# THE INFLUENCES OF DOLERITE SILL AND RING COMPLEXES ON THE OCCURRENCE OF GROUNDWATER IN KAROO FRACTURED AQUIFERS: A MORPHO-TECTONIC APPROACH

L Chevallier · M Goedhart · AC Woodford

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Water Research Commission

# INFLUENCE OF DOLERITE SILL AND RING COMPLEXES ON THE OCCURRENCE OF GROUNDWATER IN KAROO FRACTURED AQUIFERS : A MORPHO-TECTONIC APPROACH

Report to the
WATER RESEARCH COMMISSION

by

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# EXECUTIVE SUMMARY

## MOTIVATION

Jurassic dolerite sills and ring-complexes form an important part of the structural framework of the Karoo Basin and outcrop over an area covering approximately half of South Africa. They also control most of the second-order geomorphological features and drainage systems of the Basin. The exact nature and geometry of these sills and ring-complexes has never been fully documented and relevant structural observations are few compared to the large number of exposures available in the field. It is only during the past 15 years that more information has become available on the structure and tectonics of the Western Karoo dolerite intrusions.

These dolerite ring-complexes have been to a large extent been overlooked as potential groundwater exploration targets. This is probably due to a number of factors, which include the ruggedness of the terrain, the requirement for deep drilling into hard rock, and a lack of knowledge on the geometry and fracturing associated with these intrusive features.

## OBJECTIVES

The aim of the project was to assess the occurrence of groundwater associated with Karoo dolerite sill and ring – structures using morpho-tectonic models. The aim of the present research project was twofold:

- Regional study: to understand the structure of these large-scale intrusions, i.e. morphology, geometry, shape, size, fracturing, tectonics and mechanism of emplacement. The study had to be conducted on a regional scale in order to assess the spatial variability of the above parameters. The proposed study area includes the three 1 / 250 000 scale maps of Victoria West (3122), Middelburg (3124) and Queenstown (3126).
- Local study: to establish the occurrence of groundwater associated with these intrusions. A single sill and ring complex would be selected for geohydrological investigation based on information obtained from the regional study. The objective was to evaluate and refine the conceptual geohydrological model, in terms of ground water occurrence.

## MAJOR RESULTS

### Regional Study

The regional study was completed using 3D terrain modelling, map compilation, remote-sensing, aeromagnetics (magnetic fabric), detailed geological cross-sections and mechanical stress simulation. The dolerite sill and ring information were extracted from the existing 1/250 000 geological maps. The Digital Elevation Model was created from data obtained from the Chief Surveyor General: Surveys and Land Information. A total of eleven geological cross-sections were compiled from the existing 1/50 000 scale field-maps, and complemented with field observations.

The morpho-tectonic analysis shows the general "saucer-shape" of each of the sill/ring complex, which comprises a flat-lying inner sill always corresponding to low grounds, a peripheral inclined sheet forming the ring, an outer sills corresponding to high grounds and a ring feeder dyke branching into the inclined sheet. Sill and ring complexes are intruded at different stratigraphic levels, and are commonly stacked above one another in different ways resulting in various tectonic and morphological patterns. Satellite imagery and magnetic fabric demonstrate very well the concept of "ring-within-a-ring" and "ring stacking".

This regional study resulted in the classification of the Western and Eastern Karoo dolerite sill and ring complexes into three basic ***morpho-tectonic models***:

The morpho-tectonic model I is characterized by nesting of rings, and upward stacking and an accompanying decrease in ring diameter. These ring- and sill-complexes contribute to the elevated terrain of the Loxton and Victoria West highlands and correspond to a complex drainage network.

The morpho-tectonic model II is characterized by coalescing rings with downward stacking. These rings and sills correspond to low elevation terrain and large basin drained by radiating stream systems like Middelburg or Nieu-Bethesda basins.

The morpho-tectonic model III is characterized by small individual rings with perfect symmetry, complex interference between the rings (overlapping and coalescing) and vertical stacking without decrease in size. The result is a "box-type" intrusive pattern. The drainage system is very intricate. They are found in the Queenstown Basin.

A mode of emplacement is proposed for these intrusions. It takes into account all previous published observations, models and interpretations, and is complemented by our own observation. Our study shows that ring dykes act as feeders to some of the rings and inclined sheets.

Stress simulation was performed to predict the mechanical behaviour of the medium (Karoo sediment) around the sill and ring systems. The models reproduce a series of sills stacked above each other. The stress distribution pattern shows that fracturing should be developed at specific localities around the sill and ring-systems, i.e. up-stepping or kinks in the sills or at the intersection between a feeder dyke and a ring.

Finally, spatial analysis of the regional borehole information over the three maps indicated that terrain slope, which is primarily controlled by the occurrence of the sill and ring-systems, exerts a strong control on the occurrence of groundwater, as well as the intersection of dolerite dykes and sills.

**Local Study**

The occurrence of groundwater associated with these intrusions was assessed by integrating the 3D morpho-tectonic model with geohydrological information obtained from a detailed investigation, involving geological field-mapping, remote-sensing, hydrocensus of all waterpoints and exploration drilling.

The Victoria West area was chosen for this local study. The dolerite intrusive system at Victoria West is characterized by 4 sills stacked above one another. Their respective rings form a typical "ring-within-a-ring" structure.

A digital topographic model of the area was created from vectorized 1 / 50 000 topocadastral maps provided by the Chief Directorate: Surveys and Land information. The geological maps were also vectorized at the Council for Geoscience. DTM and geological maps were used to analyse the complex structural and geometrical relations between the sills, the rings and the feeder dykes.

Five E-W cross sections were done over the local study area from existing 1 / 50 000 maps and then captured digitally. These sections were complemented by field observations and exploration drilling logs. In the field, a large number of dolerite-host sediment contacts were mapped, dips were measured and relationship between dykes, sills and the rings were observed. The cross sections were adapted or revised after the results of the exploration drilling programme.

The detailed hydrocensus showed that farmers do not often drill boreholes on the dolerite ring-systems. The reluctance of 'diviners' to site bore holes on such complex intrusions, drilling of shallow boreholes required for stock-watering purposes and the limited access to the main water-bearing sections of dolerite ring-complexes restricts of usefulness of this information for assessing the groundwater potential of these features. Analysis of the hydrocensus information did, however, indicate that the majority of the more productive boreholes tap the shallow (<30m deep), weathered Karoo sediments alongside dolerite dykes. The analysis also indicated a geomorphological control on bore hole yields, where bores situated close to the drainage system in the gently sloping floodplains are most productive.

Exploration drilling was carried out at 10 sites that were chosen to investigate the morpho-tectonic complexity of the dolerite ring-system. A total of 67 boreholes with an average depth of 206m were drilled. Many high yielding water-strikes (13 to 70 l/s) were intersected along specific morpho-tectonic sections of the ring-complex, namely at the intersection of the feeder dykes and sills, up-stepping structures within sills, fractures and horizontal offshoots at the base of the sills. Increase in yield with depth was also recorded.

## CONCLUSION

This study resulted in the compilation of a ***hydro-morpho-tectonic model*** that highlights zones of potential 'open' fracturing which are associated with the emplacement of dolerite sill and ring-complexes.

Karoo dolerite rings and sills have proven to be structures conductive to the formation of deep-seated fractured-rock aquifers. The increase in yield with depth could also indicate that even higher yielding fractures may exist at greater depth.

## RECOMMENDATIONS FOR FURTHER RESEARCH AND TECHNOLOGY TRANSFER

Targeting these deep challenging fractured rock aquifers is not straightforward. Morpho-tectonic analysis plays a major role in such hydrogeological investigation.

However, in addition to surface geology it is proposed that geophysical surveys could provide more precise information concerning the structure and geometry of rings and sills at depth. Two techniques seem to be promising:

- High-resolution airborne magnetic surveys indicate major structures at shallow depth and therefore allow a more complete definition of the 3D geometry of the target features.
- Time Domain Electro-Magnetic soundings have proven to be useful to discerning deep structures and defining localized zones of low resistivity. Geophysical profiling to a depth of 600m below a potential drilling site could save a lot of time and money. The technique is available in 3D and should be further investigated as a groundwater exploration tool.

The role of groundwater in the maintenance of ecosystems, in particular deep-seated water related to fractured-rock aquifers, is unknown. Therefore, further research should also focus on this aspect, especially in terms of defining hydrogeological domains, estimating the volumes of available water and assessing their vulnerability to over-abstraction.

The WRC is in the process of publishing a handbook entitled: "Hydrogeology of the Main Karoo Basin. Current knowledge and future research needs" in which all of the above results will be summarised.

A number of the exploration boreholes drilled during this project will be developed to augment Victoria West's water supply. The monitoring of these abstraction schemes should be implemented and the results publicised as part of a technology transfer programme to enhance the understanding of groundwater utilisation and management in the Karoo.

However, there is a further need for technology transfer. On this project, close collaboration between the geologists, hydrogeologists and technicians from different institutions has proven to be very successful. In the future, such programmes should be used to train junior hydrogeologists and technical staff.

This research project is summarized in the following poster, which was presented at the Geocongress in Stellenbosch (Chevallier and Woodford, 2000).

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# Morpho-tectonics of Karoo Dolerite Sills and Rings - Influence on Fractured-Rock Aquifers

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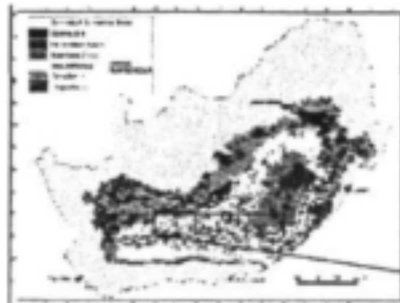
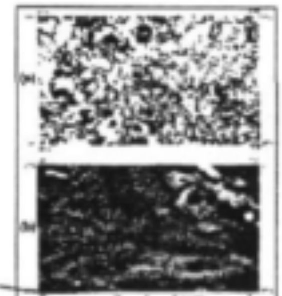
[This Project was funded by the Water Research Commission and Department of Water Affairs & Forestry]

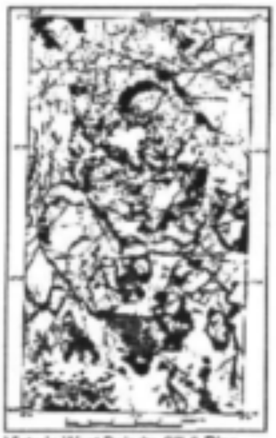
Authors at Drill Site 4
Artesian Borehole GW8011, with blow yield of 82 l/s



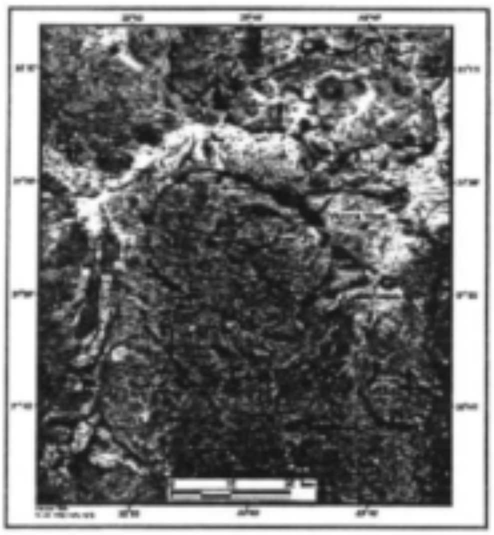
Dolerite Sills of the Main Karoo Basin

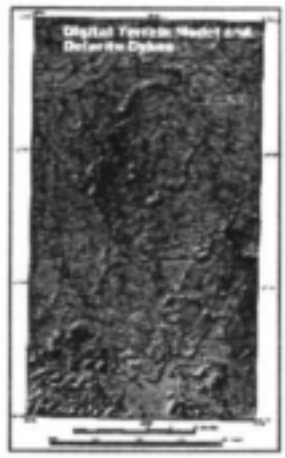


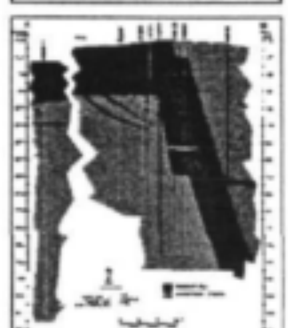
Victoria West 1:250 000 mapsheet
(a) Dolerite Sill (b) Magnetic Fabric



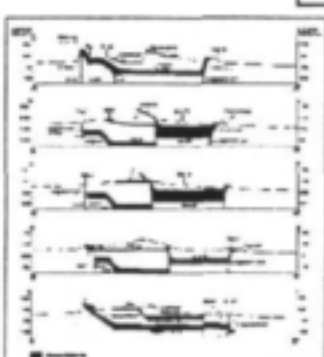
Victoria West Dolerite Sill & Ring Sills and Dykes



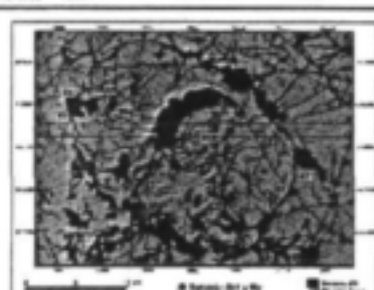


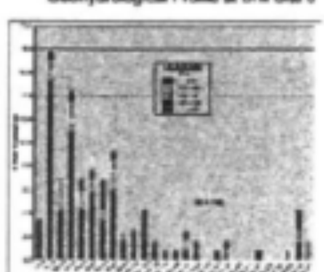
Geohydrological Profile at Drill Site 6



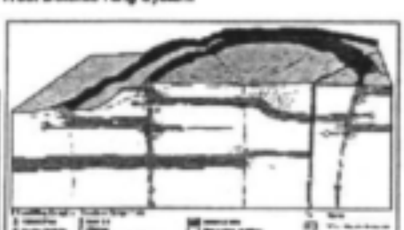
Parallel W-E Geological Sections across Victoria West Dolerite Ring System



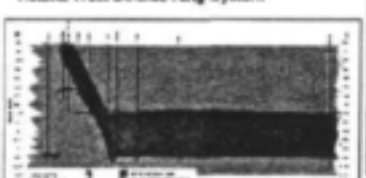
Location of Exploration Drilling Sites on the Victoria West Dolerite Ring System



Summary of Water Interceptions at the 10 Exploration Drill Sites on the Victoria West Dolerite Sill and Ring Complex



Hydro-morphotectonic Model showing main water-bearing fractures associated with Ring-Systems



Geohydrological Profile at Drill Site 2

## ACKNOWLEDGEMENTS

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

| | |
|---|---|
| Mr. K. Pietersen | Water Research Commission (Chairperson) |
| Dr. G. Green | Water Research Commission |
| Mr. N. Keyser | Council for Geoscience |
| Mr. E. Van Wyk | Department of Water Affairs & Forestry |
| Mr. M. Smart | Department of Water Affairs & Forestry |
| Mr. G. van Dyk | Department of Water Affairs & Forestry |
| Mr. M. Moseki | Department of Water Affairs & Forestry |
| Mr. S. Adams | Geology Department, University Western Cape |
| Prof. M. Watkeys | Geology Department, University of Natal |
| Dr. L. Chevallier | Research Team – Council for Geoscience |
| Mr. A. Woodford | Research Team – Toens & Partners |
| Mr. M. Goedhart | Research Team – Council for Geoscience |
| Mr. P. Dzanga | Institute for Groundwater Studies, OFS University. |

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*The researchers at drilling site 4 in the Victoria West Area*

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# 1 INTRODUCTION

## 1.1 WRC PROGRAMME ON KAROO FRACTURED-ROCK AQUIFERS

For the past twenty years the Water Research Commission has coordinated and funded numerous research projects on Karoo fractured aquifers. They involved both intensive localized and extensive regional studies and were aimed at understanding the hydrogeology, the flow characteristics and the exploitability of these aquifers. The research was conducted by various research institutions, governmental organizations and private consultants. All this scientific knowledge was recently collated and reviewed in a book published by the WRC (Woodford et al., 2001).

The present research project was first initiated in 1996 during a workshop organized by the Water Research Commission on Karoo fractured aquifers (WRC, 1996). The project was conducted from March 1998 to June 2000.

## 1.2 SCOPE AND AIM OF THE PROJECT

Dolerite rings and sills control most of the second-order geomorphological features and drainage systems of the Main Karoo Basin. The traditional "koppie" or inselberg that often catches the traveller's eyes on his journey through the Karoo, generally corresponds to an erosional remnant of a dolerite sill or ring (**Plates 1** and **2**). On a regional scale, however, these features display a great degree of variability in size, geometry, shape, level of stratigraphic emplacement and structural complexity. They form an important part of the structural framework of the Karoo Basin and outcrop over an area covering approximately half of South Africa (**Figure 1**).

The exact geometry of these sills and ring-complexes has not been fully documented and relevant structural observations are few compared to the large number of exposures available in the field. It is only during the past 15 years that more information has become available on the structure and tectonics of the Western Karoo dolerite intrusives, such as availability of:

- recently published geological maps of the Council for Geoscience (Geological Survey),
- air-borne magnetic surveys (Council for Geoscience),
- satellite imagery (Landsat TM5),
- digital elevation models (Survey and Land Information)
- regional DWAF hydrocensus data,
- numerous DWAF groundwater exploration borehole data, and
- Water Research Commission funded geohydrological investigations in the Karoo Basin, where these intrusives play an important role in the occurrence of groundwater.

Dolerite dykes are well known for their water-yielding capacity, and represent the most common exploration targets in Karoo fractured-rock aquifers, especially in the study area (Smart, 1998; Woodford et al., 2001; Woodford and Chevallier, 2001). The dolerite-ring and sill complexes have, on the other hand, been to a large extent overlooked as potential groundwater exploration targets, probably due to a number of factors:

- Ruggedness of the often topographically elevated terrain resulting in access problems for drilling-rigs,
- Successful boreholes require deep-drilling (> 60m) into hard rock, and
- Lack of knowledge on the geometry of, and fracturing associated with these intrusive features.

Plate 1: ***Koppie alignment forming the inclined sheet of the Osfontein Ring Complex, dipping to the right. Mapsheet 3122 AB.***

Plate 2: ***Close-up view of the inclined sheet of the Kwaggashoogte dolerite ring-complex, dipping approximately 40° to the left. Note dolerite sill capping the 'koppie' or Mesa in the background (Mapsheet 3122DA)***

Vandoolaeghe (1980a, b) was the first to mention their ground water potential in the vicinity of Queenstown. Smart (1998) reports that "dyke appears to be more productive than dolerite sheets; however in the same way that dolerite in general has not been adequately tested in this area, it is even more likely that dolerite sheets in particular have not been properly explored". Vandoolaeghe (1980a) concludes that "exploration of these aquifers is not straightforward, even in the best cases" and that these aquifers do not stand out for their prolificacy".

The aim, objectives and methodology of the present study were originally stated in the research proposal as follow:

- Regional study: to understand the structure of these large-scale intrusions, i.e. morphology, geometry, shape, size, fracturing, tectonics and mechanism of emplacement. The study had to be conducted on a regional scale in order to assess the spatial variability of the above parameters. The proposed study area includes the three 1 / 250 000 scale maps of Victoria West (3122), Middelburg (3124) and Queenstown (3126). The methodology to be used is 3D terrain modelling, map compilation, remote sensing, geophysics, cross sections and mechanical simulation. The result will be a ***morpho-tectonic model*** of the Karoo dolerite ring and sill complexes.

- Local study: to establish the occurrence of groundwater associated with these intrusions. One sill and ring complex would be selected for geohydrological investigation based on information obtained from the regional study. The objective was to evaluate and refine the conceptual geohydrological model, in terms of ground water occurrence. It will involve field mapping, hydrocensus, exploration drilling and pump testing. This process is aimed towards the compilation of a ***hydro-morpho-tectonic model*** showing the potential zones for enhanced fracturing associated with the emplacement of these structures. Aquifer tests at specific sites will provide information on the extent and sustainable supply potential of these fractured aquifers. The present research leads to a methodology whereby dolerite sills and rings can be defined and classified in term of ground water exploration targets. It is of direct benefit to geohydrologists involved in groundwater exploration in the Karoo as well as to the surrounding communities

## 1.3 STUDY AREA

The study area covers three 1:250 000 scale map sheets, namely Victoria West (3122), Middelburg (3124) and Queenstown (3126) (**Figure 1**). The choice of a study area was dictated by several parameters:

- It had to encompass the regional complexity and variability of the habit and structure of the dolerite sills and rings, and therefore cover an area that would be representative of the morphological diversity and lateral geological variations. The present study area extends over a strip 600 km long by 100 km wide and crosses several ring and sill systems. It was intended to remain in similar Karoo sedimenary rock formations that would prevent unecessary complication of the problem.

- It had to overlap several, still undefined, hydrogeological domains characterised by different morphologies, drainages pattern, rain fall and recharge area, in order the take into account the variability of regional hydrological parameters. The study area crosses over many capture basins and recharge areas.

- It had to lead to the selection of a local study area where a specific ring would be chosen for a drilling exploration programme. The best ring and sills systems are definitively well exposed in the study area leading to a range of choice unrivalled elsewhere.

- The scientific knowledge already acquired on the area, before the project started, was good enough to be used as a launching pad for this research. Woodford and Chevallier (2001) have been involved in a WRC regional lineament project (dolerite dykes and kimberlites) on the Victoria West sheet during which they also made numerous observations on the structure of the sills and dykes that led to the publication of a preliminary conceptual model of these structures (Chevallier and Woodford, 1999). The Department of Water Affairs has carried out many hydrogeological investigations around Victoria West, Middelburg and Queentsown (Vandoolaeghe, 1979a,b, 1980a,b, 1984). Besides, early valuable WRC work was already done on some of the Orange Free State dolerite sills and rings (Botha et al., 1998; Burger et al., 1981). Hydrological results were also available in term of hydrocensus and water development projects. In addition, the hydrogeological map of Queenstown has been published (Smart, 1998).

## 1.4 LITERATURE REVIEW

The literature review on the geology of Karoo dolerite sills and rings started in 1997 during the writing of a paper entitled the "Morpho-tectonics and mechanism of emplacement of the dolerite-rings and sills of the western Karoo" by Chevallier and Woodford (1999). The geological literature study covers historical review, map review, tectonic aspects, mechanism of emplacement and similarities to intrusives found elsewhere in the world. The literature study shows that the exact detail of shape of these sills and rings-dykes has been poorly documented and relevant structural observations were few when compared to the amount of exposure offered in field. It is only in the last 15 years that new information has become available by way of detailed geological maps, digital elevation data, aero-magnetic and satellite imagery.

The literature dealing with the occurrence of groundwater in Karoo dolerite rings and sills was recently reviewed during the compilation of the WRC handbook entitled "Hydrogeology of the Main Karoo Basin: Current knowledge and needs for future research" (Woodford et al., 2001). A limited amount of information was obtained from early studies where ring and sills were targeted for exploration drilling. These tentative results indicate that the hydrogeological importance of rings and sills have often been overlooked during groundwater exploration programmes. Before the realization of the present project the most exhaustive investigation was the one carried on the Philippolis area (Orange Free State) by Burger et al. (1981) and Botha et al. (1996) who concluded that flat transgressive fractures cutting through the rings, the sills and the sediment are more likely to be the main water bearer, rather that the structure and geometry of the sills and rings themself. However, it was our opinion that the limited information obtained from exploration boreholes targeting these features show that they could represent potentially zones of high permeability.

Digital terrain modelling forms an important part of our morphotectonic model. Several scientific and technical articles on digital terrain modelling (DTM) were consulted. Information about the availability of various coverages and data sets was also gathered from the Chief Directorate: Surveys and Land Information. DEMs (digital elevation models) are commonly stored in a raster or cell-based format. A DEM is a raster representation of a continuous surface and is used as input to Arc/Info modules such as GRID, TIN or other raster-based programs to quantify the characteristics of landforms.

Besides producing 3D topographic images, DTM also has many quantitative applications such as slope classification, drainage generation, flood hazard and stream sediment studies etc. DEM's can be generated using a number of methods: digitizing of existing contour maps and stereoscopic mapping from high-resolution air-photographs or SPOT satellite stereo-pair imagery. The resolution of the data is determined primarily by the distance between sampling points.

Mechanical simulation was used in the research project to delineate the most probable zones of fratures around the dolerite sills and rings. A comprehensive review of the theory of elasticity, stress analysis using Finite Element Modelling (FEM) would be endless and irrelevant to the problem. Only a few key articles are therefore cited in the reference list.

## 2 GEOLOGICAL FRAMEWORK

### 2.1 KAROO SUPERGROUP

The study area covers mainly the part of the Basin underlain by the continental detrital sediments of the Beaufort Group and Molteno, Elliot and Clarens Formations. In the north-west corner of the area outcrops the Waterford Formation of the Ecca Group crops out (**Figure 1a**). A geological review of the Karoo Supergroup is beyond the scope of the project. The reader is referred to the following authors for further information: Tankard (1982), Visser (1991), Cole (1992), Smith et al. (1993), Veever et al. (1994), Johnson et al. (1997), Catuneanu (1998).

**Ecca Group**

During the deposition of the Upper Ecca deep-water fans were progressively replaced by fluvially dominated sandy deltas. The sedimentary rocks of the upper part of the Waterford Formation that outcrops on the study area consist of fine- to medium-grained sandstone and siltstone. Mudstone intervals are subordinate.

**Beaufort Group**

The sediments of the Beaufort correspond to the progressive infilling and concomitant shallowing of the Basin. Subaerial depositional environments (fluvio-lacustrine) are present in mudstone, siltstone and sandstone record.

In the study area the late Permian (~260 Ma) Adelaide Subgroup consists of alternating bluish-grey, mudrock and grey, very fine to medium-grained sandstone. Sandstone generally constitutes 20–30% of the total thickness, but in certain areas may be as little as 10%, while some sandstone-rich intervals may in places contains up to 60 % sandstone. This subgroup comprises the Abrahamskraal and Teekloof Formations that are up to 2500m and 1400m thick, respectively. The sandstone units formed by the lateral migration of meandering rivers whereas the mudstone units represents deposition in a flood plain and lacustrine environment. Palaeocurrent data indicate that the source area was situated to the south, southeast and southwest of the Basin and coincided with the second major tectonic paroxysm of the Cape Fold Belt, around 260 Ma.

The early Triassic (~240 Ma) Tarkastad Subgroup is characterized by a greater abundance of both sandstone and red mudstone (less bluish-grey mudstone) than the Adelaide Subgroup. The boundary between these two subgroups is the only one in the Beaufort Group that can be traced with certainty throughout the Main Karoo Basin. The subgroup has a thickness of around 1500 m under the study area where it comprises a lower, fine- to medium-grain sandstone-rich (20–30 per cent) Katberg Formation and an upper, mudstone-rich Burgersdorp Formation. The average thickness of sandstone units is 2m. Intraformational mud-pellet conglomerates are common in both the Burgersdorp and Katberg Formations. The mudstone units in both Formations are predominately red coloured. Reptile, amphibian and to a much lesser extent fish remains are fairly common in the Tarkastad Subgroup. Meandering streams, flood basin and lacustrine palaeo-environments may have predominated Palaeocurrent data suggest a source in the South and South- East, similar to that prevailing during deposition of the underlying Adelaide Subgroup.

**Molteno, Elliot and Clarens Formations**

The sediments of the Stormberg Groups correspond to further infilling, shrinking and shallowing of the Karoo Basin, with purely fluvial and aerial depositional environments. Progressive aridification occurred during the final phase of the history of the basin as south-western Gondwanaland migrated from the polar latitudes to sub-tropical latitudes.

The late Triassic (~220 Ma) Molteno Formation attains a maximum thickness of close to 600m in the study area. The Formation comprises alternating medium- to coarse-grained sandstones and grey mudrock, with well-preserved plant fossils and sporadic coal seams. Deposition was predominantly by braided rivers flowing from a tectonically active source area, probably the Cape Fold Belt, situated to the south and southeast.

The late Triassic to Early Jurassic (~195 Ma) Elliot Formation comprises an alternating sequence of maroon and green-grey mudrock and subordinate fine- to medium-grained yellowish grey to pale red sandstone. It attains a maximum thickness of about 500m in the study area. Contacts with the underlying Molteno and the overlying Clarens Formations are gradational. The Elliot Formation comprises a lower arenaceous unit with fining-upward cycles, reflecting meandering river sedimentation and an upper mudrock-dominated unit interpreted as a playa deposit.

The Middle Jurassic (~180Ma) 100 m thick Clarens Formation forms minor outcrops in the study area. It consists mainly of well-sorted wind-blown fine-grain sandstone and siltstone.

Finally, while the southern margin of the Karoo Basin was severely deformed during the Cape Orogeny, the remaining interior portion was gently folded with a centripetal dip (<5°) towards Lesotho. In the study area this resulted in shallow, less than 5°, northwards dipping strata.

## 2.2 KAROO DOLERITE INTRUSIONS

The Jurassic dolerite dykes and sills were intruded into the sediments of the Karoo Supergroup during a period of extensive magmatic activity that took place over almost the entire Southern African subcontinent during one of the phases in the Gondwanaland break-up. They represent the roots and the feeders of the extrusive Drakensberg basalt that are dated around 180 My (Duncan et al., 1997; Fitch and Miller, 1984; Richardson, 1984) one of the largest outpouring of flood basalt in the World. The total volume of magma extruded on the Southern African Continent has been estimated at 10 million $km^3$ (White, 1997). Large-scale erosion of the main Karoo Basin has revealed the deeper portions of the intrusive system and a degree of tectonic complexity not encountered in the other major continental intrusive systems in the world (**Figure 1**).

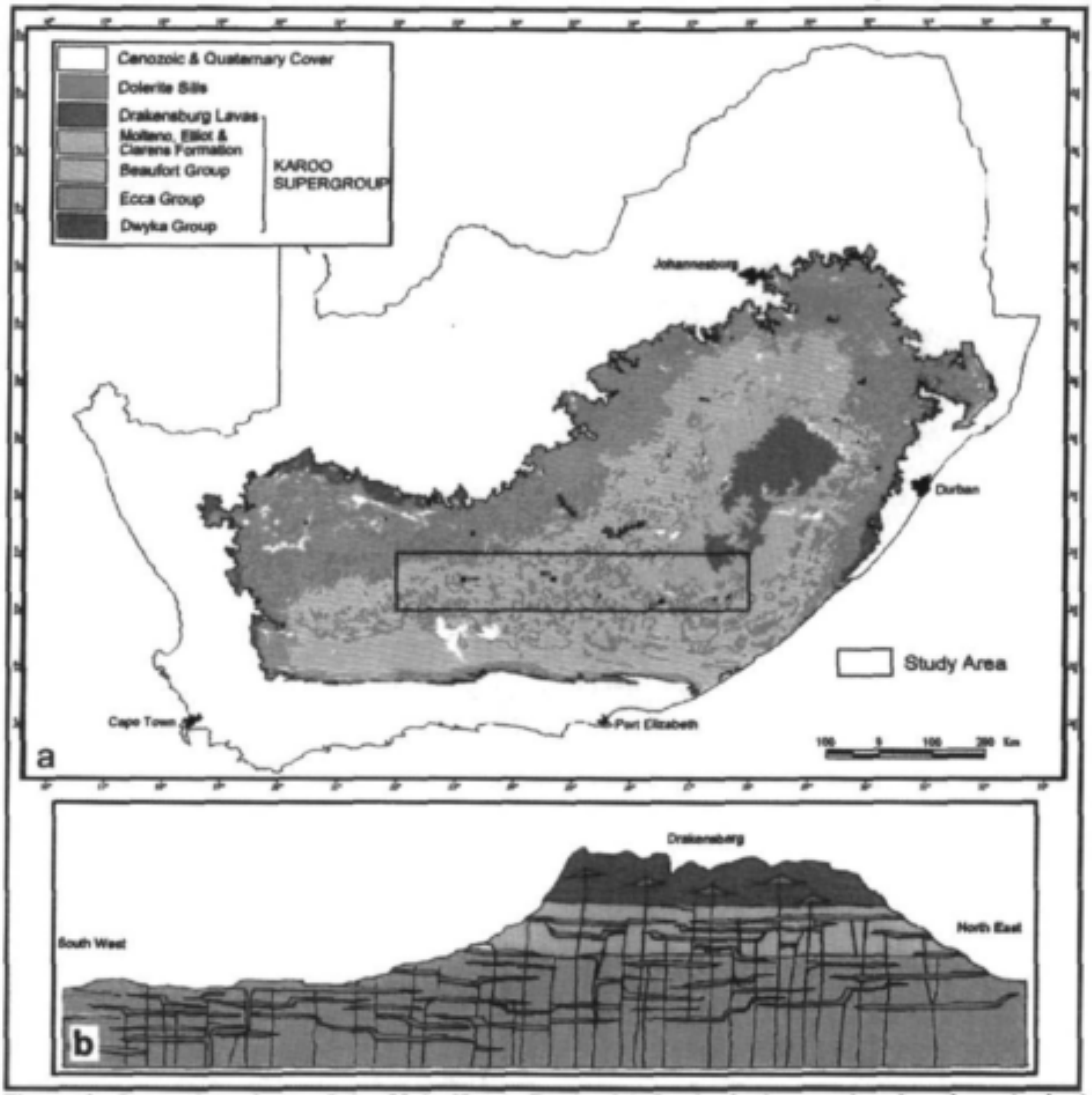



**Figure 1**: ***General geology of the Main Karoo Basin. (a) Geological map showing the principal Groups underlying the study area and the extent of the Jurassic magmatic rocks (Drakensberg lavas and dolerite sills) (b) Schematic SW- NE cross-section of the Karoo Basin showing the complexity of the dolerite sill and dyke network forming a shallow crustal stockwork-like reservoir below the erupted Drakensberg lava.***

The dolerite intrusions consist of an interconnected network of dykes and sills and it is nearly impossible to single out any particular intrusive or tectonic event. It would appear that a very large number of fractures were intruded simultaneously by magma and that the dolerite intrusive network acted as a shallow stockwork-like reservoir (**Figure 1b**). In other parts of the world extremely large-volume intrusive events are mostly expressed as extensive radiating dolerite dyke swarms (viz. The 1270 Ma Mackenzie swarm, Ernst and Buchan, 1997), but no sill / ring / dyke complexes (and associated aquifers) similar to the Karoo have ever been described, except (to a much lesser extent) for the Proterozoic intrusions of the Guiana shield (Gibbs, 1987).

The Karoo dolerite include a wide range of petrological facies; from a leuco-gabbro to granophyric dolerite; dolerite (sensus stricto) is by far the most common facies, consisting of intersertal clinopyroxene (augite and pigeonite) and plagioclase (labradorite) as the major mineral phases accompanied by subordinate olivine, orthopyroxene, and Cr-spinel, as well and opaques and biotite in the groundmass .

### Dykes

A map of the Karoo dolerite dykes has been compiled from existing 1/250 000 scale geological maps and completed by aerial photograph and satellite lineament interpretation (**Figure 2**). It appears that there is an association between lithology and dolerite distribution. This may imply a lithological control on the emplacement of dykes within the Main Karoo Basin: a sharp decrease in intrusion density is noted at the boundary between the lower Ecca (low density of intrusion) and the upper Ecca (high density of intrusion). This boundary corresponds to the appearance of the first sandstone units in the Karoo Basin.

Even if many dykes can still be seen within the lower Ecca and Dwyka Formations as well as the Nama basement the bulk of them are stratabound and concentrated in the Upper Ecca and Beaufort Sandstone. This means that the dolerite might have propagated laterally along strike, and not vertically. A magma source, corresponding to the triple junction of three rift zones, and located east of East London (**Figure 2b**), was proposed by Chevallier and Woodford (1999).

Three major structural domains, indicated by dyke distribution, have been identified in the Main Karoo Basin:

(1) The Western Karoo Domain extends from Calvinia to Middelburg and is characterised by two distinctive structural features: E-W trending zone of long and thick dykes associated with right lateral shear deformation and NNW dykes.

(2) The Eastern Karoo Domain extends from Middelburg to East London and comprises two major dyke swarms, namely: a major curvi-linear swarm of extensive and thick dykes diverging from a point offshore of East London and minor NNE trending dykes.

(3) The Transkei-Lesotho-Northern Karoo Domain consists of two swarms: NW trending dykes in the Transkei region, curving to EW in the Free State and NE trending dykes mainly occurring within and alongside the Lesotho basalt.

The study area straddles domains (1) and (2), with the Dunblane NNW dyke, west of Middelburg, acting as a transitional boundary. This dyke is in the prolongation of the curvi-linear East London diverging dykes of domain (2) but also and form part of the NNW swarm of domain (1). Note that this boundary also corresponds to a change in lithology: Beaufort Group in the West, Molteno and Elliot Formations in the East.

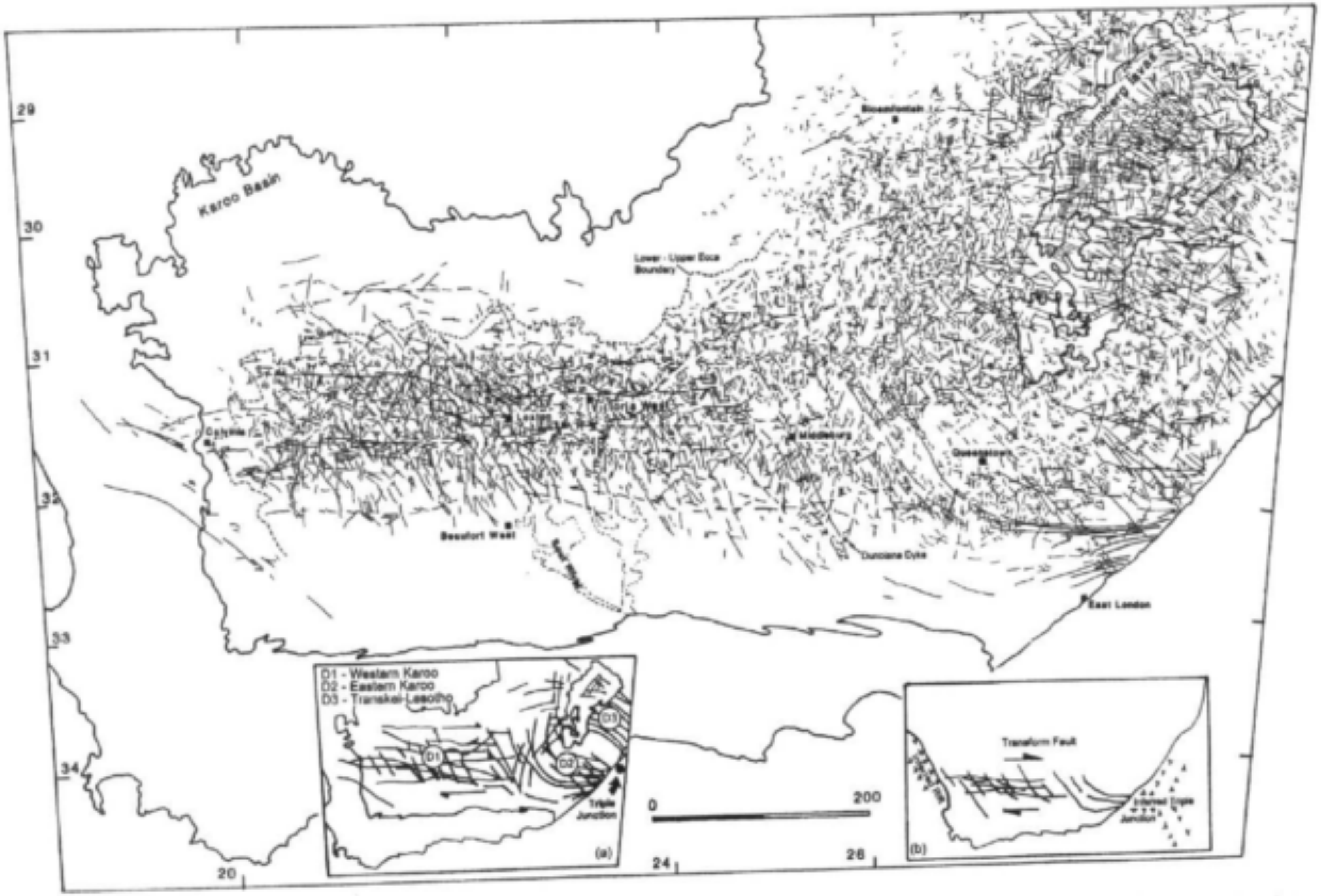



**Figure 2**: *Dolerite dykes of the Main Karoo Basin (after Chevallier and Woodford, 1999). Inset (a): simplified structural map showing the three structural domains. Insert (b): geodynamic interpretation of the Western and Eastern Karoo structural setting.*

**Sill and Ring-Complexes**

The dolerite sills and rings (**Figure 3**) have the same geographical distribution than the dykes and are by far the most common tectonic style in the Karoo basin controlling the geomorphology of the landscape to a large extent. Du Toit (1905, 1920) was the first researcher to describe these structures in the vicinity of Queenstown. However his first structural interpretation of a three dimensional undulating sill producing a "basin and dome" or "egg-box" geometry is not valid anymore. We know now that the most common geometry in the Upper Ecca and Beaufort Groups is a sub-circular saucer-like shape, the inclined rims of which are commonly exposed as topographical highs that form ring-like outcrops. The geometry becomes very complex at the regional scale since the rings form large coalescing, cross-cutting, circular, oval or kidney-shaped structural units. Each unit is in itself composed of several sub-units of smaller size which in turn are made of even smaller units and so forth, resulting in the so called "ring-within-ring" patterns (**Figure 3b**). This suggests in inherent structural control in the intrusive event; perhaps by jointing associated with initial uplift just prior to the magmatic intrusions.

Many near vertical dykes are branching onto the sill and ring complexes or cutting through them. The relationship between the dykes and sill/ring complexes is very intricate. In the Western Karoo, many of the dykes can be seen feeding into the inclined sheet and controlling the shape of the ring, sometimes resulting in a jagged rim. Some of the dykes can also branch out of one ring into another ring. As mentioned above dolerite sills and dykes form a complex intrusive network that was probably acting as a shallow magma storage system. The relation between the dykes (vertical), the ring (oblique) and the sill (horizontal) is still a matter of debate between two schools i.e. the laccolith with peripheral offshoots of Burger et al. (1981) and the saucer-shape ring-dyke model of Chevallier and Woodford (1999) (**Figure 4**). We will see in the section 3.6 "Mode of emplacement" how these two conceptual models differ from, converge, and complement each other and what the hydrogeological implications are.

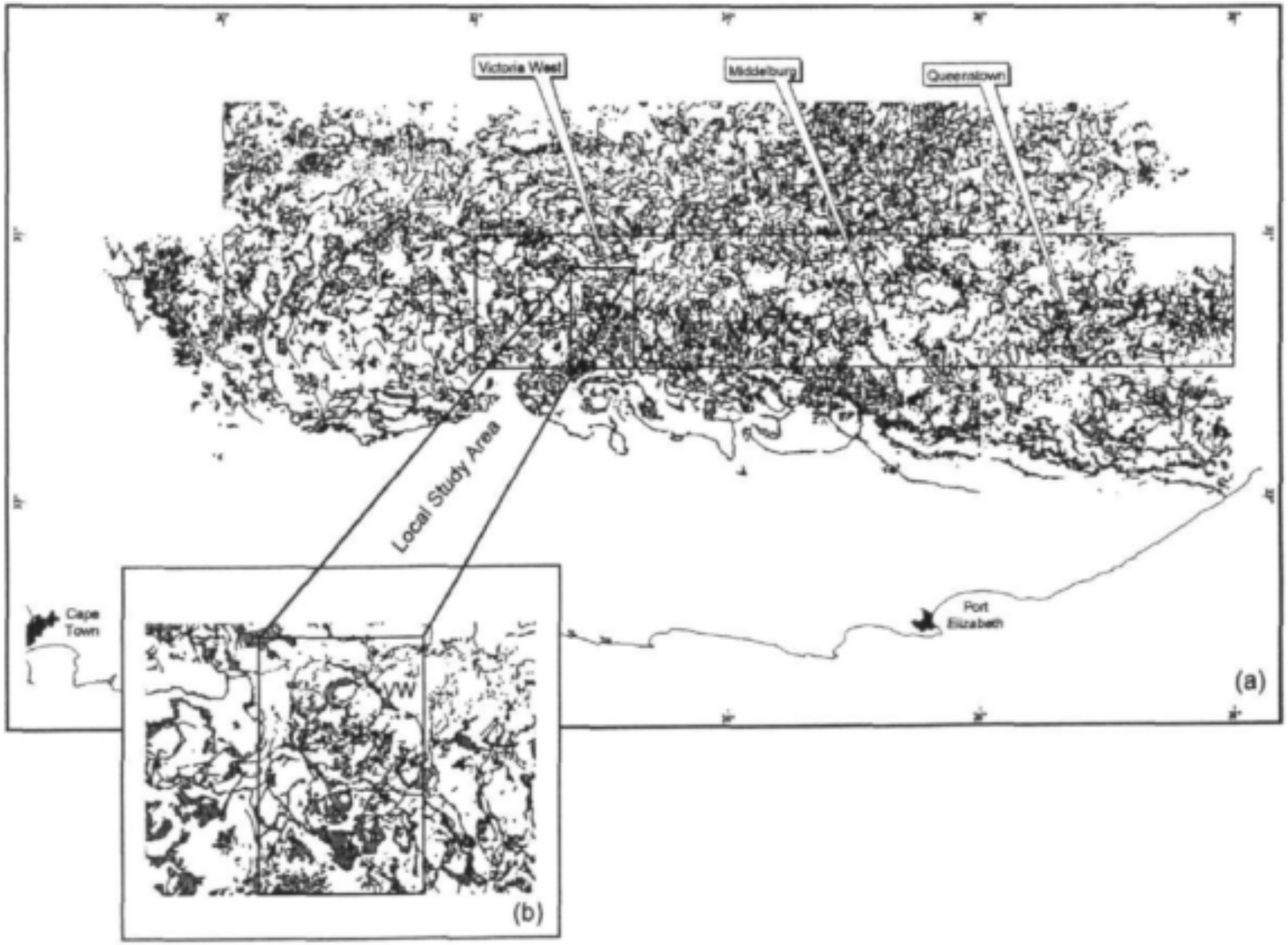



**Figure 3**: ***Dolerite sills and ring-complexes of the Western and Eastern Karoo (after Chevallier and Woodford, 1999), showing the complexity and interconnectivity of the intrusions. Inset: The local study area around Victoria West, showing the ring within a ring pattern at medium scale range***

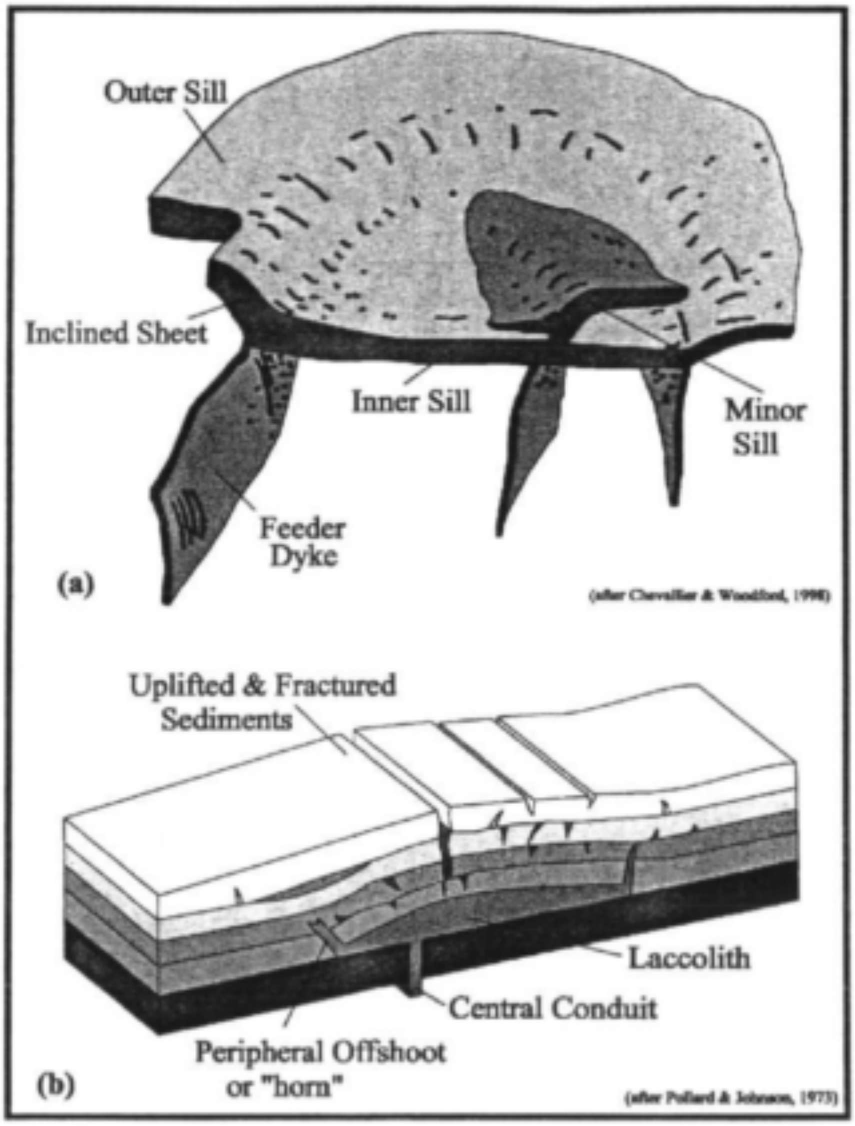



Figure 4: *Two contrasting but complementary conceptual models of the Karoo dolerite sill / ring / dyke complexes. (a) the saucer shape and ring dykes model of Chevallier and Woodford (1999) and (b) the laccolith and peripheral offshoot model of Burger et al. (1981).*

# 3 REGIONAL MORPHO-TECTONIC STUDY

## 3.1 DIGITAL ELEVATION MODELLING

The National Digital Elevation Model of the study area was built from elevation data obtained from the Chief Surveyor General: Surveys & Land Information in Mowbray in a grid format, with cell or grid-size of either 200x200 or 400x400 metres. The Council for Geoscience's GIS Section in Pretoria re-sampled the data-sets for a number of "tiles" to a common 400x400m cell-size. A total of seven data tiles were required to cover the regional study area. Each tile was checked for errors, and blocks of incorrect data were identified and removed from the source grid.

The processing of the spatial data was performed on a UNIX platform Arc/Info v7.2, and *an NT PC platform running* ArcView 3.1 *using the Spatial Analyst module. All the data* were initially projected to the Albers Equal Area map projection to minimise distortions over the entire region of interest. The data tiles were merged together and a final grid created using Arc/Info's TOPOGRID command.

The drainage data were obtained from the CCWR.

The regional terrain model shows a series of highlands and lowlands (or basins) forming several major regional geomorphological features, which from West to East are (**Figure 5**):

- The Loxton and Victoria West Highlands are characterized by relatively flat-lying topography.

- The Victoria West Basin is a shallow structure that is elongated in a N-S direction. It is divided by the Victoria West highlands into two watersheds. The Northern sub-basin represents the catchment area for the Ongers Rivers and its tributaries (Klein-Brak, Brakpoort, Visgat), whereas the Southern sub-basin is drained by the Sout River and its tributaries (Krom and Kookfontein), as well as the Buffels River and its tributaries (Tierhoek, Snyderskraal, Bakensklip).

- The Sneeuberge Highlands form a prominent positive topographic feature. It is characterised by a rough topography and a complex drainage pattern. A strong *morphostructural feature is present as a NS linear trending ridge on the western part* of the highlands.

- The Nieu Bethesda Basin is a small circular structure from which surface water *runoff flows towards Graaff-Reinet.*

- The Middelburg Basin is a prominent, deep, and well-defined circular feature. This 50 km wide structure is not entirely covered by the study area. Its southern boundary lies on the Graaff-Reinet 1/250 000 mapsheet where it also forms a rim of high relief. The basin forms the catchment area for the Great Fish River and its tributaries the Klein Brak, Groot Brak and Vlekpoort rivers.

- The Molteno Highlands form an extensive platform of high relief, essentially controlled by the Molteno, Elliot and Clarens Formations and the Drakensberg lava.

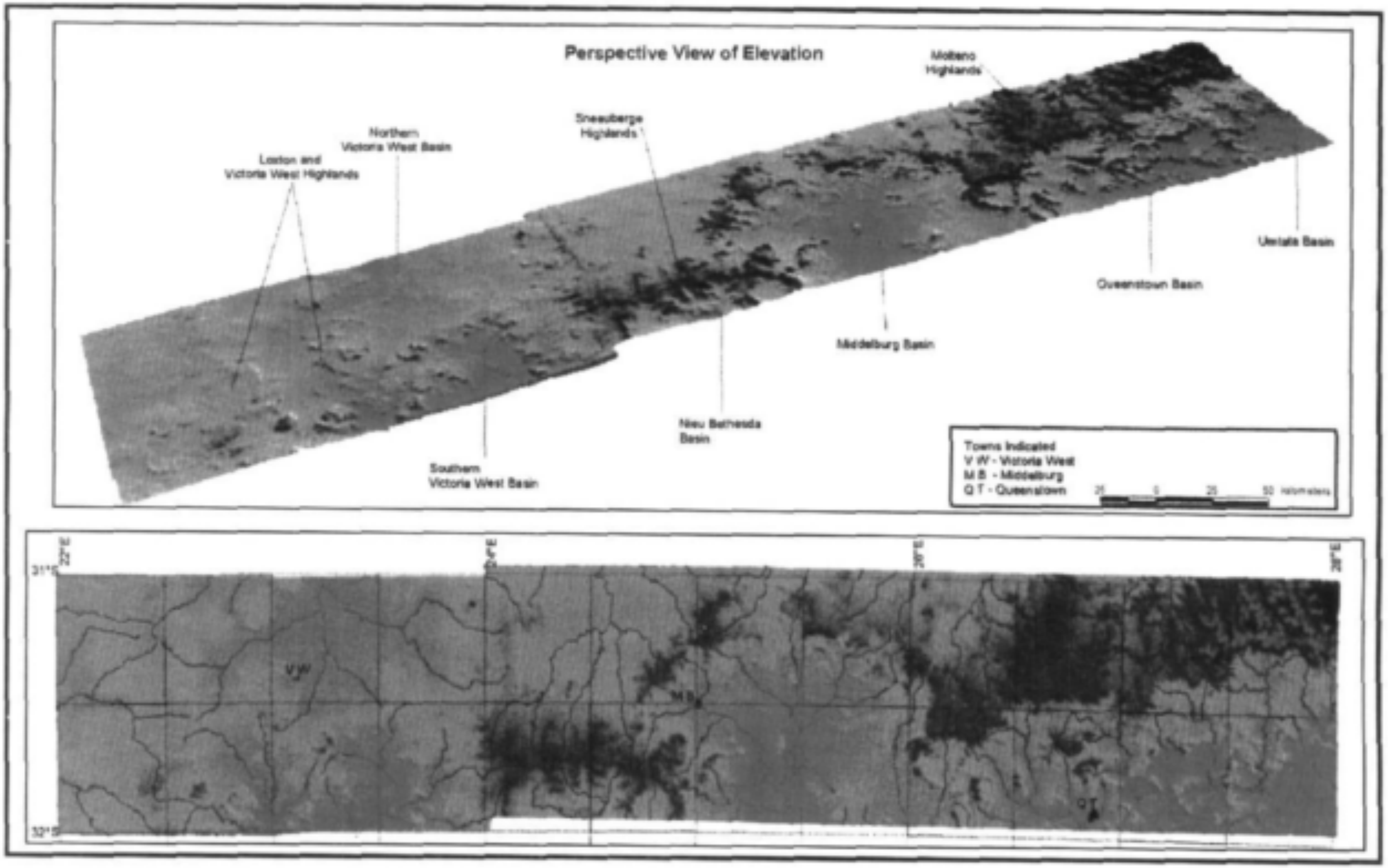



Figure 5: *Digital Elevation Model showing regional topography and drainage system of the study area. VW: Victoria West, MB: Middelburg, QT: Queenstown*

- The Queenstown Basin is poorly defined and represents the most rugged terrain in the study area. It forms an area of sharp elevation contrast where the lowlands average some 1200 m.amsl and mountain summits attain heights of up to 2000 m.amsl. The drainage system is also very irregular and corresponds to the catchment of the Swart Kei and Great Kei Rivers.

- The Umtata Basin lies on the eastern margin of the study area and forms the western extension of a much larger structure, which is seen on the adjacent Umtata 1/250 000 mapsheet. The area is low-lying and is drained by a number of SE trending entrenched meandering rivers that extend towards the coast.

