries were pinpointed.

5.2 KENHARDT

In the vicinity of Kenhardt sand and gravel are found in Driekop se Rivier, the Sandsloot, Rugzeer, Mottels and Rietfontein Rivers. In Driekop se Rivier sand and gravel, poorly rounded and sorted, clayey gravel and clay attain a maximum thickness of 11 metres (Van Dyk 1994). Saturation is generally confined to narrow slightly deeper channels that may coincide with zones of weathering in the underlying rock (see Figures 8, 9 and 10 of Nonner, 1979).

Basal deposits in the Hartbees River consist of clayey well-rounded gravel about 3 m thick (Van Dyk 1994). The gravel is overlain by sand, silt and clay about 10 m thick. The uppermost deposits consist of gravelly sand. Below the confluence of Driekop se Rivier alluvial deposits attain a thickness of up to 37 m of which the bulk consists of fine-grained and clayey material (Van Dyk 1994).

Nonner (1979) found from an exploratory drilling programme in and along Driekop se Rivier, the Sandsloot, Rugseer and Rietfontein Rivers that:

- Low yields, 5 to 50 m^3d^{-1}, were struck in the sandy deposits (7 boreholes; median yield 16 m^3d^{-1} or 0.02 ℓs^{-1}). Thickness of saturated deposit not stated; probably between 2 - 5 m.
- Yields in excess of 100 m^3d^{-1} were struck in underlying weathered and fractured metamorphic rocks (25 boreholes; median yield 94 m^3d^{-1} or 1.1 ℓs^{-1}).

6. GROUNDWATER IN HARD-ROCK FORMATIONS

6.1 SUBDIVISION OF BUSHMANLAND GROUNDWATER REGION

To determine how groundwater conditions vary over this vast Region, it was deemed necessary to divide it into 18 units. This was done on the basis of surface drainage and geology as set out in Table 18 and shown in Figure 3 (at the back of the report).

TABLE 18 HYDROGEOLOGICAL SUBDIVISION OF REGION

SUB-DIVISION	PORTION(S) OF DRAINAGE REGIONS	COMPOSED OF GEOLOGICAL FRAGMENT(S) / FRAGMENT PORTION(S) (see chapter 2)
1	D6 & D7 (i)	Draghoender-Groveput
2	D7 (ii)	Groblershoop
3	D7 (iv)	Kleinbegin-Sultanaoord
4	D5 (iii, iv, v)	Boks Puts and Hartbees River
5	D7 (iv)	Boks Puts and Hartbees River
6	D5 (iv)	De Kruis, Haakjes Doorn Kolk, Brypaal/Aggeneys and Drooge Grond
7	D7 (iii)	Boks Puts and Hartbees River
8	D4	Hartbees River
9	D8 (ii)	Hartbees River, Arribees and Drooge Grond
10	D8 (iii & iv)	Hartbees River and Arribees
11	D8 (v)	Arribees, Drooge Grond Brypaal/Aggeneys and T'Caimoeps Laagte/Kamiesberg
12	D8 (vi)	Drooge Grond and Brypaal/Aggeneys
13	D8 (vii)	Dabenoris and Brypaal/Aggeneys
14	D8 (viii)	Brypaal/Aggeneys
15	D8 (viii)	Khurisberg
16	D8 (viii) D8/6	T'Caimoeps Laagte/Kamiesberg
17 a and b	D7 (iii)	Koras Graben
18 a	D8/D6	Dwyka Transition
18 b	D5 (i, ii, & iv)	Dwyka Transition

Groundwater conditions are described in terms of statistical analyses of 5000 drillers' logs contained in the National Groundwater Database (NGWDB**.** The boreholes were drilled during the past century by the Irrigation Department and its successors, the Departments of Water Affairs and of Agriculture. Boreholes were sunk on farms for household use and stockwatering. It is a pity that borehole locations are known by farm name only and that data of an unknown number of boreholes have not been taken up in the database. For example records of several boreholes sited on geological-geophysical grounds reported on in Chapter 7 have gone astray.

One has to accept that the driller's log descriptions do not do justice to the large variety of metamorphic and igneous rocks. Granite (grnt) and quartzite (qrtz) are the terms used almost exclusively. The terms gneiss, granite-gneiss, schist, amphibolite and pegmatite turn up here and there. They usually lack further definition. Understandably more sophisticated terms such as granulite, calc-silicate rocks, marble, kinzigite, adamellite though abundantly present do not feature in the logs. In some instances sheared quartzite and quartz-sericite schist have been called sandstone. Contrary to expectation Dwyka sedimentary rocks have almost exclusively been described as shale. The term tillite has been used rarely and boulders (bldr) are mentioned occasionally. Note also that borehole positions are known by farm name only.

Water-bearing properties are not being analysed and described In terms of rock type or lithostratigraphic unit. Firstly, borehole information to do so is lacking. Secondly, resistance to brittle failure depends, besides petrographic features, on factors such as fold structure, direction of fold axis versus stress orientation, deformational history, spatially and temporally variable factors. It should become clear from the following two chapters that the occurrence of groundwater depends largely on fracturing and not on rock type or lithostratigraphic unit.

Weathering and fracturing (including jointing and drillers' broken formation) have been recorded in about one third of the borehole logs. During the past century drilling equipment underwent a transformation, from wooden-frame percussion machines and manila drilling rope through steel-frame percussion machines and steel drilling cable to air rotary machines. Despite this transformation it is assumed that over the years a fair degree of uniformity has been maintained by drillers in their description of formation as fractured, weathered and solid. Where rock type only is mentioned it is assumed to mean fresh and solid rock. Drillers' descriptions of the formation are based not only on the appearance of drill cuttings but also and perhaps even more so on comparative drilling rates, highest in weathered, alternately slower and faster in fractured and uniformly slower in fresh solid rock. In this sense a fair degree of uniformity may have been maintained.

Depending on data availability the occurrence of groundwater in the 18 subdivisions is described in terms of:

- Percentage boreholes yielding ≥ 0.1 ℓs^{-1} and distribution of yields
- Distribution of borehole depths
- Distribution of strike depths yielding ≥ 0.1 ℓs^{-1}
- Distribution of water levels
- Weathering and fracturing

Diverse attention is given to several other aspects. Statistical analysis is curtailed in the case of subdivisions 1 – 3, 13, 15 and 17. The NGWDB contains data on fewer than 100 boreholes in each of these areas.

6.2 STATISTICAL ANALYSIS OF BOREHOLE DATA

6.2.1 Subdivision 1

Subdivision 1 (Figure 3 back of report) is part of the Kaapvaal craton. It comprises Swazian metamorphosed and folded sedimentary and volcanic rocks (Marydale Group) intruded by gneiss and granite. See chapter 2 Table 1 for lithology.

NGWDB contains records of 13 boreholes only. These were drilled in Skalkseput gneiss or Draghoender granite. Five boreholes (38.5%) were successful. The data are summarized below.

TABLE 19 SUMMARY OF BOREHOLE DATA SUBDIVISION 1

	Borehole depths (m)	Strike depths (m)	Water levels (m)	Yield (ℓs^{-1})
Range	21 – 79	6 – 72	5 – 34	0.57 – 2
1st Quartile	34	27	-	-
Median	49	34	10	-
3rd Quartile	62	52	-	-

There are no NGWDB records of boreholes in rocks belonging to the Marydale Group. Marydale volcanics according to Schumann (±1975) form the slopes of ridges or low kopjes. The volcanics are therefore not considered favourable for finding groundwater. Nineteen boreholes were traced by Schumann. Nine (47.4%) of these were nevertheless successful striking water in weathered to semi-weathered volcanics between 15 and 60 m below surface and yielding an average of 0.62 ℓs^{-1}. Water levels ranged from 5 to 26 m. Boreholes tend to weaken and fail during droughts.

6.2.2 Subdivision 2

The Subdivision (Figure 3 back of report) comprises sandy valleys and northerly trending hills built by intensely folded and faulted quartzite, quartz-sericite schist, quartz-chlorite-epidote and actinolite-chlorite schists and amphibolite belonging to the Brulpan Group. These rocks have been intruded by granite-gneiss, syenite, anorthosite, gabbro and metagabbro. See Table 2a chapter 2.

The NGWDB contains records of 70 boreholes of which 36 (51.4 %) proved successful (yield ≥ 0.1 ℓs^{-1}). According to drillers' logs water was struck in granite (15 boreholes) in quartzitic rocks (18 boreholes) on the contact between granite and quartzite (2 boreholes) and in dolerite (one borehole). Rock termed sandstone by the driller, apparently quartz-sericite or related schistose rocks, are included under the term quartzitic rocks. Data are summarized in Table 20.

TABLE 20 SUMMARY OF BOREHOLE DATA SUBDIVISION 2

	Borehole depths (m)	Strike depths (m)	Water levels (m)	Yield (ℓs^{-1})
Range	21 – 251	11 – 193	5 – 135	0.11 – 10
1st Quartile	47	29	15	0.39
Median	64	44	25	0.64
3rd Quartile	92	64	42	1.5

TABLE 21 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 2

Yield range ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	15	42.9
0.5 – 0.99	10	28.6
1.0 – 4.9	9	25.7
5 – 9.9	0	0
≥ 10	1	2.9

TABLE 22a DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 2

	Depths of weathering (m) Number of boreholes 25	Depths of fracturing / jointing (m) Number of boreholes 18
Range	3 – 69	3 – 96
1st Quartile	15	20
Median	24	48
3rd Quartile	30	60

TABLE 22b BOREHOLE RESULTS: WEATHERED / FRACTURED VERSUS UNSPECIFIED

Upper section of borehole reported	Number of boreholes	Number (percentage) of successful boreholes	*Number of water levels deeper than base of weathering / fracturing or jointing	*Number of water levels shallower than base of weathering / fracturing or jointing	Number of unsuccessful boreholes with weathered or fractured section < 20 m
Weathered	26	13 (50%)	8	4	4
Fractured / jointed	17	10 (58.8)	1	8	nil
#Not specified	30	13 (43.3)	-	-	

* Water levels not available for all successful boreholes
# Except for the superficial cover of sand or calcrete drillers did not mention weathering or fracturing / jointing in the remaining 30 boreholes.

6.2.3 Subdivision 3

The subdivision (Figure 3 back of report) is underlain by quartzite and schist grading into banded gneiss, migmatite, leucogneiss, amphibolite and serpentinite. The metamorphytes are intruded by porphyroblastic biotite gneiss and weakly foliated granite. See Table 2a Chapter 2.

The NGWDB contains records of 89 boreholes of which 46 (51.7%) were successful (yield ≥ 0.1 ℓs^{-1}). Nineteen of the 89 were exploratory boreholes drilled by the Department of Water Affairs and Forestry and are to be discussed further on.

Weathered formation was reported in only 18 of the remaining 70 boreholes According to drillers' logs fractured formation was encountered in 9 boreholes. Depths of weathering ranged from 5 to 55 metres three quarters of which less than 31 metres. Data of all 89 holes are summarized below.

TABLE 23 SUMMARY OF BOREHOLE DATA SUBDIVISION 3

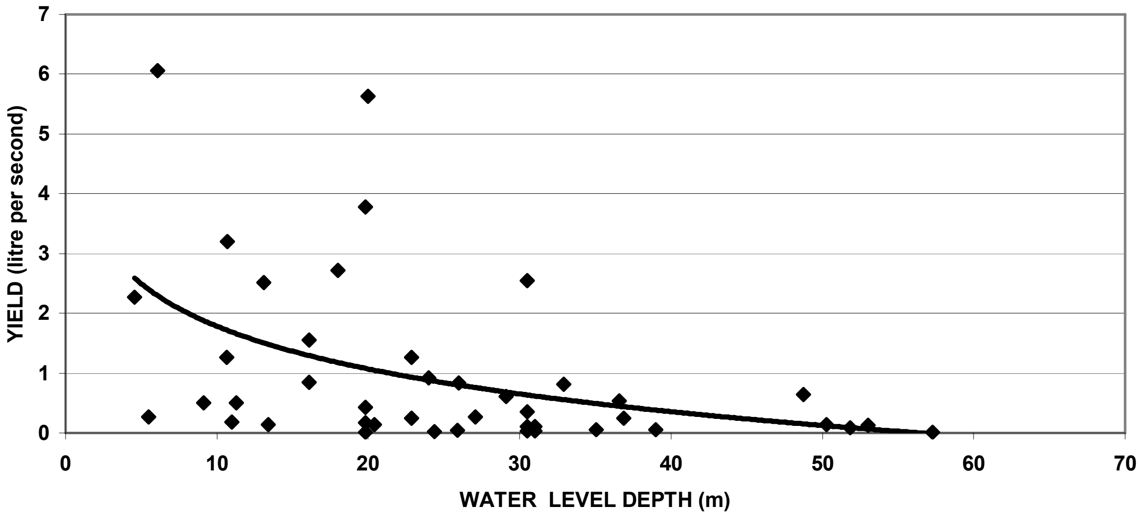
	Borehole depths (m)	Strike depths (m)	Water levels (m)	Yields (ℓs^{-1})
Range	14 – 252	6 – 67	5 – 53	0.1 – 6.1
1st Quartile	45	22	15	0.27
Median	61	32	20	0.64
3rd Quartile	100	42	30	2.1

TABLE 24 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 3

Yield range ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	15	32.6
0.5 – 0.99	12	26.1
1.0 – 4.9	17	37.6
5 – 9.9	2	4.3
≥ 10	0	0

As may perhaps be expected borehole yield diminishes with increasing water level depth (Figure 11). No relationship between yield and strike depth below water level was found.

FIGURE 11 YIELD VERSUS WATER LEVEL SUBDIVISION 3



The 19 exploratory boreholes mentioned above were sunk in the Brakbosch fault zone on the farms Matjes Rivier 41, Karos 42 and Zand Dam.52 Ten of these boreholes were successful. Seven boreholes on Matjes Rivier and Karos were drilled into quartzite (Dagbreek Formation) whilst andesite and basalt (of the Wilgenhoutsdrif Group?) was recorded in five holes. The boreholes were drilled to depths varying from 123 to 252 metres. Quartz veins of a metre or so were encountered at different depths from the surface down to the bottom of all holes.

The borehole geology does not match that of the quarter million geological Sheet 2820 Upington. The Brakbosch fault is apparently a wide, complex, multiple branching feature. Detailed mapping is required to reconcile surface and borehole geology. Water was struck only in the upper weathered / fractured zone of quartzite or lava at depths of between 20 and 55 m. The quartz veins are tight. Yield ranges between 1.3 and 4.4 ℓs^{-1}.

On Zand Dam 52 five exploratory boreholes were drilled on an E-W Ine about 860 m long and more or less at right angles to the Brakbosch fault. No rock exposures are shown on Geological Sheet 2820 Upington. The holes were drilled to depths ranging from 133 to 252 m. Phyllite with the occasional quartz vein was encountered in all five boreholes. Supplies of 0.1 and 0.8 ℓs^{-1} were struck in two of the boreholes at depths of 48 and 66 m, again in the transition between weathered / fractured and solid.

6.2.4 Subdivision 4

The subdivision (Figure 3 back of report) consists basically of the right bank catchment of the Hartbees River.

The NGWDB contains records of 662 boreholes of which 267 (40.3%) yielded ≥ 0.1 ℓs^{-1}. Of the 662 boreholes 58 were exploratory holes that were drilled in connection with a hydrogeological investigation for the Municipality of Kenhardt. To obviate distortion of statistics by the exploratory boreholes only fifteen of them, randomly selected, were included in the following analyses. Two-hundred-thirty-eight of the remaining 619 boreholes (38.4%) yielded ≥ 0.1 $\ell s.^{-1}$.

TABLE 25 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 4

Yield range ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	107	43.9
0.5 – 0.99	47	19.3
1.0 – 4.9	85	34.8
5 – 9.9	4	1.6
≥ 10	1	0.4

Further results are presented in the following Figures.

FIGURE12a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 4

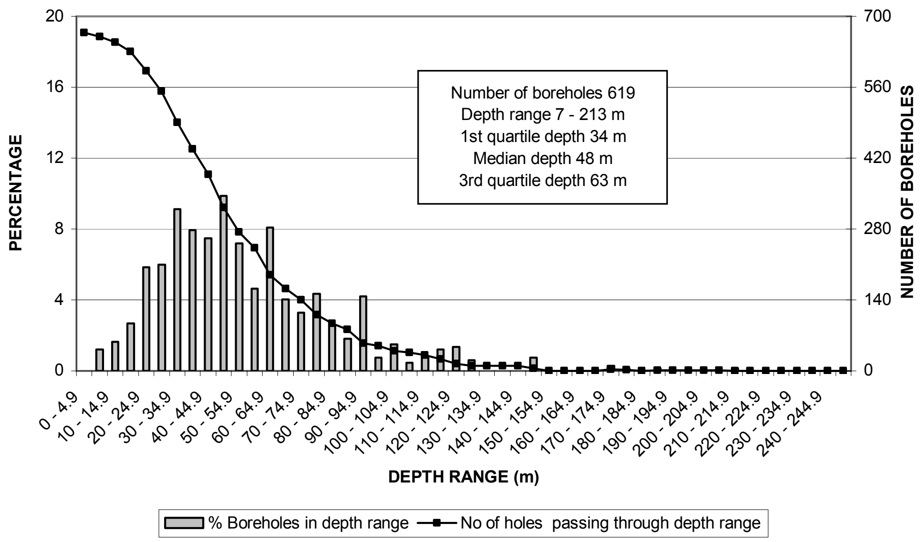
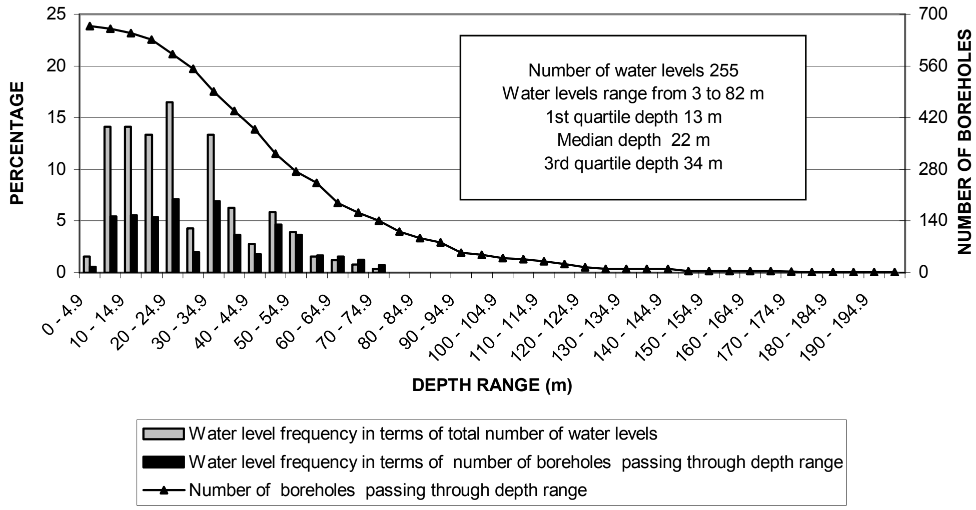
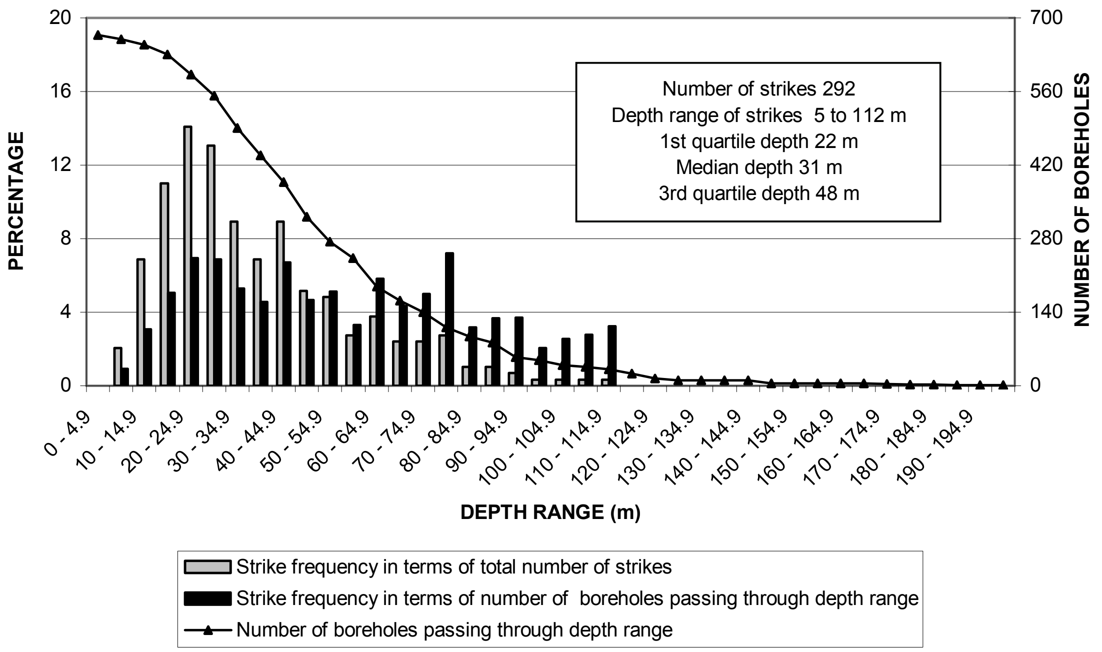


FIGURE12b DISTRIBUTION OF WATER LEVELS SUBDIVISION 4



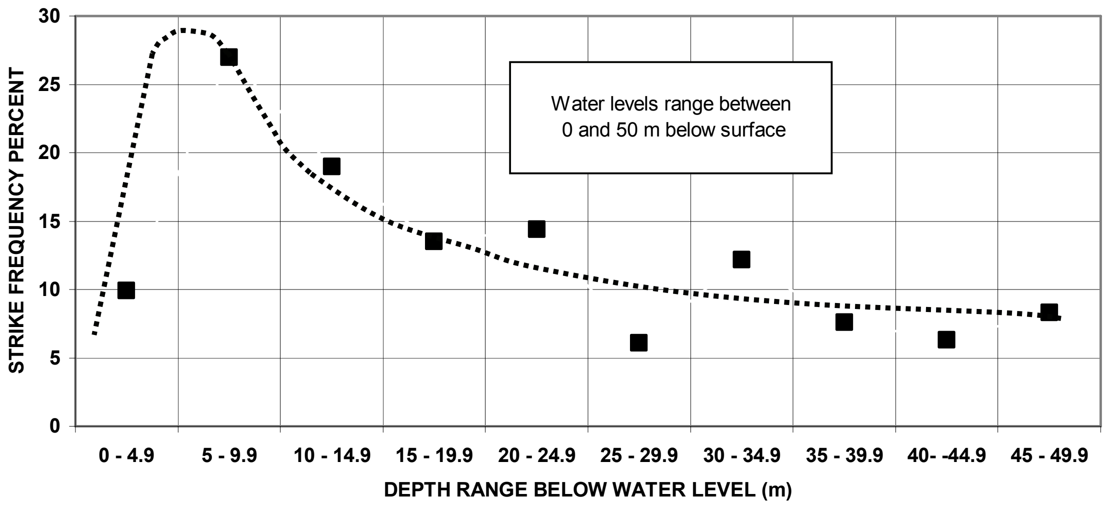
89% of the water levels lie between 5 and 55 metres. The shallowest water levels are found along the Hartbees River and tributaries. Water levels deepen towards the drainage divide in the east.

FIGURE 12c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 4



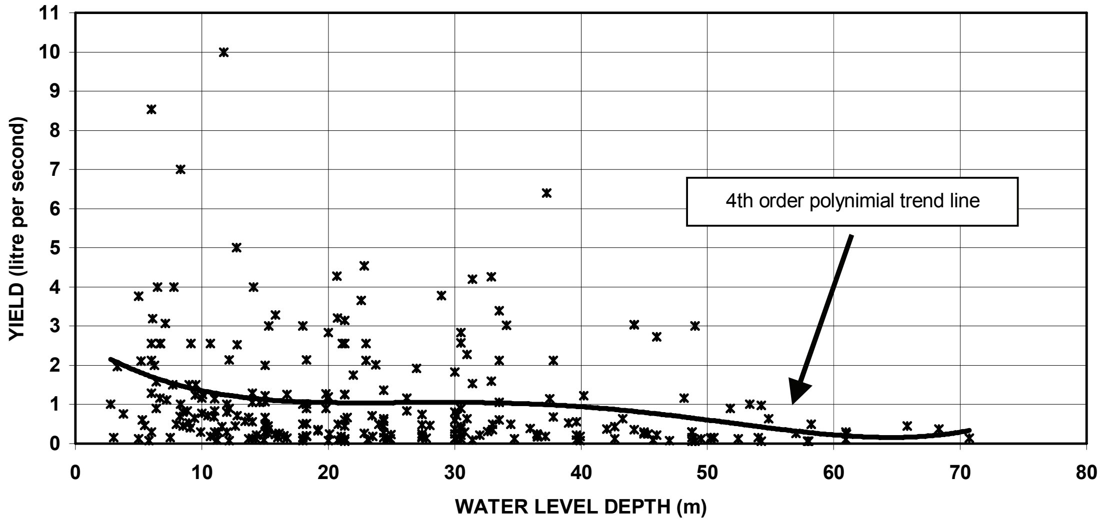
In terms of the number of boreholes passing through a five metre depth interval strike frequency averages 5.5% between 15 and 80 m below surface (Figure 12c).

FIGURE 12d STRIKE FREQUENCY BELOW WATER LEVEL SUBDIVISION 4



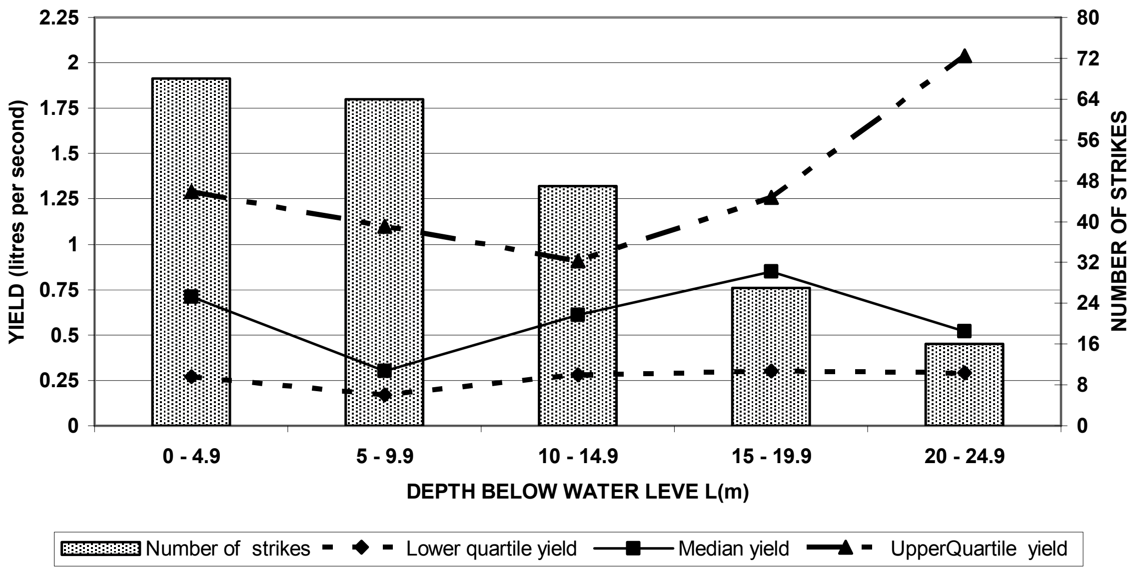
Of 233 successful strikes recorded within 50 m below water level 199 (85.4%) occurred within the first 25 m. In terms of the number of successful boreholes passing through each depth range peak strike frequency of 27% occurs in the range 5 to 10 m below water level dropping to below 10% from about 30 m below water level (Figure 12d).

FIGURE 12e YIELD VERSUS WATER LEVEL SUBDIVISION 4



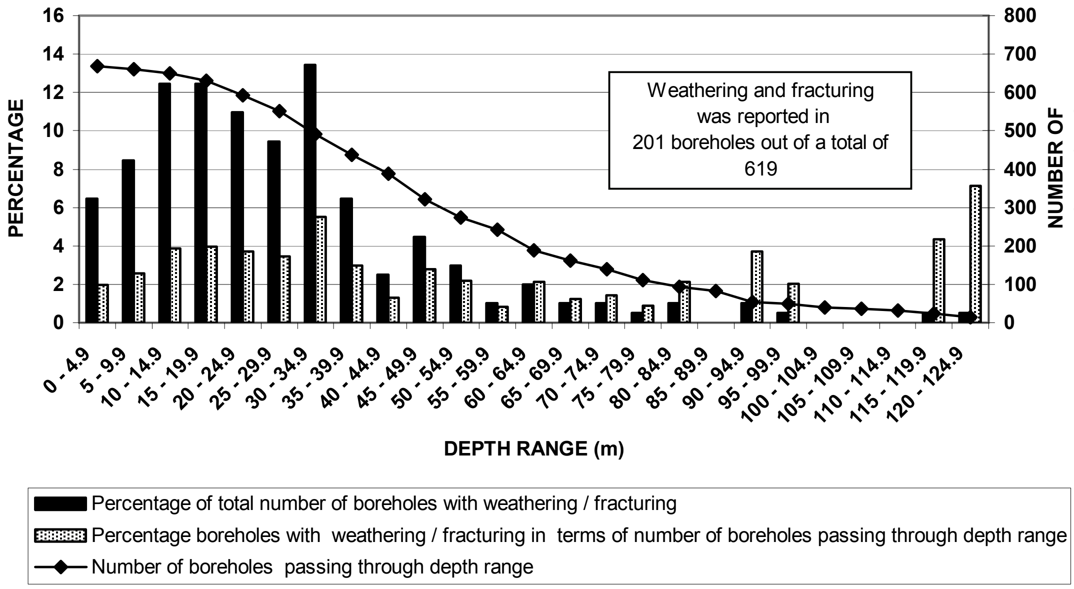
Yields of successful boreholes (Figure 12e) average 1 ℓs^{-1} (median 0.5 ℓs^{-1}) for water levels between 15 and 40 m. In the 0 -15 m range the average is 1.5 ℓs^{-1} (median 0.9 ℓs^{-1}). The average yield for water levels over 40 m is 0.58 ℓs^{-1} (median 0.27 ℓs^{-1}).

FIGURE12f BOREHOLE YIELD VERSUS STRIKE DEPTH BELOW WATER LEVEL SUBDIVISION 4



Yields vary widely irrespective of the depths below water level where strikes are made. A relationship between yield and strike depth below water level is indeterminate (Figure 12f).

FIGURE 12g DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 4



Weathering and / or fracturing were recorded in the logs of 201 boreholes out of the total of 619. The distribution of depths of weathering / fracturing is shown in Figure 12g. Weathering / fracturing ranges between 5 and 100 metres. A weathering / fracturing depth of 40 m was exceeded in only a quarter of the cases.

It was found that regardless of the depth of weathering / fracturing:

- The success rate is 41.8% where weathering / fracturing - W/F abbreviated - had been recorded against 36.8% of boreholes lacking W/F.
- That 42.8% of the successful W/F boreholes yielded ≥ 1.0 ℓs^{-1} compared to 29.9% of the successful non-W/F holes.
- That 67.1% of the successful W/F boreholes had water levels < 30 m compared to 35% of the successful non-W/F holes. As water levels are generally shallower in the valleys they appear to be more favourable loci for weathering / fracturing than higher-lying ground with deeper water levels.
- The weighted mean success rate for the 20 to 80 metre weathering / fracturing depth range is 55%.

Boreholes yielding a minimum of 0.05 ℓs^{-1} were taken into account in drawing up Table 26. Borehole yields range widely regardless of whether the water level is deeper, more or less coincident with or shallower than the depth of weathering / fracturing. There is no meaningful distinction as far as yield is concerned between the three cases.

TABLE 26 YIELDS VERSUS DIFFERENCE BETWEEN WATER LEVEL AND DEPTH OF WEATHERING / FRACTURING SUBDIVISION 4

Number of water-yielding boreholes	Difference between depth of weathering / racturing and water level (m) ranges	Yield ℓs^{-1}				
		Range	Mean	1st Quartile	Median	3rd Quartile
19	-57 to -4.	0.07 to 4.54	1.29	0.18	0.6	1.94
13	-4 to +4	0.09 to 8.53	1.25	0.16	0.49	1
48	+5 to +72	0.07 to 4.37	1.09	0.21	0.69	1.31

6.2.5 Subdivision 5

See Figure 3 at the back of the report for location. The NGWDB contains records of 332 boreholes of which 124 (37.3%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 27 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 5

YIELD ℓs^{-1}	NUMBER OF BOREHOLES	PERCENTAGE OF BOREHOLES
0.1 – 0.49	62	50
0.5 – 0.99	33	26.6
1.0 – 4.9	28	22.6
5.0 – 9.9	1	0.8
≥ 10	0	0

TABLE 28 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 5

WATER LEVEL (m)	NUMBER OF BOREHOLES	MEAN YIELD ℓs^{-1}
0 -10	16	0.65
10 – 40	81	0.78
40 – 70	25	0.48

Results of statistical analyses of the borehole data are presented in Figures 13a, b, c, d, e.

FIGURE13a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 5

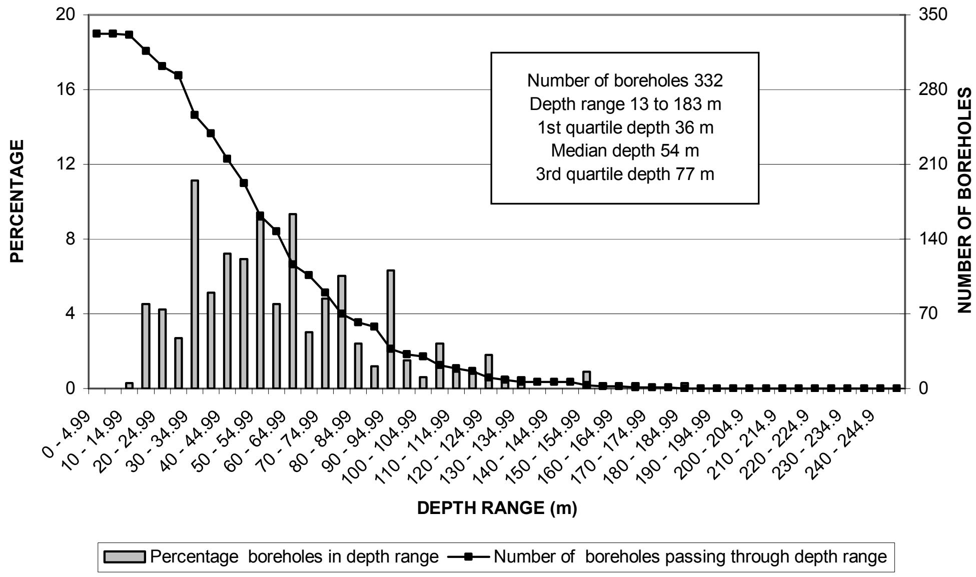


FIGURE13b DISTRIBUTION OF WATER LEVELS SUBDIVISION 5

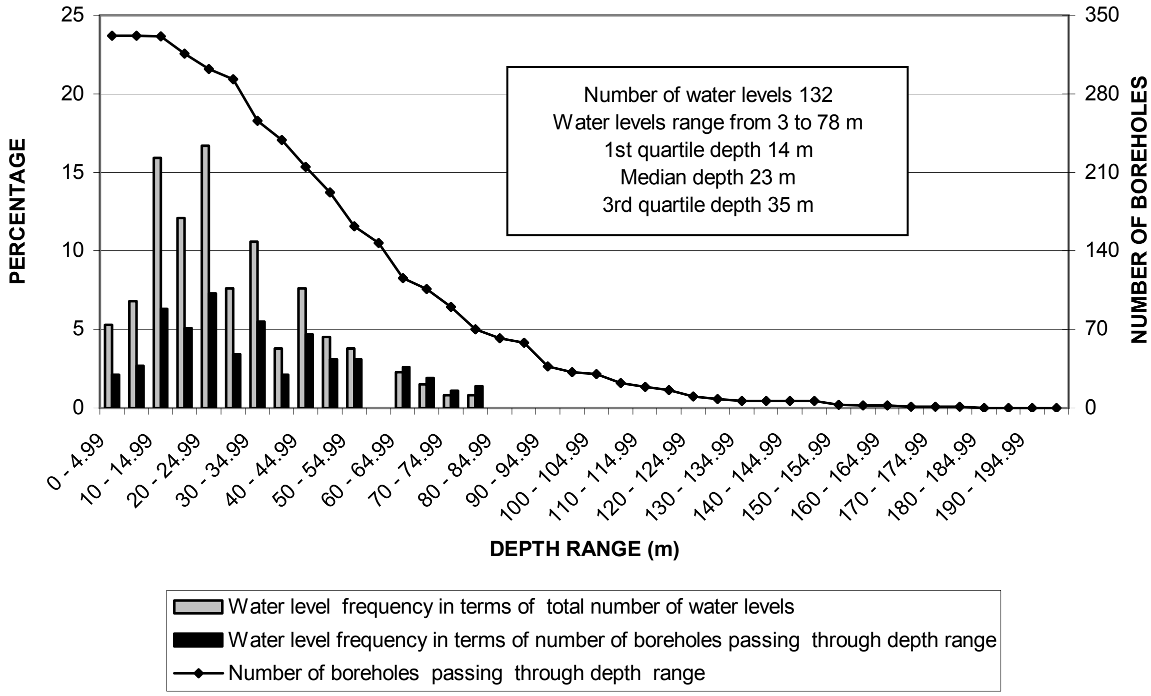


FIGURE 13c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 5

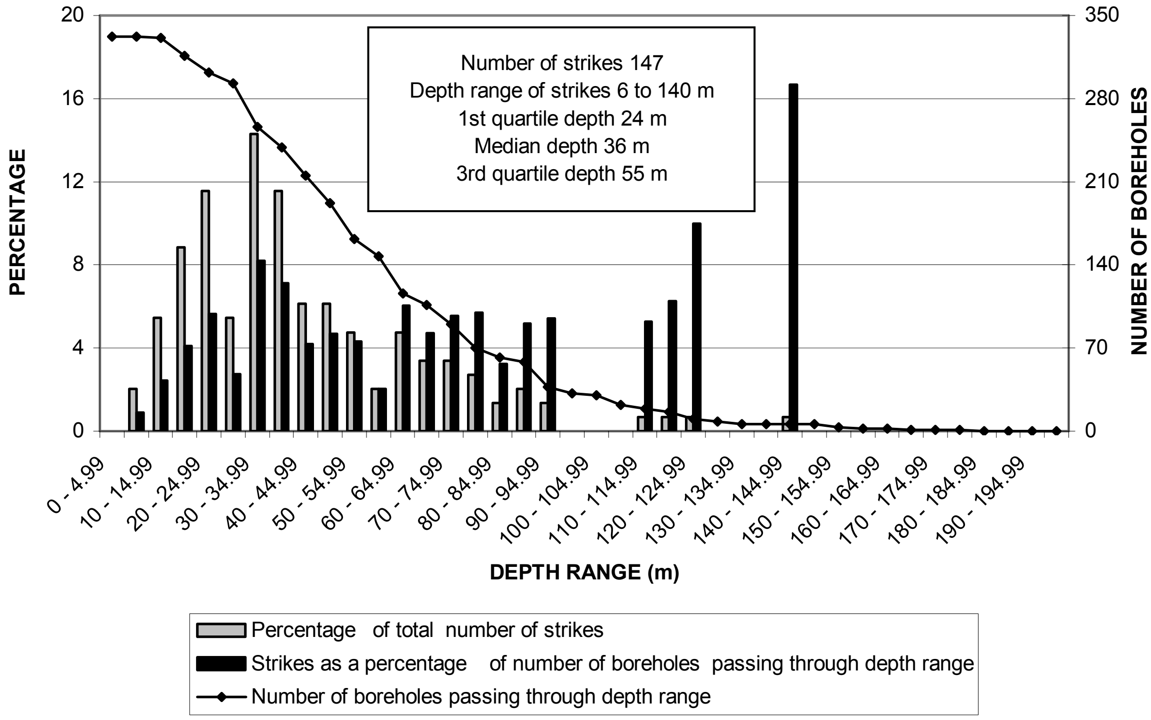
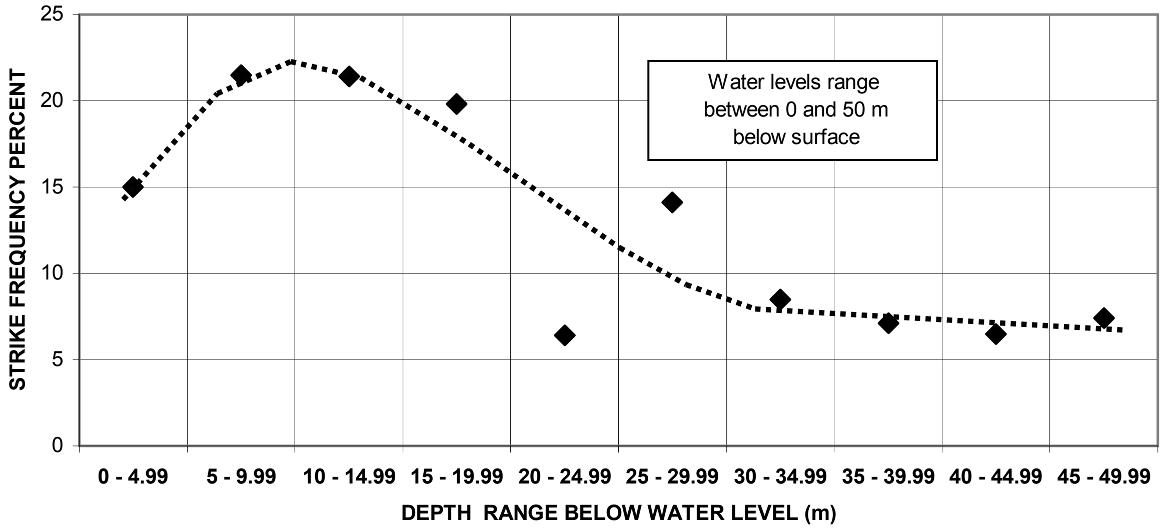


FIGURE 13d STRIKE FREQUENCY BELOW WATER LEVEL SUBDIVISION 5



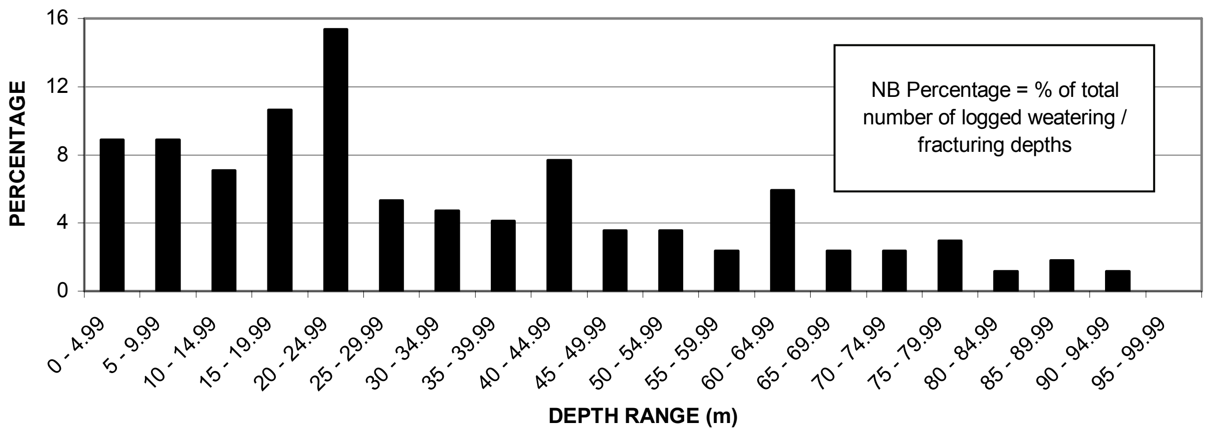
The spread in borehole depths and water levels resembles that of Subdivision 4 except that the proportion of deeper boreholes is somewhat larger. Water levels are somewhat shallower: 86% are shallower than 45 m. In terms of the number of boreholes passing through a five metre interval strike frequency averages 4.7% over the 15 to 95 m range.

Eighty-six percent of the successful strikes were recorded within 25 m below water level. In terms of the number of successful boreholes passing through each depth range peak strike frequency of 22% occurs in the range 5 to 15 m below water level dropping to below 10% from about 30 m below water level (Figure 13d).

Weathering and fracturing were recorded as follows:

Weathering only	98	
Fracturing only	54	172
Both weathering and fracturing	20	
No record of weathering or fracturing	183	

FIGURE 13e DISTIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 5



A depth of 50 m was exceeded in only a quarter of the cases. It was found that regardless of the depth of weathering / fracturing:

- success rate is about 8% higher where weathering / fracturing -W/F abbreviated - had been recorded;
- 20.3% of the successful W/F boreholes yielded ≥ 1.0 ℓs^{-1} compared to 28% of the successful non-W/F holes. This is opposite to the finding in Subdivision 5.
- 68.8% of the successful W/F boreholes had water levels < 30 m compared to 47.6% of the successful non-W/F holes.

As water levels are generally shallower in the valleys they appear to be more favourable loci for weathering / fracturing than higher-lying ground with deeper water levels.

6.2.6 Subdivision 6

The Subdivision (Figure 3 at back of report) embraces the left bank catchment of the Hartbees River. Before presenting the results of statistical analyses attention needs to drawn to:

A. During a water supply investigation in 1997 for the Municipality of Kenhardt the Department of Water Affairs and Forestry drilled amongst others 11 exploratory boreholes in the Hartbees River Thrust zone. The low-angle thrust comprises a wide zone of deformation characterized by intensive folding, a marked shear fabric, cut-off and imbrication structures, mylonisation, chloritisation and the presence of epidote and piemontite (Siegfried and Botha, 1997). Five boreholes (No's G 45389, 45390, 45396, 45397 and 45399) were drilled west of Kenhardt along a 2 km section of the Rooidam road where it crosses the thrust zone. In addition three pairs of boreholes were also drilled in the thrust zone at three other localities:
   - Two pairs in the valley of Driekop se Rivier approximately 2 and 5 km south of the section along the Rooidam road; and
   - One pair about 32 km southeast of Kenhardt where the Klein Lat River crosses the thrust zone.

   Drilling results were rather disappointing. Supplies ranging from 1.5 to 8 ℓs^{-1} were struck in four of the eleven holes. The rest were duds.

   Siegfried and Botha (1997) examined drill cuttings of the five boreholes on the Rooidam section. Identification of the lithostratigraphic units proved difficult and presentation of the geological succession and structure from the logs of five widely spaced boreholes problematic. It is however quite clear that the thrust zone does not consist in its entirety of porous permeable rock (i.e. rock with open fractures). Water was struck in minor features such as a micaceous fracture (shear?) in quartz-feldspar-biotite gneiss, a thin epidotised zone in amphibolite, the contact zone between fresh and weathered amphibolite and a fracture unidentifiable from fresh rock drill cuttings. The borehole with the yield of 8 ℓs^{-1} is atypical in that gneiss weathered to a depth of 59 m is overlain by 13 metres of water-bearing river sand - water level 3.7 m below surface.

   The following conclusion appears to be indicated: The prospects of finding water and of developing high-yield boreholes are not enhanced by drilling into this major thrust zone. This finding is in line with Norwegian experience namely: "the identification of major fracture zones ………. may not be a satisfactory method of locating groundwater resources in hard rock ……" (Banks *et al* 1993) See also Banks *et al* (1992).

B. In addition to Namaqua metamorphic and intrusive rocks, shale presumably outliers of the Dwyka Group, has been encountered in six boreholes. Three struck water in shale at depths of 25, 26 and 61 m and one on the bedrock contact at 34 m. The two dry holes passed through 18 and 21 m of shale.

C. The thickness of superficial deposits is limited to a few metres except for two instances that need to be mentioned:

   1) In the far west on Puts Berg 203 (elevation approx 1050 m.a.m.s.l) 30 m alluvium was encountered in borehole No 2919BC00053 Boring Branch No 154908. A supply of 0.45 ℓs^{-1} was struck at 74 m in basement rock rising to 24 m below surface. Puts Berg is situated on the divide between the Kaboep / Coboop and Sout River drainages.

      According to Hambleton-Jones, Levin and Wagener (1986) a large tributary of the Sout River on Brul Kolk 154 some 60 km east of Puts Berg had a shallow valley not deeper than a few metres during the Mid-Tertiary. This is still the present situation. The elevation difference between the borehole on Putsberg and the confluence of the Puts Berg and Brul Kolk tributaries on T'Oubep 156 (adjoining Brul Kolk 154) is about 175 m. The confluence is 65 km downstream of Puts Berg.

      Within 25 km north of Puts Berg the Kaboep / Coboop valley drops below 900 m.a.m.s.l. Lower down the Kaboep's course Tertiary deposits up to 75 m thick have been encountered in a borehole. It appears that the Puts Berg alluvial deposit may be part of the palaeo-Kaboep River that became extinct as result of crustal warping along the so-called Griqualand-Transvaal axis. Note also the occurrence of alluvium on neighbouring Houmoed 206 - see Subdivision 11 section 7.2.11. Tracing an in-filled palaeo-channel from Puts Berg could be of importance in the development of groundwater.

   2) In the east on Witvlei 103 a borehole penetrated 38 m of alluvium. The borehole was presumably drilled in the valley of the Hartbees or of a tributary near to its confluence with the Hartbees. No mention is made of striking water in either the alluvium or underlying bedrock. Although the alluvium may be too clayey it nevertheless points to the possible existence of large volumes of water-bearing sand albeit saline along the course of the Hartbees River.