## 3.2 STRUCTURAL ANALYSIS OF SILLS AND RING-COMPLEXES

The dolerite sill and ring information was extracted from the existing 1/250 000 geological maps and projected to the Albers Equal Area coordinate system for further spatial analysis in Arc/Info. The sills and rings have been draped over the terrain model (**Figure 6**). It is clear that these dolerite intrusions are controlling the second order morphology in the Karoo (first order morphology refers to very large scale geomorphological features like the African surface or the post-African surfaces of Partridge and Maud, 1987, that created the Orange River capture basin and the great escarpment). The Middelburg Basin is especially well defined by an area of low density of intrusion and poor connectivity contrasting with the high-density intrusion and high connectivity of the surrounding Sneeuberge and Molteno highlands. The Northern Victoria West sub-Basin also shows low density of sill and ring intrusion. The Loxton and Victoria West highlands are characterized by high density and high connectivity. The Queenstown basin is very different from the rest with low grounds and high density of intrusion. The map of sills of **Figures 7, 9 and 11** illustrates very well the structural complexity of these structures and their intricate connectivity. The "ring-within-a-ring" pattern is also well demonstrated. The outline of the dolerite sill and ring-complexes, although "circular" in broad terms, are in reality often irregular (angular to sub-angular) and may intersect one another. A exhaustive mapping of the fracture network of Victoria West sheet was completed during a former Water Research Commission project (Woodford and Chevallier, 2001) and is reported on Figure 7. The coverage (called Lincomp) is a combination of dykes from the existing geological map, air photo interpretation, satellite Image integration and fieldwork. Most of the fractures are dolerite dykes or dolerite related fractures. Master joints follow the doleritic trends most of the time. Several Cretaceous kimberlite-related fissures exist in the NW corner of the map. The Victoria West map shows that the rim of ring systems display in fact more linear than curvi-linear outlines and tend to follow the regional trends of dyke and fractures. Examples of dykes branching into a ring are numerous.

A total of eleven geological cross-sections were compiled from the existing 1/50 000 scale field-maps, i.e. 3 on the Victoria West sheet, 4 on the Middelburg sheet and 4 on the Queenstown sheet. These sections were verified and complemented with field observations. Their respective locations are shown on Figures 7, 9 and 11. The cross-sections were subsequently digitized and are presented in **Figure 8, 10** and **12**. Reference positions such as roads, farm names and boundaries, towns, dams, rivers etc; are indicated on the profiles, as well as the appropriate 1:50 000 mapsheet number, coordinates, and private borehole positions situated less than 1km from the section-line.

At some localities the mapping of dolerite intrusions is suspect, i.e. where sills thicken to form irregular "blobs". It appears that, in places, the transfer of aerial photograph information to the 1:50 000 topographic sheets took place without due regard for the intersection of the dolerite feature with the surface contour lines.

The general "saucer-shape" of the sill/ring complexes described in our conceptual model is confirmed all over the study area i.e. a flat-lying inner sill always corresponding to low grounds, an inclined sheet forming the ring, an outer sills corresponding to high grounds.

While thickness of outer sills can always be estimated from the geological maps or measured on the field, the thickness of the rarely outcropping inner sill is often guessed and can always be ascertained by drilling. Major sills often averages 60m in thickness.

Sills up to 200m are sometime reported during drilling (SOEKOR stratigraphic borehole AB 1/ 65 on Victoria West sheet, Water Affairs exploration borehole G 46020, see section on local study). Much thicker sills (500 to 1000m) of usually more gabbroic nature have been described in Eastern Cape i.e. the East Griqualand sills (Scholtz, 1936; Mask, 1966), and the Bird River Gabbro (Eales and Booth, 1973). None of these very thick sills have been reported in the western Karoo.

It would be endless to describe the structural complexities found on these cross sections. Practical and cost reasons also prevent publication on a larger format. Many ring complexes show a strong asymmetric profile with a thick and well developed inclined sheet and outer sills on one side and a thin or non-existent inclined sheet on the other side.

Several dolerite dykes are seen feeding into the inclined-sheets and ring complexes. However some of the rings do not show a feeder-dyke and are the result of a "stepping-up" of the sill. In some places a sill buttresses against a fault or a big feeder that seems to act as a barrier preventing the sill from propagating any further. When a sill does transgress that barrier it only forms a short and thin horizontal offshoot. The inclined sheet forming the ring very often corresponds to multiple magma intrusions either along the same fracture or along two or even three different fractures. Alongside the lower contact of these thick inclined sheets thin offshoots are often seen (**Figure 14 and 15**).

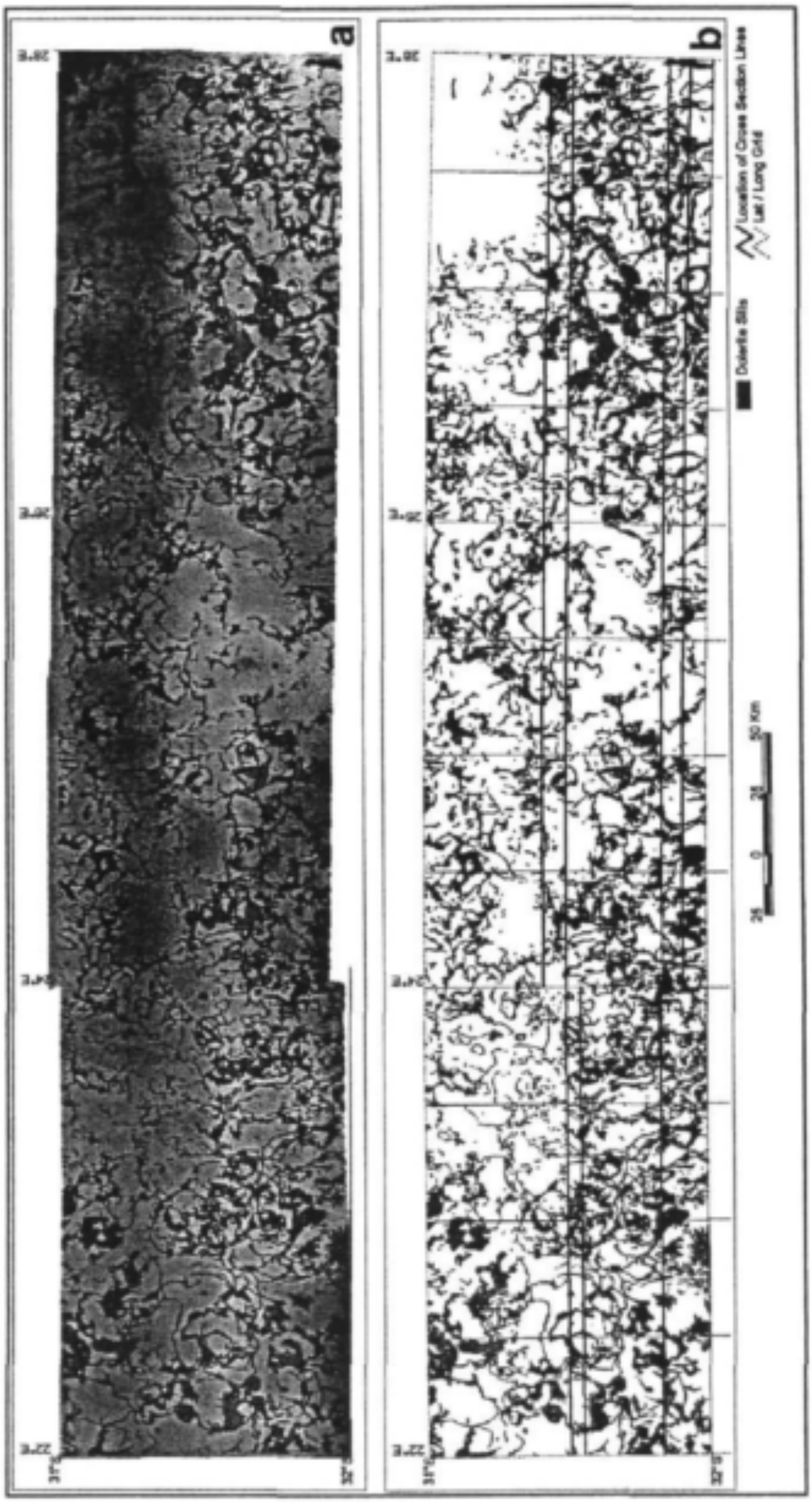



Figure 6: *Dolerite Sills and Digital Elevation Model of the Study Area.*

On a regional scale many variations in the attitude and stratigraphic position of these sills are observed with a definite change in tectonic style from west to east:

The Loxton and Victoria West highlands are characterised by complex anastomosing of sills similar to the Sneeuberge and the Molteno highlands. In these areas the sill and ring complexes form closed, individual structures staked above each other with up-ward decrease in size of the ring is common.

In the Northern Victoria West, Middelburg and Nieu Bethesda basins the sills and rings display a totally different regional pattern. They form large single structure characterized by inverted vertical stacking i.e. a downward decrease in the size of the ring (which is very different from the up-ward decrease for the Loxton, Victoria West and Nieu Bethesda highlands).

In the topographically complex Queenstown basin the sills and rings are numerous, small, interconnected and display important vertical stacking. However there is not much vertical variation in size. In places, a dyke can feed two superimposed sills of the same size, resulting in a characteristic box-like pattern.

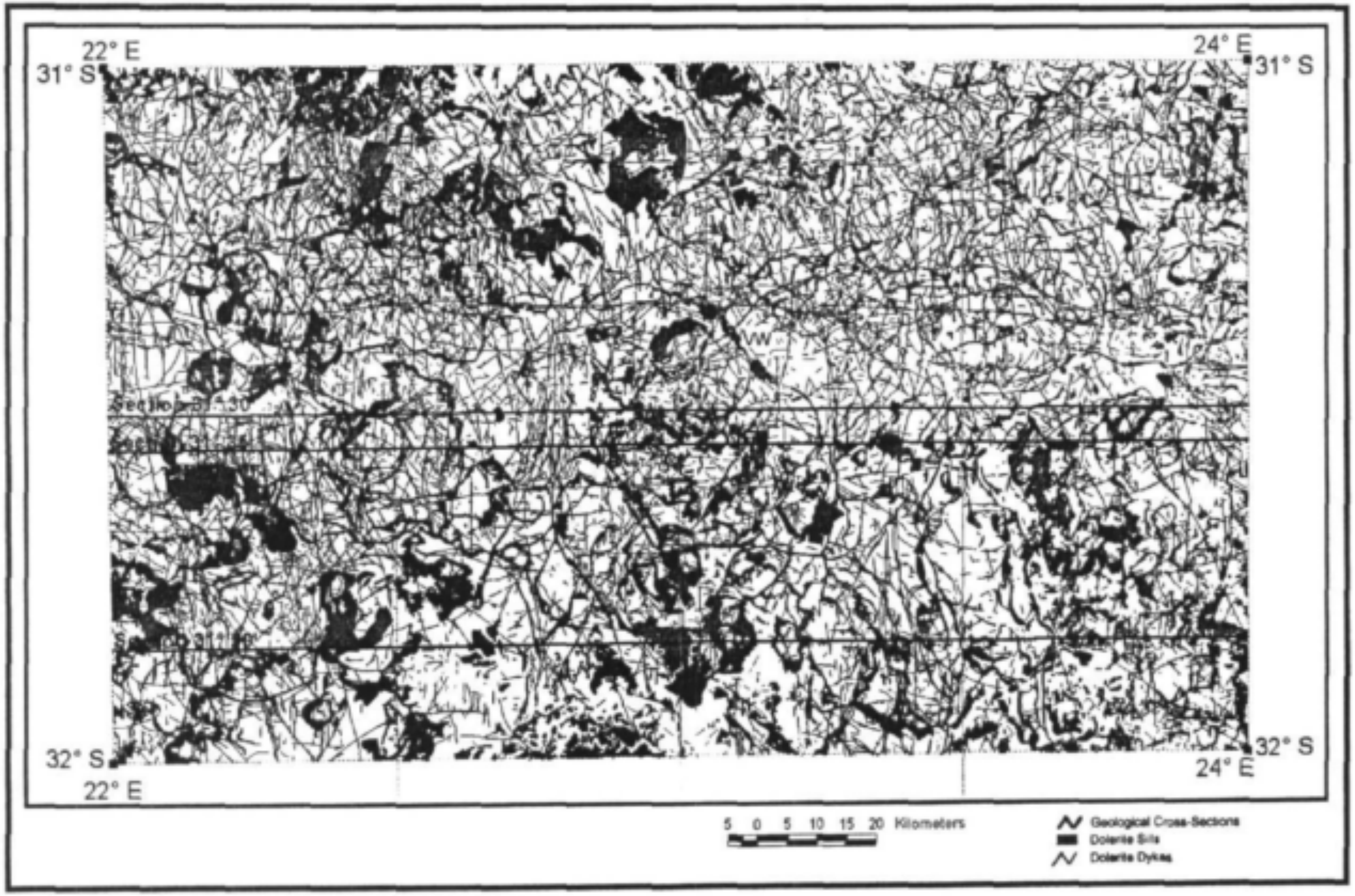



Figure 7: ***Map of dolerite dykes, sills and ring-structures over the Victoria West 1:250 000 sheet, also showing the cross-sections lines of Figure 8.***

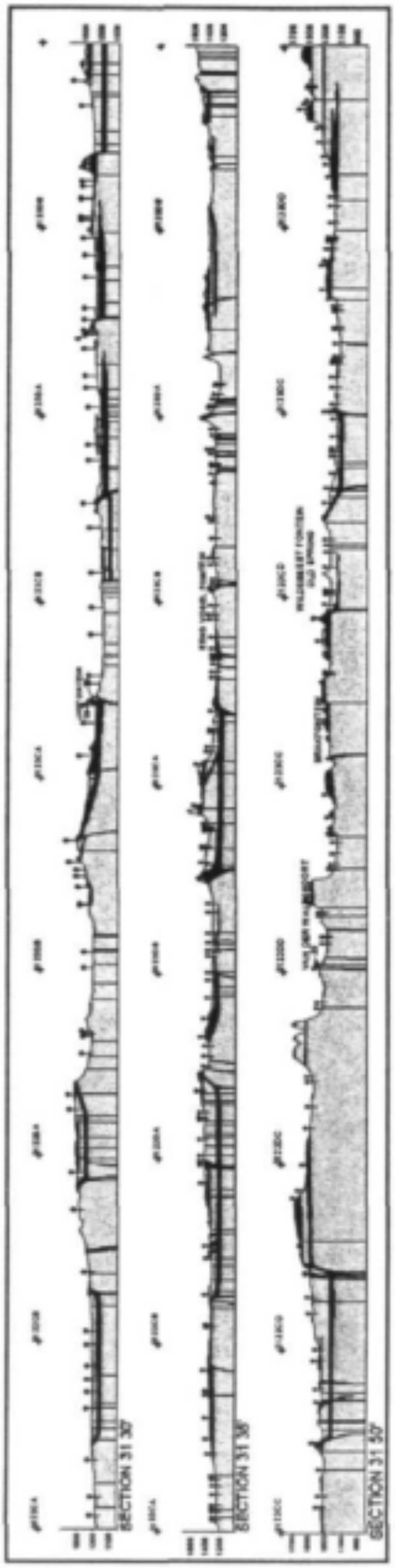



Figure 8: Geological Cross sections of the Victoria West sheet. See Figure 7 for location.

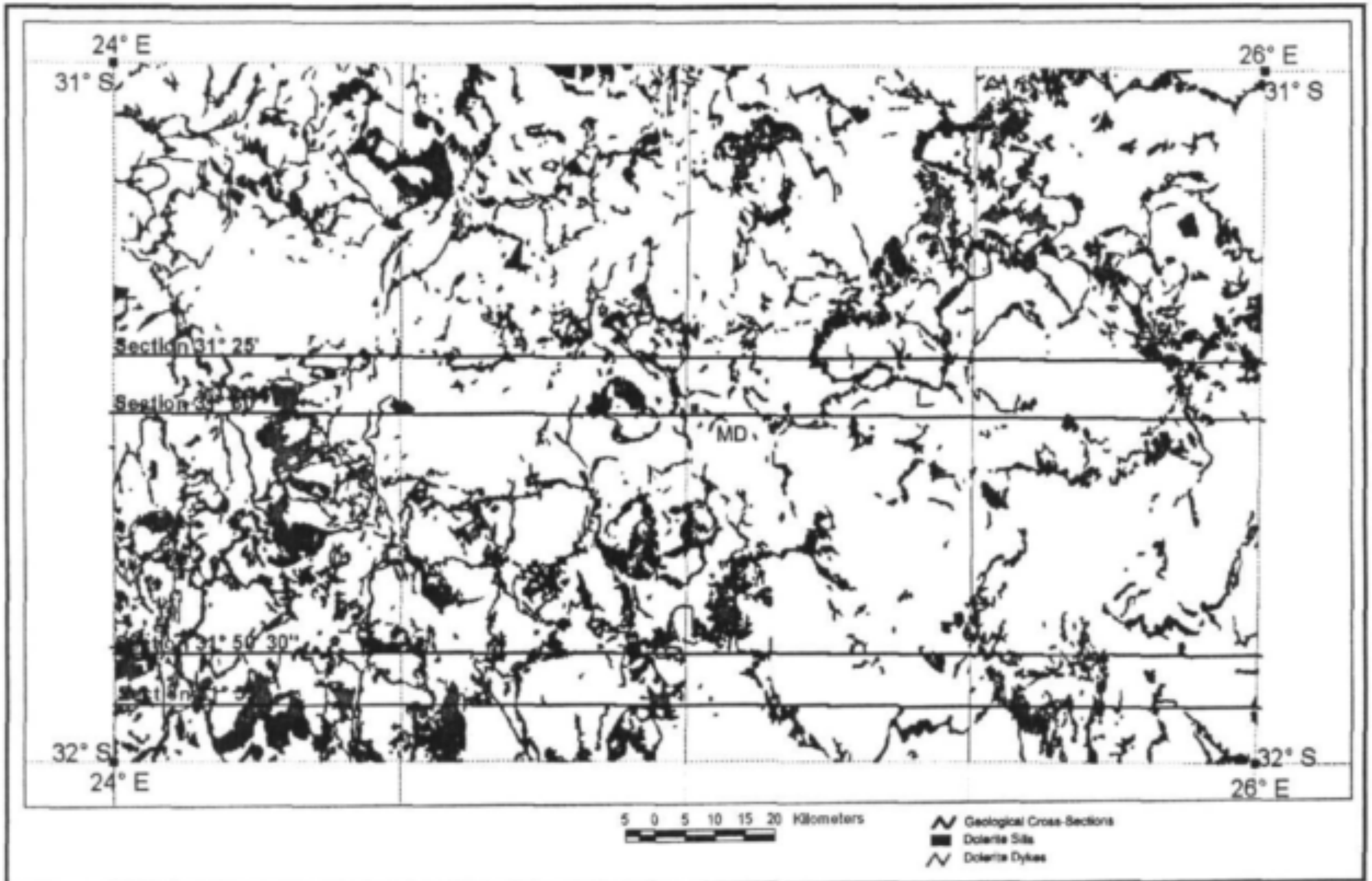
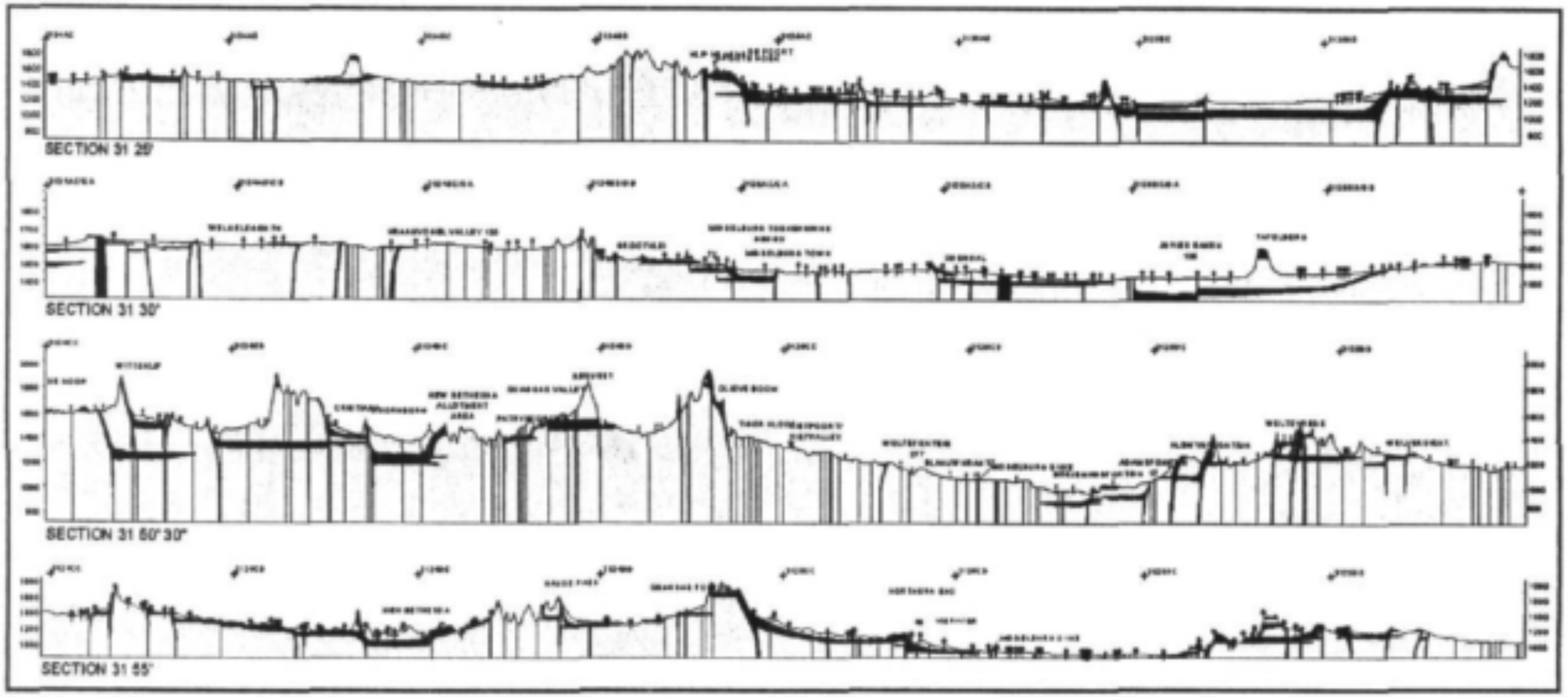



**Figure 9**: ***Map of dolerite dykes, sills and rings over the Middelburg 1:250 000 sheet, also showing the cross sections lines of Figure 10.***




**<u>Figure 10</u>: *Geological Cross-Sections of the Middelburg Sheet (See Figure 9 for location).***

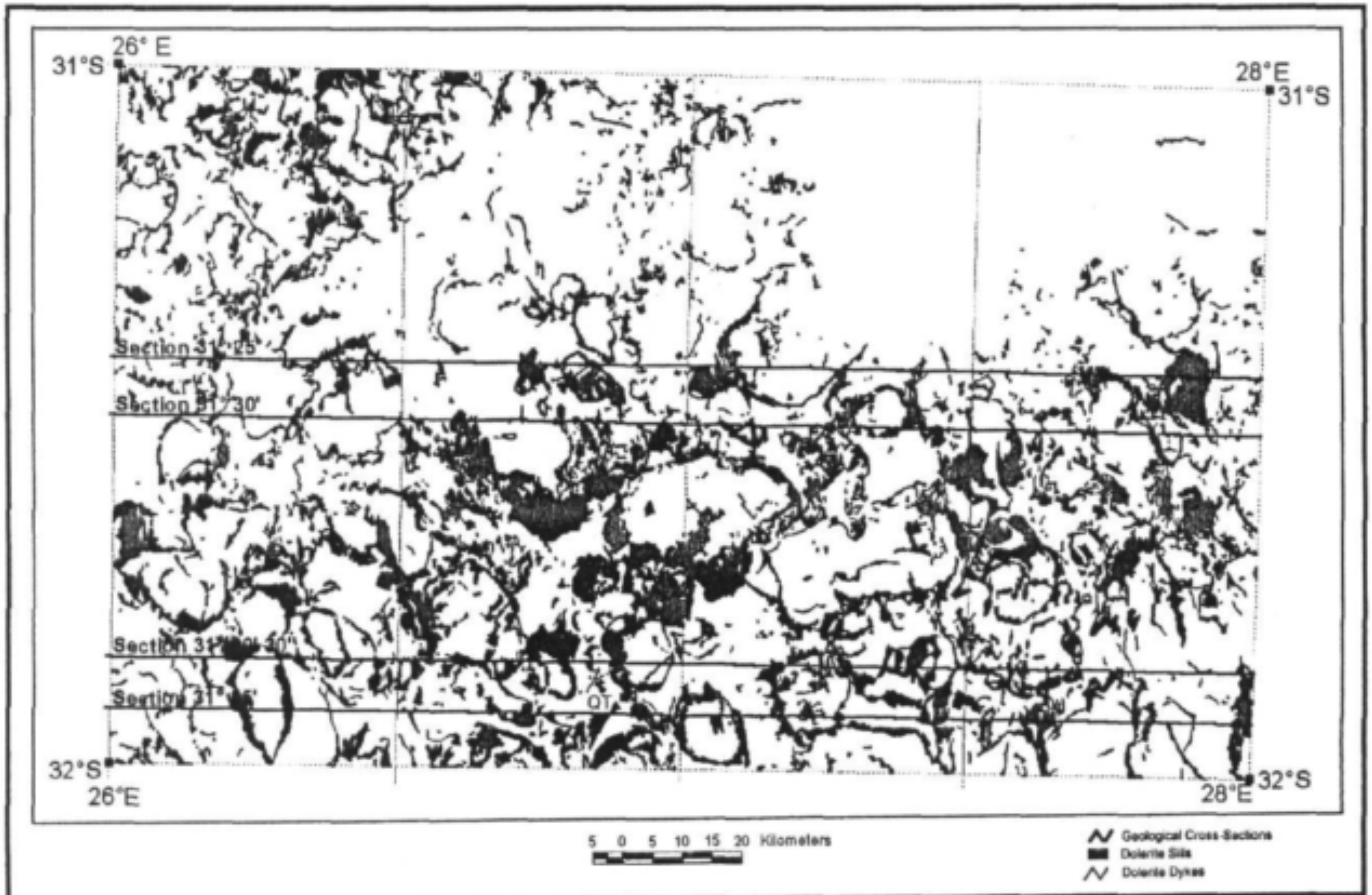



**Figure 11: *Map of dolerite dykes, sills and rings over the Queenstown 1:250 000 sheet, also showing the cross sections lines of Figure 12.***

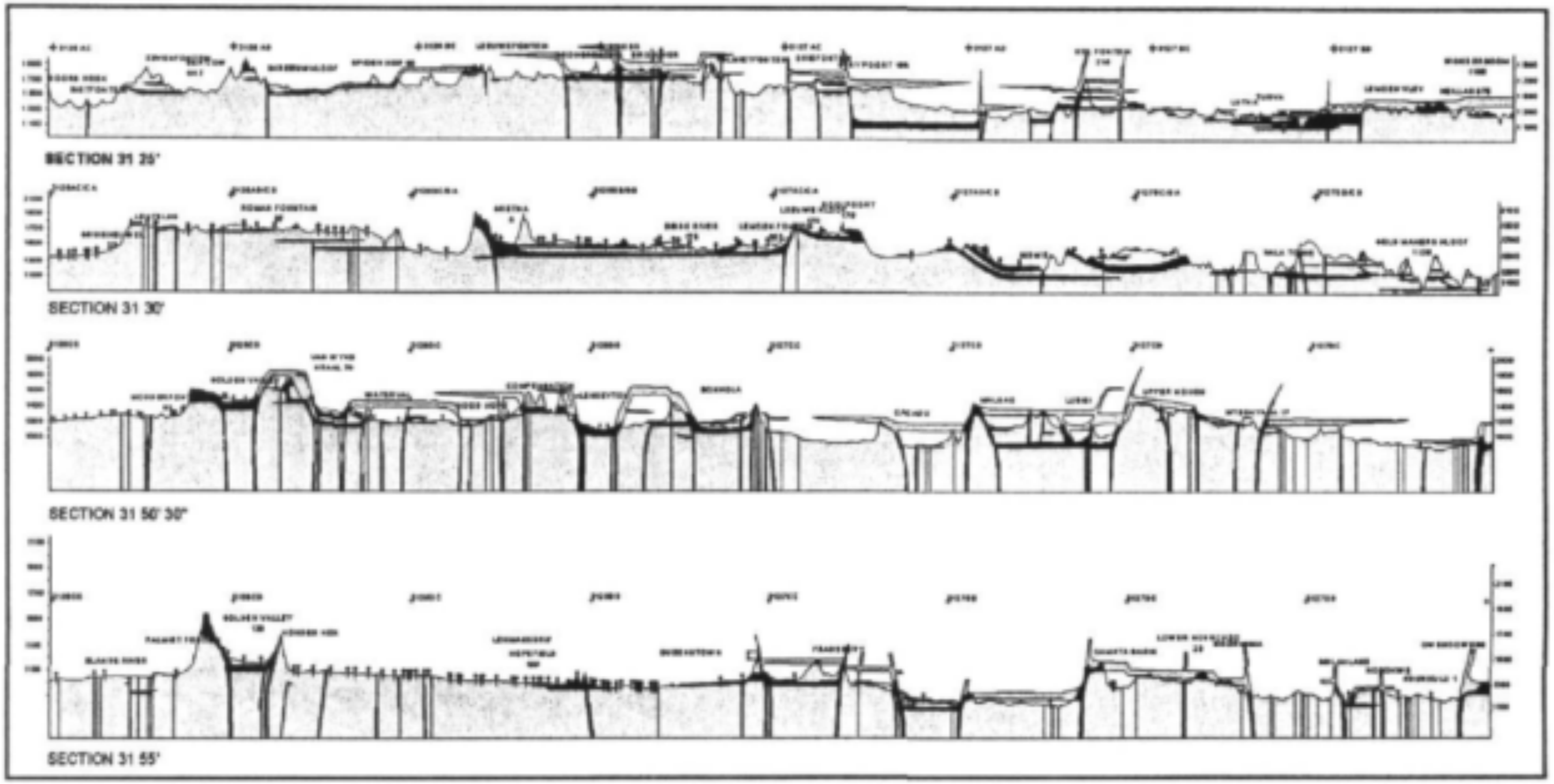



**Figure 12**: ***Geological Cross-Sections of the Queenstown sheet see Figure 11 for location.***

Many field observations were gathered along several of the geological profiles. While the sections were corrected as far as possible, not all of this information can be presented in the report (see Addendum 2), i.e. variations in dip / attitude of the inclined sheets, thickness, the nature of the contact with the sediment, local fracturing and offshoots associated with the main intrusions, relationship between dykes - inclined sheets – sills, etc. Three examples from Victoria West highlands, Sneeuberge highlands and Queesntown basin are given below.

The road between Loxton and Victoria West cross sects an impressive feeder forming part of the Ghaapkop Ring Complex (**Figure 13**).

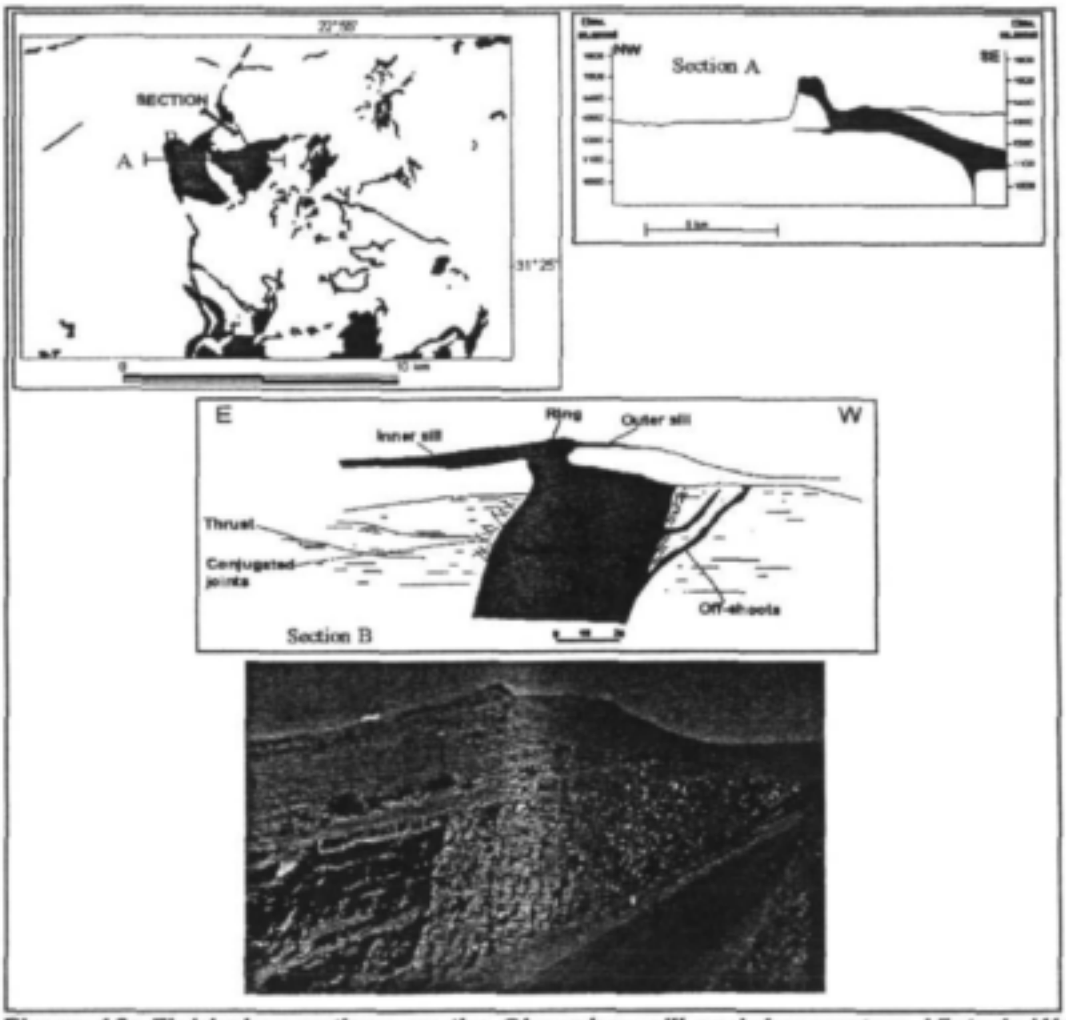
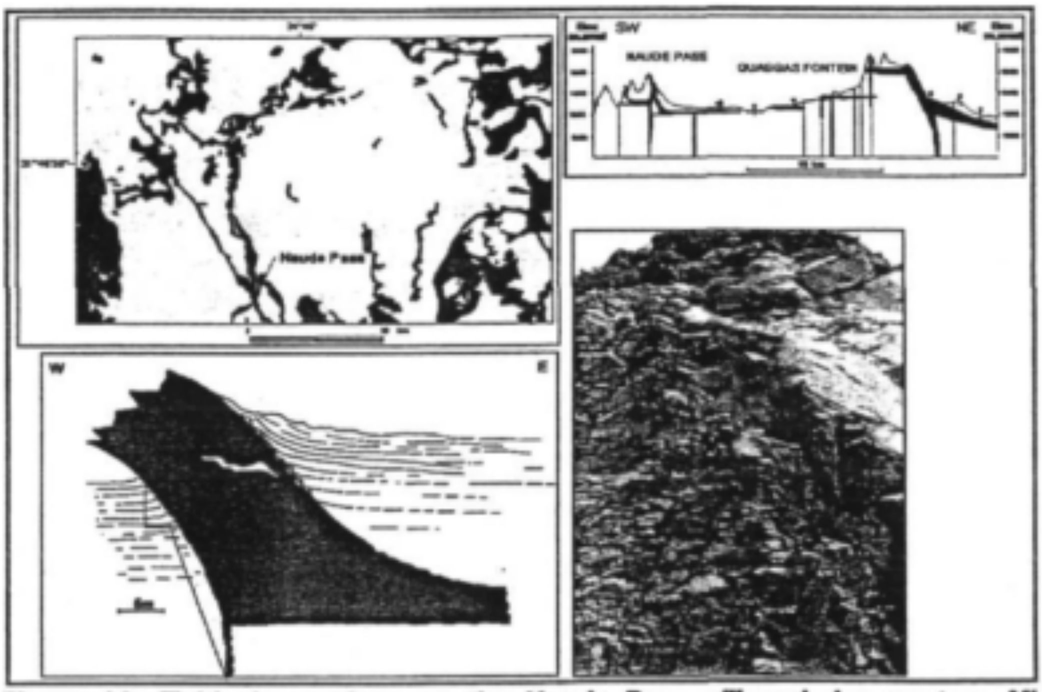



Figure 13: ***Field observations on the Ghaapkop sill and ring-system, Victoria West. Road cut (Victoria West Loxton) showing the relation between the inclined sheet, the inner sill and the outer sill (compare with conceptual model of Figure 4b).***

The dyke has a dip of 81°E and is 45m thick. At its footwall or lower western contact, the sediment is sheared and few thin (20 to 30 cm) dolerite offshoots are seen.

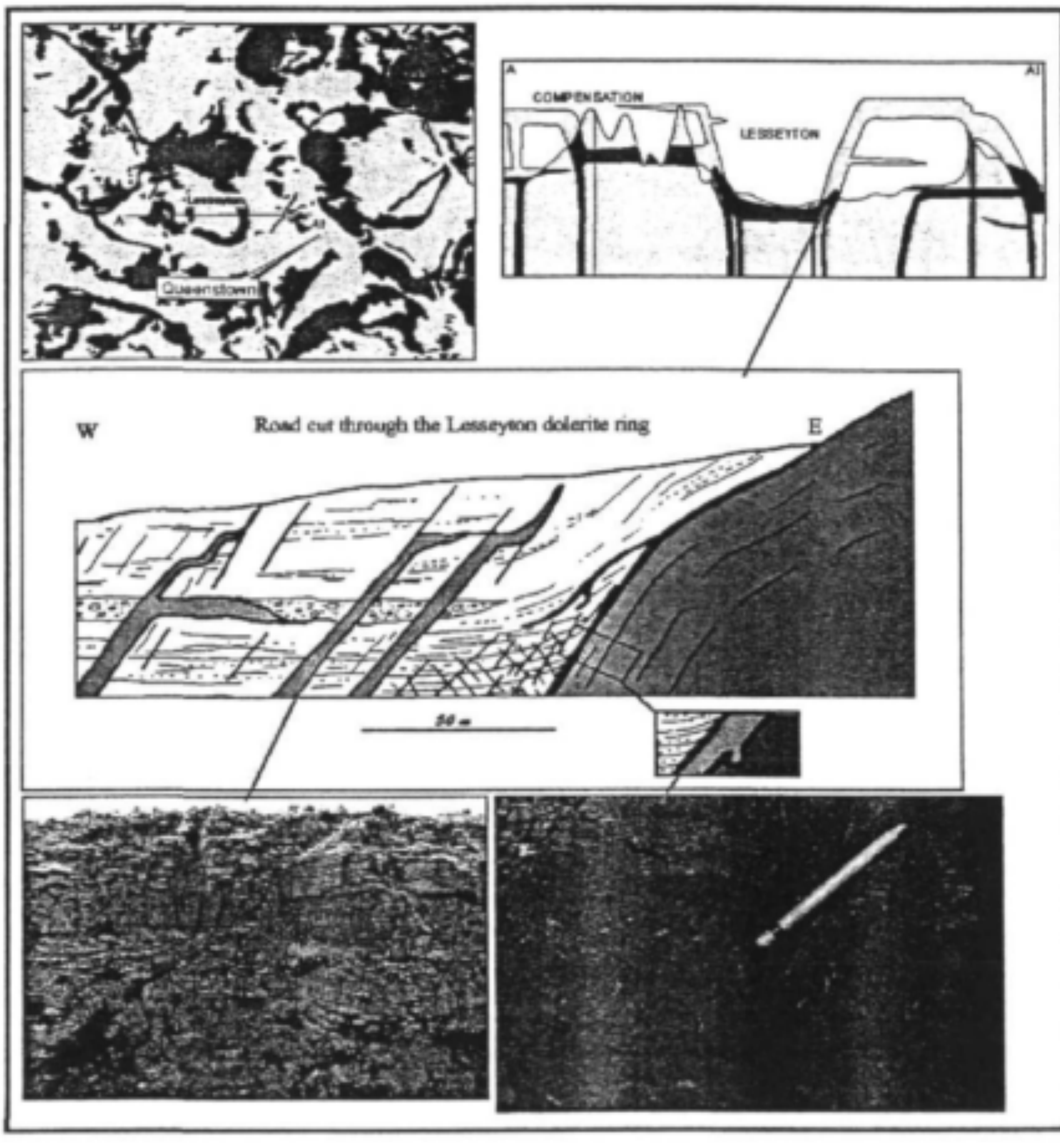
On its upper contact (east contact) vertical conjugated fracturing and thrust planes indicate hat the sediment has been uplifted and pushed inward. Further up hill the dyke feeds an inclined sheet flattening into an outer sill and a lower level inner sill.

At Naude Pass (Middelburg sheet) the road between Graaff-Reinet and Middelburg crosses a well-defined ring. Several observations can be collated as the road climbs onto the inclined sheet (**Figure 14**). Its inner eastern contact has a shallower dip than the outer one. The sediment on the lower western contact shows slight up-turning whereas on the upper contact the sediment has been sheared and dragged upward. Rafted pieces of Karoo sediments are also found trapped within the dolerite ring.



<u>Figure 14</u>: ***Field observations on the Naude Pass sill and ring system, Middelburg, showing uplifting on the hanging-wall and drag on the footwall.***

The NNW elongated Lesseyton ring is located some 3km west of Queenstown (**Figure 15**). The eastern rim of the ring-structure exhibits a dual intrusion pattern, probably linked to two NNW-trending feeder-dykes. A field cross-section was compiled along a road-cutting and supplemented by information gathered from surrounding quarries. The multiphase intrusion is shown by at least two cooling margins within the dolerite body. At the upper contact with the inclined sheet the Karoo sediments are highly fractured and up-turned. Many dolerite offshoots are seen, probably linked to the proximity of a flat-lying inner-sill below the surface. These offshoots are guided by fractures of a similar trend and attitude to that of the main intrusion. No horizontal fracturing is found within the Karoo sediment.




**<u>Figure 15</u>: *Field observations on the Lesseyton sill and ring system, Queenstown, showing offshoots alongside the inclined sheet and multiple magma intrusion.***

## 3.3 SATELLITE REMOTE-SENSING

The study area is covered by four standard Landsat TM5 scenes, namely from west to east: WRS 173-82, 172-82, 171-82 and 170-82.

Satellite imagery highlights better than any other technique the complex relation and interference between the different ring-systems. Three examples were chosen from our satellite coverage to illustrate the different morpho-tectonic expression of the dolerite sill and ring complexes.

Victoria West Highlands shows four large ring systems stacked directly above one another (**Figure 16**). The ring systems intersect or coalesce with each other. There is also a migration from south to north, as well as a decrease in the size of each ring complex as it intrudes into higher stratigraphic levels. The highlands to the north (Ghaapkop and Ruigtefontein), in the vicinity of Victoria West, were selected for local detailed investigation during this research project.

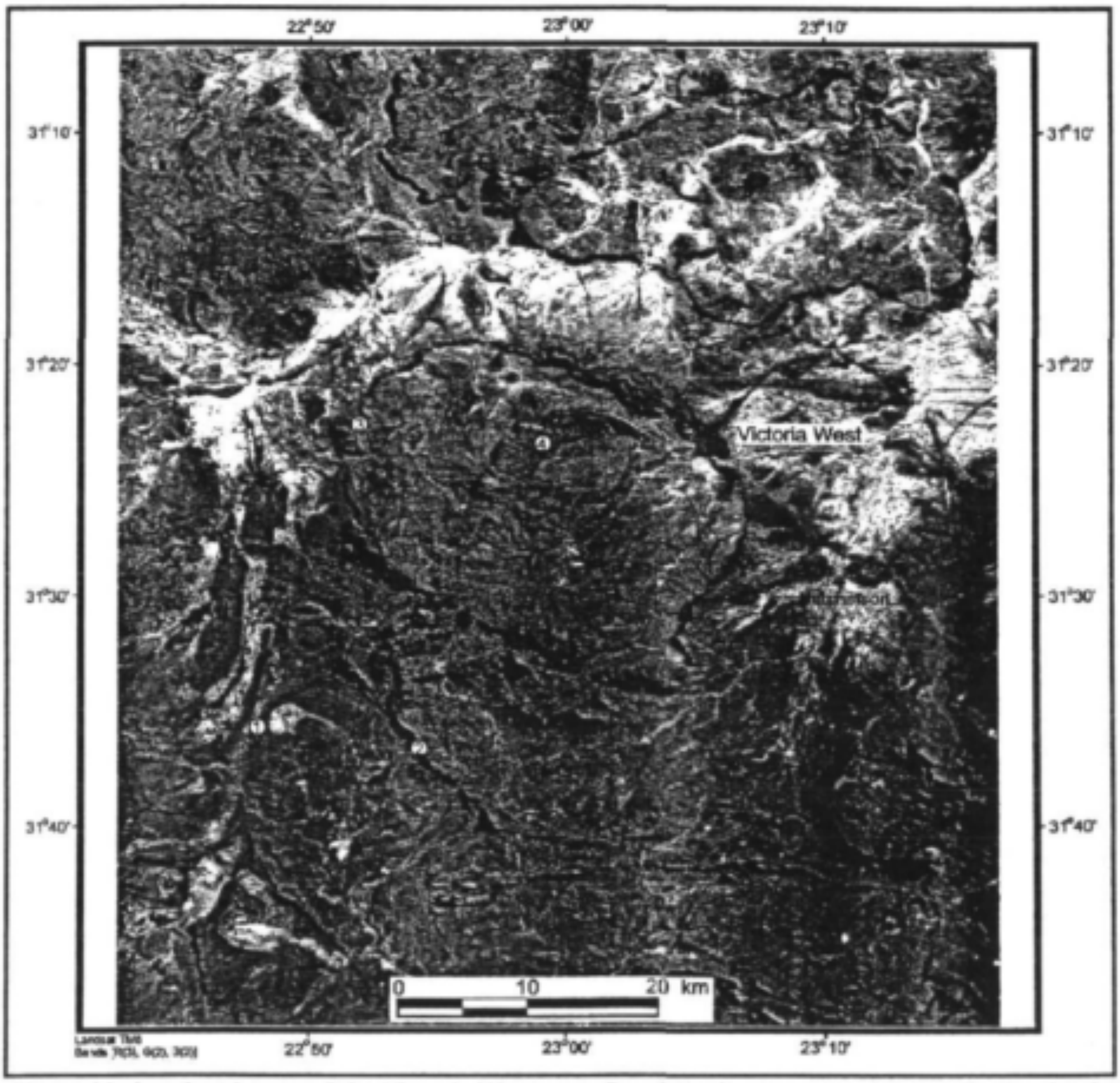
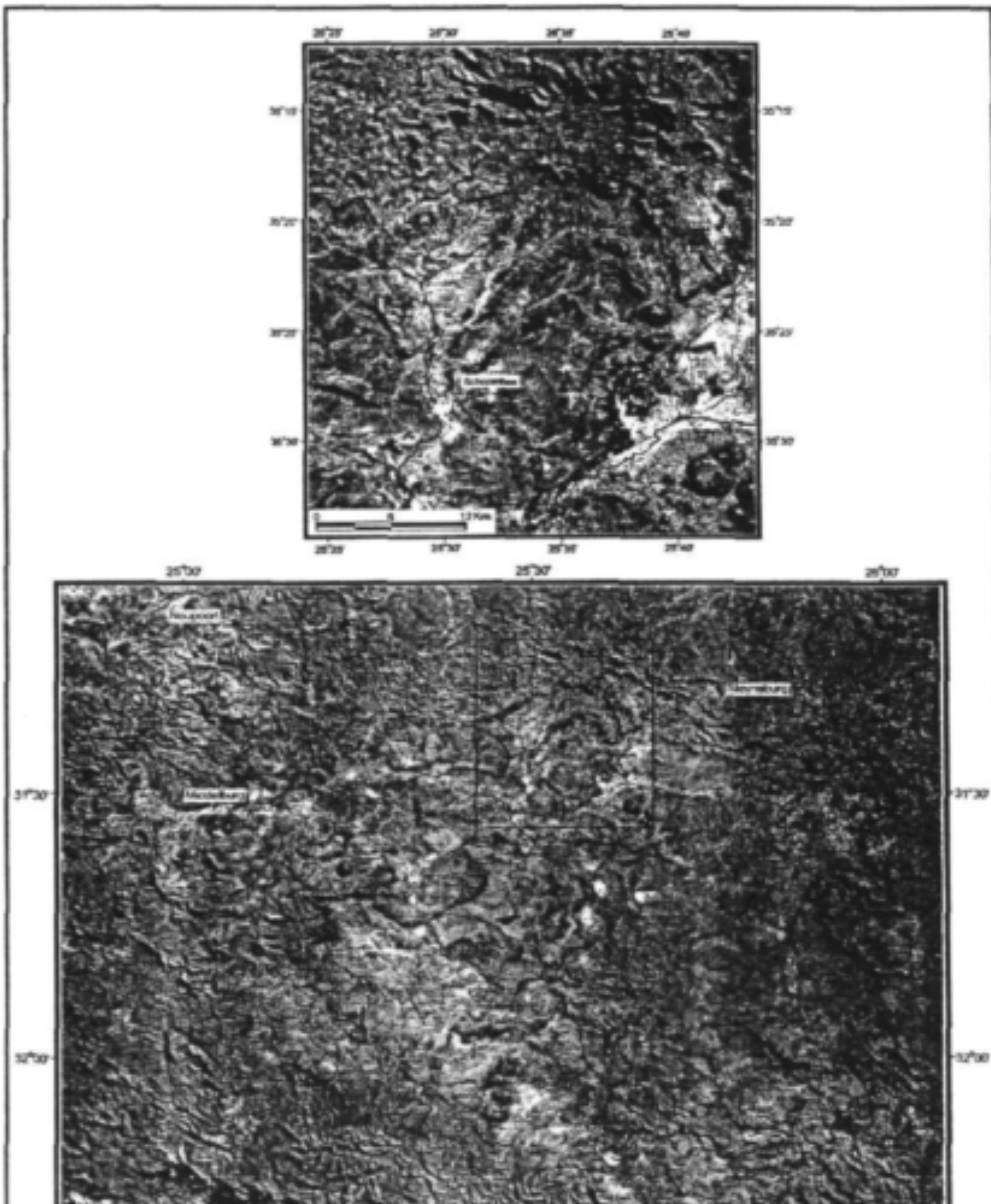



Figure 16: ***Landsat Image of the Victoria West area (local study area, see chapter 5), clearly showing the four different "layers" of sill and ring intrusions and illustrating the concept of "ring within a ring" pattern and upward stacking of sills. 1: Oorlogsfontein, 2: Wolweberg, 3: Ghaapkop, 4: Ruigtefontein***

The satellite image of the Middelburg area clearly exhibits a 'Mega-Basin' morphological structure, which is defined by prominent sill and ring systems along its rim (**Figure 17**).



<u>Figure 17</u>: ***Landsat Image of the Middelburg area. The regional image covers the Middelburg 'Mega-Basin', which shows a lack of prominent sill outcrop in the center of the structure. The inset illustrates the concept of a "ring-within-ring" system, with downward vertical stacking (the ring in the centre being at lower topographic level than the outer one).***

A less prominent inner ring-complex is evident within the center of the 'Mega-Basin'). A detail view of the Schoombee ring-complex, some 40 km east of Middelburg town shows three concentric rings. This sill and ring-complex shows a clear downward stacking, where the outer ring is intruded at a higher stratigraphic level than the middle ring, which in turn is situated at a higher elevation than the lower ring.

The imagery of Queenstown area (**Figure 18**) displays the peculiar morpho-tectonic style that characterizes this 'Mega-Basin'. The ring systems form small individual units of similar size often intruded at the same stratigraphic level. Several layers of intrusion will therefore result in a complex series of ring interference patterns (the "box" type).

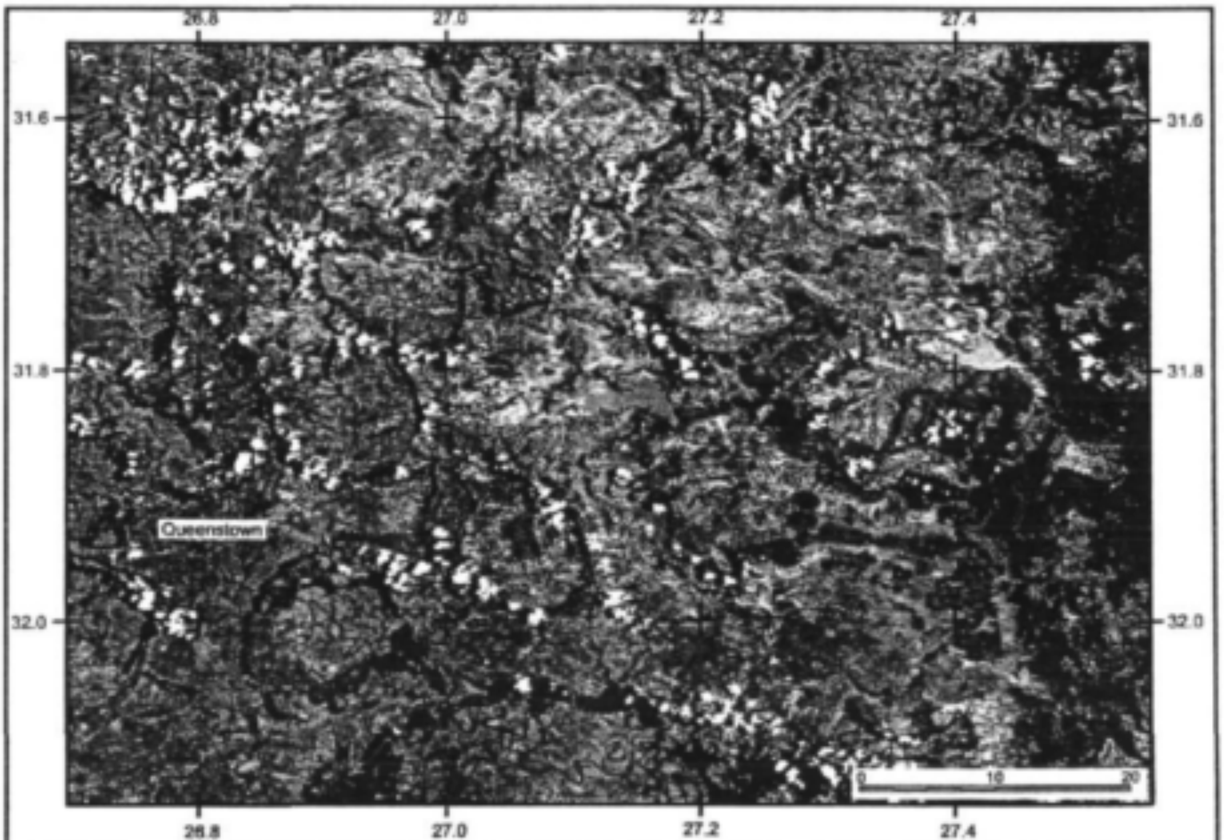



Figure 18: ***Landsat Image of the Queenstown area showing the complex "box-type" interference between the discrete ring-systems.***

## 3.4 REGIONAL AEROMAGNETIC SURVEY

The air-magnetic data is composed of two coverages: magnetic field intensity and magnetic fabrics.

### Magnetic Field Intensity

The digital data were obtained from the Council for Geoscience in Pretoria, as a 400x400m grid and as a contoured vector coverage. The magnetic intensity contours were provided in three tiles. The data were provided in Shapefile format, with labels indicating the value of the contours.

The boundary between the Kaapvaal craton and the Namaqua metamorphic belt has a very strong signature. The relations between magnetic anomalies and the mapped dolerite ring-structures are fair (**Figure 19**) but no new structural features or trends were identified that would significantly alter our interpretation. There is no well defined relationship between the magnetic anomalies and the national digital elevation model. However, the topographically prominent dolerite ring-structures of the Queenstown area are well defined on the NDEM and contoured aeromagnetic maps, while the magnetic intensity map lacks this detail.