The NGWDB contains records of 413 boreholes of which 141 (34.1%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 29 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 6

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	70	49.6
0.5 – 0.99	23	16.3
1.0 – 4.9	42	29.8
5.0 – 9.9	6	4.3
≥ 10	0	0

TABLE 30 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 6

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -10	24	1.65
10 – 15	21	1.26
15 – 25	24	1.12
25 – 35	20	0.95
35 – 45	19	0.7
45 – 55	16	1.77
55 - 115	14	1.08

FIGURE14a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 6

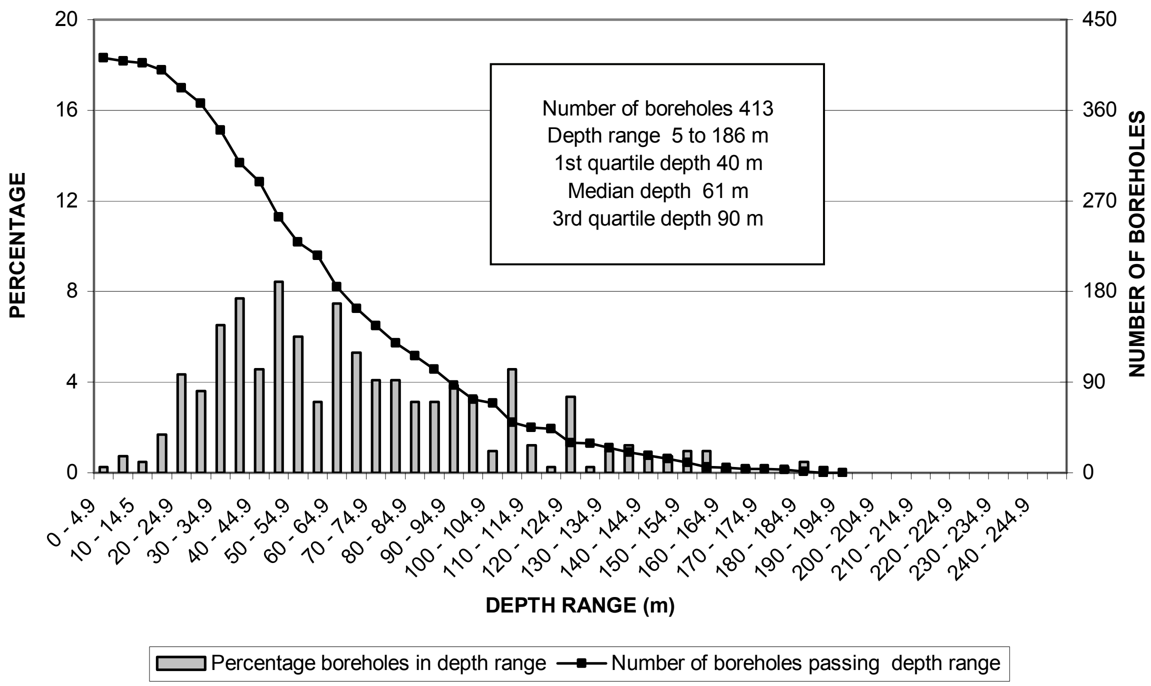


FIGURE14b DISTRIBUTION OF WATER LEVELS SUBDIVISION 6

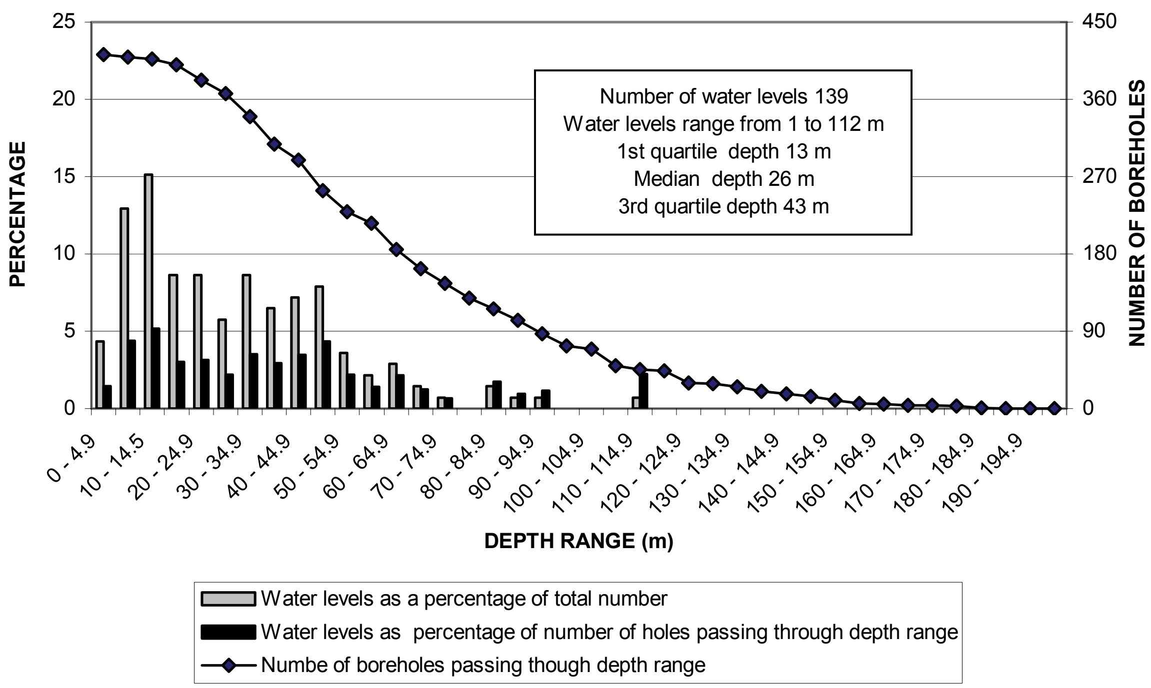


FIGURE 14c DISTRIBUTION UF STRIKES BELOW SURFACE SUBDIVISION 6

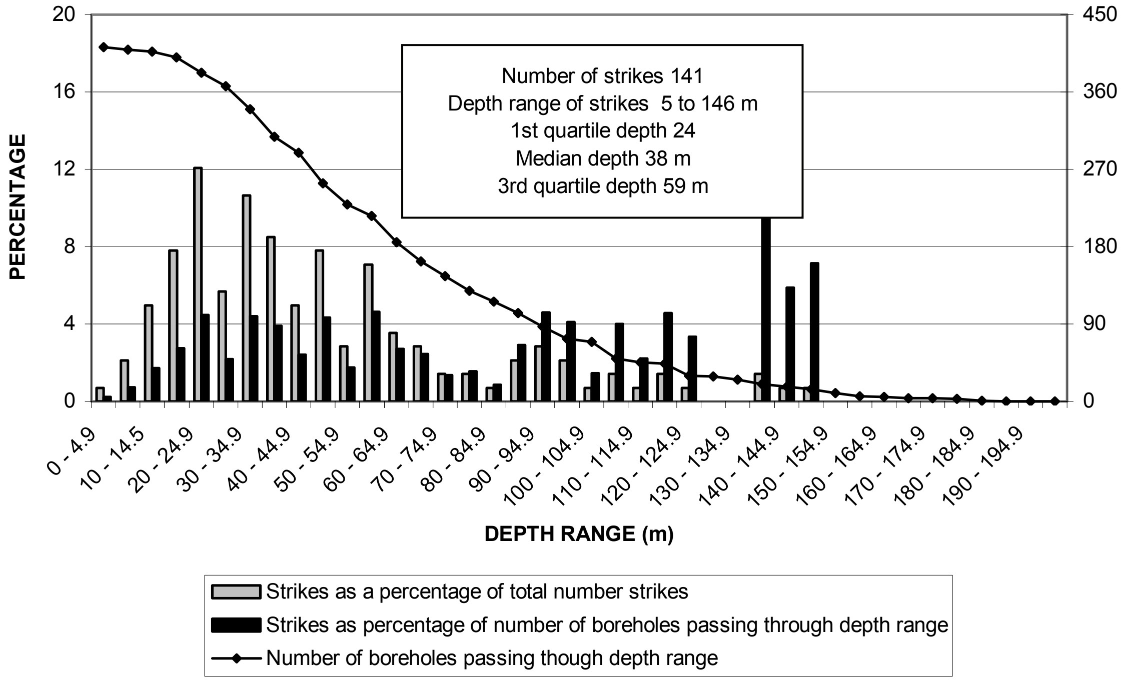
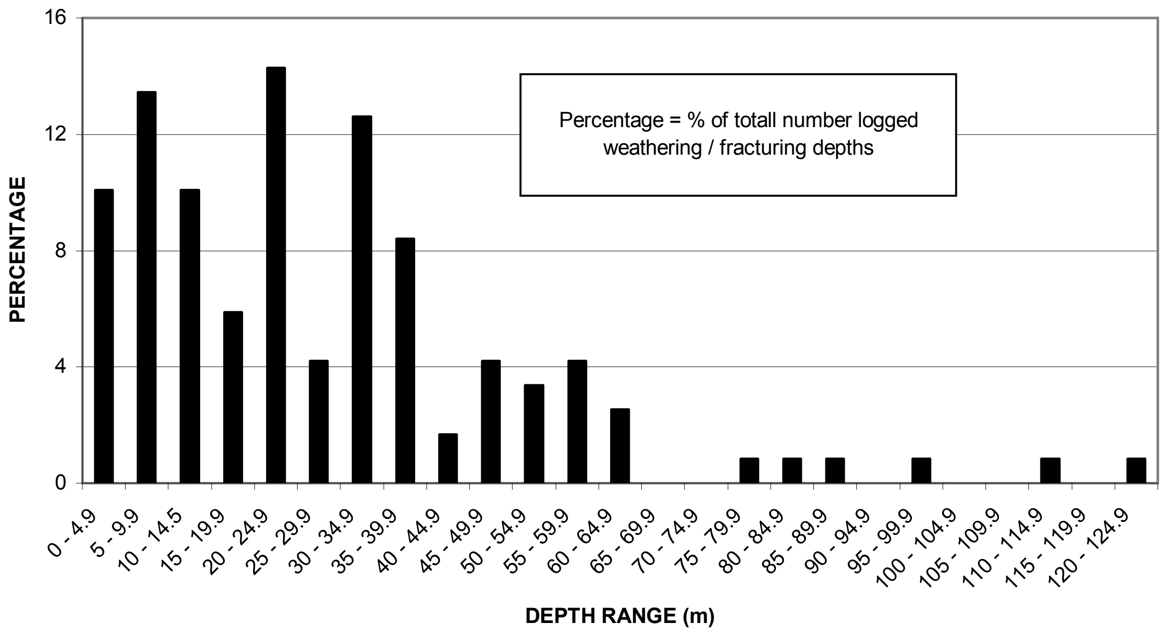


FIGURE 14d DISTRIBUTION OF LOGGED WEATHERING /FRACTURING DEPTHS SUBDIVISION 6



Results of statistical analyses of the borehole data are presented in Figures 14a, b, c and d: The spreads of water levels, borehole and strike depths are similar to that of Subdivisions 4 and 5. The proportions of deeper boreholes, strikes and water levels however are larger. A mean strike frequency of 2.9 % per 5 metre holds over the depth range 15 to 75 m. This is considerably lower than that of subdivisions 4 and 5. Strike frequencies at depths over 100 metres are probably distorted by the small number of boreholes that were drilled deeper only because the formation appeared to offer better prospects. Weathering and fracturing were reported in 29.8 % of the boreholes. Weathering / fracturing exceeds 40 m in only 1/5th of these holes.

6.2.7 Subdivision 7

The subdivision (Figure 3 at back of report) comprises the area north of the Orange River from Uitkomst east of Upington to the Molopo-Orange confluence but excludes the catchment of the Molopo River. Noteworthy thicknesses of superficial deposits occur on Baviaans Krantz 474 and Vaalhoek 469. The extent of these deposits which could be important from the groundwater point of view is unfortunately unknown. On the former 24.4 and 33.5 m of gravel was logged in boreholes No's 2829DA 00001 and 00002. No water was struck. The Vaalhoek log (No 2820DA00035) follows:

0 – 12.2 m	sand	Water struck at	179.8 m
12.2 – 153.3 m	clay	Water level	72.5 m
153.3 - 183.2 m	??	Yield	0.67 ℓs^{-1}

Of the 151 boreholes recorded in the NGWDB 40 (26.5%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 31 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 7

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	25	62.5
0.5 – 0.99	5	12.5
1.0 – 4.9	9	22.5
5.0 – 9.9	1	2.5
≥ 10	0	0

TABLE 32 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 7

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -10	7	1.92
10 – 20	4	1.61
20 – 30	5	0.8
30 – 40	12	0.39
40 – 50	3	0.39
50 – 60	5	0.4
60 - 70	3	0.76

Except for higher yields from near surface broken and weathered formation there is no definite yield trend.

Distributions of borehole depths, water levels, strikes and logged depths of weathering / fracturing are presented in Figures 15a, 15b, 15c and 15d.

FIGURE 15a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 7

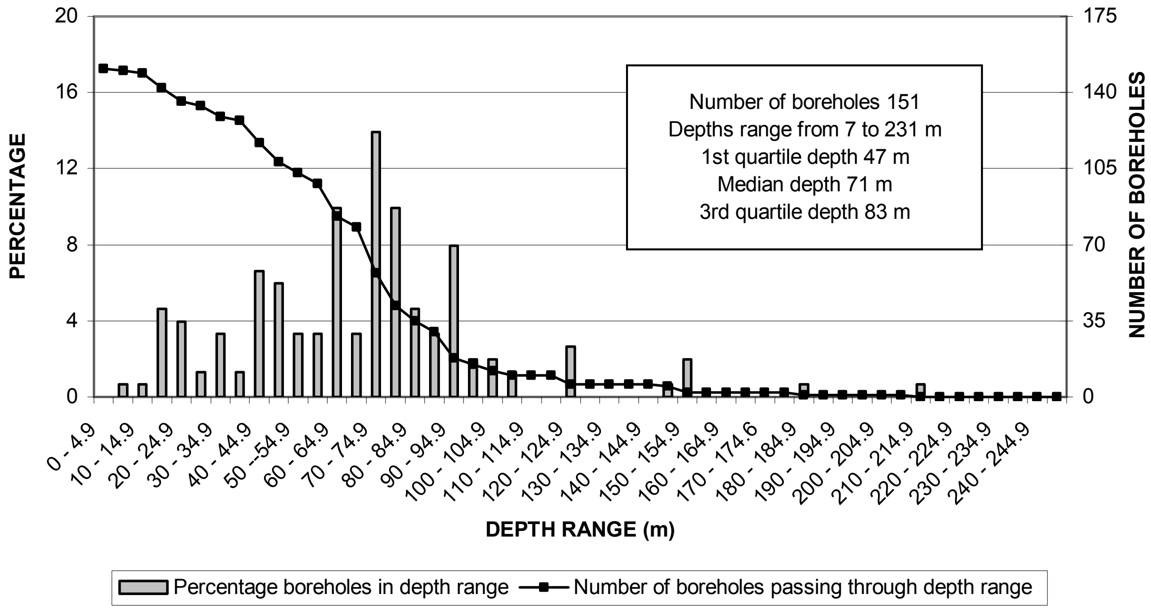


FIGURE 15b DISTRIBUTION OF WATER LEVELS SUBDIVISION 7

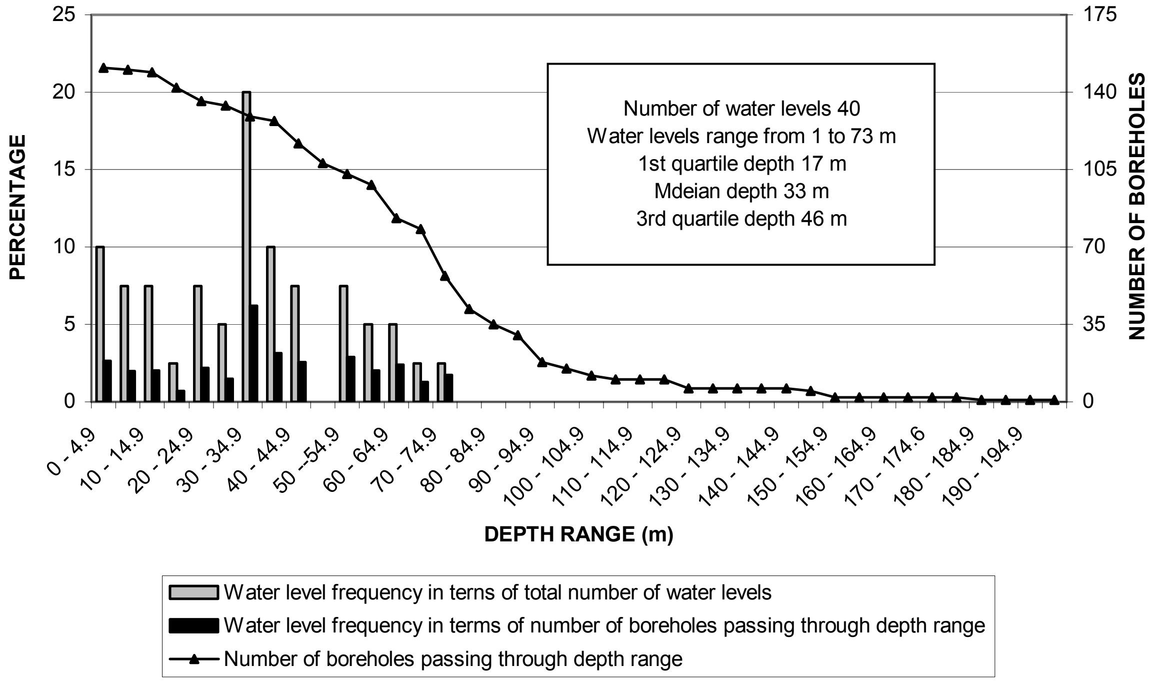
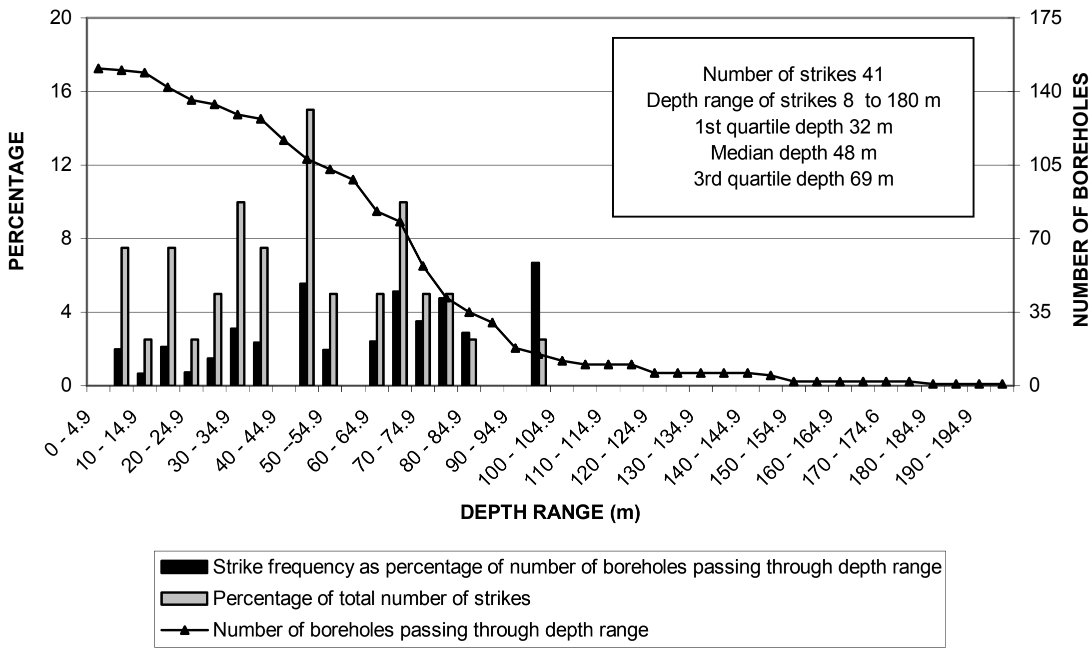
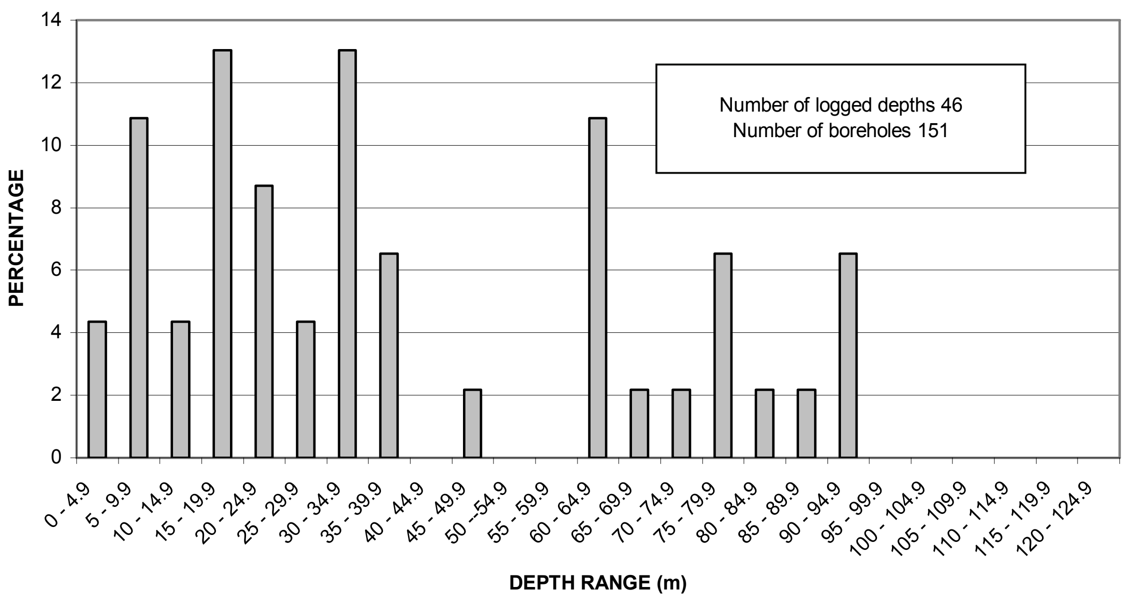


FIGURE15c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 7



Borehole depths, water levels and strikes are on the whole 10 to 20 m deeper than in Subdivision 4. Strike frequency averages 1.7% per 5 m interval from 5 to 40 m below surface and 2.9% per 5 m interval from 40 to 85 m. The deeper strikes and water levels were presumably encountered in the higher-lying area away from the Orange River.

FIGURE 15d DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 7



Sixty-five percent of the logged depths are shallower than 45 m. There is no clear difference between the depth extent of weathering and that of fracturing.

6.2.8 Subdivision 8

Subdivision 8 (Figure 3 at back of report) is also situated north of the Orange River. It occupies the lower Molopo, the Kourop and Bak River catchments. The terrain is hilly in the east. In the west the Riemvasmaak area is highly dissected and mountainous. Deep valleys have been carved through the flat-lying cover of Nama Beds into Namaqua Basement.
Of the 249 NGWDB boreholes 61 (24.5%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 33 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 8

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	34	56.7
0.5 – 0.99	11	18.3
1.0 – 4.9	14	23.3
5.0 – 9.9	1	1.7
≥ 10	0	0

TABLE 34 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 8

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -20	14	1.21
20 -30	18	1.05
30 – 50	22	0.65
50 – 70	6	0.3

FIGURE16a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 8

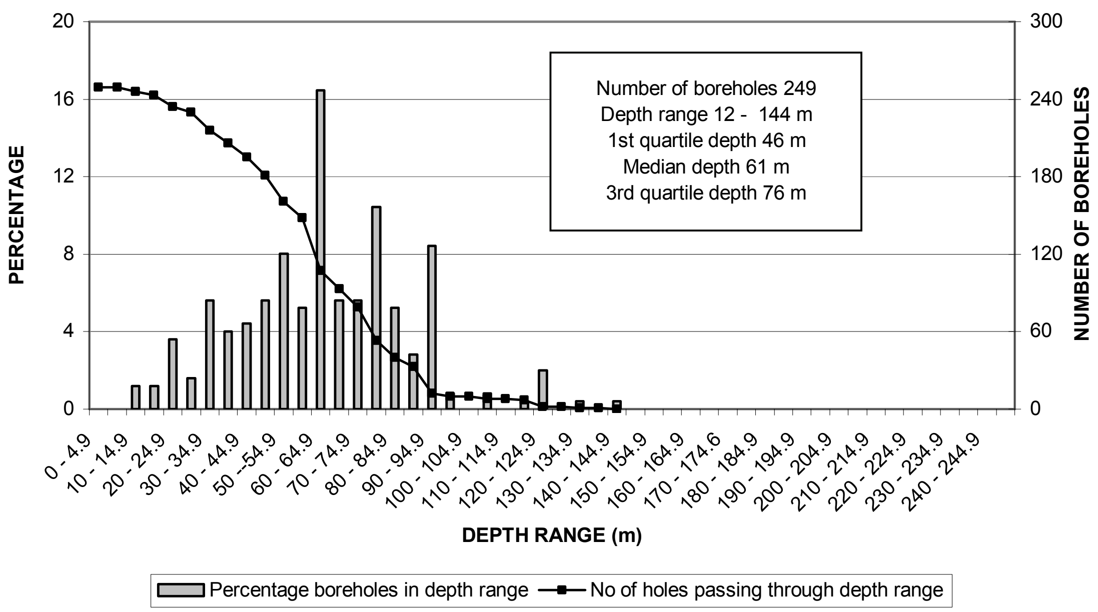


FIGURE16b DISTRIBUTION OF WATER LEVELS SUBDIVISION 8

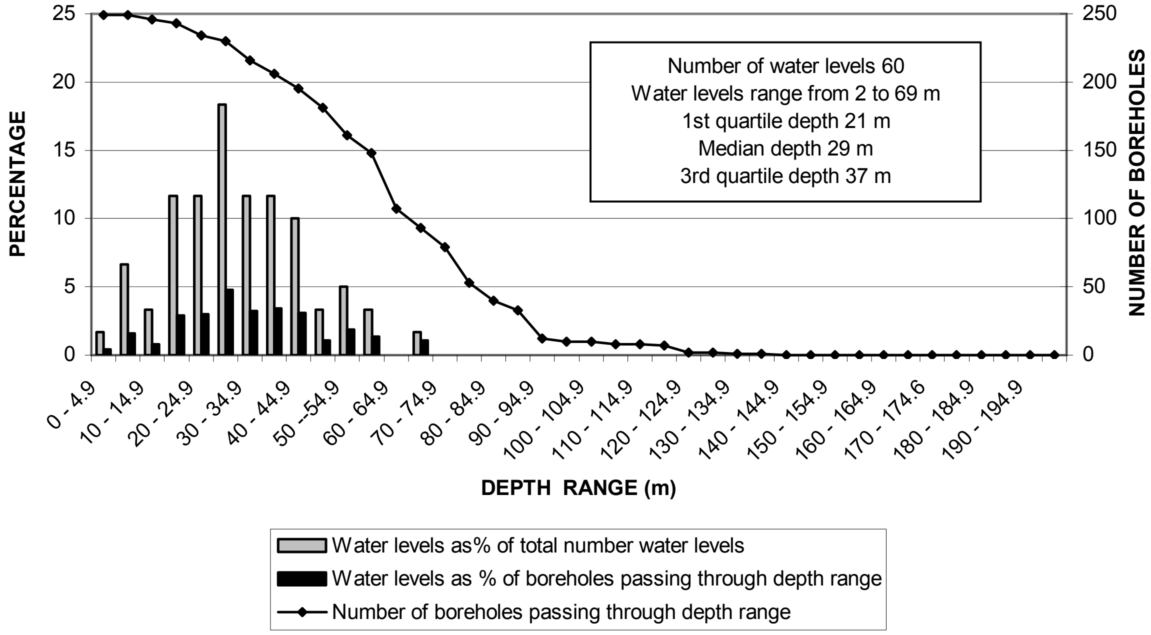
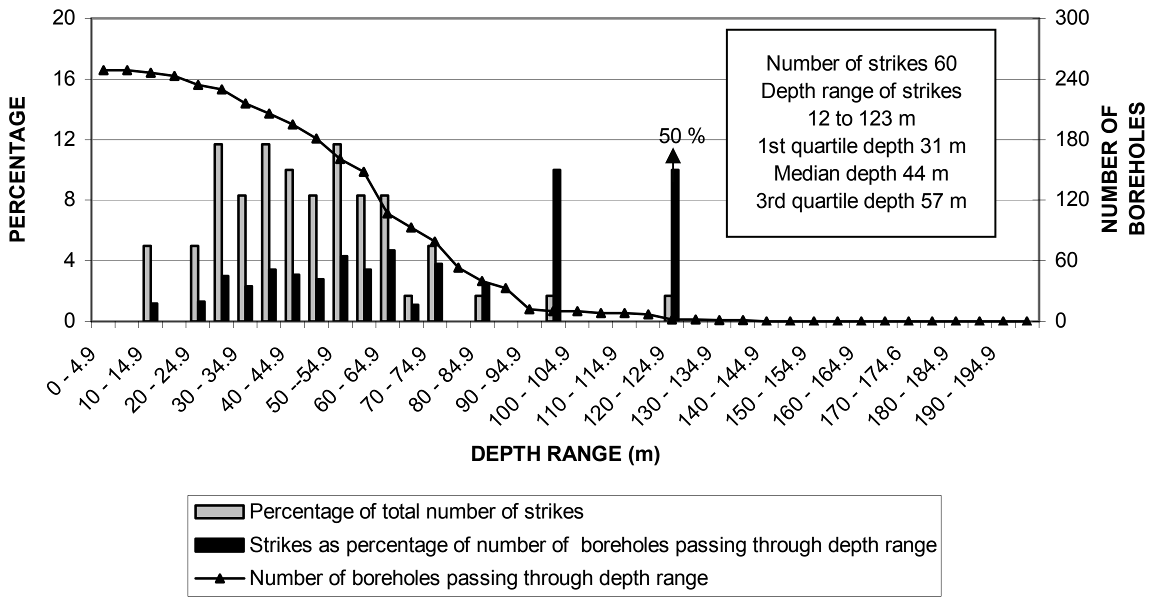
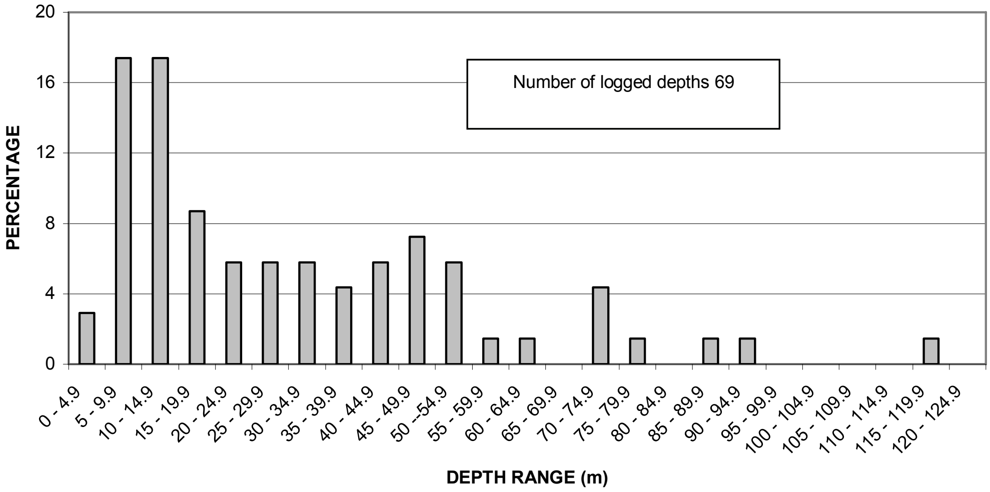


FIGURE16c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 8



Strike frequency expressed as a percentage of the number of boreholes passing through a depth interval averages 3.4% per 5 m interval between 20 and 65 m.

FIGURE 16d DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURINNG SUBDIVISION 8



6.2.9 Subdivision 9

Subdivision 9 (Figure 3 at back of report) embraces the catchments of streams flowing northwards to the Orange River between the Hartbees River in the east and Yas se Laagte in the west. Elevations of the Hartbees-Orange and Yas se Laagte-Orange confluences are approximately 650 and 450 m.a.m.s.l respectively whilst that of the quadruple drainage divide, the junction of subdivisions 6, 9, 10 and 11, is just over 1000 m.a.m.s.l From here the surface drops at an increasing rate towards the Orange. The Orange is bordered by a strip of dissected hilly to mountainous ground that increases in width from a few to about 8 km in a downstream direction.

With the exception of 18.3 and 12.2 m of surface limestone found in boreholes on Drooge Vlakte 73 and Padrooi 13 no overburden in excess of 10 m was reported in any of the other boreholes. Water-bearing fluvial deposits may however be present along stretches of the Brabees, Bul and Gamkaip Rivers. Of the 393 NGWDB boreholes 100 (25.4%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 35 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 9

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	53	53
0.5 – 0.99	15	15
1.0 – 4.9	30	30
5.0 – 9.9	2	2
≥ 10	0	0

TABLE 36 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 9

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -20	27	1.1
20 -30	33	0.8
30 – 50	20	0.72
50 – 125	20	1.21

FIGURE17a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 9

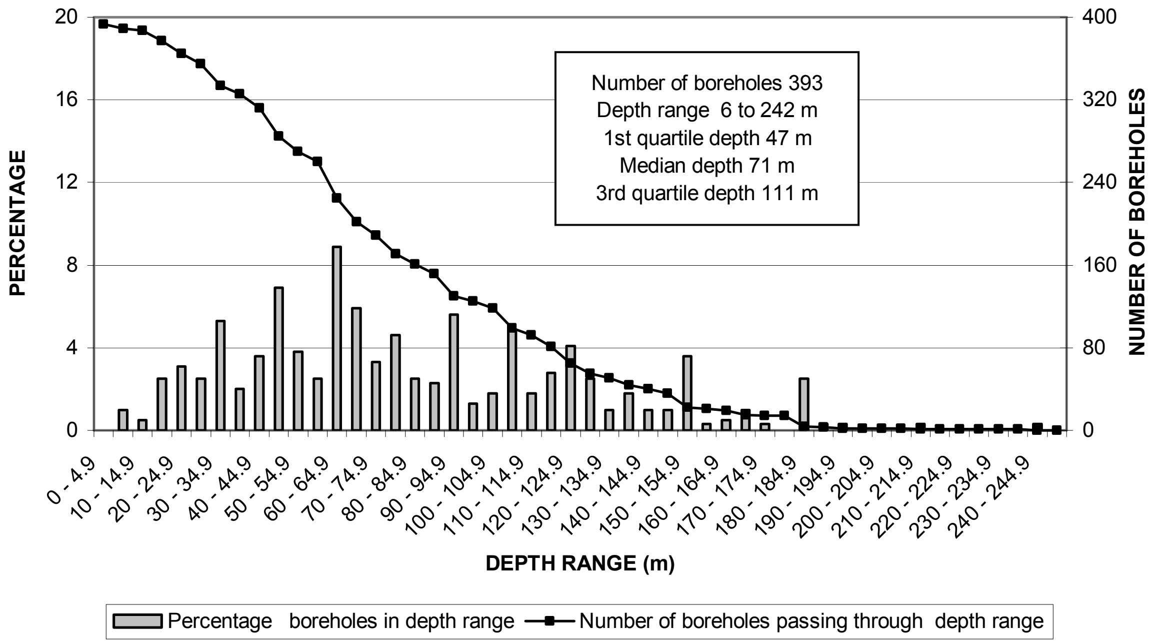
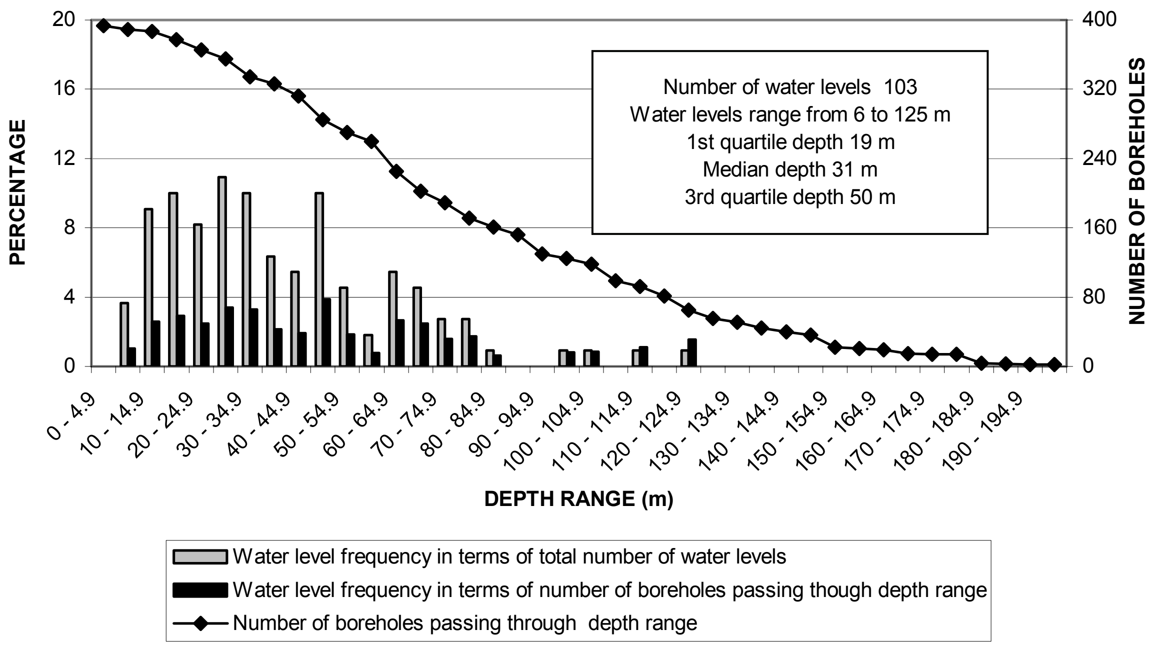
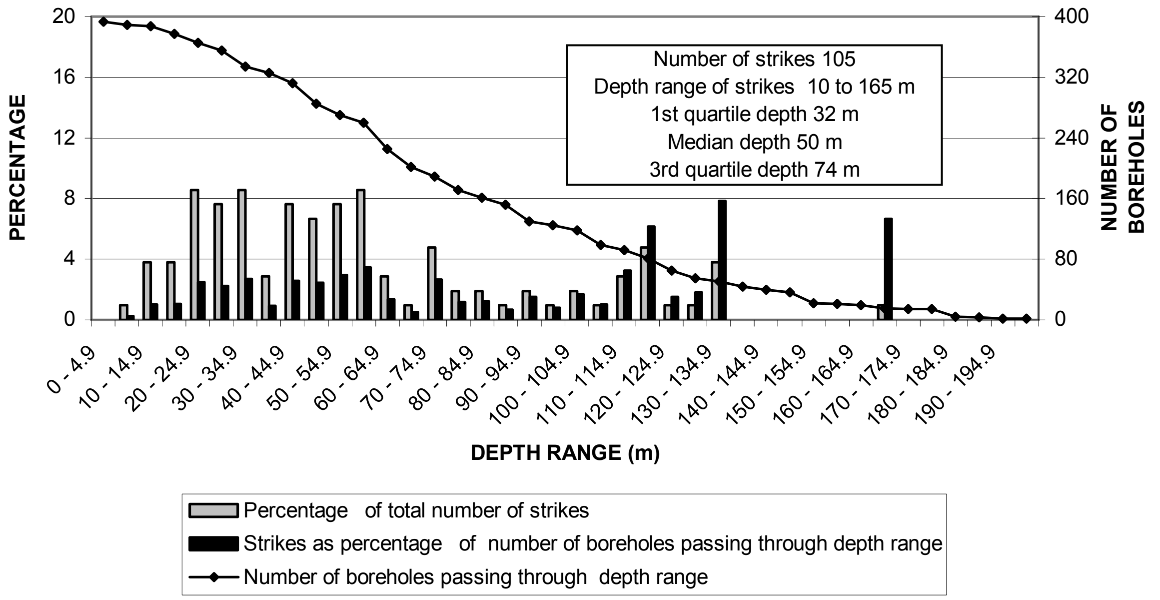


FIGURE 17b DISTRIBUTION OF WATER LEVELS SUBDIVISION 9



The deepest boreholes and water levels of 105 to 125 m are found on drainage divide farms Bank Vlei 136, Arribees (en Osvlei) 95, Drooge Vlakte 73 and Cara Ma'am 74 whilst waterlevels < 10 m have been recorded on farms Orange Fall 18, Witklip 14, Blouputs 10, Narries 7 and Daberas 6 that are situated along the Orange River.

FIGURE 17c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 9



Strike frequency averages respectively 2.1 and 3.5 % per 5 m interval for depth ranges 15 to 65 and 110 to 123 m.

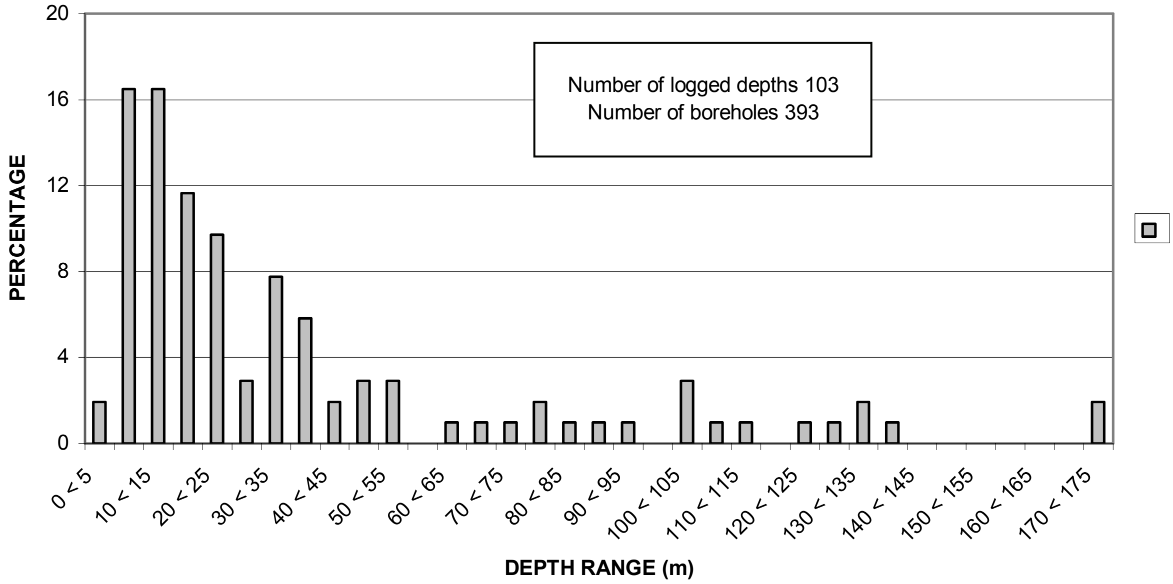
TABLE 37 DISTRIBUTION OF STRIKES BELOW WATER LEVEL SUBDIVISION 9

Strike depth below water level (m)	Number of strikes yielding ≥ 0.1 ls^{-1}	Cumulative number of strikes yielding ≥ 0.1 ls^{-1}	Cumulative % success	Mean Yield ℓs^{-1}
0	3	3	3.1	0.25
0.1 < 5	17	20	20.6	0.92
5 < 10	18	38	39.2	0.97
10 < 15	12	50	51.5	0.82
15 < 20	9	59	60.8	0.65
20 < 25	6	65	67.0	1.52
25 < 30	6	71	73.2	0.39
30 < 35	6	77	79.4	1.39
35 < 40	3	80	82.5	1.57
40 < 45	4	84	86.6	0.40
45 < 50	5	89	91.8	1.15
50 < 70	4	93	95.9	1.85
70 < 131	4	97	100	0.34

Overall mean yield 0.93 ℓs^{-1}; overall median yield 0.46 ℓs^{-1}

Water is mostly struck within 25 m below water level. No relationship between yield and strike depth below water level is evident. Note that the water level ranges between wide limits.

FIGURE 17d DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 9



73% of the logged depths of weathering / fracturing are less than 40 m deep.

6.2.10 Subdivision 10

Subdivision 10 (Figure 3) is bound by the divide east of Yas se Laagte and in the west by the Kaboep / Coboop divide (Figure 3). It embraces in addition to the Yas se Laagte or Nous River catchment those of Kotie se Laagte, Samoep se Laagte and a number of short streams. Like the adjoining Subdivision 9 the surface drops from about 1000 m.a.m.s.l to below 400 m.a.m.s.l along the Orange River. Mountainous dissected ground borders on the Orange River.

Superficial deposits thicker than 10 m were encountered in boreholes on Orange Falls 101 (21,9 m ‘chalk”), Uitdraai 82 (21.3 m gravel), Yas 3 (29 m sand) and Styerkraal 81 (30.5 m sand) Water was struck only in the last-named borehole in bedrock at 32 m, water level 24.4 m and yield 0.39 ℓs^{-1}

Number of NGWDB boreholes	398
Number of boreholes yielding ≥ 0.1 ls^{-1}	63
% success	15.8

TABLE 38 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 10

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	53	53
0.5 – 0.99	15	15
1.0 – 4.9	30	30
5.0 – 9.9	2	2
≥ 10	0	0

TABLE 39 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 10

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -20	27	1.1
20 -30	33	0.8
30 – 50	20	0.72
50 – 125	20	1.21

FIGURE18a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 10

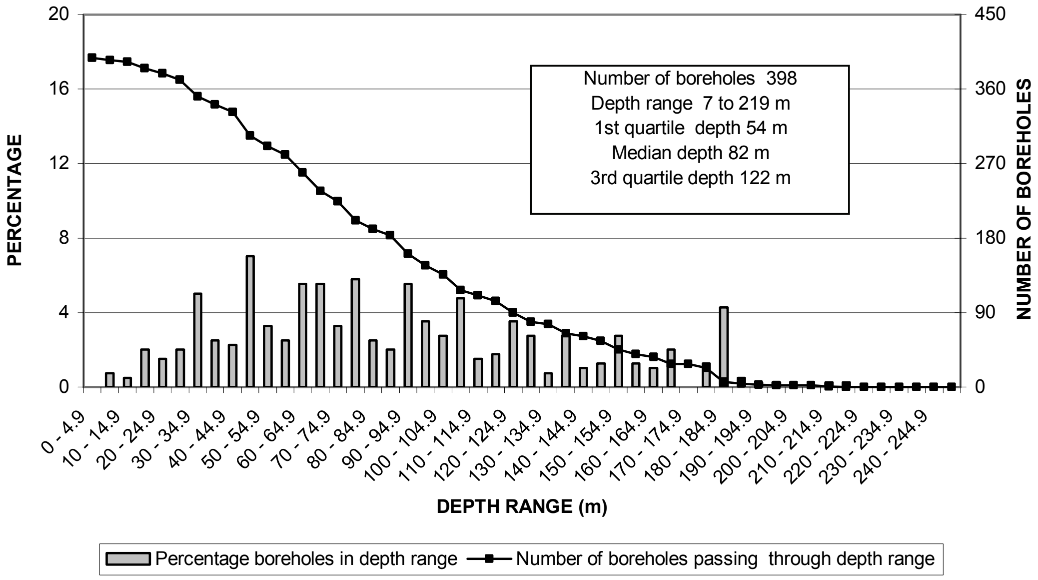
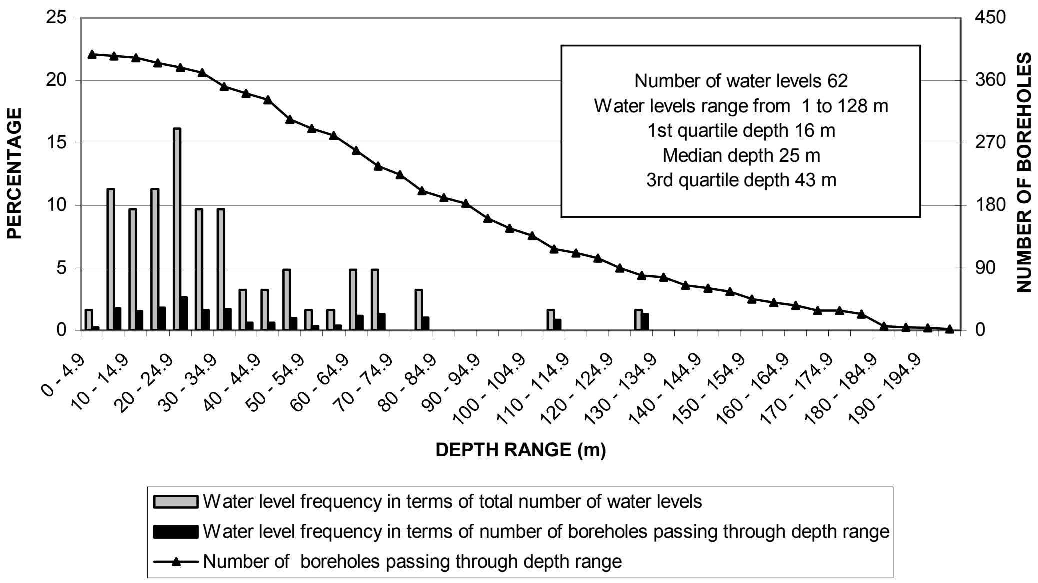


FIGURE18b DISTRIBUTION OF WATER LEVELS SUBDIVSION 10



Boreholes deeper than 150 m have been drilled on water divide farms such as Bladgrond South 94, Lukas Vlei 93, Oup 80, Oupvlakte 90 and Scuit Klip 92. On these farms waterlevels range from 58 to 128 m below surface. Water levels < 20 m are found along the major water courses Samoep se Laagte (Lower Zwart Modder 79), Nous River (Nous West 76) Yas se Laagte (Schuitdrift Oost 6) and on Warmbad Noord 1 along the Orange River.

FIGURE18c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 10

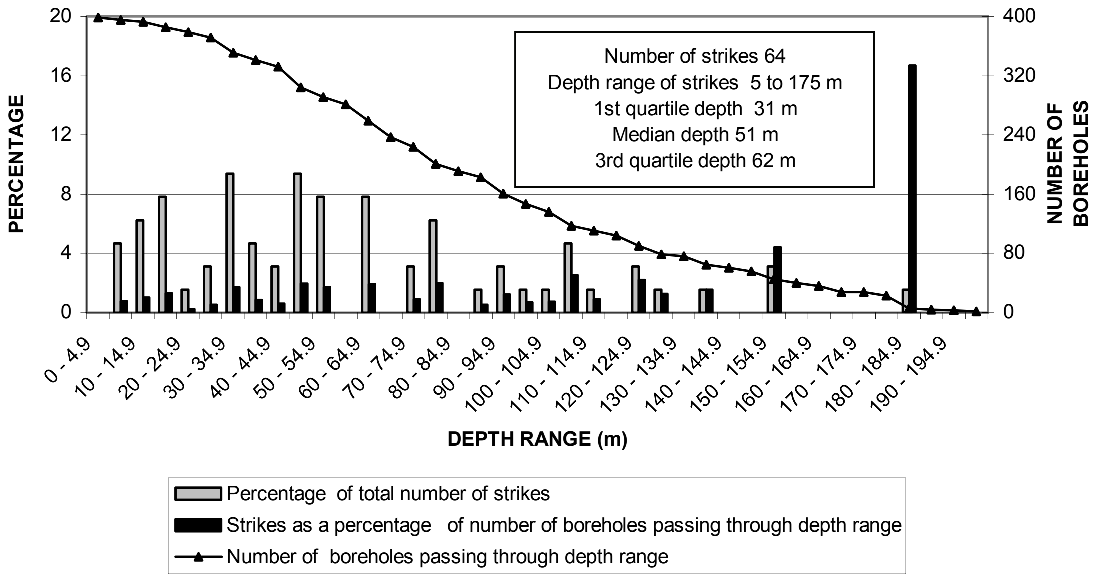
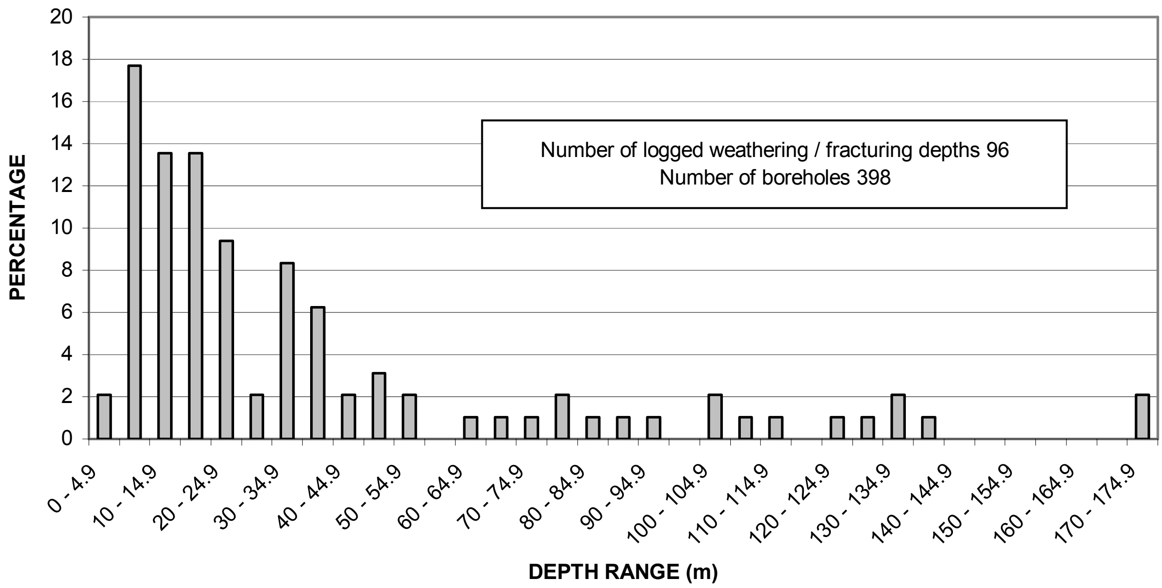


FIGURE 18d DISTRBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 10



6.2.11 Subdivision 11

Subdivision 11 (Figure 3 at back of report) consists of the Kaboep / Coboop River catchment. In the Kaboep valley unconsolidated sediments have been encountered in boreholes on Gemsbok Vlakte 140, Nongcaip 142 and Oupvlakte. 90. See Table 40.

On Houmoed 206 situated on the water divide between subdivisions 6 and 11 borehole 2919AD00039 was abandoned after drilling 60 m of alluvium. In section 6.2.6 the existence of 30 m of alluvium in a borehole on neighbouring farm Puts Berg 204 was mentioned. It is suggested that these occurrences may be parts of a palaeo-Kaboep River system.