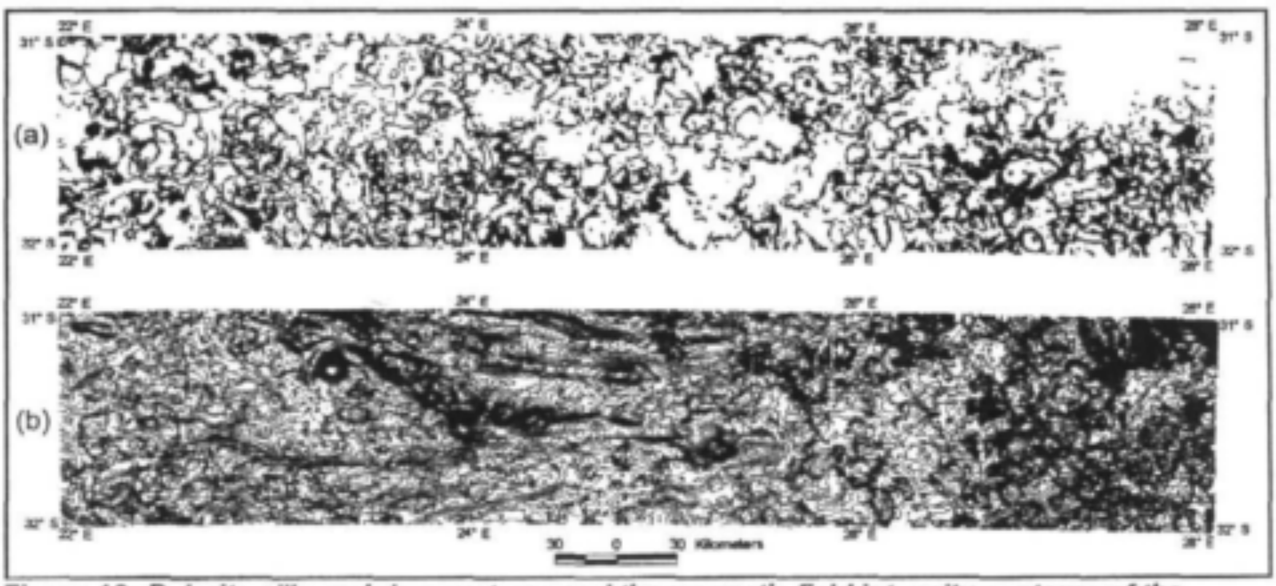
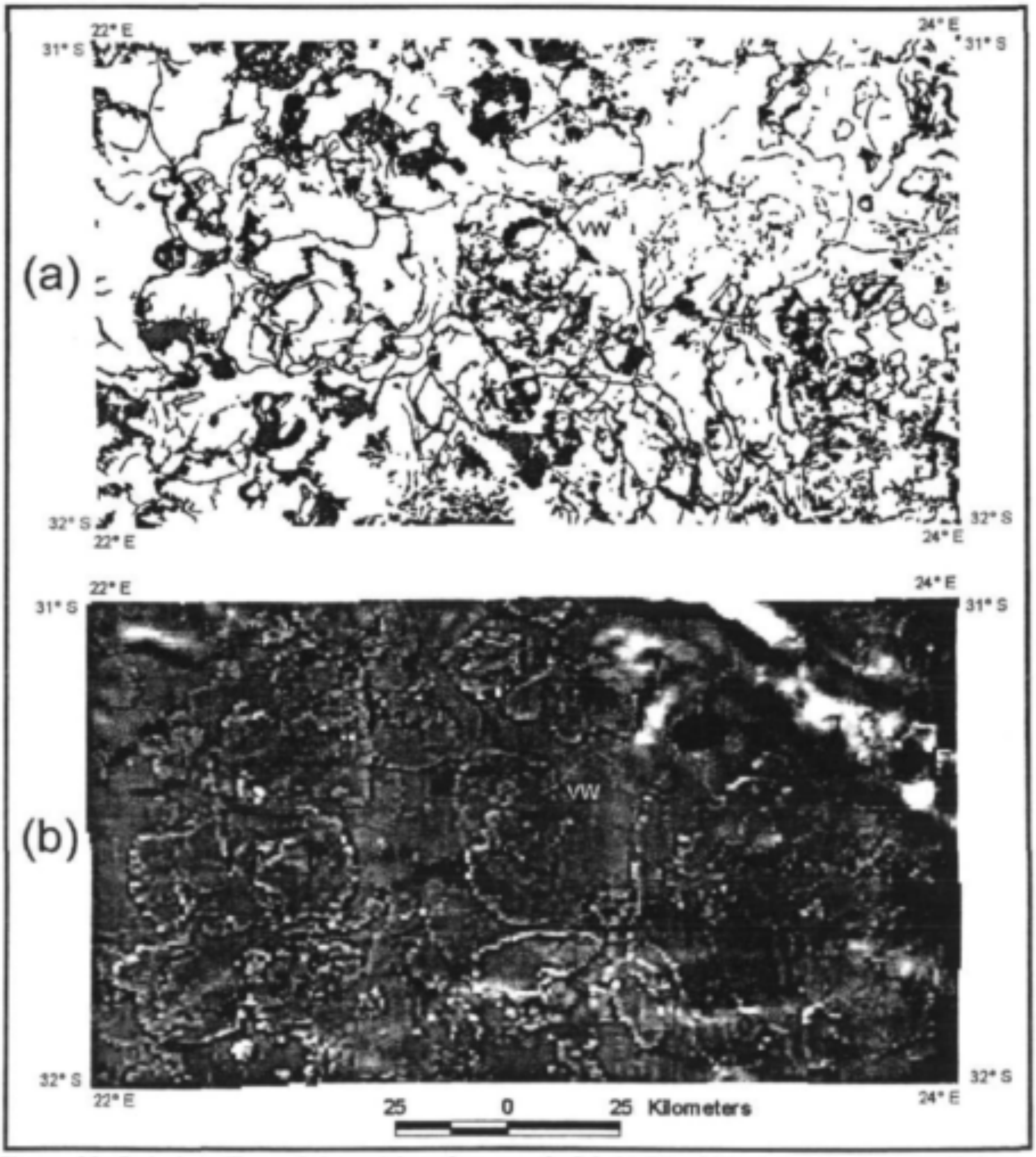



Figure 19: ***Dolerite sills and ring-systems and the magnetic field intensity contours of the regional study area.***

### Magnetic Fabric

The magnetic field intensity map is derived from the magnetic intensity data, where the low frequency information has been removed. Initially, a low pass filter was applied to the intensity field using a Fourier transform in order to remove the extremely high frequency information. The filtered data was then subtracted from the intensity field to give a residual magnetic fabric. The resulting map shows a greater degree of contrast between the deeper-seated ghost structures and the shallow dolerite intrusions (**Figure 20, 21, 22**). The majority of the sills and rings exhibit a pronounced magnetic fabric signature.




<u>Figure 20</u>: ***Dolerite sills and rings (a) and magnetic fabric (b) of Victoria West sheet. Note the different strengths of signature on the Victoria West and Loxton Highlands inferring different stratigraphic levels of intrusion. Note also the lack of strong signatures in the northern Victoria West Basin (NE corner of map).***

A distinction can also be made between deep structures and shallower ones. The most interesting result is the way the sills are vertically stacked. For instance in the Loxton and Victoria West highlands different levels of sills are visible, each of them characterised by a difference of strength or clarity of the fabrics (**Figure 20**). In the Middelburg Basin the rings do not show much stacking effect and their signature is getting weaker towards the center (**Figure 21**).

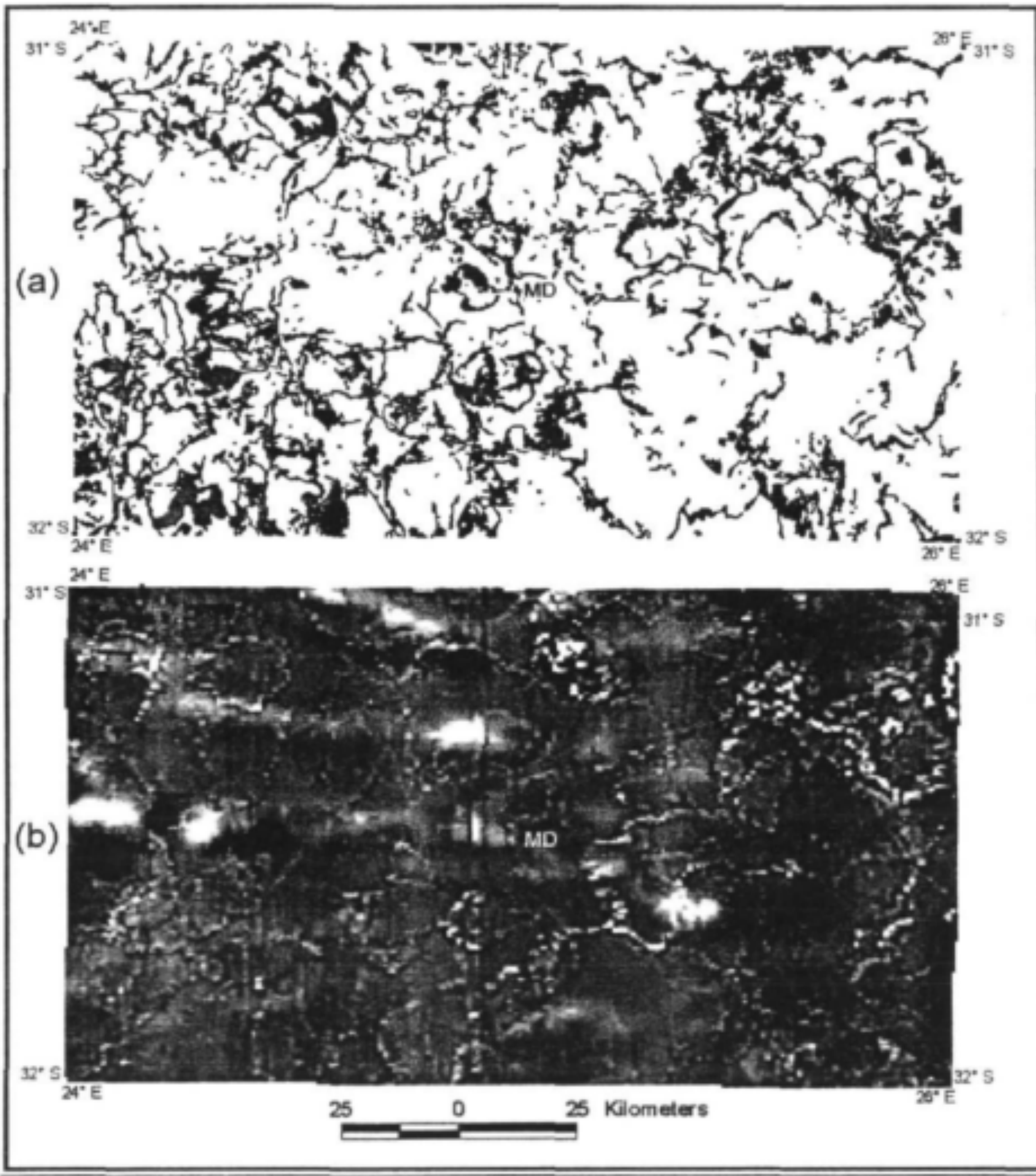
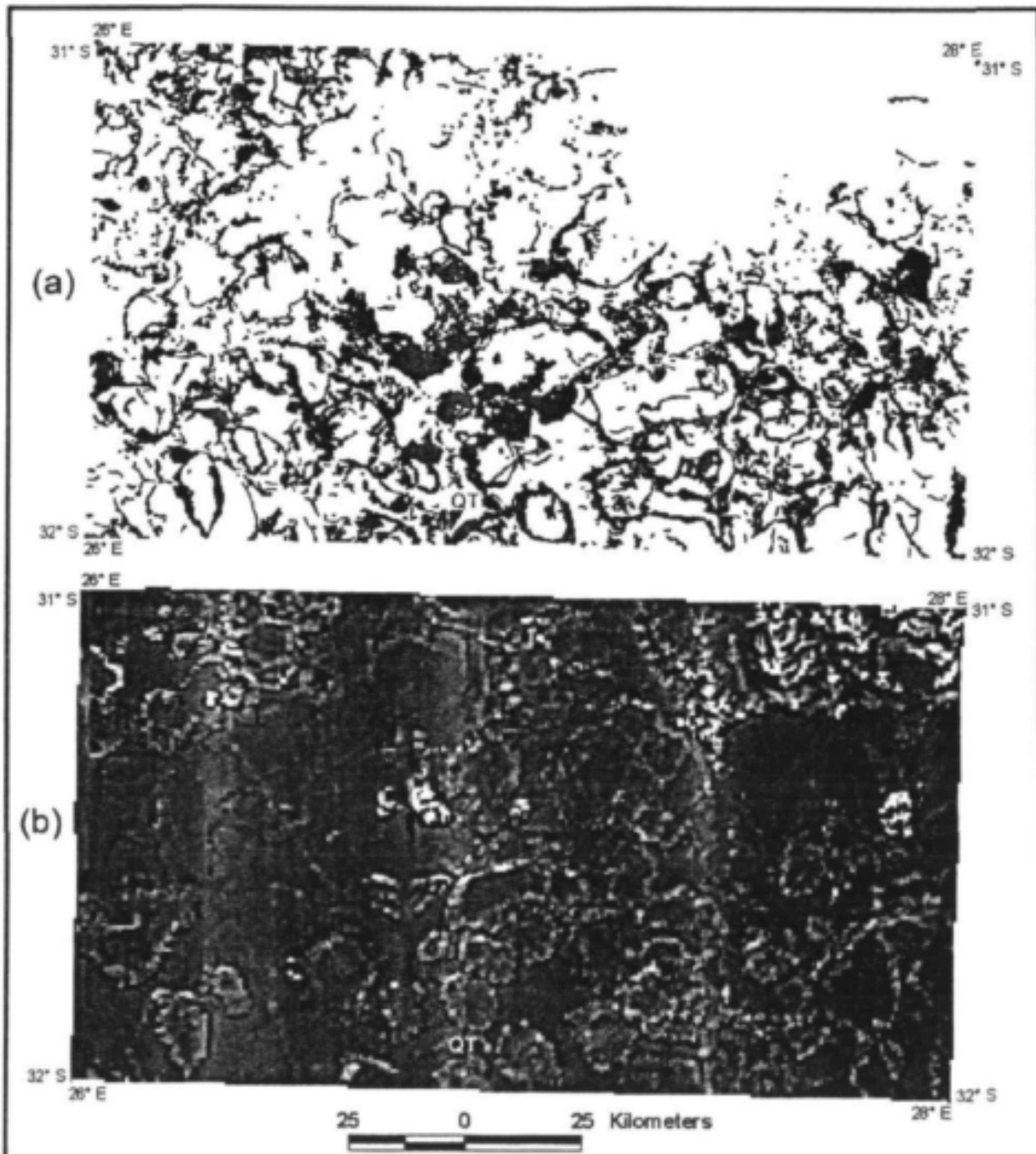



Figure 21: ***Dolerite sills and rings (a) and magnetic fabric (b) of Middelburg sheet. Note the lack of strong signature in the Middelburg Basin.***

In the Queenstown Basin the vertical stacking signature is present but shows much interference between the rings (**Figure 22**).




<u>Figure 22</u>: ***Dolerite sills and rings (a) and magnetic fabric (b) of Queenstown sheet. Note the interference patterns of the magnetic fabric of the Queenstown Basin.***

### 3.5 MORPHO-TECTONIC MODELS

The regional morphotectonic analysis, exposed in the different sections above, leads to the definition of three distinct morphotectonic models for the Western and Eastern Karoo (**Figure 23**).

The morphotectonic model I is characterised by:
- ring within a ring structure
- nested and overlapping rings
- upward-stacking with decrease in size
- they are typically asymmetrical with a thick ring on one side, feeding an outer sill and a thinner ring on the other side.
- These ring and sill complexes contribute to the elevated terrain of Loxton and Victoria West Highlands and correspond to a complex drainage network.

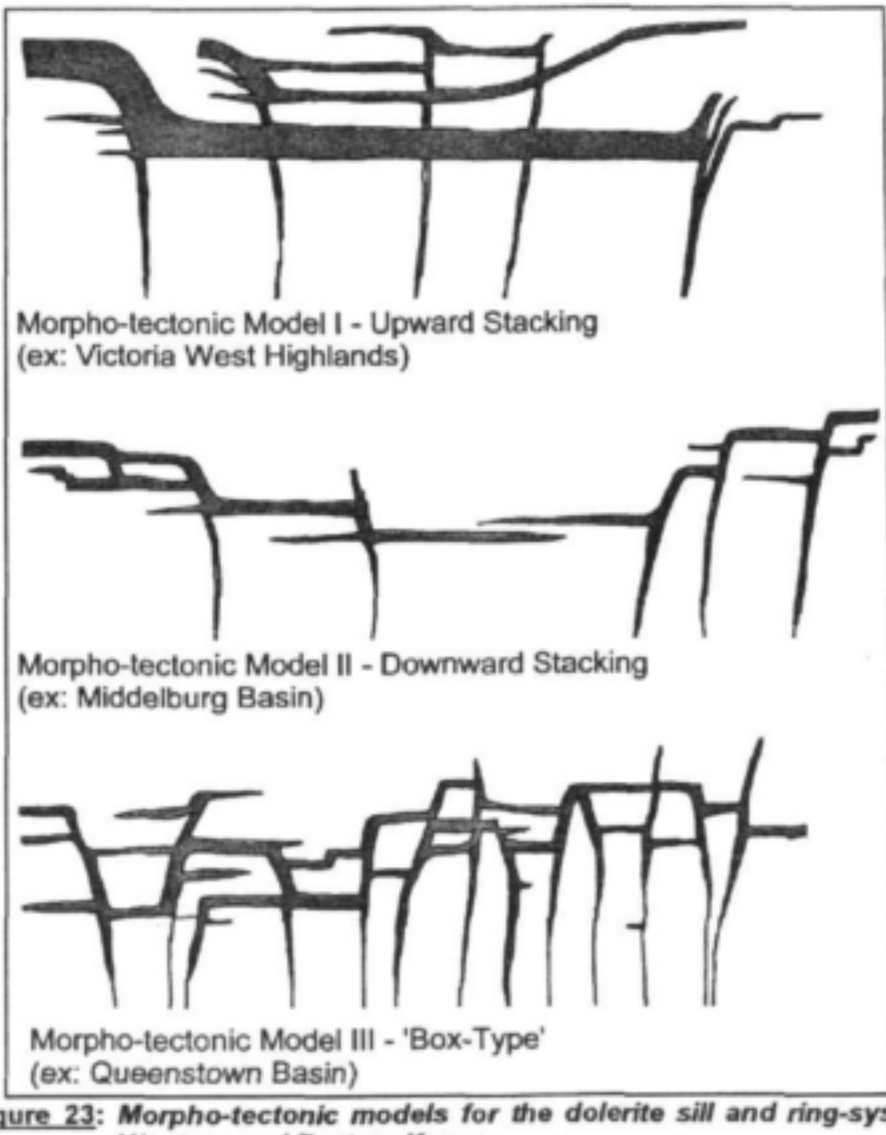



Figure 23: ***Morpho-tectonic models for the dolerite sill and ring-systems of the Western and Eastern Karoo.***

The morpho-tectonic model II is characterised by:
- ring within a ring structure
- coalescing rings rather than overlapping or nested rings
- downward stacking without decrease in size
- good symmetry of the system on the regional scale but strong asymmetry of each individual ring.

These rings and sills correspond to low elevation terrain and large basins drained by radiating stream systems like Middelburg or Nieu-Bethesda basins.

The morpho-tectonic model III is characterized by:

- weakly developed ring within a ring pattern
- small individual rings with perfect symmetry (the thickness of the ring remains the same all around)
- complex interference between the rings (overlapping and coalescing).
- vertical stacking without decrease in size

The result is a "box- type" intrusive pattern. The drainage system is very intricate. They are represented by the Queenstown Basin.

## 3.6 MODE OF EMPLACEMENT AND FRACTURING OF THE COUNTRY ROCK

**Mode of Emplacement**

Different morpho-tectonic models and mechanisms of emplacement have been proposed for the Karoo dolerite ring/sills complexes and are summarized on **Figure 24.**

Du Toit (1905) and Rogers and Schwarz (1902) suggested an undulating sill forming a series of domes and basins for the Eastern Cape intrusions (**Figure 24 A**). Scholtz (1936) adopted a similar morphotectonic model for the Insizwa sheet. Meyboom and Wallace (1978) attempted to explain the emplacement mechanism for such a model by way of variations in a "compensation surface" (theorized by Bradley, 1965) at relatively shallow depths in the crust. This 2D model of an undulating sheet has severe geological and mechanical restrictions. The geology is over simplified and does not fit the 3D geometry of the structure (saucer - like). The sills and rings are so interconnected, anastomosed and stacked above each other that a multi-layered system of compensation surfaces would have developed, which is physically impossible. However local undulations (scale of several hundred meters to a kilometer) are sometime visible in the field and can not be entirely ignored. Up-stepping along shallow dipping sedimentary contacts often give the feeling of undulation. Other phenomenon where the sills really form a dome are very isolated and few and can probably be explained by the local stress conditions.

In a second model Du Toit (1920) proposed more realistic geological cross-sections of these structures, showing flat-lying sills connected together by an inclined sheet of lesser thickness (**Figure 24 B**). In his model the dykes do not play a role in the feeding mechanism but are in fact fed by the sills. He proposed a mechanism of intrusion by which thrust would operate along the inclined sheet as a result of uplift of the upper flat sill. This model is more refined than the earlier one and corresponds to our "box type" morpho-tectonic model III. Although this model does not explain all the different ring and sill occurrences of the Karoo, the mechanism of thrusting and dragging along the inclined sheet is interesting and was adopted in our mechanical model.

Lombaard (1952) refers to the dolerite ring features as transgressive intrusions and proposed a cone-sheet mode of emplacement, because of their 3D funnel-shaped geometry (**Figure 24 C**). This mechanical model suffers from major drawbacks. The emplacement of cone sheets requires a substantial source (magma chamber) with a strong capacity for uplift (updoming, stretching and caldera formation), the development of radial fracturing (absent in the Karoo). Furthermore cone sheets rarely develop with basaltic magmatism and are mainly associated with acidic volcanism (essentially trachytes). Finally, Lombard's model does not take into account the role of dykes in the mechanism of emplacement.

Kattenhorn (1994) studied the dolerite sills of the Mhlatuze River, near Empangeni and suggested that simple upward stepping of magma along planes of weakness might not be the only mechanical explanation. He proposes that, similarly to dykes, sills can propagate through en-échelon arrays. In his model separate sill segments can dilate individually and subsequently undergo tip-to-tip linkage as a result of tip stress interaction. En -échelon segmentation is certainly a common feature in Karoo dolerite and can be observed at medium and small scale (cm to several meters) and could contribute to the formation of the inner and the outer sill of our conceptual model of **Figure 4 a**. However it cannot explain the complexity of the multi-layered, multi-stacked, interconnected and multi-fed nature of the saucer-shape ring and sill complexes.

Burger et al. (1981) and Vivier et al. (1995) adopted the laccolith emplacement model of Pollard and Johnson (1973) and Johnson and Pollard (1973) for similar Karoo dolerite intrusive complexes found in the Free State (**Figure 24 D**). This model assumes that the sill is thick enough in its centre to cause upwarping of the overlying sedimentary layers and create peripheral fracturing and dyking. Our comment is that this will only develop when the thickness-half length ratio (a/1/2L) at the center of the laccolith is great enough to provide the laccolith with sufficient leverage to uplift the overlying sediments like the sill-laccolith complexes of the Henry Mountains (Utah) described by Johnson and Pollard (1973). In fact, even under such favourable conditions, the peripheral dyke thins rapidly during upward propagation and the local tensional stress system does not generate conditions for further substantial intrusion. While this model can be applied to some of the occurrences in the Karoo it does not take into consideration the dykes and requires a central plug-like feeding intrusive which has never be documented in the Karoo nor elsewhere.

Without rejecting all these models and accepting that they could explain some, even many, of the dolerite structures, we propose an integrated and complementary mechanism of emplacement where the dykes play a dominant role and which is more in accordance with our detailed geological observations in the Western Karoo (**Figure 24E**). The different steps of emplacement of the various sills, rings and dykes are shown in **Figure 25**.

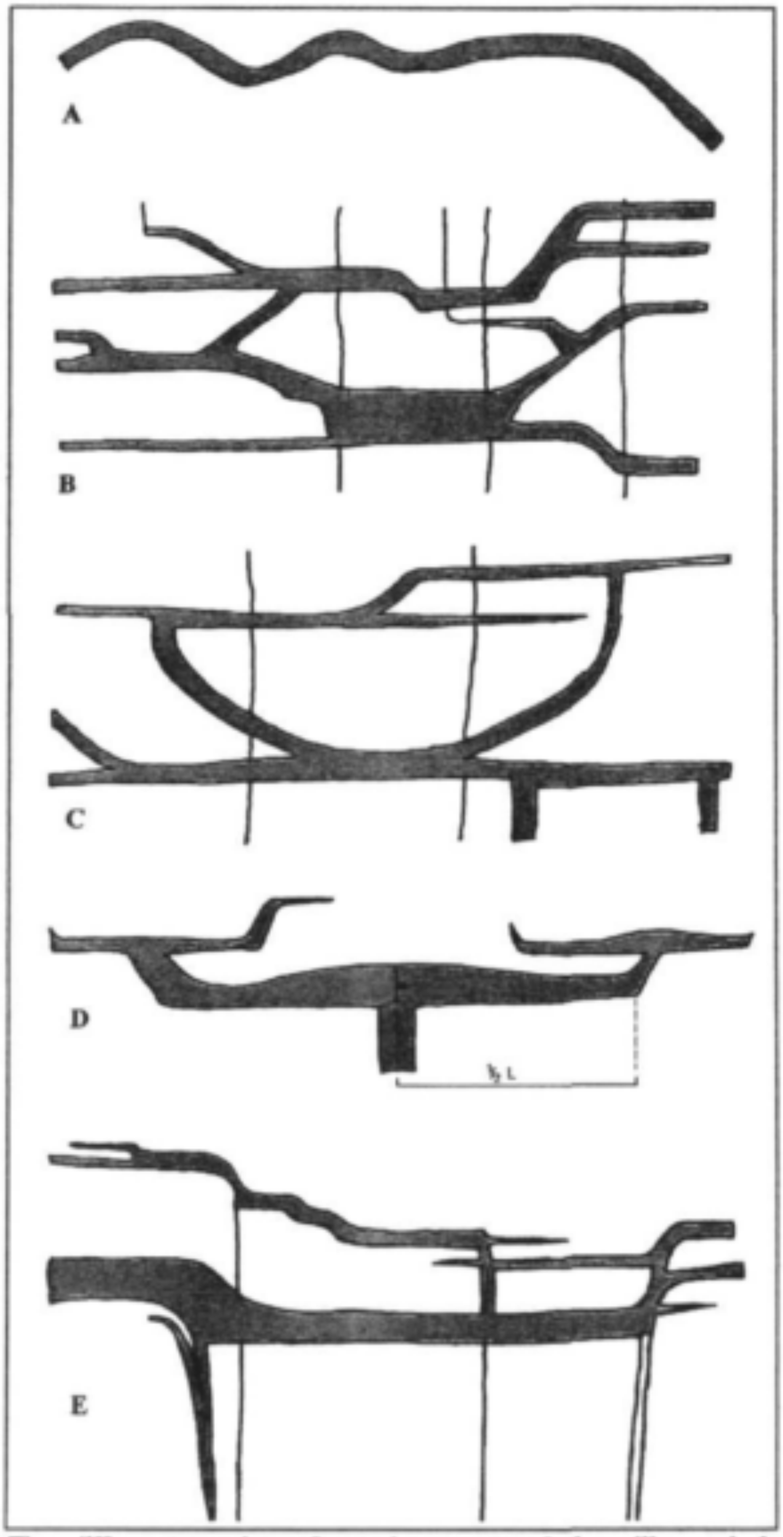
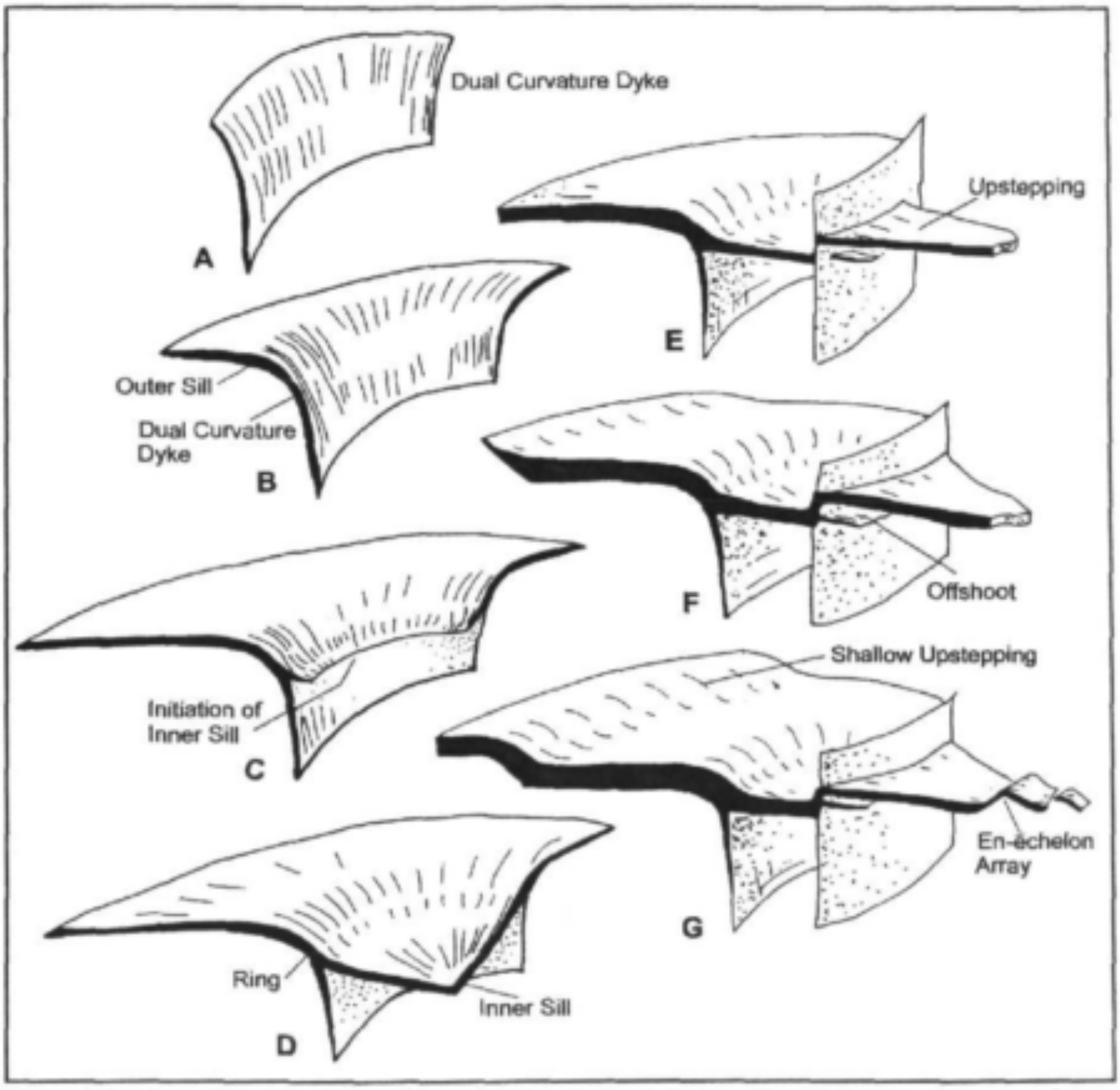



**Figure 24**: ***The different modes of emplacement of the sills and rings (modified after Chevallier and Woodford, 1999). (A) Undulating sill of Du Toit (1905), (B) the up-stepping sill of Du Toit (1920), (C) the transgressive intrusion of Lombaard (1952), (D) the laccolith of Burger et al. (1981), (E) the ring feeder dyke of this study.***

The inclined sheets form the "back-bone" of the ring-structure and are fed by regional vertical dykes, which adopt a double curvature (along strike and in vertical section), leading to a "trumpet" shaped intrusion (**Figure 25 A**). The jagged outline of the margins of the ring-structures and the curvature along strike result from the interaction between laterally fed dykes of different directions, specially the NNW dykes and E-W dykes.




<u>Figure 25</u>: ***The different steps of intrusions of the dolerite sill and ring complexes of the Karoo taking into account the various modes of emplacement exposed above (modified after Chevallier and Woodford, 1999). A) curvature along strike and dip of a regional dyke adopting a "trumpet-like shape", B) flattening and thickening of the inclined sheet and propagation of outer sill, C) gap opening at the base of the inclined sheet as a result of sediment up-drag, D) propagation of inner sill, E) buttressing of the inner sill against an existing dyke or fault and formation of offshoots across the faults, up-stepping of the inner sills along the dyke or fault, F) thickening and propagation of the outer sill and shallow angle up-stepping at the tip of the sill, G) local en-échelon array.***

The curvature of the dykes in the vertical section maybe explained if the dykes are strata-bound, i.e. if sills within a specific stratigraphic level are fed by dykes propagating within this level. For example the sills intruded at the contact of the Ecca-Beaufort Groups, which includes the Loxton - Victoria West highlands, were fed by dykes propagating within the Ecca sediments.

The inclined sheet passes upwards into a flat-lying sill, uplifting the overlying sedimentary layers and propagating laterally outwards to form the outer sill (**Figure 25 B**).

Uplift of the overlying sediments creates a "drag" upon the upper–contact or hanging wall of the inclined sheet, as already suggested by Du Toit (1920). These forces of uplift and resistance create an upwarping of the sediment and the formation of an open fracture, but at a lower level (**Figure 25 C**).

Magma then intrudes into this opening and spreads inward at a lower elevation forming the inner sill (**Figure 25 D**)

As the inner sill propagates it can buttress against an existing dyke or fault (**Figure 25 E**). The sill usually does not cross this barrier. It will be up-stepped along the fault or dyke. Such behaviour has also been described for sills of the Mesozoic Atlantic Basin (Planke et al., 1998). However a short and thin horizontal offshoot can propagate at the tip of the inner sill and cross the fault.

The outer sill thickens and continues to propagate (**Figure 25 F**). A shallow angle inclined sheet can form at the tip of the sill as a result of differentiated lifting between the centre and the tip of the sill as suggested by Burger et al. (1981).

Local en-échelon arrays can develop giving sometimes the appearance of an undulating sill (**Figure 25 G**).

### Numerical Simulation - Fracturing of Country Rock

The aim of the mechanical study is to simulate numerically the stress fields that develop within the medium (the Beaufort Sediment) during the propagation of the dolerite sill and ring-systems. It is not intended to model the propagation of the magma through a crack and inside the sediment. This aspect of the mechanical behaviour of intrusion has been dealt with by many authors (Delanay, 1982; Delanay et al., 1986; Lister and Kerr, 1990; Rogers and Bird, 1987; Spence and Turcotte, 1985). In the present study we are more interested by delimiting zones of fracturing within the medium intruded by a multi-layered dolerite complex. This simulation will be used to further constrain our morphotectonic model and our search for preferential targets for fractured aquifers.

The numerical linear elastic mechanical simulation used the Finite Element Method (Sigerlind, 1976) and was carried out by the University of Stellenbosch's Civil Engineering Department. The FEM has been used by scientists and engineers for almost four decades to design a wide variety of products (car or aircraft industries, biomedical engineering, mining and civil engineering). The method has also been used widely to model geological deformation and the dynamics of the Earth (Chevallier, 1989).

The stress simulation was carried out on two different intrusion patterns: The first pattern called A (**Figure 26**) corresponds to morpho-tectonic model I (see figure 23) and represents a ring within a ring structure with an upward stack of sills (like Victoria West Highlands) whereas the second pattern called B (**Figure 27**) represents more the "box-style" of morphotectonic model III of figure 23 (Queenstown Basin). Morpho-tectonic model II was not simulated for various reasons including programme dead lines, budgetary constraints and availability of scientific knowledge etc. In both model axisymmetric conditions were assumed and a model domain of a 20km radius and a depth of 1.5km were considered.

Four noded, axisymmetric elements were used throughout and the intrusions were modelled assuming linear hydrostatic pressure elements. The linear axisymmetric elements were required since ABAQUS (Hibbits et al., 1997), used in the present modeling, can only handle linear hydrostatic pressure elements. The material was assumed to be continuous, linear elastic and the hydrostatic pressures were applied to an unstressed domain. The Young's modulus for the bulk of the model was set to 20 Gpa. The boundary conditions were maintained as follows; the nodes at the bottom of the domain were restricted from moving vertically, whereas the centre-line and outer radius were restricted from moving in a horizontal direction. The "cavity" contained a material that was set to hydrostatic pressure in a direction normal to the "cavity" surface.

In both analyses, the magnitudes of the stresses are not realistic and only serve to indicate the relative distribution of stress resulting from the hydrostatic pressure. Standard code for structural mechanics are used i.e. negative numbers mean compression and positive numbers mean tension. The principal stress $\sigma 1$ is the most compressive (most negative) or the less tensile (less positive) whereas $\sigma 3$ is the more tensile (most positive) or the less compressive (less negative).

The results for Model A are shown on **Figure 26**. Several stress domains can be described. As expected, the tip of the upper sill (domain I) is under high tensional stress ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are positive). The most tensional stresses ($\sigma 2$ and $\sigma 3$) are lying in the plane of the section. The layers overlying the upper sill (domain II) are placed under a severe compressional stress regime ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are negative). High deviatoric stress conditions ($\sigma 1$ much higher than $\sigma 2$ and $\sigma 3$) are specifically developed above the small up-stepping intrusive feature. The area between these two domains (domain III) is characterized by low compressive stress for $\sigma 1$ and $\sigma 2$, whereas $\sigma 3$ is slightly tensile. Compressive $\sigma 1$ and tensile $\sigma 3$ are lying in the plane of the section. Domain IV corresponds to the part located below the tip of the upper sill. The medium is under compressional state ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are negative) with $\sigma 1$ and $\sigma 2$ lying in the section plane. Domain V corresponds to the intersection of feeder dyke - sill. The stress pattern is similar than domain IV. The central block between the two sills (domain VI) is characterised by hydrostatic compression ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are negative and equal). A high compressive shear stress regime ($\sigma 12$) develops from the tip of the upper sill to the small up-stepping feature.

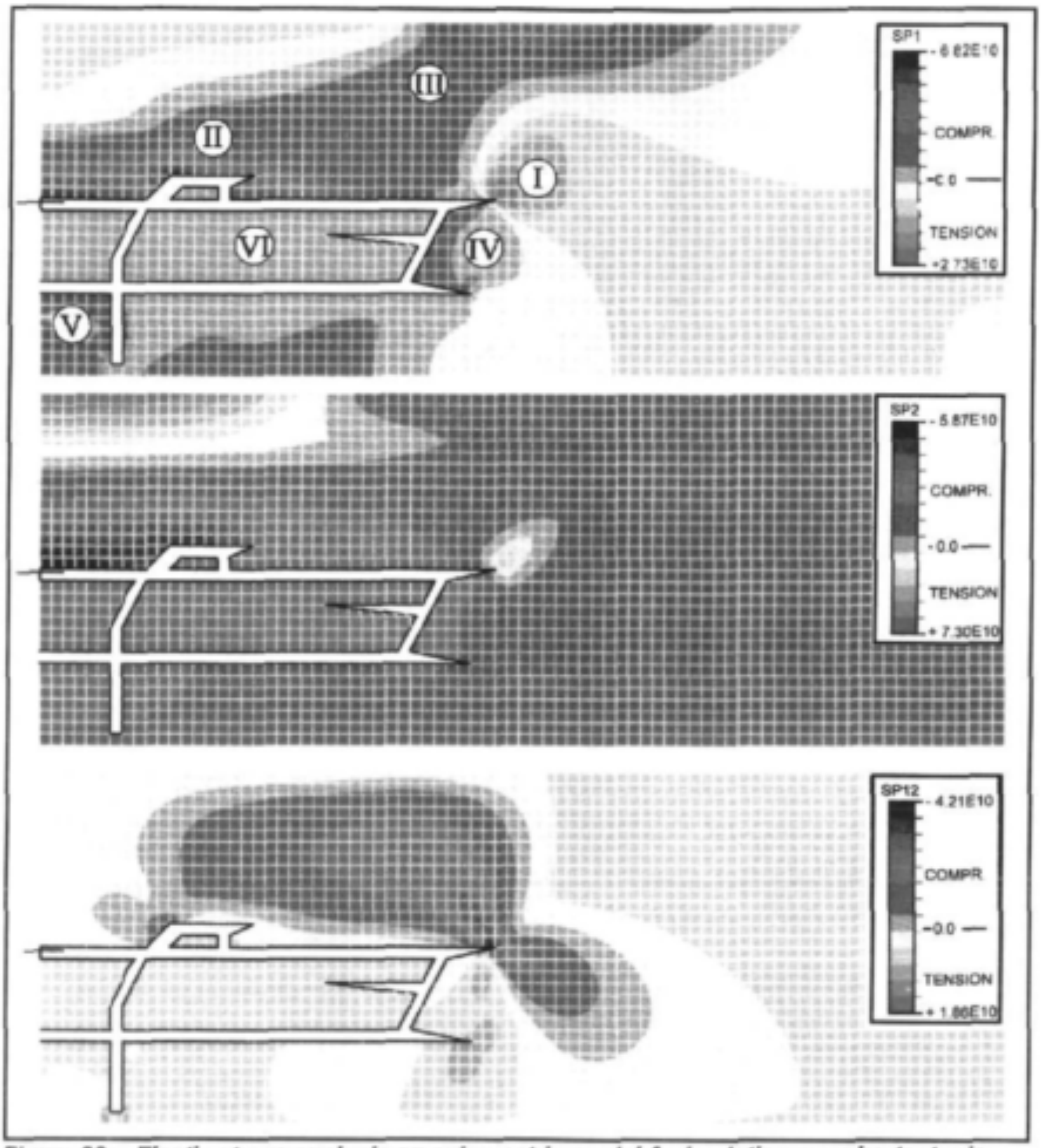



Figure 26a: ***Elastic stress analysis on axisymetric model A simulating morpho-tectonic model I - Distribution of stress with magnitude in Mpa***

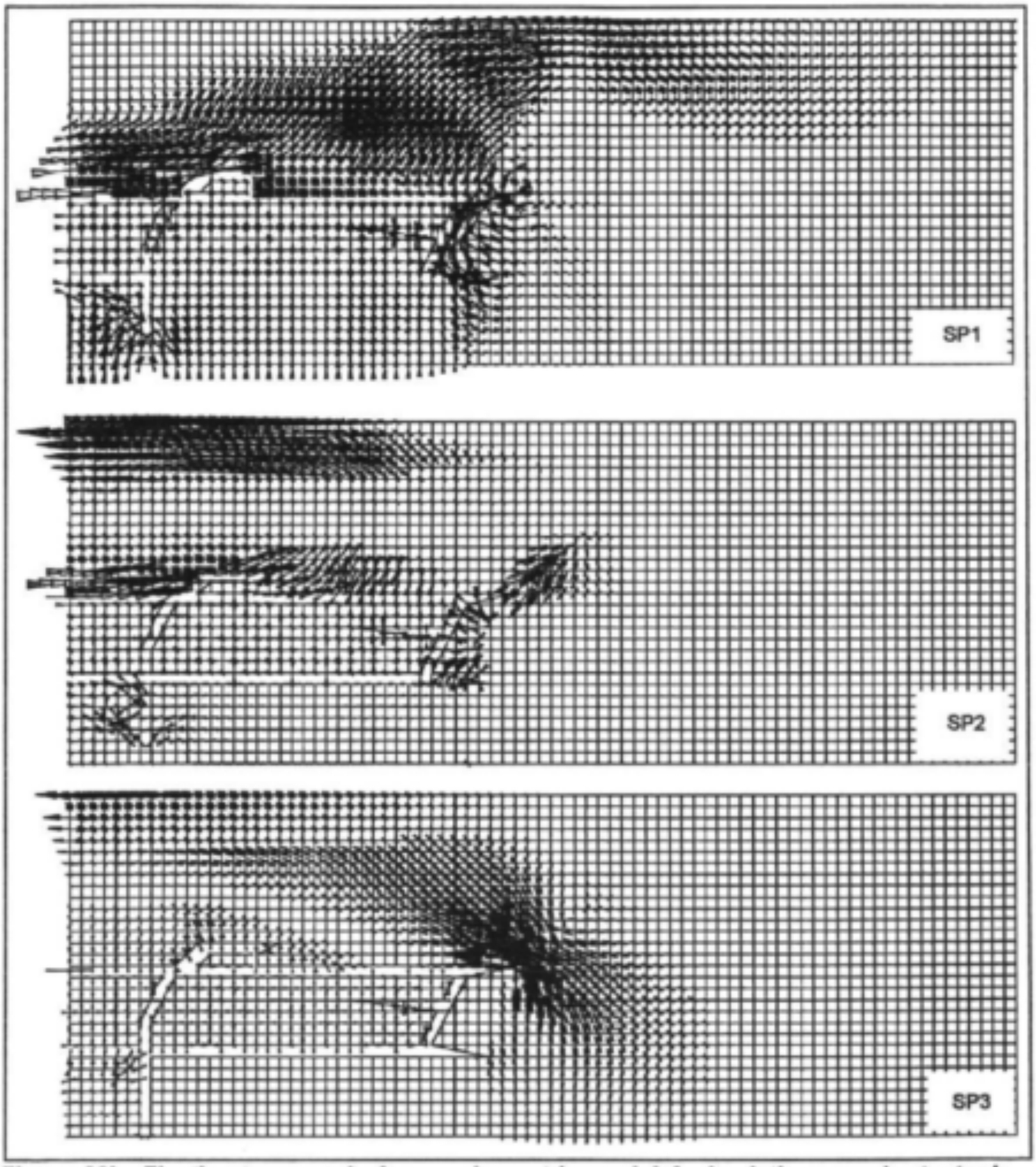



**Figure 26b**: ***Elastic stress analysis on axisymetric model A simulating morpho-tectonic model I - trajectories of three principal stresses.***

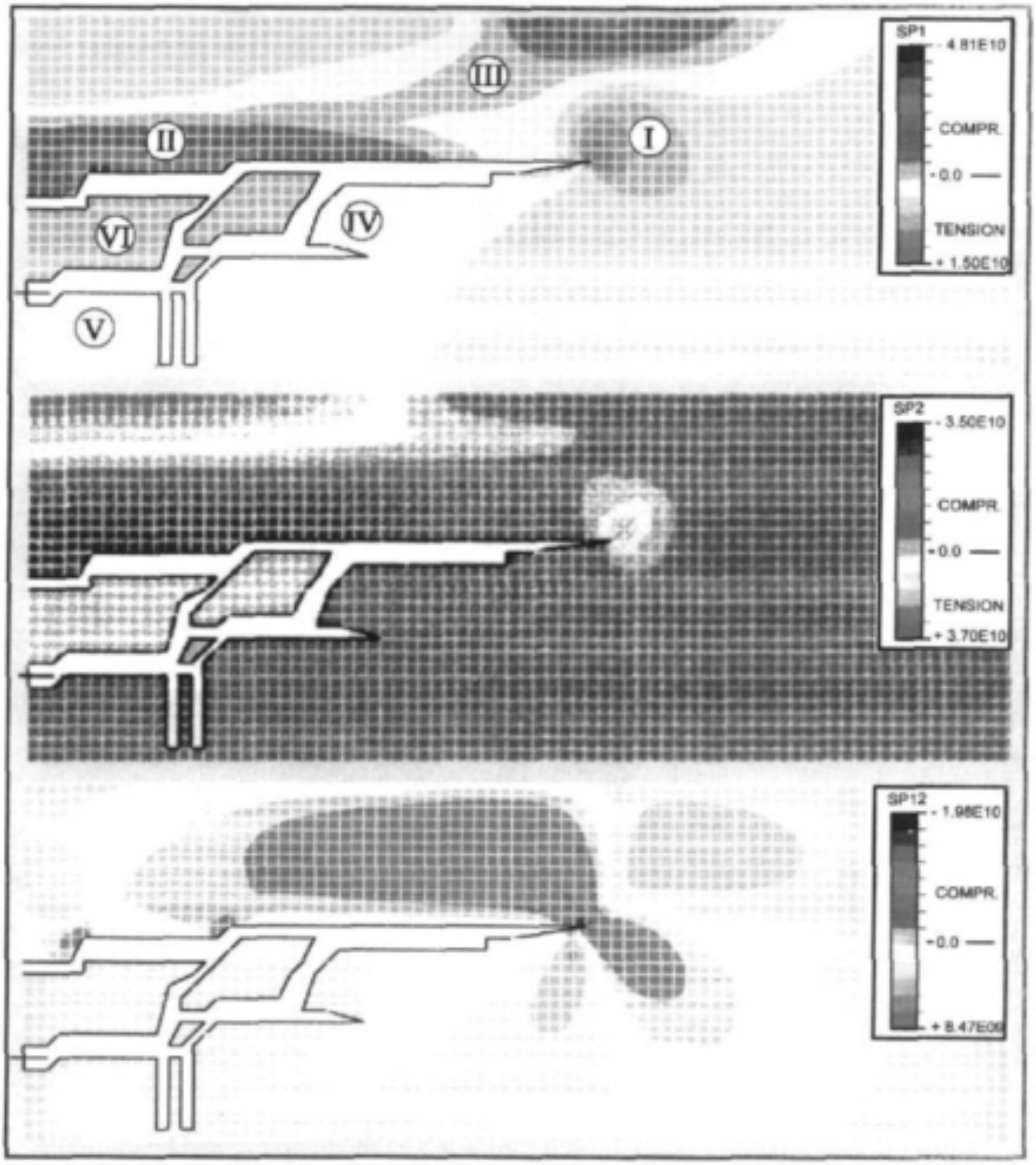



**Figure 27a**: *Elastic stress analysis on axisymetric model B simulating morpho-tectonic model III of Figure 23 - Distribution of stresses with magnitude in Mpa.*

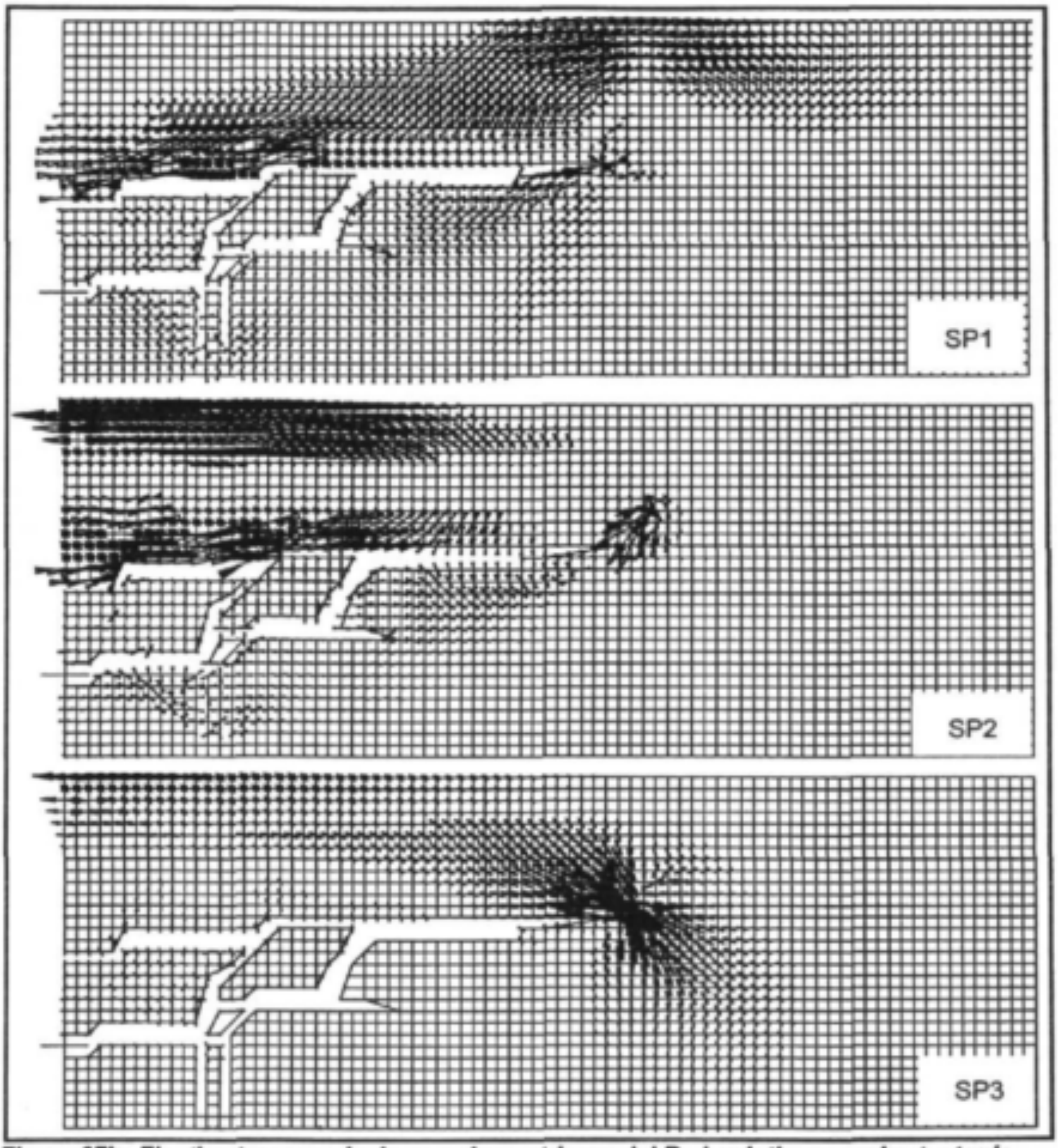
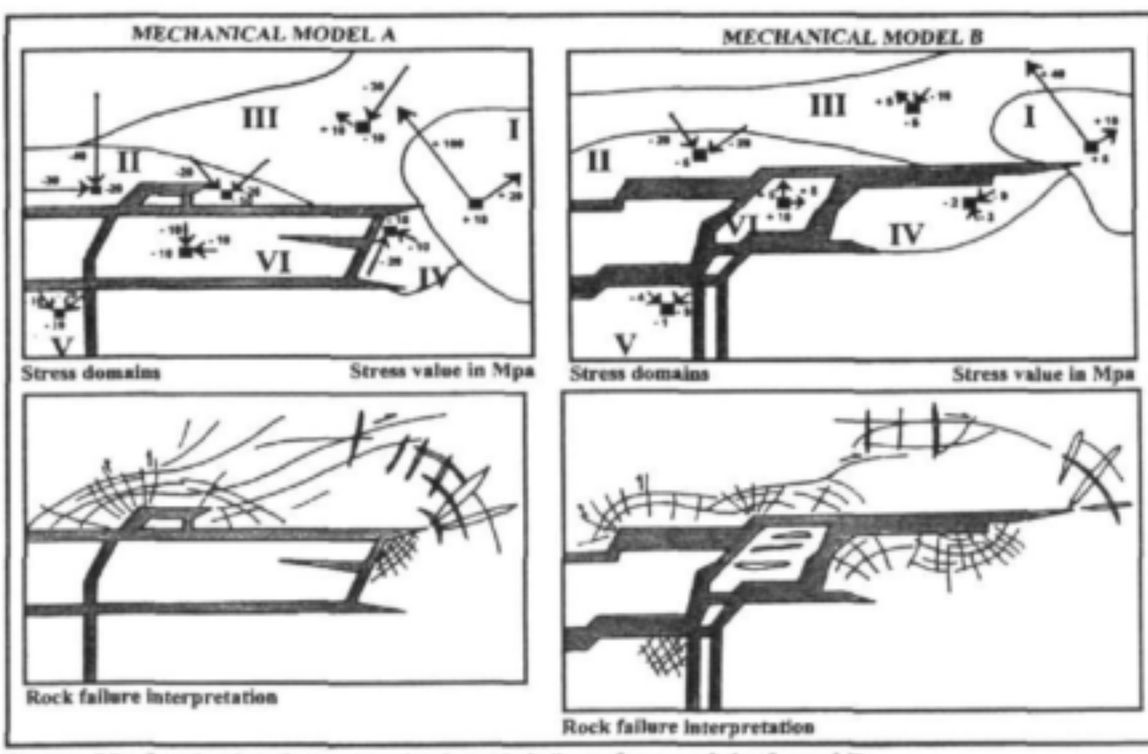



Figure 27b: ***Elastic stress analysis on axisymetric model B simulating morpho-tectonic model III of Figure 23 - trajectories of three principal stresses.***

The results for Model B are shown on **Figure 27**. Several stress domains can also be found. In domain I (tip of the upper sill) the situation is the same as model I with high tensional stresses ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are positive). The most tensional stresses ($\sigma 2$ and $\sigma 3$) are lying in the plane of the section. In domain II (above the upper sill) high compression occurs. High deviatoric stress regime is found above the two up-stepping features. In domain III (between domains I and II) $\sigma 1$ and $\sigma 2$ are compressive whereas $\sigma 3$ is tensile. Domain IV, located between the tips of the two sills, and domain V, at the contact between dyke and inclined sheet, are under compressional state ($\sigma 1$, $\sigma 2$ and $\sigma 3$ are negative but small and with similar magnitude). In the central block (domain VI) the three stresses are tensile. Compressive shear stress regime ($\sigma 12$) develops from the tip of the upper sill to the two up-stepping feature.