TABLE 40 KABOEP / COBOOP VALLEY BOREHOLES IN SUPERFICIAL DEPOSITS

Gemsbokvlakte	Gemsbokvlakte	Nongcaip 142	Nongcaip 142	Oupvlakte 90
2819BA00025	2919BA00037	131113/7	132322/3	2819CD00022
0 – 58.9 m Tuff = calcrete?	0 – 13.7 m limestone	0 – 78 m Rounded to sub-rounded quartz-feldspar sand	0 – 72 m quartz gravel and sand with feldspar biotite and muscovite	0 – 75.6 m chalk = calcrete?
58.9 – 84.9 m Vein quartz	13.7 - 54.9 m Conglomerate			75.6 – 79.3 m Granite
84.9 -106.7m Granite	54.9 – 61.5 m Granite			
	61.5 – 106.4 m Vein quartz		72 – 76 m Rounded quartz sand with feldspar and micas	
No water	Struck water 96.6 m	Struck water 73 m	Struck water 72 m	No water
	Rises to 79.3 m	Rises to 5 m	Rises to 69 m	
	Yield 0.45 ℓs^{-1}	Yield 2.56 ℓs^{-1}	Yield 2.65 ℓs^{-1}	
		Elevation ± 650 m.a.m.s.l	Elevation ±750 m.a.m.s.l	
		Two boreholes are approximately 8 – 9 km apart		

The NGWDB contains records of 308 boreholes of which 62 (20.1%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 41 DISTRIBUTION OF YIELDS SUBDIVISION 11

Yield ℓs^{-1}	Number of boreholes	Percentage
0.1 – 0.49	33	53.2
0.5 – 0.99	15	24.2
1.0 – 4.9	12	19.4
5 – 9.9	2	3.2

TABLE 42 RELATION BETWEEN YIELD AND WATER LEVEL SUBDIVISION 11

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -20	20	0.6
20 -40	24	0.7
40 – 80	15	0.78

Depth distributions of boreholes, water levels, strikes and of logged weathering and fracturing are depicted in Figures 19a, b, c and d. Water levels ≤ 20 m occur on the following farms:

a) In the Upper Kaboep catchment on Houmoed 206, Nouzees 148, Ganna Poort 202, and Lovedale 201
b) In the upper Kaboep valley on Fals Vlei 137 and Lukas Vlei Vlakte 138 and

c) In the lower valley on Nongcaip 142 (see logs Table 40) and Coboop 89.

On Fals Vlei 127 and Lukas Vlei Vlakte 138 water levels > 90 m deep are also present presumably along the drainage divide between the Kaboep and a unnamed shallow valley in Subdivision 10. The same apparently applies to deep water levels on Gemsbok Vlakte 140, Konkoonsies 91 and Oupvlakte 90 and to Sand Gat 150 on the southern side of the valley The Kaboep valley lies between 100 and 200 m below the northeastern drainage divide.

FIGURE 19a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 11

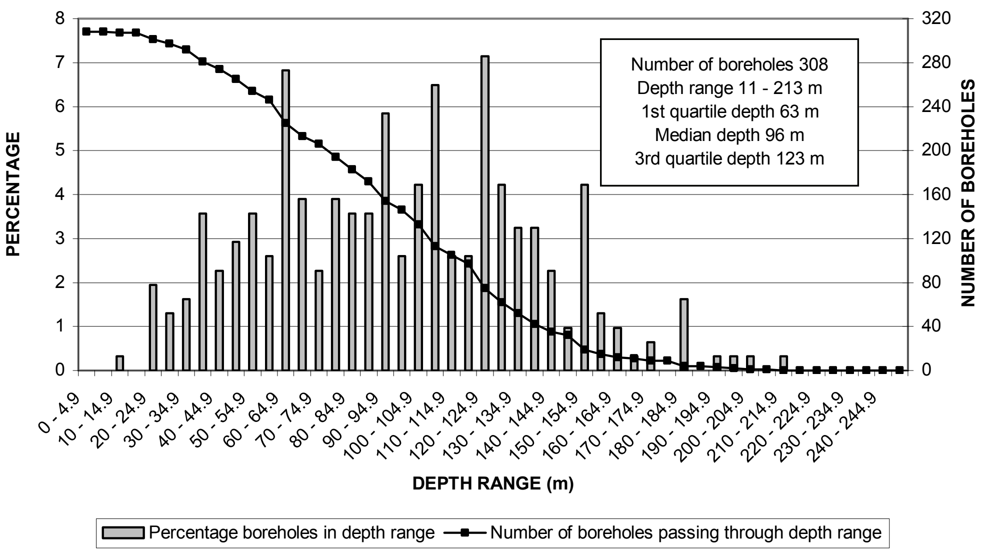


FIGURE 19b DISTRIBUTION OF WATER LEVELS SUBDIVISION 11

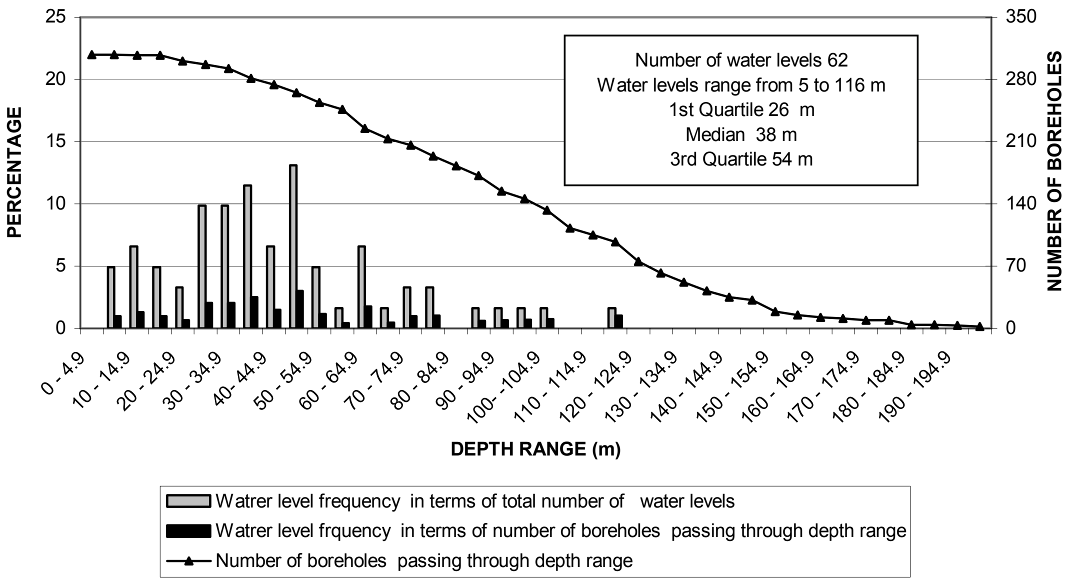


FIGURE 19c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 11

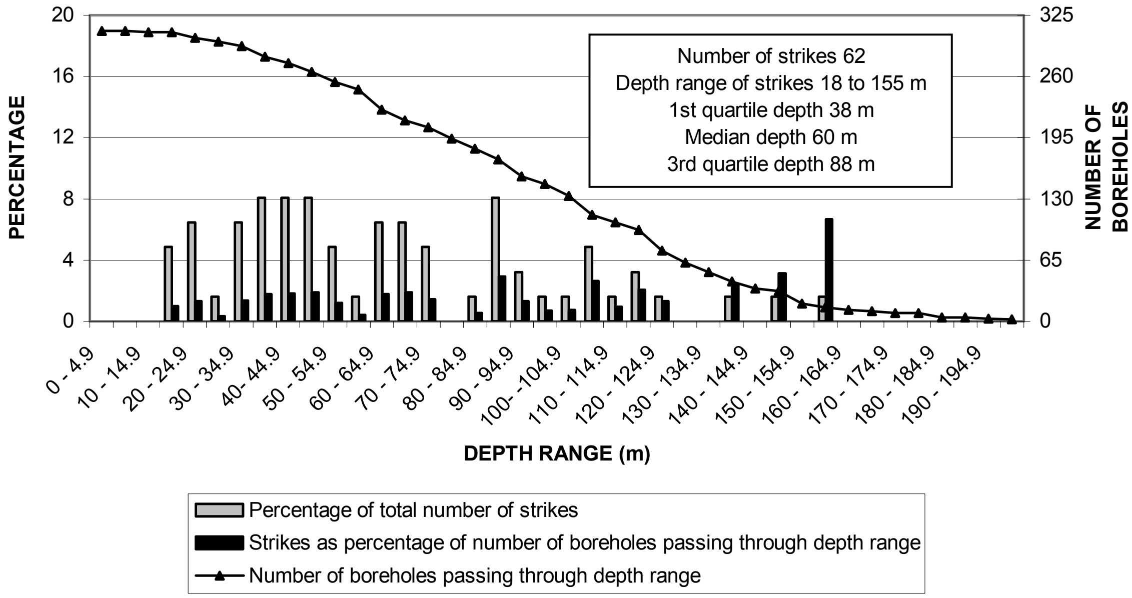
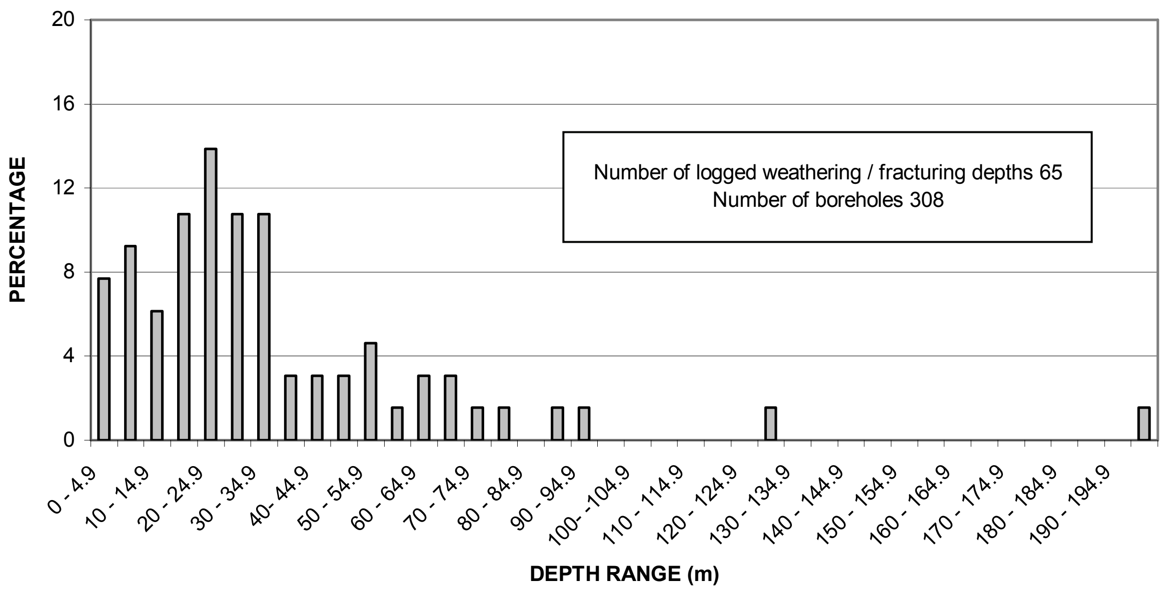


FIGURE 19d DISTRIBUTION OF LOGGED WEATHERING / FRACTURING DEPTHS SUBDIVISION 11

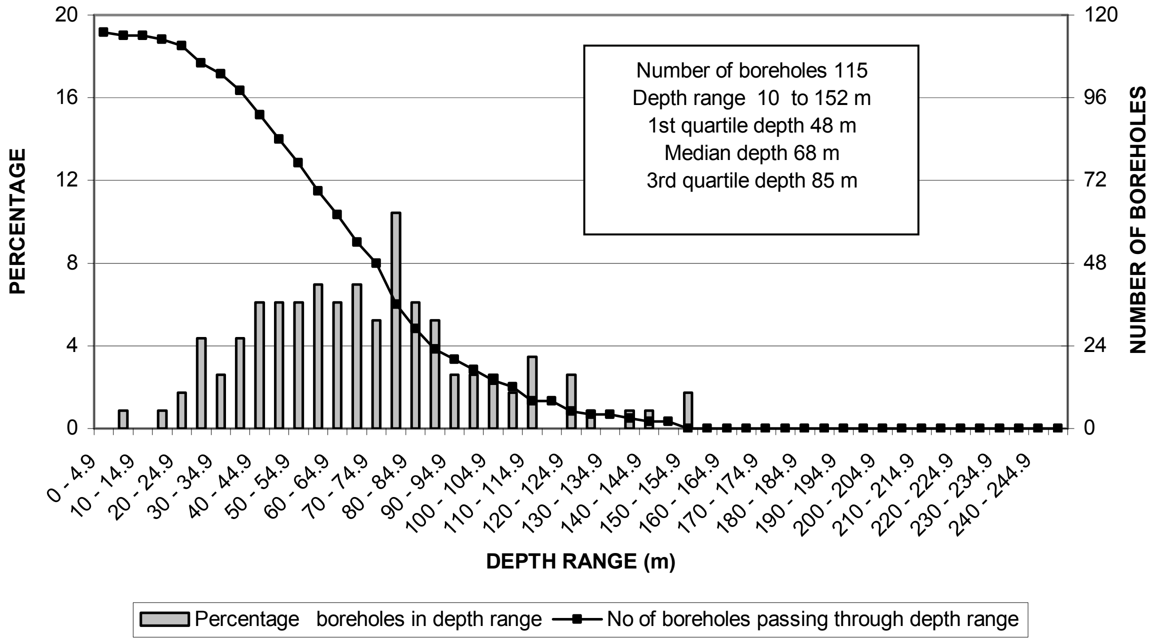


6.2.12 Subdivision 12

Subdivision 12 (Figure 3 at back of report) comprises the catchment of Pella River / Goob se Laagte. It is bounded on the northeast by the Mattheusgat Mountains 1100 to 1200 m.a.m.s.l. An east-west range of hills, Poort se Berge, Namies Mountains and Ghaamsberg rising to over 1150 m.a.m.s.l, lie just within its southern boundary. Where the Pella River joins the Orange the elevation is about 325. m.a.m.s.l. Pofadder and Pella villages are situated in the Subdivision.

The NGWDB contains records of 115 boreholes. The results of exploratory drilling during 1982 (see section 7.3.5) on behalf of the Pofadder Municipality were not incorporated in the following analyses.

FIGURE 20a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 12



Forty-one boreholes (35.7%) yielded ≥ 0.1ℓs^{-1}.

TABLE 43 DISTRIBUTION OF YIELDS SUBDIVISION 12

Yield ℓs^{-1}	Number of boreholes	Percentage
0.1 – 0.49	25	61
0.5 – 0.99	8	19.5
1.0 – 4.9	5	12.2
5 – 9.9	2	4.9
≥ 10	1	2.4

TABLE 44 RELATION BETWEEN YIELD AND WATER LEVEL SUBDIVISION 12

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -10	5	0.53
10 - 20	15	1.08
20 – 30	9	1.13
30 = 70	11	1.28

FIGURE 20b DISTRIBUTION OF WATER LEVELS SUBDIVISION 12

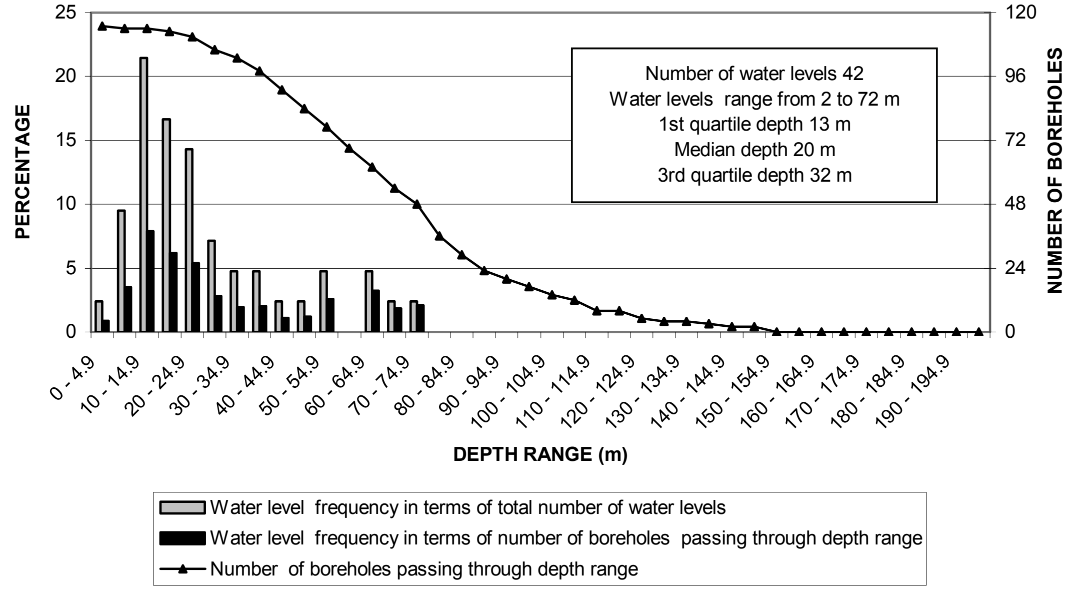
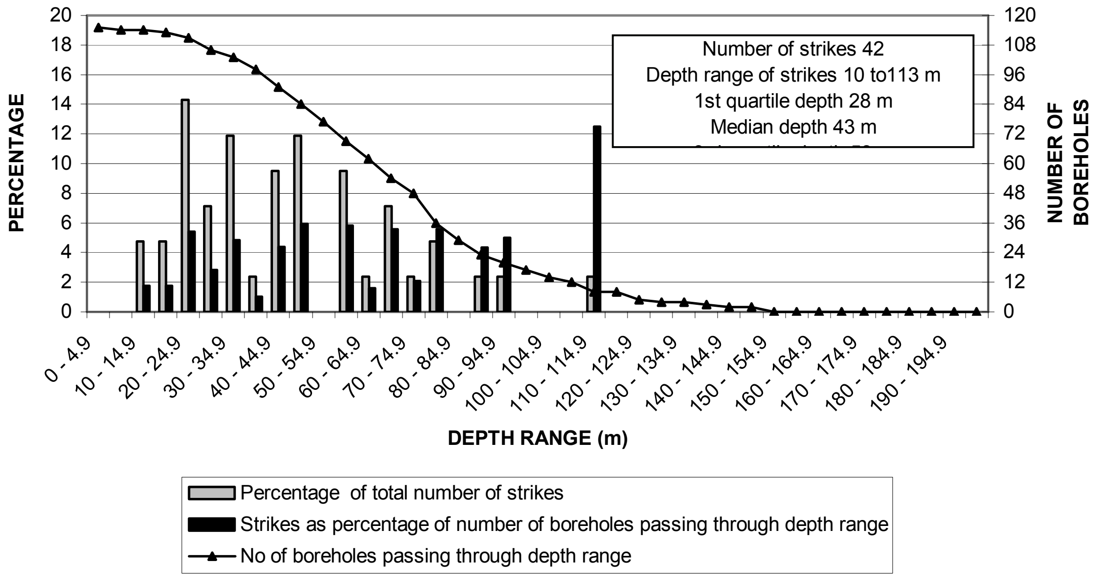


FIGURE20c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 12



6.2.13 Subdivision 13

For location see Figure 3 at the back of the report. The Subdivision may be viewed as analoguos to No's 9, 10 and 11. Elevation along the drainage divide between subdivisions 13 and 14 varies from about 1000 m.a.m.s.l in the east to 700 m.a.m.s.l in the west. The Orange River drops from approximately 325 to 250 m.a.m.s.l.

Note that owing to poor exposures there is a degree of uncertainty about the position of the boundary between the Richtersveld and Bushmanland Subprovinces and also about its relation to the drainage divide which is the boundary between subdivision 13 and 14.

The NGWDB yielded records of a mere 39 boreholes. They are located on Steinkopf 22 (farms 39 and 43), Koisabes 47, Ramons Drift 24, Abbasas 26, Witbank 30, Dabenoris 44, Sandfontein 38 and Klein Pella 40. On Koisabes 47 alone 15 holes were sunk. Thirteen reached depths of between 123 and 250 m. Koisabes 47 straddles the water divide between subdivisions 13 and 14. The depth of the piezometric level in the latter exceeds 100 metres. It would therefore appear that with the exception of only one successful borehole (water level 50.9) the rest, fourteen (all dry), were located in Subdivision 14.

Data of the remaining 25 boreholes are as follows:

Depths range from 26 to 202 m
Ten boreholes yielded between 0.1 and 5 ℓs^{-1}
Water levels range between 5 and 61 m
Water was struck between depths of 5 and 82 m.

6.2.14 Subdivision 14

For location see Figure 3 at the back of the report. The sand-filled expanse of the Koa Valley is Subdivision 14's most striking feature. Much of the metamorphic and intrusive geology of Subdivision 14 is hidden under a blanket of Cainozoic sand, clay and calcrete. Some idea of the range in thickness and extent of the overburden may be gauged from borehole logs (excluding exploratory drilling by Water Affairs 2001/2 see Chapter 5).

Overburden thickness	0 – 5 m	5 - 20 m	≥20 – 50 m	50 -100 m	> 100m
Number of boreholes (Total 393)	272	59	34	17	11

The occurrence of groundwater in the Cainozoic deposits was discussed at length in Chapter 5. Saturated overburden was found in only seven NGWDB boreholes (excluding the 13 exploratory boreholes drilled during 2000/1). In four of them water was struck in the overburden (see Table 16 in section 5.1)

On Kaitob 74 in a tributary valley of the Koa 122 m (400 ft) of sand was encountered in a borehole according to the late G.J. Ellis of the Geological Survey (borehole not listed in NGWDB). Likewise on the Kouberg portion of Koeris 78, 122 m of clay was found in NGWDB borehole No 2918CB00021 (Boring Branch No 104845). Whether these two deposits are infillings of diatremes, abound in this area, or occupy Late Cretaceous – Early Cainozoic incised tributaries of the Koa cannot be established as positions of boreholes are not known. Note however that Kaitob 74 lies in the upper reaches of the Beenbreekspruit and that a drainage line running from Kouberg across Tweeling 79, Dikbek 81, Spioenkop 97 and Hunites 64 to Zuurwater 62 in the Koa valley is indicated on the 1:250 000 topocadastral Pofadder map.

From the groundwater exploitation point of view it is important to determine whether deeply incised tributaries exist. The depth of incision controls the depth and configuration of the piezometric surface in the surrounding area (see Figure 8 at the back of the report).

The NGWDB does not contain data on boreholes that were drilled during the 1970's for water supply at the Aggeneys Mine. The boreholes are mainly confined to a 11 km long zone stretching from Black Mountain in the west past Broken Hill to Maanhaarkop in the east. Boreholes were sunk through sequences of quartzites, quartz schists, schists, pegmatite and pink and grey gneiss. Major water strikes were made irrespective of rock type between 70 and 80 m where the formations are extensively fractured and weathered (Martinelli and Associates 1978). The piezometric level lay at about 50 m. The recommended pumping rates of 15 production boreholes ranged between 1.7 and 6.3 ℓs^{-1}.

The NGWDB yielded records of 15 boreholes that were drilled into and through Dwyka shale and dolerite on Poortjie 209. These records have been omitted from analyses and have been incorporated with data of Subdivision 18a and b. Data of 391 boreholes of which 85 (21.7%) yielded ≥ 0.1 ℓs^{-1}. accordingly were analysed.

TABLE 45 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 14

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	46	54.1
0.5 – 0.99	18	21.1
1.0 – 4.9	18	21.1
5.0 – 9.9	1	1.2
≥ 10	2	2.4

FIGURE 21a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 14

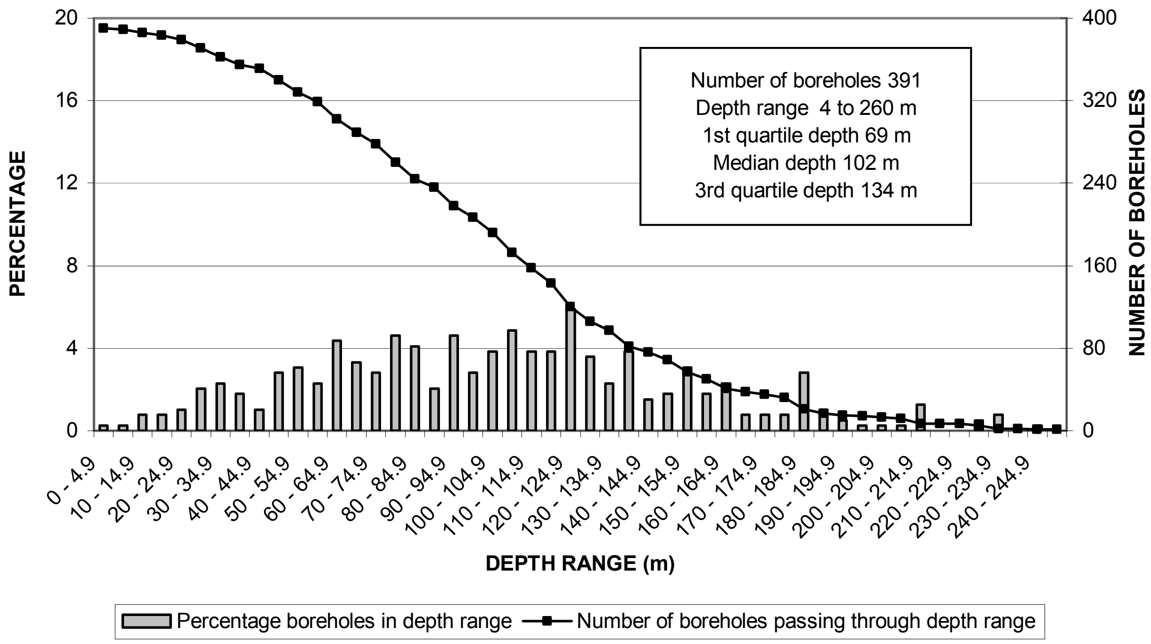


FIGURE 21b DISTRIBUTION OF WATER LEVELS SUBDIVISION 14

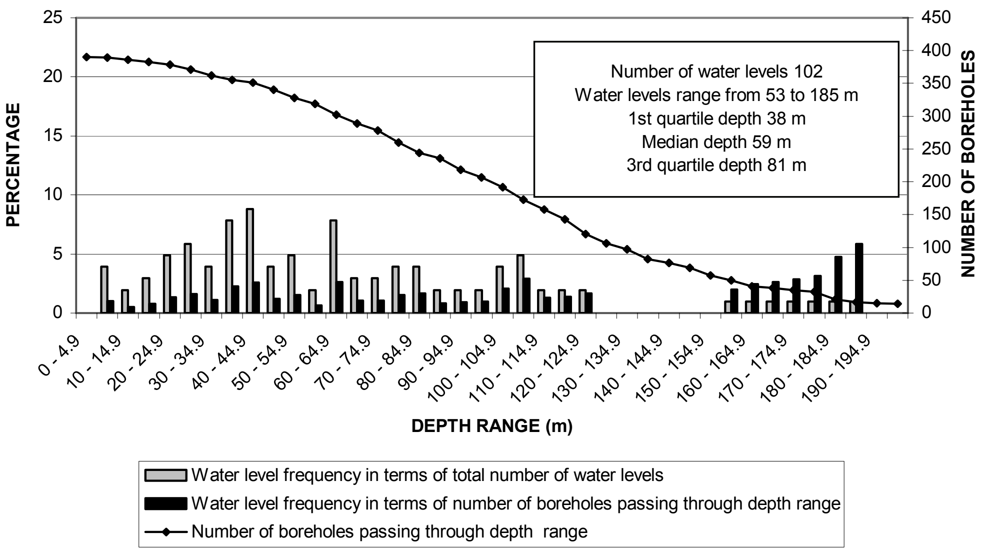


TABLE 46 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 14

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 -10	5	4.1
10 -20	5	0.69
20 – 30	8	0.6
30 – 40	11	0.57
40 – 50	12	0.7
50 – 60	6	0.52
60 – 70	6	0.91
70 – 80	7	0.62
80 – 100	8	0.73
100 – 120	8	2.14
120 - 185	8	1.14

FIGURE 21c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 14

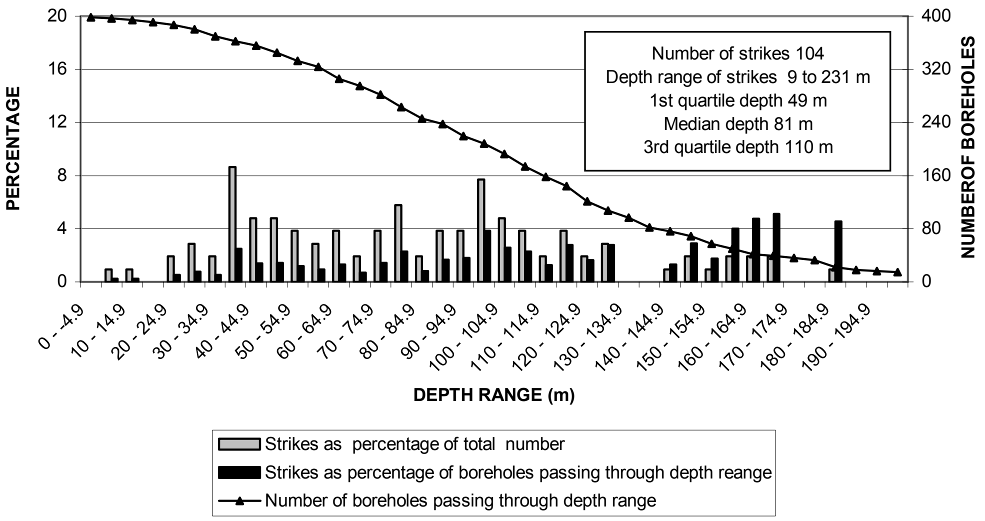


FIGURE21d YIELD VERSUS STRIKE DEPTH BELOW WATER LEVEL SUBDIVISION 14 (HARD ROCK)

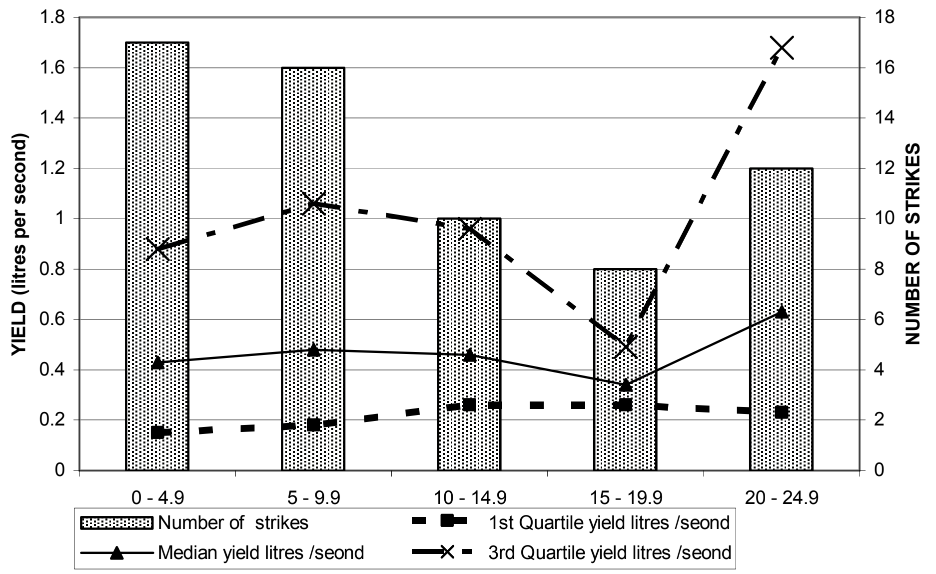
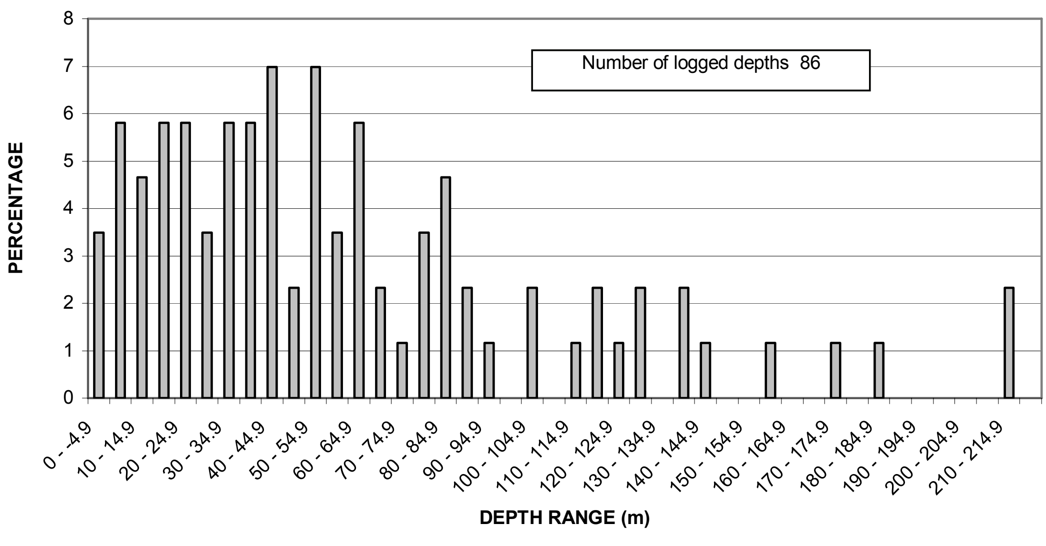


FIGURE 21e DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 14



According to drillers' logs weathered or fractured or broken formation was encountered in only 86 boreholes. Depths of weathered / fractured / broken rock range from 2 to 210 metres. Twenty-nine of these holes (33.7%) yielded ≥ 0.1 ℓs^{-1}. Of the remaining 304 boreholes that lacked logged weathered / fractured formation, 57 were successful. This is a success rate of 18.8%

The results may be broken down further. Water was struck shallower than depth of weathering / fracturing in 17 of the 29 successful boreholes. Depths of weathering / fracturing range from 29 to 174 m: Strike depths ranged from 11.3 to 126.5 m below surface. Thirteen of the 17 strikes were made within 15 to 0 metres above the base of weathering / fracturing. Yields range between 0.15 and 2.02 ℓs^{-1}.

Water strikes were deeper than depths of weathering / fracturing in the remaining 12 successful boreholes. Depths of weathering / fracturing range from 7 to 104.5 m. Strike depths ranged from 21 to 207.6 m below surface. Nine of the 12 strikes were made within 0 and 15 metres below the base of weathering / fracturing Yields range between 0.13 and 1.12 ℓs^{-1}:

In 57 successful boreholes with no logged weathered / fractured formation strike depths ranged from 14 to 231 m below surface. Yields range from 0.12 to 12.6 ℓs^{-1}. Although a higher success rate obtains where weathering and fracturing have been logged, there appears to be no significant difference in the yields of boreholes whether sunk through weathered / fractured / broken sections or as reported by the driller through unspecified, presumably fresh, rock.

6.2.15 Subdivision 15

Subdivision 15 (see Figure 3 at back of report) comprises the easternmost portion of the Khurisberg Fragment. It consists of the uppermost catchments of the Brak River, the Beenbreekspruit and other discontinuous drainage lines.

Records of 37 boreholes were abstracted from the NGWDB. Eighteen yielded ≥ 0.1 ℓs^{-1} (48.6% success). Yields range from 0.2 to 2.3 ℓs^{-1}, 1st quartile 0.39, median 0.76 and 3rd quartile 1.3 ℓs^{-1}. Water levels range from 0.5 to 106.7 m, 1st quartile 5.5, median 16 and 3rd quartile 30 m. Strikes range between 19 and 158 m, 1st quartile 33, median 43 and 3rd quartile 57 m. Weathering / fracturing was logged in 12 boreholes and ranged from 12 to 72 m.

6.2.16 Subdivision 16

Subdivision 16 (Figure 3 at back of report) comprises the upper part of the Koa catchment that is underlain by rocks belonging to the T'Caimoeps Laagte / Kamies berg Fragment. Except for the valley of the Koa and a few low hills, the area is featureless with elevations ranging from about 1070 along its boundary to 850 m.a.m.s.l where the Koa enters Subdivision 14.

In addition to rocks of the Namaqua Metamorphic Province outliers of Dwyka shale and tillite and dolerite are present notably in the southeast of the Subdivision. Dolerite apparently in the form of a sheet-like body or bodies occurs on Kyngnyps Bult 2, Gif Kop 166 and Kaps Vlei 174

Drillers have also reported sandstone in a number of boreholes. Where the sandstone overlies rock described as quartzite it is taken to represent the semi-disintegrated product of the latter. Some sandstone has also been found intercalated with Dwyka shale. Sandstone 20 to 70 metres thick and directly overlying granite has been encountered in boreholes in two areas:

A. In the southeast.
B. South of the Vaalputs radioactive waste repository

Details of these occurrences are given in Table 47.

The lateral extent and stratigraphic position of sandstone in area A is obscure. That found in boreholes on Burtons Puts 408, Bok se Puts 380 and Skimmelkoppies 377 belongs undoubtedly to the so-called Dasdaap Formation (McCarthy, Moon and Levin1985; Brandt, Andreoli and McCarthy 2003). Note that Skimmelkoppies 377 lies in Subdivision 18a.

TABLE 47 OCCURRENCES OF SANDSTONE SUBDIVISION 16

Area	Farm name and No	Borehole ID No (NGWDB)	Driller's log lmns = limestone; snds = sandstone; grnt = granite	Water struck at (m)	Water level (m)	Yield ℓs^{-1}
A	Galputs 104	2918DB00031	0 – 0.9 lmns; 0.9 – 11 snds;	-	-	-
	Bitterputs 111	2918DD00045	0 – 21 snds; 21 – 46 grnt	26	7	0.24
	Bitterputs 110	2919CA00017	0 – 11 lmns; 11 – 24.1 snds; 24.1 – 38.1 grnt	21.3	15.2	1.26
	Bitterputs 107	2919CA00027	0 – 22.9 snds; 22.9 – 96.3 grnt	-	=	-
	Tweeling 168	2919CC00060	0 – 13.7 snds; 13.7 – 149.1 grnt	-	-	-
	Tweeling 168	2919CC00061	0 – 12.2 snds; 12.2 – 139.9 grnt	-	-=	=
	Tweeling168	2919CC00063	0 – 20.7 snds; 20.7 – 81.7 grnt	=	=	=
B	Bok se Puts 380	018BA 00089	0 – 42 snds	-	-	-
	Burtons Puts 408	3018BC00065	0 – 51.8 snds	-	-	-
	Burtons Puts 408	3018BC00079	0 - 38.1 snds	10.36	6.1	0.06
	Burtons Puts 408	3018BC00081	0 – 70.1 snds	54.9	14.6	0.66
	Skimmelkoppies 377	3018BC00135	0 = 65.9 snds	36.6	36.6	0.08
	Skimmelkoppies 377	3018BC00136	0 – 42.7 snds			
	Skimmelkoppies 377	3018BC00137	0 – 46.9 snds			
	Skimmelkoppies 377	3018BC00138	0 – 16.5 snds; 16.5 – 83.5 grnt	70.7	48.8	0.3

Extensive tracts of the Subdivision have a covering of a few metres of sand or calcrete. In addition overburden from 20 to over 100 m thick has been encountered in some 70 boreholes. In drillers' logs the overburden has been described as soil, alluvium, limestone, dolomite, sand, clay, sand and clay, boulders and gravel and combinations thereof. Some of the thinner clay deposits may be residual weathered Dwyka shale. This however is not considered to apply to deposits thicker than 20 m. For example 60 metres of clay was found in a borehole on the Varsputs portion of Bitterputs 107 and 100 metres was encountered in a borehole on Bok se Puts 380.

Drilling has proved that diatremes (see section 2.6 Kimberlite and related rocks) have been filled-up with sediments to depths of as much as 250 metres (pipe on Koppies Kraal 246). According to Cornelissen and Verwoerd (1975) the filled-up pipes are important from the groundwater point of view as the sediments have been found to be water-bearing. They mention that during an intensive diamond prospecting campaign (1961/66) at least 151 pipe-like features were drilled on. Whether and to what extent the prospecting results have been made use of for developing water supplies is not known.

Whether some of the NGWDB boreholes with thick overburden were drilled in diatremes can not be established as their positions are only known by farm name and number. Some may well have been sunk in circular depressions. Others may possibly be associated with largely defunct sand-drowned drainage lines e.g. that on Klein Koumis 113 and Dirk se Kop 597; another on Lekker Drink 245 (Borehole 3018BA00076 - 54 m of alluvium), the Varsputs portion of Bitterputs107 mentioned above and one stretching from Kouberg (portion of Koeris 78) - Tweeling 79 - Dikbek 81 - Spioenkop 97 - Hunites 64 to Zuur Water 62 (see Subdivision 14).

A sample of logs of water-bearing and "dry" overburden boreholes is presented in Table 48.

TABLE 48 WATER-BEARING AND "DRY" OVERBURDEN BOREHOLES

Farm Name	No	Borehole No	Driller's log (m)	Strike Depth (m)	Water Level (m)	Yield ℓs^{-1}
#Spioenkop	97	2918BC00003	0 – 62.5 snds; 62.5 – 116.1 clay; 116.1 – 123 lmns	116.1	65.8	0.12
#Spioenkop	97	2918BC00005	0 – 20.7 sand; 20.7 - 123.1 clay	117.7	76.2	0.44
#Dikbek	80	2919DA00055	0 – 75 soil; 75 – 137 grnt	80	20	0.33
#Koumis	598	2918DB00006	0 - 10.7 lmns; 10.7 - 56.4 clay; 56.4 – 64 qrtz	51.8	37.5	1.05
#Varsputs	107	2919CA00033	0 – 60 clay; 60 – 62 vnqz; 62 – 70 grnt	60	56	0.1
#Lekkerdrink	245	3018BA00076	0 – 1 chlk; 1 – 54 alvm; 54 – 70 qrtz; 70 – 77 grnt	56	33	0.15
#Plat Bakkies	388	3018BA00130	0 – 80.2 lmns; 80.2 – 127.1 grnt	85.3	71	0.05
#Vermeulensrus	237	2918DD00011	0 – 32 lmns; 32 - 71.9 grnt	40.2	21.3	0.11
#Bosluis	238	2918DD00036	0 – 30 alvm; 30 – 180 grnt	7	2	1.25
#Banke	409	3018BC00039	0 - 20.1 clay; 20.1 – 33.5 grnt	19.8	11	0.42
#Burtons Puts	408	3018BC00077	0 – 12.1 alvm; 12.1 - 33.5 grvl; 33.5 - 73.5 grnt	73.5?	12.5	2.08
#Burtons Puts	408	3016BC00084	0 – 20 alvm; 20 – 50 qrtz; 50 – 70 grnt	42	12.8	0.21
Loerduin	1	2919CB00079	0 - 83.8 lmns; 83.8 – 97.5 qrtz	-	-	-
Bok Puts	380	3018BA00099	0 – 60 clay	-	-	-
Bok Puts	380	3018BA00108	0 – 100 clay; 100 – 115 grnt	-	-	-
Bok Puts	380	3018BA00120	0 – 58 alvm; 58 – 65 grnt	-	-	

Note: # = Saturated overburden
alvm = alluvium; grnt = granite; lmns = limestone; qrtz = quartzite; snds = sandstone; vnqz = vein quartz

At this stage it is unknown how all of the deposits found in the NGWDB boreholes are to be related to those described.

- On Banke 409 and along the Dasdaap drainage on the Kalkdraai portion of Burtons Puts 408 (McCarthy, Moon and Levin 1985; Brandt, Andreoli and McCarthy 2003).
- On Vaalputs 369 (McCarthy, Moon and Levin1985; Brandt, Andreoli and McCarthy 2003).
- In the Koa valley at Bosluis pan (De Wit 1983 and 1999).
- As crater-lake deposits (Cornelissen and Verwoerd 1975; Scholtz 1985).

The early Tertiary land surface seems to have been much more dissected and rugged than is evident today. In this connection it is important to note that the configuration of the piezometric surface is determined by bedrock topography (see sections 5.1 and 6.2.14).

The NGWDB contains records of 828 boreholes of which 238 (28.7%) yielded ≥ 0.1 ℓs^{-1}.

TABLE 49 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 16

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	128	53.8
0.5 – 0.99	50	21.0
1.0 – 4.9	55	23.1
5.0 – 9.9	5	2.1
≥ 10	0	0

TABLE 50 RELATION BETWEEN WATER LEVEL AND YIELD SUBDIVISION 16

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 - 10	19	0.91
10 - 20	28	0.80
20 – 30	35	0.83
30 – 40	48	0.52
40 – 50	44	0.80
50 – 70	37	1.05
70 – 151	26	0.89

FIGURE 22a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 16

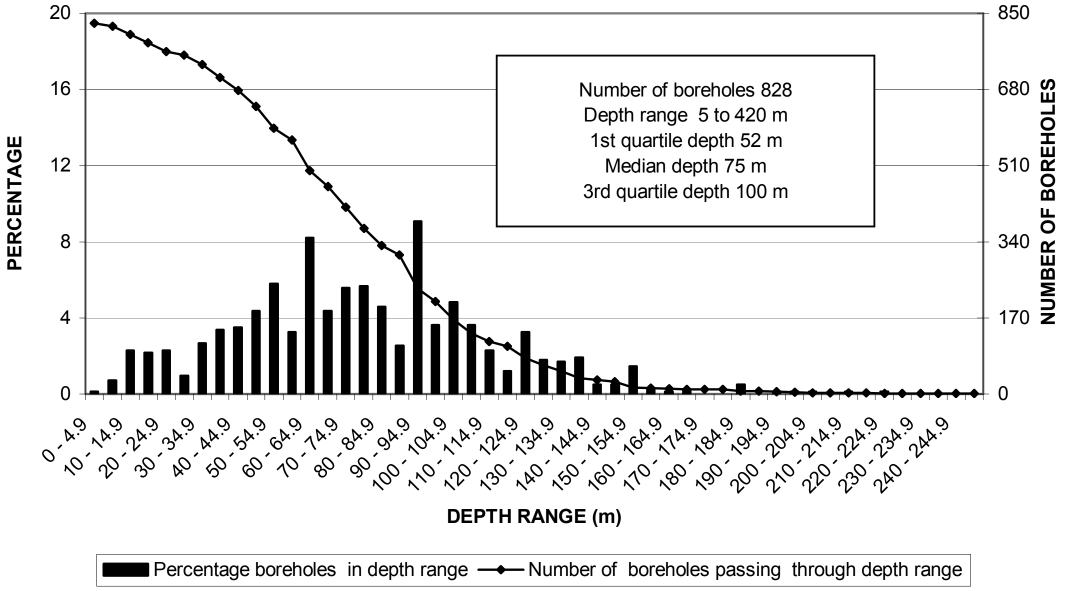


FIGURE 22b DISTRIBUTION OF WATER LEVELS SUBDIVISION 16

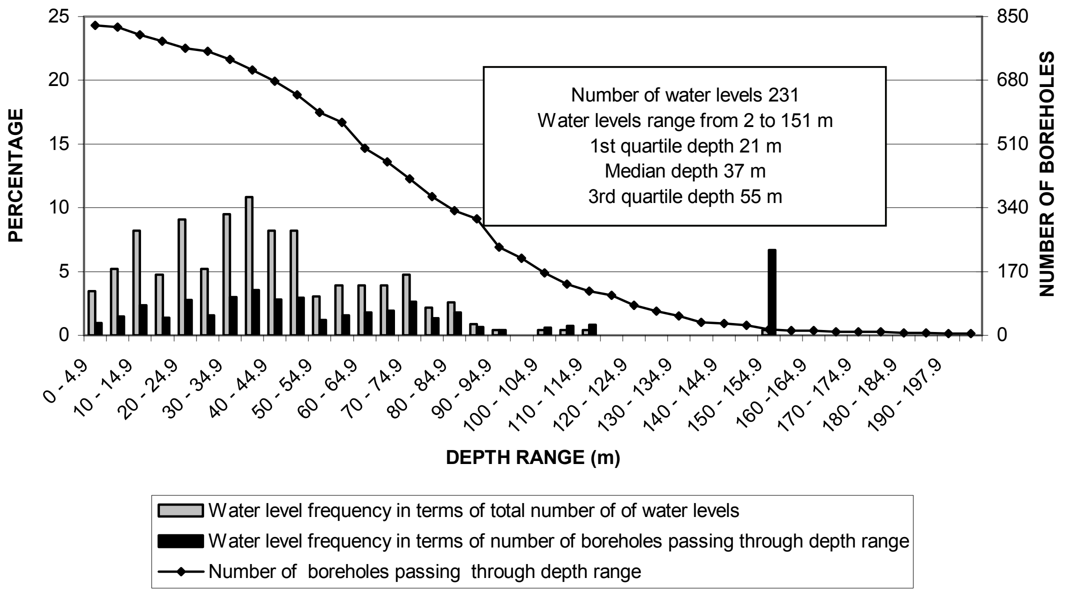


FIGURE 22c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 16

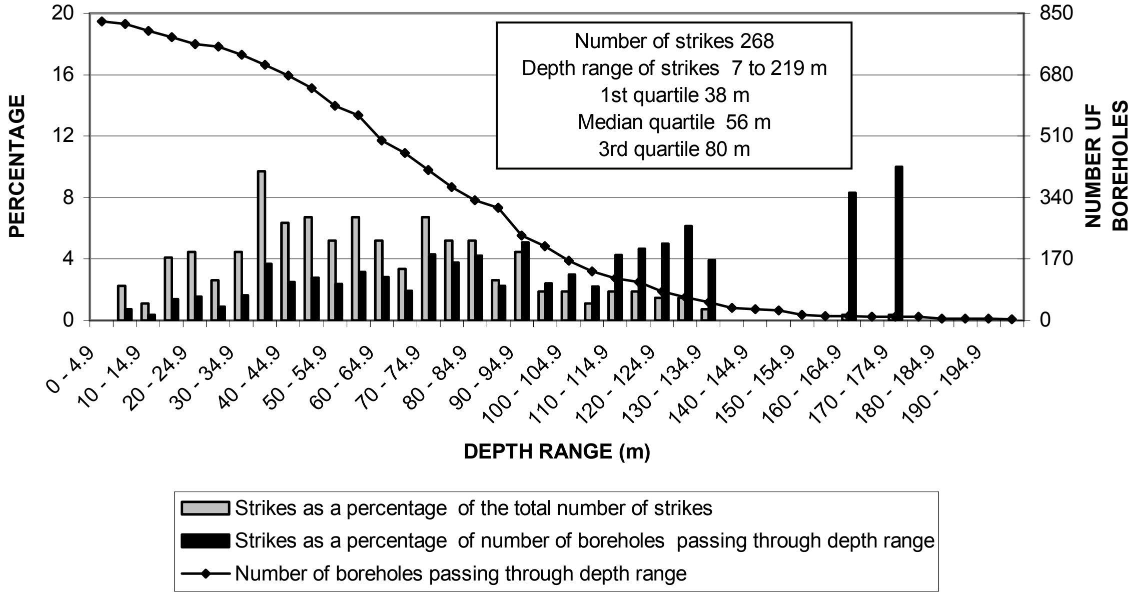


FIGURE 22d STRIKE FRQUENCY BELOW WATER LEVEL SUBDIVISION 18

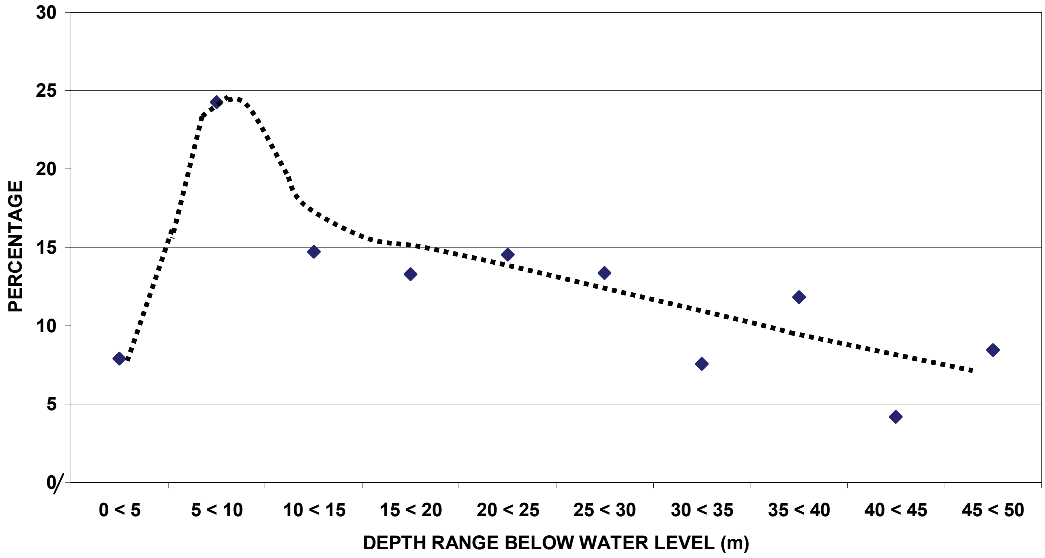
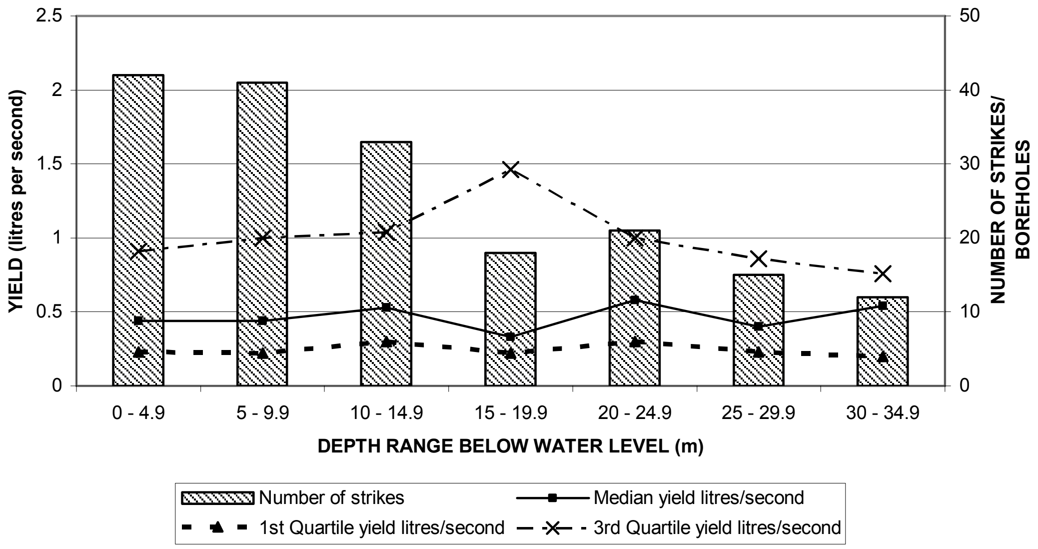


FIGURE 22e BOREHOLE YIELD VERSUS STRIKE DEPTH BELOW WATER LEVEL SUBDIVISION 16



Dwyka and dolerite outliers and occurrence of groundwater

Of the 52 boreholes drilled into Dwyka outliers and dolerite 21 i.e. 40.4% proved successful: Water levels ranged from 10 to 95 m. Yields ranged from 0.1 and 2.7 ℓs^{-1}. Six stratigraphic situations have been recognized. Results are summarized in Table 51.

TABLE 51 WATER STRIKES AND WATER LEVELS DWYKA OUTLIERS SUBDIVISION 16

Stratigraphy	Number of boreholes	Strikes ≥ 0.1 ℓs^{-1} Number and formation	Water level Number and formation
Shale / tillite only	3	1 x Ds	1 x Ds
Shale / tillite and Namaqua basement	35	1 x Ds &16 x Nb	1 x DS &16 x Nb
Dolerite only	5	1 x dol	1 x dol
Dolerite and Namaqua basement	3	1 x Nb	1 x Nb
Shale / tillite and dolerite	4	2 x dol	1 x dol
Shale / tillite, dolerite and N - basement	2	0	0
Total	52	21	20

Ds = Dwyka shale/tillite; Nb = Namaqua basement; dol = dolerite. Dolerite under- / overlies Dwyka shale / tillite

The 21 successful holes are distributed as follows:

- Of the 35 holes drilled through Dwyka shale / tillite into Namaqua basement 16 struck supplies at depths varying between 9 and 131 metres below the Dwyka base. Water was struck in shale in one borehole only - 0.3 m above Dwyka base. With the exception of the latter all water levels lie from 1 to 89 m below Dwyka base.
- In 2 boreholes only (including the one mentioned above) water was struck in shale at depths of 39.3 and 32 m below surface. The shale / tillite cover (devoid of dolerite) exceeds 25 m in less than one out of five boreholes. The limited thickness of the Dwyka sedimentary rocks tells against them acting as aquifers. It should however be

noted that no water was found in 6 boreholes in which the thickness of Dwyka strata ranged from 30 to 84 metres.

- Water was struck at 107.7 m in one of five boreholes drilled solely into dolerite (water level 48.8 m).
- Of the 6 boreholes sunk through alternations of shale and dolerite to depths varying from 41 to 373 m only one yielded water. Two of the boreholes were sunk into basement. Shale – dolerite contacts were penetrated at depths of 17.4, 33.8, 26.2, 34.8, 47, 60.9 and 84.7 m and dolerite-shale contacts at 24.1, 30, 37.2, 39.6 and 89.9 m below surface. None of these contacts yielded any water. In the successful borehole water was struck in dolerite at 38.1 m i.e. 3.3 m below a shale-dolerite contact.
- Sufficient data are lacking about the role of weathering / fracturing in transforming Dwyka shale / tillite into a water-bearing formation.

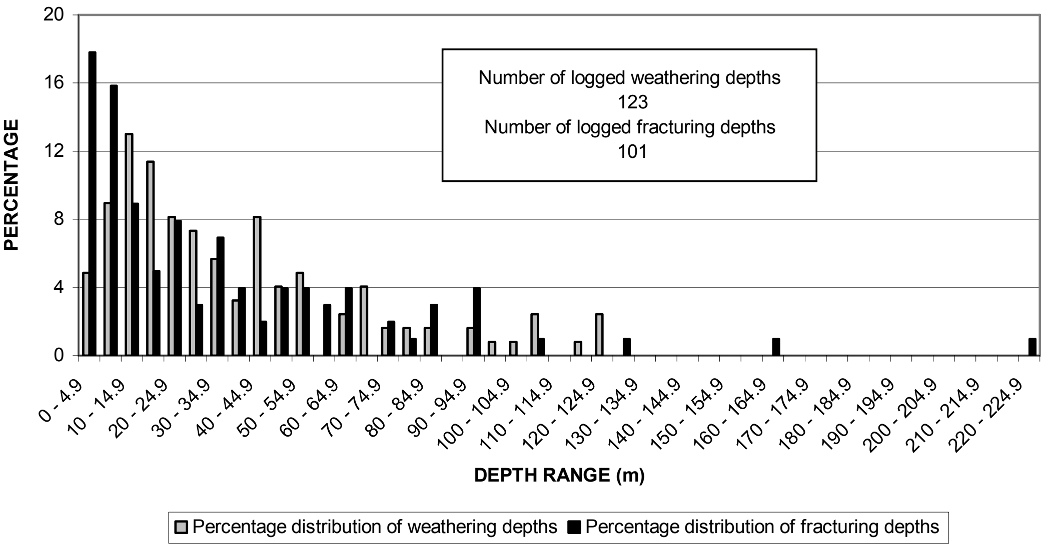
In Table 52 data of the forty boreholes that ended in basement are compared with data of all boreholes on the relevant farms and of the Subdivision as a whole.

TABLE 52 DWYKA / DOLERITE COVER PLUS BASEMENT VERSUS BASEMENT ONLY SUBDIVISION 16

	Boreholes through cover of Dwyka strata and / or dolerite			All boreholes on farms with Dwyka and dolerite outliers		Subdivision 16 as a whole	
	Depth to Namaqua basement (m)	Strike depth below surface (m)	Water level (m)	Strike depth below surface (m)	Water level (m)	Strike depth below surface (m)	Water level (m)
Range	2 - 61	18 – 137	10 – 95	15 – 137	5 – 95	7 – 209	2 – 151
1st Quartile	9	32	15	38	24	38	21
Median	12	48	22	53	32	56	37
3rd Quartile	22	59	37	74	47	80	55

Strike depths and water levels are shallower in the presence of Dwyka outliers and dolerite.

FIGURE 22f DISTRIBUTION OF DEPTHS OF WEATHERING AND DEPTHS OF FRACTURING SUBDIVISION 16



Role of weathering and fracturing in the occurrence of groundwater

Out of a total of 826 boreholes weathering and fracturing were reported in the logs of respectively 123 and 101 boreholes. The terms “fracturing” and “fractured” also covers formation described by the driller as jointed or broken. The relation between weathering / fracturing and the striking of groundwater is summarized in Table 53.

TABLE 53 WEATHERING / FRACTURING AND STRIKING OF GROUNDWATER SUBDIVISION 16

Type			Boreholes with	
			weathered sections	fractured sections
	Total number of boreholes		123	101
A	Water strikes < depths of weathering or fracturing	No of holes yielding ≥ 0.1 ℓs^{-1}	11	18
		Depth range of w / f (m)	24 – 90	12 – 230
		Water level range (m)	4.8 – 56	4 – 151
B	Water strikes > depths of weathering or fracturing	No of holes yielding ≥ 0.1 ℓs^{-1}	27	10
		Depth range of w / f (m)	5 – 80	2 – 30
		Water level range (m)	4 – 80	5 – 64
C	No water strikes and strikes < 0.1 ℓs^{-1}	No unsuccessful boreholes	85	73
		Depth range of w / f (m)	3 - 122	1 – 91
A + B	Depths of weathering or fracturing (m): Boreholes A and B	Range	5 – 90	2 – 220
		1st Quartile	16	9
		Median	32	52
		3rd Quartile	48	77
	Yield Boreholes A and B	No of holes; yielding ≥ 0.1 ℓs^{-1}	38 (30.9%)	28 (27.7%)
		Range	0.1 – 9.22	0.12 – 2.4
		1st Quartile	0.23	0.25
		Median	0.32	0.5
		3rd quartile	0.51	1

Additional remarks follow:

- Of the 11 successful boreholes with water strikes shallower than depth of weathering 10 struck water within 10 to 0 metres above the base of weathering. In the remaining borehole water was struck 51.1 m above the base of weathering at 76.5 m.
- Of the 18 successful boreholes with water strikes shallower than depth of fracturing 15 struck water within 15 to 10 metres above the base of fracturing. In the remaining 3 holes water was struck between 47 and 67 m above the base of fracturing.
- Of the 27 successful boreholes with water strikes deeper than depth of weathering 5 struck water within 10 to 0 metres below the base of weathering, 8 within 10 to 20 metres and 14 more than 20 metres below the base of weathering.
- Of the 10 successful boreholes with water strikes deeper than depth of fracturing 2 struck water within 0 to 10 metres below base of fracturing, 3 within 10 and 17 m and 5 between 30 to 92 m below the base of fracturing.

6.2.17 Subdivision 17

The Subdivision straddles the Orange River east of Upington. The greater part lies north of the river. A fault–bounded narrow wedge is situated in the south. As can be seen on geological sheet 2820 Upington the area north of the river is sand-covered with scattered outcrops of the underlying Koras Group rocks. Table 3 (Chapter 2) has to be consulted for the hard-rock lithology. The NGWDB contains records of 69 boreholes of which 29 yielded ≥ 0.1 ℓs^{-1} (42% successful).

TABLE 54 SUMMARY OF BOREHOLE DATA SUBDIVISION 17

	69 Borehole depths (m)	32 Strike depths (m)	31 Water levels (m)	29 Yields (ℓs^{-1})
Range	22 – 217	12 – 112	4 – 91	0.15 – 3.2
1st Quartile	50	34	18	0.26
Median	91	48	36	0.58
3rd Quartile	107	82	56	0.90

TABLE 55 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 17

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	13	44.8
0.5 – 0.99	11	37.9
1.0 – 4.9	5	17.2
5.0 – 9.9	0	0
≥ 10	0	0

As may be deduced from Table 56 groundwater has been struck under varied geological conditions. The sedimentary rocks have no primary porosity. Although some water strikes have been made on or near formation contacts the majority of strikes can not be related to logged features. Striking water in Koras rocks appears to be a game of chance.

TABLE 56 FORMATIONS DRILLED AND RESULTS SUBDIVISION 17

Formation according to driller's log exclusive of overburden	Number of boreholes	Number of boreholes yielding ≥ 0.1 ℓs^{-1}	Depths water was struck (m)	Water levels (m)	Remarks
Shale	9	4	20, 24, 40, 81	18, 18, 32, 63	Dry boreholes drilled in shale to depths to 29 m (underlain by schist to 107 m), 37, 46, 85 and 132 m (last fractured all the way)
Sandstone	4	3	80, 57, 31	36, 57, 28	Dry borehole drilled to 152,4 m in sandstone-
Quartzite	6	1	66	24	Successful borehole passed through 0 - 40 m broken quartzite. Five duds drilled to 65, 77,103, 104 and 137 m in quartzite.
Siltstone	1	1	38	9	Struck water 2 m above bottom contact of intercalated schist band
Sandstone and quartzite	5	1	70	59	Struck water 1 m above sandstone-quartzite contact. Sandstone-quartzite contact at 5, 23.8, 25.9 and 63,1 m above water level ?

TABLE 56 FORMATIONS DRILLED AND RESULTS SUBDIVISION 17 (continued)

Formation according to driller's log exclusive of overburden	Number of boreholes	Number of boreholes yielding ≥ 0.1 ℓs^{-1}	Depths water was struck (m)	Water levels (m)	Remarks
Dolerite	3	0	-	-	46 m of weathering too shallow?
Lava	4	2	45, 103.6	39, 91.4	Dry holes drilled 46 and 117.4 m in lava
Granite	10	5	12, 16.5, 34, 29, 51	4.0, 7.3, 24, 18, 24	Note shallow water levels. With exception of water strike at 12 m on contact between surface limestone and granite all strikes in solid or unspecified granite
Shale on granite	4	3	18, 85.3, 42	12, 85.3, 40	Shale-granite contact at 18, 48.8, 37m
Quartzite on granite	1	1	34	19	Quartzite –granite contact at 30 m both quartzite and granite fractured to 49 m
Lava on granite	2	0	-	-	Thickness of lava 7.3 and 8.2 m-
Vein quartz	8	5	83.4, 98, 103, 42.6, 93	43, 59, 36, 7, 7	First 3 boreholes struck water in vein quartz; last two in shale 18.5 and 21.6 m below vein quartz. Note depths drilled below water level before striking water. Dry boreholes: a)105 m in vein quartz b)veinquartz 51 -54 and 66-69 m in diabase c) 27 -32 m in diabase
Intercalated shale, sandstone and diabase	8	1	38.5	33.5	Struck water on sandstone-diabase contact. In 6 dud boreholes shale, quartzite, sandstone and diabase contacts were penetrated 21 times at depths varying from 19 to 108 m. .
Intercalated shale, sandstone and lava	4	2	61, 115.8	54.8, 38.1	1st borehole lava band from 38.4 to 124.7 m 2nd borehole lava 91- 122 m. No strikes in overlying layers shale, sandstone and lava
Total	69	29			

6.2.18 Subdivision 18

Subdivision 18 stretches along the Region's southern boundary. It consists of two parts:

a) An isolated area of internal drainage in the far west straddling the water divides between the Krom River and the Koa Valley.
b) A strip stretching from about 19^o 30' longitude to Omdraaisvlei in the east.

The lithology comprises:

- Mokolian metamorphites and intrusives belonging from west to east to the Kamiesberg / T'Caimoeps Laagte, Haakjes Doorn Kolk, De Kruis, Hartbees River and Groblershoop Fragments. Consult Tables 1, 2a, b, c (Chapter 2).
- Outliers of Dwyka clast-rich sandy diamictite, clast-poor clayey diamictite, sandstone, mudstone, and dolomitic limestone. Consult Table 4 (Chapter 2)
- Dolerite in the form of sheets. According to Slabbert *et al* (1999) dykes are absent in the Dwyka strata of geological sheet Kenhardt 2920.

Data on 474 boreholes were abstracted from the NGWDB; 152 yielded ≥ 0.1 ℓs^{-1} (32.1% success).

TABLE 57 DISTRIBUTION OF BOREHOLE YIELDS SUBDIVISION 18

Yield ℓs^{-1}	Number of boreholes	Percentage of boreholes
0.1 – 0.49	68	44.7
0.5 – 0.99	25	16.4
1.0 – 4.9	48	31.6
5 – 9.9	9	5.9
≥ 10.0	2	1.3

FIGURE 23a DISTRIBUTION OF BOREHOLE DEPTHS SUBDIVISION 18

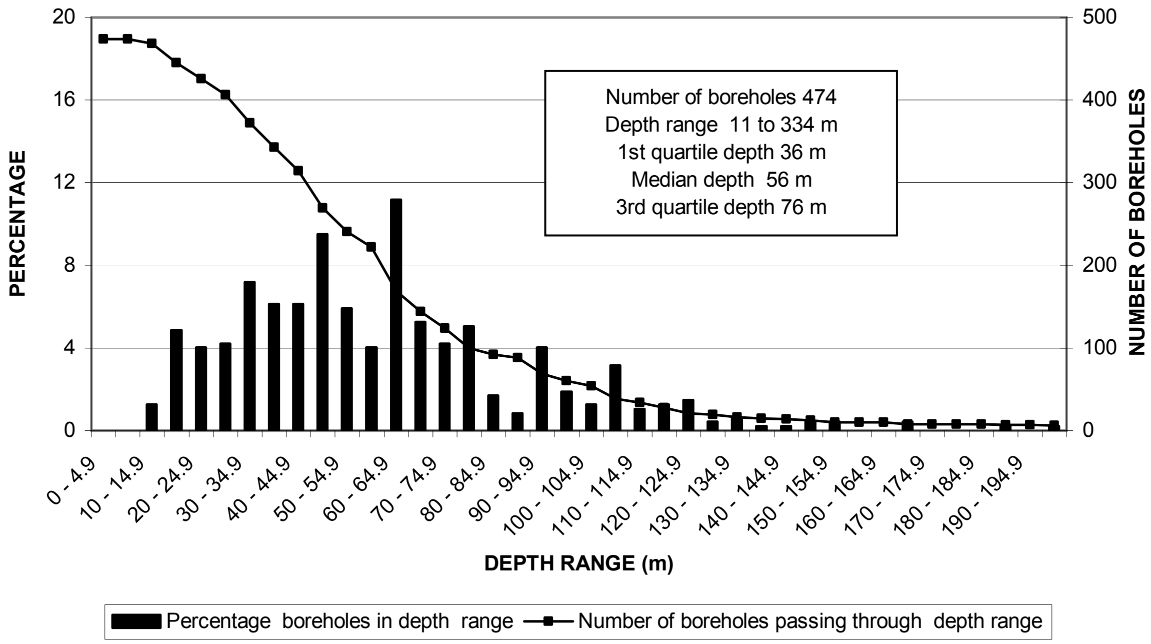


TABLE 58 WATER LEVELS AND YIELDS SUBDIVISION 18

Water level (m)	Number of boreholes	Mean yield ℓs^{-1}
0 – 10	42	1.81
10 – 20	34	1.71
20 – 30	24	0.79
30 – 40	29	0.94
40 – 50	15	1.17
50 – 80	5	1.08
70 – 151	26	0.89

FIGURE 23b DISTRIBUTION OF WATER LEVELS SUBDIVISION 18

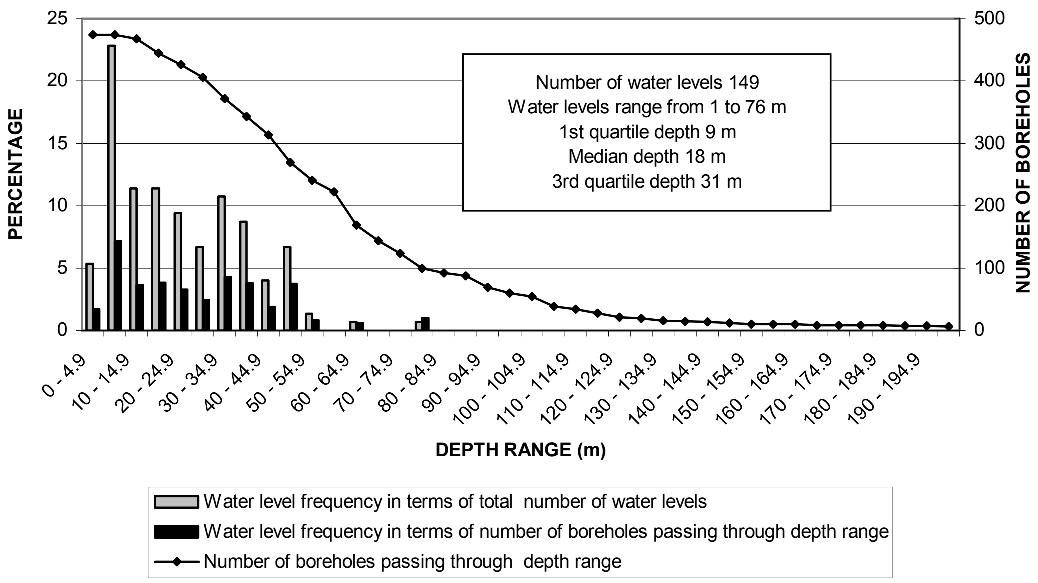
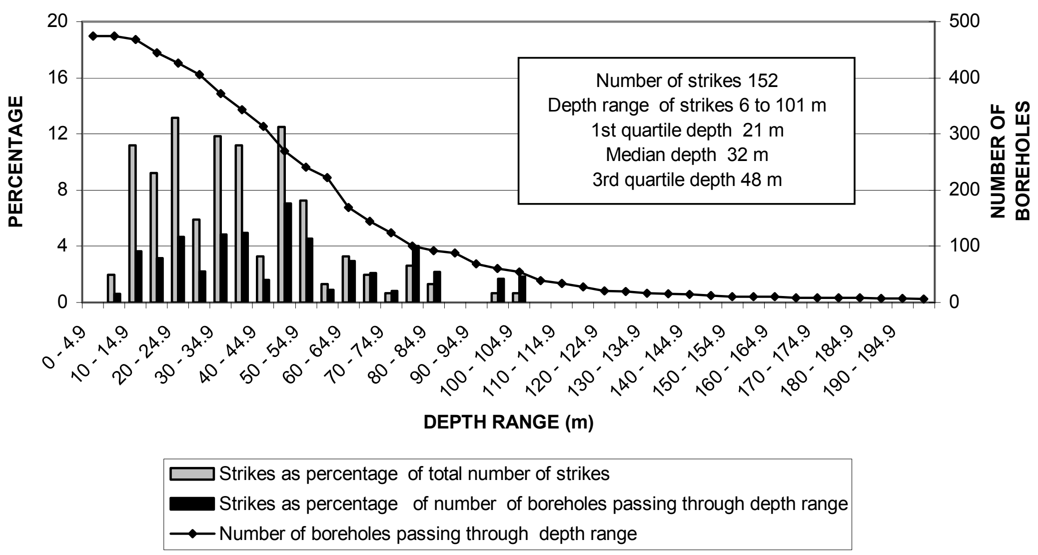


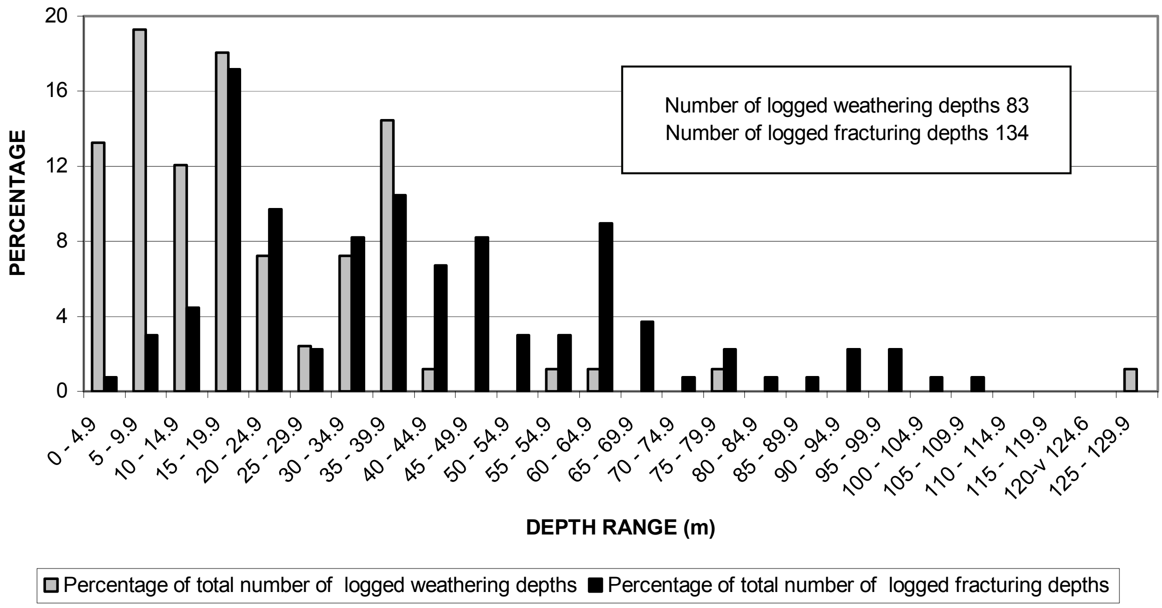
FIGURE 23c DISTRIBUTION OF STRIKES BELOW SURFACE SUBDIVISION 18



Groundwater conditions in Subdivision 18 compare favourably with most of the other subdivisions. Amongst other, water levels are shallowest (see Table 61b). Parts of the Subdivision with the deeper water levels are the area west of the Koa and the so-called “Kaiing Bult” or Hedley Plains southeast of Kenhardt where surface drainage is from Namaqua Basement outcrop towards the Dwyka cover. Shallow water levels are found east-south-eastwards from the upper catchment of the Sout River to the Sak-Hartbees River valley i.e. where surface drainage is directed from Dwyka strata towards Namaqua Basement outcrop and in the Subdivision’s southeastern extremity.

Weathering and fracturing

FIGURE 23d DISTRIBUTION OF LOGGED DEPTHS OF WEATHERING AND FRACTURING SUBDIVISION 18



Weathered Dwyka strata, dolerite and Namaqua basement were reported in 83 boreholes. Depths of weathering ranged from 1 to 59 m. Yields ≥ 0.1 ℓs^{-1} were struck in 23 boreholes (27.7% success). Water was struck in 4 boreholes within 2 m above and below the base of weathering. In 15 of the successful boreholes strike depths ranged from 3 to 73 m below base and in 5 boreholes from 5 to 12 m above base of weathering. The failure of 60 boreholes can be ascribed largely to shallow depths of weathering, 75% of the weathering depths were less than 30 metres.

Fractured / broken / jointed Dwyka strata, dolerite and Namaqua Basement were reported in 134 boreholes. Yields ≥ 0.1 ℓs^{-1} were struck in 57 boreholes (42.5% success). Depths of fracturing etc. in the successful boreholes ranged from 3 to 96 m. Water was struck in 2 holes at and within 1.5 m of the base of fracturing. In 14 boreholes strike depths ranged from 1.8 to 45.7 m below base. Strikes from 3 to 49.7 m shallower than base were reported in 41 boreholes.

No weathering / fracturing was recorded in the Subdivision's remaining 264 boreholes. Seventy-two boreholes (27.3%) yielded ≥ 0.1 ℓs^{-1}.

Dwyka outliers and dolerite

To create the largest possible data base on Dwyka outliers, data of Subdivision 16 have been included; giving a total of 197 boreholes. One hundred and sixteen boreholes penetrated Dwyka sedimentary rocks and or dolerite and ended in Namaqua basement. Basement depths below surface ranged from 1.5 to 373 m. The 1st quartile, median and 3rd quartile depths are 12, 20 and 33 m. Boreholes were classified as follows:

Set 1 Commenced and completed in Dwyka sedimentary rocks.
Set 2 Commenced in and sunk through Dwyka sedimentary rocks into Namaqua Basement.
Set 3 Sunk through a succession of Dwyka sedimentary rocks and dolerite. Boreholes commence in either sedimentary rocks or dolerite and may pass through several repetitions of dolerite and sedimentary rocks ending in either or in Namaqua basement.
Set 4 Commenced in and sunk through dolerite into Namaqua basement.
Set 5 Commenced and completed in dolerite.
Set 6 Dwyka rocks and dolerite absent.

The following 2 Tables are based on records of 96, 49 and 52 boreholes drilled into or through Dwyka sedimentary rocks and dolerite in Subdivisions 18a, 18b and 16, respectively.

TABLE 59. OUTLIER GEOLOGY, DRILLING SUCCESS AND YIELD

Set	Number of boreholes	Number of boreholes yielding ≥ 0.1 ℓs^{-1}	Percentage success	Yield ℓs^{-1}			
				Range	1st Quartile	Median	3rd Quartile
1	50	19	38	0.11 – 9	0.23	0.73	1.46
2	98	36	36.7	0.1 – 5	0.15	0.26	0.75
3	29	13	44.8	0.23 – 3.4	0.39	0.69	1.3
4	9	1	11.1	-	-	-	-
5	11	4	36.4	0.39 - 2.7	-	-	-
Total [1)]	197	73	37.0				
6 [2)]	329	130	39.5	0.1 - 12	0.3	0.7	2

[1)] Dwyka and dolerite outliers Subdivision 18 a & b and 16
[2)] Boreholes in Namaqua basement Subdivision 18 a & b only

As far as success rate goes there is little to choose between drilling into Dwyka outliers or directly into Namaqua basement.

TABLE 60 OUTLIER STRIKE AND WATER LEVEL STATISTICS SUBDIVISION 18

Set	Number of holes yielding ≥ 0.1ℓs^{-1}	Strike depth (m)				Water level (m)			
		Range	1st Quartile	Median	3rd Quartile	Range	1st Quartile	Median	3rd Quartile
1	19	11 – 40	14	25	34	5 – 36	8	15	20
2	36	18 – 137	36	47	60	5 – 95	19	27	37
3	13	12 – 74	23	52	57	6 – 51	11	20	26
4	1	-	-	-	-	-	-	-	-
5	4	30 – 107	-	-	-	6 – 49	-	-	-
6	130	6 - 172	24	36	52	1 - 100	10	23	37

Set 1 Water level and strike depths in Dwyka shale / tillite are generally shallower than in the rest of Subdivision 18a and b. Unsuccessful boreholes in shale / tillite are generally deeper than the successful ones. Depths of unsuccessful boreholes range from 24 to 126 m: Water-bearing fractures are found mostly, though not exclusively in the upper 40 m or so of shale / tillite. That non-yielding impermeable fractures exist is evident from a number of instances where zero-yield water strikes have been reported.

Set 2 The thickness of Dwyka sedimentary rocks in 96 boreholes varies from 1.5 to 114 m: 1st quartile 12 m, median 19.9 m and 3rd quartile 30 m. These values closely match those of the water levels in Subdivision 18a and b. Strikes and water levels in 36 successful boreholes are distributed as follows:

Water strikes in shale/ tillite:	In 2 boreholes respectively 2 and 0.3 m above and in a third on the Dwyka-Basement contact
Water strikes in basement	In 33 boreholes at depths ranging from 2 to 20 metres below Dwyka base
Water levels in shale / tillite	In 10 boreholes
Water levels in basement	In 26 boreholes

In 7 of the 10 boreholes with shallower water levels than the Dwyka-base water was struck between 2.9 and 20 m below the Dwyka-base compared to two instances where the Dwyka-basement zone yielded water. The Dwyka-Basement contact (below the piezometric level) is evidently not *ipso facto* water-bearing.

Set 3 The relationship between water levels and strike depths on the one hand and contacts between Dwyka sedimentary rocks, dolerite and Namaqua basement on the other is as follows:

- Dolerite-Namaqua Basement was penetrated by two boreholes. In one borehole water was struck on the contact and in the other 8.8 m below the contact. The water level stands above the contact.
- Shale-Basement was penetrated only once. Water was struck on the contact
- No successful strikes were made on six shale-dolerite and three dolerite-shale contacts (contacts above the water level disregarded)
- Water was struck in either shale or dolerite from 2 to 20 m below the contacts - water levels stand above the contact.

Set 4 The thickness of dolerite directly overlying Basement ranges between 5 and 16 m in 7 of the 9 boreholes. In two boreholes 33 and 35.1 m of dolerite was encountered. Water was struck in one borehole only, namely in Basement under a cover of 4.9 m dolerite at a depth of 29.9 m. The rest of the boreholes were drilled without success into Basement to depths varying from 40 to 131 m.

Set 5 Records are available of 11 boreholes that were drilled in dolerite to depths varying between 18 and 134 m. Four yielded water. On Uitzigt 69 and Jonkerwater 131 in the Prieska District water was struck in two boreholes in fractured / jointed dolerite. In a third borehole on Welgevonden 97 water was struck in fractured and calcified dolerite. In the far west on Gifkop 166 Calvinia District, water was struck in apparently fresh dolerite at a depth of 106.7 m. Water rose to 48.8 m.

Set 6 Weathered / jointed / fractured or broken formation was reported in some 70 boreholes out of the 329 that were sunk in Namaqua Basement without a covering of Dwyka sedimentary rocks and / or dolerite. In 38 holes the weathered, jointed or fractured section extended deep enough for at least 0.1 ℓs^{-1} to be struck either within it or within a metre or two of its base. A small number of boreholes however failed to yield usable supplies despite deep enough weathering / fracturing. The reason appears to be a lack of permeability. Driller's logs of the remaining 92 successful boreholes provide no information about the condition of the rock where water was struck. Water was apparently struck in a single fracture or joint in fresh rock.

The Dwyka ice sheet has apparently removed any pre-existing near-surface layer of weathered and fractured Basement rocks. Under such conditions the chances of striking water in Basement rocks are considered better where the Dwyka cover is relatively thin and patch-like than under an uninterrupted thick cover. Where this is the case the aim should be to develop supplies in Dwyka sedimentary rocks. Whether electrical resistivity depth probing is capable of distinguishing between permeable water-bearing and impermeable Dwyka shale / tillite is questionable.

6.3 SUMMARY

Data presented in the preceding sections are summarized below.

TABLE 61a SUMMARY OF DRILLING SUCCESS RATE AND YIELD

Sub-division	Number of boreholes	Percentage successful	Yield ℓs^{-1} (successful boreholes only i.e. ≥ 0.1 ℓs^{-1})			
			Range	1st Quartile	Median	3rd Quartile
1	13	38.5	0.57 - 2	-	-	-
2	70	51.4	0.11 - 10	0.39	0.64	1.5
3	89	51.7	0.1 – 6.1	0.27	0.64	2.1
4	619	38.4	0.1 - 10	0.25	0.64	1.71
5	332	37.3	0.1 – 3.2	0.2	0.5	0.88
6	415	34.1	0.1 -7.2	0.22	0.5	1.84
7	151	26.5	0.1 – 6.4	0.19	0.38	0.84
8	249	24.5	0.11 – 9.7	0.2	0.4	0.98
9	393	25.4	0.1 – 5.1	0.25	0.46	1.13
10	398	15.8	0.1 – 3.6	0.28	0.46	0.81
11	308	20.1	0.1 – 6.7	0.29	0.47	0.96
12	115	35.7	0.1 – 11.3	0.15	0.43	0.85
13	25	40	0.1 - 5	-	-	-
14	391	21.7	0.12 – 12.6	0.29	0.5	1.0
15	37	48.6	0.2 – 2.3	0.39	0.76	1.3
16	828	28.7	0.1 – 9.2	0.2	0.44	1
17	69	42.0	0.15 – 3.2	0.26	0.58	0.9
18	474	32.1	0.1 – 11.4	0.27	0.62	1.84

TABLE 61b SUMMARY OF BOREHOLE DEPTHS AND WATER LEVELS

Sub-division	Borehole depths (m)				Water levels (m)			
	Range	1st Quartile	Median	3rd Quartile	Range	1st Quartile	Median	3rd Quartile
1	21 – 79	34	49	62	5 – 34	-	10	-
2	21 – 251	47	64	92	5 – 135	15	25	42
3	14 – 252	45	61	100	6 – 67	15	20	30
4	7 – 213	34	48	63	3 – 82	13	22	34
5	13 – 183	36	54	77	3 – 78	14	23	35
6	5 – 186	40	61	90	1 – 112	13	26	43
7	7 -231	47	71	83	1 – 73	17	33	46
8	12 -144	46	61	76	2 – 69	21	29	37
9	6 – 242	47	71	111	6 – 125	19	31	50
10	7 – 219	54	82	122	1 – 128	16	25	43
11	11 - 213	63	96	123	5 – 116	26	38	54
12	10 - 152	48	68	85	2 – 72	13	20	32
13	26 - 202	-	-	-	5 – 61	-	-	-
14	5 - 260	69	102	134	53 - 185	38	59	81
15	31 - 212	47	66	100	1 – 107	-	-	-
16	5 - 420	52	75	100	2 – 151	21	37	55
17	22 - 217	50	91	107	4 – 91	18	36	56
18	11 - 334	36	56	76	1 – 76	9	18	31

TABLE 61c SUMMARY OF STRIKE AND WEATHERING / FRACTURING DEPTHS

Sub-division	Strike depths below surface (m)				Percentage boreholes with logged weathering & fracturing	Depths of weathering/fracturing (m)			
	Range	1st Quartile	Median	3rd Quartile		Range	1st Quartile	Median	3rd Quartile
1	6 - 72	27	34	52	100	3 - 60	12	18	27
2	11 - 193	29	44	64	60	3 - 96	20	29	53
3	6 - 67	22	32	42	38.6	5 - 67	17	20	37
4	5 - 112	22	31	48	32.5	1.5 - 123	13	24	36
5	6 - 140	24	36	55	48.5	0.9 – 153	13	25	48
6	5 – 146	24	38	59	28.7	1 - 112	10	24	36
7	8 – 180	32	48	69	29.8	3 – 153	17	30	93
8	12 - 123	31	44	57	29.3	3 – 70	11	23	44
9	10 – 165	32	50	74	21.1	3 – 101	16	24	39
10	5 – 175	31	51	62	24.2	3.1 – 174	12	21	43
11	18 - 155	38	60	88	21.1	1.5 - 199	15	27	42
12	10 – 113.	28	43	58	56.5	3 - 144	12	30	47
13	5 - 82	-	-	-	37.5	2 - 100	-	-	-
14	9 - 231	49	81	110	21.7	2.1 - 210	26	49	82
15	19 - 158	-	-	-	32.4	12 - 72	-	-	-
16	7 - 219	38	56	80	23.6	1 - 220	12	33	57
17	12 - 116	34	48	82	21.4	4.6 - 132	-		
18	6 - 101	21	32	48	44.3	1 - 126	15	27	43

TABLE 61d SUMMARY OF YIELD DISTRIBUTION

Subdivision	Borehole yield distribution (percent)f				
	0.1 < 0.5	0.5 < 1.0	1.0 < 5.0	5.0 < 10.0	≥ 10.0
1	-	-	-	-	-
2	42.9	28.6	25.7	0	2.9
3	32.6	26.1	37.6	4.3	0
4	43.9	19.3	34.8	1.6	0.4
5	50	26.6	22.6	0.8	0
6	49.6	16.3	29.8	4.3	0
7	62.5	12.5	22.5	2.5	0
8	56.7	18.3	23.3	1.7	0
9	51.9	15.4	30.8	1.9	0
10	53.2	29.0	17.7	0	0
11	63.2	24.2	19.4	3.2	0
12	61	19.5	12.2	4.9	2.4
13	-	-	-	-	-
14	54.1	21.2	21.1	1.2	2.4
15	-	-	-	-	-
16	53.8	21.0	23.1	2.1	0
17	44.8	37.9	17.2	0	0
18	44.7	16.4	31.6	5.9	0.3

By ranking subdivisions in terms of:

- Decreasing success rate;
- Decreasing median yield and increasing % of boreholes yielding < 0.1 ℓs^{-1};
- Increasing median borehole depth;
- Increasing median water level and increasing difference between 1st and 3rd quartile depths;
- Increasing median strike depth and increasing difference between 1st and 3rd quartile depths;

and adding together the five ratings scored by each subdivision, the classification listed in the second column of Table 61e is obtained. Subdivisions No 1, 13 and 15 have been excluded because of a paucity of data and No 17 and 18 because they involve Koras and Dwyka Group strata. The third column includes subdivisions 17 and 18.

TABLE 61e SUBDIVISIONS ARRANGED IN DECREASING ORDER OF MERIT

Rank	Subdivision	Subdivision
1	3	3
2	4	4
3	5	18
4	2	5
5	6	2
6	12	6
7	8	12
8	9	8
9	10	17
10	7	9
11	16	7
12	11	10
13	14	16
14	-	11
15	-	14

In accordance with decreasing rainfall and an increase in the extent and thickness of superficial deposits there is a corresponding though not uniform deterioration in groundwater conditions from east to west. The first four subdivisions No's 2 to 5 (to which No 1 may be added) lie east of the Hartbees River in the higher rainfall part of the Region. Superficial deposits that impede recharge are thin or absent. Conditions are further enhanced in subdivisions No's 2 and 3 by the presence of fractured quartzite of the Brulpan and Vaalkoppies Groups building hilly ground.

The worst conditions are encountered in the contiguous subdivisions 10 and 11 (Kaboep / Coboop Valley) and in adjoining subdivisions 14 and 16 (Koa Valley). The next in rank after subdivisions 2 to 5 is surprisingly situated in the west between subdivisions 11 and 14. Subdivision 12 which is centered on Pofadder occupies higher-lying and partly mountainous ground sloping rather steeply northward down to the Orange River. Attention is drawn to the following:

- With the exception of Subdivision 14 minimum water levels ranging from 1 to 6 m deep have been recorded in all of the subdivisions (Table 61b). Note that In the case of Subdivision 14 only hard-rock water levels are shown. Subdivision 14 however includes the Koa Valley and Henkries spring and seepages where groundwater is discharged from Cainozoic deposits. Groundwater loss through evapotranspiration from areas with shallow water levels means groundwater flow, no matter how sluggish, in all of the subdivisions and therefore groundwater recharge, albeit at widely and irregularly spaced intervals and only over portions of subdivisions.
- Fault zones such as Brakbosch, Hartbees River consist mainly of impermeable rock with sparsely distributed water-bearing fractures.
- Higher drilling success rates obtain where the formation is weathered or fractured regardless whether logged weathering / fracturing is deeper or shallower than the water level. (5 and 8% respectively better in subdivisions 4 and 5).
- Most water strikes are made within 25 metres below water level; optimum strike frequency is around 10 metres below water level.
- The Dwyka-Basement contact should not be regarded a target for striking water.
- No water was struck in Dwyka sediment – dolerite and dolerite – Dwyka sediment contact zones.

7 GEOPHYSICAL EXPLORATION AND BOREHOLE SITING

7.1 GENERAL

Despite the great variety of metamorphic and igneous rocks, they are homogeneous in two respects they have; a) virtually no primary porosity and b) a secondary porosity due to fracturing and weathering. In hydrogeological terminology they are referred to as hard rocks.

The water-bearing capacity of unweathered hard rock is restricted to an interconnected system of fractures that is mainly the result of tectonic phenomena. Weathering processes - mechanical disintegration, chemical solution and deposition - modify the porosity of the original fracture system. These actions imply either an increase or decrease in porosity and / or permeability.

Because much of Bushmanland hard rock is hidden under a cover of soil, sand and calcrete and as the water-bearing capacity of hard rock in depth can not be gauged with assurance from its physical appearance where exposed, electrical resistivity and electromagnetic exploration methods have been employed to find respectively:

a) places where weathering and fracturing extend to below the piezometric level; and
b) narrow and steeply dipping zones of fracturing.

In-depth description of geophysical instrumentation and discussion of theory, field techniques and physical interpretation lie outside the scope of this monograph. Nevertheless as most of the investigations date back to the period 1945 – 1980 equipment of that period is briefly described. Significant development and refinement of instrumentation, techniques and interpretation since then have not changed the fundamental principles and inherent limitations of these prospecting methods. The intention is to discuss and illustrate how electrical resistivity and electromagnetic exploration methods have been employed, what has been achieved and what remains unresolved.

7.2 ELECTRICAL RESISTIVITY METHOD

There are two ways of making resistivity measurements:

1. Depth sounding by means of an expanding array of current (AB) and potential (MN) electrodes in either the Wenner or the Schlumberger electrode configuration.
2. Horizontal profiling by keeping:
   a) The dimensions of the entire Wenner or Schlumberger electrode array constant as it is moved from station to station
   b) The current electrodes stationary and moving the potential electrodes over an area where the electric field is fairly uniform - rectangle or gradient array.

The resistivity method is ideally applicable but not restricted to depth determination of horizontally layered ground. Enslin (1943) demonstrated that water-bearing basins of decomposition in crystalline rocks may be located by electrical resistivity depth probing.

7.2.1 Empirical Wenner depth sounding

Investigations for borehole siting in Bushmanland were undertaken during 1940 to 1980 with the Gane-Enslin instrument operating on the Gish-Rooney principle (Heiland 1940; Enslin 1944) and assembled in the Geological Survey workshop. Its main features were:

- Periodically reversed DC current from high tension batteries 45 -180 volt range, current 1 milliamp to 1 amp;
- Broken uni-directional potential through a second commutator on the same shaft as the current commutator;

- Wheatstone bridge and Cambridge spot galvanometer 10 or 40 ohm internal resistance and critical damping resistance of 150 or 550 ohm respectively. Measuring capability 0.2 millivolt – 1 volt;
- Steel electrodes; and
- Wenner electrode configuration - generally in expanding depth sounding mode; occasionally with constant electrode spacing in horizontal profiling mode.

Van Zijl (1985) commented on drawbacks of Wenner soundings and empirical interpretation. These are briefly outlined below. Commutated direct current is used to neutralize natural ground potentials and speed-up measurements compared to direct current depth probing. However if care is not taken its use introduces inductive and capacitive coupling between current and potential circuits. The degree of coupling escalates with increasing electrode contact resistance in both the current and potential circuits. Potential measurements appear adversely affected by coupling with contact resistances greater than 5 000 ohm and / or potential readings of less than 5 mV (Meyer et al 1980). At times and in certain areas reliable depth probing in Bushmanland has been hampered by poor electrode contacts in dry shallow soil, calcrete and windblown sand. Such conditions are no impediment to modern DC equipment using a high impedance voltmeter.

Wenner sounding entails simultaneous movement of both current and potential electrodes. The movement of potential electrodes (MN) over near-surface conductive and resistive heterogeneities produces apparent resistivity deviations which are much larger than those produced by similar movement of current electrodes (AB). With the more time-consuming Schlumberger sounding the AB separation is increased whereas the MN separation is small and is increased only periodically. Overlap measurements are made with AB constant. In this manner the effect of near-surface heterogeneities on MN measurements can be corrected.

Despite this inherent weakness the Wenner configuration has been employed by the Geological Survey as it and the empirical method of interpreting depth probe curves go hand in hand. The so-called empirical method of interpretation was developed by Enslin (1948 and 1963) during the 1940's and 50's. Its development originated from the need for a rapid and simple means of interpreting depth probes in the field for siting water boreholes. At that time interpretation techniques and the limited variety of standard curves were not considered suitable for use in the field.

The depth of investigation is empirically assumed to be AB/3 i.e. the distance between the equally spaced AMNB electrodes. Interpretation through comparison between field and two- and three-layer theoretical curves that were available (Hummel 1932; Watson 1934; Roman 1934; Wetzel and McMurry 1937) was found unworkable (Vegter 1953). Thus in spite of being theoretically unsound (Jakosky 1940 p 316- 317; Meyer et al 1980; van Zijl 1985) the empirical method of interpretation of depth probes had to suffice in the past where on the spot decisions about siting a borehole had to be made. For an exposition of the empirical method of interpretation consult Enslin (1948 and 1963).

After comparing empirical determinations of depth to bedrock at several dam sites Enslin (1944) concluded that "an error of about 10 to 15% over a section or over an area can be expected by the empirical method". Vegter (1953) found maximum errors of +18.4 and -12.3% in the empirically interpreted depths of weathering at some 30 boreholes in the Kenhardt and Prieska Districts. During a joint investigation by the National Physical Research Laboratory CSIR and the Directorate of Geohydrology at Kenhardt Wenner depth probe curves were interpreted empirically and by matching with standard curves (see Nonner's contribution to WRC project K5/18 Doornberg 1980). He found the accuracy of depth determination to bedrock of both the empirical and curve matching methods poor. The depths to solid / slightly weathered bedrock were estimated by an average margin of 25% either too shallow or too deep. To simulate conditions generally encountered in the field, curve matching was done without the support of geological and resistivivity borehole logs. Thus no correction for equivalence and suppression could be made (see exposition below).

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7.2.2 Fundamentals of Schlumberger depth sounding and interpretation

To place Wenner depth probing and empirical interpretation in proper context it is necessary to describe briefly the main features of interpretation by determining Dar Zarrouk parameters, matching curves and computer modeling. Albums of homogeneous and isotropic two- and three-layer theoretical curves for large ranges of layer thicknesses and resistivities became available after the mid-sixties (Orellana and Mooney 1966; Joubert 1977). According to van Zijl (1985) curve matching works well for two- and three-layer field curves but it becomes increasingly difficult to determine thicknesses and resistivities of layers beyond the third. In these cases the number of layers has to be reduced in steps to two or three by means of auxiliary point diagrams.

It can be shown that a succession of homogeneous and isotropic layers characterized by a total transverse resistance **T** and a longitudinal conductance **S** and a thickness **H** is electrically equivalent to a single layer characterised by the same **T** and **S** values but with a thickness λ**H** and an average resistivity $\rho_m = \lambda\rho_\ell$, where $\lambda = \sqrt{\rho_t} / \sqrt{\rho_\ell}$. ρ_t is the average transverse resistivity **T/H** and ρ_ℓ is the average longitudinal resistivity **H/S** of the succession of layers. λ is always **> 1**. The total transverse resistance of a package of n-1 layers resting on a substratum is given by:

$\mathbf{T} = \sum_{I=1}^{n-1} \rho_I \mathbf{h}_i$ where ρ_I is the resistivity of i-th layer and $\mathbf{h}_i$ its thickness. **T** is measured in ohm.m^2. The longitudinal conductance S of the package of layers is given by:

$\mathbf{S} = \sum_{I=1}^{n-1} \mathbf{h}_I / \rho_I$ where ρ_I is the resistivity of i-th layer and $\mathbf{h}_i$ its thickness. **S** is measured in Siemens.

The foregoing means that:

- An isotropic bed of thickness **h** and resistivity ρ can not be distinguished from an anisotropic bed of thickness λ**h** and average resistivity ρ_m
- An anisotropic bed is thinner than interoreted.

This ambiquity manifests itself in:

a) The principle of equivalence which means that in practice sounding curves of conductive (or resistive) layers of different resistivities and thicknesses but with the same longitudinal conductance (or transverse resistance) are indistinguishable.

b) The principle of suppression which means that a bed which has a resistivity intermediate between the layer above and below it is unnoticeable unless it is very thick when its effect remains indistinguishable from that caused by changes in thickness or resistivity in one or both of the enclosing layers.

Quoting van Zijl (1985) verbally: “Even under the most favourable conditions for electrical sounding i.e. when the beds are horizontal and there are no lateral variations in resistivity, it is seldom possible to determine the absolute thicknesses and true resistivities of beds underlying the surface layer from one or a few isolated soundings due to the principles of equivalence and suppression except of course when the layers are thick.”

The first step in interpreting depth soundings is the determination of the Dar Zarrouk parameters **T** and **S**. Although the results are only qualitative, S profiles or contour maps for example can be useful in portraying the configuration of a resistive substratum e.g. the base of the weathered zone. The contrast in resistivity between weathered and fresh rock should be large and the resistivity of the weathered sequence essentially constant. An example of this type of presentation is the total longitudinal conductance map of the 1 km x 1.6 km radioactive waste disposal site on Vaalputs which was covered by 220 Schlumberger soundings (de Beer and Blume 1984).

Resistivities (or thicknesses) of layers are however needed in order to determine thicknesses (or resistivities) from the Dar Zarrouk parameters. This information may be provided by a calibration sounding at an existing borehole that was logged geologically or electrically or by an exploratory borehole(s) specially sunk for that purpose. Bounds may also be placed on resistivity values by paying attention to common characteristics and progressive changes in the form of a series of depth sounding curves.