The two models have generated similar general stress regimes inside the medium. Small variations will result in different mechanical failures. A mechanical interpretation of the stress pattern is given on **Figure 28**. The tip of the uppermost sill, under severe tensile regime, is likely to propagate horizontally or with an upward-stepping manner towards the surface as a function of the tensile strength of the surrounding sediment. On the roof of the upper sill complex a conjugated fracture pattern can develop but where sill up-stepping is present high deviatoric compressive stress occurs and simple shear along a preferential weak plane can develop. The same situation is found below the tip of the upper sill and at the contact dyke/sill. In domain II simple shear along flat fractures will accompany vertical open cracks that will be used as channels for new magma intrusion towards the surface. The hydrological implication of this mechanical modeling is discussed in chapter 9 "hydro-morpho-tectonic model and exploration targets".




<u>Figure 28</u>: ***Analysis of mechanical rock failure for models A and B***

# 4 HYDROGEOLOGY OF THE REGIONAL STUDY AREA

## 4.1 SURFACE HYDROLOGY AND CLIMATE

In the main Karoo Basin the river-flow is highest in the east due to increased rainfall in these areas. The major drainage features are the Orange River and its perennial tributaries, the Vaal and Caledon Rivers. Other drainage is mostly peripheral, with the high-gradient rivers flowing from the escarpment to the coast.

The greater part of the Karoo Basin is classified as a summer rainfall region, with the exception of the south-eastern coastal zone that receives both summer and winter rains. Mean annual precipitation decreases from east to west, with the central regions, i.e. the study area, receiving less than 200mm per annum (**Figure 29a**). The highest values (up to 2000mm per annum) are noted in the eastern escarpment area, corresponding well with altitude. Evaporation is greatest during the hot summer months, further depleting the available moisture in the arid areas of the western part of the basin (**Figure 29b**). This deficit over the study area is clearly illustrated in **Figure 29c**.

## 4.2 GENERAL HYDROGEOLOGY

**Karoo Supergroup Sediments**

In the study area the Beaufort Group sediments are characterized by the virtual absence of primary porosity and permeability (Woodford, 2001). The geometry of these poor aquifers is complicated by lateral changes in the stratigraphic succession. The life-span of a high-yielding borehole in the unweathered non-fractured Beaufort Group may therefore be limited if the aquifer is not recharged frequently. The Molteno, Elliot and Clarens Formations (coarser grain sandstone in general) are characterised by rocks with slightly better porosity but very low permeability, forming aquitard rather than aquifer. The area underlain by these rocks correspond to a high incidence of dry boreholes (Smart, 1998). However, in the weathered zone of the Karoo sediments (20 to 30m deep) the yield of such aquifers can sometime be sufficient for windpump supply between 0.5 and 1.0 l/s (Vandoolaeghe, 1979,a, 1980,b). The water yielding capacity of the Karoo sediments can also be largely improved by the presence of fracturing, especially nearby dolerite dykes, sills or rings.

**Recent Alluvial Deposits**

Primary intergranular aquifers in modern alluvial deposits can sometime form an important part of the groundwater town supply in the Main Karoo basin, especially along large drainage systems.

Victoria West map sheet is characterized by the quasi absence of well-developed quaternary alluvial plains. Substantial deposits only form sporadical, discontinuous patches (5 to 20 km) of thin alluvium coating (2 to 4m thick), made of gritty and clayey loose material. In these often dry and barren plains yielding bore holes are commonly sunk next to a dolerite dyke the surface expression of which always corresponds to a line of green bushes.

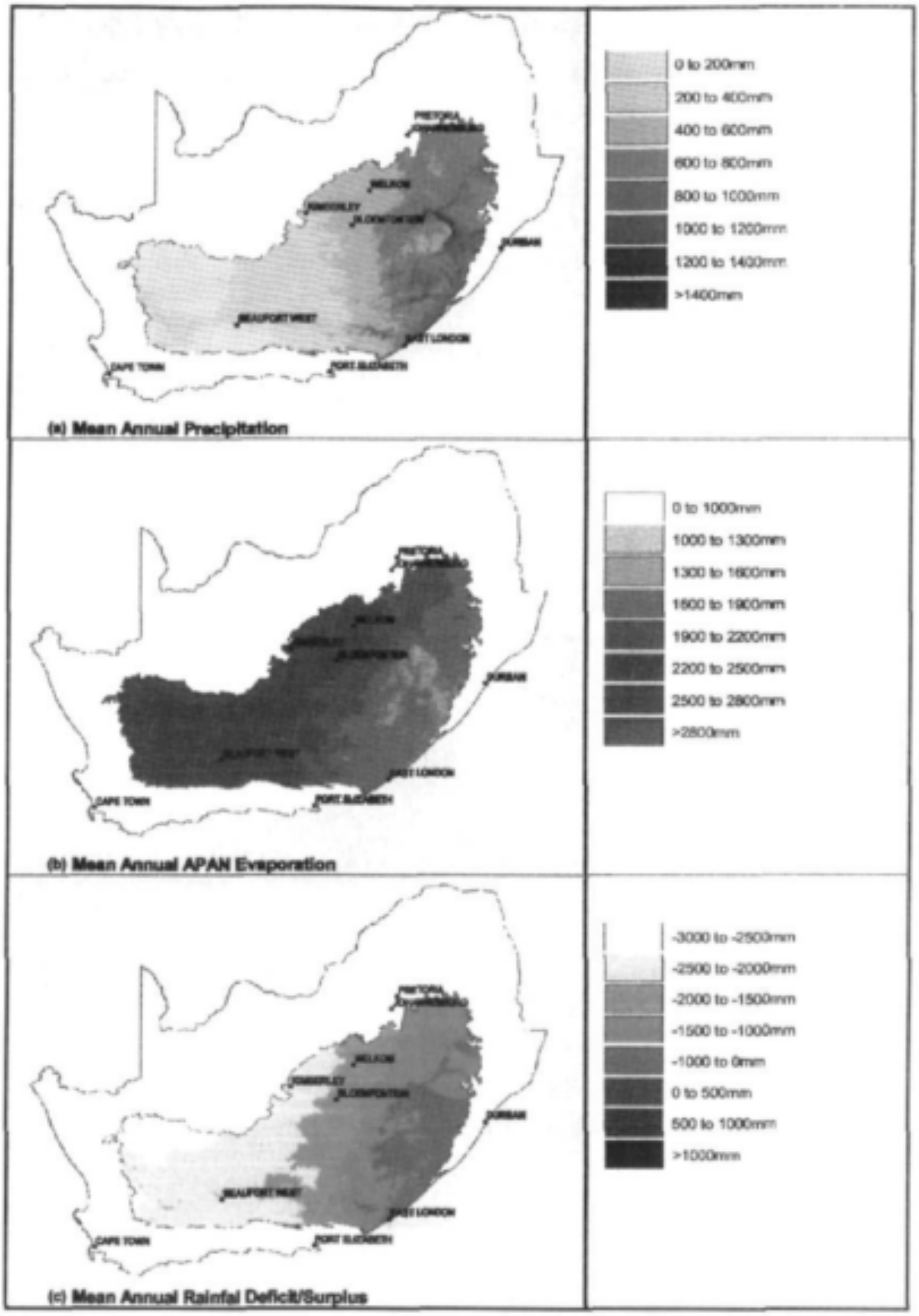



**Figure 29**: ***Distribution of (a) Mean Annual Precipitation, (b) Evapotranspiration and (c) Rainfall deficit/Surplus. Data supplied by CCWR.***

On the Middelburg map sheet two fair size quaternary alluvial plains are present. One occurs on the Eastern part of the map and corresponds to the Springbokvlakte catchment of the Teebusrivier. The other one occurs around Middelburg municipal grounds and corresponds to the Klein-Brakrivier catchment area. Both catchment areas are morphologically and geologically defined by a dolerite ring system some 45km across responsible for the individualized drainage systems. Hydrogeological investigation was carried out on the Middelburg Municipal catchment by the Directorate: Department of Water Affairs and Forestry from 1977 to 1978 (Vandoolaeghe, 1979a and b, Seward, 1987). The hydrocensus survey carried out on 690 private boreholes shows that the mean depth of drilling is 32m. The main aquifer is shallow and unconfined within the surficial alluvial deposits. It has a maximum thickness of 25 m and consists of an argillaceous sequence underlain by a gravelly sequence and the upper weathered, jointed and argillaceous or arenaceous zone of the Beaufort Group sediments. The aquifer is characterized by transmissivity ranging from 200 to 1800 $m^2$ /day. Yields between 3 and 10 l/s are common. The aquifer is capable of sustaining high yields, probably as high as 3500 $m^3$/day, for a single well in some places. The strongest boreholes are generally located along the alluvial valley of the Klein Brakrivier and its tributaries and tap the shallow alluvial water. Water abstraction for the period 1977-78 was estimated at12.8 x $10^6$ $m^3$/year. The largest abstractions were recorded on cadastral farms Buffels Valley, Bultfontein, Rietfontein and Middelburg Allotment area. During the period from 1978 to 1987 municipal abstraction rose from 0.9 x $10^6$ $m^3$/year to 1.3 x $10^6$ $m^3$/year and irrigation abstraction from 11,0 x $10^6$ $m^3$/year to 18,9 x $10^6$ $m^3$/year, without causing any dramatic drop in the regional waterlevels (Seward, 1987). Highly mineralised water (2000 mg/l TDS) is confined to the fine grained upper part of the alluvium, the weathered Beaufort sediments bordering the alluvial valleys and the dolerite ring of Middelburg.

On the Queenstown map sheet, characterized by a young, incised landscape, alluvial deposits with a substantial shallow aquifer are only developed west of Queenstown municipal area and correspond to the Zwart Kei River catchment area (Vandoolaeghe, 1980a, b). These aquifers are however far inferior to the fractured dolerite aquifers. The only alluvial deposit of geohydrological significance occurs in the Lehmansdrift area along the Klaas Smits River west of Queenstown, where it is used for irrigation purpose. The mean saturated thickness of the fine grain alluvial aquifer is 8 m. Good yields are exceptional, but can locally reach 5.5 l/s. Its dimensions are limited and it makes better storage reservoir (1.5 $10^6$ $m^3$) than a production field. The piezometric depression at Hopefield is caused by heavy abstraction from wells tapping the unconfined alluvial aquifer. The water quality of the alluvial aquifer is reported as below average.

**Dolerite Dykes**

Dolerite dykes represent thin, linear zones of relatively higher permeability which act as conduits for ground water flow within the aquifer. They have always been, and still are, the preferred drilling targets for ground water in the Karoo, away from the big valleys. Dyke contact aquifers are confined and yields around 2 to 3 l/s are common and enough for windpump supply. Transgressive oblique fractures extend tens of meters away from the dyke into the country rock. These transgressive fractures are related either to another dolerite sheet intrusion nearby or to late tectonic stress during the cooling and hydrothermal activity that followed the magmatic event. These fractures, together with other structural complication along the dykes (offshoots, en-echelon segmentation, change in dip, etc.), substantially improve the yield.

An exhaustive hydrogeological investigation of the lineaments, and specially dolerite dykes, was carried out for Victoria West sheet by Woodford and Chevallier (2001) and summarized by Woodford and Chevallier (1996) and Woodford (2001). Spatial analysis of the hydrocensus data shows a clear relation between borehole yields and lineaments. In high-density intrusive areas a high percentage of borehole with yield between 2 and 10 l/s is found, whereas in lower density areas lower yields (below 1.5 l/s) are encountered. Exploration drilling has also shown high success rate along dolerite dykes especially in structurally complex areas, with a high strike frequency and many yields above 3 l/s. Dyke orientation also seems to play a role. Boreholes drilled into E-W trending regional intrusions show the highest rate of success. Finally shallow dipping, horizontally striking fractures cross cutting the dyke commonly deliver the highest yields.

No thorough hydrogeological work has been done on Middelburg dolerite dykes. A preview of the 1:250 000 geological map shows that among the farming community and away from the main valleys, dolerite dykes are the preferred targets for drilling. Detail investigation on the Dunblane dyke (Grootfontein farm, East of Middelburg town) is an example of a dolerite intrusion cut by a shallow dipping fracture. It has delivered good yield (14 l/s). The dyke forms part of an extensive NNW dyke system that can be traced across the sheet (**Figure 1**).

On the Queenstown map sheet Vandoolaeghe (1980a) and Smart (1998) show that boreholes targeting dolerite are more successful than bore holes not - targeting dolerite, specially in the medium-range yields between 4 and 7 l/s. Boreholes along the Lehman's Drift dyke, west of Queenstown, ounce again shows that transgressive cross-cutting oblique fractures play an important role on water occurrence and yields. Yield between 3 and 8 l/s are reported along the structure.

### Dolerite Sill and Ring-Complexes

Dolerite sill and ring complexes have to a large extent been overlooked by hydrogeologists in the Karoo. However Vandoolaeghe (1980a, b) was the first to mention their ground water potential in the vicinity of Queenstown. He also stipulated that the presence of water bearing fractures near dolerite sheets is conditioned by three parameters: an optimal thickness of 30 to 50 m for the intrusion, the curvature in the sheet (from horizontal to inclined), and the relative position of the upper and lower sides of the sheet in respect of the regional piezometric head. From yield frequency histograms for the Queenstown area, Smart (1998) reports that "dykes appear to be more productive than dolerite sheets. However in the same way that dolerite in general has not been adequately tested in this area, it is even more likely that dolerite sheets in particular have not been properly explored". Vandoolaeghe (1980a) concludes that "exploration of these aquifers is not straightforward, even in the best cases" and that these aquifers do not stand out for their prolificacy, a blow yield of 10 l/s is considered to be good but 4 l/s is more near average.

On cross-sections of **Figures 8**, **10** and **12** private borehole positions (wind pumps) situated less than 1km from the section-line are reported. There is no obvious relation between borehole positioning and the occurrence of dolerite rings or sills. All these boreholes are very shallow and probably do not individually reflect the underlying deeper geology. However on a regional scale it is possible that large geomorphological structures like the Middelburg or the Nieu Bethesda basins where many boreholes are recorded could have an influence on water occurrence and success rate. In the Queenstown basin many boreholes appear to be more concentrated along the topographic highs and alongside rings or inclined sheets.

The following section will try to use and analyze the most recent hydrocensus survey over the study area in order to assess the contribution of sills and rings to the general groundwater occurrence of the study area.

## 4.3 SPATIAL ANALYSIS OF THE BOREHOLE HYDROCENSUS

The following borehole information has, according to the three 1/250 000 scale mapsheets, been sourced and used to compile a GIS database for the regional study area:

- Victoria West (**Figure 30**) borehole data includes hydrocensus information compiled for WRC Project K5/653 and the relevant DWAF National Groundwater Borehole Database (NGDB) information. The hydrocensus information related to the Local Study of this research project is also included.

- The Middelburg mapsheet (**Figure 31**) contains borehole information obtained from DWAF's NGDB and Technical Reports, especially from that of Vandoolaeghe (1979) in the Middelburg area. The borehole data is limited to the Middelburg, Noupoort and Steynsburg areas.

- The Queenstown mapsheet (**Figure 32**) contains borehole information obtained from DWAF's NGDB and Technical Reports, especially the Queenstown report (Vandoolaeghe, 1980). This mapsheet contains a reasonable spread of boreholes due mainly to the recent compilation of the 1/500 000 scale Queenstown (3126) geohydrological map (Smart, 1998).

Only boreholes with a positional accuracy of 100m or less were used for further spatial analysis and the results are reported separately as per 1/250 000 mapsheet, which approximates the east-west change in the style of ring complex intrusion and terrain ruggedness.

Preliminary analysis of the regional borehole database confirmed the researchers concern that very few boreholes actually target the proposed water-yielding portions of the dolerite ring complexes. Furthermore, those boreholes actually sited upon or within the vicinity of these intrusive are not drilled deep enough to adequately test the water-bearing potential of the feature.

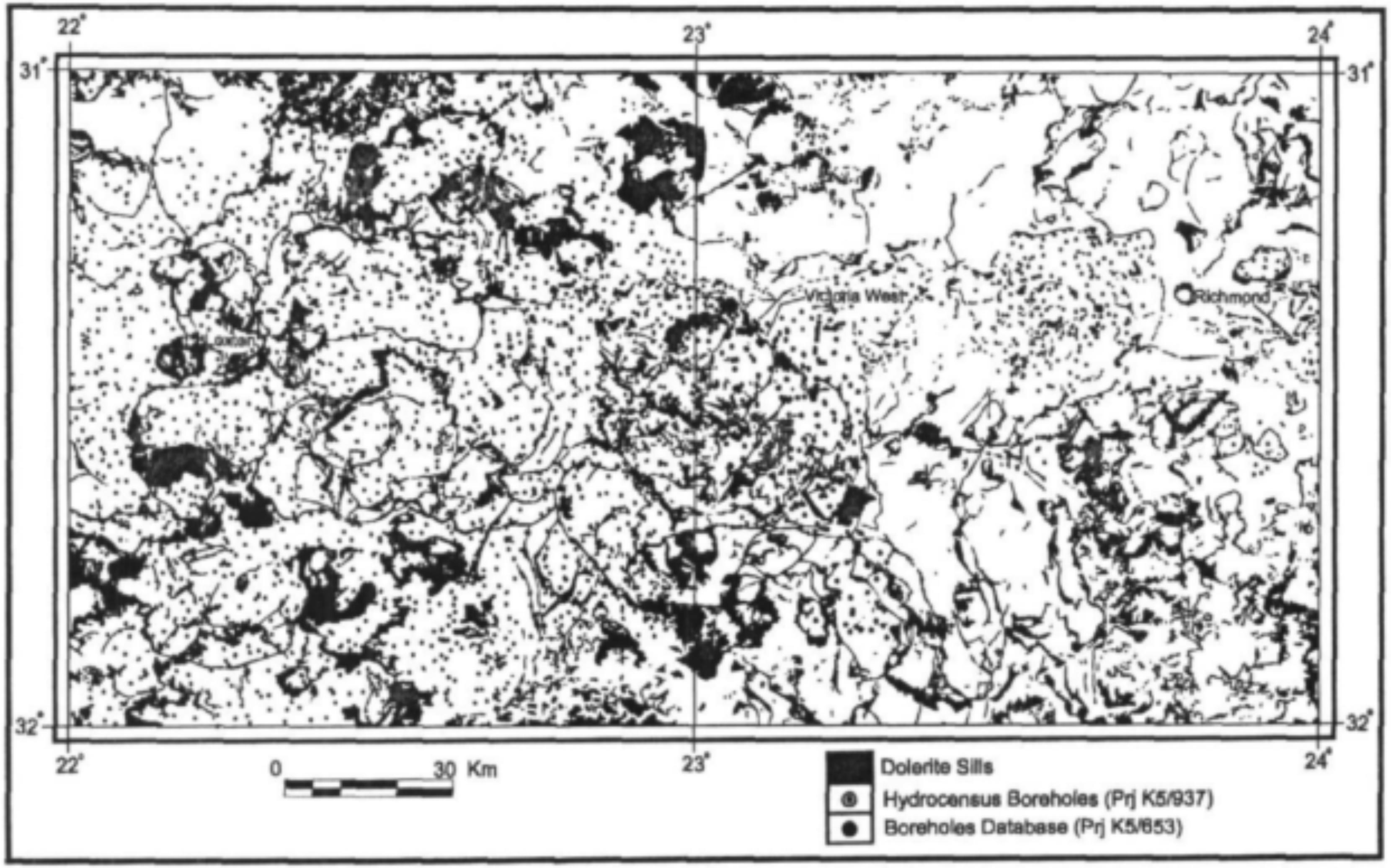
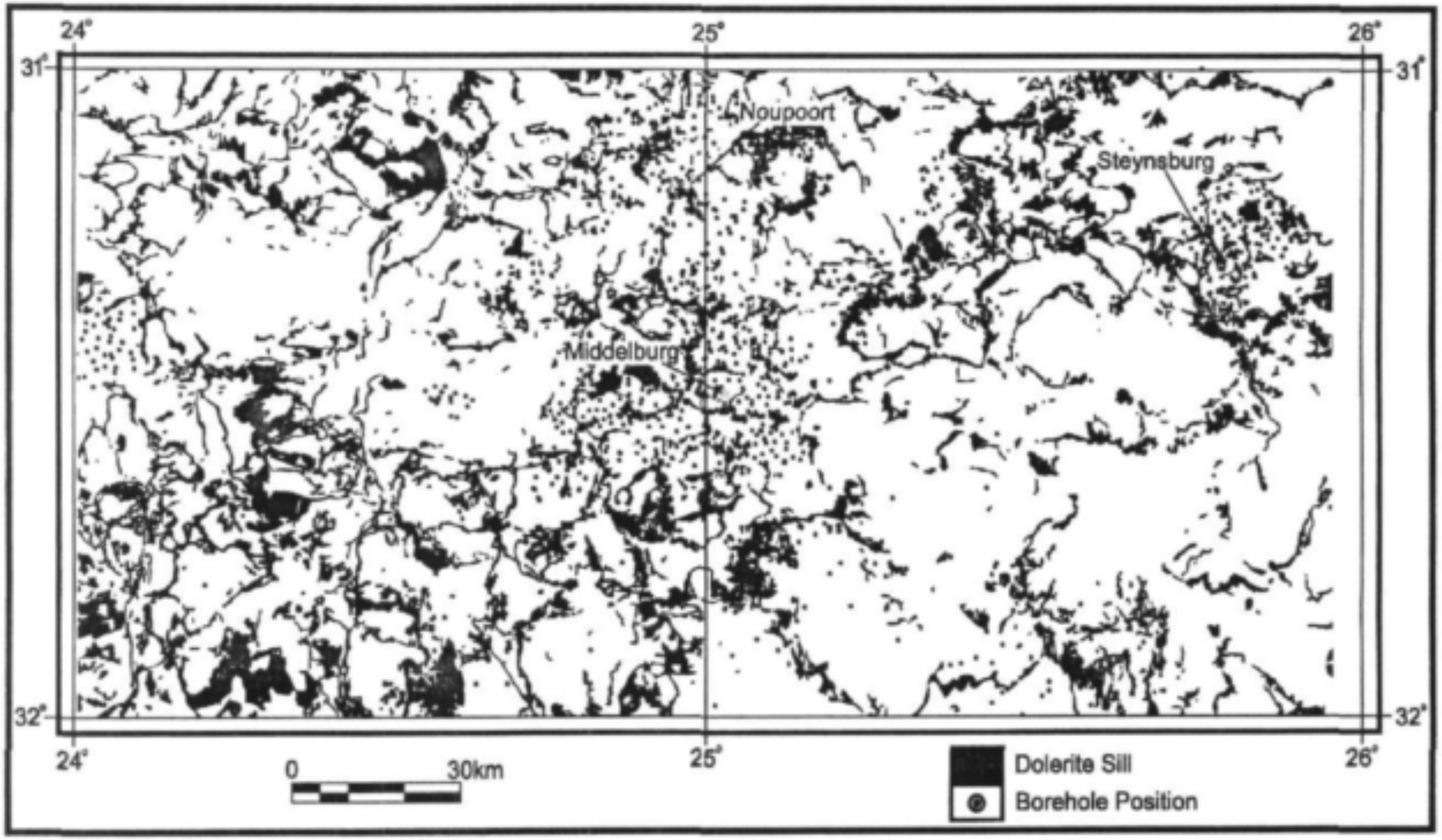



**Figure 30**: *Victoria West Hydrocensus - Borehole Locality in relation to Dolerite Sills and Ring Complexes*




<u>Figure 31</u>: ***Middelburg Hydrocensus – Borehole Locality in relation to Dolerite Sill and Ring Complexes***

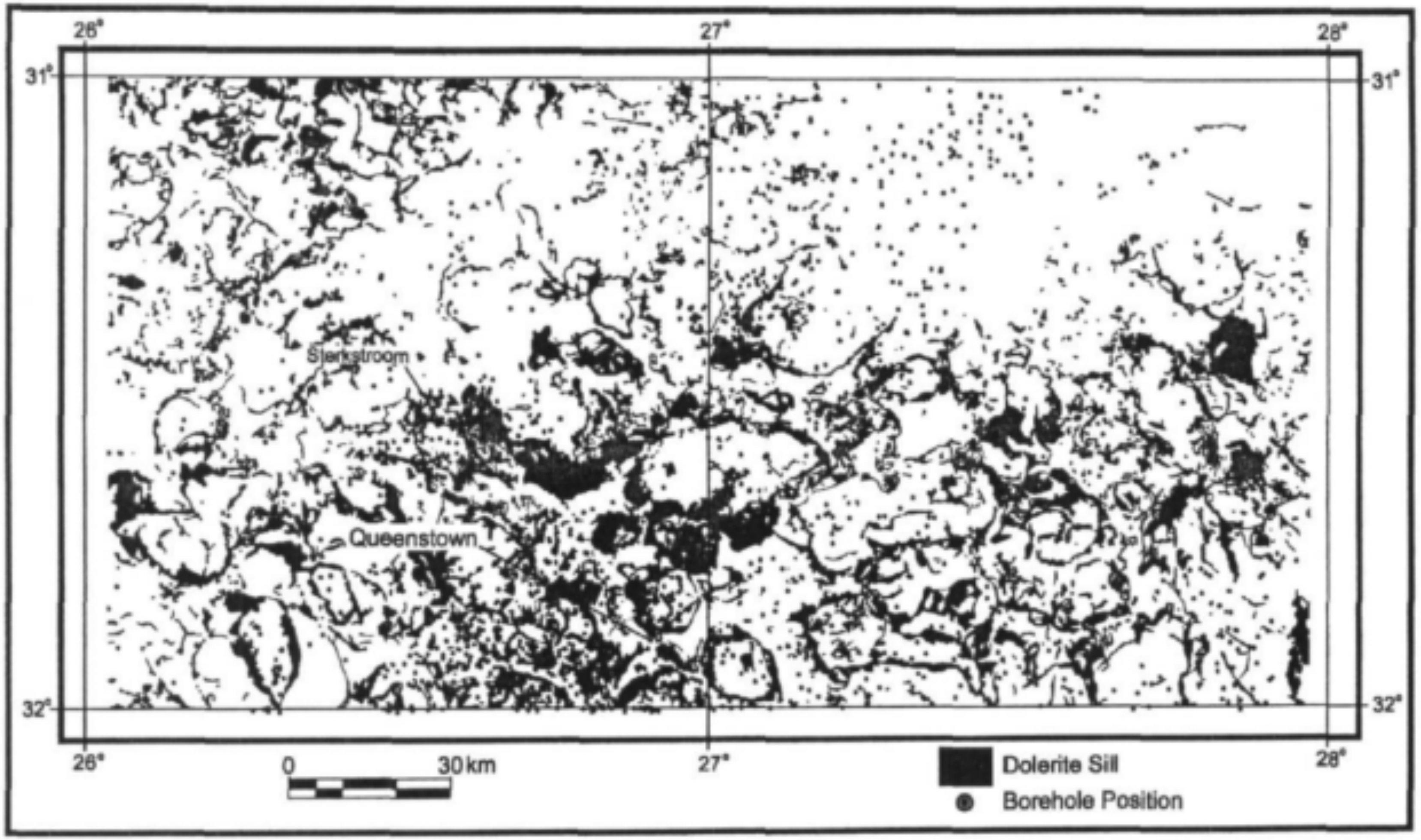



**Figure 32**: ***Queenstown Hydrocensus – Borehole Locality in relation to Dolerite Sill and Ring Complexes***

**Influence of Terrain Slope**

The regional study area was subdivided into 4 terrain slope classes using the Surveyor General's 400x400m digital elevation data (**Figure 33**), namely:

1. 0-1° Slope – reflects the large proportion of generally flat-lying areas to the west of longitude 26°E,
2. 1-3° Slope – mainly lower slopes of valleys, more abundant to the East of longitude 26°E,
3. 3-10° Slope – more steeply sloping surfaces forming the more mountainous areas of the region, especially to the east of longitude 26°E, and
4. > 10° Slope – steep slopes near the summit of more mountainous areas, mostly to the East of longitude 26°E.

In general, slope classes 2 and 3 define the more topographically elevated dolerite ring complexes to the east of longitude 26°E, whilst classes 3 and 4 more or less define the regional ring complexes to the west of longitude 26°E. Spatial analysis of borehole information indicates the following:

- Very few boreholes have been drilled in areas where the slope of the terrain exceeds 10°.
- The mean and median borehole yields decrease with increasing terrain slope.
- The drilling depth and depth to the groundwater-level increases with increasing slope of terrain (~topographic expression).
- The mean and median borehole yields of the Middelburg area are considerably higher than those in the Queenstown and Victoria West area. It is probable that this phenomenon is due to the exceptionally high reported borehole yields (>60 l/s) and the greater proportion of scientifically sited, government boreholes in the Middelburg area.

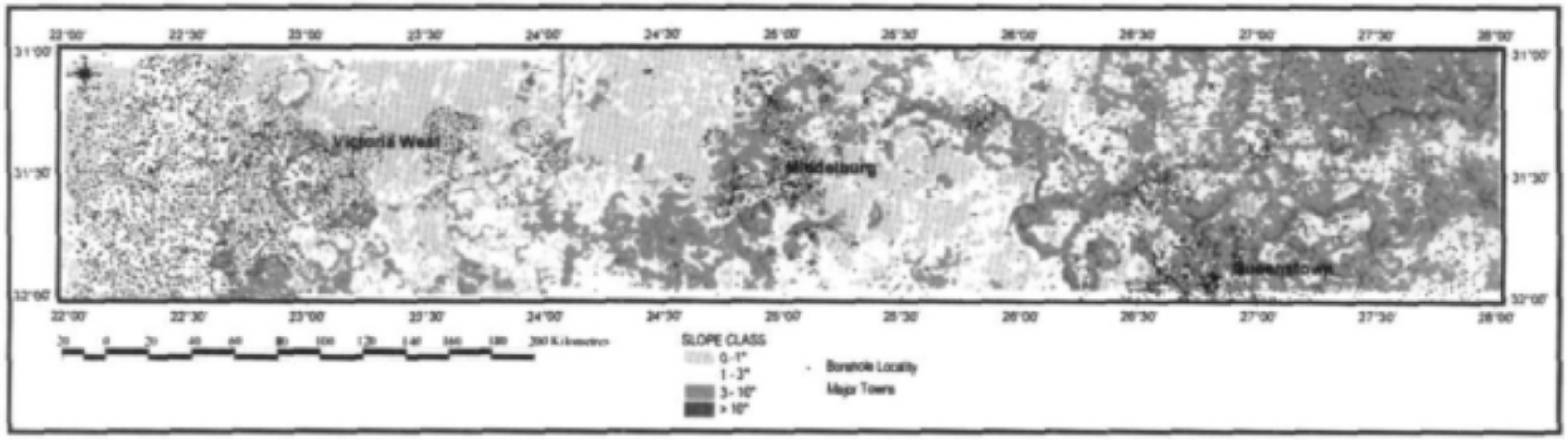



Figure 33: ***Borehole Locality and Terrain Slope Classes in the Regional Study Area.***

**Table 1:** ***Queenstown Hydrocensus – Influence of Terrain Slope***

| Yield Statistics (l/s) | TERRAIN SLOPE CLASS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-1° | | | 1-3° | | | 3-10° | | | >10° | | |
| | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) |
| No. Bores | 273 | 340 | 173 | 454 | 467 | 244 | 213 | 218 | 141 | 4 | 2 | 1 |
| Mean | 3.9 | 42.0 | 10.73 | 2.9 | 45.09 | 15.56 | 2.8 | 49.3 | 20.62 | 6.7 | 75.0 | 30.75 |
| Median | 2.0 | 35.5 | 9.16 | 1.4 | 42.0 | 11.64 | 1.1 | 45.70 | 15.42 | - | - | - |
| Std. Dev. | 5.22 | 22.53 | 6.69 | 4.21 | 22.26 | 12.36 | 4.54 | 24.75 | 14.65 | 12.40 | 63.6 | - |
| Maximum | 29.0 | 109.5 | 40.0 | 45.6 | 154.0 | 75.8 | 30.5 | 120.0 | 61.0 | 25.3 | 120.0 | - |
| Minimum | 0.02 | 0.50 | 0.40 | 0.02 | 0.50 | 0.03 | 0.01 | 0.05 | 1.26 | 0.06 | 30.0 | - |

- Std. Dev. – Standard Deviation.
- No. Bores – Number of boreholes within each category.
- Only 'wet' boreholes were considered in the analysis.

**Table 2:** ***Middelburg Hydrocensus – Influence of Terrain Slope***

| Yield Statistics (l/s) | TERRAIN SLOPE CLASS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-1° | | | 1-3° | | | 3-10° | | | >10° | | |
| | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) |
| No. Bores | 568 | 625 | 499 | 472 | 469 | 398 | 177 | 203 | 157 | 4 | 2 | 4 |
| Mean | 6.8 | 34.1 | 7.6 | 5.8 | 35.9 | 10.46 | 4.3 | 35.6 | 12.35 | 0.5 | 55.4 | 28.38 |
| Median | 3.2 | 30.0 | 6.3 | 2.3 | 31.4 | 8.58 | 1.3 | 31.0 | 10.05 | 0.3 | - | 26.00 |
| Std. Dev. | 9.62 | 17.4 | 4.93 | 10.33 | 19.1 | 7.43 | 10.0 | 18.8 | 7.99 | 0.62 | 18.9 | 18.44 |
| Maximum | 88.9 | 121.9 | 41.5 | 107.4 | 137.2 | 51.96 | 100.0 | 120.0 | 44.00 | 1.40 | 68.8 | 53.09 |
| Minimum | 0.03 | 3.0 | 0.03 | 0.01 | 2.4 | 0.42 | 0.01 | 7.60 | 0.12 | 0.10 | 42.0 | 8.44 |

- Std. Dev. – Standard Deviation.
- No. Bores – Number of boreholes within each category.
- Only 'wet' boreholes were considered in the analysis.

**Table 3:** ***Victoria West Hydrocensus – Influence of Terrain Slope***

| Yield Statistics (l/s) | TERRAIN SLOPE CLASS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-1° | | | 1-3° | | | 3-10° | | | >10° | | |
| | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) |
| No. Bores | 1668 | 2110 | 2082 | 838 | 1054 | 967 | 130 | 171 | 166 | 0 | 0 | 0 |
| Mean | 3.4 | 29.56 | 8.71 | 2.4 | 33.37 | 10.91 | 2.3 | 34.03 | 14.88 | - | - | - |
| Median | 1.6 | 26.00 | 7.10 | 1.3 | 30.00 | 9.04 | 0.9 | 29.30 | 13.34 | - | - | - |
| Std. Dev. | 5.4 | 20.93 | 5.97 | 3.16 | 23.57 | 7.48 | 3.8 | 22.48 | 10.211 | - | - | - |
| Maximum | 69.0 | 253.0 | 74.48 | 25.2 | 251.0 | 60.07 | 22.7 | 171.0 | 68.33 | - | - | - |
| Minimum | 0.01 | 0.170 | 0.20 | 0.01 | 0.15 | 0.01 | 0.05 | 1.17 | 0.70 | - | - | - |

- Std. Dev. – Standard Deviation.
- No. Bores – Number of boreholes within each category.
- Only 'wet' boreholes were considered in the analysis.

### Influence of Dolerite Intrusions

The following spatial analyses was carried out to investigate the influence of the dolerite intrusions on the productivity of the boreholes:

- A dolerite sill GIS coverage was compiled from the Council for Geoscience's 1/250 000 scale geological mapsheets 3122, 3124 and 3126 (**Figures 30, 31** and **32**). The dolerite sills were 'buffered' by 250m to take into account the flat-lying nature of these features and the positional inaccuracies in the borehole dataset.
- A dolerite dyke GIS coverage was compiled from the Council for Geoscience's 1/250 000 scale 3122 and 3126 mapsheets, unfortunately the vector data for mapsheet 3124 is not available. The dykes were 'buffered' by 50m and 250m to simulate the baked-fractured zone alongside the dyke, as well as to take into account borehole positional inaccuracies.
- The GIS was used to 'intersect' the borehole database with the above dolerite intrusion coverages, thereby identifying whether a particular borehole lies upon (ON) or away (OFF) from the particular feature. The basic yield statistics for each of the two new classes (ON and OFF) of boreholes were used to assess the relationship between the borehole productivity and the type of intrusion (**Tables 4, 5, 6, 7,** and **8**).

<u>Table 4:</u> ***Queenstown Hydrocensus – Influence of Dolerite Intrusions on Borehole Productivity***

| Yield Statistics (l/s) | SILL | | SILL (Buffer 250m) | | DYKE (Buffer 50m) | | DYKE (Buffer 250m) | |
|---|---|---|---|---|---|---|---|---|
| | On | Off | On | Off | On | Off | On | Off |
| Number Bores | 104 | 950 | 312 | 742 | 23 | 1031 | 128 | 926 |
| % of N | 9.8 | 90.2 | 29.6 | 70.4 | 2.2 | 97.8 | 12.1 | 87.9 |
| Mean Yield | 3.4 | 3.3 | 3.4 | 3.2 | 2.7 | 3.3 | 2.7 | 3.4 |
| Median Yield | 1.3 | 1.5 | 1.6 | 1.5 | 1.0 | 1.5 | 1.3 | 1.5 |
| Std Deviation | 6.27 | 4.63 | 5.28 | 4.61 | 5.70 | 4.80 | 3.82 | 4.93 |
| Maximum Yield | 44.1 | 45.6 | 44.1 | 45.6 | 27.7 | 45.6 | 27.7 | 45.5 |
| Minimum Yield | 0.02 | 0.01 | 0.02 | 0.10 | 0.01 | 0.01 | 0.01 | 0.01 |
| • N = 1054<br>• Only 'wet' boreholes were considered in the analysis. | | | | | | | | |

<u>Table 5:</u> ***Queenstown Hydrocensus – Influence of Sill and Dyke intersections on Borehole Productivity***

| Yield Statistics (l/s) | SILL (Buffer 250m) and DYKE (Buffer 250m) | | SILL (Buffer 250m) and DYKE (Buffer 50m) | |
|---|---|---|---|---|
| | On | Off | On | Off |
| Number Bores | 19 | 633 | 4 | 723 |
| % of N | 2.9 | 97.1 | 0.6 | 99.4 |
| Mean Yield | 4.4 | 3.4 | 8.6 | 3.3 |
| Median Yield | 2.5 | 1.5 | 2.8 | 1.5 |
| Std Deviation | 6.51 | 4.81 | 12.79 | 4.65 |
| Maximum Yield | 27.7 | 45.6 | 27.7 | 45.6 |
| Minimum Yield | 0.13 | 0.01 | 1.00 | 0.01 |
| | • N = 652 | | • N = 727 | |
| • Only 'wet' boreholes were considered in the analysis. | | | | |

**Table 6**: ***Middelburg Hydrocensus – Influence of Dolerite Sills on Borehole Productivity***

| Yield Statistics (l/s) | SILL | | SILL (Buffer 250m) | |
|---|---|---|---|---|
| | On | Off | On | Off |
| Number Bores | 106 | 1115 | 309 | 912 |
| % of N | 8.7 | 91.3 | 25.3 | 74.7 |
| Mean Yield | 5.7 | 6.1 | 6.0 | 6.1 |
| Median Yield | 2.5 | 2.5 | 2.0 | 2.5 |
| Std Deviation | 7.47 | 10.9 | 11.11 | 9.57 |
| Maximum Yield | 33.3 | 107.4 | 107.4 | 88.9 |
| Minimum Yield | 0.03 | 0.01 | 0.01 | 0.03 |
| • N = 1221<br>• Only 'wet' boreholes were considered in the analysis. | | | | |

**Table 7**: ***Victoria West Hydrocensus– Influence of Dolerite Intrusions on Borehole Productivity***

| Yield Statistics (l/s) | SILL | | SILL (Buffer 250m) | | DYKE (Buffer 50m) | | DYKE (Buffer 250m) | |
|---|---|---|---|---|---|---|---|---|
| | On | Off | On | Off | On | Off | On | Off |
| Number Bores | 306 | 2330 | 921 | 1715 | 664 | 1972 | 1572 | 1064 |
| % of N | 11.6 | 88.4 | 34.9 | 65.1 | 25.2 | 74.8 | 59.6 | 40.4 |
| Mean Yield | 2.3 | 3.1 | 2.9 | 3.1 | 3.3 | 2.9 | 3.3 | 2.7 |
| Median Yield | 1.3 | 1.5 | 1.3 | 1.5 | 1.6 | 1.3 | 1.5 | 1.30 |
| Std Deviation | 3.62 | 4.88 | 4.64 | 4.81 | 5.07 | 4.64 | 4.99 | 4.36 |
| Maximum Yield | 25.0 | 69.0 | 69.0 | 63.1 | 56.8 | 69.0 | 63.1 | 69.0 |
| Minimum Yield | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| • N = 2636<br>• Only 'wet' boreholes were considered in the analysis. | | | | | | | | |

**Table 8**: ***Victoria West Hydrocensus – Influence of Sill and Dyke Intersections on Borehole Productivity***

| Yield Statistics (l/s) | SILL (Buffer 250m) and DYKE (Buffer 250m) | | SILL (Buffer 250m) and DYKE (Buffer 50m) | |
|---|---|---|---|---|
| | On | Off | On | Off |
| Number Bores | 509 | 652 | 186 | 1237 |
| % of N | 43.8 | 56.2 | 13.1 | 86.9 |
| Mean Yield | 3.2 | 2.7 | 3.5 | 3.1 |
| Median Yield | 1.5 | 1.3 | 1.9 | 1.4 |
| Std Deviation | 4.52 | 4.09 | 4.98 | 4.69 |
| Maximum Yield | 37.9 | 40.0 | 30.2 | 63.1 |
| Minimum Yield | 0.01 | 0.05 | 0.01 | 0.05 |
| | • N = 1161 | | • N = 1423 | |
| • Only 'wet' boreholes were considered in the analysis. | | | | |

The borehole yield statistics for each of the 1/250 000 scale mapsheets tends to indicates that:

- A relatively small number (<10%) of production boreholes tap dolerite sills in the Queenstown and Middelburg areas, which increases to approximately 12% in the Victoria West area. This is to be anticipated as the sills, and especially the ring complexes, generally form the higher-lying portions of the study area and the terrain becomes progressively more rugged from the west towards the east – making such areas more and more inaccessible for drilling-rigs.

- There is no clear indication that higher yielding boreholes are associated with the dolerite sills, even when their 'zone of influence' has been increased by 250m. In fact there is a slight bias towards the converse being true.
- Boreholes in the Middelburg area, for reasons mentioned earlier, are generally higher yielding than in the adjoining Victoria West and Queenstown areas.
- The number of production boreholes drilled along dolerite dykes in the Queenstown area is very low (between 2-12%), when compared to elsewhere in the Karoo Basin. This is probably due to the incomplete mapping of dolerite dykes on the 1/250 000 scale geological map and this could be verified via detailed lineament mapping from remote-sensing imagery.
- In the Queenstown area, the drilling on dolerite dykes, alone, does not appear to result in higher yielding boreholes. Also boreholes drilled on dykes (mean 2.7 l/s, median 1.0 l/s) are generally lower yielding than those drilled into dolerite sills (mean 3.4 l/s, median 1.3 l/s).
- In the Victoria West area, production boreholes drilled alongside dolerite dykes (mean 3.3 l/s, median 1.6 l/s) are generally slightly higher yielding than those drilled away from these structures (mean 2.9 l/s, median 1.3 l/s). Also boreholes drilled alongside dykes are more productive than those drilled on dolerite sills (mean 2.3 l/s, median 1.3 l/s).
- Boreholes drilled at the intersection of dolerite sills and dykes (**Tables 5** and **8**) are more productive than those drilled away from such structural targets. In the Queenstown area, the yields of boreholes drilled at dyke-sill intersections (mean 4.4 l/s, median 2.5 l/s) are higher than those only on dykes (mean 2.7 l/s, median 1.0 l/s) or sills (mean 3.4 l/s, median 1.3 l/s).

## 4.4 SPRINGS ASSOCIATED WITH DOLERITE SILL AND RING-COMPLEXES

Kent (1972) reviewed the occurrence of springs across South Africa. It is evident that many municipalities depend largely or entirely on springs for their water supply, and others still draw on springs for part of their needs (e.g. Kokstad).

In Karoo rocks, spring water is derived from meteoric water circulating at depths along secondary aquifers such as fractures and faults (Kent, 1972, Visser, 1989). Kok (1992) supported this meteoric origin by finding a linear relationship ($r = 0.977$) between average annual rainfall and recharge of a number of Karoo springs. He measured average annual spring discharge as an indication of the average annual recharge in the catchment area (after discounting runoff, evapotranspiration, leakage and abstraction).

Kok (1992) estimated that no significant recharge to the Karoo springs occur in areas where the average annual rainfall is less than 100mm. Cold-water springs in these low-rainfall areas should be absent. In areas with more than 100mm rainfall, recharge to the Karoo springs was estimated to be, on average, about 8% of the rainfall for that area. However, areas with low mean rainfall can experience infrequent extreme events that can contribute to recharge. Thermal springs (>25 $^{0}$C) may be present, related to a deeper regional groundwater system that extends beyond the localized rainfall catchment area.

In the study area, several isolated springs rise beside dolerite dykes and inclined sheets or ring. However, the following field observations are not the result of an extensive survey of all springs in the region.

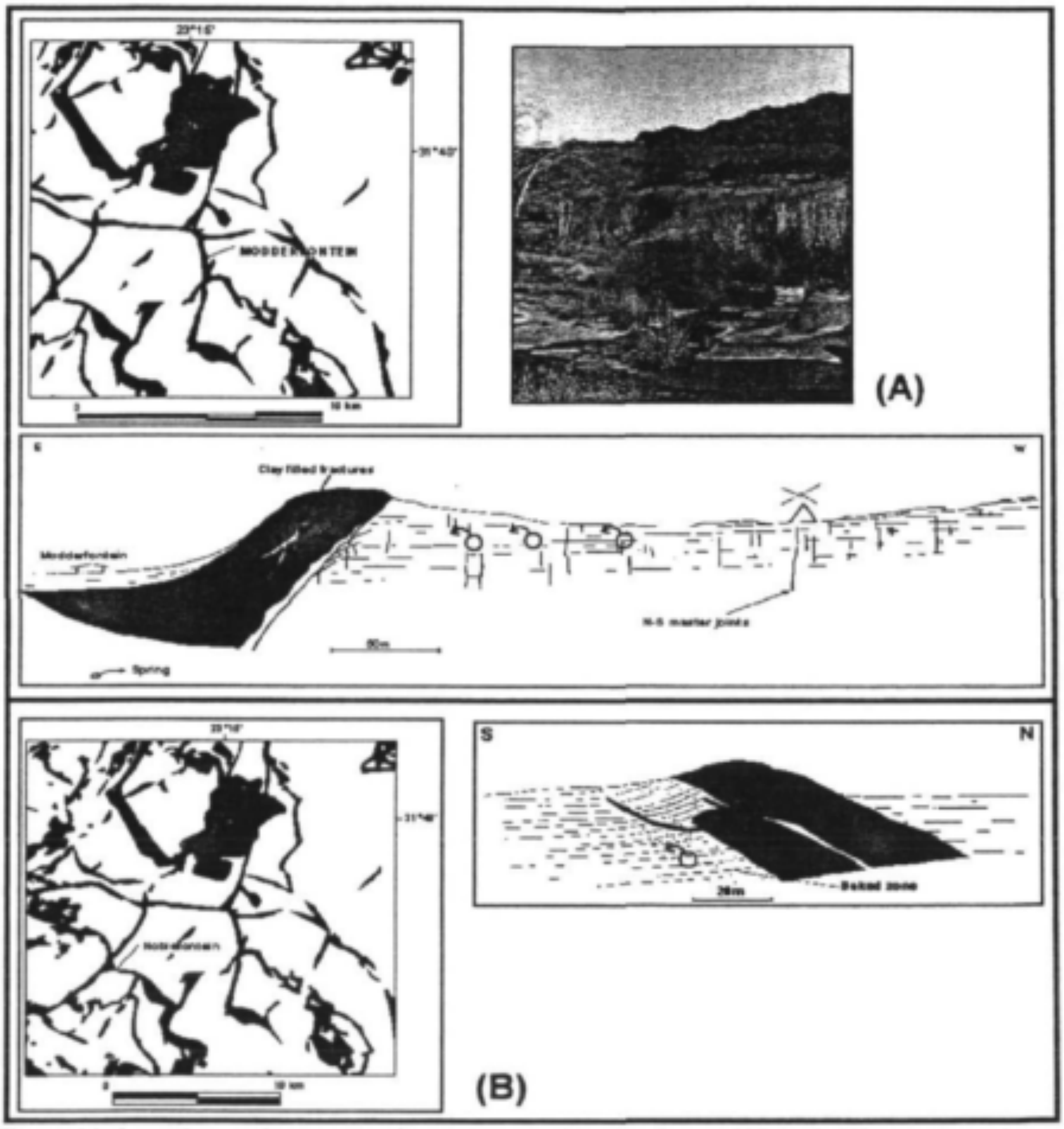
**Springs associated with Topographically High-lying Ring-Complexes**

Many perennial shallow springs, seasonal water discharges or seepages occur at the point where a dolerite ring creates dam effect against the surrounding sediment. It is no surprise that many Karoo homesteads have been built in the vicinity of a dolerite "poort". This is where the drainage system funnels through a cut in the dolerite, and where emerging shallow ground water brings massive greenery contrasting with the surrounding dry Karoo country side. There are numerous springs of that kind over the study area and it was out of the scope of the present project to give an exhaustive list of these water points. Basically, almost every homestead erected at a "poort" with overgrowth indicates the presence of that type of spring. Palaeo-springs are indicated by abundant calcrete in the vicinity of the poort. It also means that virtually every homestead can be without water and ecosystems affected by abstraction if these shallow waters are over exploited.

On the Victoria West map sheet only few of them were visited by the research team. Two exemples are given on **Figure 34**. The Modderfontein spring (sheet 3123 CB) is a very shallow water emerging some 70m away from the dolerite ring at three different levels in between the flat-lying Beaufort sandstone beds. According to the farm owner it never dries out but the flow fluctuates after each rain fall, so does the yield of a nearby wind pump. When it was visited in August 1999, after a dry year, the yield of the spring was low and estimated at 1.5 to 2 l/s. After the rainy season in February 2000 the yield increase to 10 l/s. The sediment is very fractured next to the dolerite ring but only shows well developped master joints at the spring. The second example is given by the well known Noblefontein spring the water of which is bottled and commercialized by the farm owner under the brand "Karoo Water". The spring emerges in the Beaufort sediment within the baked zone some 20 m away from the dolerite ring. This inclined sheet is a double intrusion with a typical network of offshoots at its lower contact. The yield of the spring was reported as 2 l/s by the farmer. When visited in august 1999, after the dry year, the spring flow had stopped and the owner had to dig a well few meter deep to recover the water.

Outside Victoria West (sheet 3123 CC), the Brakkefontein spring occurs adjacent to the road, as the road passes through a poort. This poort and spring occur at the intersection of a regional fracture and the step-up of the inclined sheet forming the margin of the main Victoria West ring structure. This shallow spring supports dense vegetation (reeds, grass, shrubs and trees) and is used by locals and livestock.

In the Middelburg catchment area eighteen springs have a yield exceeding 0.3 l/s and are only reported as temporarly persistent after rainfall season (Vandoolaeghe, 1979a). Only the weir spring at Grootfontein, just north of the Middelburg dolerite ring, is reported as being perennial. Other strong springs like Onbekendt and Wolvekop are in a similar geological setting.




<u>Figure 34</u>: ***Location and cross-sections of some dolerite rings of Victoria West area and their relation with shallow springs. (A) Modderfontein and (B) Noblefontein***

At Nieu-Bethesda (south of Graaff-Reinet), Kok (1992) measured the mean annual discharge from a spring as 42 l/s. The spring occurs at the contact between a dolerite dyke and the surrounding Beaufort Group shales. He concluded that under a mean annual rainfall of 317 mm over a catchment area of 60km$^2$, this represented a 6.97% recharge rate, with the remaining rainfall lost to runoff, evapotranspiration, possibly abstraction, etc. A similar spring, near Nieu-Bethesda, occurs at the foot of Witnek Pass, at Kareel Laagte. The inclined sheet contains abundant blocks of rafted sediment, and bedrock is highly fractured and upturned at the contact. This spring supports abundance of trees, and wildlife, such as kudu.

In the Queenstown area springs and seepages at the contact with the dolerite rings are numerous but are most of the time insufficient for irrigation purposes. A spring occurs at the upstream contact of the inclined sheet forming the northern perimeter of the Golden Valley ring structure. This gives rise to a small northward-draining stream that supports a ribbon of vegetation and a grove of trees, easily visible from the Lelykpoortjie turnoff to Hofmeyer.

**Springs associated with Ring Feeder-dykes**

Feeder dykes (the root of the rings) do not form high topographic relief. Springs occur less commonly along these linear inclined sheets. The comprehensive hydrocensus data base over the sudy area does not show the detailed relationships between the geology and the springs. Once again it was outside the scope of the present project to visit all the strong springs and establish their detailed geological context. Few examples are therefore given below.

The Noupoort spring is located on the Middelburg sheet (3125 BB, 31°11', 25°57') along a series of anastomosed ring feeders. The spring was not visited by the authors but Kok (1992) measured a discharge of 19 l/s. For a low average rain fall of 254 mm and a moderate catchment area of 72 $km^2$ the recharge is very low (3.3 %), below other dolerite-related springs surveyed in the Karoo (8 %).

The Morning Sun spring is located in the South-West corner of Queentown sheet on the Carrickmoor homestead. It is located along a north-trending, 100 m thick, few km long inclined dyke, that acted as a feeder for the group of Golden Gate coalescing rings. The road-cutting south of the homestead shows a clear section of this composite intrusion characterised by two magmatic pulses (**Figure 35**). The exact position of the spring in relation with the dyke can not be seen. It emerges on low grounds covered with loose sediments and a wide patch of excessive overgrowth. It lies in line with two major dolerite outcrops and seems to be at the lower eastern contact of the inclined intrusion. The farm owner has always known the spring as perenial with a consant yield of 15 000 gal/hr (18.5 l/s) all through the year. The spring was not visited after the heavy rainfalls of February 2000.

At Taaiboschfontein, (sheet 3123 CD), the N1 crosses a dolerite dyke that extends east-west for a number of kilometres, connecting two ring structures. The dyke is about 100m thick, and, at one site is characterized by gum and willow trees. Although the bed of the stream there is dry, it appears that a spring once flowed from the dolerite/bedrock contact since secondary calcrete fills a large number of joints, and coats the rock and floor of the channel. Further along, at Wildebeesfontein, another spring occurs on the upstream side of the feeder dyke.

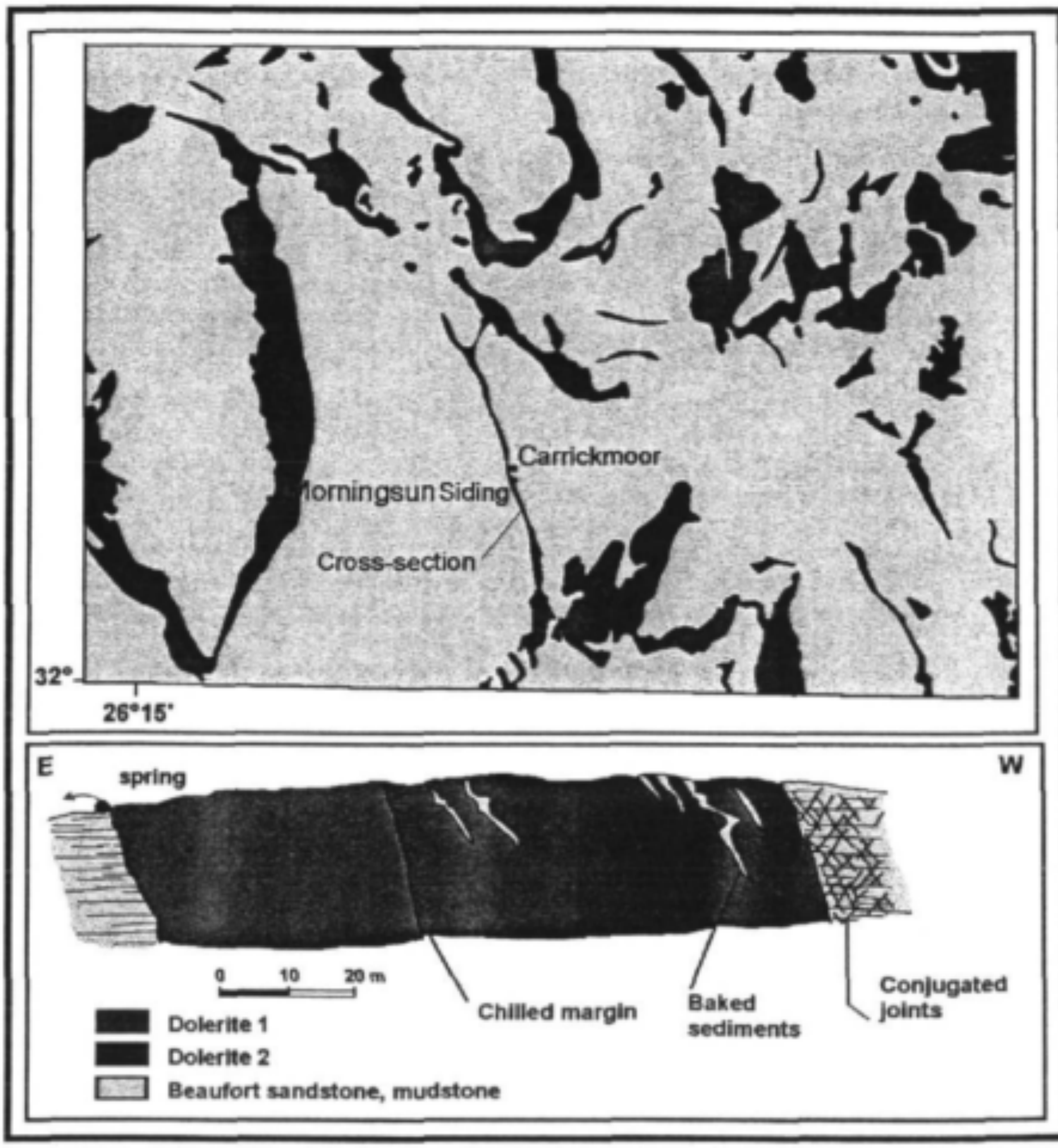



Figure 35: ***Location of the dolerite ring at the Morning Sun spring and cross section along the road cut (Queenstown map sheet)***

## 4.5 FLOODING OF THE ORANGE-FISH RIVER TUNNEL

The Orange-Fish tunnel, used to pipe irrigation water from the Gariep Dam (Hendrik Verwoerd Dam on maps) on Colesberg sheet in the North to the valleys of the Great Fish and Sundays River on the Middelburg sheet in the south, is 83km long and is 5.3m in diameter. It was excavated in predominantly fine-grained sandstone, interbedded with mudstone of the Beaufort Group. Two different geohydrological zones were encountered; a weathered and jointed upper zone, and an unweathered lower zone. Depending on surface topography, depth varies between 40 - 110 m.bgl. During construction, pilot boreholes ahead of the operations indicated a groundwater elevation of 9 - 40 m.bgl.

A 2.8 m wide zone of NE-SW to E-W trending fissures, parallel to most of the other fissures in the tunnel, and not directly related to a particular dolerite intrusion, was intersected at 110 m.bgl, while tunneling some 550 m south of Shaft 2 (on Colesberg sheet). Water flooded into the tunnel at 860 l/s, mainly from three permeable fractures: 3.2 cm, 3.2 cm, and 7.6 cm wide. Other open water-bearing fissures in the vicinity of shaft 2, occur as horizontal bedding-plane joints between rock layers of different lithological character in the upper weathered zone, 6-15m.bgl, (Olivier, 1972).

Of the 55 dykes intersected by the tunnel, 49 were dry. One, a 6m wide east-west trending dyke in the vicinity of shaft 2, with open fractures up to 10 cm wide, and sheared margins, yielded up to 75l/s. As for most of the dykes encountered, there is evidence of syn- and post-intrusive shearing (slick-en-slides, chlorite, etc).

Water in the fissure zone was 230 -240C (warm) and had high TDS (500-550 mg/l). Chemistry was vaguely similar to that of two springs occurring a few kilometres to the west, and two deep (650-700m) high-yielding boreholes (25 l/s), that occurred a few kilometres to the east. These water sources occur in a line parallel to the high yielding dyke and high yielding fractures. When the tunnel penetrated the fissures and flooding occurred, waterlevels in the boreholes in line with the fissures and dyke dropped by 1.8m, while those only 40m and further away to the north and south, remained relatively unaffected. This indicates the tunnel penetrated a fracture zone that was hydraulically connected to the southern fractured and sheared margin of a nearby east-west orientated dyke. The deep-seated origin of the water is supported by the minimal drawdown experienced by "near surface" boreholes during the 15 month de-watering process in which $1.6x10^6$ $m^3$ was pumped from the area around the tunnel.

It was concluded that the narrow fissure zone is of Post-Karoo age related to sagging of the Karoo system, immediately after the intrusion events. The presence of secondary calcite, chlorite, and zeolite in many of the fissures in the tunnel indicate these fractures were groundwater conduits following the intrusion and sagging events.

While no dolerite was encountered at the point of intersection the possibility that the high-yielding fractures are associated with the intrusion of an adjacent or overlying dolerite ring structure, above the present day surface, cannot be ruled out. Since it is common that ring structures occur within other ring structures, it is possible that the tunnel was drilled through the intermediate zone between them, the overlying sill being now removed by erosion. Our structural and mechanical study has shown that complex shearing (vertical, oblique and horizontal) has developed in the sediment in specific places next to the sill and ring complexes. In the vicinity of shaft 2, this would account for both the near vertical high-yielding fractures, and the horizontal bedding-parallel fractures.

Inspection of unpublished 1:50 000 geological maps at the Council for Geoscience indicates that the area in the vicinity of shaft 2 is cut by numerous dykes which have orientations almost identical to the high-yielding fractures in the tunnel. It is also evident that the region through which the tunnel was bored has a high density of rings, although the area at shaft 2 lies in an inter-ring area. For instance, the dolerite exposed at Elandsfontein 117, some 2km south of the tunnel fissure zone, does have some morphological elements typical to the margin of a ring structure, but outcrop does not extend laterally far enough to confirm the presence of a deep seated ring, below the tunnel. At present, although the high-yielding fissures closely match the dolerite dyke orientations in the inter-ring area at shaft 2, there is insufficient evidence to link the fissures directly to a ring system, either above, or below, the tunnel.

## 5 LOCAL MORPHO-TECTONIC STUDY

### 5.1 SELECTION OF THE CASE STUDY AREA: VICTORIA WEST

The regional study has shown the existence of three morphotectonic models of sill and ring systems (**Figure 23**). Since it was not possible to individually treat each case. The local study will be focussed on the sill and ring system extending from Victoria West south. This system belongs to model I and is of special interest because:

- It exhibits the typical "ring-within-ring" structure and the topographic expression of a number of different vertically-stacked sills (at least four) are clearly visible,
- A comprehensive lineament map of the area has already been compiled (WRC 653 by Woodford and Chevallier, 2001; Woodford and Chevallier, 1996),
- An exploration-drilling programme targeting various geological lineaments has recently been completed for project 653,
- Detailed hydrocensus information is available for the western portion of the study area (WRC project 653), and
- Victoria West experienced water-supply problems during 1997 and any high-yielding boreholes drilled during this project could be incorporated into the towns supply scheme.

The area covered by the Local Study in respect to the regional study is shown in **Figure 3**. It consists of six 1:50 000 scale sheets namely: 3122BD, 3122DB, 3122DD, 3123AC, 3123CA and 3123CC.

### 5.2 DIGITAL TERRAIN MODELLING

A digital terrain model (DTM) at resolution of 25x25m grid-cell size has been created from the original map separates by raster-scanning and vectorisation to a REGIS format. The REGIS vector data for the following six 1/50 000 scale mapsheets, covering the local study area, were purchased from the Chief Directorate: Surveys and Land Information.

The REGIS contour vectors were imported into Arc/Info and interpolated into a raster-based or grid coverage using the TOPOGRID utility.

The TIN model (with 34 000 nodes) is shown in 3D perspective on **Figure 36**. The resultant hill-shaded DTM with a 25x25m cell-size is shown in **Figure 37**. On both models the geometry of the dolerite ring system is clearly defined as four overlapping sub-circular units stacked above each other. They are from South to North: the Oorlogsfontein ring, the Wolweberg ring, the Ghaapkop ring-system and the smaller Ruigtefontein ring.

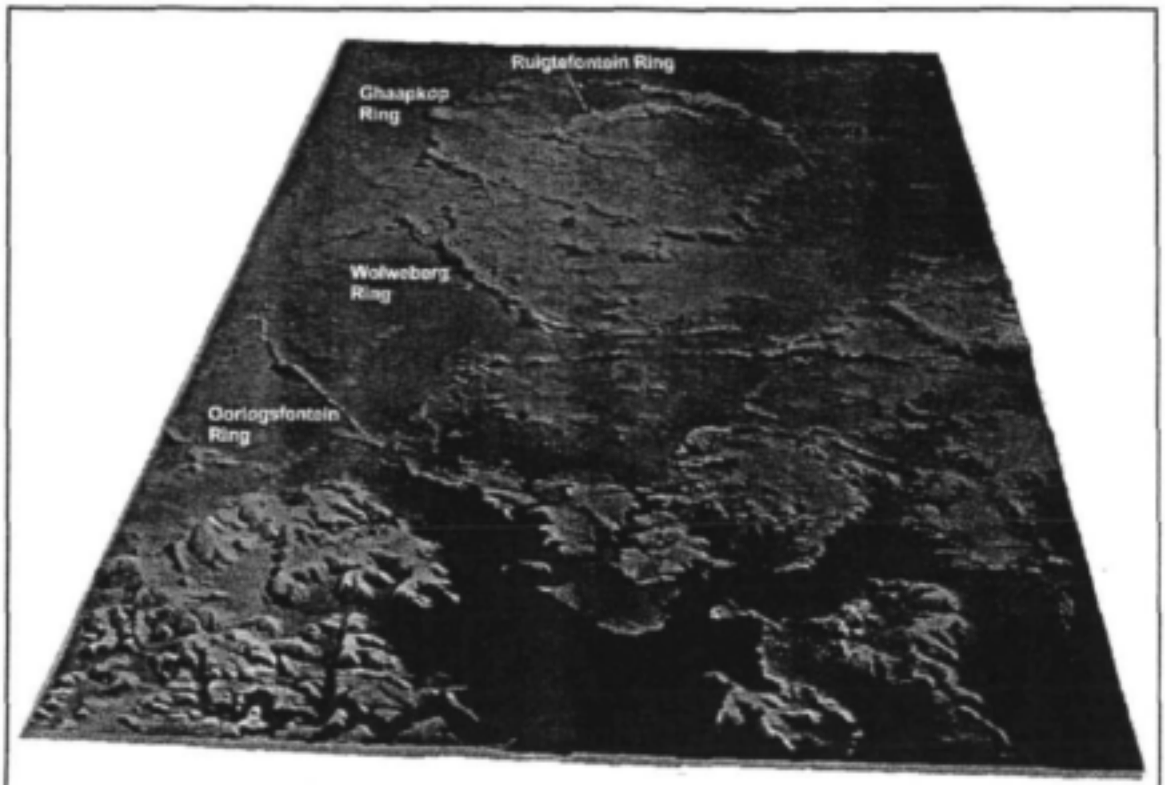



Figure 36: ***3D perspective view of the local study area showing the relation between the four ring units forming around Victoria West. Note the overlapping nature of the units, the units as a result of migration to the north and 'up-stacking'.***

## 5.3 STRUCTURAL ANALYSIS OF THE VICTORIA WEST RING-COMPLEX

The dolerite sill and ring-structure database was captured and compiled from the existing 1/50 000 scale field-maps at the Council for Geoscience in Bellville. The fracture pattern (Lincomp) was imported from a previous WRC project (653) and is a synthesis of existing geological maps, air photo interpretation, satellite imagery (**Figure 38** and **Figure 39**). Most of the lineaments represent dolerite dykes or fractures associated with dolerite dykes (jointing parallel to dykes). The four overlapping ring units are explicitly displayed. A simplified NS cross-section illustrates the vertical upward-stacking of the four major sills as they decrease in size. The larger unit (Oorlogsfontein) occurs at a low stratigraphic level and the smaller one (the Ruigtefontein unit) was emplaced at the highest level. The map also shows how the dolerite dykes and related fractures have controlled the shape of the ring system. Many curve dykes are seen feeding into the dolerite ring. Examples of these structural relations are especially well illustrated on the south-western side of the Oorlogsfontein and Wolweberg units.

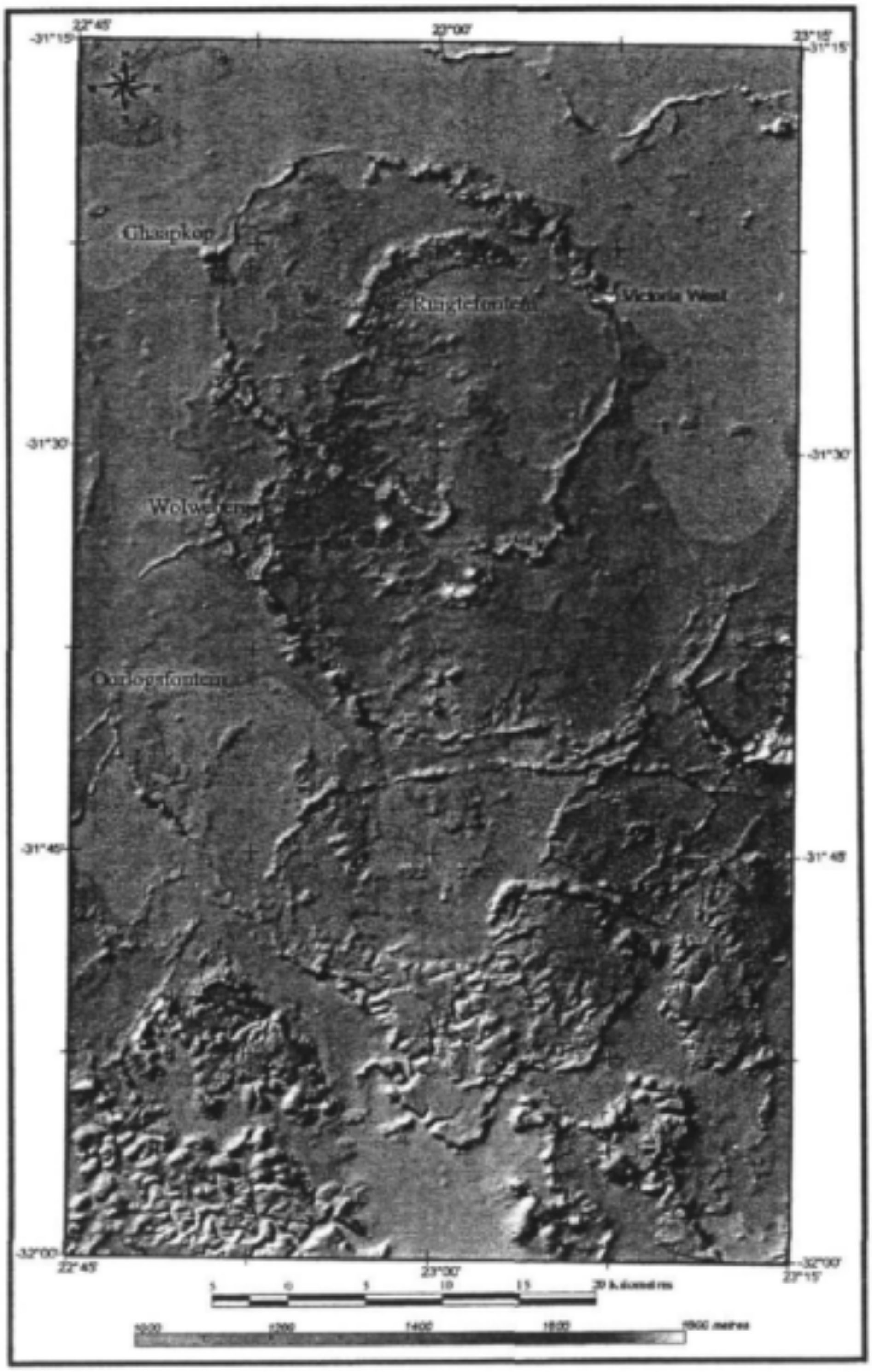



**Figure 37**: *Hill shade DTM of the local study area showing the up-stacking effect of the rings, with the high elevations in the northern unit (Ghaapkop ring) and lower elevation in the southern Oorlogsfontein ring.*

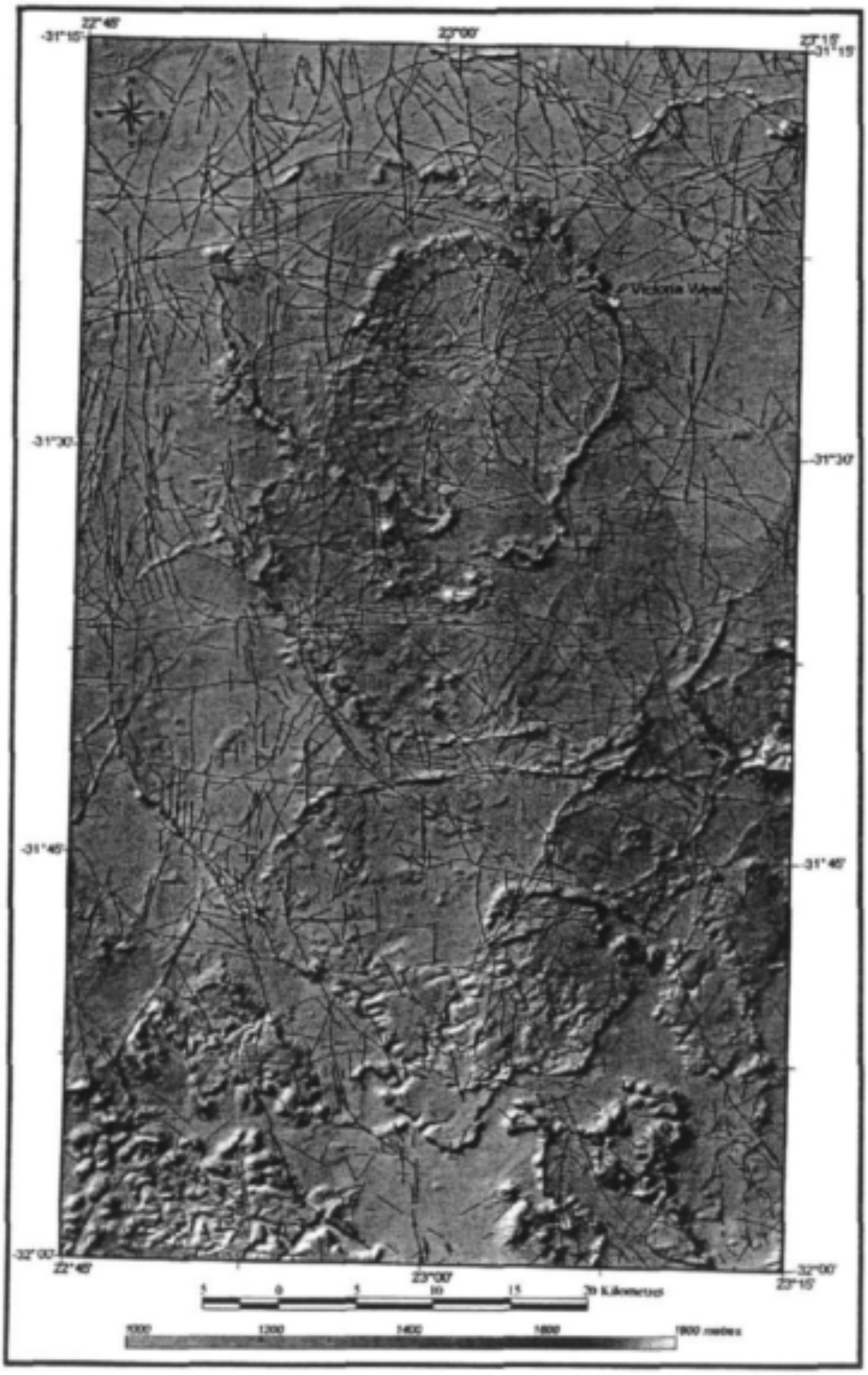



Figure 38: *DTM of the local study area showing the relation between the rings and the fracture pattern. Most of the fractures are dolerite dykes or dolerite related fractures*

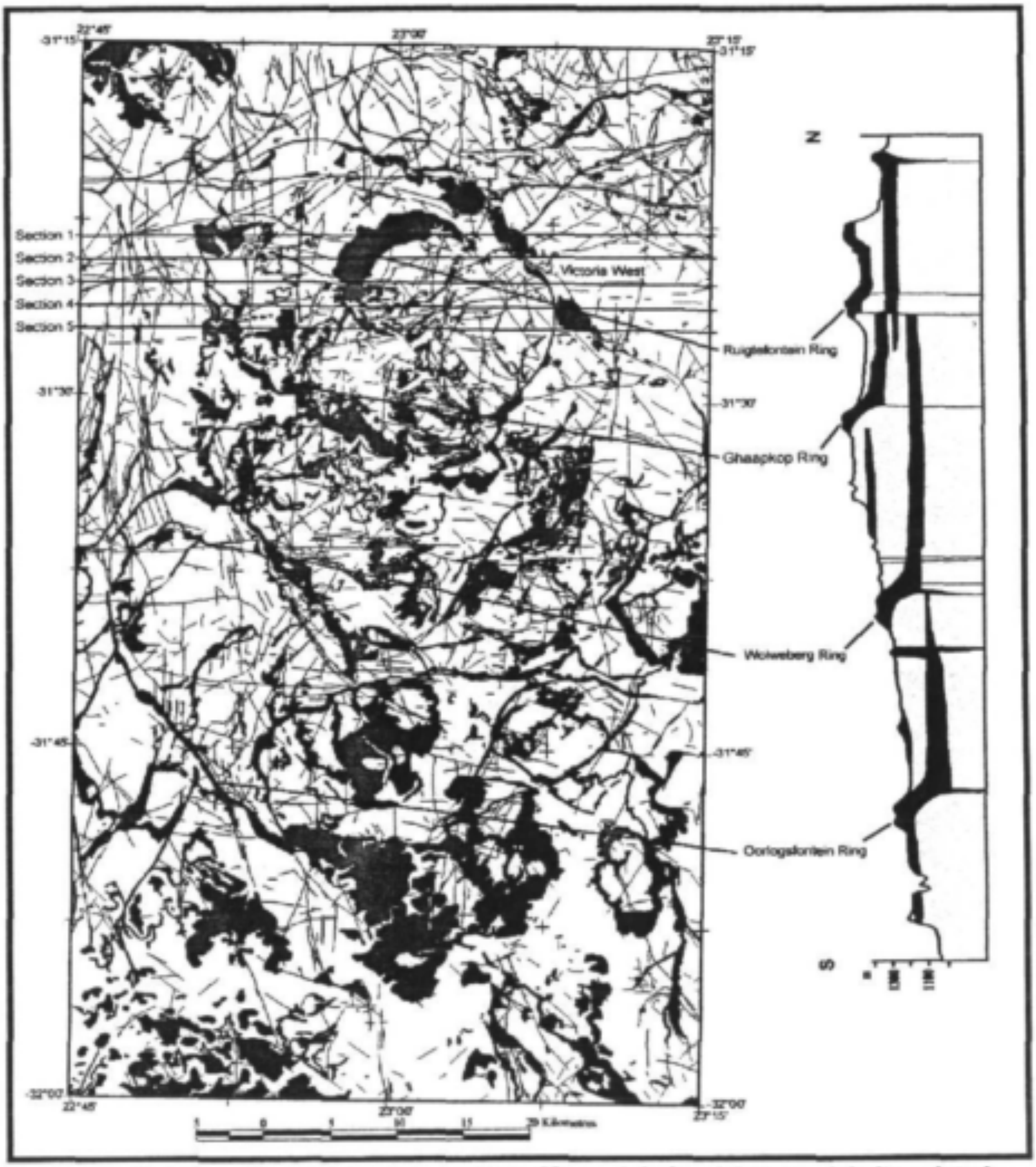
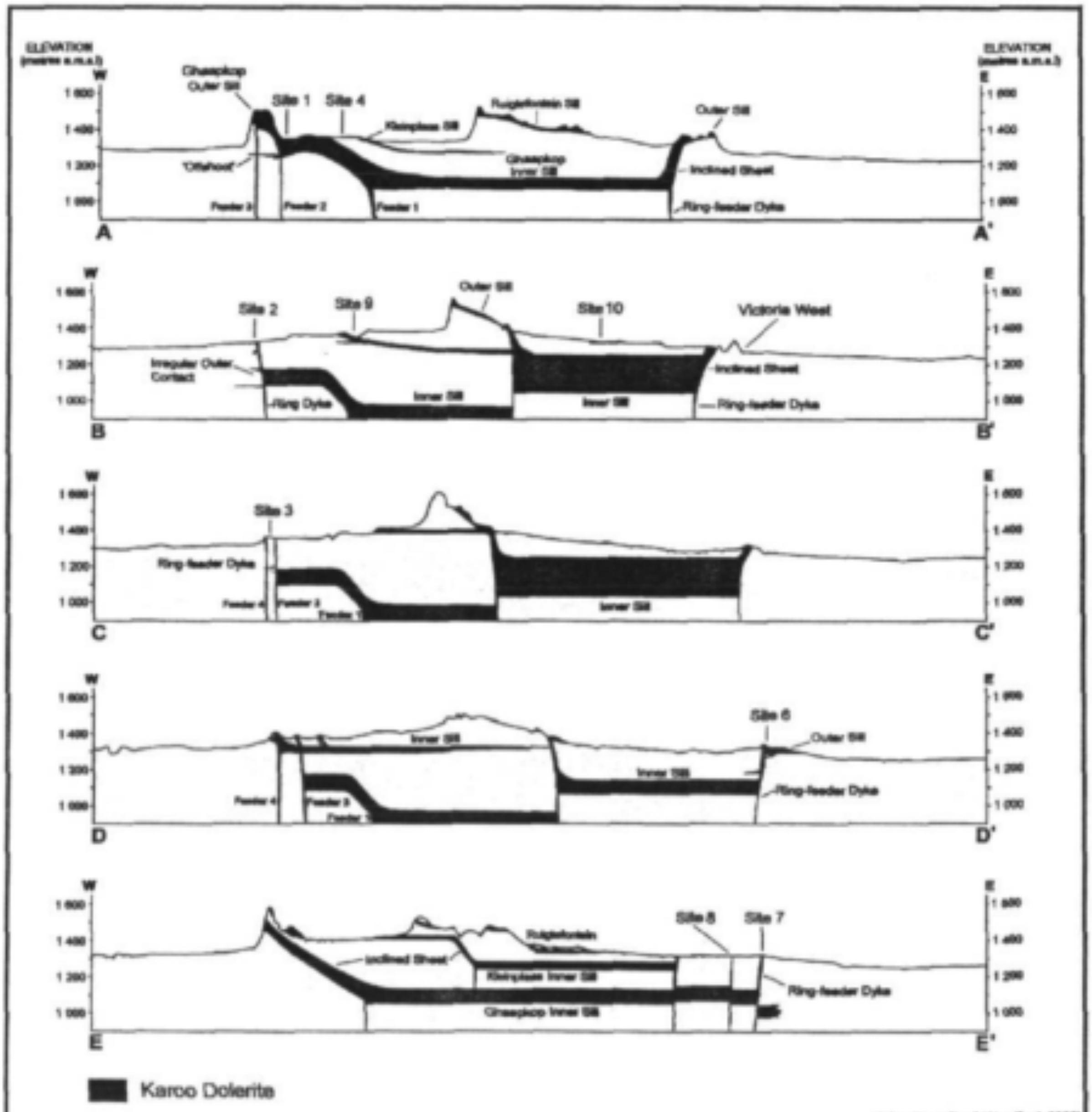



Figure 39: ***Dolerite sills and fracture pattern. Many dolerite dykes or dolerite related fractures feed into the ring-complexes. Also shown are the lines of the E-W cross-section of Figure 40 (b) On the side, is N-S cross-section over the study area showing the vertical stacking of the four ring units.***

A detailed analysis of the entire Victoria West area was not possible, so the study was further focussed onto the Northern unit across which five W-E sections were completed. These sections were complemented by field observations and exploration drilling logs. In the field, a large number of dolerite-host sediment contacts were mapped, dips were measured and relationship between dykes, sills and the rings were observed. The cross sections were adapted or revised after the results of the exploration drilling programme (**Figures 40**). Three sills characterize this northern structural unit: The Ghaapkop sill, the Kleinplaas sill and the Ruigtefontein sill.




<u>Figure 40</u>: ***Serial E-W cross-sections of the Victoria West sill and ring-complex. For location of the sections see Figure 39.***

Section No 1 (31°23') shows that the three sills are separate entities. The Ghaapkop sill is very asymmetrical displaying more tectonic complexity in the West where three dykes are shown feeding the ring. Feeder 1 is interpretative but related to the up-stepping in the sill. Feeder 2 can be seen along the Victoria West road (**Figure 13**). Feeder 3 can be seen at drilling site 3. The section is parallel to the Ruigtefontein ring and its outer sill, and can not therefore show the complexity of the structure. On the eastern side the ring is thinner and does not show structural complexity.

Section No 2 (31°24') shows that the Ruigtefontein inner sill is 200m thick. This observation was extracted from two exploration boreholes No 8 and 10. Such thick sills are uncommon in the Karoo Basin and can extend very far. However the Ruigtefontein sill is of limited lateral extent. We interpreted this sill as being fault bounded. Its relation with the lower Ghaapkop sill remains ambiguous. Feeder 2 of Ghaapkop sill is no longer present.

Sections No 3 (31°25') and No 4 (31°26') show dyke 4 feeding the Kleinplaas sill. The cross sections should be compared with the two above as well with **Figure 39** to see the link between the different feeder dykes and the Ghaapkop sill

Section No 5 (31°27') shows the asymmetry of the ring complex, i.e. thick and complex in the West, thin and simple in the East.

# 6 HYDROGEOLOGY OF THE LOCAL STUDY AREA

## 6.1 GENERAL HYDROLOGY AND WATER SUPPLY

The local study area is characterized by the virtual absence of perennial rivers. The drainage system of the area is controlled by the dolerite sills forming individual small 'closed' basins (**Figure 41**) and is only flowing following abnormally high seasonal rains, such as during February 2000. Sheetwash deposits cover the flat plains inside the rings. They are few meters thick and are composed of gritty colluvial material: unconsolidated mixture of dolerite and sediment grains. These deposits are too thin and sporadical (pod-like) to produce good or even average aquifers. The water for irrigation or livestock comes from shallow boreholes usually sited along lineaments (green bushes) or from earth dams.

Up until 1984, Victoria West derived its water from shallow production boreholes drilled in the sediments of the dam west of town as well as few other boreholes east of town. All the boreholes were sited along dolerite dykes. The water was intercepted between 14 and 60 m often some distance away from the dyke (5 to 10m). Borehole yields vary from 3 to 8 l/s. Alternative groundwater resources had to be acquired as the Victoria West aquifer unit, with a 'safe yield' of 860 $m^3$/day, was not capable of meeting the town's water requirements and due to the poor quality of the groundwater (445 mg/l to 780 mg/l) (Vandoolaeghe, 1984).

The Biesiesfontein aquifer unit at Hutchinson is located some 13 km SE of Victoria West and was used to supplement water storage from 1985. It is a shallow aquifer at the contact between superficial calcretised sediments and a shallow dipping dolerite sill. A spring or perennial seepage marks the overflow of this shallow aquifer. A minimum value of 2000 $m^3$/day was calculated on the basis of long abstraction record (Vandoolaeghe, 1984).

At present, the wellfield to the west and east of town only supplies approximately 20 to 30% of the town's water, whilst the remaining 70% to 80% is abstracted from boreholes at Hutchinson. During the period 1994 to 2000, the annual volumes of water abstracted from Victoria West and Hutchinson wellfields varied between 63400-79000 and 157000-255000 $m^3$/year, respectively. The water from the dam is not use for the town consumption but only for irrigation purposes.

## 6.2 SPATIAL ANALYSIS OF THE VICTORIA WEST HYDROCENSUS

The Directorate: Geohydrology of Department of Water Affairs and Forestry offered the research team the assistance of an experienced technician to conduct a detailed hydrocensus study of all water-points in the Victoria West area, covering the following topocadastral maps 3122BD, 3122DB, 3123AC and 3123AC. The western portion of the area was covered by an earlier hydrocensus for WRC project 653. Information contained on DWAF's National Groundwater Database was also incorporated into this study.


**Figure 41**: ***Map showing how the dolerite sill and ring complexes control the secondary drainage system of the Karoo Basin in the Victoria West area.***

A total of 1222 water-points were identified and compiled into a GIS database, of which 1156 boreholes were of an acceptable positional accuracy (±100m) for further spatial analysis. Only 603 boreholes in the database had yield information required for the productivity analysis. This database excluded the exploration drilling conducted during this project and thus represents the present the status of privately owned boreholes in the area of interest. The average borehole depth is 28m (N= 837), with a standard deviation of 18.2m. The median borehole drilling depth is 24.9m. A maximum borehole drilling depth of 171m was recorded. The private boreholes are normally drilled to the depth of the first major water interception, which is sufficient for erecting a windpump for stock-watering purposes.

The influence of proximity to drainage features, dolerite intrusions and terrain slope on nature and occurrence of groundwater in the local study area was investigated using a GIS.

**Influence of Terrain Slope**

The local study area was subdivided into four zones of equivalent terrain slope (**Figure 42**), namely:

1. Slopes of less than or equal to 1°, covers areas inside the rings, 70% of the study area is flat-lying,
2. Slopes of 1° to 3°, which covers the gently sloping areas in and along the edges of the valleys and hill slopes (approximately15% by area),
3. Slopes of 3° to 15°, which highlight the more topographically elevated portions of the study area and also clearly reflects the occurrence of the major dolerite sills and ring complexes (approximately 10% by area).
4. Slopes in excess of 15°, which only occur near the summits of the mountains (approximately 5% by area).

The terrain slope map (**Figure 42**) is therefore an indirect representation of the major geomorphological features of the local study area, which are in turn controlled to a large extent by the occurrence of dolerite sill and ring intrusions.

The effect of terrain slope on groundwater occurrence is illustrated in **Table 9**, where:

- The majority of the boreholes are drilled in the easily accessible, flat-lying areas.
- Borehole productivity or yield is the highest in the more flat-lying areas and decreases steadily as the steepness of the terrain increases.
- The average depth to the first water-bearing fracture, as reflected in the depth to the watertable and drilling depth, increases with increasing slope of the terrain (i.e. more topographically elevated areas).

The dolerite ring-systems are not commonly targeted by the farmers when drilling production boreholes. The analysis of such shallow borehole information does not therefore reflect the true potential of the structures, but reflects more the shallow-seated influences of terrain morphology, erosional unloading and weathering (i.e. the shallow 'weathered/jointed hardrock aquifer').

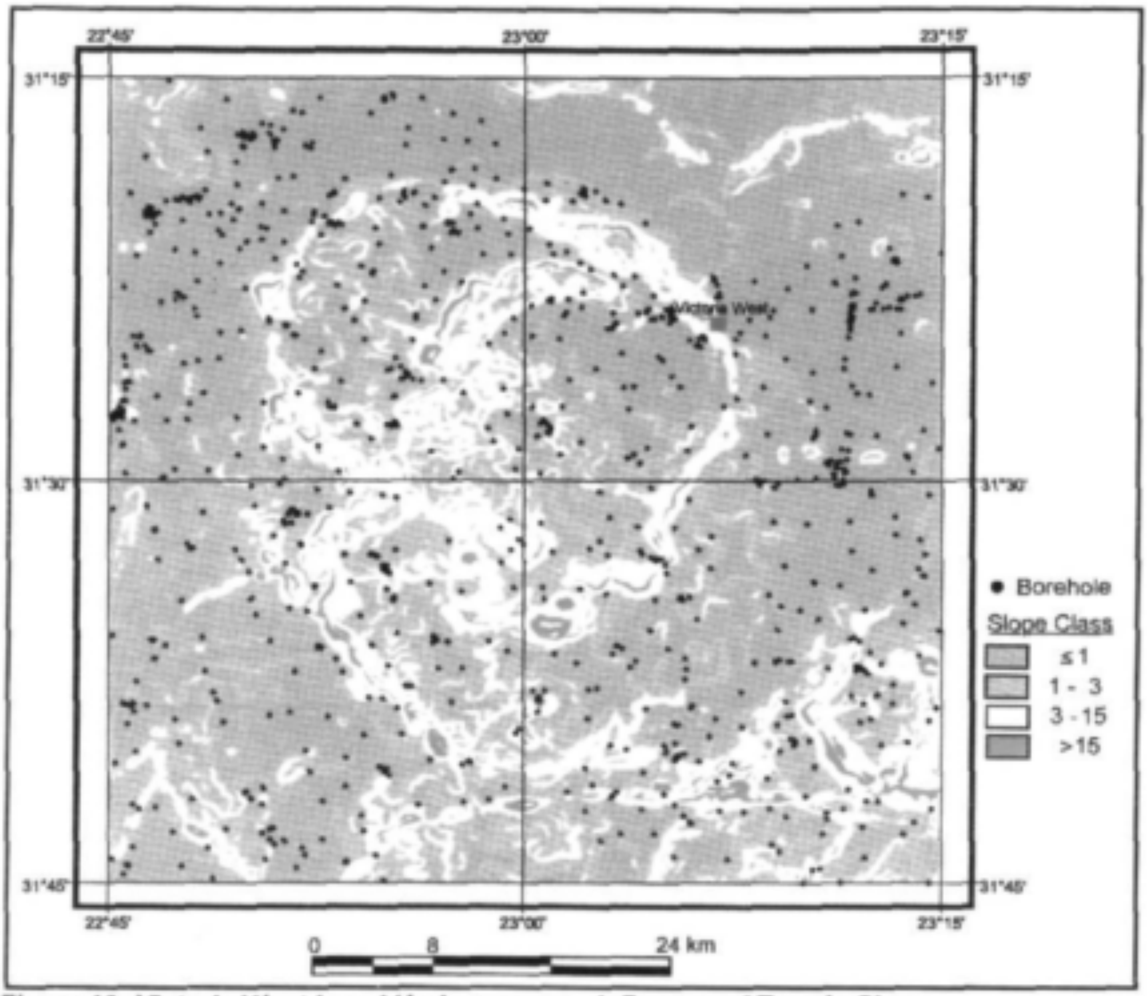



**Figure 42:** ***Victoria West Local Hydrocensus – Influence of Terrain Slope***

**Table 9:** ***Victoria West Local Hydrocensus – Influence of Terrain Slope***

| Statistics | TERRAIN SLOPE CLASS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Slope 0-1° | | | Slope 1-3° | | | Slope 3-15° | | |
| | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) | Yield (l/s) | Depth (m) | Water-level (m.bgl) |
| Number Bores | 753 | 479 | 588 | 318 | 243 | 249 | 84 | 67 | 62 |
| Mean | 3.10 | 26.80 | 7.97 | 2.32 | 29.2 | 10.90 | 1.79 | 32.5 | 11.05 |
| Median | 1.51 | 24.40 | 6.56 | 1.28 | 24.80 | 10.00 | 0.80 | 27.3 | 8.72 |
| Std Deviation | 4.01 | 16.04 | 4.56 | 2.83 | 20.8 | 7.21 | 2.37 | 24.3 | 8.42 |
| Maximum | 30.20 | 106.7 | 39.2 | 22.56 | 171.0 | 43.18 | 12.60 | 158.5 | 40.20 |
| Minimum | 0.02 | 0.2 | 1.35 | 0.04 | 0.2 | 0.23 | 0.05 | 0.2 | 0.20 |

**NOTE:**

- No boreholes were drilled in areas with slopes in excess of 15°
- Only 'wet' boreholes were considered in the yield analysis.

**Influence of Drainage System**

The influence of the proximity to an ephemeral drainage channel on borehole productivity was investigated by analyzing borehole yield variations within and away from 150m and 500m 'buffered' drainage systems, obtained from the 1/50 000 scale topocadastral maps (**Figure 43**). The results are presented in **Table 10**.

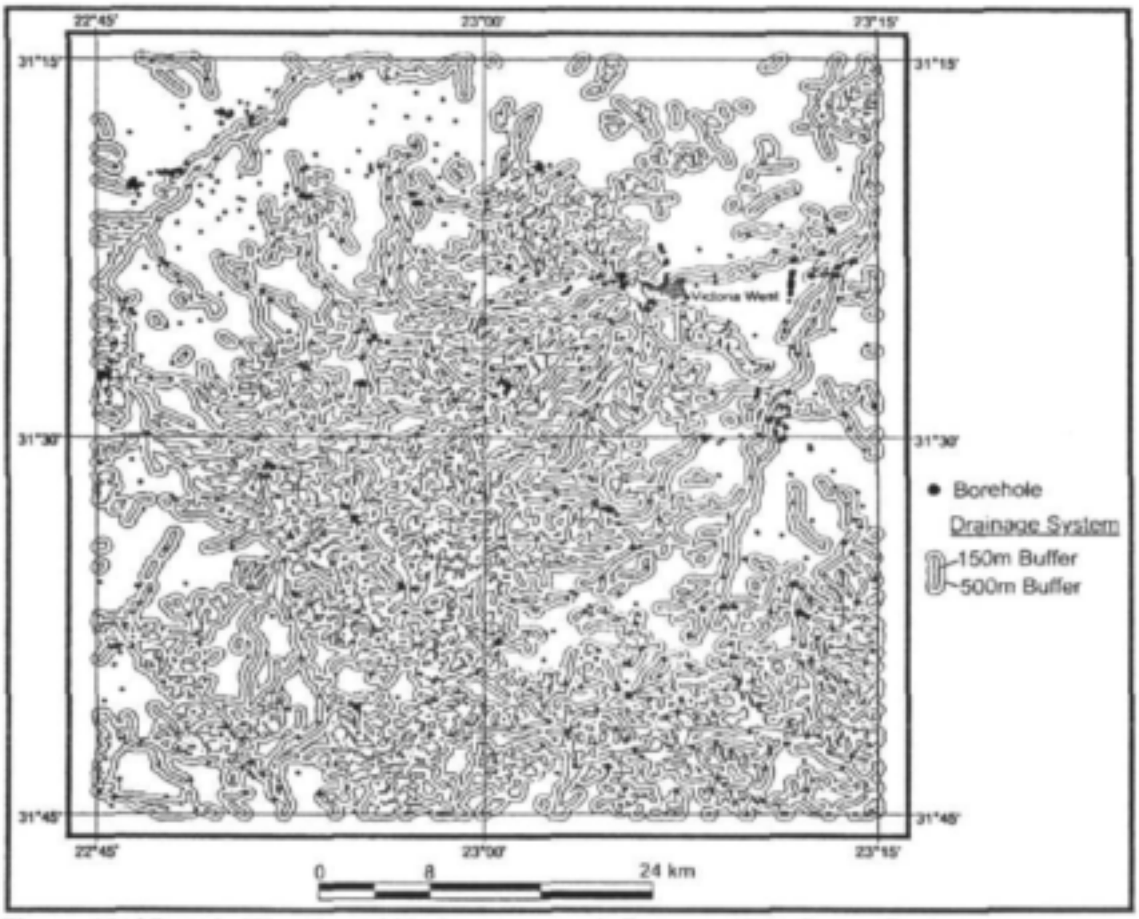



Figure 43: *Victoria West Local Hydrocensus – Influence of Drainage System*

Table 10: *Victoria West Local Hydrocensus – Influence of Drainage System*

| Yield Statistics (l/s) | DRAINAGE (Buffer 150m) | | DRAINAGE (Buffer 500m) | |
|---|---|---|---|---|
| | On | Off | On | Off |
| Total Bores | 245 | 358 | 451 | 202 |
| Mean Yield | 2.75 | 2.71 | 2.71 | 2.76 |
| Median Yield | 1.50 | 1.30 | 1.30 | 1.30 |
| Std Deviation | 3.77 | 3.41 | 3.71 | 3.08 |
| Maximum Yield | 30.00 | 30.20 | 30.15 | 17.70 |
| Minimum Yield | 0.05 | 0.02 | 0.05 | 0.02 |
| NOTE: Only 'wet' boreholes were considered in the analysis. | | | | |

Generally, borehole yields are slightly higher when drilled within 150m of a drainage channel. The effects of proximity to a drainage channel are not evident when a 500m wide 'zone of influence'. This indicates that the drainage systems does exert a small influence on borehole yields when they are located within 150m of the channel, probably related to the fact that most of the drainage system is controlled by geological structures, as well as the associated enhanced degree of weathering.

**Influence of Geological Lineaments**

The majority of privately drilled production boreholes are drilled alongside linear geological structures, particularly dolerite dykes. The influence of these features on borehole productivity was investigated by assessing the yield condition within or away from the 50m and 200m 'buffered' geological lineaments (LINCOMP) (**Figure 44**). The statistical results of this analysis are presented in **Table 11**.

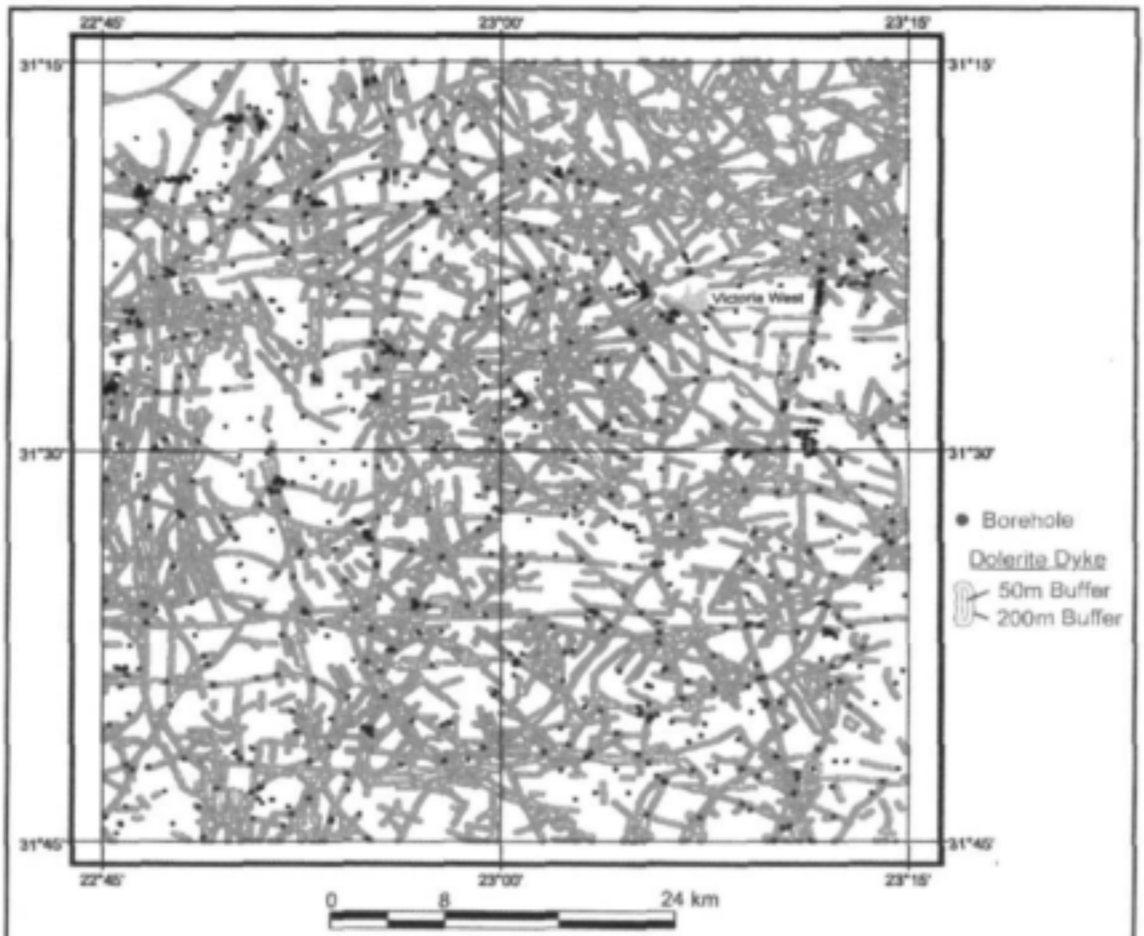



**Figure 44**: ***Victoria West Local Hydrocensus – Analysis of Borehole Proximity to Geological Lineaments***

The local farmers and diviners preference for drilling alongside geological lineaments is vindicated by the statistical results (**Table 11**). Both the 50m and 200m 'buffered' geological lineaments indicate that boreholes drilled into these linear structures are more productive than those drilled away from lineaments.

**Influence of Dolerite Sills**

The occurrence of groundwater in the proximity of dolerite sills was investigated by analyzing the yield of borehole drilled 'within' and away from dolerite sill. The dolerite sills were obtained from the Council for Geoscience's 1/50 000 scale geological field maps. The productivity of boreholes drilled directly into a dolerite sill, as well as those drilled within 250m of such intrusions was considered (**Figure 45**). A 250m buffer was used to incorporate borehole positional inaccuracies and the possible interception of a sill at shallow depth due to their flat-lying nature. The statistical results of the analysis are presented in **Table 11**.

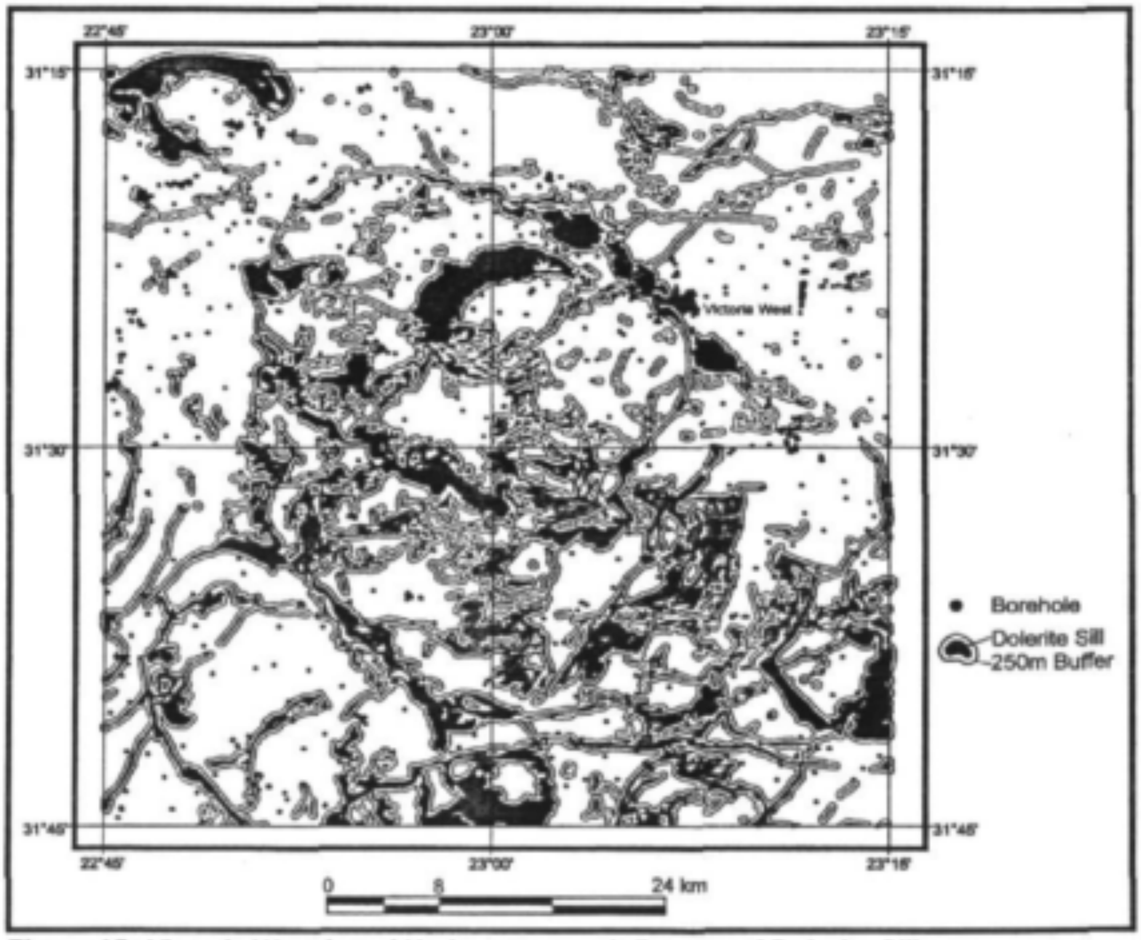



Figure 45: *Victoria West Local Hydrocensus – Influence of Dolerite Sills*

The occurrence of groundwater related to dolerite sills is not clearly apparent in **Table 11**, although only relatively few successful boreholes (34) have been drilled directly into dolerite sills. The effect of the relatively flat-lying sills on borehole productivity is more realistically illustrated in the '250m buffer' analysis, where the mean and median borehole yield is slightly higher when drilled in the proximity of a sill.

<u>**Table 11:**</u> ***Victoria West Local Hydrocensus – Effect of Dolerite Sills and Geological Lineaments***

| Yield Statistics (l/s) | SILL | | SILL (Buffer 250m) | | LINEAMENT (Buffer 50m) | | LINEAMENT (Buffer 200m) | |
|---|---|---|---|---|---|---|---|---|
| | On | Off | On | Off | On | Off | On | Off |
| Number Bores | 34 | 569 | 259 | 344 | 173 | 430 | 388 | 215 |
| Mean Yield | 2.28 | 2.75 | 2.78 | 2.68 | 3.30 | 2.49 | 3.06 | 2.12 |
| Median Yield | 1.55 | 1.30 | 1.50 | 1.29 | 1.80 | 1.30 | 1.56 | 1.20 |
| Std Deviation | 2.25 | 3.62 | 3.73 | 3.42 | 3.98 | 3.36 | 3.81 | 2.98 |
| Maximum Yield | 10.00 | 30.20 | 30.20 | 3.43 | 30.15 | 29.98 | 30.20 | 30.00 |
| Minimum Yield | 0.02 | 0.04 | 0.02 | 0.50 | 0.05 | 0.02 | 0.02 | 0.04 |
| NOTE: Only 'wet' boreholes were considered in the analysis. | | | | | | | | |

**Morpho-tectonic Components of Dolerite Ring-Complexes**

The groundwater occurrence associated with the various morpho-tectonic components of ring-complexes was assessed using borehole productivity. Each borehole in the database was classified by onscreen into one of the following settings; Linear Dyke, Ring Feeder Dyke, Inclined Sheet, Inner Sill, Outer Sill, Sediment overlying a Sill and Sediment (**Table 12**).

<u>**Table 12:**</u> ***Victoria West Local Hydrocensus – Influence of various morpho-tectonic components of Ring-Complexes***

| Yield Statistics (l/s) [N=603] | MORPHO-TECTONIC CLASS | | | | | | |
|---|---|---|---|---|---|---|---|
| | Linear Dyke | Feeder Dyke | Inclined Sheet | Inner Sill | Outer Sill | Sediment above Sill | Sediment |
| Number Bores | 245 | 56 | 77 | 4 | 15 | 101 | 105 |
| % of Total | 41 | 9 | 13 | 1 | 3 | 16 | 17 |
| Mean Yield | 2.80 | 3.44 | 2.01 | 1.93 | 2.26 | 3.39 | 2.16 |
| Median Yield | 1.25 | 2.15 | 1.25 | 1.59 | 0.88 | 1.90 | 1.30 |
| Std Deviation | 3.56 | 3.50 | 2.34 | 1.15 | 2.94 | 5.17 | 2.17 |
| Maximum Yield | 25.00 | 15.90 | 12.00 | 3.56 | 10.00 | 30.15 | 12.60 |
| Minimum Yield | 0.05 | 0.10 | 0.02 | 0.97 | 0.15 | 0.05 | 0.04 |
| NOTE: Only 'wet' boreholes were considered in the analysis. | | | | | | | |

Analysis of the borehole yield statistics per category shows that:

- The mean (2.2 l/s) and median (1.3 l/s) yields of successful boreholes in the 'sediment' category are considered to represent the ambient groundwater conditions in the undisturbed Beaufort country rock.