For a demonstration of the interpretation technique the reader is referred to a step-by-step description by Meyer et al (1980) of a quantitative interpretation of a series of Schlumberger depth probes on a section line on the Kenhardt town lands (Part 4 Addendum 1 of report on WRC project K5/28). Quantitative interpretation was made possible by virtue of a borehole log that disclosed the presence of a suppressed layer of weathered gneiss.

7.2.3 Resistivity soundings Vaalputs

Two hundred and twenty Schlumberger soundings on a 100 m square grid and data of 31 exploratory boreholes allowed the compilation of a conductive overburden isopach map of the 1.6 km^2 Vaalputs disposal area (de Beer and Blume 1984 and 1986). The overburden which varies in thickness between 6.6 and 36.5 m consists of a surface layer of sand, calcareous sand and calcrete (mean resistivity 70 ohm.m), an intermediate layer of sandy gritty clay, sandy clay and calcareous clay (mean resistivity 8.2 ohm.m), kaolinitic clay and calcareous kaolinitic clay (mean resistivity 101 ohm.m) and weathered basement (31 ohm.m).

Interpretation of the survey followed the following steps:

- Determination of resistivities of the different overburden components from calibration electrical soundings at the 31 boreholes.
- Determination of Dar Zarrouk parameters of all the soundings and compilation of a total longitudinal conductance map.
- Matching field curves with two- and three layer master curves and compilation of geoelectrical profiles.
- Checking and adjusting the quantitative interpretation by computing theoretical sounding curves for the postulated model.
- Compilation of an overburden isopach map.

Differences between this isopach map and that obtained from a seismic refraction survey by NUCOR (presently known as NECSA) were found to be relatively small. A noteworthy feature of the longitudinal conductance and isopach maps is a linear north-northwesterly striking conductive zone of thicker overburden. This feature probably coincides with one of a set of NNW trending faults which not only displace kaolinised and silicified basement but also CaInozoic Vaalputs sediments (Brandt et al 2005).

The geoelectrical profiles elicit the following comments:

1. The overburden does not strictly conform to a horizontally homogeneous stratified medium.
2. The depth probe spacing of 100 m is too large for covering lateral variability of overburden (mean thickness 20 m).
3. The interpreted resistivity of supposedly fresh basement rock varies from 20 to 5000 ohm.m. No explanation is offered as to why short sections of basement with resistivities ranging between 20 and 100 ohm.m have not been interpreted as weathered / fractured. Unweathered basement is characterized for the greater part by interpreted resistivity of 5000 ohm.m. Are these "conductive basement" soundings irresolvable in terms of stratified media despite computer modelling? The depth probe spacing is too large to ascertain whether lateral effects of near-by conductive vertical structures e.g. fracture or fault zones are involved.

The resistivity survey which must have demanded a considerable amount of fieldwork and office processing, largely fulfilled its aim of delineating the resistivities and thicknesses of overburden. Furthermore 4 out of 5 exploratory boreholes drilled at three sites within the linear conductive zone struck water. These results appear very gratifying were it not for the following facts:

- Strikes were made at depths of between 63 to 80 m in rock that has been logged as fresh from depths of 20 – 32 m down. In the disposal area the water level stands around 55 m below surface.
- Water was struck in 7 out of 12 geohydrological monitoring boreholes that were subsequently sited randomly in the area covered by resistivity soundings (so-called MON holes). Water strike depths vary from 59 to 105 m.

From the viewpoint of developing a groundwater supply resistivity sounding failed in that fractured rock below the piezometric level was not located. The question about "fresh" basement with resistivity < 100 ohm.m might have been resolved had closer spaced sounding been undertaken and exploratory boreholes been sunk where low basement resistivities were interpreted. The inability of the resistivity method of locating water-bearing fractured hard rock under cover of a low resistivity layer has been clearly demonstrated.

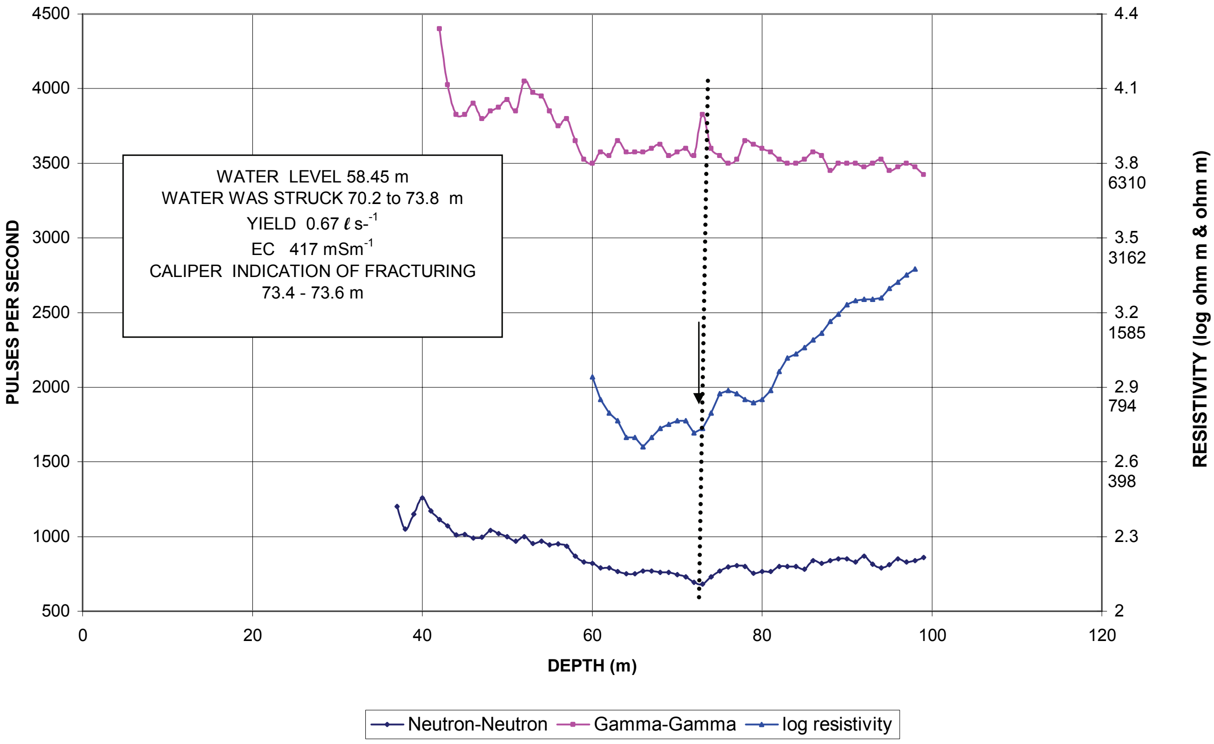
7.2.4 Geophysical borehole logging Vaalputs

At the request of NUCOR (presently known as NECSA), the Directorate of Geohydrology logged 28 boreholes geophysically in and outside the waste disposal area. Depending on the condition of the boreholes the following analogue-recorded logs were run:

Natural gamma	Normal resistivity	Water resistivity
Gamma-gamma	Single point resistance	Water temperature
Neutron-neutron	Self potential	Caliper

Log combinations are presented by way of examples in Figures 24 to 30. Attention is focused on the log sections below the water level and then only on the normal resistivity, gamma-gamma, neutron-neutron and caliper logs. Resistivity (below water levels of around 55 m) ranges from 100 to 3000 ohm.m. It fluctuates generally between 700 and 1000 ohm.m.

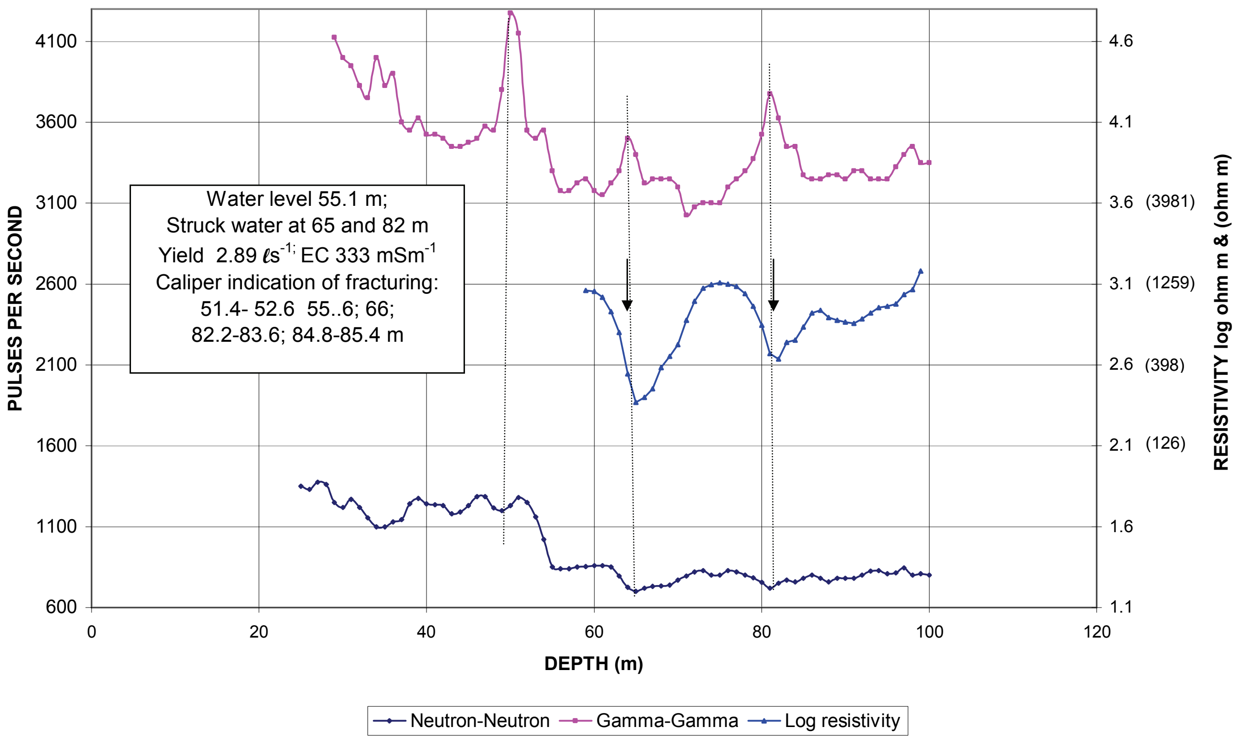
FIGURE 24 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS OF BOREHOLE PBH 16 VAALPUTS



Lithological Log of PBH 16		Resistivity according to Schlumberger depth probe	
Depth (m)	Lithology	Depth (m)	Resistivity ohm m
0 - 1	Red sand	0 – 1.1	70
1 – 3	Calcareous sand	1.1 – 5.1	10
3 - 8	Sandy gritty clay	5.1 – 19.1	6
8 – 36.5	Coloured clays with kaolinitic lumps	19.1 -34.1 -	14
36.5- 45.8	Medium grained red and pinkish granite	> 34.1	5000
45.8 – 46.7	Metaquartzite		
49-6.7 - 73	Medium grained red and pink granite		
73 - 75	Mixture of fresh red granite and weathered feldspar forming kaolinitic lumps		
75 - 100	Fresh medium and fine grained granite		

Borehole PBH 16 (Figure 24) is situated in the NNW-striking conductive zone mentioned in section 7.2.3. Fresh granite was drilled from 36.5 down to 100 m with a weathered zone between 73-75 m. The orientation of the 2-metre wide zone in which water was struck, is unknown. Whether the 15-metre wide zone (64 -79 m) of resistivities varying between 450 and 800 ohm.m indicated by resistivity borehole logging, represents or is part of the NNW-striking, presumably steeply dipping feature can likewise not be determined from the available data. The lithological log does not mention weathered or fractured formation other than the 73 -75 m zone. The water strike at 73 m by contrast is marked by an increase in borehole diameter, a positive gamma-gamma and a small negative neutron-neutron anomaly. Note that borehole diameter changes have a significant effect on gamma-gamma logs. Neutron-neutron logs are similarly affected though to a lesser degree.

FIGURE 25 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS BOREHOLE MON 4 VAALPUTS



MON 4

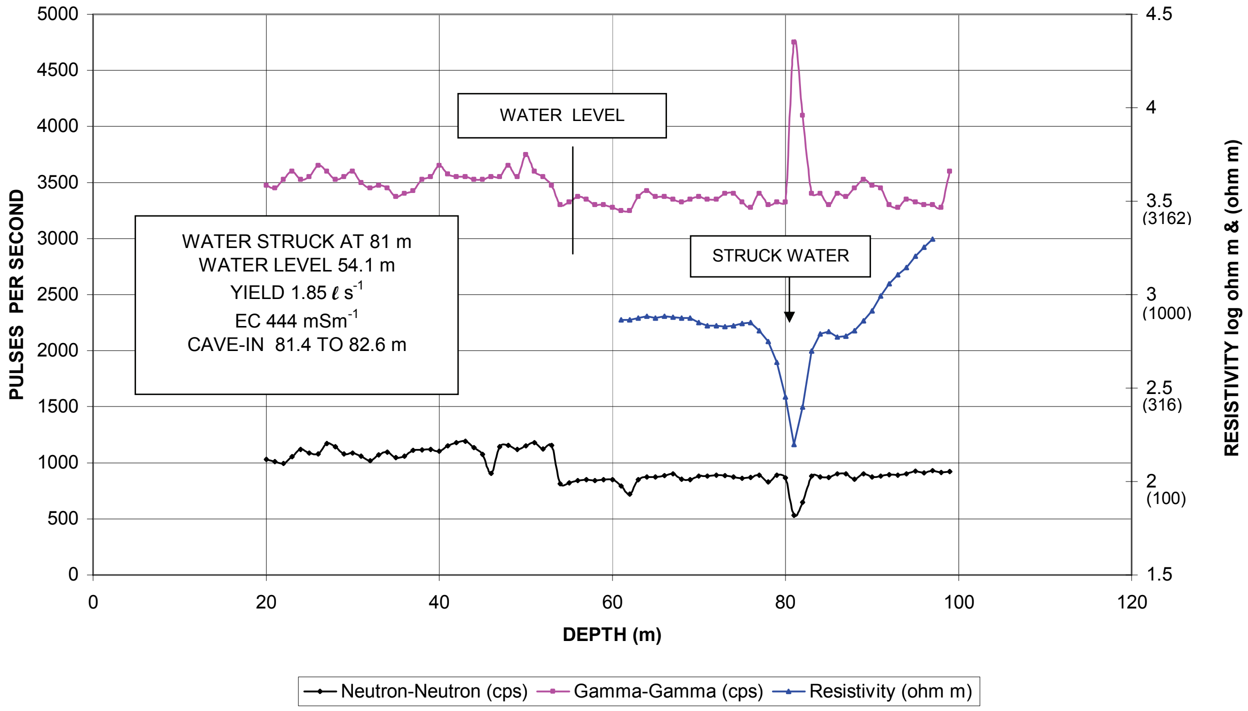
0 – 20 m	Overburden
20 – 29 m	Slightly to highly weathered granite
33 – 43 m	Quartz-biotite-magnetite-pyroxene rock
43 – 78 m	Magnetite quartzite with sulphides 53 to 54 m
78 – 85 m	Pale pink coarse-grained granite
85 – 96 m	Magnetite quartzite
06 – 100 m	Pale pink coarse-grained granite

TABLE 62 JOINTS / FRACTURES AND CALIPER, GAMMA-GAMMA AND RESISTIVITY LOGGING BOREHOLE MON 4 VAALPUTS

Depth of joint (m)	Dip of joint (degrees)	Depth of “cave-ins” (m)	Depth of G-G anomalies (m)	Depth of Resistiviity “lows” (m)
51.2 & 52.1	0	51.4 to 52.6	50	-
54.9	80	55.6	54	-
66.5	0	66	64 to 69	65 (233 ohm.m)
81.4, 82.1 & 83.2	80	82.2 to 83.6	81 to 84	82 (433 ohm.m)
84.0, 84.2	80	84.8 to 85.4	-	-

Hodgson (1986) reported on video recordings to ascertain the nature of joints and fractures in borehole MON 4 (Figure 25). The depth and dip of joints are compared to caliper indications, gamma-gamma anomalies and resistivity lows in Table 62. Caliper, gamma-gamma and resistivity responses are lacking for video-recorded joints at 87.3, 88.8 and 90 m dipping 60^0, at 92 m dipping 30^0 and at 92.6 m dipping 80^0. They appeared to be tight.

FIGURE 26 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS OF BOREHOLE MON 11 VAALPUTS



0 – 20 m	Overburden and weathered granite
20 – 100 m	Medium to coarse-grained red and pink granite slightly weathered at 82m

The water strike at 81 m in borehole MON 11 (Figure 26) coincides with sharp negative resistivity and neutron-neutron lows, a prominent positive gamma-gamma anomaly and widening of borehole wall.

In borehole MON 12 (Figure 27) a fine-grained greyish-blue rock possibly magnetite-quartzite is sandwiched from 73 to 88 m between coarse-grained granite. The lithological borehole log follows:

MON 12

0 -15 m	Overburden, sand and clay
15 – 26 m	Leucogranite possibly weathered
26 – 67 m	Medium and coarse-grained pink granite
67 – 71 m	Medium and coarse-grained pink granite, feldspar slightly weathered
71 – 73 m	Weathered medium and coarse-grained pink granite
73 – 88 m	Magnetite quartzite?
88 – 96 m	Slightly weathered pink coarse-grained granite

The magnetite quartzite manifests itself by the bulge in the resistivity log. A 2-metre wide zone of weathered granite occurs on the upper contact. From 88 to 96 m the granite is apparently very slightly weathered. Irregular fluctuations of the gamma-gamma and neutron-neutron logs correlate with a zone of anomalous natural gamma activity and the layer of magnetite quartzite - see Figure 28.

FIGURE 27 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS OF BOREHOLE MON 12 VAALPUTS

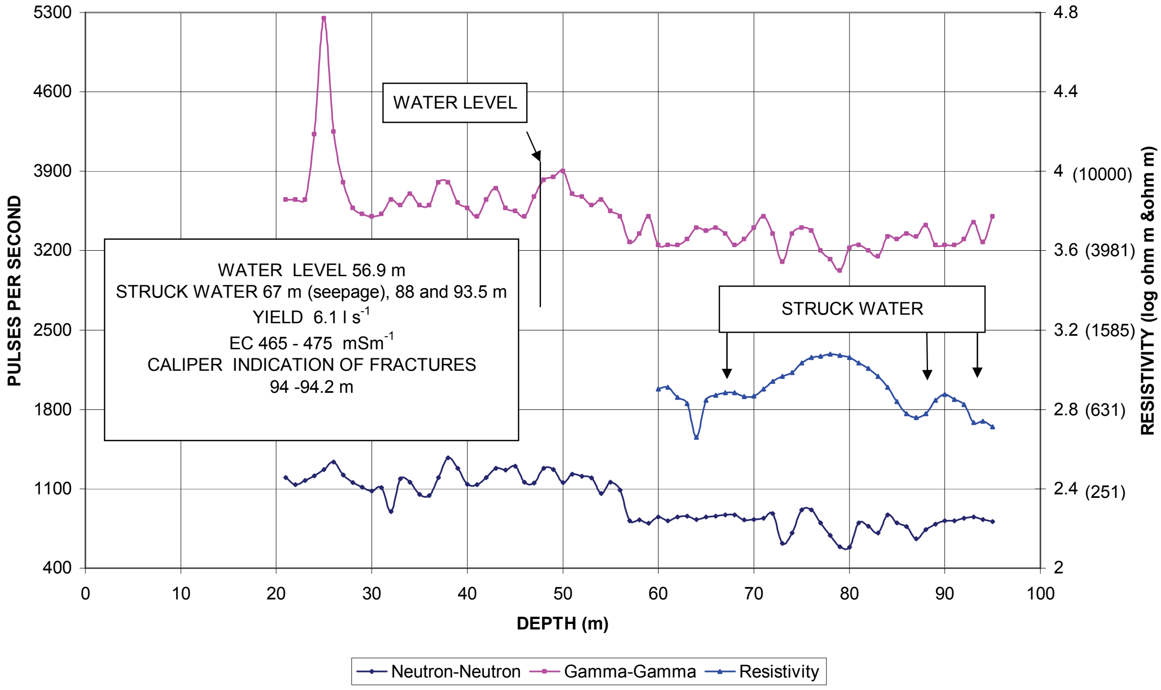


FIGURE 28 GAMMA-GAMMA, NATURAL GAMMA AND NEUTRON=NEUTRON LOGS OF BOREHOLE MON 12 VAALPUTS

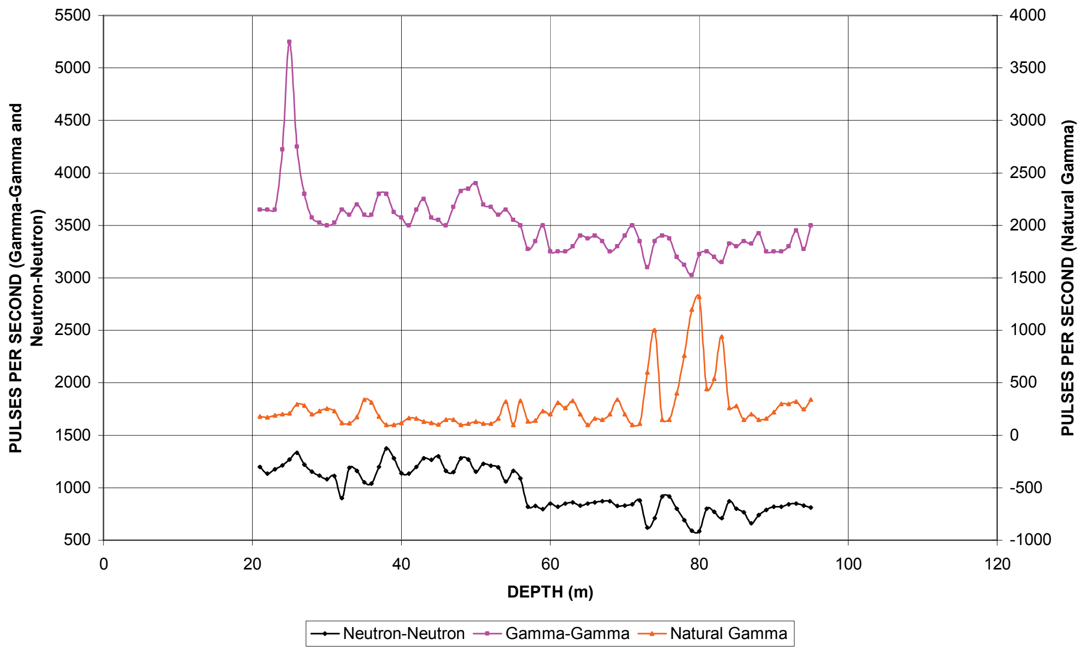
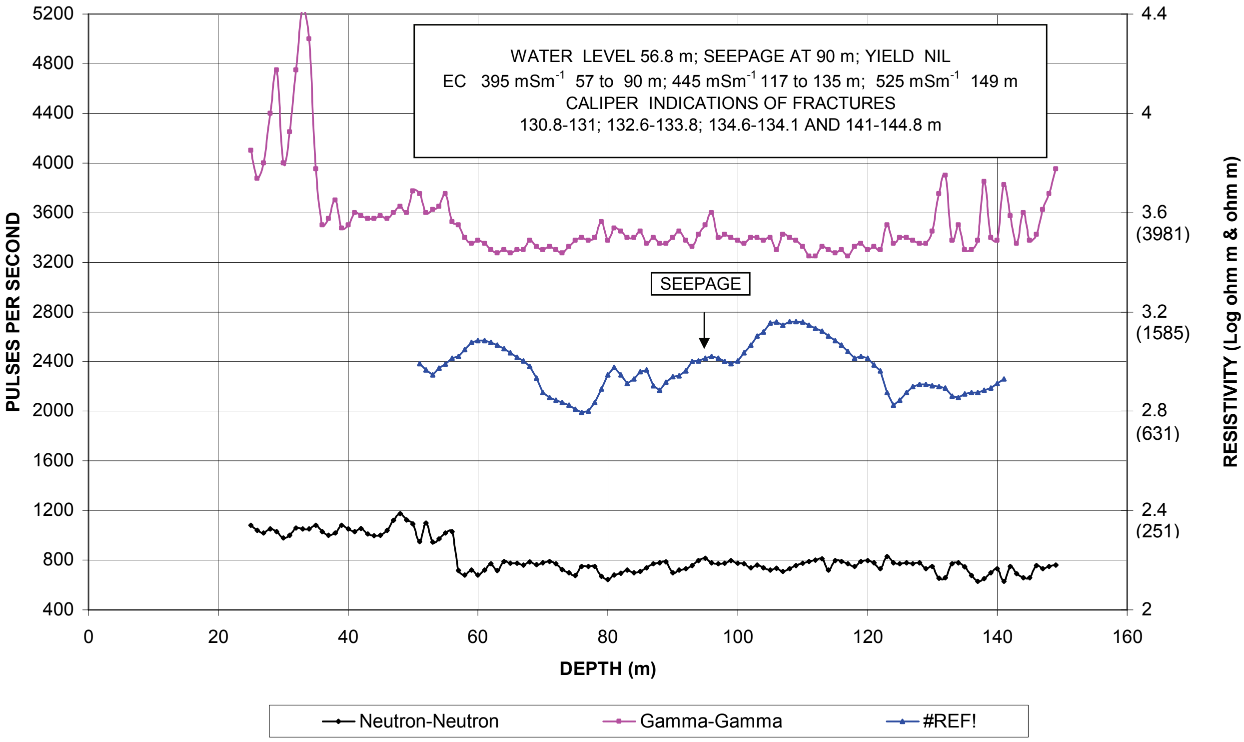


FIGURE 29 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS OF BOREHOLE MON 14 VAALPUTS



MON 14

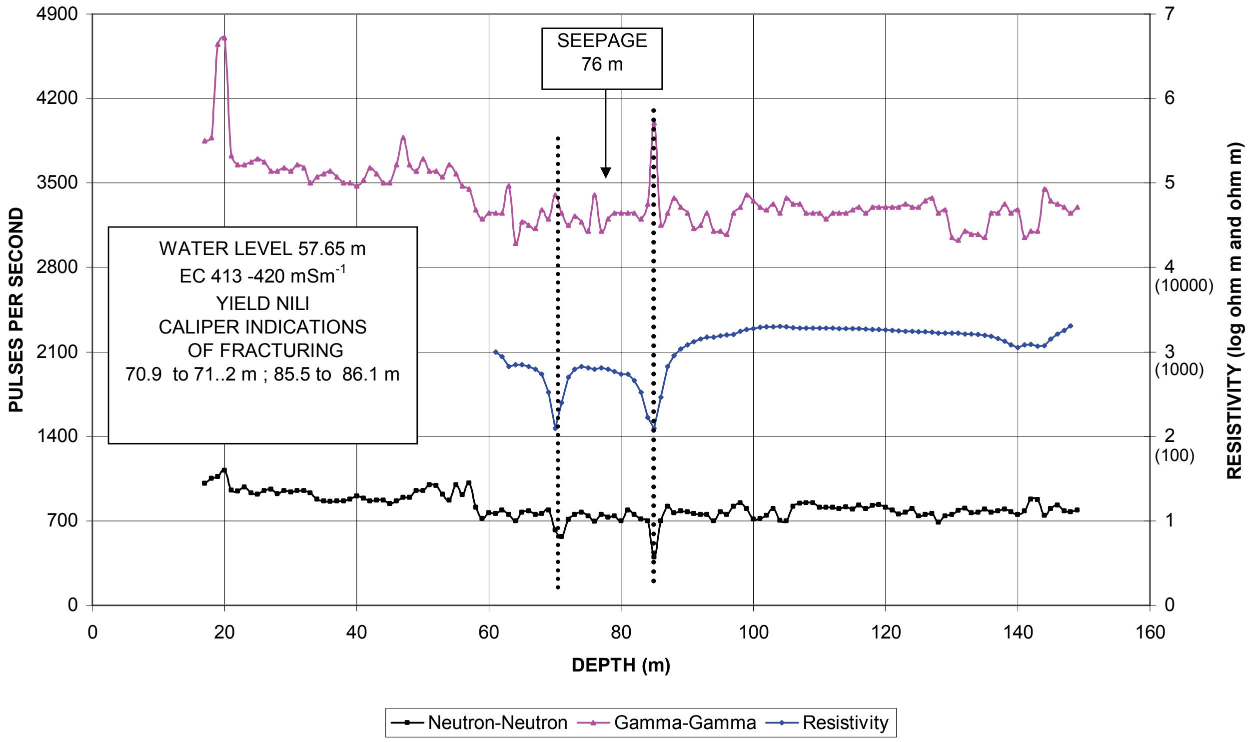
0 – 25 m	Overburden
25 – 65 m	Coarse-grained pink granite with epidote veinlets?
65 – 85 m	Streaked leucogranite
85 – 90 m	Coarse-grained pink granite jointed and damp between 83 and 95 m

The resistivity response of an 85 to 90 m well-jointed and damp section of leucogranite (borehole MON 14 Figure 29) is outclassed by wide and large resistivity fluctuations that can not be explained in terms of the geological borehole log. Gamma-gamma and much smaller neutron-neutron fluctuations from 130 m onwards are ascribable to the rugosity of the borehole.

Prominent resistivity lows yielded no water in borehole MON 15 (Figure 30). The lows coincide with gamma-gamma and neutron-neutron anomalies and “cave-ins”. Seepage at 76 m correlates with a gamma-gamma peak. It was noticed that the water resistivity log showed deviations that were more prominent than those obtained with the caliper opposite borehole “cave-ins” Whereas virtually no deviation was obtained at 76 m with the latter, the water resistivity log deflected clearly towards a lower resistivity. The lithological log follows:

0 – 20	Overburden and weathered granite
20 – 90	Coarse-, medium- and fine-grained pink granite with admixture of magnetite-bearing rock 56 -76 m
90 – 97	Magnetite quartzite
97 – 150	Pink and pale pink medium- to coarse-grained granite

FIGURE 30 GAMMA-GAMMA, ELECTRICAL RESISTIVITY AND NEUTRON-NEUTRON LOGS BOREHOLE MON 15 VAALPUTS



Geophysical borehole logging produces additional information that may not be evident from drill cuttings and presently be explicable. Clearly geophysical logging and video-recording of borehole walls are indispensable tools if progress is to be made in determining the character of water-bearing features in Bushmanland rocks.

7.2.5 Horizontal Wenner profiling

Horizontal profiling is aimed at exploring the subsurface laterally at a more or less constant depth. Thus profiling with the Wenner configuration involves moving the AMNB electrode line as a unit sideways. The electrode spacing is held constant and the electrode line is oriented parallel to the strike or expected strike of geological features. Horizontal profiling can not stand on its own as lateral change in apparent resistivity is determined not only by changes in depth of the feature under investigation (e.g. depth to bedrock) but also by individual thickness and resistivity changes in the overlying layers. Horizontal Wenner profiling has therefore played a very minor role in the siting of boreholes in Bushmanland. Wherever undertaken it has to be underpinned by soundings.

7.2.6 AB rectangle (gradient) array profiling Vaalputs

In this array the current electrodes AB remain stationary and measurements are made between potential electrodes M and N which are moved along lines parallel to AB in a rectangle centered at the midpoint of AB with length AB/3 parallel to AB and width AB/2 perpendicular to AB. The station interval is MN where AB/MN can vary between 20 and 100. (van Zijl 1985). The AB line is oriented perpendicular to the structure sought.

In the Vaalputs area lineaments that are related to fracturing and faulting were investigated by De Beer and Blume (1984; 1986) by means of rectangle profiling. Of these the Garing lineament - fault zone - is the most important. It is a clear linear feature on aerial photographs, on thermal infrared line-scanning images and on aeromagnetic contour maps. Rectangle profiles across the lineament showed that stretches of the feature are characterized by apparent resistivity lows indicative, according to De Beer and Blume (1986), of fractures in depth that are filled with water. Other stretches of the lineament that lack low apparent resistivity anomalies are interpreted by De Beer and Blume as characteristic of solid unfractured basement rocks The conclusion is drawn that the Garing linear is “open” along some parts and “closed” along others leading to the formation of water compartments that are sealed–off by recrystallization of fault breccia.

The correctness of these deductions is seriously doubted. In the author’s opinion the resistivity lows are solely attributal to the weathered upper part of the fault zone and not to water-bearing fractured rock in depth. The absence of anomalies over resistive (silicified?) sections of the fault zone does not rule out the possible existence of water-bearing fractures in depth. This has been the experience with some silicified breccia zones elsewhere in Bushmanland.

Nowadays the moving source – moving receiver frequency domain electromagnetic method is as efficient in locating the upper weathered and conductive part of fault zones as the rectangle technique. It is far less cumbersome and manpower intensive to use.

7.2.7 Summary

It is estimated that around 20 000 Wenner depth probes have been made in Bushmanland and that some 1000 borehole sites have been selected by the Geological Survey on resistivity as well as purely geological grounds. Geophysical observation points and borehole sites have with some exceptions not been surveyed. Data and information are thus unfortunately inadequate for a thorough assessment of the value of Wenner resistivity depth probing and empirical interpretation. The NGWDB contains records of only 283 scientifically sited boreholes of which 94 (33.2%) yielded ≥ 0.1 ℓs^{-1}. The reasons for this state of affairs are:

- Not every selected site was drilled on;
- Drillers omitted site (G) numbers on borehole completion reports;
- Misplacement and loss of borehole completion reports or of borehole record cards (MD 306A);
- Borehole siting reports (MD 995 forms) and cards (MD 1031) with geophysical data and interpretation are likewise incomplete; and
- Depth probe positions not surveyed.

Apart from the inherent shortcomings of the Gane-Enslin instrumentation, of the Wenner electrode configuration and of empirical interpretation, failure to recognise the effect of near-surface heterogeneities on potential measurements and failure to distinguish between lateral and depth effects has in the author’s opinion, been responsible for a number of erroneously sited boreholes. Deflections of Wenner depth probe curves at electrode spacings corresponding to depths of (fortuitous) water strikes undoubtedly have been mistakenly ascribed to depth instead of near-surface effects. In this way the case for faulty interpretation has been strengthened and promoted.

The applicability of resistivity depth probing to the siting of water boreholes in crystalline rocks depends on the incidence of weathered / fractured rock bodies that extend down to or deeper than the zone of saturation and on the method’s capability of locating and delineating such bodies which may be three-dimensional basin-shaped or two-dimensional narrow linear structures.

Although theoretical sounding curves are available not only for successions of horizontal layers but can also be calculated for vertical discontinuities, dipping layers and two-dimensional bodies such as dykes, a priori interpretation of field curves in terms of any of these physical structures can not be done unambiguously. Type of structure and additional data such as characteristic resistivity must be known which means information from existing or exploratory boreholes has to be available. This is generally not the case.

With the advent of the personal and laptop computer, direct modelling of depth probe curves on site has become feasible (Van Zijl 1985). It should be noted however that no matter how close the calculated model fits field curves the solution is one of many and not necessarily a true reflection of conditions under foot.

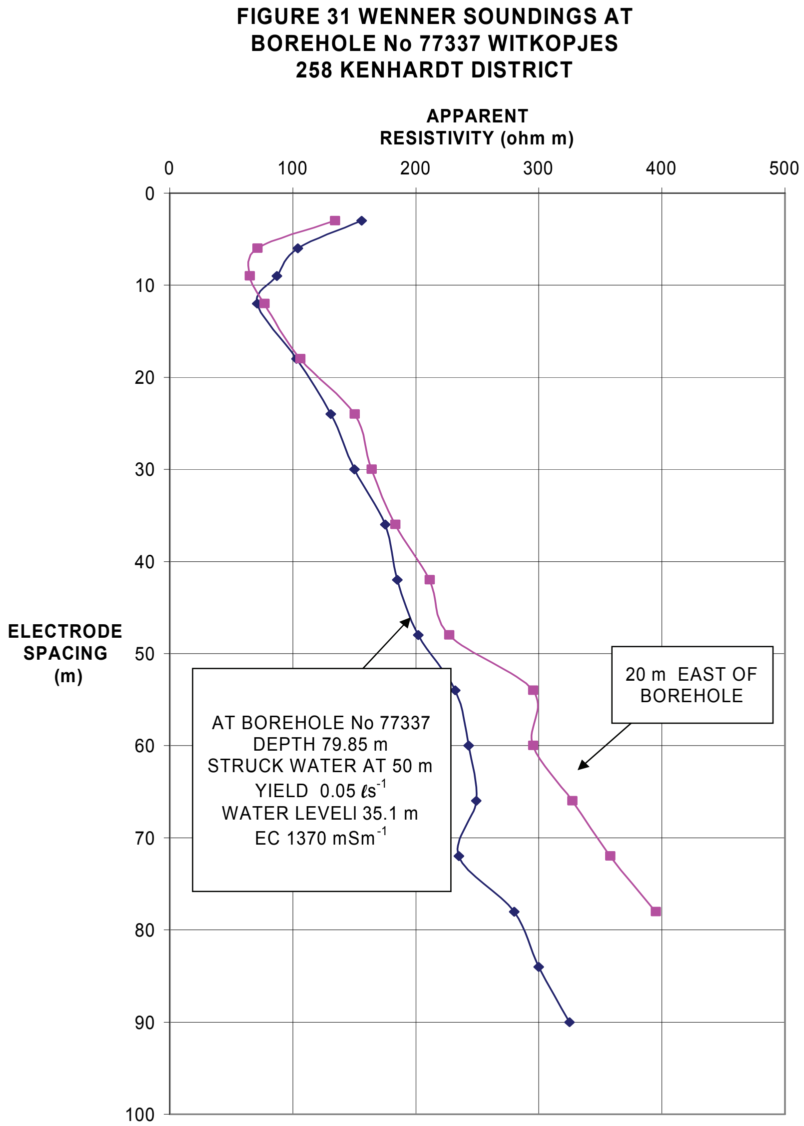
A horizontally stratified earth is assumed as physical model for interpretation of depth to fresh unweathered rock or of the longitudinal conductance of the weathered zone. This applies whether interpretation is done empirically or through curve matching and computer modelling. Conversion of longitudinal conductance to depth requires a resistivity or thickness value from a calibration borehole. As a rule they are non-existent. Furthermore the use of a calibration resistivity or thickness assumes horizontal layering, a condition that may not be satisfied in the case of a differentially weathered succession of steeply dipping and banded metamorphic and intrusive rocks. Owing to lateral effects depths of weathering of narrow conductive zones are indeterminable.

Determination of depth of weathering / fracturing must therefore be seen as proximate - all the more as the base of weathering is a transitional zone rather than a sharp contact. The process of choosing a borehole site is one of comparing depth probes along a section line. Interpretation, whether done empirically or through curve matching and computer modeling should never be based on a single curve but rather on a series of probes. The probe spacing should be smaller than the depth investigated so that lateral changes can be recognized, followed from depth probe curve to depth probe curve and thus taken into account.

Weathered and fractured formation was reported in only 26.8% of the NGWDB boreholes. It is furthermore evident from Table 61c that on a Region-wide basis weathering and fracturing exceeded 15 m in no more than 20 % of the boreholes in which weathering / fracturing was reported i.e. in about 5% of the total number of NGWDB boreholes In subdivisions No's 6 to 11, 14 and 16 median water levels exceed median weathering / fracturing depths. With exception of No 6, median strike depths in these subdivisions range from 18 to 33 m below median depths of weathering / fracturing. Water is evidently mostly struck in fractures in fresh hard rock. Deep weathering and fracturing (see Table 61c) seem to be limited to narrow linear features. In areas with water levels in excess of about 30 metres basins of weathering that extend down to the water level or deeper appear to be very sparse or non-existent.

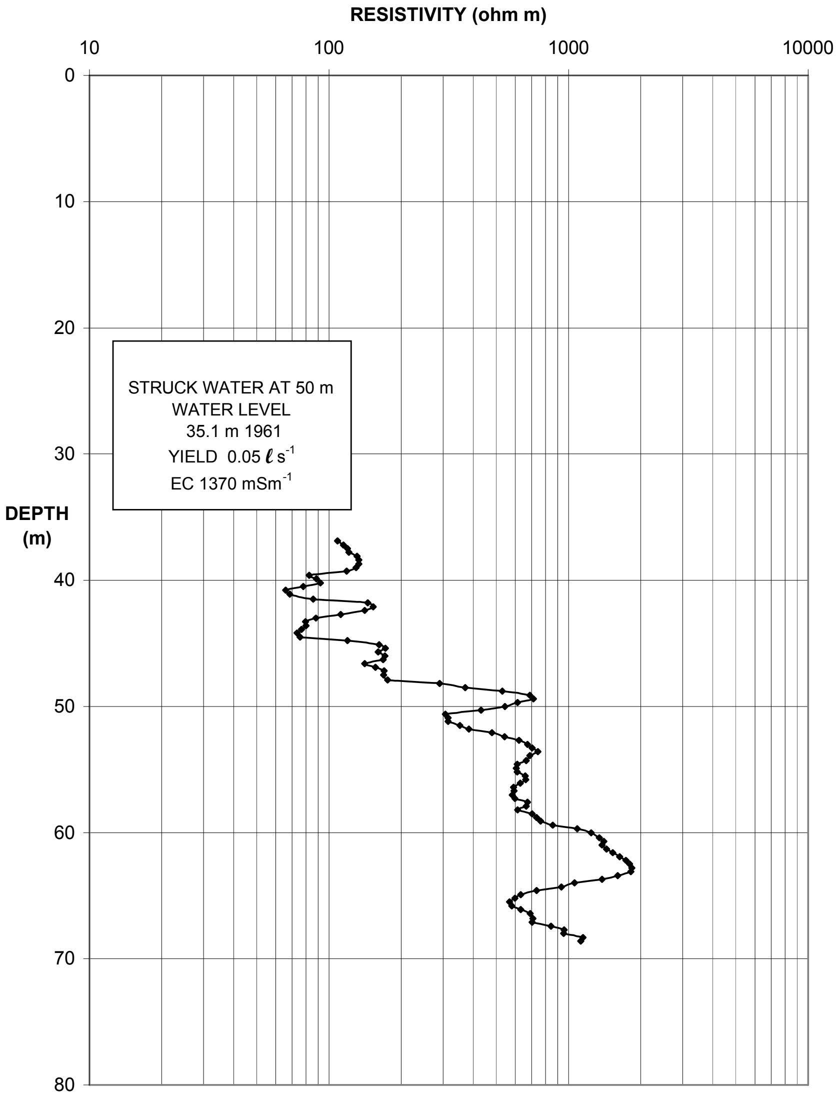
Figures 31 and 32 illustrate the problem of siting boreholes geophysically on steeply dipping metamorphic rocks, conditions that are atypical of basins of weathering in igneous rocks. Wenner probes were taken at a previously drilled borehole No 77337 on Witkopjes 258. According to the geological log the borehole was sunk in quartzite to a depth of 79.9 m. No mention is made of weathering or fracturing. Witkopjes 258 is underlain by the Mottels River Formation which comprises aluminous gneiss with lenses of calc-silcate rocks, amphibolite and marble. The strata dip eastward at around 70^0 – 75^0 (see 1:250 000 Geological Sheet 2820 Kenhardt). It is surmised that the log's quartzite is probably quartz-feldspar gneiss.

The Wenner probes (Figure 31) are both distorted beyond the 50 metre electrode spacing by near-surface inhomogeneities. That deflections of the two depth probes at 50 metre electrode spacing coincided with the water strike in borehole No 77377 is purely fortuitous. According to the depth probes overburden and weathered rock, about 10 m thick and resistivity $\approx$ 50 ohm.m, is followed by bedrock with an overall resistivity of at least 300 ohm.m. Electrical logging (Figure 32) however revealed the presence of apparent resistivity values of less than 100 ohm.m between 40 to 45 m. The resistivity of the quartzite or feldspar-gneiss above the water level therefore evidently varies between wide limits, from < 100 to possibly 1000 ohm.m.



This is characteristic of fractured rather than of weathered formation. That merely a very small supply was struck in spite of the fact that fracturing according to the resistivity log extended to well below the water level points to poor permeability possibly due to infilling of fractures by clay. Permeable and impermeable fractured hard-rock can not be distinguished from each other on the basis of resistivity.

FIGURE 32 ELECTRICAL RESISTIVITY LOG OF BOREHOLE 77337 WITKOPJES 258 KENHARDT



Note also that under field conditions fractured and solid bedrock can not be distinguished from each other where they are overlain by a low resistivity layer. Whereas water in Bushmanland is mostly struck in virtually unweathered fractured rock, usefulness of resistivity depth probing appears largely restricted to determining depths of weathering and thicknesses of alluvial deposits in areas with shallow water levels. Elsewhere resistivity surveys though not ideally suited may be of assistance in locating narrow electrically conductive zones that potentially may be deeply weathered / fractured. Chances of striking water may be somewhat enhanced by siting boreholes where the formation is weathered / fractured, regardless of depth.

7.3 ELECTROMAGNETIC METHOD

7.3.1 Introductory remarks

During 1946-48 F.W. Schumann, C.V. Joubert and J.R. Vegter of the Geological Survey carried out several electrical resistivity surveys aimed at siting boreholes on Lucas Vlei 93 (Subdivision 10). Lucas Vlei is one of a group of farms some 50 to 60 km east of Pofadder that lie on the divide between the northeasterly flowing tributaries of the Hartebees River, the northwesterly directed Kaboep / Coboop Valley and several north-flowing streams. The farms are Longziek Vlei 151, Bank Vlei 136, Lucas Vlei Vlakte 138, Scuit Klip 92 and Blad Grond South 93. On them steady groundwater supplies are almost completely lacking.

Because groundwater levels range from 30 to 90 m and weathering varies between 10 and 25 m according to resistivity depth probing, the usefulness of the electrical resistivity method was severely curtailed. Boreholes had to be sited purely on geological grounds on zones of brecciation and mylonitisation, silicification and epidotisation and renewed fracturing. Results were not encouraging.

During April-May 1953 J.R. Vegter and P.L.V. Hugo undertook experimental galvanic electromagnetic surveys using the circular Enslin technique (Enslin 1952 and 1955) at a number of boreholes that had previously been sited and drilled on fracture zones. The purpose was to establish whether this method could assist in distinguishing between water-bearing and "dry" fracture zones. Several drilling sites were also selected. Subsequently drilling was undertaken on three EM anomalies on three different farms. The drilling operations were supervised hydrogeologically by D.H. van der Merwe of the Geological Survey. At the same time a number of previously drilled boreholes were logged electrically.

In 1997/8 as part of the hydrocensus undertaken by the Directorate of Geohydrology for the compilation of the 1:500 000 Hydrogeological maps Springbok 2916 and Prieska 2920 a special effort was made at measuring water levels on Lucas Vlei and surrounding farms on the drainage divide.

7.3.2 Instrumentation

During the latter 1940's Enslin (1955) investigated the applicability of the electromagnetic method as used by Sundberg (1931) and Hedstrom (1937). He found that practically no anomalies were observed across known fault zones when the earth is energised inductively by alternating audio-frequency current flowing through a large insulated loop. Therefore as the inductive method offered very little chance of detecting narrow zones of medium conductivity further investigation was restricted to using earthed primary current.

Initially the equipment consisted of a generator and ossilator capable of producing a stabilized alternating 500 hertz current of 0.5 to 1 amp for energizing the ground conductively and large hand-held coils for measuring absolute horizontal electromagnetic field strength (Bellairs 1955). The generator–ossilator unit was subsequently replaced by a 400 hertz generator and the large measuring coils by ferrite–core coils. Two techniques were used:

1. Enslin's technique (1955) consists essentially of measuring the tangential component of the horizontal electromagnetic field at stations on concentric circles around a centre point at which alternating current is introduced conductively into the ground. Current concentrations in narrow conducting zones give rise to anomalies in the horizontal magnetic field.
2. Vegter's technique (1962) consists of measuring the amplitude of the horizontal electromagnetic field along a traverse line that is perpendicular to and bisects the line joining two electrodes at which current is introduced into the ground. The electrodes are spaced 800 to 1000 metres apart. The horizontal field is measured in the direction of the traverse line.

The need for cumbersome EM equipment fell away in the 1980's with the advent of porTable frequency–domain electromagnetic equipment such as the Scintrex SE-88 Genie which is capable of inductively energizing and detecting zones of medium conductivity - see de Jonge (1987) and Wiegmans (1990).

Electrical borehole logging reported on below was conducted with the Gane-Enslin resistivity instrument. The so-called normal electrode configuration AMN (Scott Keys 1989) with 3 ft (91.4 cm) separation was used. Measurements were taken at 3 ft intervals. In a number of cases boreholes were logged above the water level by filling up holes with water.

7.3.3 Electromagnetic surveys at and electrical logging of existing boreholes 1953

A selection is presented below:

1 Boreholes No's 35770 and 36011 Lucas Vlei 93

See Figure 33 for location. Borehole site G503 was selected in 1947 by the author on the basis of electrical resistivity depth probing. The expected depth of weathering in coarse-grained Skuitklip Granite was 21 m. The site was marked more or less on the projected extension of a north trending epidotised fracture zone. Borehole 35770 was drilled to a depth of 60 m. The formation was weathered according to the driller to a depth of 23 m. In the absence of scientific control, drill cuttings were not examined. Neither was electrical borehole logging undertaken. No water strike was recorded. However in 1997, the partially collapsed hole was found to contain water.

After the failure of borehole 35770, site G2644 was marked in 1948 south of the Kakamas – Pofadder road where the fracture zone outcrops (Figure 34a). The zone has a westerly dip of about 75 – 80^{o}. The site was accordingly offset to the west so as to penetrate the fracture zone at a depth of around 40 m. Borehole No 36011 was drilled to a depth of 46.3 m in 1948. About 0.003 ℓs^{-1} of saline water (EC 1333 mSm^{-1}) was struck at 33.5 m. Again, in the absence of scientific control drill cuttings were not examined. Wenner depth probes at the two borehole sites are shown in Figure 34b. Weathering appears to be about 10 m at site G2644. The probe is affected laterally by shallower weathering as is evident from the slope of the curve of less than 45^{0} for electrode spacing greater than 10 metres.

An experimental electromagnetic survey was made during April-May 1953 (see Figure 34a). Although the EM anomalies do not coincide with the outcrops of the fracture zones, there can be little doubt that the anomalies are associated with the fracture zones. At the time of the EM survey borehole No 36011 was logged electrically (see Figure 34c). Note the shallow water level of 25.9 m. As the borehole was not filled up with water no log is available for the part above the water level.

In view of the relatively low apparent resistivity values – between 300 and 400 ohm.m below 35 m, the question may be asked whether the borehole should not have been drilled deeper. Was drilling stopped because of the bad quality of the water? An alternative may have been to site a borehole about 8 m further west so as to strike the fracture zone (which apparently may have been penetrated around 33.5 m) at a depth of about 60 m. Yield and water quality may be better in less weathered more permeable fractured formation.