- Very few successful boreholes have been drilled into the Inner and Outer dolerite sills, although the mean and median yield of those boreholes penetrating these structures is low.
- The majority (41%) of the boreholes, as mentioned earlier, have been drilled into or alongside geological lineaments (dolerite dykes).
- The highest mean (3.4 l/s) and median (2.2 l/s) borehole yields occur on dolerite ring-feeder dykes, although only 56 (9%) are in this morpho-tectonic class.
- The second most productive category (sediment above the sill) of boreholes, where it is evident that the borehole penetrated a zone of baked sediment directly overlying a dolerite sill, also indicates a relatively high mean (3.4 l/s) and median (1.9 l/s) borehole yield. The borehole yields in this category are somewhat variable, with a relative high standard deviation of 5.2.
- Boreholes drilled into inclined sheets are relatively low yielding. This somewhat unexpected result is probably a reflection of the difficulties encountered by farmers in correctly siting boreholes on these features.

# 7 EXPLORATION DRILLING

## 7.1 PREVIOUS EXPLORATION DRILLING ON SILLS AND RING-COMPLEXES

### Philippolis Study

The Philippolis dolerite sill and ring system (Colesberg 1:250 000 geological sheet, Orange Free State) was investigated by Burger et al. (1981) and Botha et al. (1998). Different parts of the ring-dyke and sill system were targeted for exploration drilling (**Figure 46**).

The exploration drilling concentrated mostly upon the shallow weathered sections of the inclined sheet at Site A of the Philippolis complex. A total of sixteen boreholes were drilled to depths of between 25 and 70m (**Figure 47**). The dolerite inclined sheet is some 50m thick and is negatively weathered.

The geohydrological information obtained from the drilling programme is presented in **Figure 48**. The inclined sheet is highly decomposed to a depth of 13.5 m and weathered to a depth of 15m. Numerous water strikes were encountered between 20 and 40m below surface. The highest water yields were intercepted along the outer contact of the structure and in the sediments away from the inner contact of the ring. No deep boreholes were drilled to test for fracturing within or below the dolerite sheet. The drilling does not exclude the possibility of a feeder dyke extending below inclined-sheet. Similar water-strike depths below surface were encountered at the Campus Test Site, University of the Orange Free State, and at Dewetsdorp (Botha et al., 1998), both of which are also underlain by the Adelaide Formation (mudrock and subordinate sandstone). It would thus seem that this zone of frequent water interceptions is more related to the characteristic depth of weathering / erosional unloading of the Adelaide Formation in this part of the Karoo Basin, than the actual type of dolerite intrusion.

Other boreholes penetrating the Philippolis inclined dolerite sheet are 12, 13 and 14 (**Figure 47**). The drillstem blow-yields of boreholes 12 and 13 were considerably lower than the 4.4 l/s reported by Burger et al., (1981). Borehole 14 yielded 11.9 l/s, with the highest water interceptions occurring at 43, 45 and 50m below surface. The drilling of boreholes 12 and 13 into the sheet had no influence on the waterlevels in boreholes 1, 5 and 9. However, the waterlevels in all three boreholes (1, 5 and 9) immediately *responded when the first water was struck at a depth of 37m below the sheet in borehole* 14. One can thus conclude that the sheet is solid and highly impermeable, and that fractures in the baked contact zone can extend for considerable distances (1km) along strike.

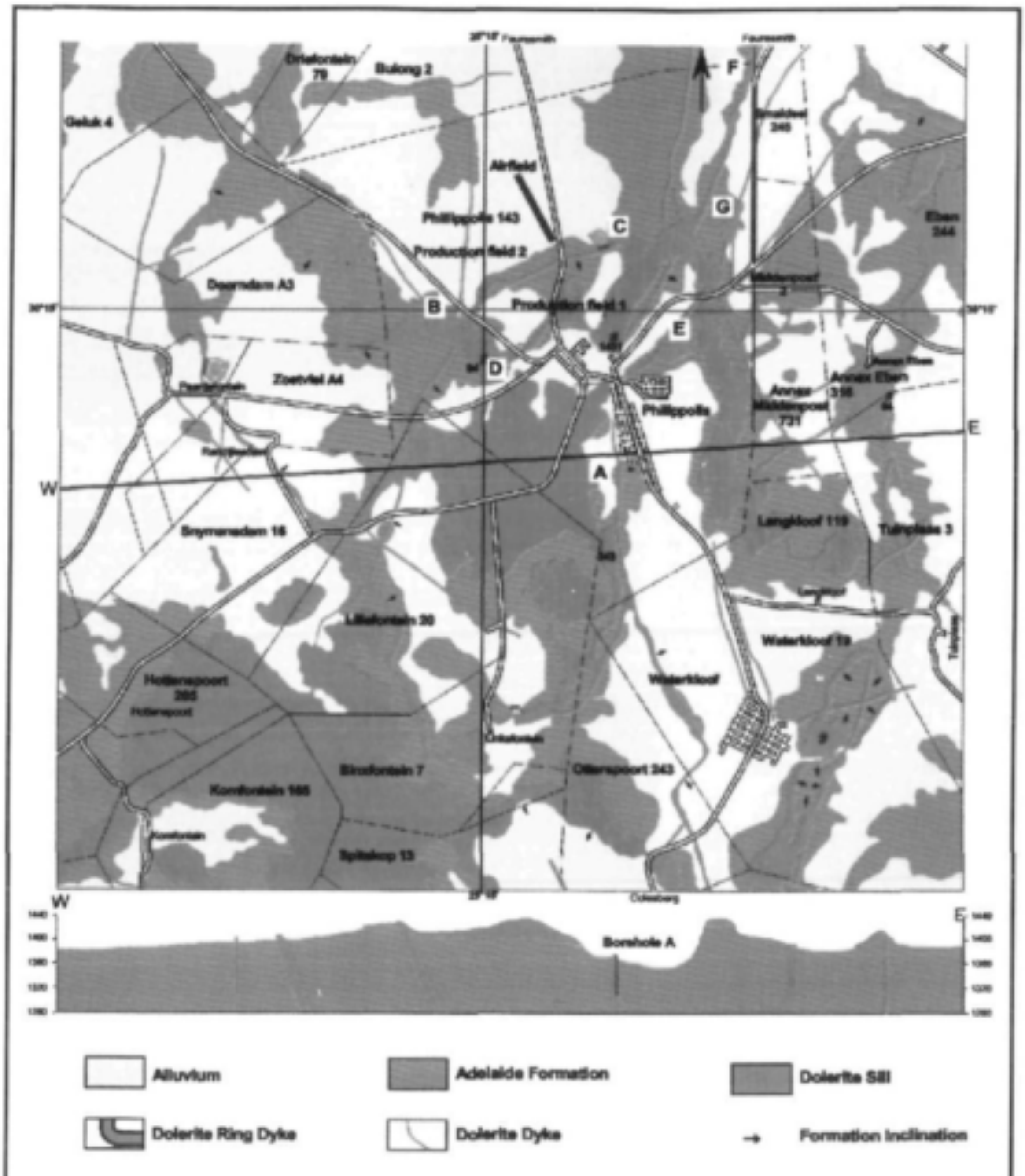



**Figure 46**: ***Geological map and cross-section of the Philippolis Area, Free State (after Burger et al., 1981)***

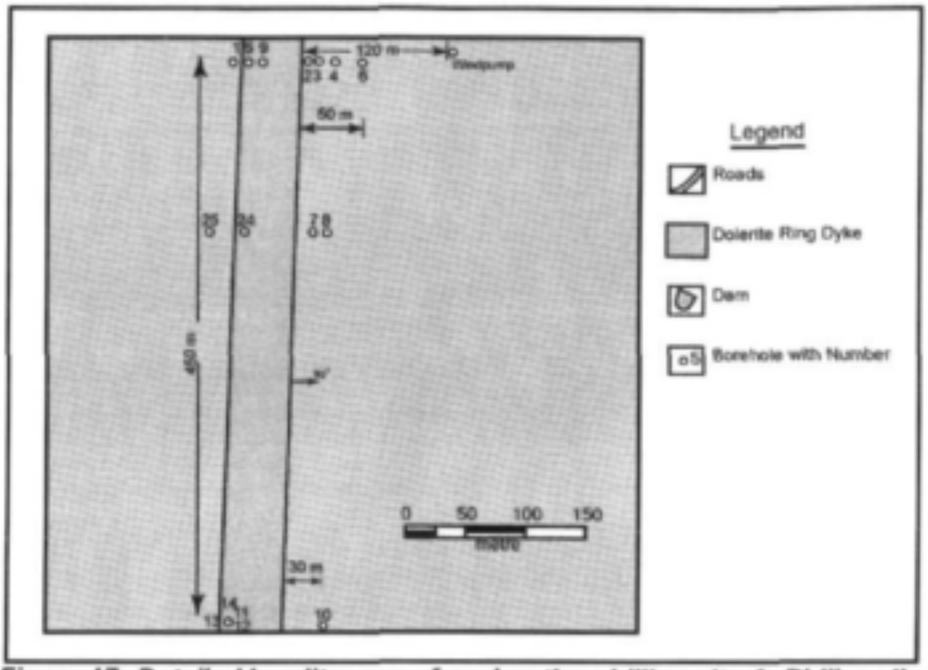



**Figure 47**: ***Detailed locality map of exploration drilling site A, Philippolis (after Botha et al., 1998)***

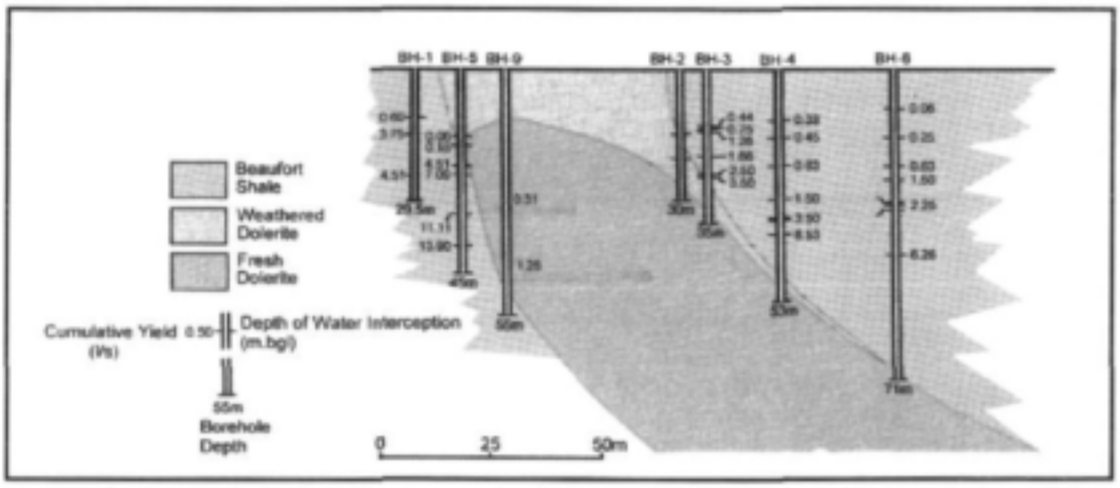



**Figure 48**: ***Geohydrological cross-section through the Philippolis inclined-sheet (after Botha et al., 1998)***

### Williston Study

A large number of boreholes have been drilled into the Williston ring-complex (**Figure 49**). The boreholes penetrated the inner- and outer-sill, but missed the inclined-sheet. A second deeper, 100m thick sill was also encountered in the northern portion of the ring system. Large differences in yield are observed between the inner-sill (low yield along the upper- and lower-contacts, as well as within the sill) and the outer sill (high yields constrained between the upper and the lower sill contacts).

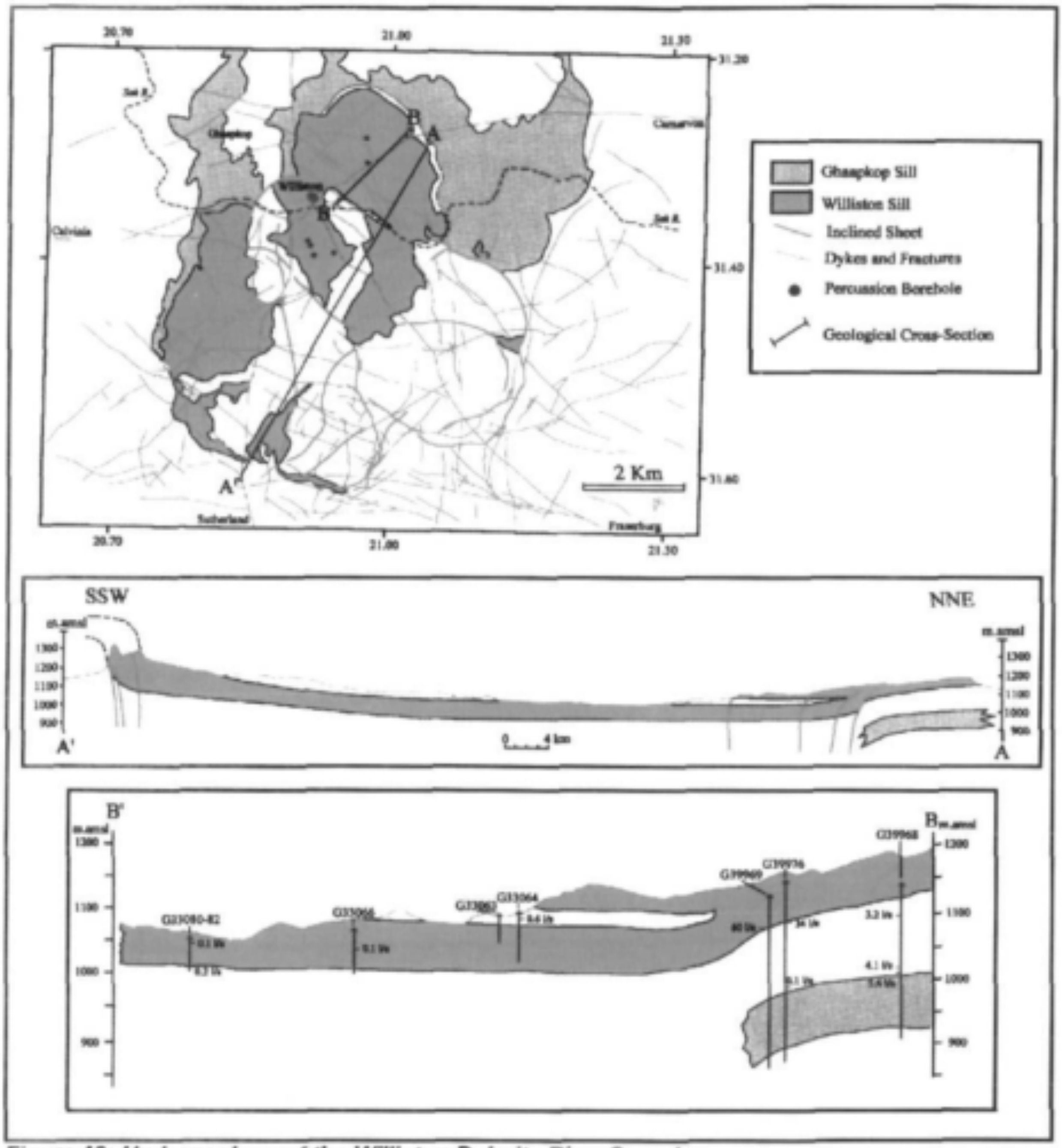



**Figure 49**: ***Hydrogeology of the Williston Dolerite Ring-Complex***

## Vanwyksvlei Study

An inclined sheet on the farm Smouskolk, 18km south of Vanwyksvlei, is controlled by dyking and regional tectonics (**Figure 50**). Several high-yielding boreholes were drilled into this structure (Woodford, 1992). The two boreholes drilled in the inner-sill gave poor results, whereas the six boreholes in the inclined sheets showed a higher number of individual water-strikes and relatively higher yields. Two of these boreholes, the highest yielding freshwater resources in the area, have since been commissioned to supply Vanwyksvlei with water.

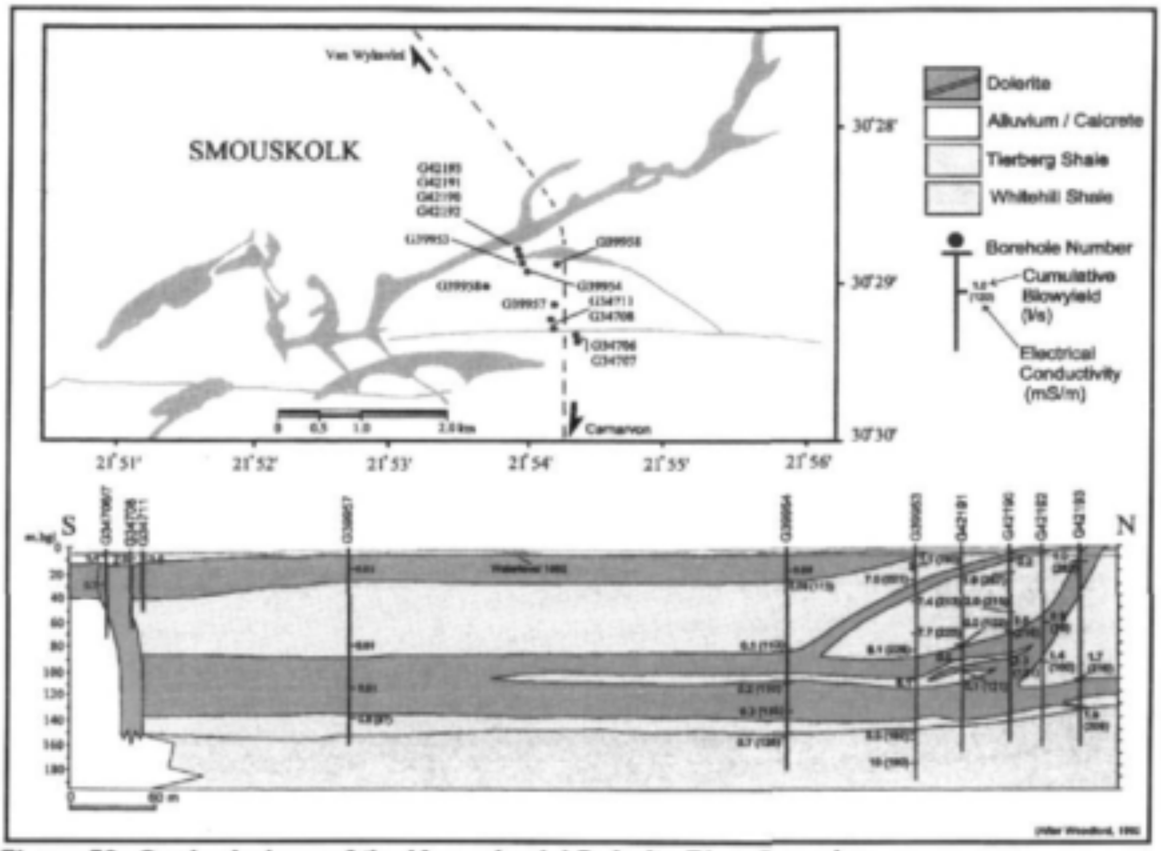



**Figure 50**: ***Geohydrology of the Vanwyksvlei Dolerite Ring-Complex***

### Calvinia Study

The Calvinia area is characterised by a succession of extensive, flat-lying sills. Directly north of Calvinia, the Kareedam sill shows a step-up and this change in the stratigraphic level is accompanied by a thinning out of the structure (**Figure 51**). A number of the boreholes are drilled into the lower contact of the structure and delivered moderate blow-out yields (Seward, 1983). Most of the boreholes were not drilled deep enough to test the upper-contact of an extensive, thick underlying sill. Borehole CT59 yielded 5.6 l/s on this contact, while G32626 and G32635 yielded variable results. This illustrates the point that has been made by many authors (Van Wyk, 1963), that high-yields are occasionally intercepted at certain localities on sills - both in the upper- and lower contact, and especially near the sill edge. The authors state that the action of weathering played a major role in locally enhancing the permeability of incipient joints.

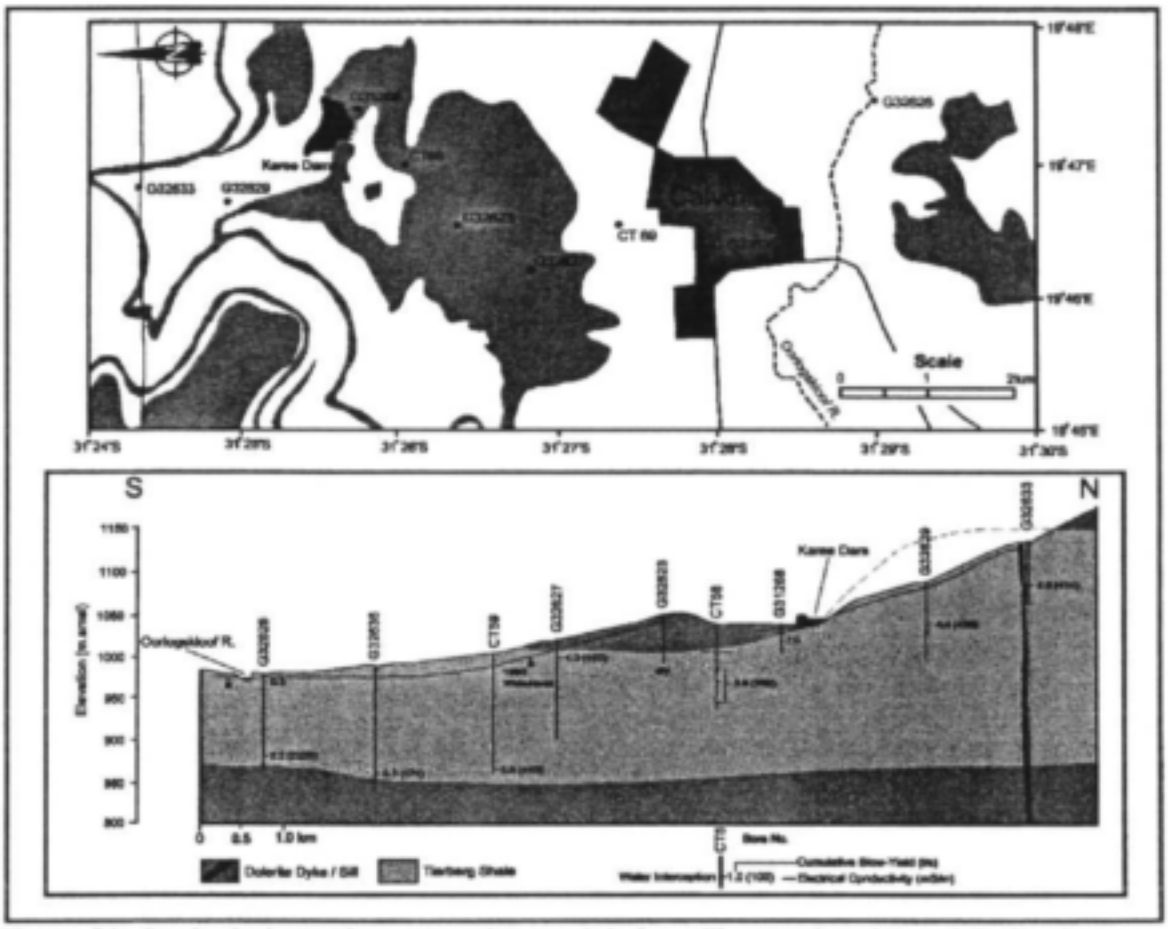



Figure 51: ***Geohydrology of an extensive, undulating sill, not related to a dolerite ring-complex, Calvinia***

**Queenstown Study**

The Hopefield boreholes (Vandoolaeghe, 1980a,b), west of Queenstown, were drilled into the transition zone between an inclined-sheet and the outer-sill of a ring-complex (**Figure 52**). The regular depth and yield of individual water-strikes suggest the presence of three sub-horizontal fractures that transgress the structure and extend into the host sediment. High borehole yields were struck within the dolerite in this transition zone, as well as in the often highly-fractured hinge zone between the outer-sill and the inclined-sheet at the base of the dolerite body.

**Other Studies**

Similarly high yields were intercepted in the upper- and lower-contacts of the Dalham outer-sill and its intersection with an inclined-sheet, north of Graaff-Reinet (**Figure 53**), (Woodford, 1984). Vandoolaeghe (1979) obtained high-yields at the lower-contact of an inclined-sheet that forms part of the Matjieskloof ring-complex, near Middelburg (**Figure 54**). The influence of weathering on fracturing in the near surface zone is clearly evident, although no boreholes penetrated the potentially fractured lower-contact of the sheet.

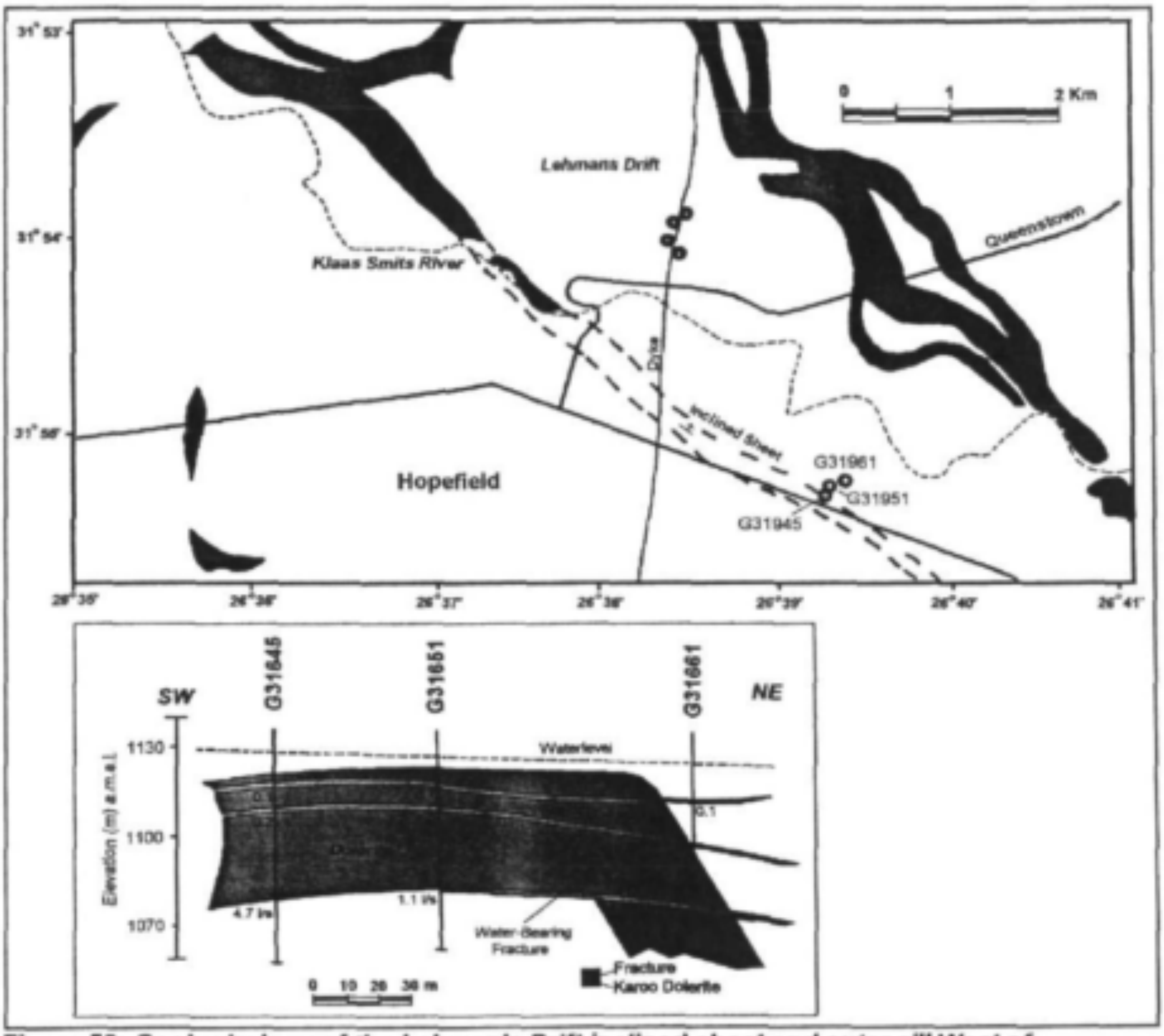



**Figure 52**: ***Geohydrology of the Lehman's Drift inclined sheet and outer sill West of Queenstown (after Vandoolaeghe, 1980).***

The inner-sill / inclined-sheet intersection zone of the Roodekraal and Caroluspoort ring-complex, south-east of De Aar (**Figure 55** and **56**), contains high-yielding open fractures (Woodford, unpublished data). High yielding fractures also occur at the lower contact of the Caroluspoort inner sill. Note the groundwater salinity (EC's) contrast between the water in the upper weathered dolerite and the lower fractures of the sill, indicating a poor hydraulic connectivity between the two systems. The shallow groundwater in the alluvium has a high salinity (EC > 200 mS/m), which is a result of salt accumulation in this zone due to the high rates of evapotranspiration (> 1500mm per annum).

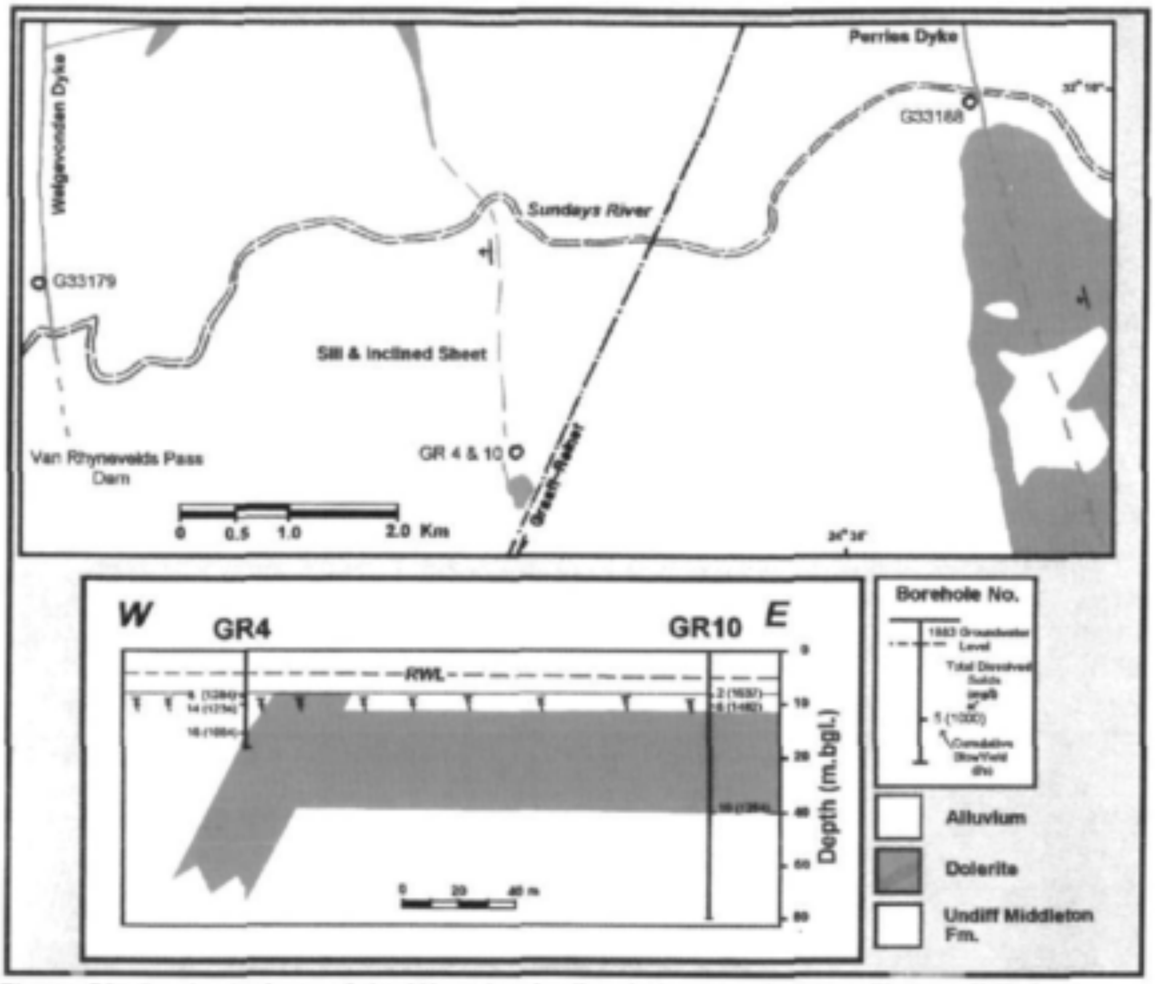



Figure 53: *Geohydrology of the Waterloo inclined sheet and outer sill, Graaff-Reinet (Woodford, 1984)*

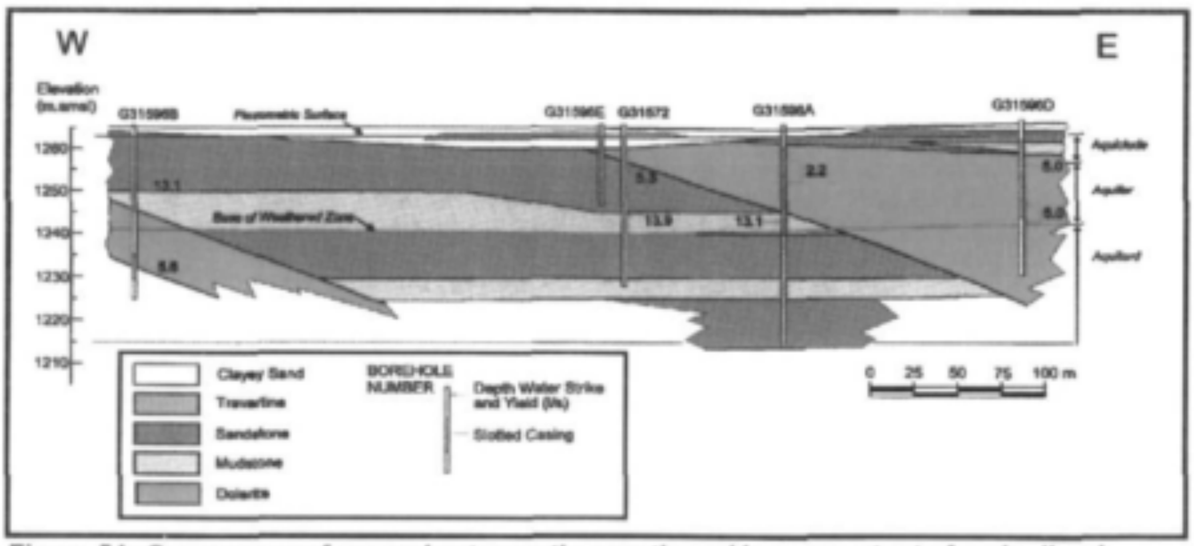



Figure 54: *Occurrence of groundwater on the weathered lower-contact of an inclined-sheet, Middelburg (Vandoolaeghe, 1979)*

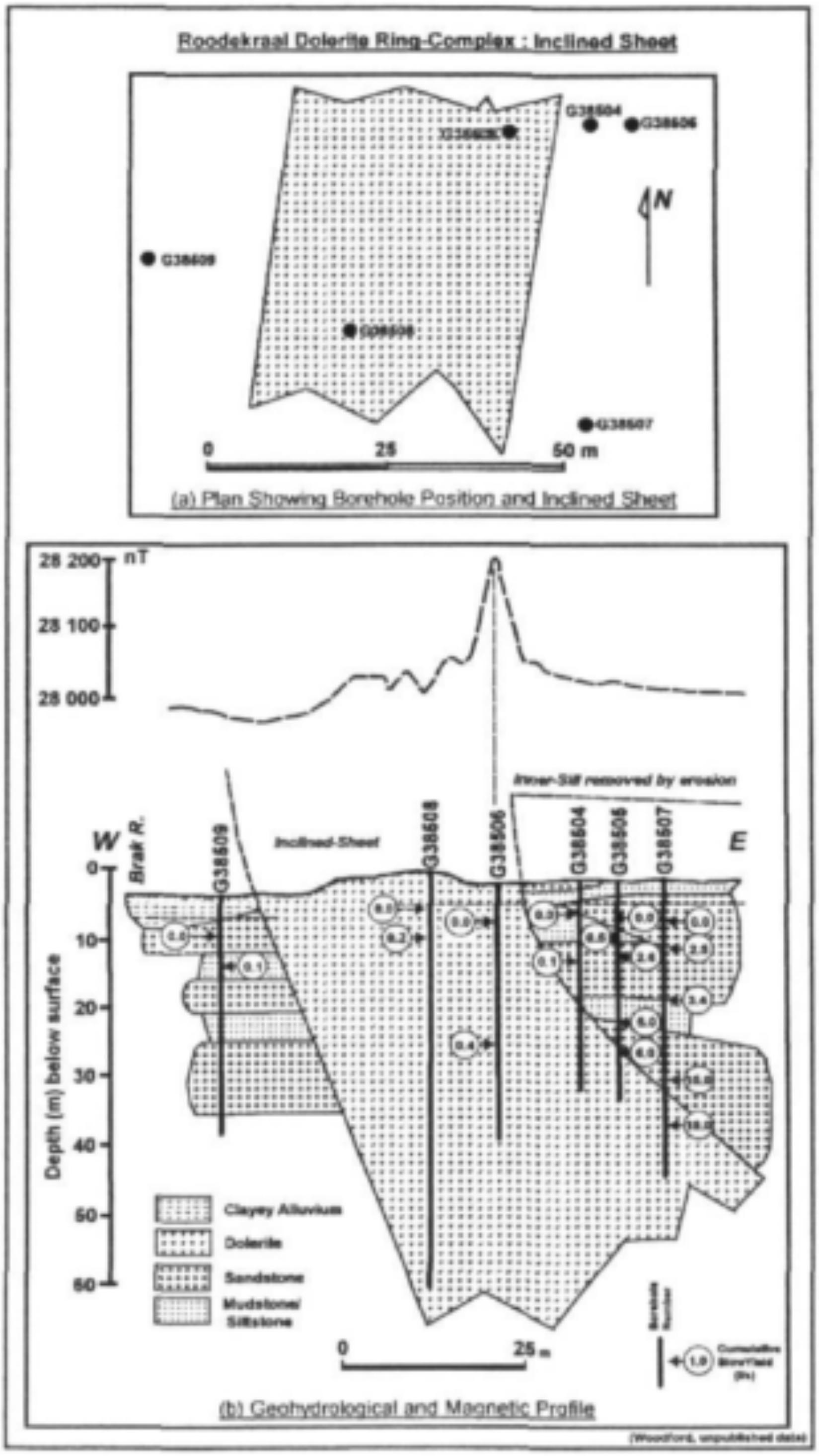



**Figure 55: *Geohydrology of the Roodekraal inclined sheet, De Aar (Woodford, 1989).***

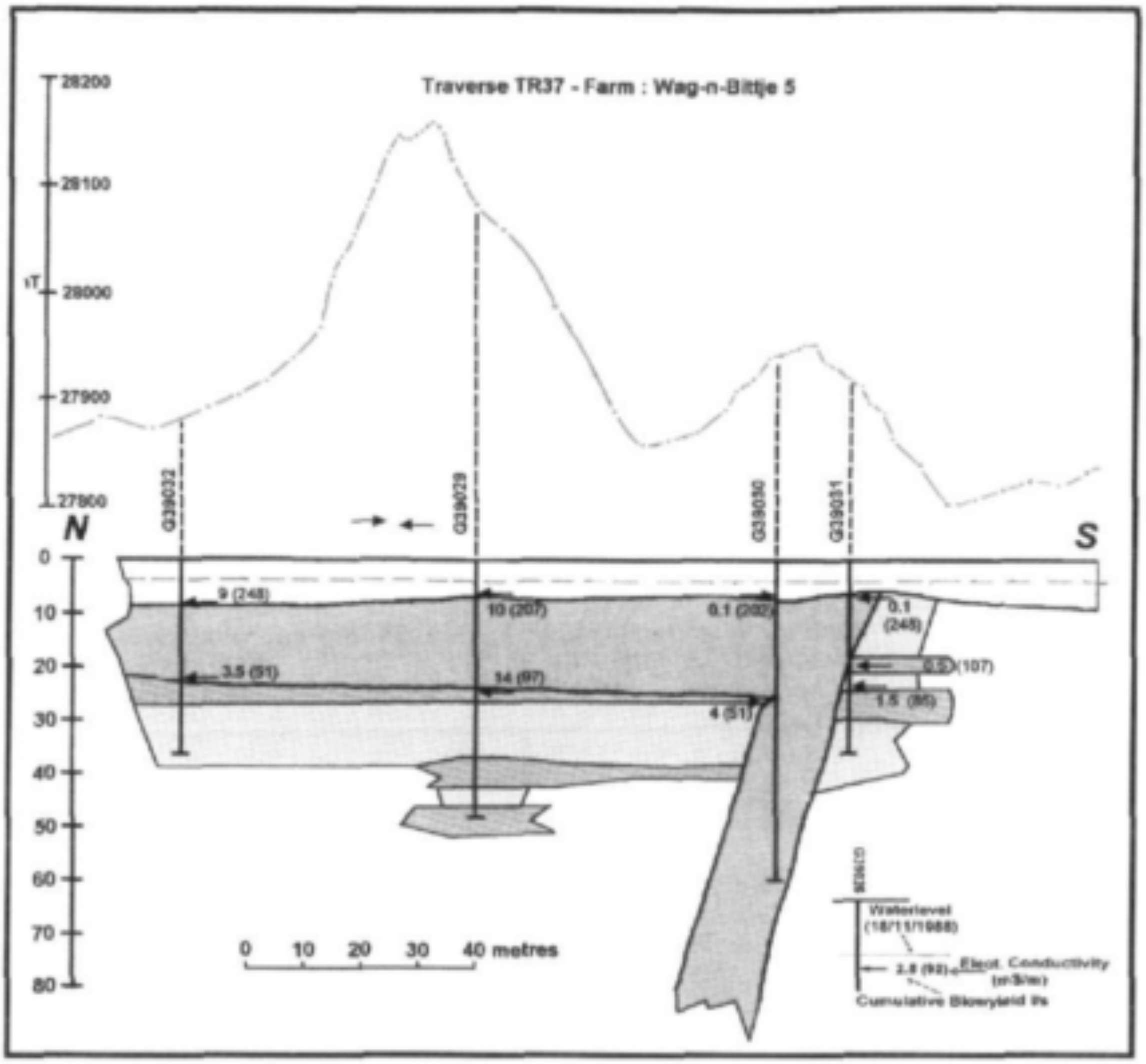



Figure 56: ***Geohydrology of the Caroluspoort feeder-dyke and inner-sill, De Aar (Woodford, 1989).***

## 7.2 EXPLORATION DRILLING IN THE VICTORIA WEST AREA

The Directorate of Geohydrology (DWAF) kindly offered to drill exploration boreholes in the Victoria West district as part of the local-scale dolerite ring-complex study. The drilling commenced in June 1998 and was completed in April 2000. A total of 67 boreholes (total drilling depth 13 799m) were drilled at 10 exploration sites located on the Victoria West ring-complex.

The structural targets in the Victoria West ring-complex were relatively easily accessible with the drilling-rig, although at places short sections of "road" had to be constructed and the drill site leveled. The ease of access to this ring-complex was one of the criteria used to select it for detailed investigation.

The locations of the exploration drill-sites are indicated on the **Figure 57**, while the relevant technical and geohydrological results are summarized in **Table 13**. The detailed drilling and hydrogeological logs of the exploration boreholes are archived at Directorate: Department of Water Affairs and Forestry, Bellville.


***<u>Figure 57</u>: Exploration Drill Sites on the Victoria West Dolerite Sill and Ring Complex***

**Table 13:** ***Summary of the Exploration Borehole Information***

| Number Borehole | Drilling Number | Drill Site Number | Depth (m.bgl) | Rest-Waterlevel (m.bgl) | Date Measured | Final Blow-Yield (l/s) | Final Elect. Cond. (mS/m) |
|---|---|---|---|---|---|---|---|
| G40021 | W5488 | 1 | 252 | 26.925 | 3/21/2000 | 0.8 | 239.0 |
| G40022 | W5489 | 1 | 252 | 28.200 | 3/21/2000 | 0.0 | 137.0 |
| G40064 | W5490 | 1 | 252 | 30.435 | 3/21/2000 | 0.2 | 39.3 |
| G40065 | W5491 | 1 | 150 | 30.890 | 3/21/2000 | 0.0 | - |
| G40066 | W5492 | 1 | 128 | 2.605 | 3/21/2000 | 0.0 | - |
| G46007 | W6983 | 1 | 106 | - | - | 0.0 | - |
| G46007A | W6984 | 1 | 260 | 15.015 | 3/21/2000 | 0.0 | - |
| G40067 | W5493 | 2 | 150 | 3.624 | 3/21/2000 | 20.6 | 93.0 |
| G40068 | W5494 | 2 | 120 | 3.660 | 3/21/00 | 15.1 | 112.2 |
| G40069 | W5495 | 2 | 108 | 3.405 | 3/21/00 | 24.1 | 93.0 |
| G40070 | W5496 | 2 | 108 | 3.400 | 3/21/00 | 24.1 | 93.0 |
| G40071 | W5497 | 2 | 256 | 3.830 | 3/21/00 | 3.0 | 81.0 |
| G40072 | W5498 | 2 | 298 | 2.830 | 3/21/00 | 2.7 | 72.5 |
| G40079 | W6957 | 2 | 260 | 4.955 | 1/2/99 | 15.3 | 73.0 |
| G40191 | W6963 | 2 | 260 | 4.955 | 1/2/99 | 16.0 | 69.6 |
| G46008A | W6987 | 2 | 260 | 4.175 | 21/03/2000 | 8.5 | 66.3 |
| G46008 | W6985 | 2 | 222 | 5.21 | 20/11/1999 | 1.8 | 68.5 |
| G46009 | W6986 | 2 | 280 | 7.44 | 21/03/2000 | 3.4 | 70.2 |
| G40073 | W5499 | 3 | 298 | 27.015 | 3/21/00 | 0.5 | 85.2 |
| G40074 | W5500 | 3 | 252 | 27.750 | 3/21/00 | 0.5 | 85.0 |
| G40075 | W6952 | 3 | 204 | 28.735 | 3/21/00 | 0.6 | 62.6 |
| G40076 | W6953 | 3 | 240 | 29.320 | 3/21/00 | 0.8 | 62.6 |
| G40077 | W6954 | 3 | 91 | - | - | 0.0 | 47.0 |
| G40077A | W6955 | 3 | 252 | 20.430 | 3/21/00 | 0.8 | 61.0 |
| G40078 | W6956 | 3 | 252 | 13.850 | 3/21/00 | 5.0 | 62.0 |
| G40080 | W6958 | 4 | 114 | 4.600 | 3/21/00 | 14.2 | 59.0 |
| G40081 | W6959 | 4 | 218 | 5.345 | 3/21/00 | 15.3 | 53.7 |
| G40082 | W6960 | 4 | 67 | 4.700 | 3/21/00 | 86.5 | 58.0 |
| G40083 | W6961 | 4 | 76 | 6.515 | 3/21/00 | 58.9 | 60.0 |
| G40190 | W6962 | 4 | 100 | 3.210 | 3/21/00 | 69.1 | 62.0 |
| G46011 | W6980 | 4 | 78 | 0.000 | 21/03/2000 | 51.4 | 59.0 |
| G46012 | W6981 | 4 | 294 | 5.120 | 21/03/2000 | 6.9 | 63.5 |
| G46013 | W6982 | 4 | 280 | 4.820 | 21/03/2000 | 4.0 | 71.4 |
| G40186 | W6507 | 5 | 199 | 22.360 | 3/21/00 | 2.4 | 44.7 |
| G40187 | W6508 | 5 | 151 | 29.590 | 3/21/00 | 0.9 | 41.3 |
| G40188 | W6509 | 5 | 103 | 24.900 | 3/21/00 | 0.8 | 36.8 |
| G40189 | W6510 | 5 | 100 | 24.235 | 3/21/00 | 0.7 | 41.0 |
| G46001 | W6511 | 5 | 150 | 23.860 | 3/21/00 | 0.5 | 36.2 |
| G46002 | W6512 | 5 | 120 | 24.760 | 3/21/00 | 0.8 | 33.8 |
| G46003 | W6513 | 5 | 151 | 17.015 | 3/21/00 | 28 | 39.2 |
| G46004 | W6514 | 5 | 151 | 18.700 | 3/21/00 | 20.5 | 38.8 |
| G46005A | W6515 | 5 | 151 | 15.115 | 3/21/00 | 33.7 | 40.1 |
| G46006 | W6516 | 5 | 258 | 10.505 | 3/21/00 | 3.4 | 31.0 |
| G40192 | W6964 | 6 | 250 | 41.965 | 3/22/00 | 1.3 | 36.2 |
| G40193 | W6965 | 6 | 250 | 42.280 | 3/22/00 | 0.6 | 43.8 |
| G40194 | W6966 | 6 | 250 | - | - | dry | - |
| G40195 | W6967 | 6 | 252 | 40.980 | 3/22/00 | 5.1 | 36.0 |
| G40196 | W6968 | 6 | 150 | 39.415 | 3/22/00 | 6.9 | 50.7 |
| G40197 | W6969 | 6 | 174 | 37.370 | 3/22/00 | 5.6 | 47.3 |
| G40198 | W6970 | 6 | 174 | 36.500 | 3/22/00 | 1.7 | 37.6 |
| G46015 | W6990 | 6 | 298 | 32.140 | 3/22/00 | 0.1 | - |

Table 13: ***continued***

| Number Borehole | Drilling Number | Drill Site Number | Depth (m.bgl) | Rest-Waterlevel (m.bgl) | Date Measured | Final Blow-Yield (l/s) | Final Elect. Cond. (mS/m) |
|---|---|---|---|---|---|---|---|
| G40199 | W6971 | 7 | 252 | 14.480 | 3/22/00 | 5.6 | 30.4 |
| G40200 | W6972 | 7 | 252 | 13.350 | 3/22/00 | 2.1 | 30.2 |
| G40201 | W6973 | 7 | 252 | 13.160 | 3/22/00 | 2.0 | 68.2 |
| G40202 | W6974 | 7 | 264 | 12.880 | 3/22/00 | 1.4 | 70.5 |
| G40203 | W6975 | 7 | 280 | 13.065 | 3/22/00 | 0.8 | 78.4 |
| G40204 | W6976 | 7 | 252 | 14.075 | 3/22/00 | 0.8 | 55.7 |
| G40205 | W6977 | 7 | 190 | 12.750 | 7/20/99 | 19.5 | 40.0 |
| G40205A | W6988 | 7 | 260 | 15.070 | 3/20/00 | 1.3 | 52.3 |
| G40206 | W6978 | 7 | 225 | 14.735 | 3/22/00 | 0.0 | 0.0 |
| G46010 | W6979 | 7 | 290 | 13.135 | 3/22/00 | 2.0 | 81.5 |
| G46014 | W6989 | 7 | 298 | 14.835 | 3/20/00 | 4.9 | 53.1 |
| G46016 | W6991 | 8 | 160 | 5.070 | 3/20/00 | 37.0 | 75.7 |
| G46017 | W6992 | 8 | 126 | 5.275 | 3/20/00 | 22.9 | - |
| G46018 | W6993 | 8 | 290 | 8.615 | 3/20/00 | 1.3 | 77.7 |
| G46019 | W6974 | 9 | 240 | 5.000 | 3/4/00 | 4.4 | 102.6 |
| G46020 | W6995 | 10 | 298 | - | - | 5.2 | 48.2 |
| | Total | | 13799 | | | | |

Locality of individual boreholes at each site are schematically illustrated in **Figure 58** while geohydrological cross-sections at each of the 10 drill-sites are presented in **Figures 59** to **68**, while the main objectives of the drilling programme was to determine the subsurface geometry of and to evaluate the water-bearing potential of the various structural components of the dolerite ring-complex, as outlined in the morpho-tectonic Model I of **Figure 23**.

The drilling results are in line with what one has come to expect from groundwater exploration in Karoo fractured-rock aquifers, where dry boreholes and high-yielding borehole are drilled within relatively short distances of one another. Borehole blow-test yields varied form 0.001 to 86.5 l/s. The drilling results have indicated that:

- The inclined sheet or feeder dyke was targeted in at least four of the 6 drill sites, namely Sites 2 – **Figure 60**, 3 – **Figure 61**, 6 – **Figure 64** and 7 – **Figure 65**). Site 1 required an additional borehole to ascertain if the ring-feeder dyke is actually present or not. The outer contact of the feeder dyke often exhibits an irregular contact with the sediment host rock and offshoots of thin dolerite or 'open' fractures (e.g. **Figures 60, 61**). The four drill-sites were all successful (yield greater 5.0 l/s). Yields of up to 24 l/s were obtained in offshoots of dolerite / fractures at Site 2. Notice that these high-yielding fractures only extend some 30m away from the dyke contact.

- A number of moderate- to high-yielding fractures were intercepted in the sediments overlying an inner-sill at Site 2 (borehole G40079, **Figure 60**), Site 5 (boreholes G46005A and G46006, **Figure 63**), Site 8 (borehole G46017, **Figure 66**) and Site 10 (borehole G46020, **Figure 68**).

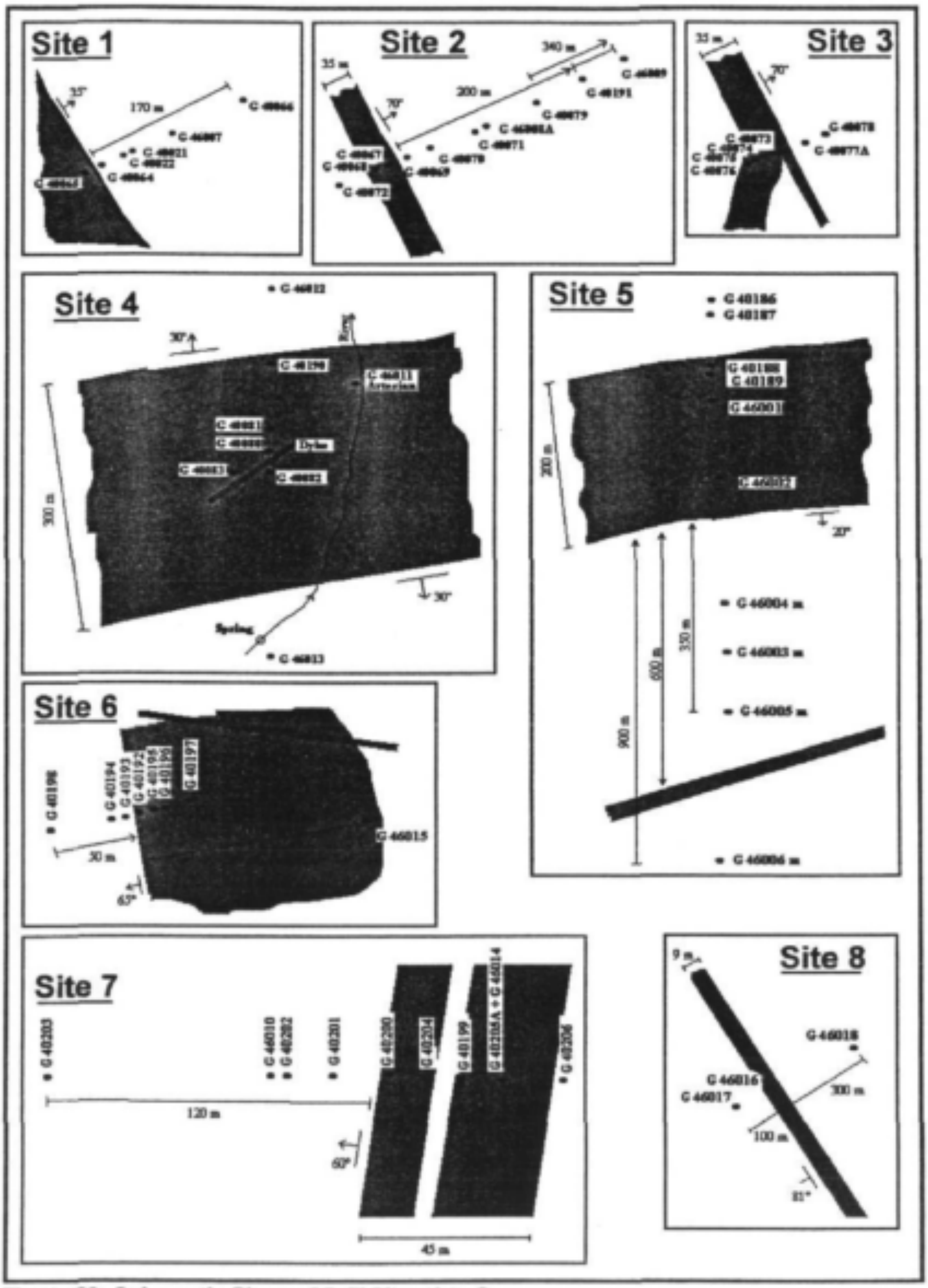



**Figure 58**: ***Schematic Plans of Drill Sites 1 to 8***

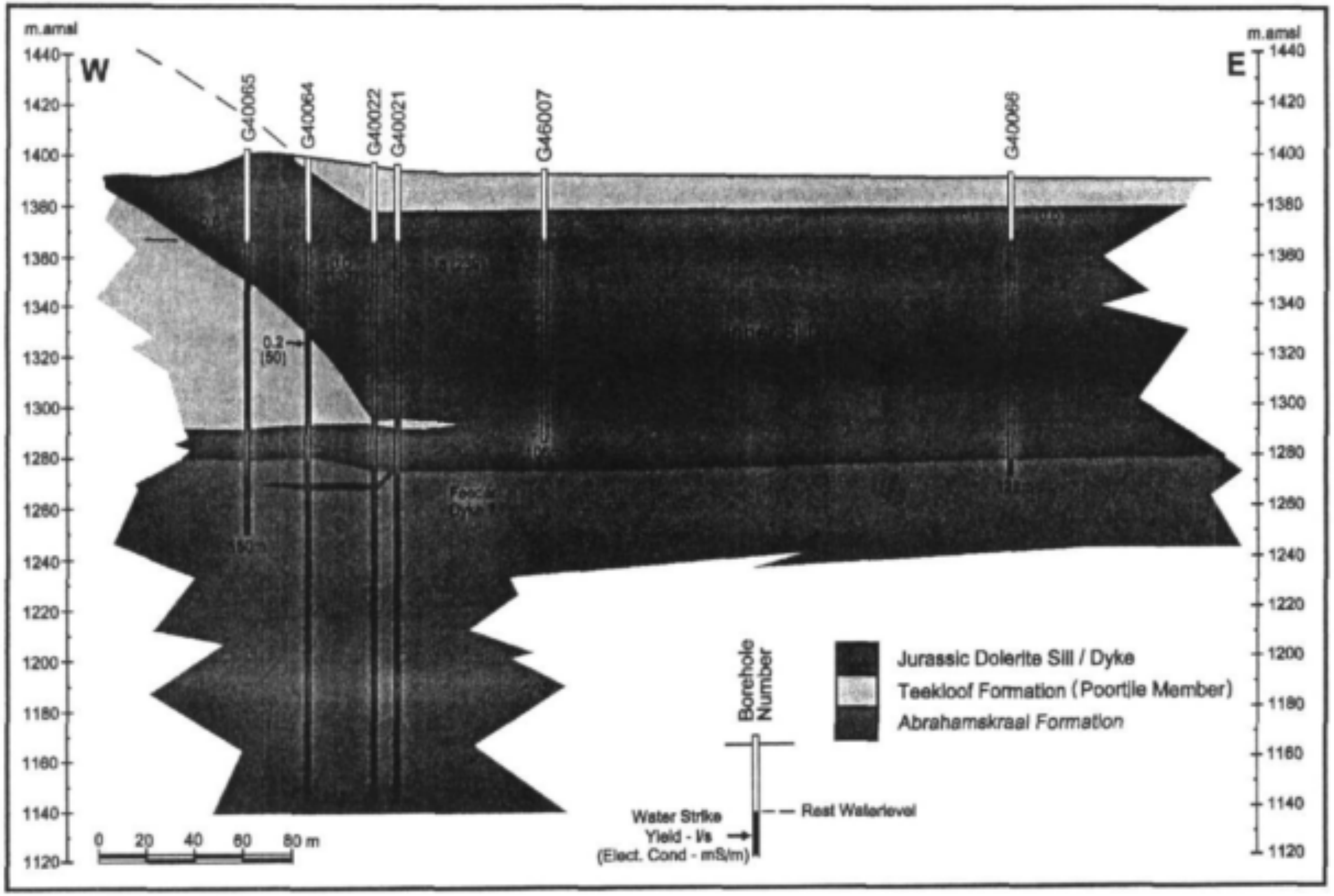



**Figure 59**: ***Geohydrological Profile at Exploration Drill Site No. 1***

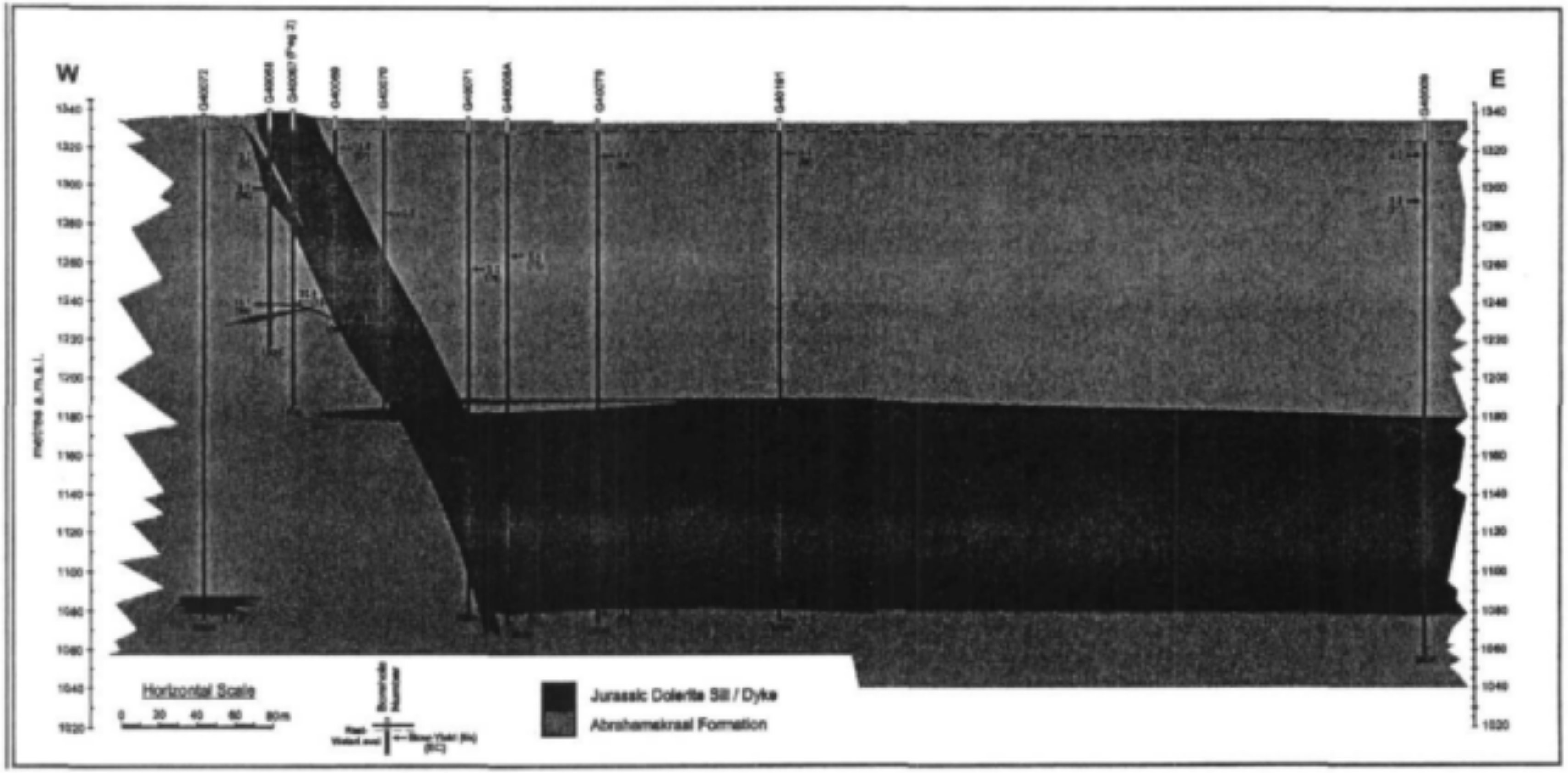



*Figure 60: Geohydrological Profile at Exploration Drill Site No. 2*

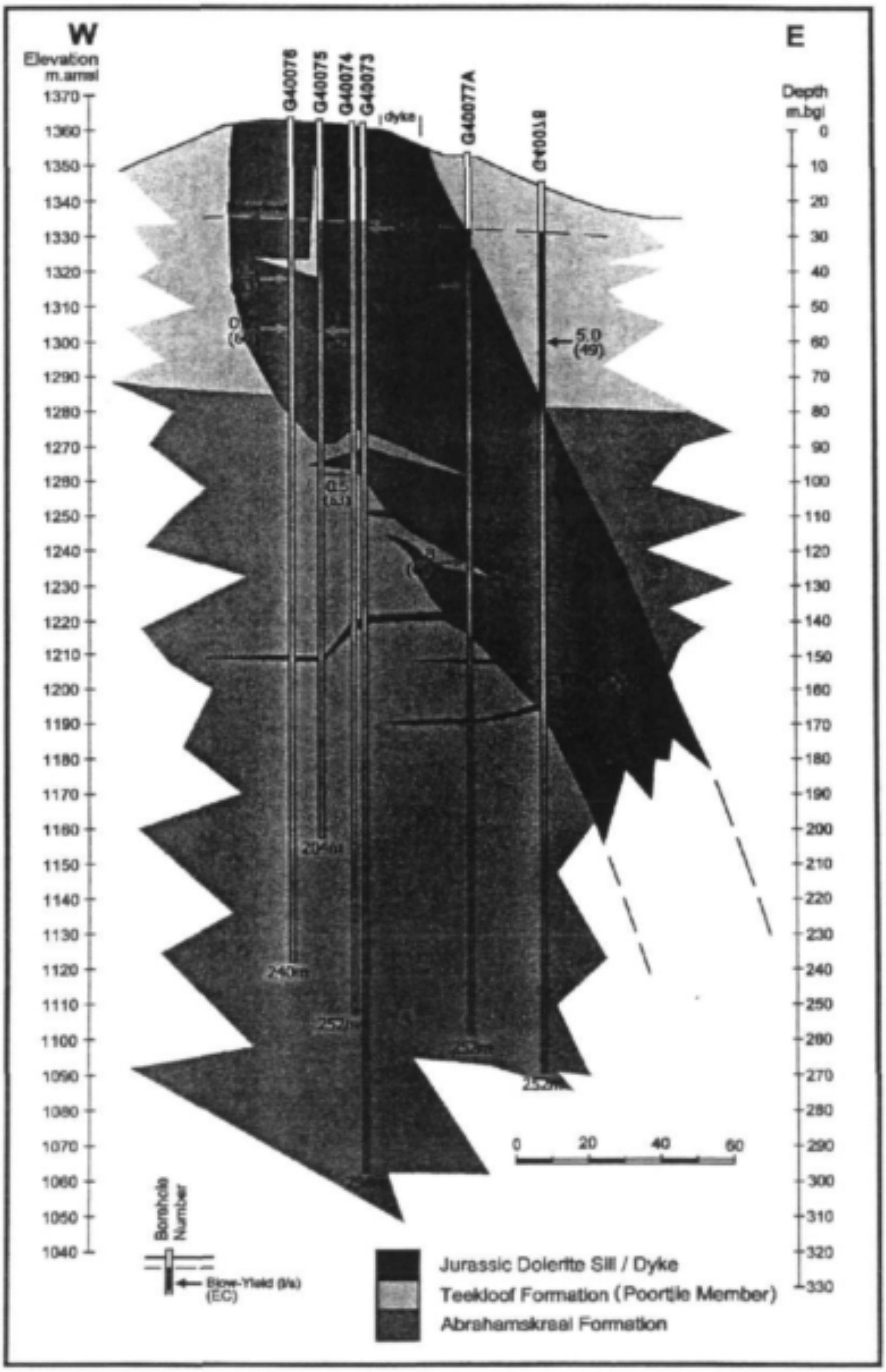



**Figure 61**: ***Geohydrological Profile at Exploration Drill Site No. 3***

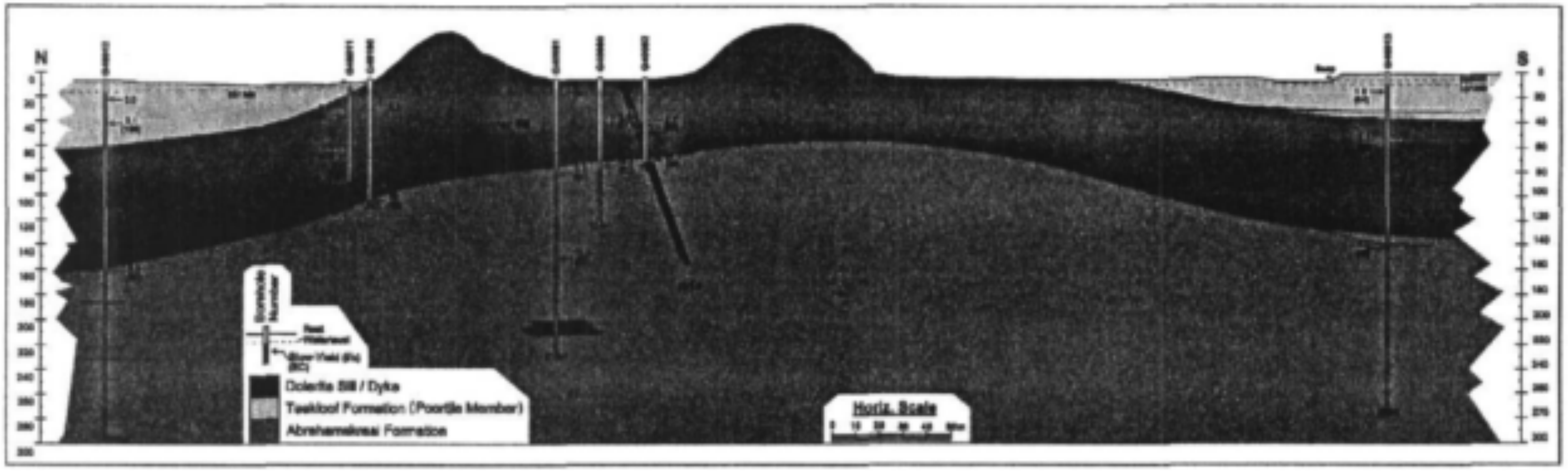



**Figure 62**: ***Geohydrological Profile at Exploration Drill Site No. 4***

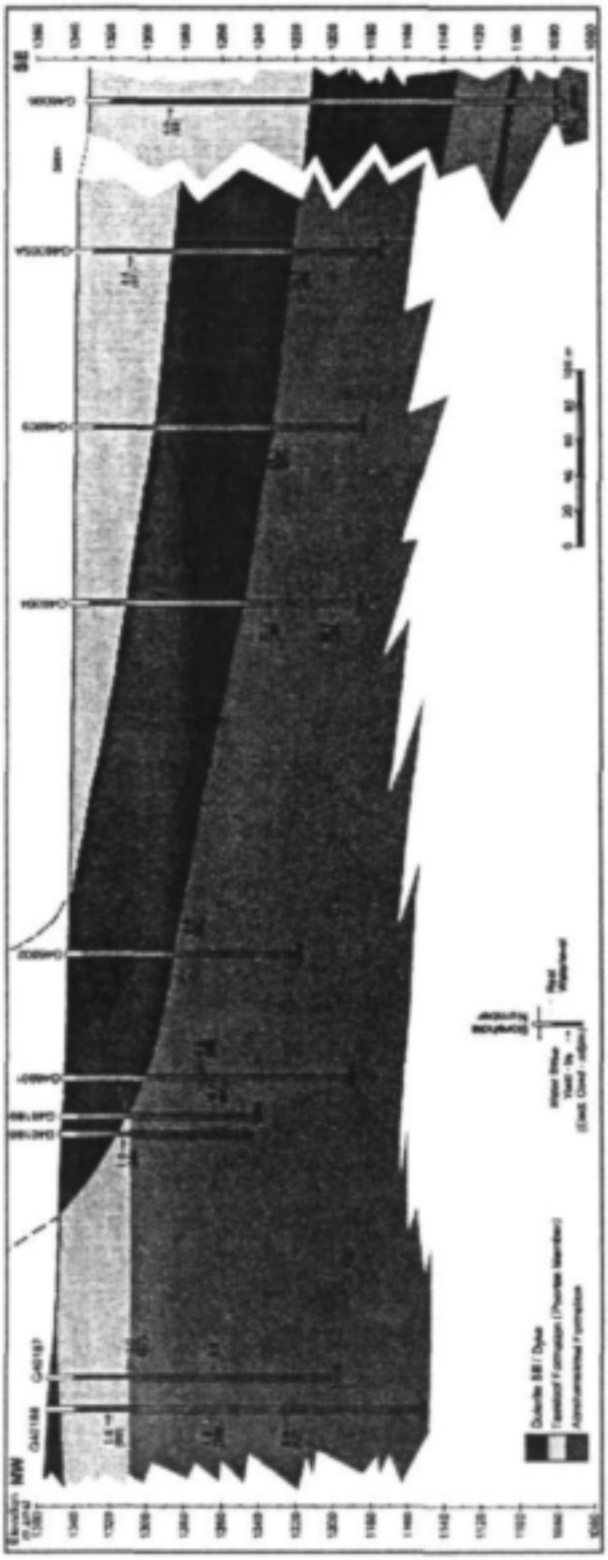


Figure 63: Geohydrological Profile at Exploration Drill Site No. 5

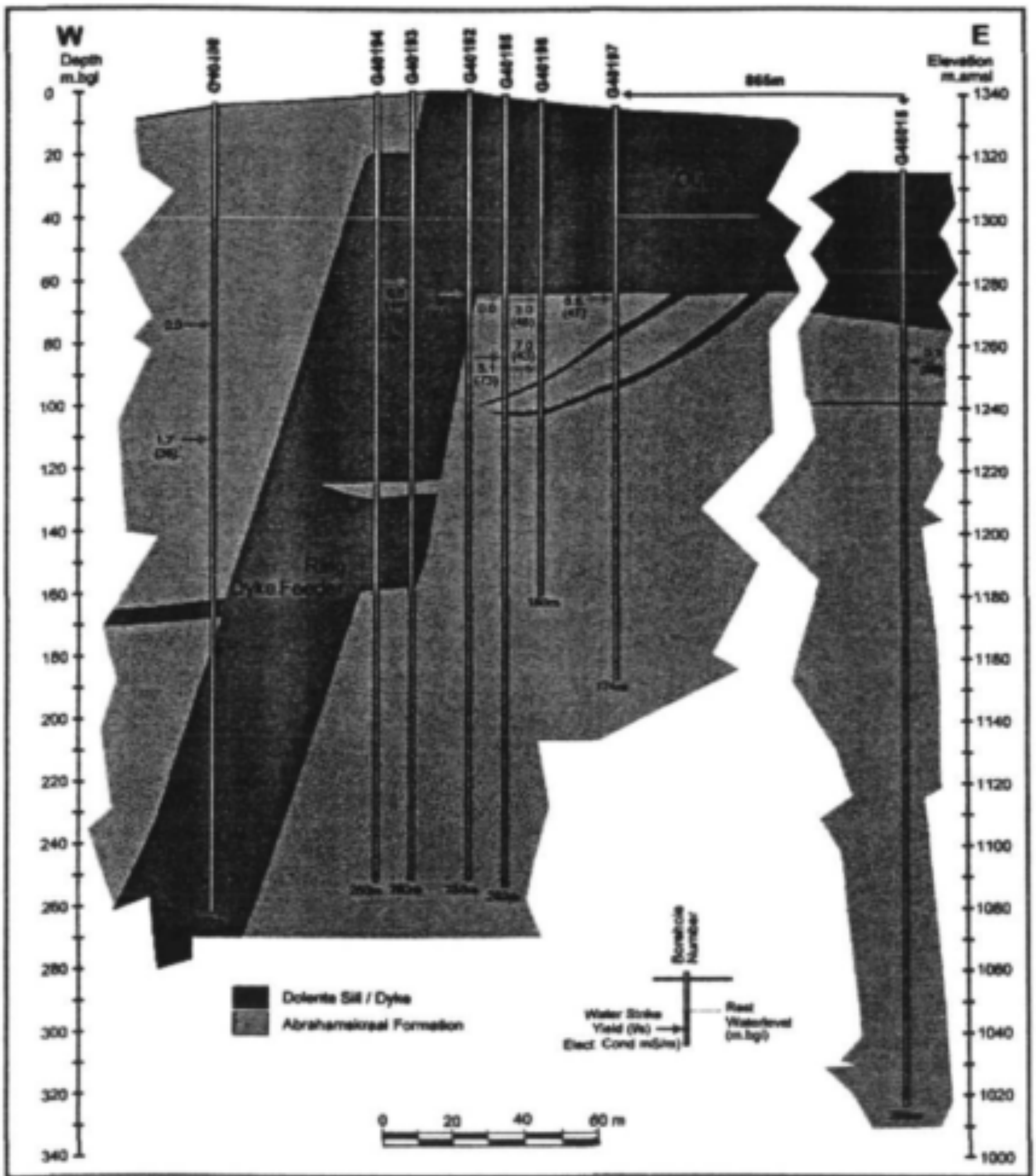


Figure 64: *Geohydrological Profile at Exploration Drill Site No. 6*

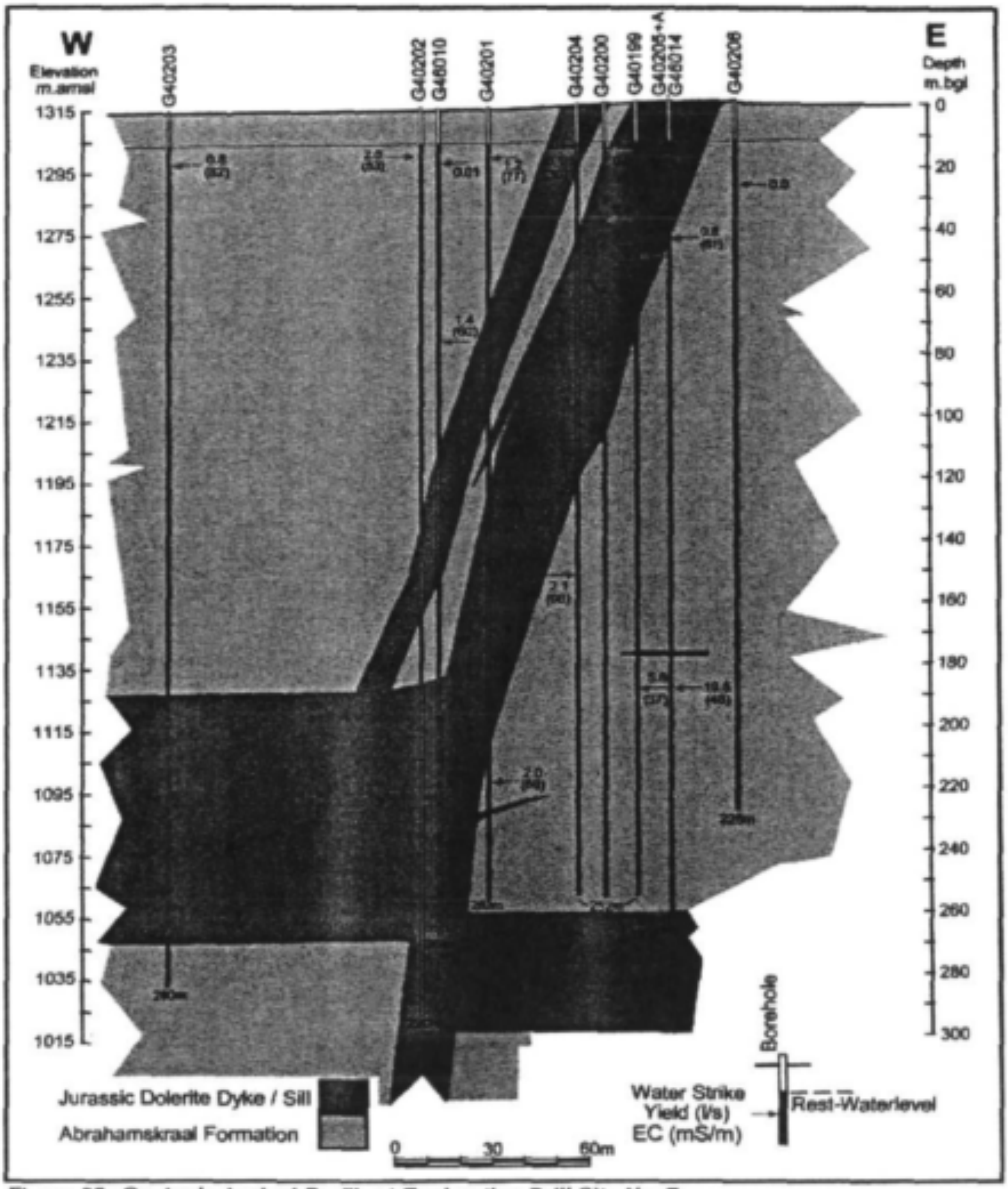



Figure 65: *Geohydrological Profile at Exploration Drill Site No. 7*

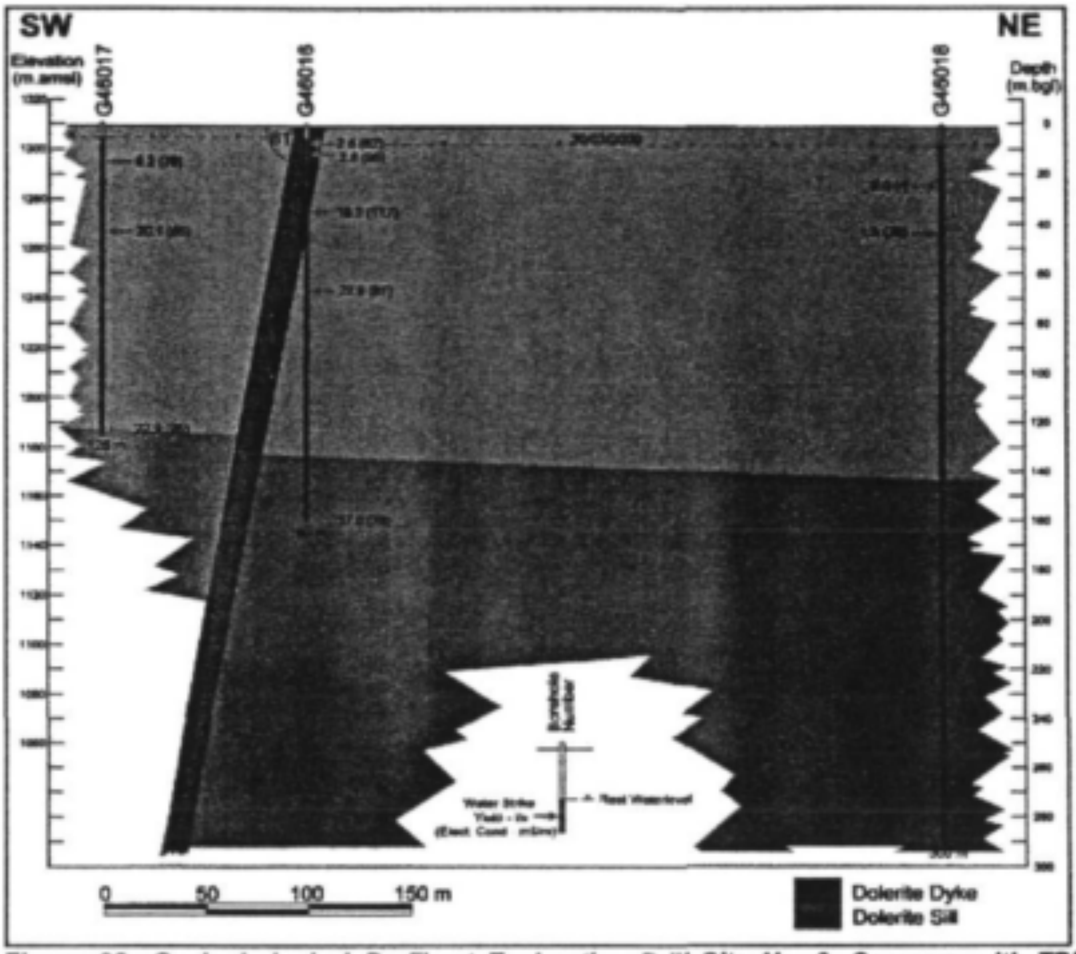



*Figure 66: Geohydrological Profile at Exploration Drill Site No. 8. Compare with TDEM profiling of Figure 72.*

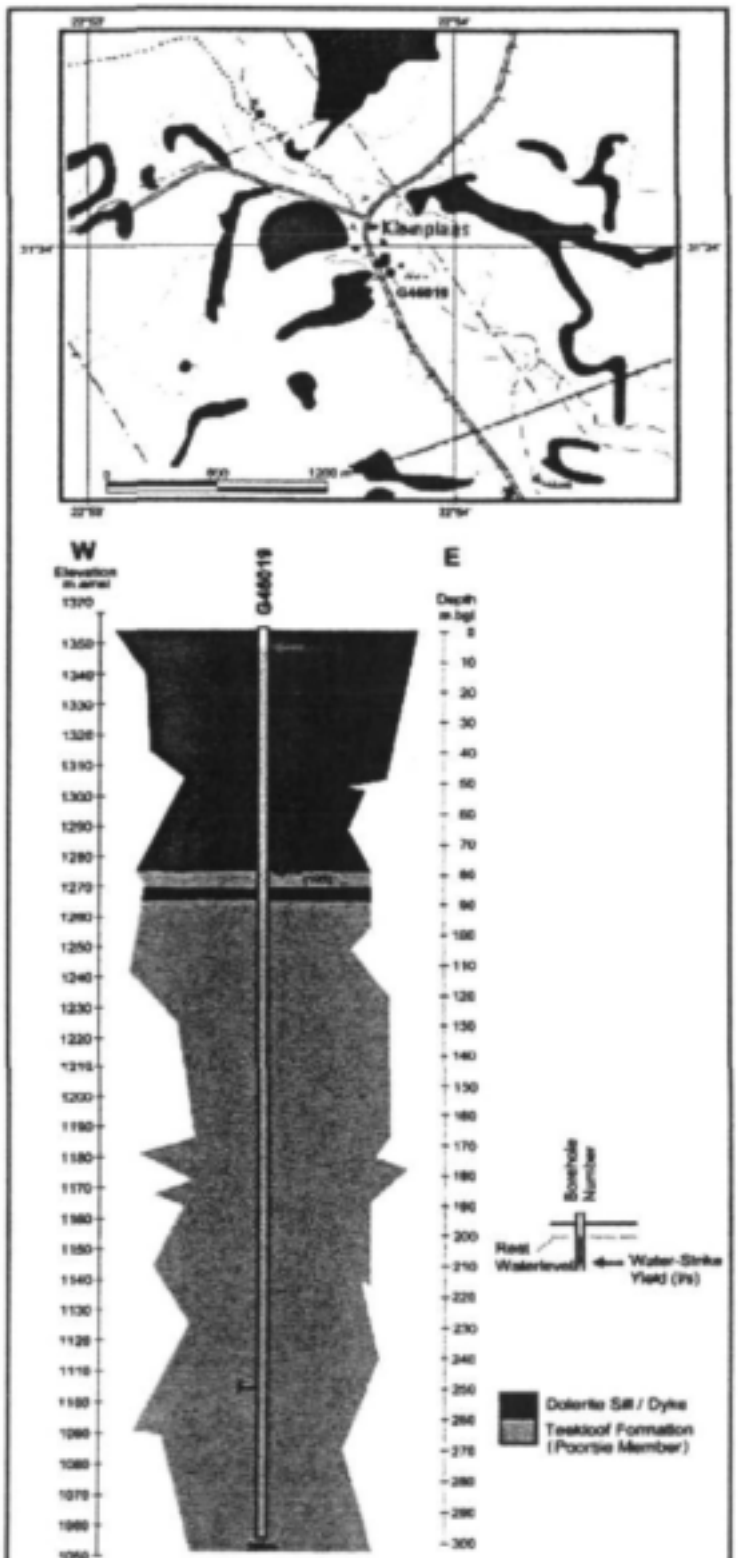


Figure 67: Geohydrological Profile at Exploration Drill Site No. 9

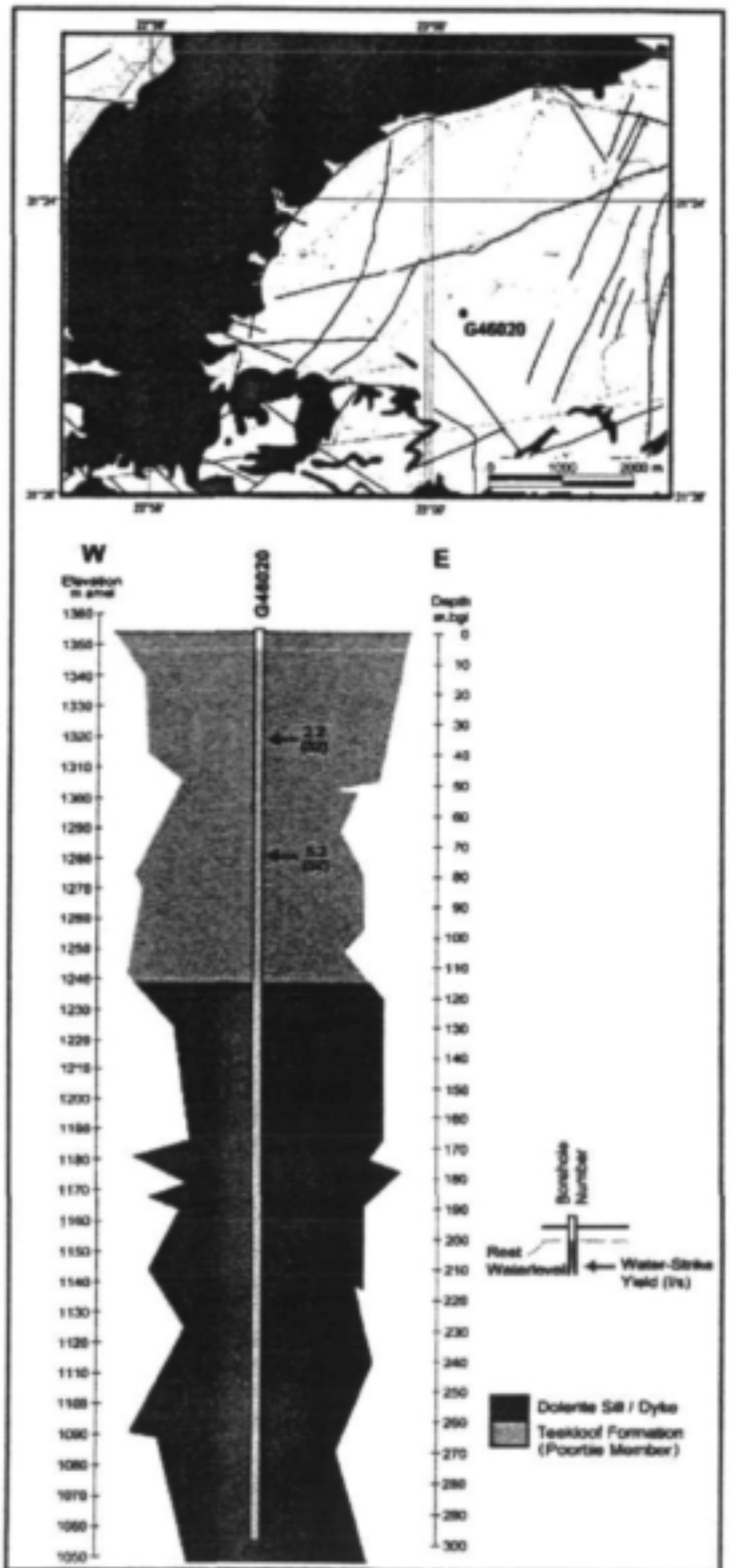



Figure 68: *Geohydrological Profile at Exploration Drill Site No. 10*

- The inner-sill was explored at Sites 1,2, 4, 5, 8, 9 and 10. Drill site 1 (**Figure 59**) was not successful, which is partially due to the elevated position of the drill terrain in relation to the main drainage features. Elsewhere moderate to high yields were intercepted (>4 l/s). At Site 2 (**Figure 60**), borehole G40191 intercepted high-yields (16 l/s) in a horizontal fracture situated some 250m.bgl at the base of the inner-sill. A similar situation was encountered at Site 4 (**Figure 62**), where blow-yields of up to 87 l/s were encountered at the base of the sill. The extremely high yields encountered at this site are probably related to enhanced fracturing associated with a "kink" in the sill in the vicinity of borehole G40190 and a linear dolerite dyke / fissure at borehole G40082. High yields (27-34 l/s) were intercepted in fractured sediments below the inner sill at Site 5 (boreholes G46003, G46004 and G46005A - **Figure 63**).

- The outer-sill was only tested at Site 6 (**Figure 64**), due to limited accessible outcrops of these features. Blow-yields of 5 l/s were intercepted in borehole G40197. The relatively high yield of this borehole may actually be related to fracturing associated with the nearby feeder dyke. Borehole G46015 drilled directly into the outer sill, some 865m from the feeder dyke, only intercepted minor amounts of groundwater in the sediments below the lower contact of the sill.

- The groundwater quality in these fractured-rock aquifers is good, with a total salt content of generally less than 600 mg/l (total dissolved solids).

Many of the high-yielding (> 20 l/s) boreholes could not be completed to the required drilling depth (i.e. to fully penetrate the high-yielding fracture zone) due to limitations of the drilling-rig.

The statistical analysis of the groundwater interceptions (**Table 14**) in the 63 exploration boreholes indicates that:

- The first water strike commonly occurred at 40m.bgl (median 34m.bgl), which is below the mean drilling depth of private boreholes in the area (Chapter 6.2). The mean depth to the waterlevel is 16.2m.bgl (median 13.9m.bgl).
- The yield of individual water strikes increases with increasing number of interceptions and increasing drilling depth.
- There is no significant increase in the groundwater salinity with increasing depth.

The strike frequency and yield variations of water-bearing fractures are summarized in **Figure 69**, where it is evident that:

- The frequency histogram of groundwater interceptions indicates, as is typical of most Karoo fractured rock aquifers, a 'peak' that extends from the regional waterlevel to some 60m below this level. Thereafter, the frequency of water-bearing fractures decreases markedly. Approximately 73% of all water interceptions occur within 80m of the surface.

- Approximately 62% of the individual water-strikes yielded less 3 l/s, 10% yielded between 3 and 5 l/s, 9% yielded between 5 and 8 l/s, 5% yielded between 8 and 12 l/s and 14% yielded in excess of 12 l/s.

- The proportion of high-yielding fractures tends to increase with increasing drill depths and individual water strikes in excess of 12 l/s only occur below 40m.bgl.

Table 14: *Summary of the Groundwater Interception Information*

| Statistics | WATER INTERCEPTION | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st Strike | | | 2nd Strike | | | 3rd Strike | | | 4th Strike | | |
| | Depth (m) | Yield (l/s) | EC (mS/m) | Depth (m) | Yield (l/s) | EC (mS/m) | Depth (m) | Yield (l/s) | EC (mS/m) | Depth (m) | Yield (l/s) | EC (mS/m) |
| No. Bores | 64 | 64 | 46 | 39 | 39 | 38 | 12 | 12 | 11 | 2 | 2 | 2 |
| Mean | 39.6 | 2.65 | 64.9 | 106.0 | 8.4 | 68.9 | 115.0 | 12.6 | 69.7 | 129 | 32.4 | 105 |
| Median | 33.5 | 0.60 | 61.4 | 78.0 | 2.86 | 64.7 | 102.5 | 4.5 | 62.0 | - | - | - |
| Std. Dev. | 31.3 | 5.64 | 33.15 | 79.2 | 14.4 | 22.2 | 79.6 | 23.1 | 22.2 | - | - | - |
| Maximum | 186.0 | 28.0 | 239 | 262.0 | 65.1 | 130 | 263.0 | 83.8 | 117 | 160 | 18.0 | 134 |
| Minimum | 5.0 | 0.008 | 35 | 12.0 | 0.009 | 36 | 24.0 | 0.10 | 42 | 98 | 13.4 | 76 |

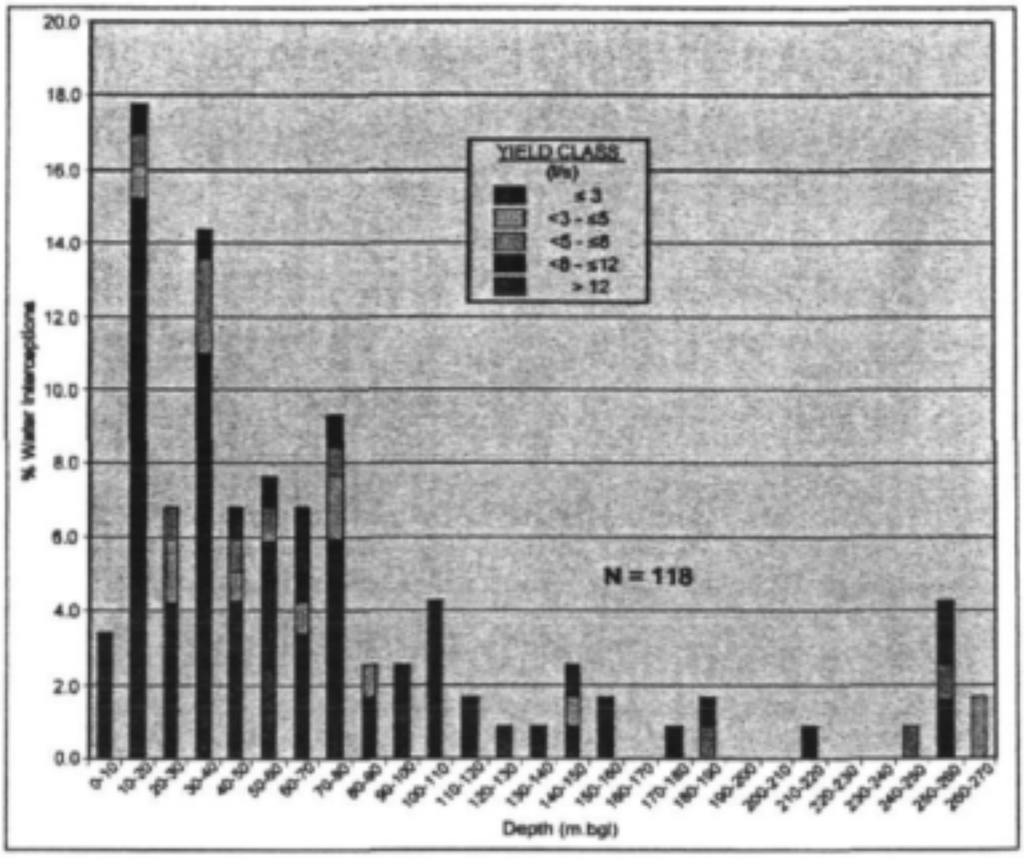



Figure 69: *Histogram showing percentages of water interceptions and relative percentages of drillstem yields per 10m drilling depth intervals below ground surface*

## 8 CONCLUSION: HYDRO-MORPHO-TECTONIC MODEL AND EXPLORATION TARGETS

The hydro-morpho-tectonic model of **Figure 70** synthesises the results of the local study of the Victoria West ring-complex and other investigations conducted by the authors. It corresponds to morphotectonic model I of **Figure 23**, and is characterised by a vertical upward-stacking of the sills and an upward decrease in size of the rings.

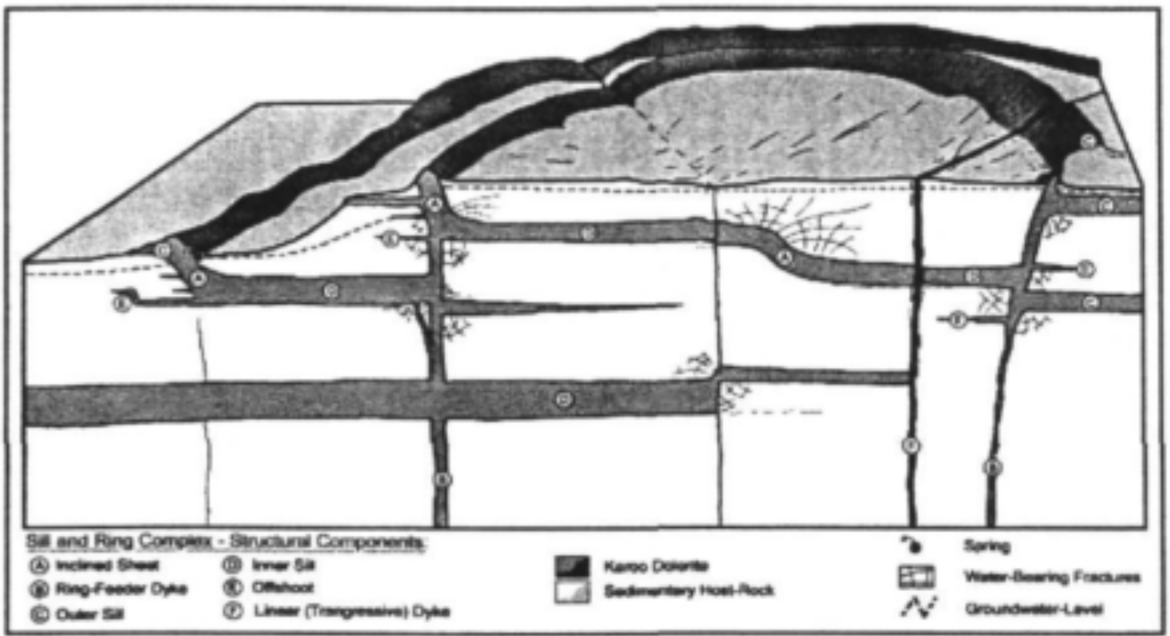



Figure 70: ***Schematic Hydro-morphotectonic Model of a Dolerite Sill and Ring Complex***

The mechanical simulation has shown that, during intrusion, complex shear fractures can develop at specific places in the surrounding host rock, i.e. at the junction between a feeder dyke and a sill or above an up-stepping of a sill (**Figure 70**). In the first case fracturing is very localised, whilst in the second case shear fractures can extend some distance away from the dolerite contact into the country rock. After magma cooling such fractures can be reactivated, resulting in fractures that transgress the up-stepping sill. Tensile or 'open' fractures, on the other hand, tend to develop ahead of the tip of a propagating sill. The magma is likely to have filled these fractures, creating horizontal offshoots, unless the pressure was not great enough to dilate them any further. Offshoots also develop when the sill up-steps at a vertical discontinuity such as a fault, joint or dyke.

Exploration drilling on dolerite ring-complexes has shown that:

- The sharp contact between a feeder dyke and an inner or outer sill was targeted at sites 2, 6 and 7 with a good success rate. However, the steeply dipping lower contact of the feeder dyke was also targeted at site 3, 6 and 7 with a poor rate of success but slightly improved rate on its upper contact.

- The inclined sheet forming the prominent ring and corresponding to the thickening of the feeder dyke and the transition inner sill - outer sill, or to simple upward-stepping, was targeted at sites 1 and 5 without any success.

- The sediments above up-stepping sills were not specifically targeted since such structure is difficult is assess from the surface. However the good yields obtained at site 5, 8, and 10 can be attributed to fractures that developed in the sediment away from the nearby Ruigtefontein inclined sheet.

- Thin horizontal off shoots and fractures parallel to the bottom of the sills were targeted at sites 2, 4, 5, 7 and 9 with good rate of success.

- The intersection between a major lineament and a sill was targeted at site 4 with a very good rate of success.

Karoo dolerite rings and sills have been proven to be structures conducive to the formation of deep-seated fractured aquifers. The increase in yield with depth could also mean that fractures with even higher yield might exist at greater depth. However, targeting these challenging aquifers is not a straightforward process and a thorough morpho-tectonic study will play a major role in any hydrogeological investigation of that type.

Our regional study has shown that the dolerite rings and sills of the Western and Eastern Karoo can be classified in three morphotectonic categories (**Figure 23**). Only morphotectonic model I has been investigated in detail. It was beyond the scope of the project to explore the hydrogeological characteristics of model II and III. Similar groundwater targets should however be expected. The down-stacking model of Middelburg basin may reveal many up-stepping sills whereas the "box-type" structural pattern of Queenstown basin could be conducive to many deep targets associated with contact between ring feeder and sill. Such investigation has been left for future research and exploration.

# 9 RECOMMENDATIONS FOR FURTHER RESEARCH AND TECHNOLOGY TRANSFER OF RESULTS

Two recommendations are made for future research:

- To improve the targeting of these challenged fractured rock aquifers by experimenting new sounding technologies
- To evaluate the impact of abstracting these deep water bodies on the ecosystem.

## 9.1 NEW GEOPHYSICAL TECHNIQUES FOR BOREHOLE SITING

Two techniques have been investigated to improve targeting of hidden sill and ring structures. These studies were carried out towards the end of the project and are therefore briefly mentioned here as potential tools for further work in targeting fractured aquifers linked to dolerite in the Karoo basin.

### High-resolution Airborne Radiometric and Magnetic Surveys

The Council for Geoscience performed a high-resolution airborne radiometric and magnetic survey over an area covering the two 1 / 50 000 maps of Melton Wold (3122BD) and Victoria West (3123AC), and corresponding to the local study where drilling was performed (see **Figure 57**).

The specifications and statistics of the survey are as follow:

- Survey flying height: 50m (as low as possible)
- Line Spacing: 200m
- Sample Spacing Magnetics: 3m
- Sample Spacing Radiometrics: 30m
- Calculated Magnetic Grid Spacing at a quarter of the line spacing
- The 200m survey consisted of 278 lines.
- Traverses are numbered 20 to 2880.
- Tie lines are numbered 9010 to 9100.
- A total of 7510 km was flown on line.

The survey was undertaken using the following equipment:

- A Jabiru ultralight aircraft
- Geometrics G822A cesium vapour magnetometer
- A Bicron 4l NaI(Tl) detector with ancillary equipment, in an onboard PC.
- A SATLOC real-time differential GPS recording once a second to an accuracy of less than 3 m in x and y and 5 m in Z is utilized.
- The SATLOC GPS controls the navigation.
- A highly focused Riegl laser altimeter is utilized.
- A Geometrics G856AG or Geotron G5 is utilized for sunspot monitoring and for diurnal correction.

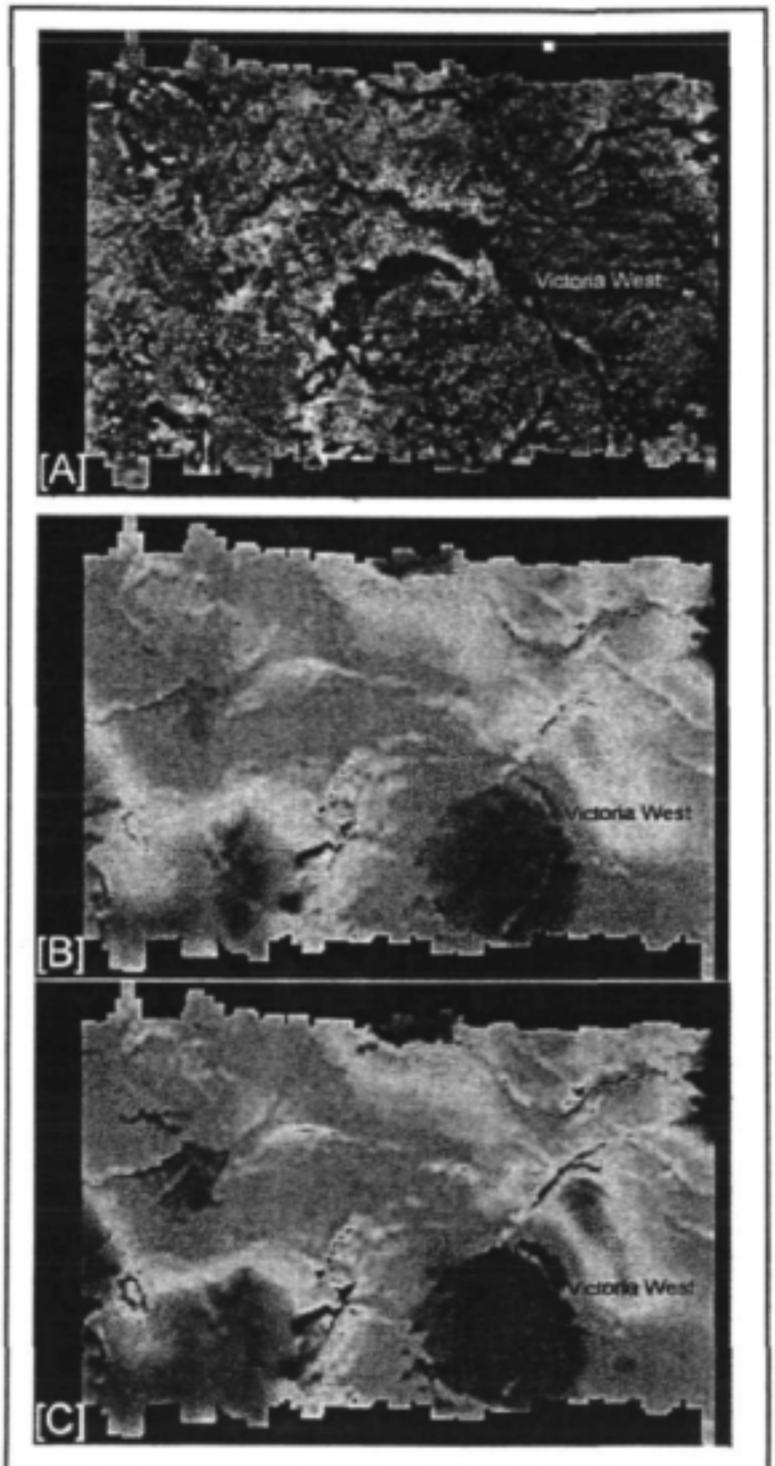



Figure 71: *High-resolution airborne radiometric (A) and magnetic (B) survey over an area covering the two 1 / 50 000 maps of Melton Wold (3122BD) and Victoria West (3123AC). (C) Total count: radiometric plus magnetic*

The results of the survey are shown on **Figure 71**. A very interesting feature is the circular structure of low magnetic intensity in the SE part of the area (blue to southwest of Victoria West). We know from drilling that it corresponds to a flat inner sill some 120 m deep below the surface. Its Western rim is particularly important since it seems to correspond to a hidden ring fed by a feeder dyke branching in from the NE. Such a structure is worthy of further investigation.

**Time Domain Electro-Magnetic Profiling**

Time domain electro-magnetic profiling was conducted by Terra Sounding and Analytical in order to obtain additional information on potential water-bearing layers and their relationship to the dolerite intrusions.

The experiment was conducted at drilling Site 8 along a profile-line extending from borehole G46017 to G46018. The profile also included borehole G46016, which is situated on the dolerite dyke.

The method employed a set of 100 x 100m transmitter loops, to enable a depth penetration in excess of 200m. The centres of the loops were arranged at 50m intervals and a total of nine stations were established. The receiver loops used had an effective size of 25 x 25m. Measurements were conducted using a ZIKL-5 TDEM instrument, which allows signal recording from about 7 µsec onwards.

The interpretation was carried out in two steps:

- Conversion of the signal output into longitudinal conductivity as a function of time (depth).

Mathematical modeling using all data obtained.
Examples of the converted signals (S-plane version) are shown in **Figure 72 B** and **C**. The signal registered in close proximity to the dyke (Station 12, Figure **72 B**) is typical of signals received form the stations along the southwestern section of the profile. It shows a higher, general resistivity for the sediments within the profile compared to the northeast section where the resistivity is considerably lower. The difference is, however, slight in comparison to similar sediments elsewhere. It could be due to the higher clay content in the sediments along the NE portion of the profile.

The resistivity for the dolerite, as shown on the final model (**Figure 72 A**), was found to be high to very high (400 to more than 1000 Ωm) as is expected for this type of rock. An enclave of low resistivity (30 Ωm) at depth on the NE section of the profile (stations 8a & 9), are interpreted as a brecciated, porous rock mass (lower part of curve in **Figure 72 C**).

Within the sediments, thin layers of low resistivity can be discerned. Sharp changes in the conductivity curves (**Figure 72 B**) mark their positions. Their resistivity values are in the order of 38 Ωm and are typical of water-bearing, sandy sediments. The lower horizon, at a depth of about 130m, was estimated to have a thickness of less than 1m. Closer to the surface a second horizon occurs with an estimated average thickness of about 1m. In the section NE of the dyke this layer does not appear to be continuous.