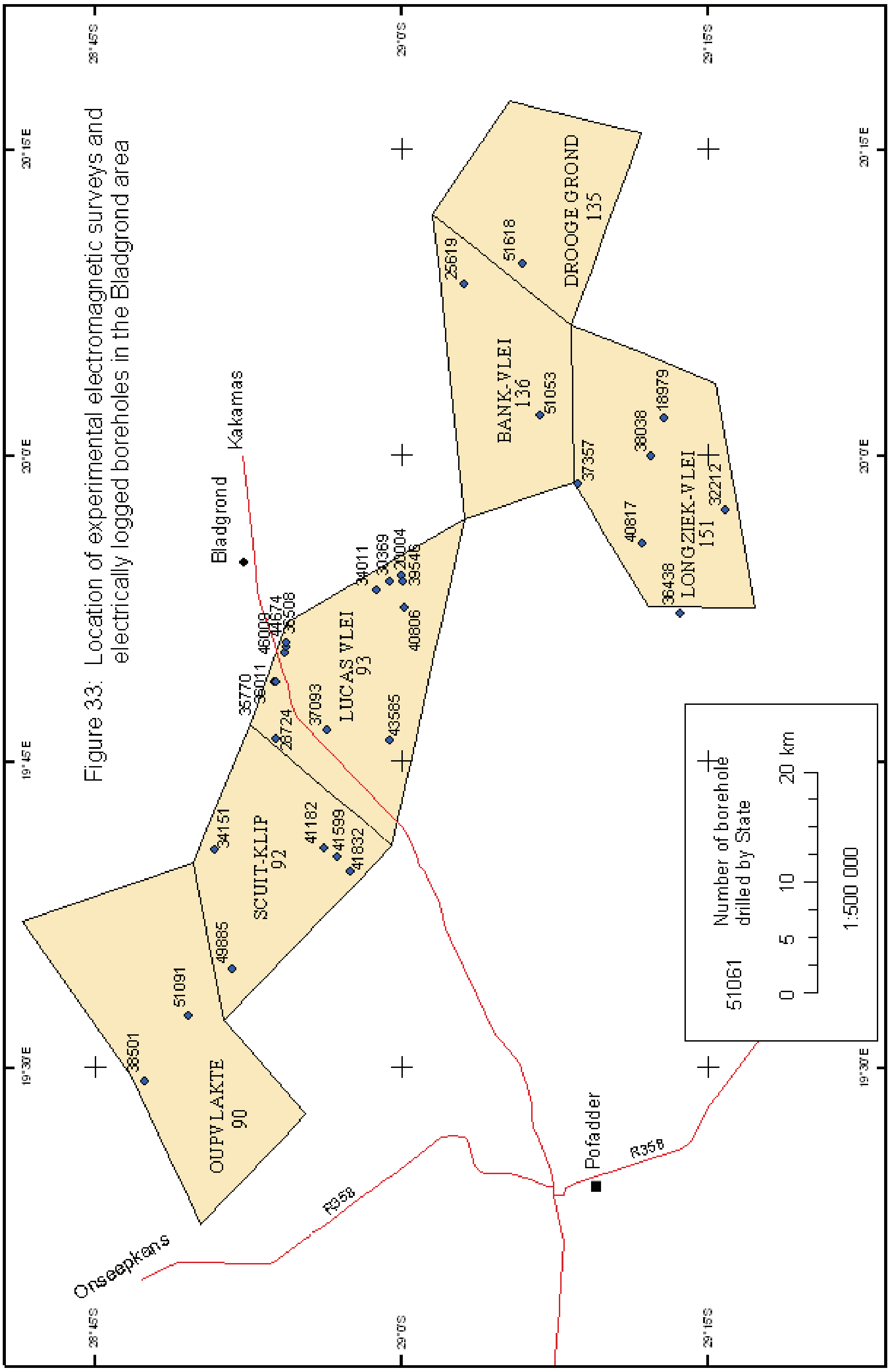


Figure 33: Location of experimental electromagnetic surveys and electrically logged boreholes in the Bladgrond area

Figure 34a: Electromagnetic survey at sites G503 and G2644 (boreholes No's 35770 and 36011) Hellum 2 portion of Lucas Vlei 93 Kenhardt District

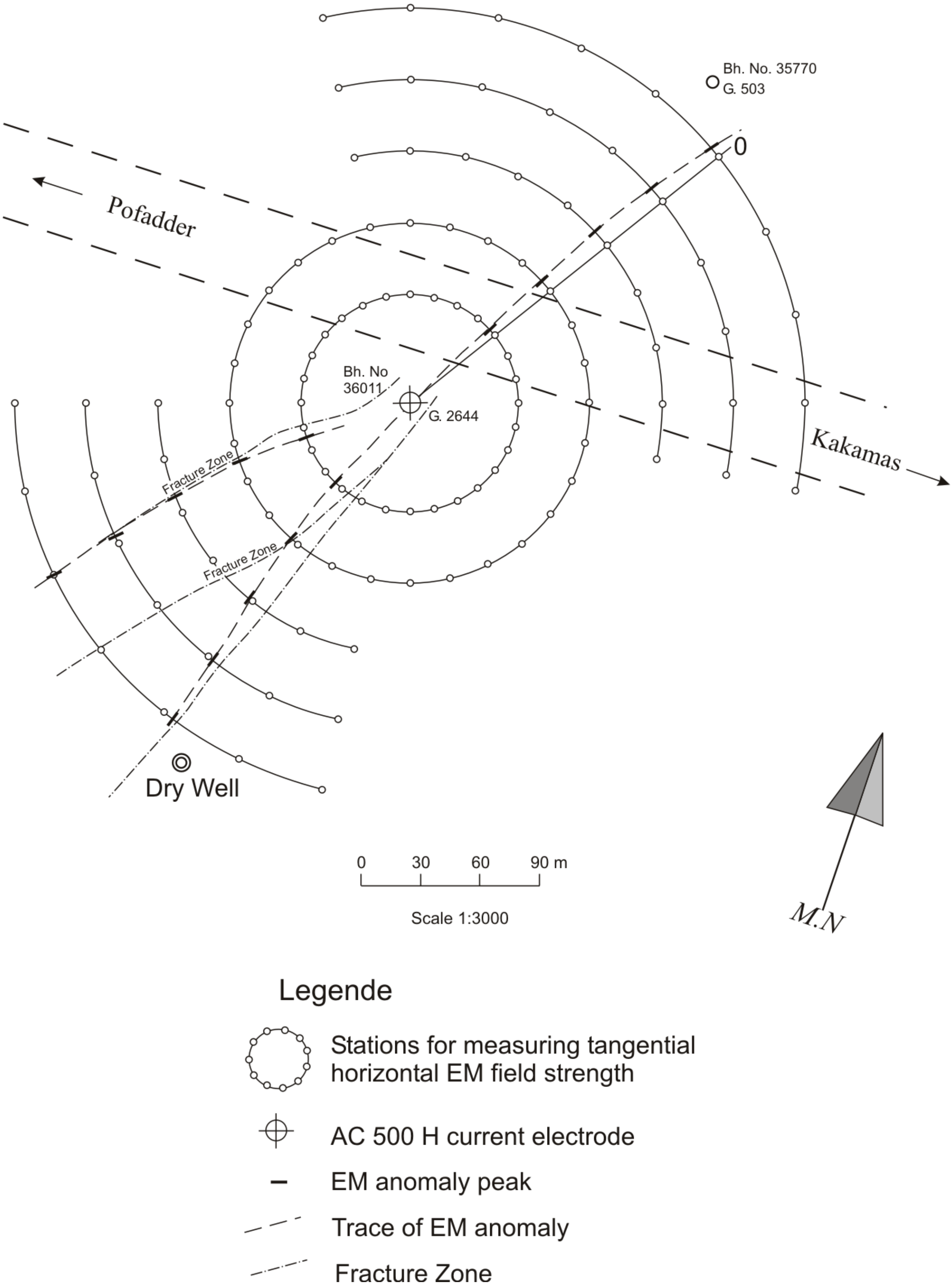


FIGURE 34b WENNER DEPTH PROBES AT BOREHOLES No's 35770 (G 503) AND 36011 (G 2644)

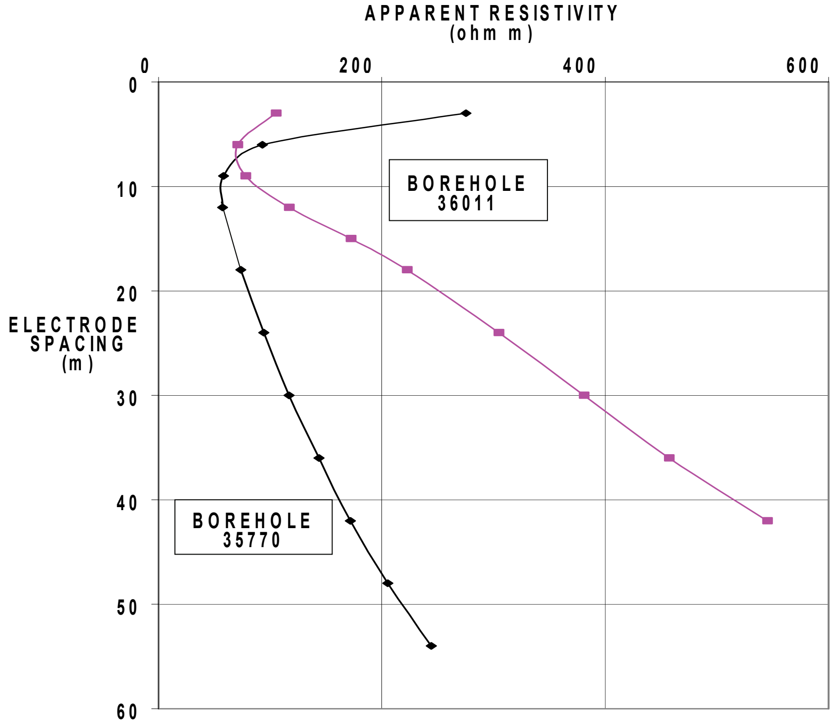
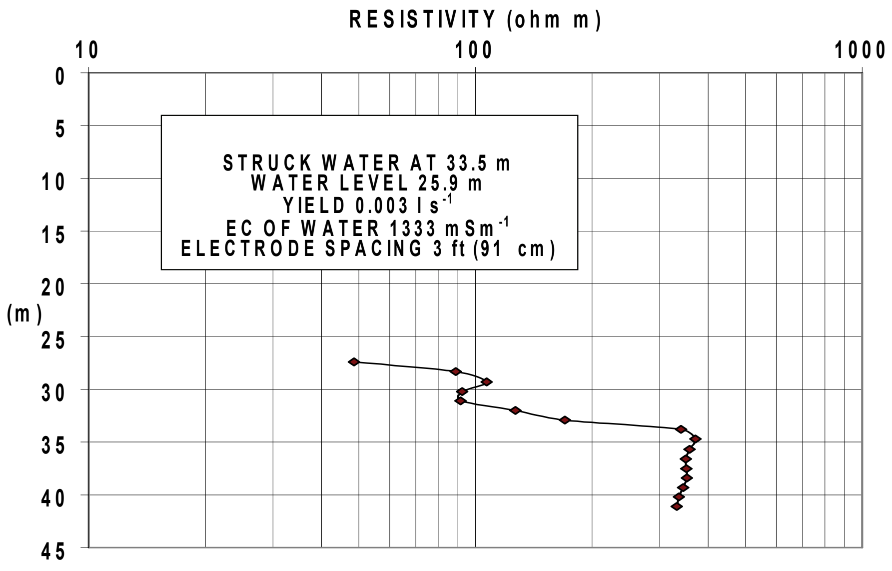


FIGURE 34c ELECTRICAL RESISTIVITY LOG OF BOREHOLE No 36011



2. <u>Boreholes No's 36508, 44674 and 46009 Lucas Vlei 93</u>

See Figure 33 for location. Drilling site G2512 (Borehole No 36508) is situated on a silicified fracture zone that is a few metres wide, trends roughly E – W and cuts through quartzite and calc-silicate rocks of the Arribees Group. Borehole No's 46009 and 44674 respectively about 690 and 330 metres to the west have also been drilled into this fracture zone. The EM surveys around boreholes 36508 and 44674 found no EM anomalies that are associated with the fracture zone. Driller's data about the boreholes follow below.

TABLE 63 BOREHOLES 36508, 44674 AND 46009 LUCAS VLEI 93

Bh No	Depth (m)	Water struck at (m)	Water level (m)		Yield (ℓs^{-1})	Thickness of near-surface weathered / fractured zone deduced from Wenner probe	Resistivity of upper weathered / fractured zone (ohm m)	Bedrock resistivity (ohm m)
			Driller's log	May 1953				
36508	102.1	86.6	92.7?	54.6	0.01	12 m	100 to 600	> 1000
44674	152.5	96.6	60.0	48.9	0.05	24 m	100 to 300	> 1000
	Water level on 13/08/1997 — 32.6							
46009	138.7	123.4	59.1	-	0.06	-	-	-

FIGURE 35a ELECTRICAL RESISTIVITY LOG OF BOREHOLE No 36508 (G2512) HELLUM PORTION OF LUCAS VLEI 93

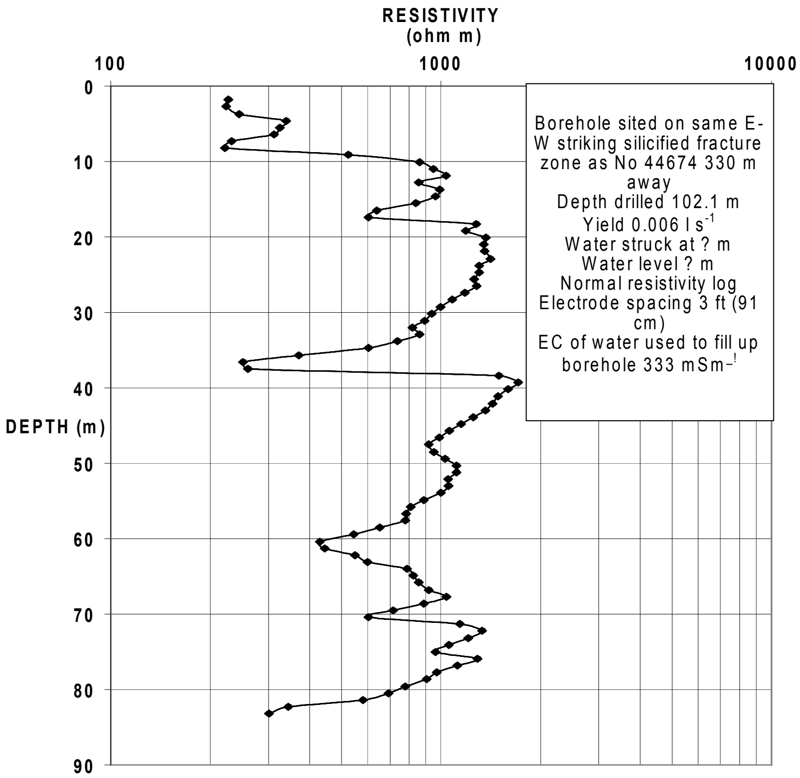


FIGURE 35b ELECTRICAL RESISTIVITY LOG OF BOREHOLE No 44674 HELLUM PT. LUCAS VLEI 93

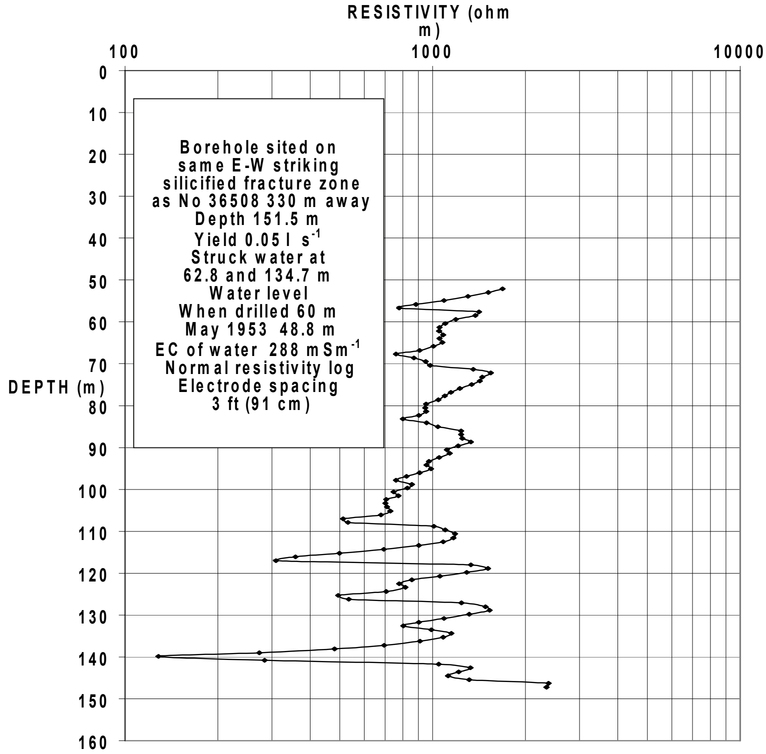
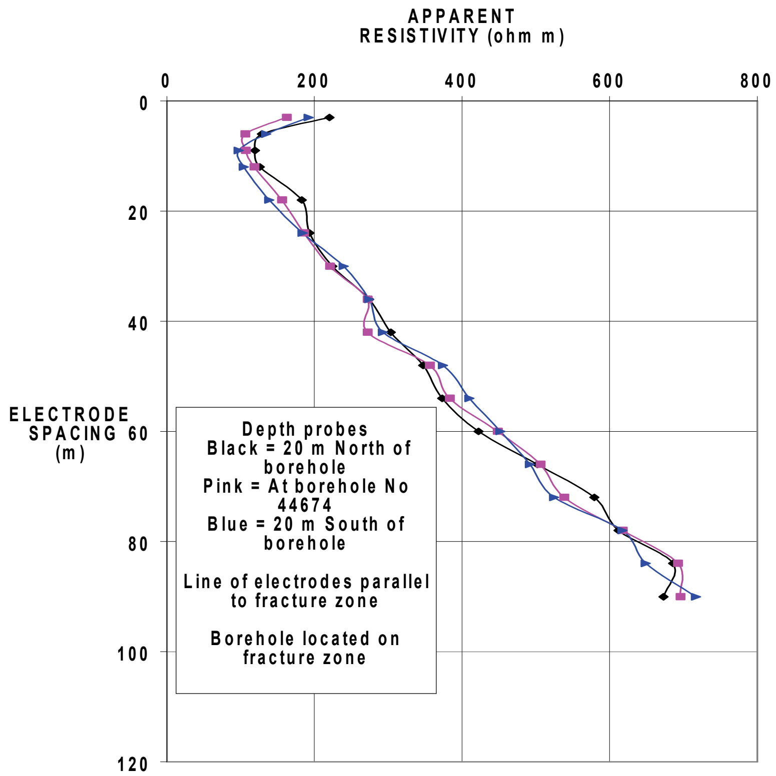


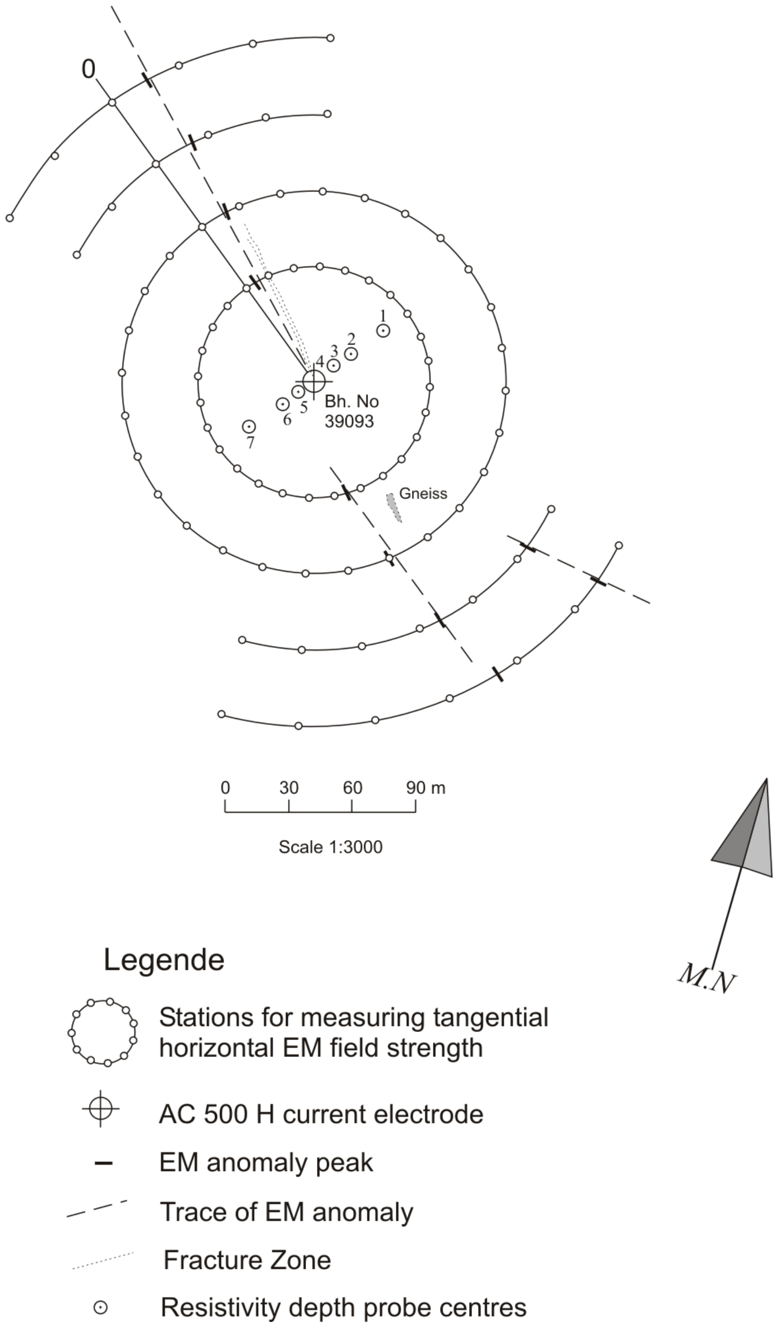
FIGURE 35c WENNER DEPTH PROBES AT BOREHOLE No 44674 HELLUM PT LUCAS VLEI 93



Electrical logs of boreholes No's 36508 and 44674 are depicted in Figure 35a and 35b. Despite the fractured nature of the rock to depths well below the water level, useable supplies of water were not struck. Wenner depth probes with electrode line parallel to the fracture zone are shown in Figure 35c - depth of weathering/ fracturing about 10 m; resistivity ≈ 100 ohm m; bedrock resistivity ≥ 1000 ohm.m.

3. Borehole No 37093 Lucas Vlei 93

Figure 36a: Electromagnetic survey at site G2648 (borehole No 37093)
Hellum 1 portion of Lucas Vlei 93 Kenhardt District



Site G2648 (Figure 33) was marked in 1948, purely on geological grounds, on a narrow E-W trending fractured mylonite zone in metamorphic rocks currently assigned to the Arribees Group. Borehole 37093 was sunk to a depth of 125.2 m. No yield was reported. However, in May 1953 water stood 82.9 m below surface. In boreholes LV 5 and LV 6 (not shown in Figure 33), respectively about 1 km north and 2 km south of borehole 37093, water levels of 45.1 and 37.4 m were measured on 13/08/1997. In view of the flatness of the terrain the water level, may have been around 40 m in borehole 37093 had it been in existence on that date. Note the large postulated water level difference between 1953 and 1997.

The galvanic EM survey which was run in 1953 located an anomaly that runs parallel to the mylonite zone and is offset 6 metres to the south (see Figure 36a). The anomaly appears to follow an en echelon pattern. A set of Wenner depth probes (electrode line parallel to the fracture zone) is shown in Figure 36b. At the borehole and to the south the formation is weathered / fractured to between 15 and 20 metres – resistivity 250 to 300 ohm m. To the north very high resistivity is indicative of no weathering / fracturing. The three northerly probes are excellent examples of the lateral effect of the low resistivity in the south.

The electrical borehole log is shown in Figure 36c. Despite low resistivity zones below the water level viz. at 88-89, 102 and 107 m, borehole 37093 failed to yield water. Taking into account the fractured nature above 82.9 m and the projected water level of 40 m in 1997, it appears likely that borehole 37093 temporally might have been capable of yielding water, provided the fractured formation is permeable. The water level appears to fluctuate by as much as 40 metres,

FIGURE 36b WENNER DEPTH PROBES AT BOREHOLE No 37093 (G 2648) LUCAS VLEI 93 portion HELLUM

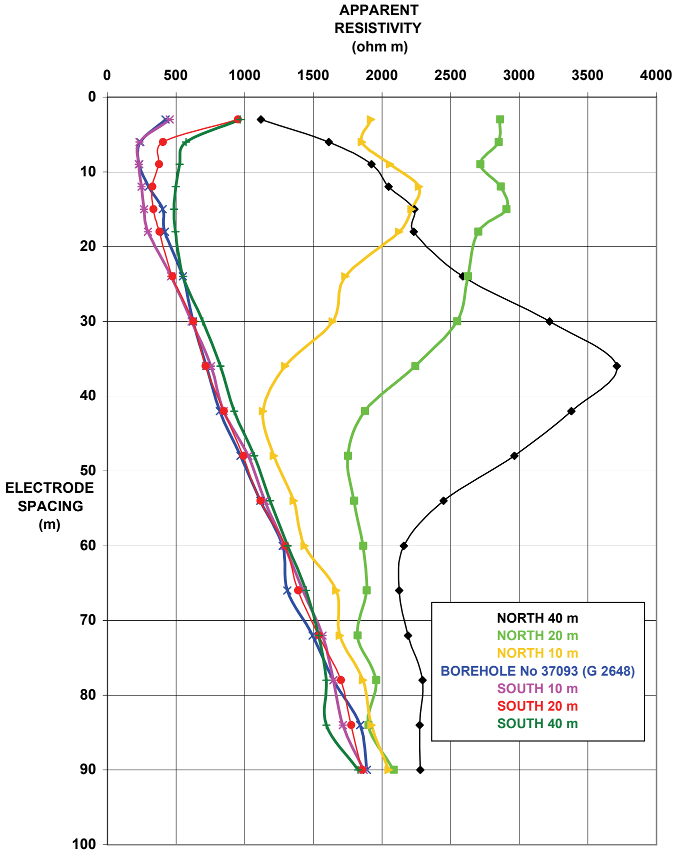
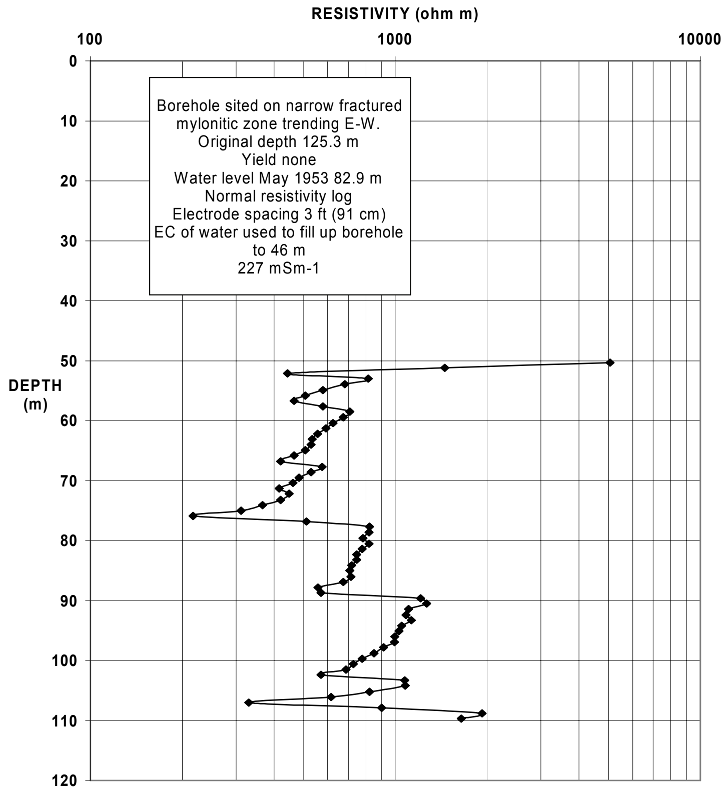


FIGURE 36c ELECTRICAL RESISTIVITY LOG
OF BOREHOLE No 37093 (G2648) HELLUM
PORTION OF LUCAS Vlei 93



4. Boreholes No's 41182, 41599 and 41832 Scuit Klip 92

In 1950 three boreholes were drilled in the southeastern corner of the farm which is underlain by Tafelkop Gneiss, a leucocratic medium-grained to augen pink gneiss (Figure 33). The holes were drilled into three more or less E-W trending fracture zones. The three holes lie almost on an N-S line – No 41182 in the north, 41599 - 1100 m away in the middle and No 41832 another 1700 m further south. Elevation differences are small – at most between 10 - 20 metres judged from the topocadastral map. Borehole data are summarized in Table 57.

On 13/08/1997 the water level in LV 13 (presumably borehole No 41832) was 73.3 m. Electrical logs of boreholes No's 41182 and 41599 are shown in Figures 37a and 37b. Borehole No 41832 was not logged being equipped with a pump. As all three boreholes lie at about the same elevation and on the same slope it is thought that their water levels should also have been approximately the same provided water had been struck in all three. If this supposition is correct hole No 41599 should have been drilled in 1950 well beyond the 76.2 m level.

TABLE 64 BOREHOLE DATA SCUIT KLIP 92

Borehole No	Depth (m)	Water struck at (m)	Yield (ℓs^{-1})	Water level (m)		
				When drilled 1950	When logged electrically June 1953	13/08/97
41182	118	-	nil	no level	55.5	-
41599	80.5	-	nil	no level	no level	-
41832	144.5	82.3 & 109.7	0.18	76.2	not available	73.54

Also one would have expected a water level around 55 m in this borehole when it was logged in 1953. Borehole No 41182 was drilled considerably deeper and nevertheless failed to strike water. With the exception of several lows in borehole No 41599, resistivity ranges in both boreholes mostly between 300 and 700 ohm m. The formation appears to be fractured but impermeable.

FIGURE 37a ELECTRICAL RESISTIVITY LOG OF BOREHOLE No 41182 SCUIT KLIP 92

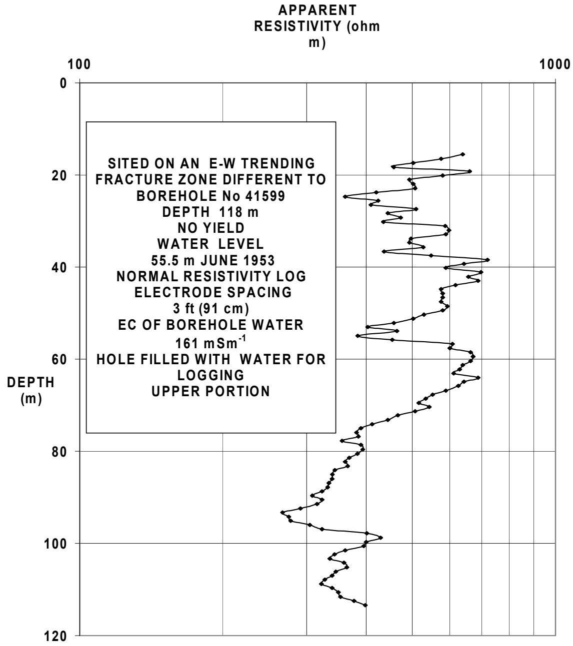


FIGURE 37b ELECTRICAL RESISTIVITY LOG OF BOREHOLE 41599 SCUIT KLIP 92

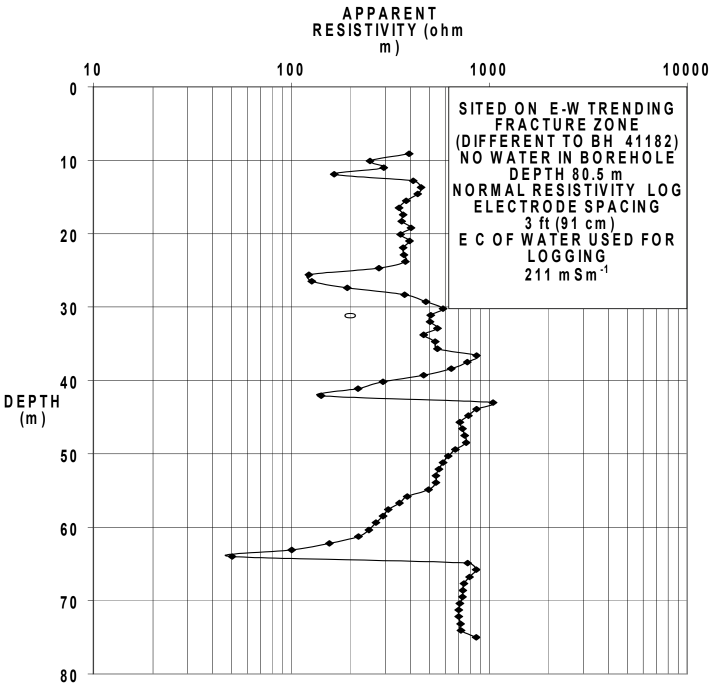
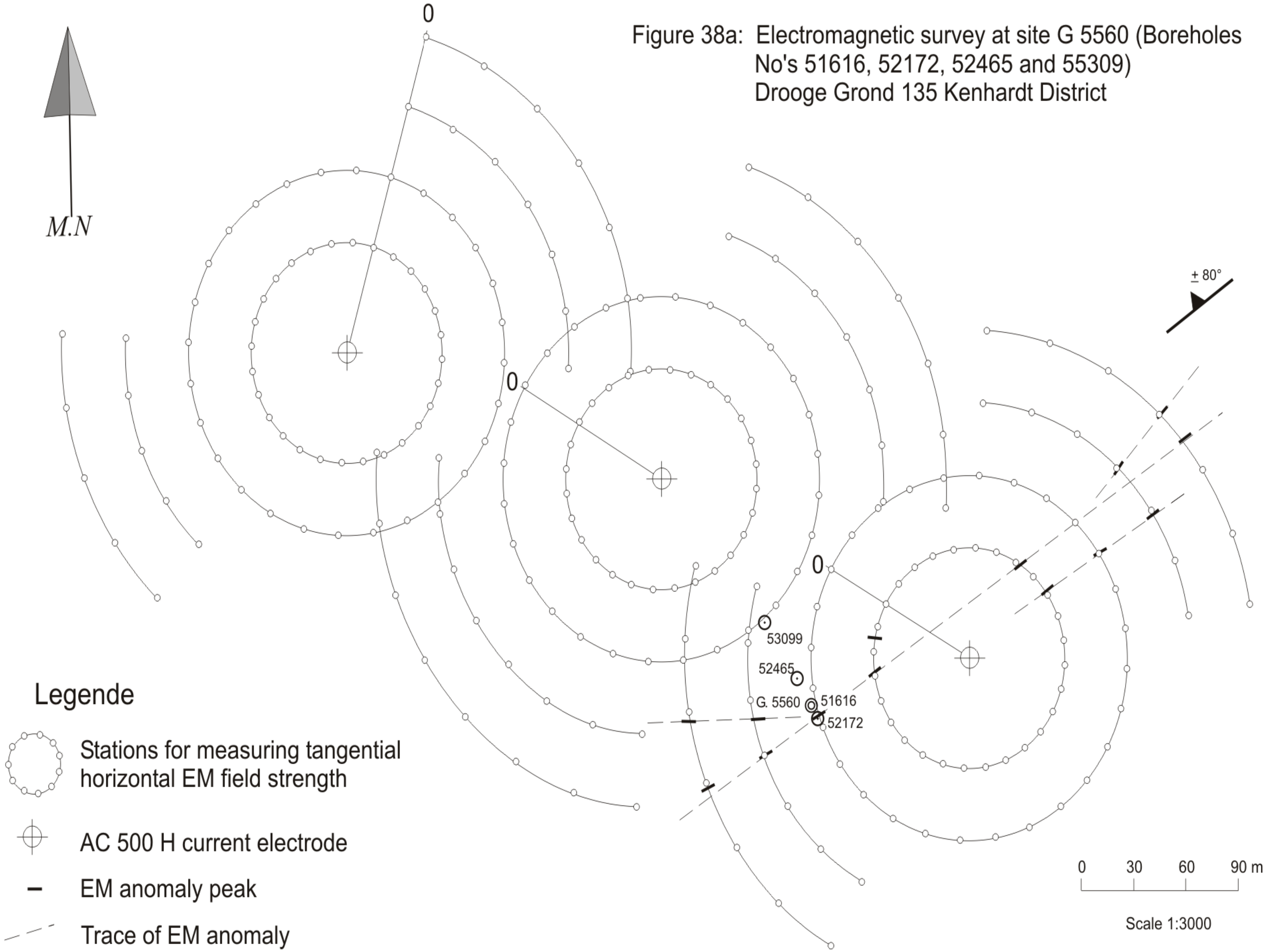


Figure 38a: Electromagnetic survey at site G 5560 (Boreholes No's 51616, 52172, 52465 and 55309) Drooge Grond 135 Kenhardt District



7.3.4 Boreholes sited and drilled on electromagnetic indications 1953

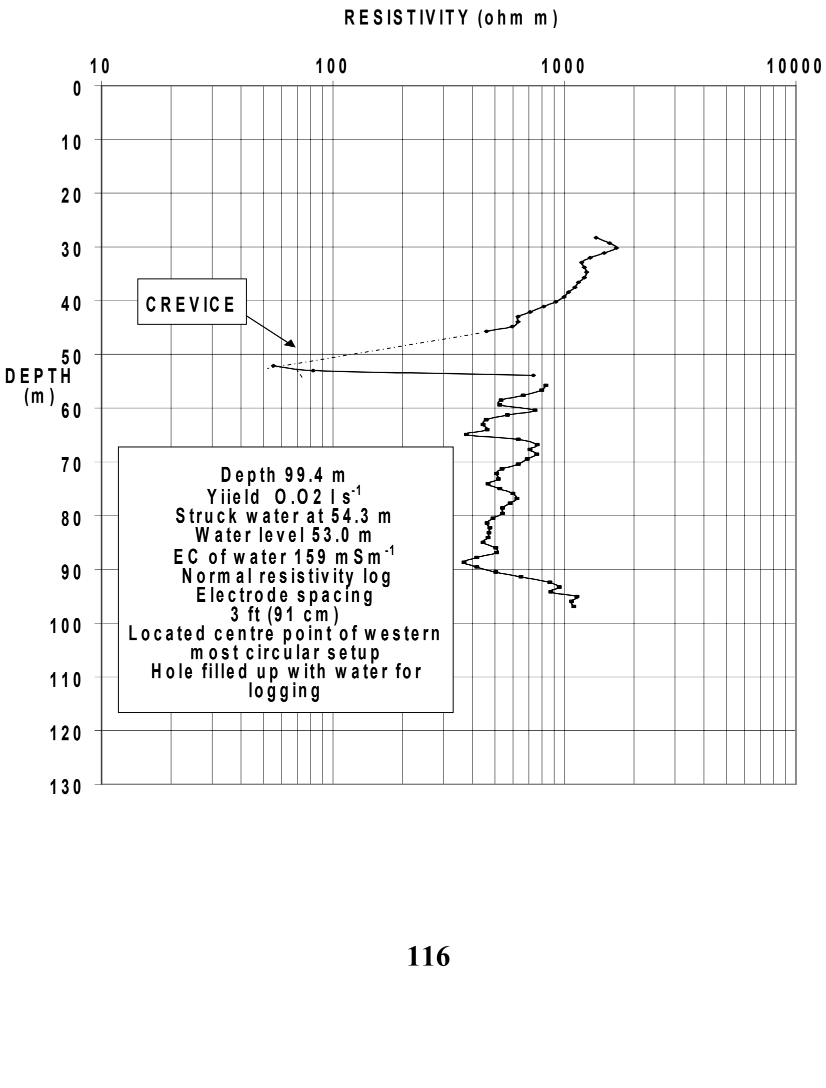
1. Drooge Grond 135 Kenhardt District:

The locality and extent of the EM survey carried out in 1953 is shown in Figure 38a. Because the note book with the EM observations is no longer available, plots of the EM anomaly can unfortunately not be produced. The conductive zone strikes approximately 40^0 East of North. The asymmetrical form of the anomaly was taken to indicate a northwesterly dip of the conductor. According to the 1:250 000 Geological Sheet Kenhardt published in 2001, the EM anomaly parallels the strike of the Droëgrond Formation of the Droëboom Group (Slabbert, Moen and Boelema 1999) which at this locality comprises of quartz-feldspar gneiss dipping about 80^0 NW.

Before four prospecting holes were drilled on the strength of the EM survey an unnumbered borehole sited by the Drilling Inspector was sunk about 320 m west of boring site G5560 and about 280 m northwest off the strike of the EM anomaly. According to electrical resistivity depth probing the depth of weathering here is about 6 metres. In this borehole which was drilled to a depth of 99.4 m a small supply of about 0.02 ℓs^{-1} (conductivity 159 mSm^{-1}) was struck in a crevice at a depth of 54.3 m – static water level 53 m (see Figure 38b for resistivity log). From 54 down to 90 m apparent resistivity ranges between 400 and 800 ohm m. No water was struck within this depth range.

The first of the four prospecting boreholes was drilled 6.1 m (20 ft) NW of the EM anomaly peak (site G5560; borehole No 51618). In this borehole (depth 65.8 m) the formation is weathered to a depth of 26 m. A zone of low resistivity was penetrated at 43.9 m (see Figure 38c).

FIGURE 38b E. R. LOG OF BORING
INSPECTOR'S BOREHOLE
DROOGEGROND 135

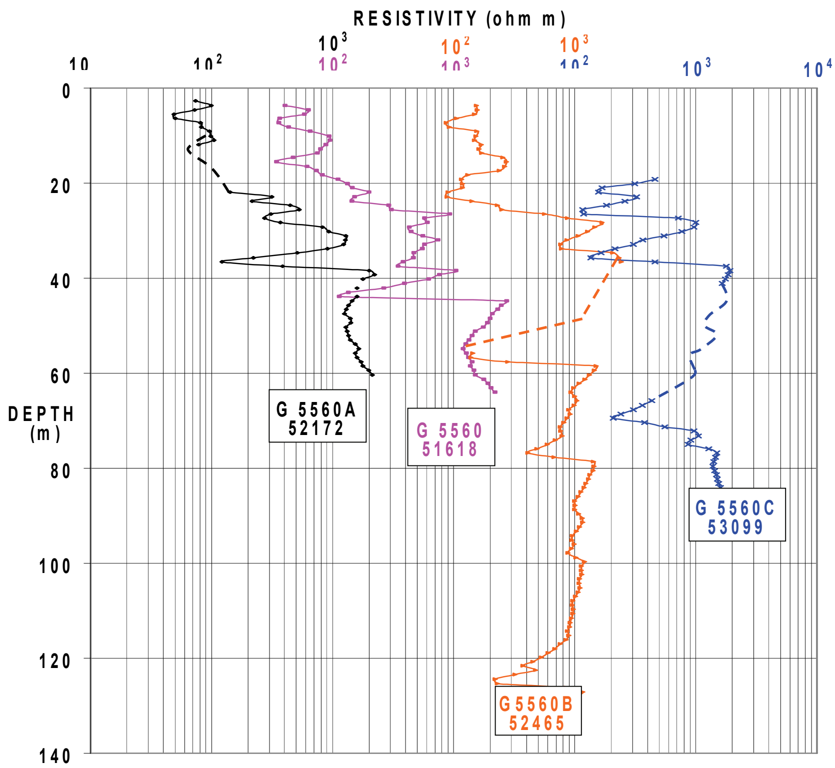


The second borehole (No 52172; site G5560A) was drilled on the EM anomaly peak. Drill cuttings indicated weathering to a depth of about 24 m and a low resistivity zone presumably corresponding to that encountered at 43.9 m in the first borehole was penetrated at a depth of 36.6 m – see Figure 38c. The 10 m section between 11.9 and 21.9 could not be logged electrically because it would not hold water. Water poured into the borehole drained away so fast that the water level could not be raised above 20 m (the section above 20 m had been logged separately before drilling proceeded deeper).

The third borehole (No 52465; site G5560B, depth 129.8 m) was sunk 24.4 m (80 ft) NW away from the EM anomaly peak. Drill cuttings indicated weathering to a depth of 29 m. This hole was unfortunately not logged electrically between 36.6 and 55.8 m (see Figure 38c). Hard fresh rock was encountered in this section. The stippled line (Figure 38c) indicates the possible appearance of this portion of the resistivity log. A low resistivity zone apparently corresponding to that in the first two boreholes appears to have been penetrated at 55 - 56 m. Water was struck at a depth of 56.4 m, static level 53.3 m and yield about 0.019 $\ell\ s^{-1}$.

Based on the assumption that the low resistivity zones in the previous three boreholes are the same feature, borehole No 53099 (site G5560C) was sited 24.4 m (80 ft) NW of the previous one with a view of striking the low resistivity zone at a depth of about 75 m. The electrical log of this borehole is unsatisfactory as one continuous log was not run once drilling was complete. Section by section was logged as drilling progressed. The result is depicted in Figure 38d. Resistivity values differed greatly where logging sections overlapped. In solid formation electrical current distribution is largely determined by the position of the electrodes relative to borehole bottom and the level to which the borehole had been filled up with water on each logging occasion. Based on the description of drill cuttings and shot drill core the probable appearance between 40 and 66 m of a continuous resistivity log is shown as a stippled line in Figure 38c.

FIGURE 36c E.R. LOGS OF BOREHOLES ON AND OFF EM ANOMALY DROOGE GROND 135



	Position relative to EM peak	Depth (m)	Water struck (m)	Water level (m)	Yield $\ell\,s^{-1}$	EC mSm^{-1}
G5560A / 52172	On peak	61.9	No	-	-	238
G5560 / 51618	20 ft (6.1m) NW	65.08	No	-	-	174 & 235
G5560B / 52465	80 ft (24.4 m) NW	129.8	56.4	53.3	0.019	270
G5560C / 53099	160 ft (48.8 m). NW	86.3	?	56.4	0.003	392

FIGURE 36d BOREHOLE 53099 (G5560C) LOGGED SECTION BY SECTION AS DRILLING PROGRESSED DROOGEGROND 135

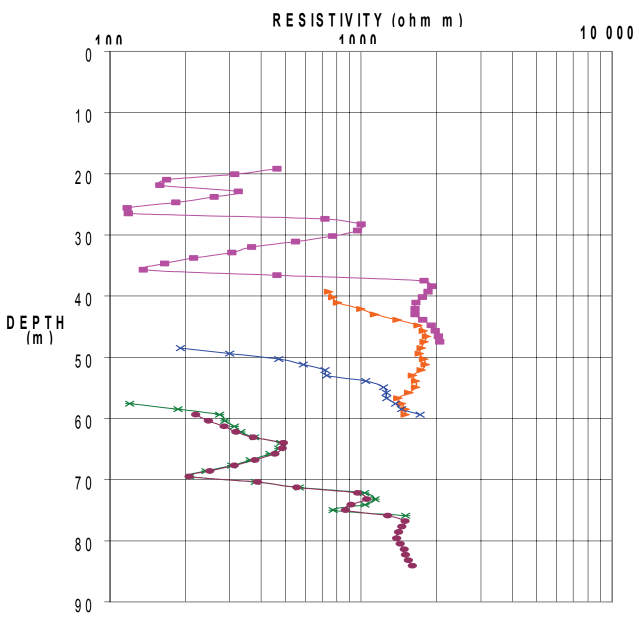


FIGURE 38e SECTION THROUGH BOREHOLES DRILLED TO STRIKE LINEAR CONDUCTIVE FEATURE DROOGE GROND 135 DISTRICT KENHARDT

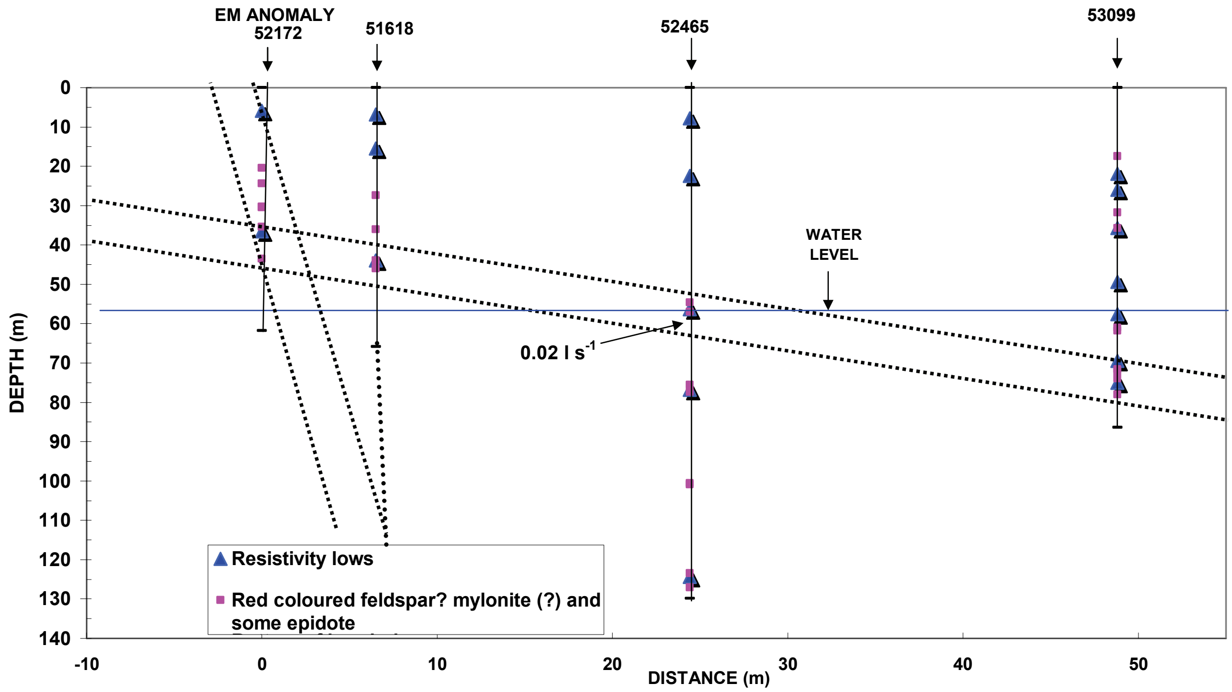
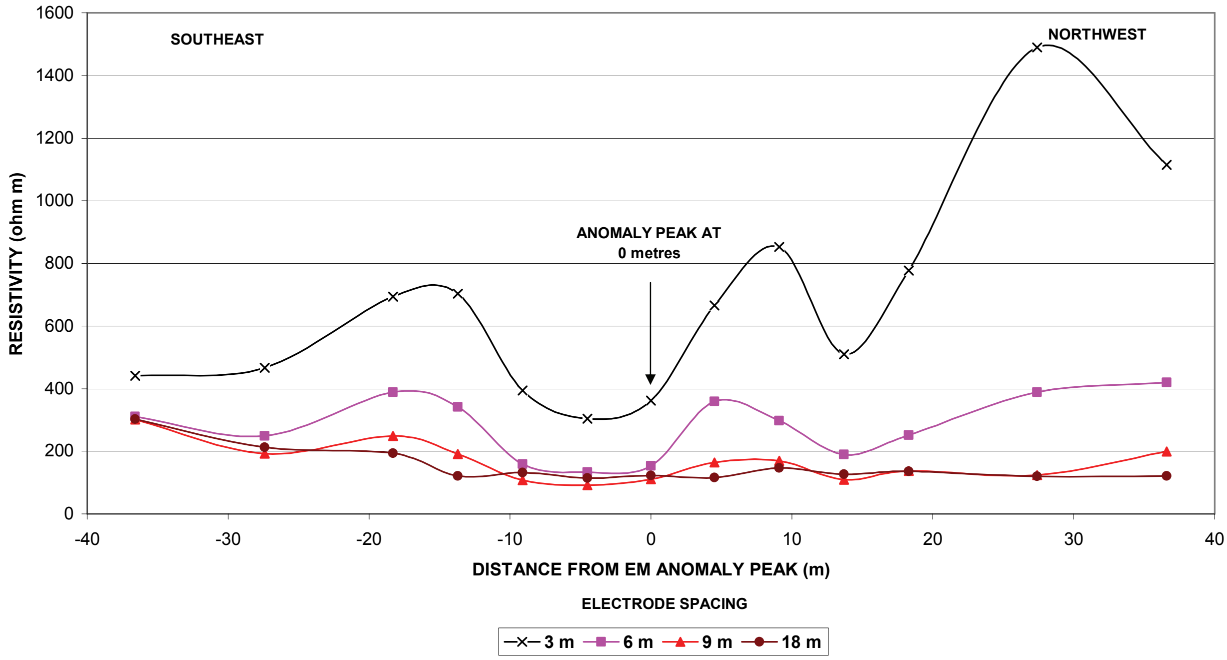


FIGURE 38f HORIZONTAL WENNER PROFILING ACROSS EM ANOMALY
DROOGE GROND 135 DISTRICT KENHARDT



On a section through the four boreholes (Figure 38e) occurrences of red drill cuttings (mylonite?) accompanied in places by epidote and the more prominent resistivity lows and their probable correlation are indicated. The question arises whether the EM anomaly is caused by the postulated feature with its dip of about 35^0. The feature should outcrop some 40 or more metres southeast of borehole 52172 (site G5560A). However, according to a series of Wenner depth probes (Figure 38f) the lowest apparent resistivity for 3 and 6 metre electrode spacing is found 5 metres to the southeast of the EM anomaly i.e. more or less where one would expect it to be in the case of a steeply dipping conductive feature. A steeper dip for the EM-traced conductive zone therefore seems to be indicated as shown in Figure 38e. If so, two drilling alternatives present themselves – borehole No 51618 could be deepened to about 120 -130 metres or a borehole could be sited between holes 52172 and 51619 so as to strike the steeply dipping feature shallower below water level. Resistivity lows yielded little water in borehole No 52465 and the one sited by the Drilling Inspector. Whether resistivity low / mylonite zones are permeable enough to yield useable supplies of water remains questionable.

1 Bank Vlei 136 Kenhardt District

The farm lies on a watershed that slopes gently in all directions. It is situated in the so-called Droogegrond Fragment (Slabbert, Moen and Boelema 1999). The locality and extent of the EM survey carried out in 1953 is shown in Figure 39a. The EM anomaly, which strikes roughly northeast, coincides with a zone of “soft” ground marked by ant-bear and mongoose holes. The “soft” ground appears to coincide with a silicified fracture zone striking parallel to that of the formation. Drill cuttings of boreholes sunk here have been described as mainly light-coloured granite with some darker zones. The Formation is therefore taken to be Droëgrond which consists of quartz-feldspar gneiss (Slabbert, Moen and Boelema 1999).

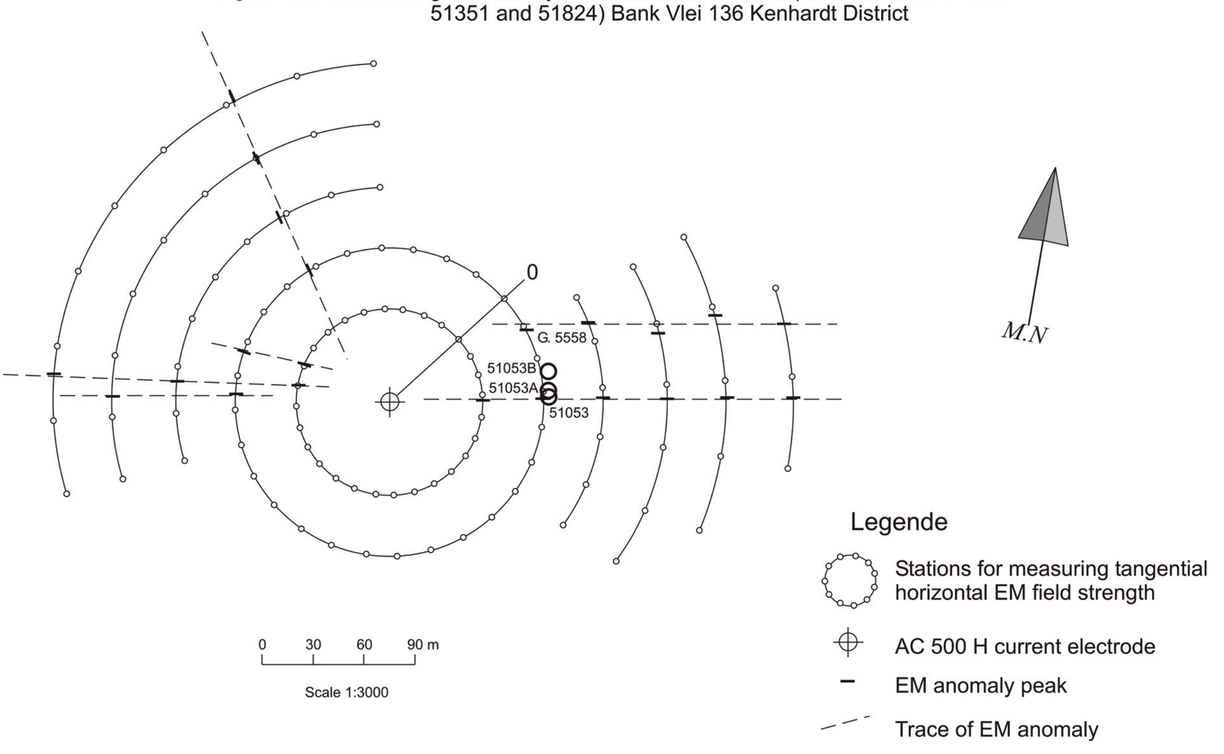
Three boreholes were drilled. The first G5558 (No 51053) on the peak of the EM anomaly was initially drilled to a depth of 64 m where after G5558A was sunk 10 ft (3 m) northwest of G5558 to a depth of 75 m. The borehole had to be abandoned at that depth as the drilling tools got stuck in the hole. Borehole G5558C 50 ft northwest of G5558 had to be abandoned likewise at a depth of 40.2 m. Eventually G5558 was deepened to 120.4 m. Water was struck at 102.1 metres (and deeper?). Upon completion the hole yielded 2.1 ℓs^{-1} and the water level stood at 97.2 metres.

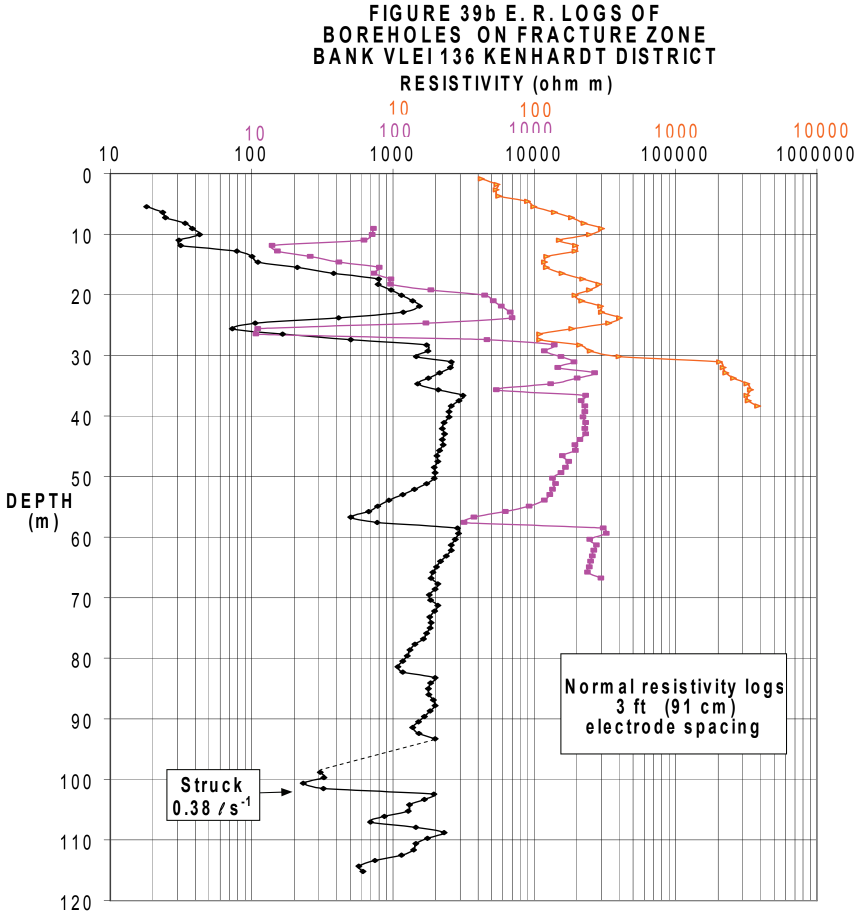
The electrical resistivity logs are depicted in Figure 39b and the geological log of borehole G5558 (D.H. van der Merwe) follows below:

TABLE 65 LOG OF BOREHOLE 51053 (G5558) BANK VLEI 136

0 to 20 m	Weathered granite (quartz-feldspar gneiss) – 20 to 1000 ohm m
20 to 31.4 m	Lesser weathered granite (alternating weathered and fresh) – 70 to 1500 ohm m
31.4 to 86 m	Hard fresh rock – 2000 ohm m – with thin zones, some rust-coloured; others described as containing some red feldspar (mylonite?) and epidote – presumably indicative of fracturing They show up as resistivity lows and were found at the following depths: 35 – 36 m; 56.7 m; 70 – 70.7 m; 79 – 80 m; 82 m and 84.- 85.6 m
86 to 120.4 m	White quartz rusty in places with yellow clay from 106 to 107 m; chunks of quartz up to 2.5 cm in size between 118 to 119,5 m Resistivity fluctuates between 250 and 2000 ohm m

Figure 39a: Electromagnetic survey at borehole site G 5558 (Borehole No's 51053, 51351 and 51824) Bank Vlei 136 Kenhardt District





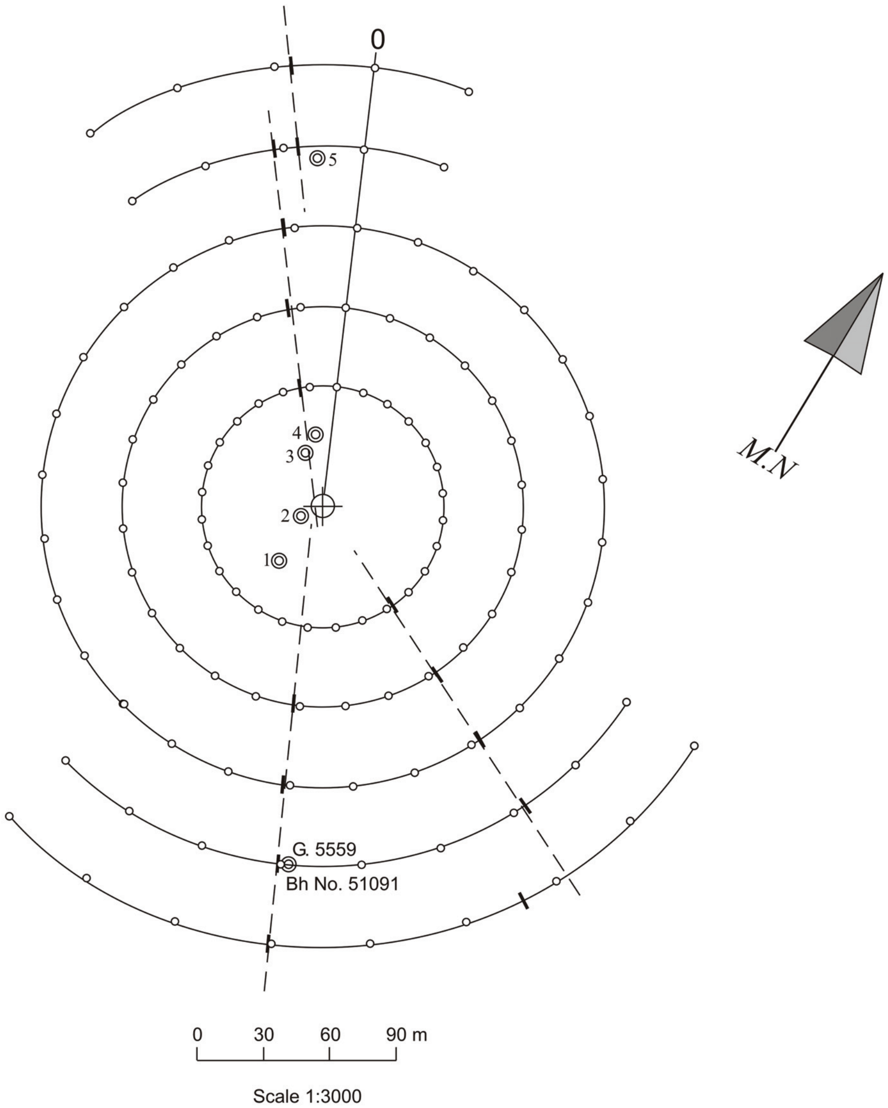
The presence of epidote, white quartz and red material (mylonite?) in certain sections of G5558 is taken as an indication that the EM anomaly corresponds to a zone of shearing / fracturing and silicification. That three holes drilled here appears fortuitous as it demonstrates that fractures (i.e. resistivity "lows") at 11, 25.6, and 34.7 m dip at low angles to the northwest. It is possible that the resistivity "lows" at 98.8 to 101.5, 107 and 114.3 m are also caused by sub-horizontal fracturing. If so, it would appear that permeable conditions are produced at the intersection of steeply dipping and sub-horizontal fracture sets.

2 <u>Swart Oup 80 Kenhardt District.</u>

Highly dissected mountainous terrain occupies the northeastern two-thirds of the farm. In its southwestern corner which is situated 15 km from the Orange River, a SE – NW trending epidotised shear zone is present in a broad sandy valley. The valley slopes in a northwesterly direction towards the Orange at a rate of about 30 m per km. The country rock is coarse-grained garnetiferous biotite-amphibolite gneiss.

The locality and essentials of the EM survey carried out in 1953 over the shear zone are shown in Figure 40a The asymmetrical form of the EM anomaly associated with the fracture zone (unfortunately not reproducible here as the field notes have been lost) led to the supposition of a northeasterly dipping structure. Drilling site G5559 (No 51091) was accordingly selected 15 ft (4.6 m) NE of an anomaly peak. After drilling this hole to a depth of 84.4 m without striking a supply, borehole No 51617 was sunk on the anomaly peak to a depth of 123.4 m – also without success. Electrical resistivity logs of the two holes are shown in Figure 40b.

Figure 40a: Electromagnetic survey at borehole site G 5559 (Boreholes No's 51091 and 51616) Swart Oup 80 Kenhardt District



Legende

Stations for measuring tangential horizontal EM field strength

AC 500 H current electrode

EM anomaly peak

Trace of EM anomaly

Borehole No	Depth (m)	Yield
1	34,7	dry
2	123.7	dry
3	Unknown	dry
4	50.9	dry
5	Unknown	dry

FIGURE 40b E. R. LOGS OF
BOREHOLES No's 51091 AND 51617
SWART OUP 80 KENHARDT DISTRICT

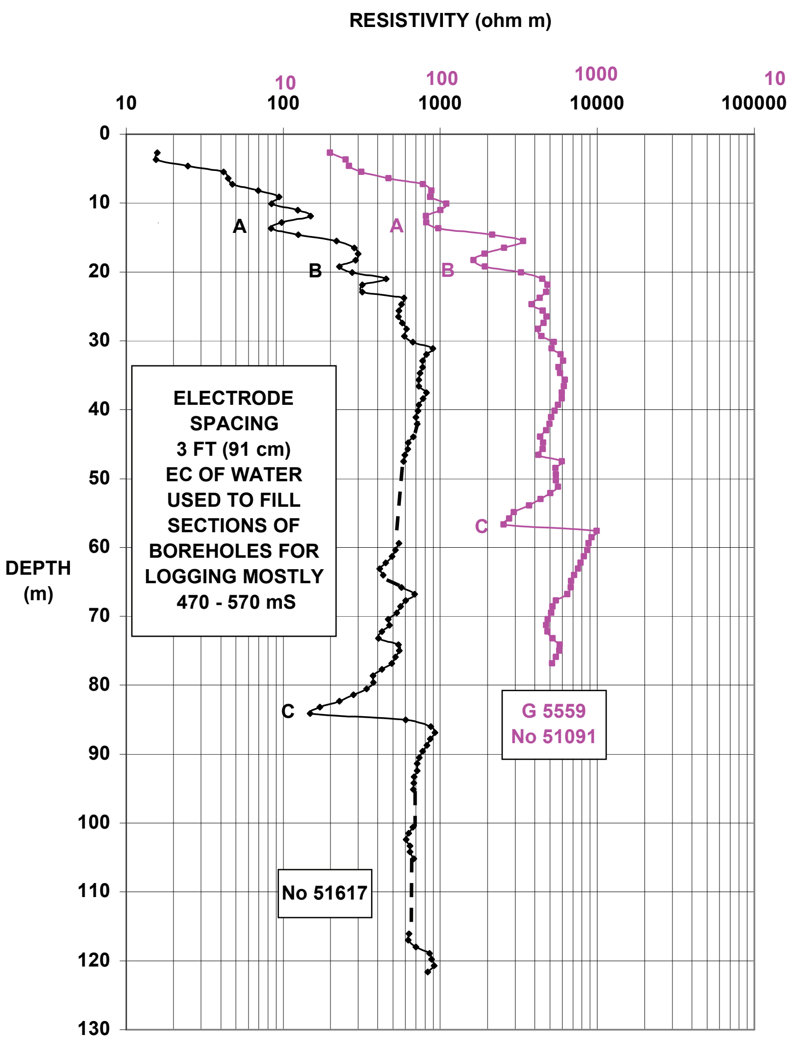


TABLE 66 GEOLOGICAL LOG OF BOREHOLE No 51091 (G5559)

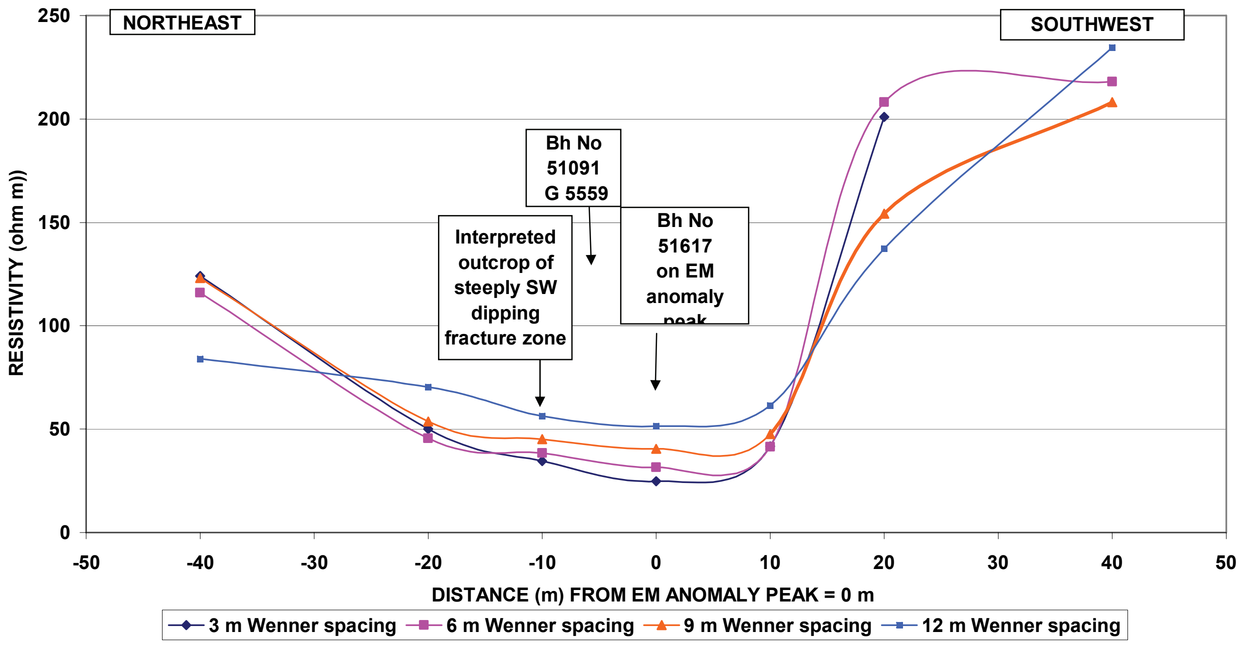
0 to 11.5 m	Weathered gneiss	20 to 110 ohm m
11.5 to 20 m	Weathered gneiss	80 to 350 ohm m
20 to 30 m	Transition from weathered to fresh hard rock	400 t0 500 ohm m
20 to 84.4 m	Fresh hard gneiss with “softer” fractured zones between 43 – 47 m, 50 – 57 m, 71 – 77 m; epidote and red-coloured chips present	500 to 600 ohm m; lower resistivity zones coincide with “softer” zones mentioned alongside

TABLE 67 GEOLOGICAL LOG OF BOREHOLE No 51617 (G5559A)

0 to 12.5 m	Weathered gneiss	15 to 150 ohm m
12.5 to 23 m	Weathered gneiss	80 to 400 ohm m
23 to 123.4 m	Fresh hard gneiss with “softer” fractured zones between 61 -70 m epidote and red feldspar (mylonite?) in cuttings, 84 -85 m red feldspar (mylonite?) and 102 - 103 m	600 to 700 ohm m Lower resistivity zones coincide with “softer” zones mentioned alongside

As in the case of Bank-Vlei, resistivity lows marked “A” and “B” indicate fracturing at about 14 and 18 m below surface. The dip is southwestwards at a low angle. Correlation of resistivity lows marked “C” at 56.7 and 84.1 m below, if correct, signifies a feature dipping at an angle of about 80^{0} SW instead of NE. According to the CST resistivity traverses (Figure 40c) near-surface resistivity is lower on the NE up-dip than on the down-dip side. This explains the asymmetrical form of the EM anomaly and the originally deduced NE dip.

FIGURE 40c HORIZONTAL WENNER PROFILING ACROSS EM ANOMALY SWART OUP 80 KENHARDT DISTRICT



There appears to be two reasons for failure to strike water:

a) The fracture zone is impermeable; and/or

b) The water level is deeper than 84 m.

The first has been proven to a depth of 84.1 m by the fact that water used to fill up the boreholes for logging did not drain away.

The elevation of the water level at site G5559 may be interpolated from the following:

- the estimated surface elevation of 790 m.a.m.s.l and a water level of 40.5 m at borehole No 49885 on Scuit Klip 92 approximately 4,8 km upstream; and
- the estimated surface elevation of 600 m.a.m.s.l and a water level of 93 m at borehole No 38501 on Oupvlakte 90 about 7 km downstream.

Interpolation yields a water level of about 80 m (estimated surface elevation 730 m.a.m.s.l). Considering that this is a very rough estimate and that the fractures may be clay-filled above the water level, an attempt at penetrating the fracture zone at a depth of 100 m or more below surface may be justified especially if cognizance is taken of the large temporal fluctuations of the water level in this area.

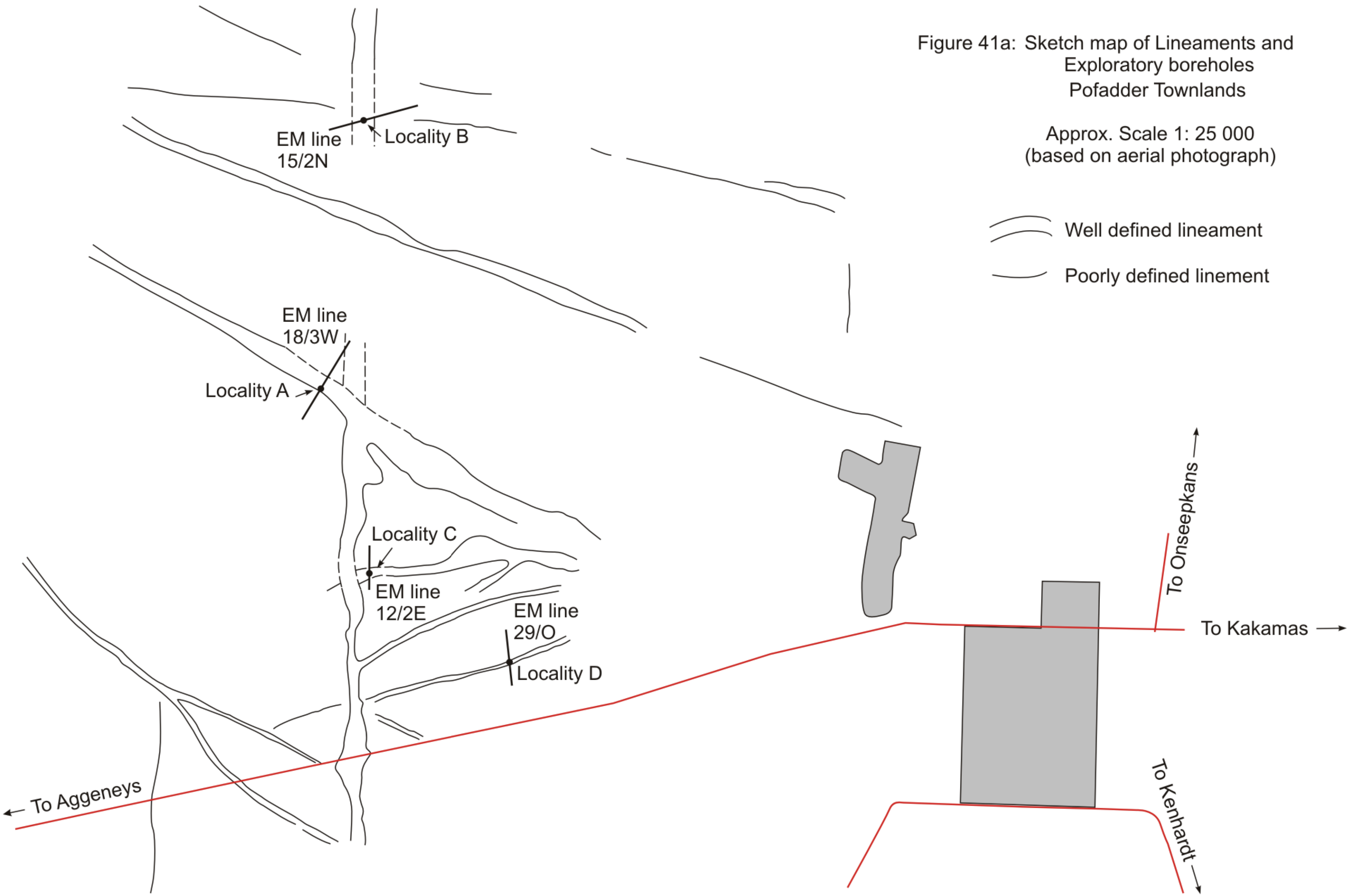


Figure 41a: Sketch map of Lineaments and Exploratory boreholes Pofadder Townlands

Approx. Scale 1: 25 000
(based on aerial photograph)

7.3.5 EM survey, drilling and electrical borehole logging Pofadder Town lands

In 1981-2 M. Jackson of the Directorate of Geohydrology undertook a hydrogeological cum geophysical survey and supervised a drilling programme that was undertaken with the aim of augmenting the municipal water supply (Jackson 1982; Kok 1982). B. L. Venter of the Directorate undertook the continuous analog logging with Mount Sopris equipment.

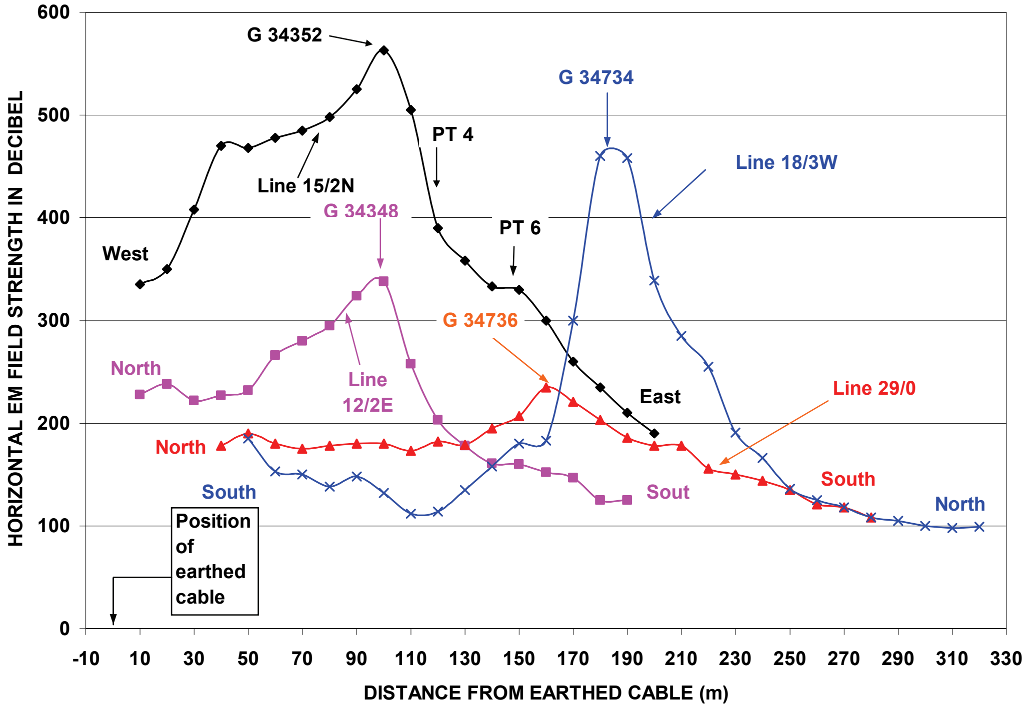
Fracture traces northwest of the town that are clearly visible on aerial photographs and are marked in places by "gannabos" *(Salsola* species) were surveyed electromagnetically (see Figure 41a). The country rocks comprise porphyroblastic granite-gneiss and grey gneiss. M. Jackson (1982) described the vein-filled fractures associated with the lineaments as follows:

a) An east-west set mainly less than 30 cm in width that is partially or wholly in-filled with drusy quartz and calcite.
b) A north-south to northwest-southeast trending set of fractures that are commonly in-filled by amorphous silica or by veins of pegmatitic material.

Weathering is very shallow on the porphyroblastic granite-gneiss and grey gneiss – mostly not more than several metres. The degree of weathering is slight overall.

The galvanic EM technique employed is that described by Vegter (1962). Most of the lineaments that were investigated produced a related EM anomaly. The lines of anomalies were approximately parallel to the lineaments but not necessarily coincident with fracture outcrops. Not all of the lineaments produced EM anomalies. Horizontal resistivity profiling or depth probing across the lineaments / EM anomalies was unfortunately not done.

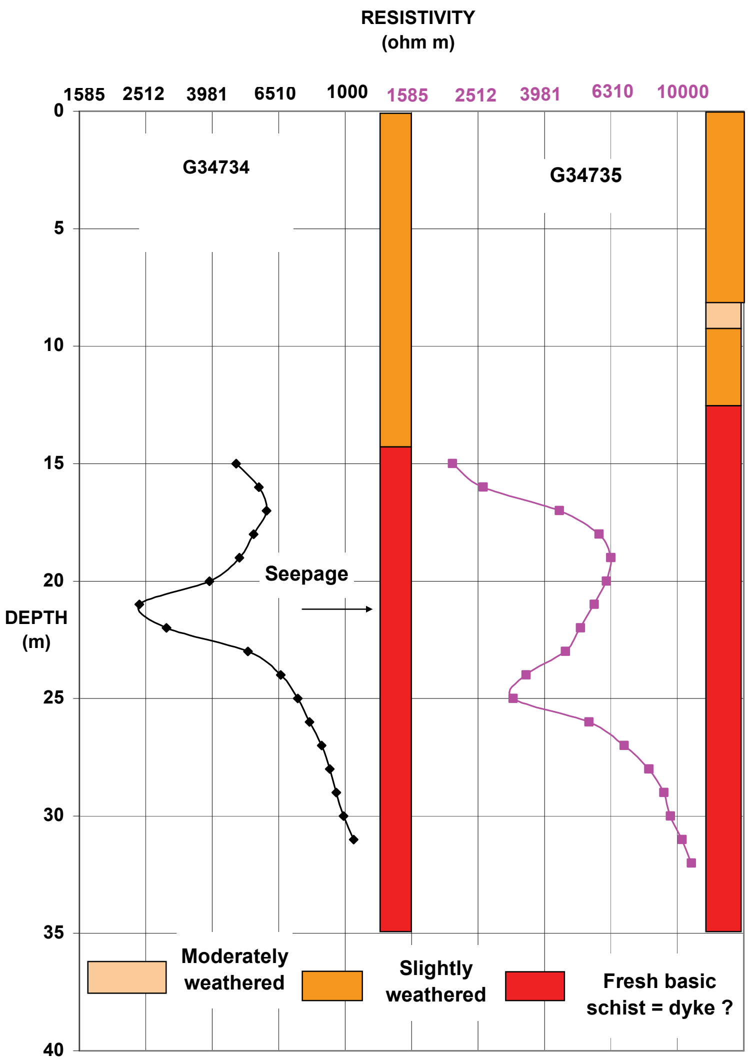
FIGURE 41b ELECTROMAGNETIC ANOMALIES ACROSS LINEAMENTS POFADDER TOWN LANDS



On lineaments that produced EM anomalies twenty-one exploratory boreholes were drilled at seven different localities. A total of 1650 m was drilled. Borehole depths ranged from 27.5 to 152 m. Water was struck in 19 holes at depths ranging from 10 to 100 metres. The results were not very encouraging. Ten of the sixteen boreholes at five localities yielded between 0.11 to 1.82 ℓs^{-1}. Two localities (5 boreholes) yielded less than 0.1 ℓs^{-1}. Water levels are rather shallow: they ranged from 7.5 to 15.7 m. Electrical conductivity of the groundwater ranges from 40 to 100 mSm^{-1}. The temperature gradient from the water level to 50 metres below surface averages 0.0066 $^{0}C\ m^{-1}$. Below 50 metres it increases to 0.0158 $^{0}C\ m^{-1}$. Some of the drilling results are discussed below.

Locality A: Boreholes G34734 and G34735

FIGURE 41c E.R.HOLES G 34734 AND G34735 LOCALITY A POFADDER



NOTE Borehole G34734 on EM peak; G14735 5 m off peak. Normal 40 cm electrical log; EC of water 54.5 and 43.5 mSm^{-1}.

The holes were drilled on a line of prominent EM anomalies following a 3 km long NW trending lineament. See Figures 41a, 41b and 41c for respectively location, EM anomaly, the electrical resistivity and geological borehole logs. Note the sharpness and magnitude of the EM anomaly compared to the other anomaly curves. Qualitatively this is indicative of current flow along a shallow and narrow zone. Note also the very high resistivity of the fresh rock, the shallow water level and for these parts, the comparatively low conductivity of the water.

A narrow zone of weathered rock 13 to 15 metres thick as encountered in the two boreholes appears to be responsible for the EM anomaly. Apart from mentioning the presence of well-weathered basic schist as reason for the EM anomaly Jackson has not provided lithological logs. Is this lineament a metamorphosed basic dyke? Note that the lateral extent of weathering has not been determined by electrical depth probing.

The resistivity "lows" penetrated at 21 and 25 metres in the two boreholes were not evident in the drill cuttings. The feature responsible for the resistivity "lows" was apparently not penetrated. It appears to be close to but offset from the boreholes. Its apparent dip is 39^0 northeast. Its relationship, if any, to the EM anomaly and northwesterly striking lineament remains obscure.

Locality B: Boreholes No's G 343 52 to G 343 57

Six boreholes were drilled in grey gneiss across a north-south lineament that can be followed for 4.5 km. See Figures 41a and 41b for location and the EM anomaly. Electrical resistivity logs of the six and of two prior sunk boreholes, PT 4 and PT 6 are depicted in Figures 41d and 41e. Geological logs with the exception of boreholes G34356, PT 4 and PT 6 are shown in Figure 41f.

FIGURE 41d E.R. LOGS OF BOREHOLES No's G 34352 TO G 34357 LOCALITY B POFADDER

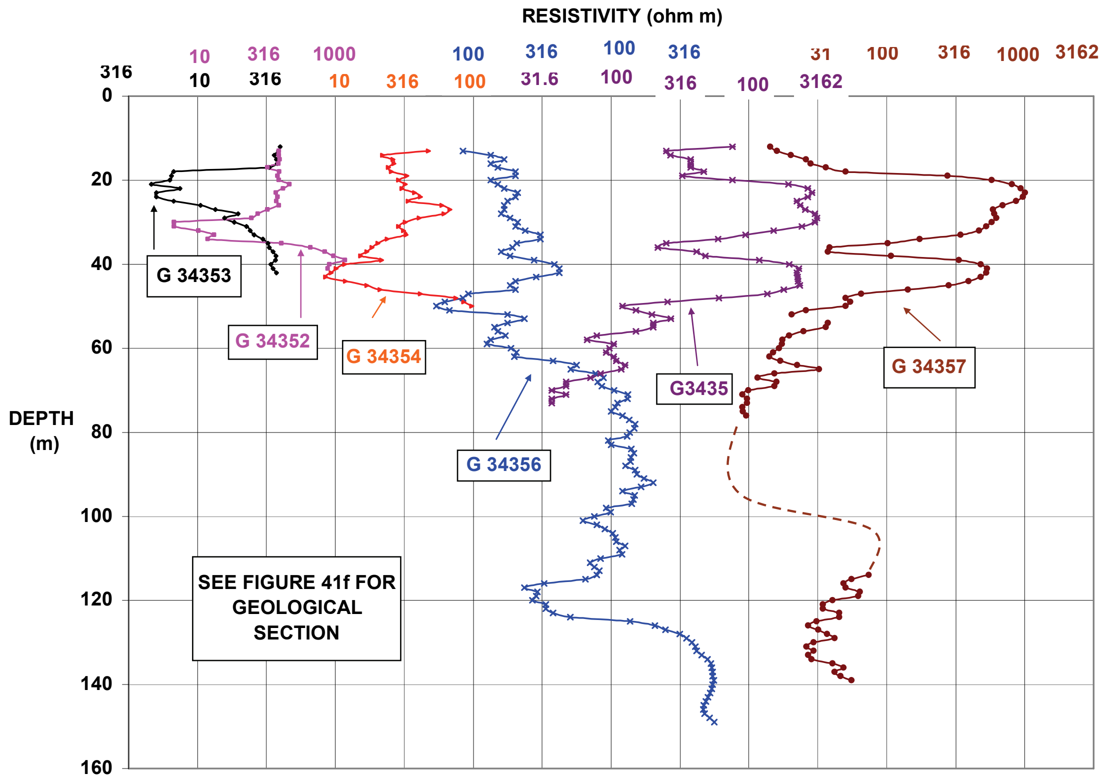
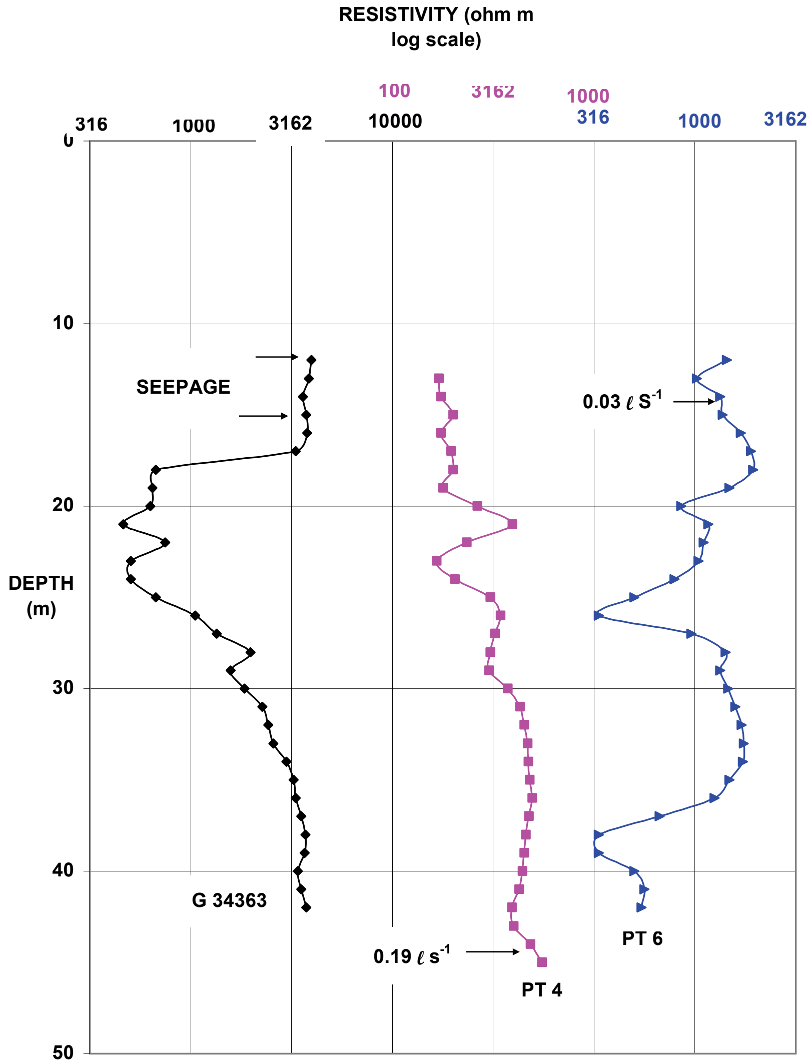


FIGURE 41e E. R. LOGS OF
BOREHOLES G 34353 . PT 4 AND PT 6
LOCLITY B, POFADDER

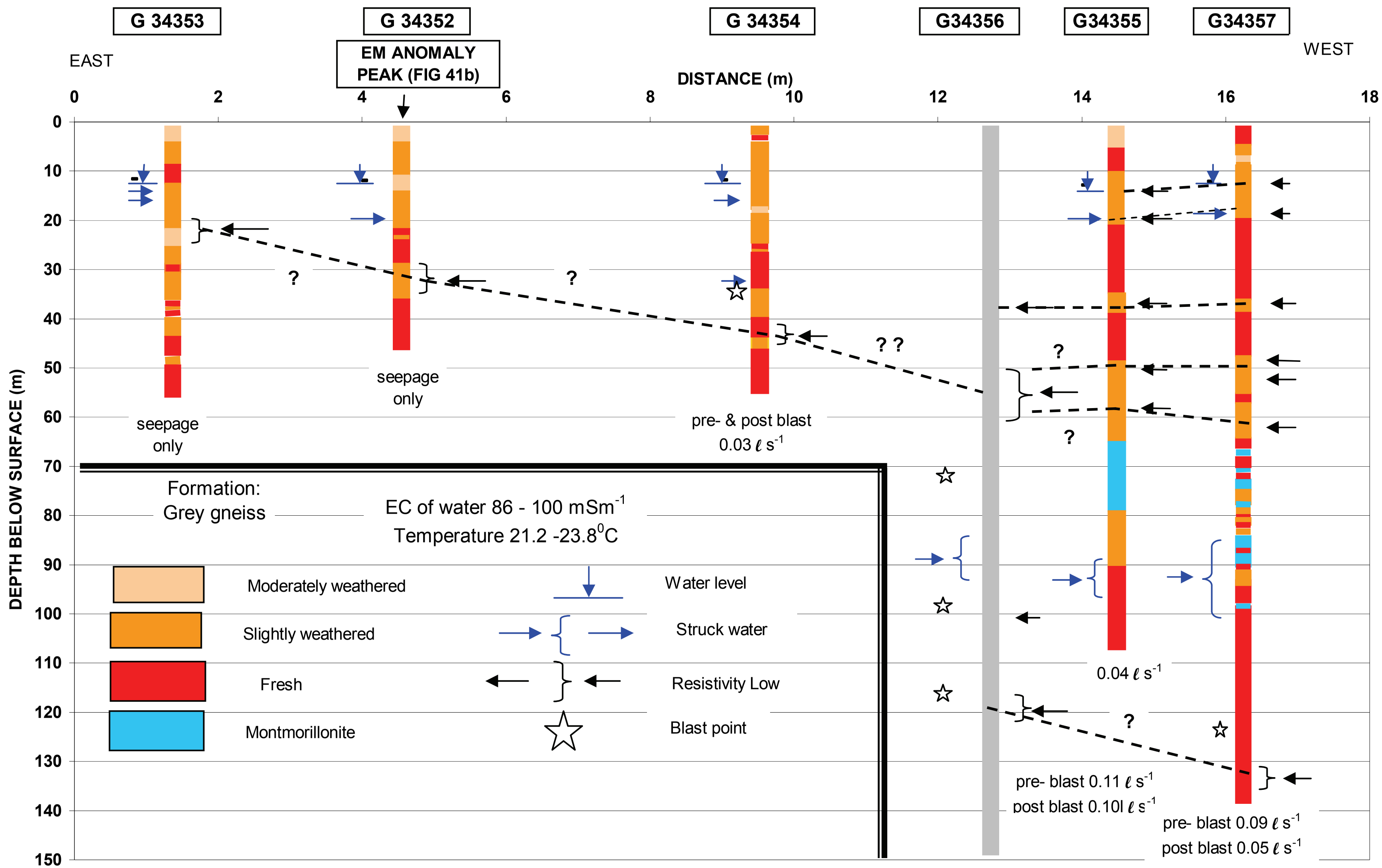


According to Jackson no fracturing was encountered in the six holes. However, alternating bands of weathered and fresh rock presumably indicative of fracturing were penetrated. In G 34355 a 14 metre thick zone of highly weathered material composed mainly of montmorillonite was encountered at 63 metres. A similar weathered zone but with intermittent montmorillonite was found in G 34357. Caving of borehole walls occurred in all six boreholes generally at or close to resistivity "lows". Borehole G 34357 had to be cased to 112 m because of collapse below 80 metres.

It is a pity that the log description of G 34356 is missing. If the correlation of resistivity-low zones indicated by stippled lines in Figure 41f is correct, this hole occupies a position between two domains as shown in Figure 41f:

- The eastern domain is characterized by a resistivity 'low' that dips westward at an angle of about 70^0.
- In the west several resistivity "lows" are present that either lie more or less horizontal or dip eastward at low angles.

FIGURE 41f GEOLOGICAL SECTION THROUGH BOREHOLES No's G 34352 TO G 34357 ACROSS EM ANOMALY LOCALITY B POFADDER TOWN LANDS



Boreholes PT 4 and PT 6 are situated on the steep eastern flank of the EM anomaly respectively 14 and 44 m east of borehole G 34353 (Figure 41d and 41e) i.e. 19 and 49 m east of the EM anomaly peak. For comparison the electrical log of G 34353 has been included with those of PT 4 and PT 6 in Figure 41f. Resistivity ranges between 1600 and 5500 ohm m in borehole PT 4 and between 333 and 2000 ohm m in borehole PT 6. The electrical logs of G 34353, PT 4 and PT 6 are not obviously correlable. The electrical conductivity of the water in these two boreholes is 80 and 83 mSm^{-1} comparable to the 85 to 100 mSm^{-1} range in boreholes No's G 34352 to 57.

Borehole No's G34352 to G343457 show that the lineament represents a zone of en echelon fracturing rather than a single well-defined fracture. The core of the zone appears to be about 10 metres wide from borehole G34352 to G34356. It either stands vertical or dips steeply to the west. Note also the double-peaked character of the EM anomaly. The existence of a parallel zone of fracturing some 50 – 60 metres farther west is indicated.

In spite of the shallow water level and weathering / fracturing to about 100 m one hole only yielded just over 0.1 ℓ s^{-1}.

<u>Locality C: Boreholes No's G 34348 to G 34351</u>

FIGURE 41g E. R. LOGS OF BOREHOLES No's G 34348 TO G 34351 LOCALITY C POFADDER

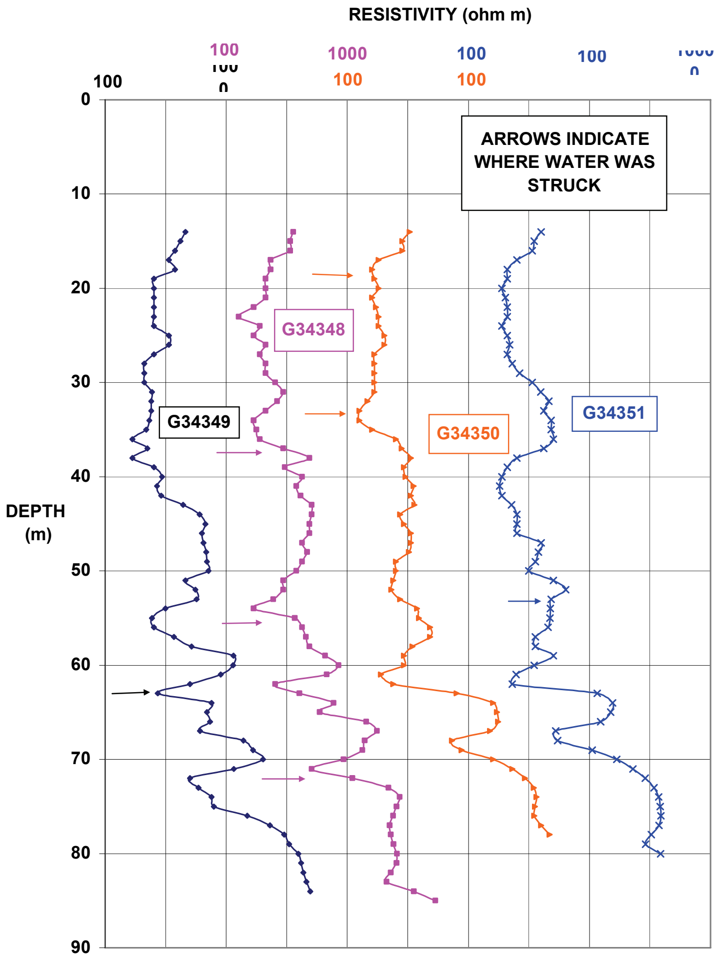
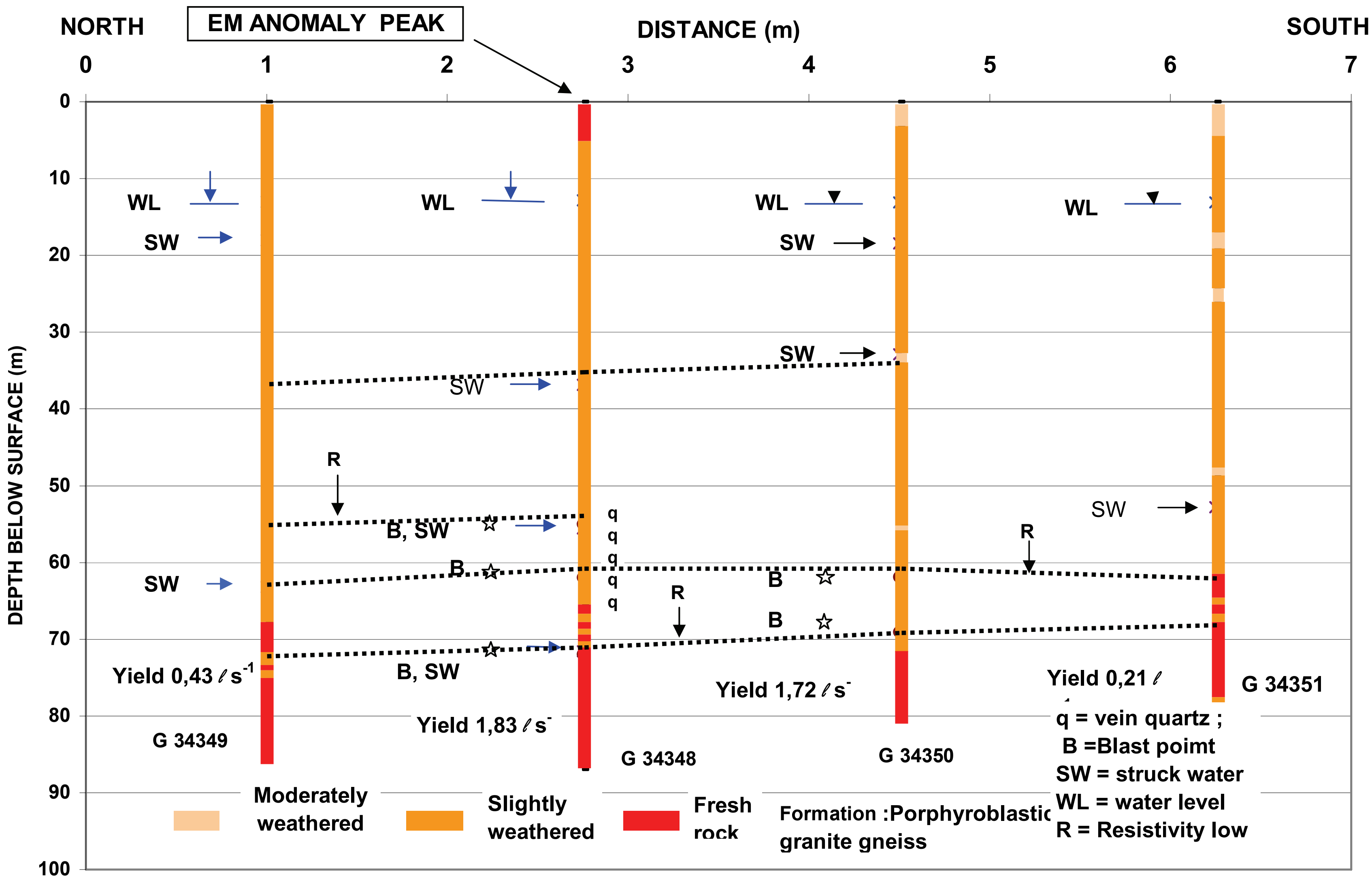


FIGURE 41h GEOLOGICAL SECTION THROUGH BOREHOLES No's G 34348 TO G 34351
LOCALITY C POFADDER TOWN LANDS



Four boreholes were drilled across an east-west lineament that can be followed for 1.5 km in porphyroblastic granite gneiss. From several small outcrops and surface float it is apparent that the feature is a fracture zone partially infilled with drusy quartz and calcite. The feature is similar to the fracture on which the then main municipal production boreholes had been drilled. See Figures 41a and 41b for location and the EM anomaly. Electrical resistivity logs of the four boreholes are depicted In Figure 41g. Geological logs and section are shown in Figure 41h.

The line of EM anomaly peaks does not coincide with the strike of the vein outcrop but corresponds to a linear occurrence of “ganna” shrubs. Borehole G34348 was drilled on an EM anomaly peak about 9 metres north of the vein feature. The formation was weathered down to 72 metres. The main water strike was in a 2-metre wide fracture zone with considerable amount of drusy quartz between 55 and 57 metres.

In the other three boreholes (see Figure 41h) the depth of weathering is roughly the same. However no drusy quartz was encountered in any of the holes. The lateral extent of weathering is unknown as it was unfortunately not determined by electrical depth probing. With the exception of borehole G 34349 evidence of fracturing was found in the drill cuttings of remaining three holes. Resistivity “lows” as indicated by stippled lines in Figure 41h dip northwards around 40^0.

The resistivity “lows’ are presumed to be planes of jointing in the granite gneiss unrelated to the EM anomaly. It is thought that the EM anomaly is caused by a more or less vertical zone of weathering and en echelon fracturing. The zone appears to be 10 or more metres wide. Drusy quartz occurs presumably as lenticular bodies within this zone.

<u>Locality D: Boreholes No’s G 34736 to 34738</u>

FIGURE 41i E. R. LOGS OF BOREHOLES No's G34736, G34737 AND G34738 LOCALITY D, POFADDER

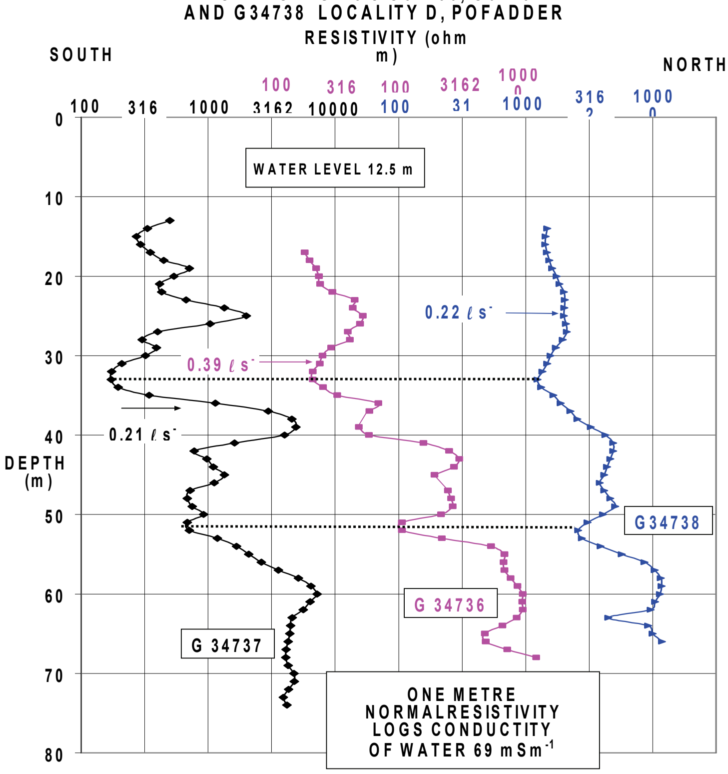
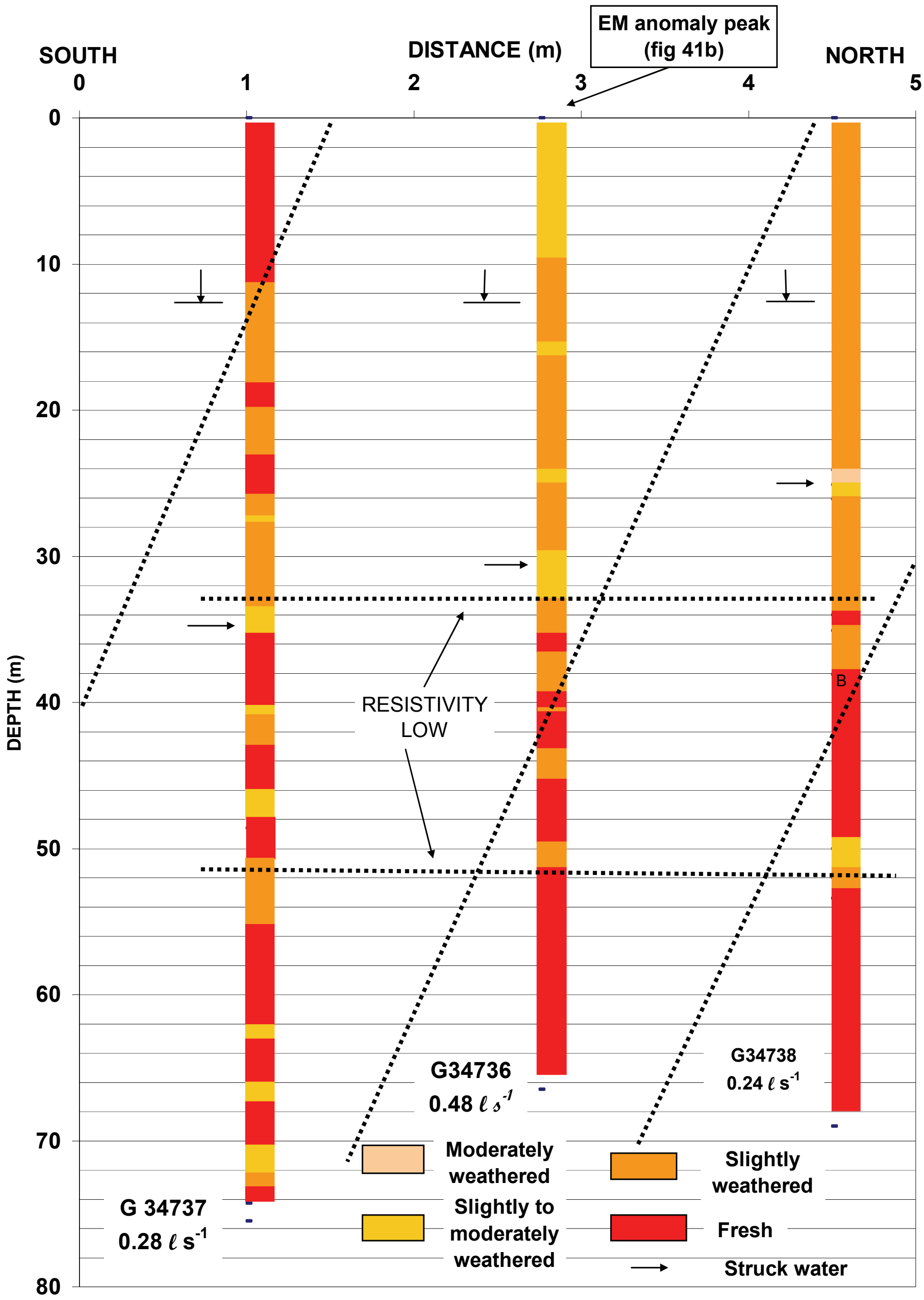


FIGURE 41j GEOLOGICAL SECTION THROUGH BOREHOLES
G 34737, G34736 AND G34738 LOCALITY D, POFADDER



Three boreholes were drilled across an east-west lineament similar to the previous. The drusy quartz character however is less developed. See Figures 41a and 41b for location and the EM anomaly. Electrical resistivity logs of the three boreholes are depicted In Figure 41i. Geological logs and section are shown in Figure 41j.

As in the previous case the line of EM anomaly peaks does not coincide with the outcrop of vein-filled fractures, but follows a line of well-burrowed ground and “ganna” vegetation. Consistent weathering was found to a depth of 35 metres in borehole G34736 after which fresh and weathered zones alternated down to 51 metres. The first 35 m is characterized by resistivity values ranging between 200 and 500 ohm.m. From 40 to 50 m resistivity ranges between 1900 and 3000 ohm m before dropping to a low at 52 m. Thereafter resistivity increases to more than 4500 ohm.m.

Borehole G 34738 follows the same pattern as G 34736. Although the formation in borehole G 34738 is also consistently weathered down to 35 m the degree of weathering is mainly slight. The lesser degree of weathering is also indicated by resistivity values varying from 1200 to 2100 ohm.m. The section 35 to 52 metres is also characterized by higher resistivity.

Apart from resistivity “lows” at 33 and 52 metres that can be correlated with “lows” of boreholes G 34736 and G 34738, geological and resistivity logs of borehole G 34737 are different. The first 11 metres consist of fresh rock where after alternating zones of weathered and fresh formation follow to beyond 70 metres.

The higher resistivity values and lesser degree of weathering at G34738 probably indicate that the borehole was drilled close to the northern edge of the fracture zone. As G 34737 started in fresh rock it likewise is situated at the southern edge. It is surmised that the fracture zone is about 5 metres wide and dips south at an angle of about 88^0 as shown in Figure 41j.

Blasting

Because of the disappointing drilling results – only two boreholes yielded more than 1 ℓs^{-1} – experimental down-hole blasting was undertaken in 5 boreholes at localities B and C in an attempt to increase their yields. Explosive charges of pentolite of about 5 kg were made up and detonated per blast point. Blast points are shown on geological sections Figures 41f and h. The results are shown in the Table 68.

TABLE 68 RESULTS OF BLASTING EXPLORATORY BOREHOLES

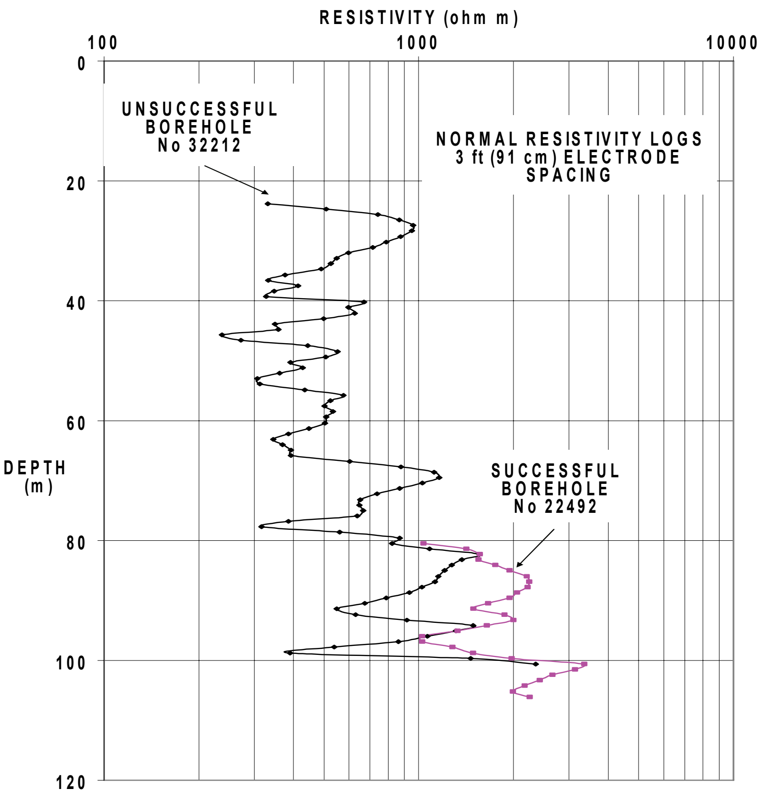
Locality	C	C	B	B	B
Borehole No	G 34348	G 34350	G 34357	G 34356	G 34354
Depth of hole (m)	87	80.75	140	152	55
Depth of casing (m)	9.7	8.1	111.8	4.1	1.75
Blasting depths (m)	55, 63, 75	62, 69	124	72, 99, 117	30
Yield before blasting	1.83	1.72	0.09	0.11	0.03
Yield after blasting	2.9	3.16	0,05	0.10	0.03

7.4 CONCLUSION

The usefulness of resistivity depth probing in the Bushmanland Groundwater Region is largely restricted to determining depths of weathering and thickness of alluvial deposits in areas with shallow water levels, weathering depths and water level < about 30 m. The 30 to 40 % chance of striking water may otherwise be enhanced by around 5 - 8 percent by siting boreholes on the greatest depth of weathering / fracturing even though the interpreted depth falls short of the water level. Rectangle profiling though cumbersome may further be of assistance in locating narrow electrically conductive zones that potentially may be deeply weathered / fractured.

Galvanic and inductive electromagnetic surveys are useful in locating and tracing two-dimensional bodies of weathered or fractured rock. With the modern frequency-domain equipment inductive EM techniques should supersede (if it has not already done so) horizontal resistivity profiling and galvanic EM surveying in the location of narrow linear conductive zones As electromagnetic anomalies are caused by the concentration of current in the near-surface weathered sections of fracture zones, anomalies as such are not indicative of deep fracturing. Not all fracture zones and lineaments produce EM anomalies. Lack of response does not necessarily entail lack of fracturing in depth. In some instances water has been struck in silicified breccia zones that appear tight on the surface.

FIGURE42 E. R. LOGS OF TWO BOREHOLES LONGZIEK VLEI 151 DISTRICT KENHARDT



Borehole Information

Borehole Number	22492	32212
Depth (m)	107.9	111.3
Struck water (m)	98.8	93.3
Yield (ℓs^{-1})	3.8	0.01
Water level (m)	61 (1937); 78 (1953)	81.8 (1946(
Electrical conductivity (mSm^{-1})	115	222 (filled-up for logging)

A successful borehole is not guaranteed once weathered / fractured formation has been located below the water level. In addition to providing storage space, the voids produced in hard rocks by fracturing and weathering must allow a flow rate capable of maintaining a borehole supply. Lack of permeability is due to either fracture tightness or to secondary infilling. The condition of permeability is not met in a large number of cases for example:

- On Long Ziek Vlei 151 (Figure 42) fractured formation yielded water in one instance and failed in another under conditions that appear to be similar.
- Figures 31, 34c, 35a and b, 38a *inter alia* and the Pofadder exploration results clearly demonstrate the presence of weathered / fractured rock that is deficient in permeability.
- In the 416 NGWDB boreholes of Subdivision 6 for example, 290 water strikes were reported. The 290 strikes were made in 266 i.e. 63.9% of the boreholes. Only 140 i.e. 48.3% of the strikes exceeded the minimum of 0.1 ℓ s^{-1}. Ninety-eight were reported to

be zero whilst 52 yielded between 0.01 and 0.09 ℓ s^{-1}. (zero-yield strikes are presumably manifested by damp drill cuttings).

- In an appreciable number of successful NGWDB boreholes throughout Region 26, one, two even three shallower zero-yielding strikes below water level have been reported in addition to the deeper successful one. In these cases infilling of fractures by secondary weathering products rather than fracture tightness appears to be the reason for lack of permeability.

The existence of dry fractures within the zone of saturation has been advanced as reason for failure to yield water. Hodgson (1985 and 1986) reported on transmissivity determinations in 24 boreholes surrounding the nuclear waste disposal site on Vaalputs (for more see Chapter 4 paragraph J and section 7.2.3). Eight of these boreholes were also test pumped. The transmissivity measurements consisted of isolating 5-metre sections of boreholes at a time and injecting water under pressure into them. According to Hodgson the existence of permeable joints and cracks below the water table was proven by these tests not only in water-yielding but in dry boreholes as well. This led Hodgson, followed by Levin (1988) to conclude that a large proportion of fractures are not interconnected with water-filled ones.

The packer tests however produced transmissivity values ranging between 0.01 and 1 m^2d^{-1} irrespective whether boreholes yielded water, were damp or dry. These transmissivities are in line with zero or virtually zero borehole yields. Five-metre sections containing logged damp spots and water strikes yielded values approaching 1 m^2d^{-1}. These values however are at least one order of magnitude smaller than transmissivities derived from test-pumping. Hodgson does not comment on this discrepancy. The current author is loathe accepting the idea of dry fractures within the zone of saturation and suggests that something is amiss with the packer tests and their evaluation. Failure of fractured formation to yield water is more likely ascribable to a lack of permeability caused by deposition of secondary minerals. In Vaalputs borehole PBH 16 a 2-metre wide zone in which water was struck is described as a "mixture of fresh red granite and yellowish and white weathered feldspar forming kaolinitic lumps". Test pumping yielded a transmissivity of 26 m^2d^{-1}, whilst packer testing of the water-yielding zone produced a transmissivivity of 0.92 m^2d^{-1}.

By plotting on stability diagrams after Freeze and Cherry (1979 p 277) log $(Na^+)/(H^+)$, log $(Ca^{2+})/(H^+)$, and log $(K^+)/(H^+)$ against log $Si(OH)_4$ of groundwater from the Vaalputs disposal site, Levin (1988) showed that sodium silicate minerals in solution are in equilibrium with montmorillonite while the potassium silicate minerals fall on the boundary between potassium feldspar and kaolinite. The stability of these minerals in the geochemical environment is confirmed by the presence of kaolinite, illite and montmorillonite in the surficial sediments.

Levin (1988) also plotted the Ca^{2+} and the CO_3^{2-} activities calculated for some groundwater samples from the disposal site on a calcite activity diagram. It was found that the water is saturated with respect to calcite. This is supported by the presence of calcite veins in the clayey formations in the unsaturated zone and in fracture fillings below the water table.

As groundwater from the Vaalputs disposal site conforms to that of the Region (see Chapter 9) lining of fractures by secondary clay minerals and / or calcite seems also likely elsewhere in the Region especially under conditions of sluggish groundwater flow and long contact time.

8. RECHARGE AND WATER LEVEL FLUCTUATION

Infiltration

Factors determining groundwater recharge under reigning Bushmanland climatic and geological conditions were discussed by Vegter (1953). He concluded that in contrast to areas with thick sand cover, recharge is favoured by shallow sandy soil, calcrete and exposures of fractured rock. The reasons are twofold:

- A thick sand-cover retains and prevents rain water from entering the underlying formation and thus allows its complete dissipation through evapotranspiration. On the other hand once rain water has passed through the shallow cover and has entered the underlying fractured rock evapotranspiration loss is minimized.
- Runoff is promoted by shallow sandy soil, calcrete and rock exposure and accumulates in laagtes and rivers. Here the concentrated volume favours recharge provided infiltration is not inhibited by the presence of clayey soil.

Tritium determinations of moisture in the surficial deposit profile at the Vaalputs radioactive disposal site (Levin et al 1986) indicated that "young" recharge water only percolates down to about 3 metres. Changes in soil moisture were also closely monitored with a neutron soil moisture meter in 9 aluminium-lined auger holes. After 128 mm of rain on four days in December 1985 infiltration only reached 2.5 to 3 m.

It is of interest to note that the sandy gritty clay in which the disposal trenches at Vaalputs are located has a sodic character (Levin 1986 et al; Levin 1988). Sodic soils inhibit downward movement of moisture because of their sodium exchange capability. The colloidal soil fraction becomes dispersed or deflocculated when in contact with rain water. The distribution of sodic soils throughout the Region and hence the extent to which they inhibit recharge is not known.

Water level fluctuations

Large fluctuations came to light when water levels on the farms Lucss Vlei 93, Bank Vlei 136 and Longziek Vlei 151 were measured by the Directorate of Geohydrology during the 1997/8 hydrocensus. Borehole positions on these farms had been mapped in 1953. Thus water levels recorded when the boreholes were drilled could be compared to those measured in 1997/8.

These fluctuations are evidence of:

- Groundwater recharge. The nearest rainfall station to these farms (No 247/ 688A) is at Pofadder where the mean annual rainfall amounts to 122 mm. During the period 01/07/1996 to 30/06/1997 220 mm were recorded here. Rainfall at Kenhardt was also above normal during this period. It is surmised that this season was one of above normal rainfall over the greater part if not all of Bushmanland and that the high levels found in August 1997 may be ascribed to recharge.
- Groundwater flow and discharge despite groundwater's chemical character which is generally assumed to be indicative of sluggish / stagnant conditions (Levin 1988; Johnson 1975; see Chapter 9). The 1953 water level in borehole No 51053 on Bank Vlei 136 was measured at the time the borehole was drilled and electrically logged (see section 7.3.4). The nearest pumped borehole at that time was 12 km away. Borehole 53051 has been in use since then.
- Storage very limited - restricted to the occasional open fracture in fresh hard rock as has been clearly demonstrated by the very poor drilling results.

TABLE 69 WATER LEVEL FLUCTUATIONS ON DRAINAGE DIVIDE FARMS EAST OF POFADDER

Farm Name & No	Borehole No	Water level (m)	Date measured	Fluctuation (m)
Lucas Vlei 93	44674 (LV 9)	60	1951	27.4
		32.6	13/08/97	
	37803	36.7	1949	56.3
		93	1956	
		79	14/08/1997	
		88.3	18/08/1998	
	45166 (LV2A)	69.5	07/02/1952	31.7
		37.8	13/08/97	
	20004 (LV 30)	77.4	16/07/1935	42.2
		35.2	13/09/1997	
Scuit Klip 92	41832 (LV13)	76.2	1951	2.7
		73.5	13/08/97	
Bank Vlei 136	51053	97.2	09/1953	28.2
		69	15/08/1997	
	25619	68.3 79.7	15/04/1940 03/11/1998	11.4
	20550 25853	61	1936	42.6
		103.6	1940	
Longziek Vlei 151	22492	61	1937	17.8
		78.9	11/08/1953	

Figure 43 depicts monthly rainfall at Kenhardt and water level fluctuations in the sandy bed of Driekop se Rivier from where the town obtains its water supply. The geological log of borehole G27973 is as follows:

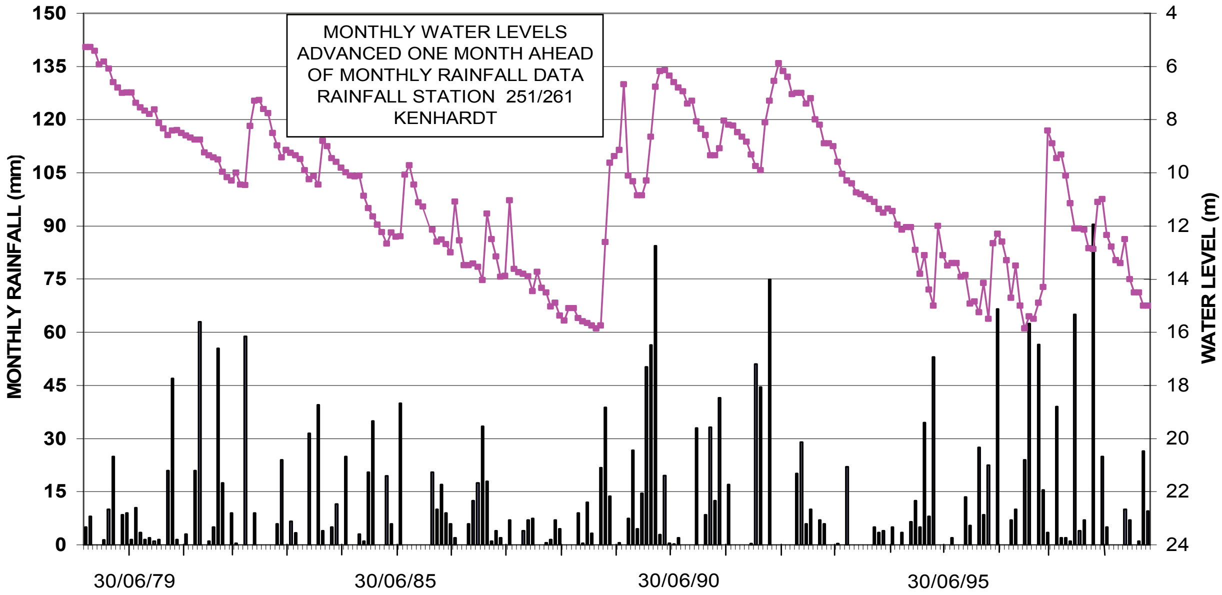
0 – 8 m	Unsorted slightly silty and clayey sand
8 – 21 m	Weathered gneiss and schist
21 – 24 m	Fractured slightly weathered gneiss and schist
24 – 35 m	Solid gneiss and schist.

Close correlation between daily rainfall and water level is not possible:

- Only monthly water level readings are available
- The effect of a varying municipal pumping schedule is unknown
- Daily rainfall is recorded 5 km away)
- Role played by runoff unknown

For recovery to the initial water level well above normal rainfall is clearly required (rainfall during the three preceding seasons 1975/6, 1976/7 and 1977/78 was substantially above normal).

FIGURE 43 WATER LEVEL FLUCTUATION VALLEY OF DRIEKOP SE RIVIER kENHARDT (BOREHOLE G 27973)



National groundwater recharge map

According to the mean annual recharge map that was published as part of a set of maps depicting national groundwater resources (1995) mean recharge over Bushmanland varies from east to west from less than 1 mm to more than 5 mm per annum The 5 mm contour on this map is based on a recharge value of 5.9 mm at Kenhardt that was calculated according to Vegter's De Aar recharge model.

Estimation of recharge Kenhardt

The occurrence of groundwater in the catchment of Driekop se Rivier, from which Kenhardt draws its supply, was investigated by Nonner (1979) and again by Van Dyk (1994). The upper part of the catchment south of the Kalkputs thrust fault is underlain by gneiss and associated pegmatite-like rocks of the Kokerberg Formation and intrusive porphyritic biotite granite. The lower part of the catchment lies on biotite gneiss, calc-silicate gneiss and subordinate amphibolite, quartz-feldspar gneiss and marble assigned to the Moddergat Gneiss, Slypsteenkrans and Poliesberg Formations.

The sand and gravel deposit in the lower Driekops River is up to 11 metres thick. Water is found in fractured and weathered bedrock as well as in the alluvial deposit. Nonner estimated that during a year of average rainfall (156 mm) recharge in the catchment (about 220 km^2) amounts to 40 000 m^3 i.e. equivalent to about 0.6 mm over the catchment's area. A fixed relationship between (mean) annual rainfall and (mean) annual recharge however does not exist as recharge is controlled amongst others by the amount, intensity, duration and temporal distribution of individual storms especially whether and to what extent runoff is produced or not.

Estimation of recharge at Marydale

Schumann (±1975) investigated recharge over the period 1964 to 1969 in the 282.5 km^2 upper catchment of the Marydale River south and southeast of the village of Marydale. Mean annual rainfall amounts to 185 mm. The catchment is underlain by:

- Spioenkop Formation consisting of quartzite, metabasite, quartz-muscovite schist, phyllitic schist and amphibolite.
- Kaboom Formation comprising white and grey quartzite and subordinate schist.
- Uitdraai Formation consisting of quartzite and quartz sericite schist.
- Biotite-hornblende granite and augen gneiss.
- Superficial deposits consisting of soil, clay, calcrete, sand and gravel.

In the poort directly upstream of the village the superficial deposit is 14 m thick of which 12 m is water-bearing. Higher up in catchment on Rooidam and Neeldale the deposits are up to 33 m thick of which 5.5 to 10 m are water-bearing.

Ground water discharge consisted of:

- Ephemeral spring flow and municipal pumpage which were measured and recorded.
- Subsurface loss through alluvium in the poort above the village. This was calculated from the transmissivity of the alluvium and the piezometric gradient. Transmissivity was determined by test pumping.
- Use on farms for household purposes, stockwatering and irrigation was estimated.

Whereas the estimate of discharge appears fairly sound and that through bedrock presumably negligibly small, assumptions about changes in storage volume appear uncertain. Schumann arrived for several periods at recharge values ranging from 0.9 to 2.2% of the precipitation. In terms of the mean annual rainfall this amounts to 1.7 to 4.1 mm.

9. HYDROCHEMISTRY AND WATER QUALITY

The geographic distribution of chemical type is depicted on Sheet 2 of the "Groundwater Resources of the Republic of South Africa" map set (WRC and Department of Water Affairs and Forestry 1995). In broad outline calcium and magnesium chloride and sulphate groundwater is characteristic of the Swazian-Randian Kaapvaal craton and Kheis Subprovince formations. Sodium / potassium chloride and sulphate groundwater predominates over the rest of the Groundwater Region. Two-type dominance (see Vegter 1995 p B27) is found in the Upington-Kakamas area and south of Marydale. Total dissolved solids increase from east to west in unison with the change in chemical type.

As part of a site-selection program for a low and intermediate-level radioactive waste disposal site the Atomic Energy Corporation collected and analysed 850 groundwater samples from an area of 29 300 km^2 (Camisani-Calzolari 1985; Levin 1988). The area is irregularly shaped very roughly triangular in form with apices at Nababeep in the northwest (17^0 45'E, 29^0 30'S), Kanakies siding on the Kathu-Saldanha railway line in the south (19^0E, 31^0S) and the Onseepkans turnoff on the Kakamas-Pofadder road in the northeast (20^0E, 29^0S). On average one sample was collected per 30 to 35 km^2. Samples were analysed for both major ion and trace elements. Levin's findings are summarized below:

A dominant sodium chloride / sulphate character is evident in that the bulk of analyses plot in the upper half of the Piper diagram's diamond shaped field. The concentration of analyses plot around 60 % ($Na^+ + K^+$) and around 90 % ($Cl^- + SO_4^{2-}$). In the anion field $Cl^- > SO_4^{2-} > (HCO_3^- + CO_2^{2-})$ and in the cation field Mg^{2+} dominates Ca^{2+} slightly.

TABLE 70 SUMMARY OF AEC HYDROCHEMICAL DATA

Temperature	Range	Mean
pH	19 – 26^{0}C	
Conductivity mSm^{-1}	200 - 900	480
TDS mg.l^{-1}		3100
Cl^{-1} mg.l^{-1}	450 - 3300	1500
SO_4^{-2} mg.l^{-1}	90 - 800	380
$HCO_3^{-1} + CO_2^{-2}$ mg.l^{-1}	110 - 310	250

Water samples were analysed for the following trace elements: Al, As, B, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Ti, U, V and Zn. By kriging data for each trace element and plotting all the anomalous areas a northeasterly trending metallogenic zone was identified (Camisani-Calzolari 1985; Levin 1988).

A number of persons suffering from haematological anomalies related to leukemia have been reported from the surroundings of Pofadder. At the instigation of the Department of Internal Medicine and Community Health of the Faculty of Medicine University of Stellenbosch the AEC's study of groundwater chemistry was taken forward as WRC project K5/839. Toens et al (1998) found a positive correlation of + 0.60 between elevated levels of a combination of uranium and arsenic in groundwater and the incidence of atypical lymphocyte counts (as a proxy of haematological abnormality).

Simonic of Hydromedia Solutions (Pty) Ltd. classified the overall potability of 968 water samples from the Region as a whole. The chemical criteria are laid down in the manual "Quality of domestic water supplies Vol. 1 Assessment Guide" of the Department of Water Affairs and Forestry, the Department of Health and the Water Research Commission. The result is produced below.

TABLE 71 POTABILITY CLASSIFICATION

Class	1-blue	2-green	3-yellow	4-red	5-purple
Description	Ideal	Good	Marginal	Poor	Unacceptable
No of samples	8	62	182	351	365
% of samples	0.83	6.40	18.80	36.26	37.71

Seventy-four percent of the water samples are not suitable for drinking.

TABLE 72 DISTRIBUTION OF HARMFUL ION CONCENTRATIONS – DOMESTIC USE

Ion	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3^{-}	F^{-}	$EC^{\#}$
No of analyses	956	956	947	948	956	947	975	955	902
No of samples containing harmful concentration	107	99	265	10	281	189	301	473	218
% of analyses	11.19	10.36	27.98	1.05	29.39	19.96	30.87	49.53	24.17

$^{\#}$EC = Electrical conductivity

Harmful major constituents in order of frequency of occurrence are **F^{-}**, **NO_3^{-}**, **Cl^{-}**, **Na^{+}, SO_4^{2-}.**

References

Acocks, J.P.H., 1953. Veld types of South Africa with map scale 1:1 500 000. bot. Surv. S. Afr. 28

Agenbacht, A. L. D., 1992. Geologiese ondersoek van die T'Oubep Suite suidwes van Kakamas, Noordwes-Kaap. Bull. geol. Surv. S. Afr. 115

Anderson, N.J.B., Faure, J.N. and Fernandez, L.M., 1986. Geophysical investigations on the Vaalputs waste disposal site in the Republic of South Africa. Conf. treatment, containment radioactive waste disposal arid environ. Cape Town South Africa.

.
Andreoli, M.A.G., Anderson, N.J.B., Levin, M. and Niemand, N. 1987. Geology of the Vaalputs radioactive waste disposal site in the Republic of South Africa: Explanatory notes for the geological map of the site on the scale 1:25 000: Atomic Energy Corporation of South Africa Ltd.

Banks, D., Solbjorg, M.L. and Rohr-Torp, E., 1992. Permeability of fracture zones in a Precambrian granite. Quart J. Eng.Geol. 25 pp 377 – 388.

Banks, D., Rohr-Torp, E. and Skarphagen, H., 1993. Groundwater resources in hard rock Experiences from the Hvaler study, southeastern Norway. Memoires XXIVth IAH Congress Oslo.

Bellairs, G. ff. 1955. Instrumentation for a new electromagnetic field technique. Geophysics No1 p 155 – 162.

Botha, B.V.J., Grobler, N.J., Linström, W and Smit, C.A., 1977. Major structural features of the area between the Langeberg and Kenhardt, Northern Cape Province. Trans. geol. Soc. S. Afr. 80 p 101 - 110.

Brandt, D., Andreoli, M.A.G. and McCarthy, T.S., 2003. Mesozoic fluvial deposits on a rifted continental margin near Vaalputs Namaqualand, South Africa. S. Afr. J. Geol. 106 No 1

Brandt, D., Andreoli, M.A.G. and McCarthy, T.S., 2005. The late Mesozoic paleosoils and Cenozoic fluvial deposits at Vaalputs, Namaqualand, South Africa: possible depositional mechanisms and their bearing on the evolution of the continental margin. S. Afr. J Geol. 108 No 2

Camisani-Calzolari, F.A.G.M. 1985. Geostatistical investigation of the hydrogeochemistry of groundwaters in the northwestern Cape. Unpublished report, Atomic Energy Corporation of South Africa

Cape of Good Hope, 1893. Report of the geological and irrigation surveyor of the Cape Colony for 1892.

Colliston, W.P., Praekelt, H. E. and Shoch, H. E., 1989. A broad perspective (Haramoep) of geological relations established by sequence mapping in the Proterozoic Aggeneys terrane Bushmanland. S. Afr. J. geol. Vol. 92 pp 42 – 48.

.
Colliston, W.P. and Shoch, A.E., 2002. The structural development of the Aggeneys Hills, Namaqua Metamorphic Complex. S.Afr. J Geol 105 (4) p 301-324

Cornelissen, A.K. and Verwoerd, W.J., 1975. The Bushmanland kimberlites and related rocks: Phys. Chem. Earth 9 p 71 - 80

Department of Water Affairs and Forestry 1993. South African water quality guidelines Volumes 1 and 4.

De Beer J.H. and Blume J., 1984. A geo-electrical study of the Vaalputs radioactive waste disposal site. Geophysics Division, NPRL, CSIR Pretoria.

De Beer J.H. and Blume J., 1986. Resistivity studies on the Vaalputs radioactive waste disposal site. Conf. on treatment and containment of radioactive waste and its disposal in arid environments Cape Town S. Afr. 7 -12 Sept. 1986
.
De Jonge, J. M., 1987. Preliminary evaluation of the applicability of electromagnetic and resistivity methods applied during a groundwater investigation in Namaqauland. Report Gh 3504 Directorate of Geohydrology Dept. Water Affairs

De Wit, M.C.J., 1993. Cainozoic evolution of drainage systems in the northwestern Cape. PhD thesis, Univ Cape Town

De Wit, M.C.J., 1999. Post-Gondwana drainage and the development of diamond placers in western South Africa: Economic Geology 94 p 721 -740

Du Toit, A.L., 1954. The geology of South Africa (3rd edition) Oliver and Boyd Edinburgh.

Du Toit, M.C., 1965 A geological investigation and correlation of rocks belonging to the Koras Formation in the Gordonia and Kenhardt Districrts, Northern Cape Province: MSc thesjs Univ. Orange Free State

Du Toit, M.C., 1998. The metallogeny of the Upington-Kenhardt Area. Expl. Metallogenic sheets 2820 and 2920 scale 1:250 000. Council for Geoscience, geol. Surv. S. Afr.

Enslin, J.F., 1943. Basins of decomposition in igneous rocks – their importance as underground water reservoirs and their location by the electrical resistivity method. Trans. geol. Soc. S, Afr. vol 46

Enslin, J.F., 1944. The electrical resistivity method of geophysical prospecting and its practical application to geological problems of economic importance in the Union of South Africa. DSc thesis Univ. Stellenbosch

Enslin, J.F., 1948. Lateral effects on electrical resistivity depth probe curves. Trans. geol. Soc. S. Afr. 51.

Enslin, J.F., 1952. Waterare en 'n nuwe tegniek om dit op te spoor vir aanwys van boorplekke. Tydskr.Wet. Kuns 12

Enslin, J.F., 1955. A new electromagnetic field technique. Geophysics XX (2)

Enslin, J.F., 1963. Verslag oor grondwaterpotensiaal by Henkries en in die Koavallei met aanbevelings vir verdure ondersoek. Report Gh 3015 Geohydrology Dept, Water Affairs

Fourie, S.A., Verster, H. and Van Dyk, G.S.du T.1999. Groundwater level monitoring to qualify the effect of eradication of the SP Prosopis on the Rugseer aquifer, Kenhardt

Northern Cape. Technical Report Gh 3944 Geohydrology, Northern Cape Region Dept. Water Affairs and Forestry

Frick, C. and Wheelock, G. 1983. Evidence for a sedimentary origin of the pink gneisses of the Kokerberg Formation, Korannaland. Trans. geol. Soc. S. Afr. 86 (2) p 81 -86.

Frommurze, H.F., 1937. The water=bearing properties of the more important geological formations in the Union of South Africa. geol. Surv S. Afr. Mem 24.

Geringer, G.J., 1979. The origin and tectonic setting of amphibolites in part of the Namaqua Mobile Belt, South Africa. Trans. geol. Soc. S. Afr. 82 p287-303

Geringer, G.J., Botha, B.V.J. and Slabbert, M.J., 1988. The Keimoes Suite – a composite granitoid batholith along the eastern margin of the Namaqau Mobile Belt. Trans. geol. Soc. S. Afr.91 (4) p 465 - 476.

Gevers, T.W., Partridge, F. C. and Joubert, G. K., 1937. The pegmatite area south of the Orange River in Namaqualand. Mem. 31 geol. Surv. S.Afr.

Grobler, N.J., Botha, B.J.V. and Smit, C.A., 1977. The tectonic setting of the Koras Group: Trans. geol. Soc. S. Afr. 80 (3) p 167 – 176.

Hambleton-Jones, B.B., Levin, M. and Wagener, G.F. 1986. Uraniferous surficial deposits in Southern Africa. In *Mineral deposits of Southern Africa Vol II Editors C.R. Anhausser and S. Maske geol. Soc. S. Afr. p 2269 – 2287.*

Hartnady, C.J.H., Joubert, P. and Stowe, C.W., 1985. Proterozoic crustal evolution in southwestern Africa. Episodes (4) p 236 - 244.

Heiland, C.A., 1940. Geophysical exploration. Prentice-Hall Inc. NY

Hedstrom, H., 1937.Phase measurements in electrical prospecting. A.I.M.E. tech. Publ. T.P.827; or A.I.M.E. Geophysics 1940 p 456 – 471

Hodgson, F.D.I., 1984. Report on pumping and packer tests at Vaalputs site. Report of the Institute for Groundwater Studies, University of Orange Free State, Bloemfontein to the Atomic Energy Corporation of S.Afr.re Selection program for the disposal/storage of radioactive waste in South Africa (report GEA-558)

Hodgson, F.D.I., 1986. Design and installation of a borehole monitoring system at the Vaalputs Nuclear Waste Disposal Site. Report of the Institute for Groundwater Studies, University of Orange Free State, Bloemfontein to the Atomic Energy Corporation of S.Afr.(report GEA 799) .

Hummel, J.N., 1932. A theoretical study of the apparent resistivity in surface potential methods. Trans.A.I.M.E. Vol 97 Geophysical Prospecting pp 392 – 422

Jackson, M.L., 1982. Geohydrological investigation at Pofadder and surrounding area. Report Gh 3234 Geohydrology. Water Affairs, Dept. Environment Affairs

Jakosky, J.J., 1940. Exploration geophysics. Times Mirror Press. Los Angeles.

Johnson, J.H., 1975. Hydrochemistry in groundwater exploration. Groundwater Symposium Bulawayo.

Joubert, P. 1974. The gneisses of Namaqualand and their deformation. Trans.geol.Soc. S.Afr. vol 77 p 339 – 345.

Joubert, P., 1986a. Namaqualand – a model of Proterozoic accretion. Trans. geol. Soc. S. Afr. 89 (2) p 79 - 96.

Joubert, P. 1986b. The Namaqualand metamorphic Complex – a summary p 1395 -1420 In *Anhaeusser, C.R. and Maske, S. eds., Mineral deposits of Southern Africa II,* g*eol. Soc. S. Afr.*

Joubert, S. J. 1977 Standard graphs for Schlumberger electric soundings Special publication A 37 CSIR Pretoria.

Kent, L. E., (compiler) 1980. Stratigraphy of South Africa. Geol. Surv. S. Afr. Handbook 8.

Kok, T.S., 1982. Pofadder grondwaterondersoek (Opsomming van verslag Gh 3236 deur M.L. Jackson) Report Gh 3236. Geohydrology. Dept. Water Affairs and Forestry.

Levin, M., Hambleton Jones, B. B., Raubenheiner, E. and Niemand, M. 1986. Geohydrology of the Vaalputs radioactive waste disposal facility. Conf. Treatment Containment, Radioactive waste disposal arid environm. CapeTown S. Afr.

Levin, M., 1988. A geohydrological appraisal of the Vaalputs radioactive waste disposal facility in Namaqualand, South Africa. PhD thesis University of the Orange Free State, Bloemfontien.

Mabbutt, J. A., 1951. Transverse terraces in the lower Henkries valley. Trans.geol. Soc. S.Afr. vol.LIII p 253 – 266.

Marais, J.A.H., Agenbacht, A.L.D., Prinsloo, M. and Basson, W.A., 2001. The geology of the Springbok Area. Expl. Sheet 2916 scale 1:250 000 Council for Geoscience, geol. Surv. S. Afr.

Martinelli, E and Associates, 1978. The assessment of groundwater supplies – Aggeneys Mine Reports A75 and A75B; prepared for Brian Colquhoun, Hugh O'Donnell and Partners Consulting Civil Engineers.

McCarthy, T.S., Moon, B.P. and Levin, M. 1985. Geomorphology of the western Bushmanland Plateau, Namaqualand South Africa. S. Afr. geogr. J. 67 (2).

Meyer, R., van Zijl J.S.V., Nonner J.C. and Mulder M.P., 1980. Die ontwikkeling en evaluasie van tegnieke vir die bepaling van die ontginningspotensiaal van grondwaterbronne in die Doornberg-breuksone. Deel 4: Kenhardt-omgewing ─ Geofisiese studies. National Physical Research Laboratory CSIR Pretoria. Prepared as part of WRC contract K 5/28 Sept. 1980.

Moen, H. F. C., 1999. The Kheis tectonic subprovince, Southern Africa: A lithostratigraphic perspective. S. Afr. J. Geol. Vol.102 No 1.

Moore, A.E. and Verwoerd, W.J., 1985. The olivine-melilite-kimberlite-carbonatite suite of Namaqualand and Bushmanlnd, South Africa. Trans. geol. Soc. S. Afr. 88 pp 281 -296.

Mulder, M.P.,1980. Kenhardt omgewing - Samevattende geohidrologiese verslag. Report Gh 3156, Geohydrology, Dept, of Water Affairs.

Nieuwoudt, A.P.C. 1964. Ondersoek na die voorgestelde waterskema vir Pofadder, Distrik Kenhardt. Report Gh 3102, Geohydrology, Dept. of Water Affairs.

Nonner, J.C., 1979. Groundwater resources investigation for Kenhardt Municipality, Cape Province. Report Gh 3102, Geohydrology, Dept, of Water Affairs.

Orellana E. and Mooney, H. M. 1966. Master Tables and curves for vertical electrical sounding over layered structures. Interciencia Madrid.

Partidge, T. C. and Maud, R. R. 1987. Geomorphic evolution of Southern Africa since the Mesozoic. S. Afr. J Geol. Vol. 90- No 2 pp 179 – 208.

.

Praekelt, H.E. and Shoch, H.E.,1997.Statigraphical synthesis of the metasediments of the Aggeneys terrane in the Namaqua Mobile Belt. S. Afr. J. Geol. Vol. 100 No 1.

Prinsloo, M.C., 1989. Die geologie van die gebied Britstown. Expl. Sheet 3022 1:250 000) Geol. Surv. S. Afr.

Rogers, A.W. and Du Toit, A.L., 1909. Report on the Geology of parts of Kenhardt, Prieska and Carnarvon. 14th Annual Rep. geol. Comm. Cape Good Hope.

Rogers, A. W., (1915). The geology of part of Namaqualand. Trans. geol. Soc. S. Afr. 18.

Roman, I., 1934. Some interpretations of earth resistivity data. Trans.A.I.M.E. Vol 97 Geophysical Prospecting pp 183 – 200.

Rutherford, M.C. and Westfall, R.H., 1986. Biomes of Southern Africa – An objective categorization. bot. Surv. S. Afr. Mem. 54.

Schlegel, G.C.L., 1988. Contribution to the metamorphic and structural evolution of the Kheis Tectonic Province, Northern Cape, South Africa. S. Afr J. Geol 91 (1) p 27 - 37.

Scholtz, A., 1985. The palynology of the upper lacustrine sediments of the Arnot pipe, Banke, Namaqualand. Ann. S. Afr. Mus. 95 (1).

Schulze, B.R., 1994. Climate of South Africa - Part 8 General Survey. Weather Bureau Dept. Environ. Affairs.

Schultze, R.E., 1989. ACRU: Background, concepts and theory. WRC Report No 154.1.89.

Schumann, F.W., ±1973. Ondersoek na aanvulling van grondwater op die dorpsmeent Marydale. Report Gh 1466 Geohydrology Dept. Water Affairs and Forestry.

Schumann, F.W. ±1975. A comparative study of the geohydrology of Archaean Formations in the North-western Transvaal and the North-western Cape Province Ph.D Thesis University of Cape Town.

Scott Keys, W. 1989. Borehole geophysics applied to ground-water investigations.National Water Well Association, Dublin Ohio.

Siegfried, H.P. and Botha, P.M.W., 1997. Studie van boorgatmonsters en geologie van die gebied wes van Kenhardt. Council for Geoscience, Upington.

Slabbert, M.J., Moen, H.F.G. and Boelema, R., 1999. Die geologie van die gebied Kenhardt Explanation of Sheet 2920 scale 1:250 000 Council for Geoscience, geol. Surv. S. Afr.

Smith, R.M.H., 1986. Sedimentation and palaeo-environments of Late Cretaceous crater-lake deposits in Bushmanland, South Africa: Sedimentology 33 p 369 -386.

Stowe, C.W., Hartnady, C.J.H. and Joubert, P., 1984. Proterozoic tectonic provinces of South Africa. Precambrian Res. 25 p 229 -231.

Sundberg, K., 1931. Principles of Swedish geo-elecrtrical methods.Gerl. Beitr.Geoph.Vol 1 p 296 – 361.

Taljaard, J.J., 1944.Verslag van ondersoek vir water vir Kenhardt Munusupaliteit. Report Gh 266 Geohydrology Dept. Water Affairs and Forestry.

Theart, H. F. J., 1980. The geology of the Precambrian terrane in parts of Western Namaqualand. Bull. Precambrian Res, Unit U.C.T. No 30.

Toens, P. D., Stadler, W. and Wullschleger N.J.,1998. The association of groundwater chemistry and geology with atypical lymphocytes (as a biological indicator) in the Pofadder area North Western Cape, South Africa. WRC report No 839/1/98 Pretoria.

Toens, P.D., Visser, D and du Toit A.I.,1995. Steinkopf landelike gebied: Grondwaterondersoeke uitgevoer. Vorderingsverslag Nr 89, Dept of Housing, Prov. Adm. Northern Cape.

Van Dyk, G.S. du T., 1994.Geohidrologiese ondersoek van grondwaterbronne vir watervoorsiening aan Kenhardt. Report Gh 3944 Geohydrology, Dept. Water Affairs and Forestry.

Van Dyk, G.S. du T and Fourie, S.A., 1999.Oorsig oor volhoubare watervoorsiening aan Kenhardt uit grondwaterbronne. Dept. Water Affairs and Forestry.

Van Zijl, J.S.V., 1985. A practical manual on yhe resistivity method.CSIR report K70.

Vegter, J.R., 1953. Underground water supplies in the crystalline complex of the Kenhardt District C.P. and the water supply of Walvis Bay. M.Sc thesis University of Pretoria.

Vegter, J.R., 1962. Locating zones of weathering and fracturing by the electromagnetic technique of using a long earthed cable. Ann. Geol. Surv. S. Afr. 1.

Vegter, J.R.,1992. De Aar's groundwater supply:a digest of the past and an outlook for the future Tech, Rep. Gh 3775 Geohydrology Dept. Water Affairs ans Forestry.

Vegter, J.R., 1995. An explanation of a set of national groundwater maps. WRC report No KV 77/95.

Vegter, J.R., 2001.Groundwater Development in South Africa and an Introduction to the Hydrogeology of Groundwater Regions. WRC Report No TT 134/00 Pretoria.

Visser, D.L.J., 1962. Die warmbronne op Warmbad Noord en Skuitdrift Oost Distrik Kenhardt K.P. Report Gh 3944 Geohydrology, Dept. Water Affairs and Forestry.

Visser, D.L.J., (compiler) 1989. Die geologie van die Republieke van Suid-Afrika, Transkei, Bophuthatswana, Venda en Ciskei en die Koninkryke van Lesotho en Swaziland: Expl. geol. Map scale 1:1 000 000 1984. geol Surv. S. Afr.
.
Visser J.N.J. 1985. The Dwyka Formation along the northwestern margin of the Karoo Basin in the Cape Province, South Africa. Trans. geol. Soc. S. Afr. 88 (1) p 37 - 48.

Von Backström, J. W., 1962. The geology along the lower reaches of the Molopo River and a note on the Riemvasmaak thermal spring, Gordonia District, Cape Province. Ann.geol.Surv.S.Afr.,1 p 57 – 64.

Von Backström, J. W., 1964. The geology of an area around Keimoes, Cape Province, with special reference to phacoliths of charnockitic adamellite-porphyry. geol. Surv. Mem. 53.

Von Backström, J. W., and de Villiers, J., 1972. The Geology along the Orange River Valley between Onseepkans and the Richtersveld: geol Surv. S. Afr. Expl. Sheets 2817D (Vioolsdrif) 2818C (Goodhouse) and 2918D (Dabenoris) and 2819C (Onseepkans).

Watson, R. J., 1934. A contribution to the theory of the interpretation of resistivity measurements obtained from surface potential observations. Trans.A.I.M.E. Vol 110 Geophysical Prospecting pp 205 – 236.

Wetzel, W. W. and McMurry, H. V., 1937. A set of curves to assist in the interpretation of the three layer resistivity problem. Geophysics Vol 2, No 4.

Wiegmans, F. E., 1990. Evaluation of frequency-domain electromagnetic methods in groundwater exploration. MSc thesis, Univ.Pretoria.

Maps

Geological sheets

- Marydale scale 1:238 000, Geological Commission Cape of Good Hope 1910
- Keimoes 2820D and Louisvale 2821C scale 1:125 000, Geol. Surv. S.Afr. Pretoria 1966
- Vioolsdrif 2817D, Goodhouse 2818C, Dabenoris 2818D and Onseepkans 2819C scale 1:125 000 Geol. Surv. S.Afr. Pretoria 1972
- Postmasburg 2822 (1977)
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- 2918 Pofadder
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- 3022 Britstown