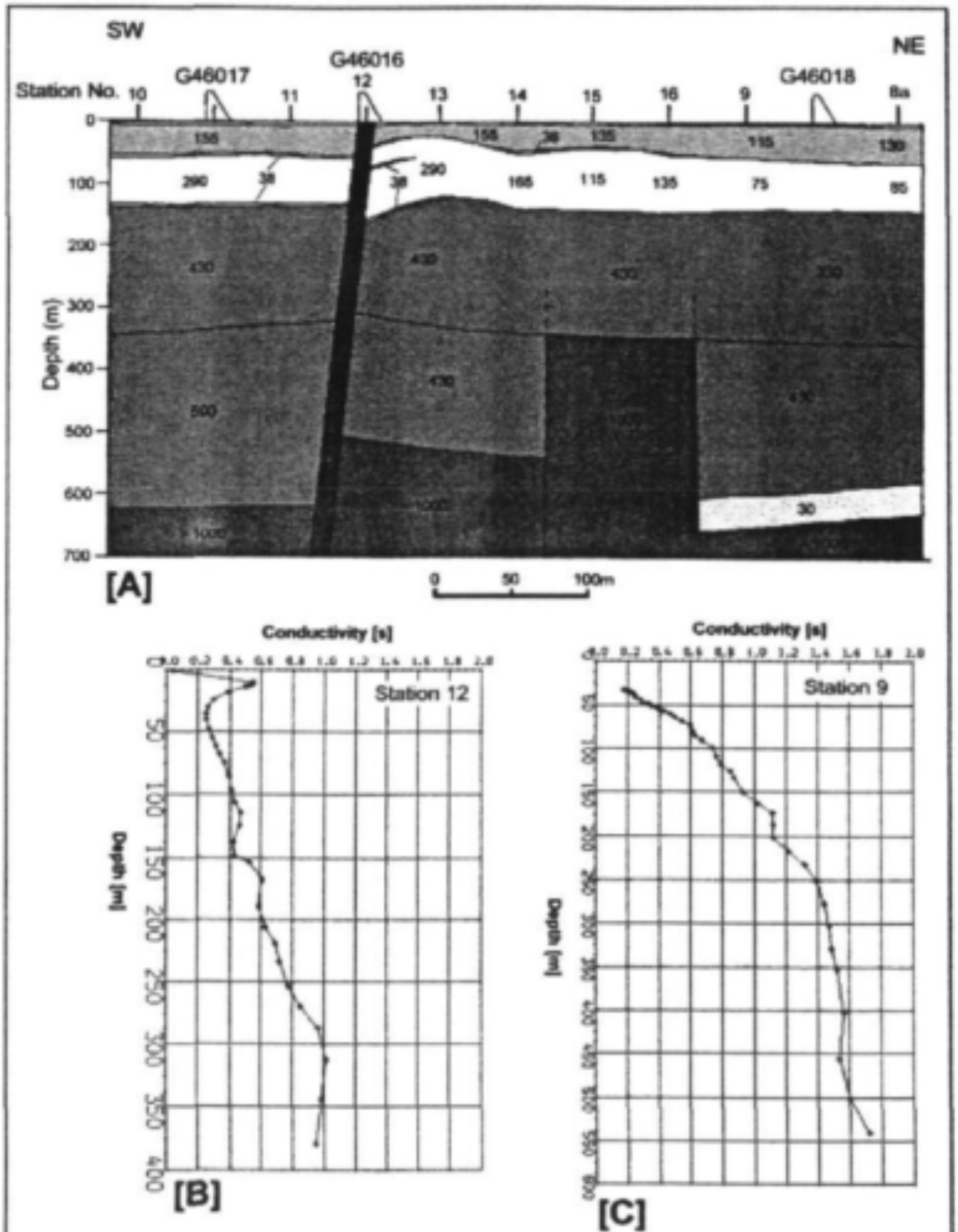


Figure 72: *TDEM survey at Drill Site No. 8See Fig. 57 for location and Fig. 66 for comparison with geological cross-section. (A) Geo-electric cross-section along a SW-NE profile, produced by mathematical modeling of TDEM data. The numbers inside the profile indicate the resistivity of the layers in Ωm. (B) Curve showing the change of the apparent longitudinal conductivity with depth for Station 12. (C) Curve showing the change of the apparent longitudinal conductivity with depth for Station 9*

The upper part of **Figure 72 B**, which shows a slow, steady increase of conductivity at depth, is typical of a section without thin layers of high conductivity. Instead, a thicker layer of relatively low resistivity occurs. A surface layer of between 3 and 5m thickness could also be distinguished. It has a low resistivity of about 28 Ωm and could represent the vadose zone with remnants of atmospheric moisture.

This preliminary survey shows that the TDEM method can be successfully used to obtain detailed depth profiles in areas of high resistivity, such as the Karoo environment. However, substantially more information could be obtained by a revised field strategy using a grid-layout of measurements instead of individual profiles. Such spatial measurements could utilize a 100 x 100m loop for up to 16 receiver loop readings. This approach would not increase fieldwork substantially but would provide a tomographic view of such blocks and result in a greater understanding, as well as a spatial interpretation of subsurface structures.

## 9.2 SENSITIVITY OF KAROO ECOSYSTEMS TO GROUNDWATER ABSTRACTION

In order to define the influence of dolerite ring- related ground water on ecosystems, the following twofold approach should be implemented:

- Definition of hydrogeological domains characterised by their water reserve (physical characteristics), aquifer recharge (flow dynamics) and water quality.
- Vulnerability and assessment of impact of abstraction on the aquifer.

### Hydrogeological Domains

The dolerite sills and ring-complexes might play a very prominent role in the definition of hydrogeological domains in the Karoo. Our regional study area has been subdivided into several morpho-tectonic provinces, namely: the Loxton, Victoria West and Sneeuberge Highlands for morpho-tectonic model I, the Middelburg and Nieu-Bethesda basins for morpho-tectonic model II, and the Queenstown Basin for morpho-tectonic model III. Each of these provinces could be classified, according to this system, into separate, may be subtle, hydrogeological domains characterised by their geological structure, morphology, drainage, micro-climate, water chemistry etc.

However, the relation between these morpho-tectonic domains and the physical characteristics of the groundwater (e.g. water occurrence and quality, extent of aquifer units, aquifer recharge, flow dynamics) on a regional scale has not been established yet. In general, it is possible that a Victoria West model I (i.e. highlands with vertical upward-stacking) could be hydrogeologically different from a Middelburg model II (basin with vertical downward-stacking), which in turn may differ from a Queenstown model III ("box-type"). Although speculative at this stage, the complex interaction between aquifer units of varying geometry and depth can only be better understood through thorough hydrostratigraphic investigations.

**Aquifer Vulnerability and Impact Assessment**

Aquifer vulnerability assessments can be looked at two scales:

Regional: The extent to which the hydrostratigraphy affects ecosystems i.e. are extensive regional elaborate ecosystems controlled by groundwater flow along extensive deep-seated structures, whilst the local ecosystems by the shallow groundwater system? That question cannot be answered and will definitely require more research and investigation in the future.

Local: The influence of large-scale groundwater abstraction from aquifers related to sill and ring-complexes on associated springs. For example, the shallow spring located in the vicinity of drilling site 4 (**Figure 73**), where excessively high-yielding boreholes have been developed.

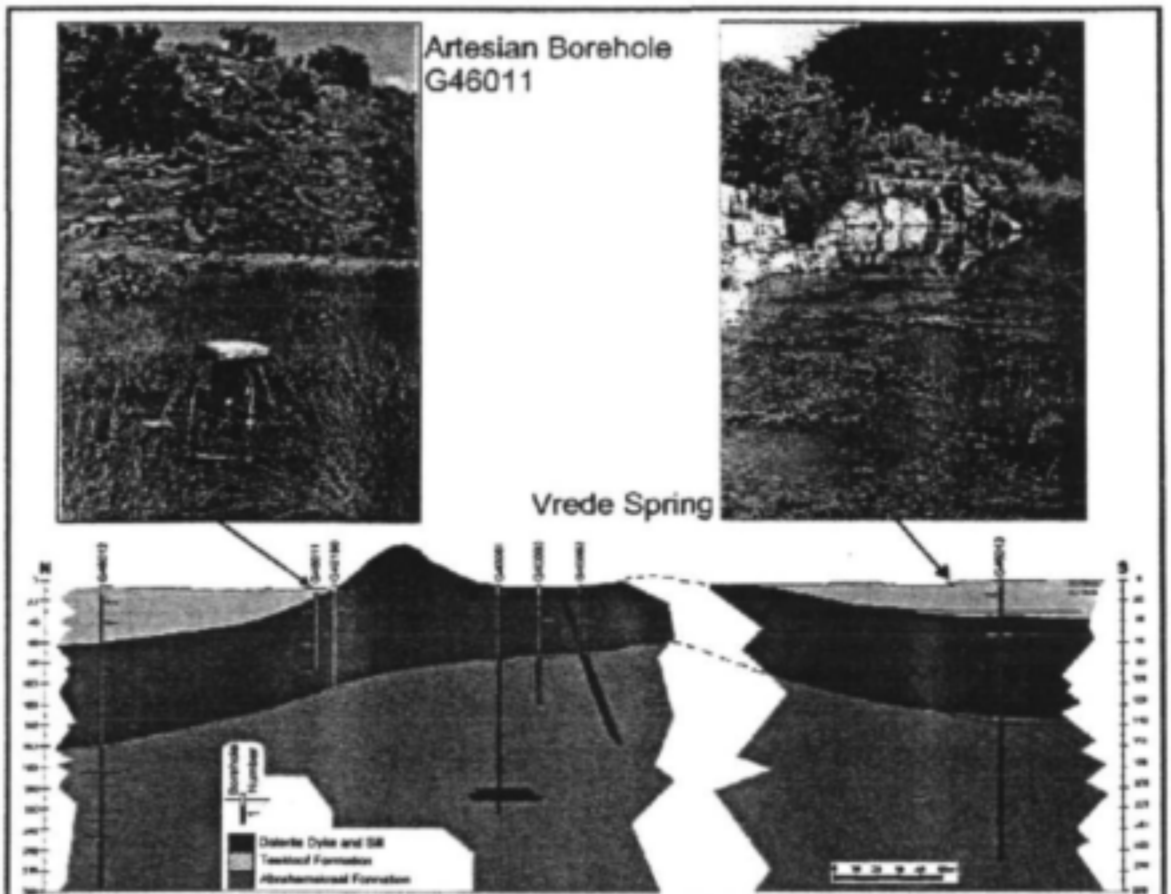



Figure 73: ***Hydrogeological setting of the Vrede Spring at drilling Site 4. See text for explanation.***

During the drought of the late nineties the spring almost completely dried up. However, after the October 1999 rainfall of 75mm the spring started to flow strongly (>5 l/s). In January 2000, the spring dried out during a 72-hour pumping-test on the artesian borehole G46011. During the pumping-test the waterlevel in borehole G46013, some 430m from the production bore, dropped by 26m. After the heavy rains of February 2000 (150mm) the spring was again flowing with a yield of about 10 l/s and the artesian borehole was strongly overflowing. The dolerite sill at site 4 is characterized by a slight undulation or up-stepping. It has been shown (**Figure 70**) that extensive transgressive 'open' fractures commonly develop with such structures, as well as surrounding host rock. Groundwater can thus rapidly flow over large distances in such shallow dipping fractures.

In conclusion, the assessment of hydro-ecosystems in the Western and Eastern Karoo will have to take into account the hydrogeology of dolerite sills and ring-systems. As mentioned in our introduction, these intrusions form an important part of the morpho-tectonic framework of the Karoo Basin and their role in the hydrostratigraphy is still to be investigated.

## 9.3 TECHNOLOGY TRANSFER

### Actions taken during the Project

The following technology transfer actions were taken during the project:

- In 1998, contacts were taken with Dr S Planke, from the University of Oslo (Norway), during the Congress of the International Association of Volcanology and Chemistry of the Earth Interior. Dr Planke works on similar geological problems i.e. 3d structure of sills within the Atlantic sedimentary basin, with a special interest to oil exploration and groundwater. He revisited us in November and paid a visit to Victoria West to look at the Karoo dolerite. He will probably be coming back in November 2000 with more people. We proposed to guide him around.

- In 1999 Chevallier and Woodford published a paper entitled 'Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo', South Africa@. S. Afr. J. Geol., No 102 (1), 43 - 54.

- From July to August 1999 we received Mss Cecile Martino, a visiting student from Reunion Island. Mss Martino did a honours in Applied Geology, and her visit was part of her post graduate training, in order learn our way of approaching and solve problems in hydrogeology of fractured aquifers in sub-volcanic environment. Mss Martino is currently helping us organising a volcanological tour to Reunion Island for the Mineralogical Society, during which hydrogeological problems in volcanic terrains will be addressed.

- In August 1999 we organized a field excursion to Victoria West for the Steering Committee. The following problems were discussed: Structure, Morpho-tectonics, General Hydrogeology, Drilling results and Springs. The field trip led to many interesting discussions.

- On 24 May 2000, A. Woodford was invited by the Ground Water Division (Western Cape Branch) of the Geological Society of South Africa to give a presentation on our investigation. His presentation was well received and created many interests among the scientific community.

- In July 2000 a poster will be presented at the $27^{th}$ Earth Science Congress of the Geological Society of South Africa, in Stellenbosch: Morphotectonics of Karoo dolerite sills and rings: their influence on fractured aquifers.

**Actions to be taken in the Future**

The WRC is in the process of publishing a handbook entitled: *"Hydrogeology of the Main Karoo Basin. Current knowledge and future research needs"* (Woodford, Edit, 2001) in which all the above results will be summarised and illustrated. We must ensure that this book will have a wide distribution.

Some of the exploration boreholes might be used for supplying water to Victoria West. Monitoring these bore holes and publicising the results could be part of a technology transfer programme.

However, there is a further need for technology transfer. On this project, close collaboration between the geologists, hydrogeologists and technicians from different institutions has proven to be very successful. In the future, such programmes should be used to train junior hydrogeologists and technical staff.

# ADDENDUM 1: ANALYSIS OF AQUIFER TESTS

## Analysis of Aquifer-Tests

A total of seven step-drawdown (SD) and 3-day constant-discharge (CD) tests were conducted at drill-sites numbers 2 to 8 over the period November 1999 to March 2000 (**Tables A** and **B**). The aquifer-tests were conducted by HIPPO on behalf of the Department of Water Affairs and Forestry (DWAF). Mr. P.L. Havenga of the Directorate: Geohydrology (DWAF) supervised the aquifer-testing programme. The positions of the production and observation boreholes at each test site are indicated on **Figure 58**.

<u>Table A</u>: *Summary of Step-Drawdown Testing Programme*

| Borehole Number [Site No.] | Date | Step No. | (min) | Pump Rate (l/s) | Max. Drawdown (m) | Eff (%) | Ave. T ($m^2/d$) | Coefficient* B | Coefficient* C |
|---|---|---|---|---|---|---|---|---|---|
| G40068A | 25/01/00 | 1 | 60 | 0.9 | 0.95 | 95 | | | |
| [2] | | 2 | 60 | 1.7 | 1.29 | 91 | | | |
| | | 3 | 60 | 2.6 | 1.80 | 86 | 239 | $4.195 \times 10^{-3}$ | $2.998 \times 10^{-3}$ |
| SWL = | | 4 | 60 | 3.4 | 2.34 | 83 | | n = 2.0 | n = 2.0 |
| 4.14 m.bgl | | 5 | 60 | 4.1 | 2.88 | 80 | | | |
| | | 6 | 60 | 5.3 | 3.74 | 76 | | | |
| G40078 | 18/01/00 | 1 | 60 | 0.6 | 3.09 | 82 | | | |
| [3] | | 2 | 60 | 1.3 | 7.06 | 69 | | | |
| | | 3 | 60 | 1.9 | 12.17 | 60 | 14 | $4.569 \times 10^{-2}$ | $1.899 \times 10^{-4}$ |
| SWL = | | 4 | 60 | 2.5 | 19.83 | 53 | | n = 2.0 | n = 2.0 |
| 14.90 m.bgl | | 5 | 60 | 3.2 | 26.99 | 47 | | | |
| | | 6 | 60 | 3.8 | 59.92 | 42 | | | |
| G40082 | 11/01/00 | 1 | 60 | 7.0 | 3.03 | 93 | | | |
| [4] | | 2 | 60 | 14.0 | 4.05 | 87 | | | |
| | | 3 | 60 | 21.0 | 5.13 | 81 | 905 | $1.069 \times 10^{-3}$ | $1.374 \times 10^{-7}$ |
| SWL = | | 4 | 60 | 28.0 | 6.51 | 76 | | n = 2.0 | n = 2.0 |
| 4.90 m.bgl | | 5 | 60 | 35.0 | 8.21 | 72 | | | |
| | | 6 | 60 | 45.0 | 9.99 | 67 | | | |
| G46005 | 04/12/99 | 1 | 60 | 2.0 | 2.62 | 89 | | | |
| [5] | | 2 | 60 | 5.0 | 7.14 | 76 | | | |
| | | 3 | 60 | 7.0 | 12.59 | 69 | 65 | $1.272 \times 10^{-2}$ | $9.400 \times 10^{-8}$ |
| SWL = | | 4 | 60 | 9.2 | 19.27 | 63 | | n = 2.0 | n = 2.0 |
| 10.86 m.bgl | | 5 | 60 | 12.0 | 26.68 | 57 | | | |
| | | 6 | 60 | 13.5 | 33.22 | 54 | | | |
| G40196 | 25/11/99 | 1 | 60 | 1.5 | 0.82 | 57 | | | |
| [6] | | 2 | 60 | 3.0 | 1.54 | 40 | | | |
| | | 3 | 60 | 5.0 | 5.05 | 28 | 115 | $3.194 \times 10^{-3}$ | $1.867 \times 10^{-5}$ |
| SWL = | | 4 | 60 | 7.0 | 9.28 | 22 | | n = 2.0 | n = 2.0 |
| 35.50 m.bgl | | 5 | 60 | 9.5 | 15.50 | 17 | | | |
| | | 6 | 60 | 11.6 | 23.85 | 15 | | | |
| G40199 | 10/02/00 | 1 | 60 | 0.9 | 11.19 | 82 | | | |
| [7] | | 2 | 60 | 1.8 | 21.07 | 70 | | | |
| | | 3 | 60 | 2.7 | 34.94 | 60 | 11 | $6.788 \times 10^{-2}$ | $1.910 \times 10^{-4}$ |
| SWL = | | 4 | 60 | 3.5 | 51.03 | 54 | | n = 2.0 | n = 2.0 |
| 21.50 m.bgl | | 5 | 50 | 4.6 | 69.13 | 47 | | | |
| G46017 | 29/03/200 | 1 | 60 | 5.9 | 2.09 | 99 | | | |
| [8] | | 2 | 60 | 10.0 | 3.64 | 97 | | | |
| | | 3 | 60 | 14.3 | 6.09 | 93 | 259 | $4.032 \times 10^{-3}$ | $1.278 \times 10^{-12}$ |
| SWL = | | 4 | 60 | 20.4 | 9.11 | 83 | | n = 3.7 | n = 3.7 |
| 5.99 m.bgl | | 5 | 60 | 24.7 | 12.93 | 74 | | | |
| | | 6 | 60 | 29.6 | 17.90 | 64 | | | |

* $S_w = BQ + CQ^n$

Where :
Sw – Drawdown (m), B – Coefficient Aquifer Loss, C – Coefficient Well Loss, Q – Discharge ($m^3$/day) and
n – constant (n=2, after Jacob, 1947)

**<u>Table B</u>: *Summary of Constant Discharge Aquifer-Testing Programme***

| Site No. | Borehole Number | R (m) | Total Volume Pumpec $(m^3)$ [l/s] | Static-Water-level (m.bgl) | Maximum Drawdown (m) @ 4320 min | Recovery Time (min) | Recovery Water-level Deficit (m) | Water-Strike (m) [Yield (l/s) per strike] in Production Borehole |
|---|---|---|---|---|---|---|---|---|
| 2 | G40068 [P] | 0 | | 4.91 | 7.01 | 4320 | -0.19 | 15 [0.01], 21.5 [3.1], 37 [2.7], 98 [9.4] |
| | G40069 [O] | 32 | 1470 [5.7] | 3.98 | 5.80 | 4320 | -0.23 | |
| | G40072 [O] | 35 | | 3.37 | 6.76 | 4320 | -0.26 | |
| | G40079 [O] | 173 | | 4.32 | 3.24 | 4320 | -0.05 | |
| | G46009 [O] | 704 | | 7.44 | 2.50 | 4320 | -0.04 | |
| | G40075 [O] | 884 | | 28.83 | 2.06 | 4320 | -0.16 | |
| 3 | G40078 [P] | 0 | | 14.38 | 17.52 | 4320 | +0.63 | 44 [5] |
| | G40077A [O] | 21 | 226 [0.9] | 20.69 | 5.77 | 4320 | -0.26 | |
| | G40073 [O] | 49 | | 28.39 | 3.44 | 4320 | -0.02 | |
| | G40075 [O] | 62 | | 30.10 | 4.50 | 4320 | -0.05 | |
| 4 | G40082 [P] | 0 | | 12.82 | 11.84 | 4320 | -4.95 | 33 [0.05], 35 [2.7], 65-67 [83.8] |
| | G40080 [O] | 19 | 4640 [17.9] | 12.45 | 11.84 | 4320 | -5.00 | |
| | | | | | | 9120 | -0.70 | |
| | | | | | | 10380 | +0.02 | |
| | G40083 [O] | 43 | | 13.32 | 10.79 | 4320 | -4.62 | |
| | G40190 [O] | 124 | | 11.35 | 11.76 | 4320 | -5.18 | |
| | | | | | | 10380 | -1.40 | |
| | G46012 [O] | 32 | | 8.72 | 3.43 | 4320 | -2.19 | |
| | | | | | | 11280 | -0.72 | |
| | G46013 [O] | 304 | | 12.17 | 10.43 | 4320 | -7.49 | |
| | | | | | | 10020 | -3.19 | |
| 5 | G46005A [P] | 0 | | 16.48 | 50.18 | 4320 | -25.85 | 28 [4.4], 117 [27.7] |
| | G46003 [O] | 100 | 2553 [9.9] | 18.07 | 38.21 | 4320 | -26.35 | |
| | G46004 [O] | 200 | | 20.10 | 36.90 | 4320 | -26.03 | |
| | | | | | | 34020 | -1.69 | |
| | G46002 [O] | 414 | | 25.67 | 36.72 | 4320 | -25.87 | |
| | | | | | | 34020 | -1.73 | |
| 6 | G40196 [P] | 0 | | 36.81 | 22.19 | 4320 | -12.23 | 59 [3.0], 80 [4.0] |
| | G40195 [O] | 10 | 1814 [7.0] | 39.92 | 21.76 | 4320 | -10.82 | |
| | G40197 [O] | 20 | | 35.58 | 13.48 | 4320 | -10.63 | |
| 7 | G40199 [P] | 0 | | 23.19 | 57.19 | 4320 | -1.24 | 38 [0.01], 187 [5.6] |
| | G40204 [O] | 10 | 3038 [1.5] | 22.66 | 47.36 | 4320 | -2.05 | |
| | G40206 [O] | 30 | | 18.05 | 13.04 | 4320 | +0.70 | |
| 8 | G46017 [P] | 0 | | 7.96 | 17.87 | 4320 | +1.26 | 15 [6.2], 43 [16.7] |
| | G46016 [O] | 100 | 5228 [20.2] | 7.56 | 8.94 | 4320 | +4.04 | |
| | G46018 [O] | 410 | | 8.76 | 1.13 | 4320 | +0.22 | |

**Notes:**

R – Radial distance from production borehole.

<u>Site 5</u> The following boreholes showed no response to the pumping: G46006. Other boreholes showed response, but problems with recorders made the results meaningless. The waterlevel in borehole G40188 was 18.110 m.bgl on the 3/12/1999. The pump test start on 5/12/1999 and the waterlevel dropped to 22.250 m.bgl during the test. Thereafter, the waterlevel continued declining to 23.435 m.bgl by the 14/12/1999 and leveled out at 25 m.bgl on the 17/12/1999. On the 5/1/2000 the waterlevel had further declined to 25.725 m.bgl.

<u>Site 6</u>: No waterlevel response was observed in borehole G40198, some 84m west of G40196. Other boreholes showed response, but problems with recorders made the results meaningless.

<u>Site 7</u>: Borehole G40202 (60m west of G40199) showed continual decline from start of test on 09/02/2000 (Waterlevel = 12.86m) and steadily declined to waterlevel = 12.93m on the 22/02/2000. Similarly, borehole G40203 (140m west of G40199) declined waterlevel 13.03m.bgl on 09/02/2000 to waterlevel 13.105 on 22/02/2000.

**SITE 2 – Borehole G40068**

Initially, a 6-stage step-drawdown test was conducted on borehole G40068 located on a ring feeder-dyke (**Figure 60**), where the discharge rate was varied between 0.9 and 5.3 l/s (**Table A & Figure A**). Unfortunately, the pump equipment was not capable of fully testing the yield capacity of the borehole (i.e. 1st water strike of 3 l/s at 21.5 m.bgl and main water strike of 10 l/s at 98 m.bgl) and therefore a maximum waterlevel drawdown of only 3.74m was attained.

Similarly, the constant-discharge test was conducted at 5.7 l/s, the maximum discharge rate of the pump, and a maximum drawdown of only 7.0m was obtained after 3 days (**Table B & Figure B**). Neither tests adequately tested the anticipated weathered-zone (i.e. 15 m.bgl) hydraulic boundary or main water-bearing fractures. Reasonable hydraulic parameters, particularly transmissivity, were obtained from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for confined, porous aquifers (**Table C**). Sites 2 and 3, some 884m apart, are clearly in hydraulic connection with one another – as illustrated by the waterlevel response in borehole G40075 at Site 3. This is to be expected as the boreholes at both sites are drilled into the same ring feeder-dyke.

The high degree of fracture interconnectivity at this tectonic zone (i.e. intersection of a feeder-dyke and an inner-sill) and the confined nature of the aquifer system is indicated by the systematic waterlevel response recorded in all observation boreholes (**Figure B**) – i.e. borehole G46009 drilled into the inner-sill, some 700m from the production borehole and on the opposite side of the feeder-dyke (**Figure 60**). The waterlevels recovered reasonably well for Karoo aquifers and a waterlevel deficit of less than 0.2m was recorded 3-days after pump-shutdown.

**Table C**: ***Borehole G40068 – Aquifer Transmissivity and Storativity Values***

| Borehole Number | Distance (m) | Drawdown | | Recovery |
|---|---|---|---|---|
| | | Transmissivity ($m^2$/day) | Storativity | Transmissivity ($m^2$/day) |
| G40068 | 0 | 32 | - | 26 |
| G40069 | 32 | 34 | $1.29 \times 10^{-3}$ | 27 |
| G40072 | 35 | 32 | $6.35 \times 10^{-5}$ | 25 |
| G40075 | 884 | 46 | $3.80 \times 10^{-5}$ | 43 |
| G40079 | 173 | 43 | $3.08 \times 10^{-4}$ | 34 |
| G46009 | 704 | 48 | $2.96 \times 10^{-5}$ | 33 |
| Average | | 39 | $3.5 \times 10^{-4}$ | 31 |

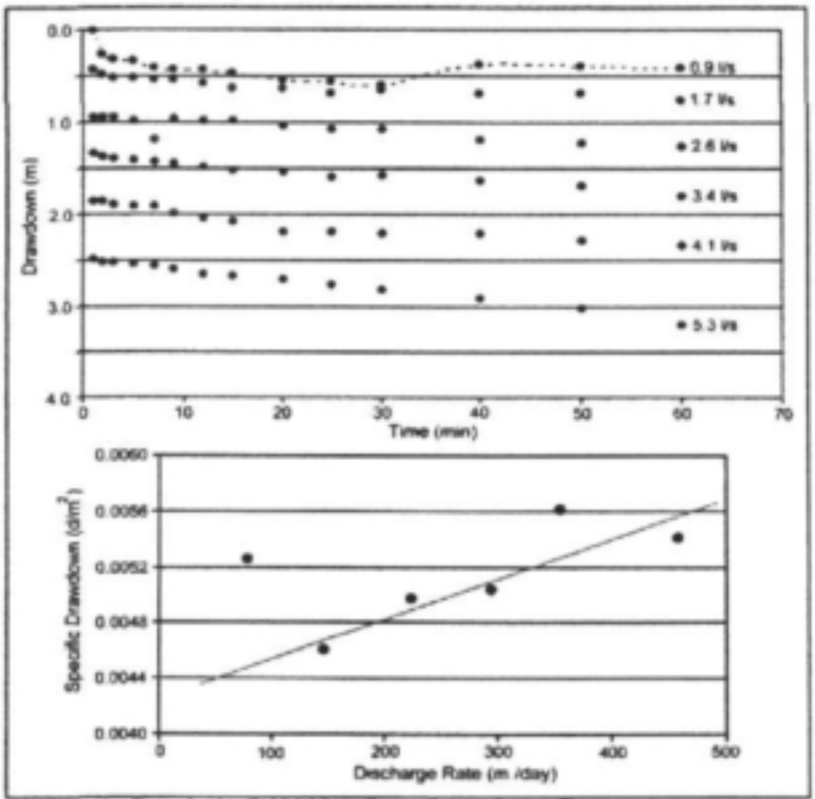



Figure A: *Borehole G40068 – Step-Drawdown Test*

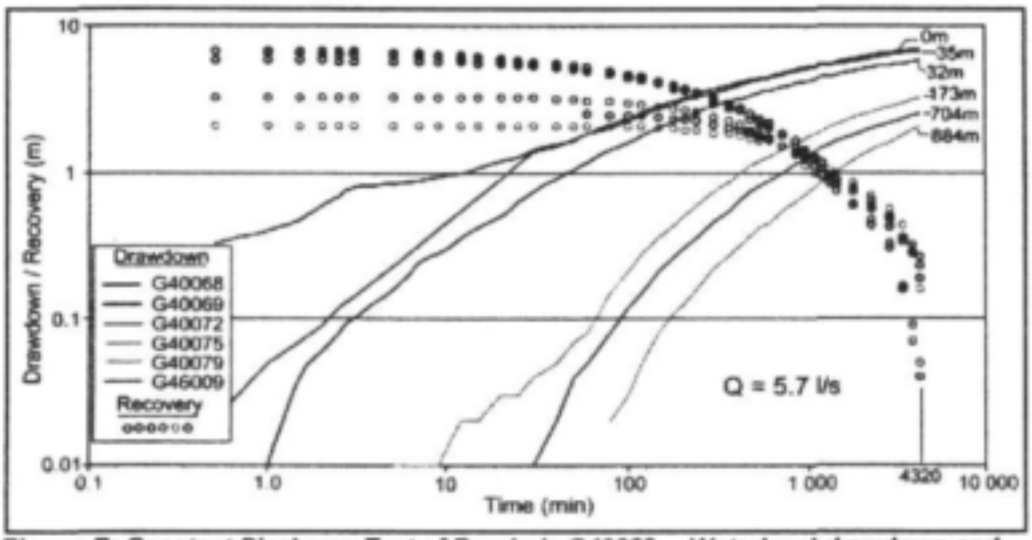



Figure B: *Constant Discharge Test of Borehole G40068 – Waterlevel drawdown and Recovery*

**SITE 3** – **Borehole G40078**

Initially, a 6-stage step-drawdown test was conducted on borehole G40078 located on a ring feeder-dyke (**Figure 61**), where the discharge rate was varied between 0.6 and 3.2 l/s (**Table A & Figure C**). The only significant water-bearing fracture (± 5 l/s at 44 m.bgl) was dewatered during the 5th step at a discharge rate of 3.2 l/s, which is the maximum yield of the borehole.

A 3day constant-discharge test was conducted at a discharge rate of 0.9 l/s and a maximum drawdown of 17.5m was obtained after 3 days (**Table B & Figure D**). A total volume of 226 $m^3$ of groundwater was abstracted from the aquifer during this test. Reasonable hydraulic parameters, particularly transmissivity, were obtained from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for confined, porous aquifers (**Table D**). The waterlevels had recovered almost completely recovered after 3-days, with the exception of borehole G40077A (**Table B**).

**Table D**: ***Borehole G40078 – Aquifer Transmissivity and Storativity Values***

| Borehole Number | Distance (m) | Drawdown | | Recovery |
|---|---|---|---|---|
| | | Transmissivity ($m^2$/day) | Storativity | Transmissivity ($m^2$/day) |
| G40078 | 0 | 3.0 | - | 4.3 |
| G40073 | 49 | 4.7 | $2.59 \times 10^{-4}$ | 4.9 |
| G40075 | 62 | 7.5 | $1.85 \times 10^{-4}$ | 6.9 |
| G40077A | 21 | 6.0 | $2.55 \times 10^{-4}$ | 5.0 |
| Average | | 5.3 | $2.33 \times 10^{-4}$ | 5.2 |

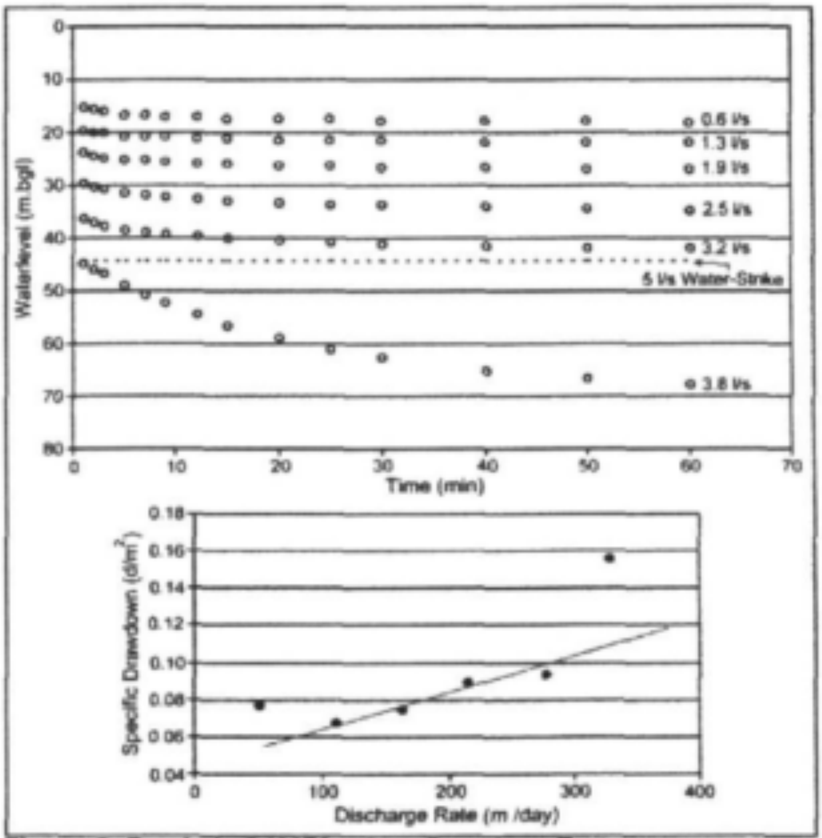



Figure C: *Borehole G40078 – Step-Drawdown Test*

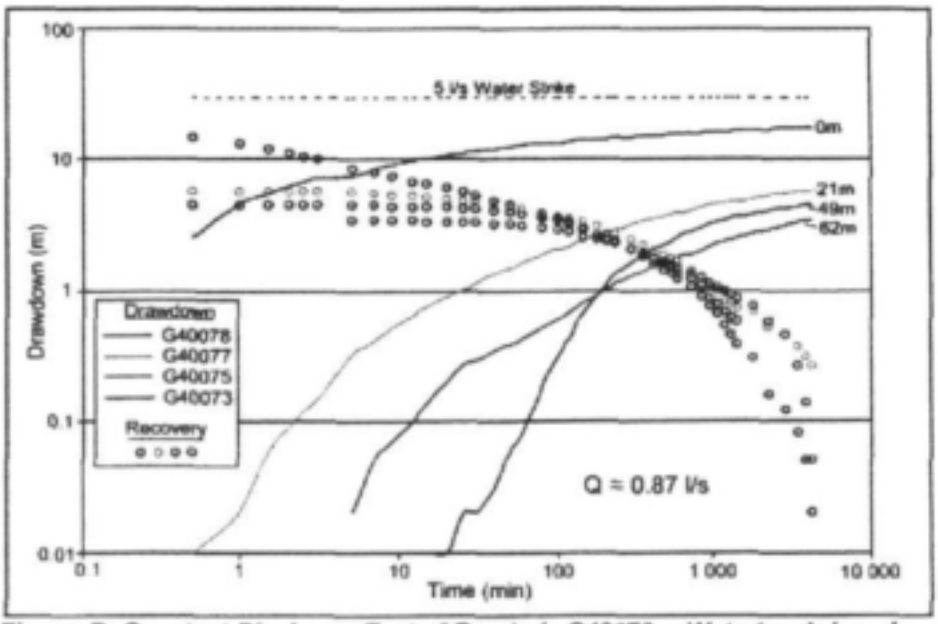



Figure D: *Constant Discharge Test of Borehole G40078 – Waterlevel drawdown and Recovery*

**SITE 4 – Borehole G40082**

Initially, a 6-stage step-drawdown test was conducted on borehole G40078 located at the intersection of a fissured dyke and inner sill (**Figure 62**), where the discharge rate was varied between 7 and 45 l/s (**Table A& Figure E**). The pump equipment was not capable of fully testing the yield capacity of the borehole and a maximum yield of 110 l/s was estimated from the step-drawdown data.

A 3-day constant-discharge test was conducted at a discharge rate of 17.9 l/s and a maximum drawdown of only 11.8m was obtained after 3 days (**Table B& Figure F**). It must be noted that the aquifer had not recovered from the earlier step-drawdown test (i.e. in G40082 static waterlevels of 4.90 and 12.82 m.bgl were measured prior to the SD and CD tests, respectively). A total volume of 4640 $m^3$ of groundwater was abstracted from the aquifer during this test.

The drawdown-curves for the pump and observation boreholes do not exhibit the flow response of a confined, porous aquifer (i.e. straight-line on a log-normal plot – **Figure F**). The anisotropic nature of the aquifer is indicated by the variable drawdowns measured at various distances from the pumped borehole (i.e. a maximum drawdown of 3.43m in borehole G46012 at some 232m and 10.43m in borehole G46013 at 304m from the pumped borehole). During the test observation boreholes G40083 (r = 43m) and G40080 (r = 19m) mirrored the drawdown response of the pump borehole G40082, as is to be expected, since they tap the same open-fissure at the base of the dolerite sill (**Figure 62**). The recovery of the waterlevels occurred slowly and waterlevel deficits of 2 to 5m remained after 3 days of recovery monitoring. The waterlevels in the vicinity of the production borehole recovered to their rest-levels after 6 days, whilst waterlevel deficits of 0.7 to 3.2m remained in the more distant boreholes.

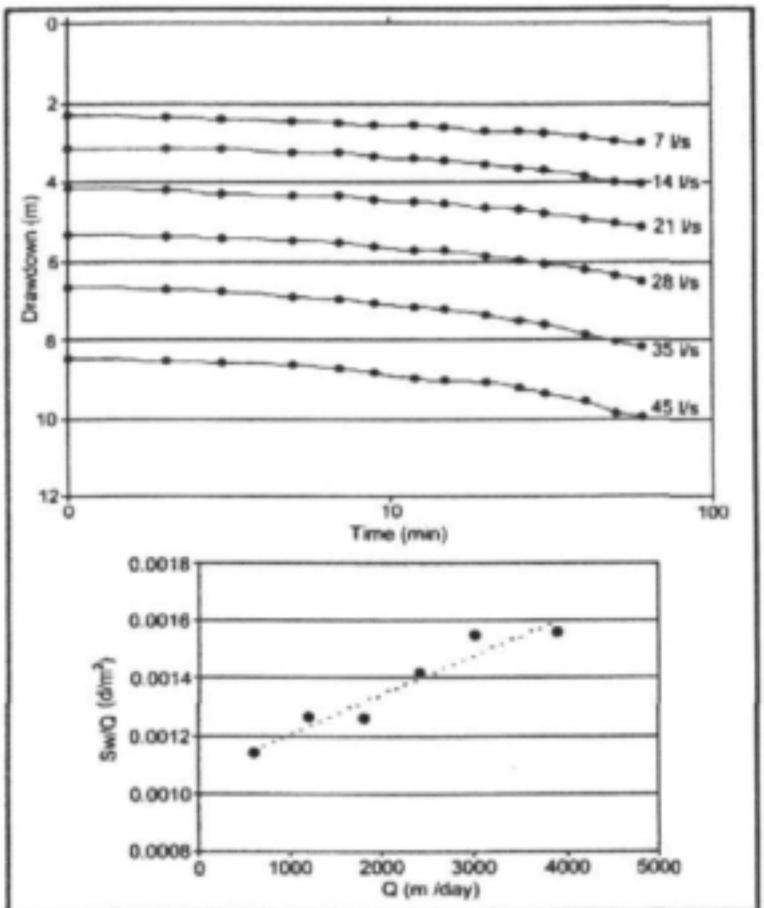



Figure E: *Borehole G400 82 – Step-Drawdown Test*

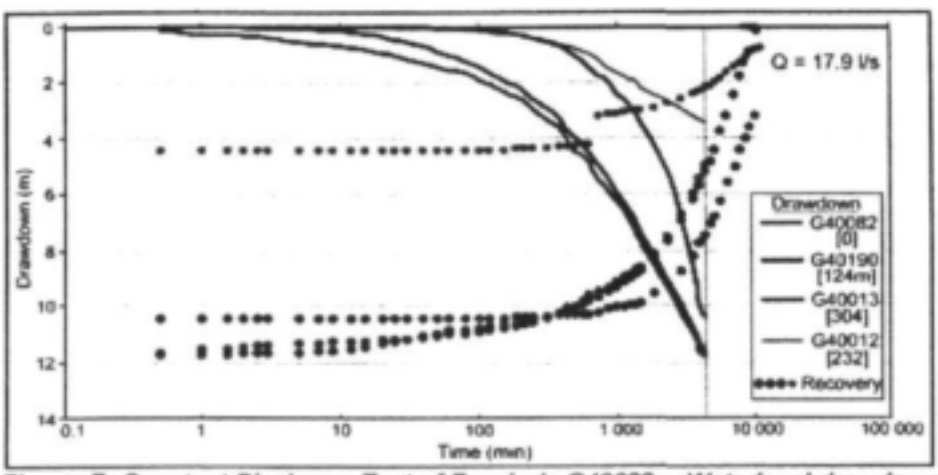



Figure F: *Constant Discharge Test of Borehole G40082 – Waterlevel drawdown and Recovery*

**SITE 5 – Borehole G46005A**

A 6-stage step-drawdown test was conducted on borehole G46005A located on an inclined inner-sill (**Figure 63**), where the discharge rate was varied between 2 and 13.5 l/s (**Table A** & **Figure G**). The 1st water-bearing fracture (± 4 l/s) at 28 m.bgl was dewatered during the 4th step at a discharge rate of 9.2 l/s.

A 3-day constant-discharge test was conducted at a discharge rate of 9.9 l/s and a maximum drawdown of 50m was attained after 3 days (**Table B** & **Figure H**). A total volume of 2553 $m^3$ of groundwater was abstracted from the aquifer during this test. Boreholes G46002, G46003, G46004 and G46005A intersected he same sub-horizontal, 'open' fracture at the base of the dolerite sill (**Figure 63**). This coupled with the confined nature of the aquifer resulted in the waterlevels in the observation piezometers mirroring those in the pumped borehole (i.e. acting as 'extended wells'). The aquifer parameters were estimated from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for confined, porous aquifers (**Table E**). The transmissivity values obtained using the Theis Method tends to underestimate the actual T-value of the fracture, due to its limited extent. Observation borehole G46002 represents the most northerly extent of this fracture system. The low storativity values are indicative of the confined nature and limited extent of this fracture system. Note the log-log linear drawdown of the waterlevel up until the 1st water-bearing fracture above the sill, whereafter the rate of decline decreases. The recovery data clearly indicates the 'recharging' of this partially de-watered, limited fracture and the resumption of the waterlevel rise thereafter. A waterlevel deficit in excess of 25m remained 3-days after pump shutdown, and a waterlevel deficit of 1.6m remained after some 23 days.

Hand measurements of waterlevels in borehole G40188 indicated no effect of pumping. Borehole G46006, situated some 590m southeast of G46005A, also showed no response to the pumping. Unfortunately, faulty automatic-recorders on observation boreholes to the northwest of borehole G46002 resulted in meaningless waterlevel information. Hand measurements of the waterlevel in borehole G40188 indicated that its waterlevel declined by 4.14m during the step-drawdown and constant-discharge tests. The waterlevel in this borehole continued to decline after pump shutdown on completion of the CD test.

**Table E**: *Borehole G46005A – Aquifer Transmissivity and Storativity Values*

| Borehole Number | Distance (m) | Drawdown | | Recovery |
|---|---|---|---|---|
| | | Transmissivity ($m^2$/day) | Storativity | Transmissivity ($m^2$/day) |
| G46005A | 0 | 22 | - | 28.9 |
| G46002 | 414 | 9 | $2.97 \times 10^{-6}$ | - |
| G46003 | 100 | 9 | $4.91 \times 10^{-5}$ | - |
| G46004 | 200 | 10 | $1.20 \times 10^{-5}$ | - |
| Average | | 12.5 | $2.14 \times 10^{-5}$ | - |

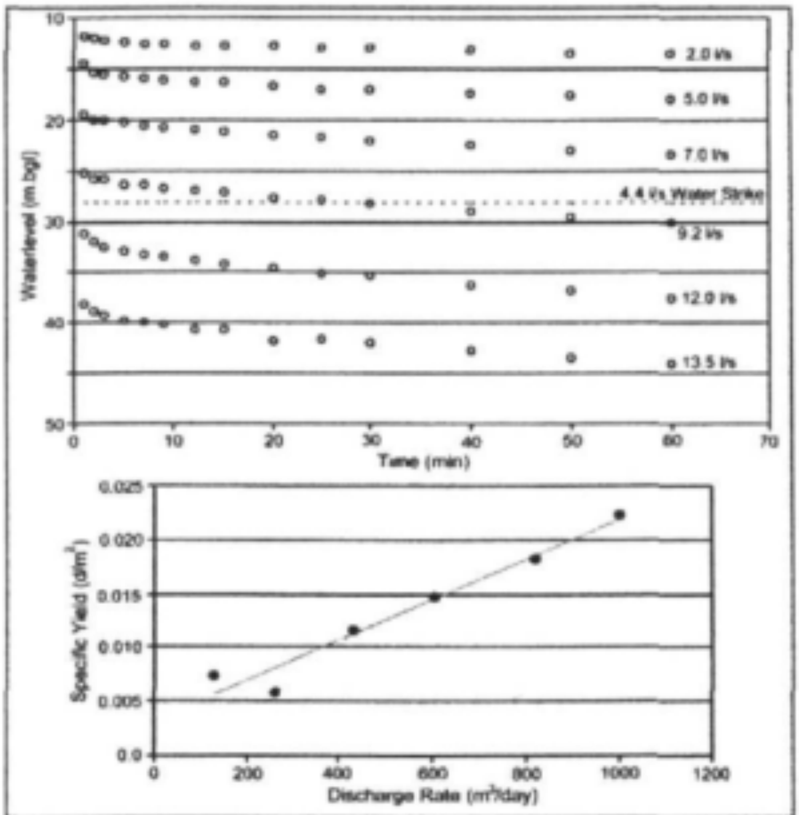



Figure G: *Borehole G46005A – Step-Drawdown Test*

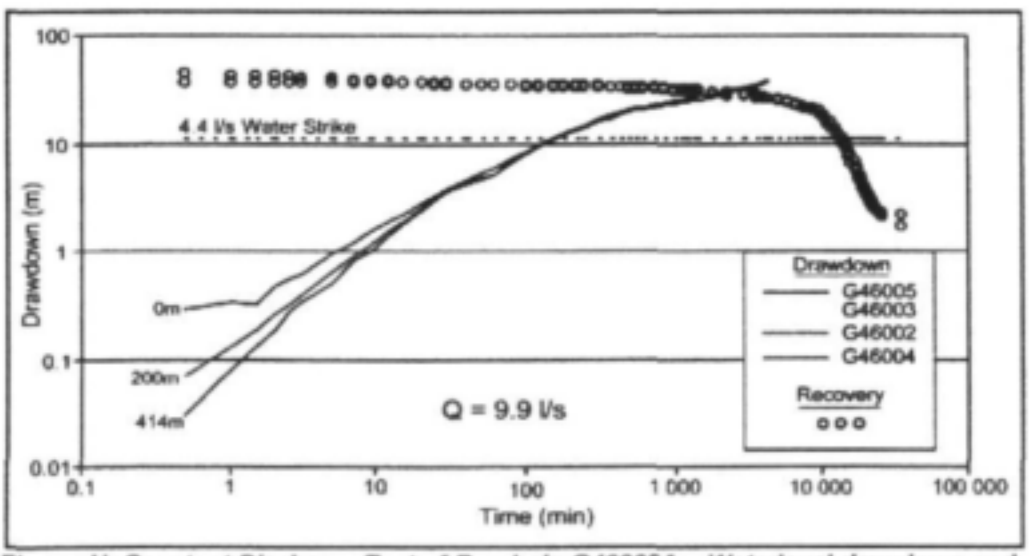



Figure H: *Constant Discharge Test of Borehole G46005A – Waterlevel drawdown and Recovery*

**<u>SITE 6</u> – Borehole G40196**

The production borehole, G40196, is drilled into the intersection between the outer-sill and a ring feeder-dyke (**Figure 64**). A 6-stage step-drawdown test was conducted on borehole G40196, where the discharge rate was varied between 1.5 and 11.6 l/s (**Table A & Figure I**). The 1$^{st}$ major water-bearing fracture (± 3 l/s) at 59 m.bgl was dewatered during the 6$^{th}$ step at a discharge rate of 11.6 l/s.

A 3-day constant-discharge test was conducted at a discharge rate of 7 l/s and a maximum drawdown of 22m was attained after 3 days of pumping (**Table B & Figure J**). The drawdown curves indicate the presence of a dual-porosity aquifer system, where initially fracture flow is dominant, followed by an intermediate period of lower rates of waterlevel decline and finally a period where both fracture and matrix flow dominates. The waterlevel in the pump borehole declined to the level of the 1$^{st}$ water-bearing fracture towards the end of the CD-test. The aquifer parameters were estimated from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for confined, porous aquifers (**Table F**). No waterlevel response was noted in borehole G40198, some 81m west of the production borehole, during the test. The waterlevels in the remaining boreholes did show response to the pumping, but faulty autographic recorders made the results the meaningless.

The limited extent of the fracture system is indicated by the extremely slow rate of recovery, where 3-days after pump shutdown the waterlevel deficit was still in excess of 10m (**Table B**).

**<u>Table F</u>**: ***Borehole G40196 – Aquifer Transmissivity and Storativity Values***

| Borehole Number | Distance (m) | Drawdown | | | Recovery |
|---|---|---|---|---|---|
| | | Transmissivity ($m^2$/day) | | Storativity | Transmissivity ($m^2$/day) |
| | | Early | Late | | |
| G40196 | 0 | 26 | 7 | - | - |
| G40195 | 10 | 26 | 13 | $1.20 \times 10^{-4}$ | - |
| G40197 | 20 | 55 | 15 | $2.90 \times 10^{-3}$ | - |
| Average | | 36 | 12 | $1.51 \times 10^{-3}$ | - |

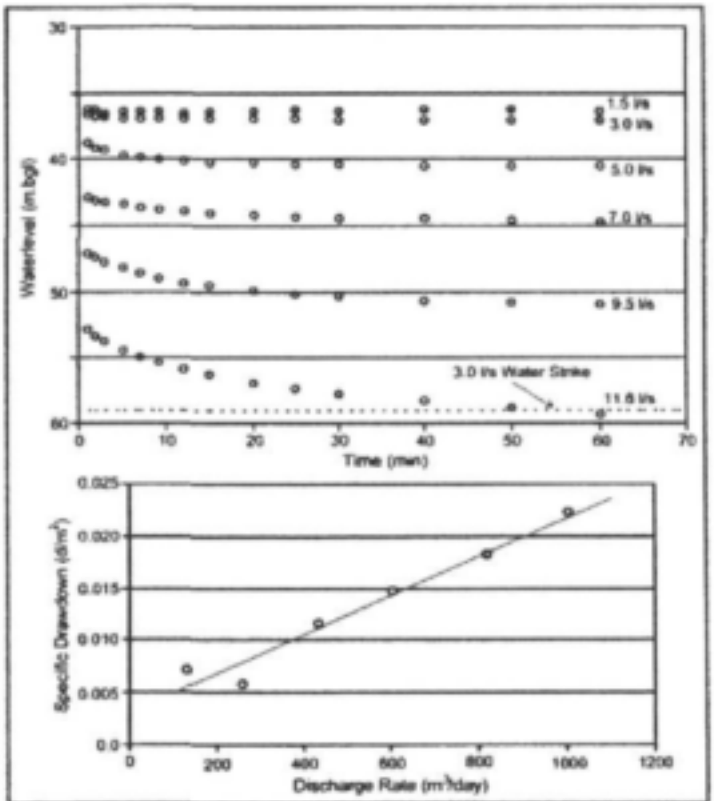



Figure I: *Borehole G40196 – Step-Drawdown Test*

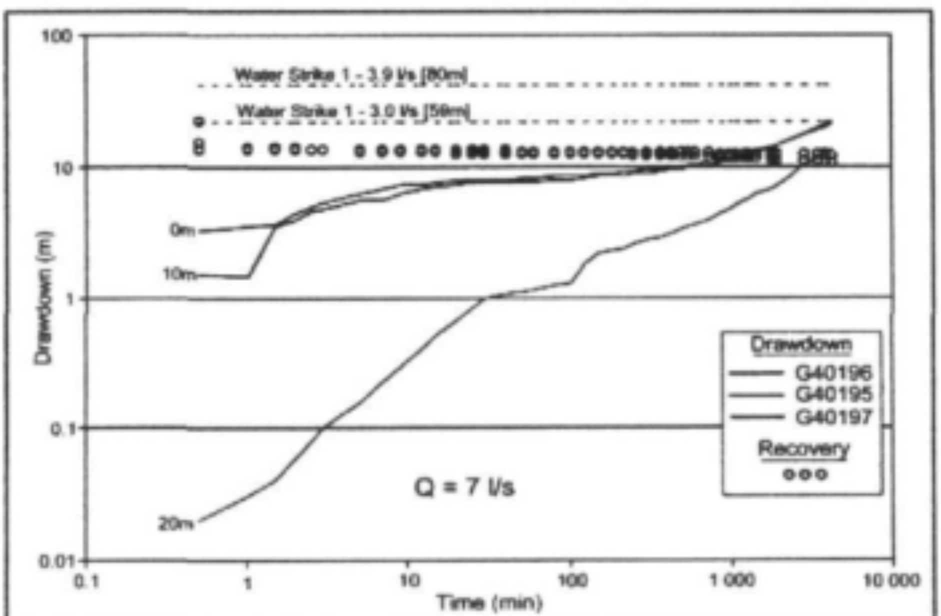



Figure J: *Constant Discharge Test of Borehole G40196 – Waterlevel drawdown and Recovery*

## SITE 7 – Borehole G40199

The production borehole, G40199, is drilled into the intersection between the inner-sill and a ring feeder-dyke (**Figure 65**). A 5stage step-drawdown test was conducted on borehole G40199, where the discharge rate was varied between 0.9 and 4.6 l/s (**Table A & Figure K**).

A 3day constant-discharge test was conducted at a discharge rate of 1.5 l/s and a maximum drawdown of 57m was attained after 3 days of pumping (**Table B & Figure L**). The waterlevel in observation piezometer G40204 declined rapidly after the only water-bearing fractures were dewatered, whereafter it mirrored the waterlevels in the pumping borehole. The waterlevel drawdown and recovery curves show clear inflections at a drawdown of 10-11m (**Figure L**), which corresponds with the position of a minor water-strike. This is interpreted to represent the base of the 'weathered' zone. Reasonable hydraulic parameters were estimated from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for confined, porous aquifers (**Table G**). The waterlevels in boreholes G40203 and G40202, situated on the opposite side of the dyke, did show a response to the pump testing (drawdown < 0.1m), but faulty autographic recorders made the data the meaningless.

Table G: ***Borehole G40199 – Aquifer Transmissivity and Storativity Values***

| Borehole Number | Distance (m) | Drawdown Transmissivity ($m^2$/day) | | Drawdown Storativity | Recovery Transmissivity ($m^2$/day) |
|---|---|---|---|---|---|
| | | Early | Late | | |
| G40199 | 0 | 3.5 | 1.1 | - | 0.5 |
| G40204 | 10 | - | 1.1 | $5.74 \times 10^{-4}$ | 0.8 |
| G40206 | 30 | - | 1.6 | $1.10 \times 10^{-3}$ | 1.0 |
| Average | | - | 1.2 | $8.37 \times 10^{-4}$ | 0.8 |

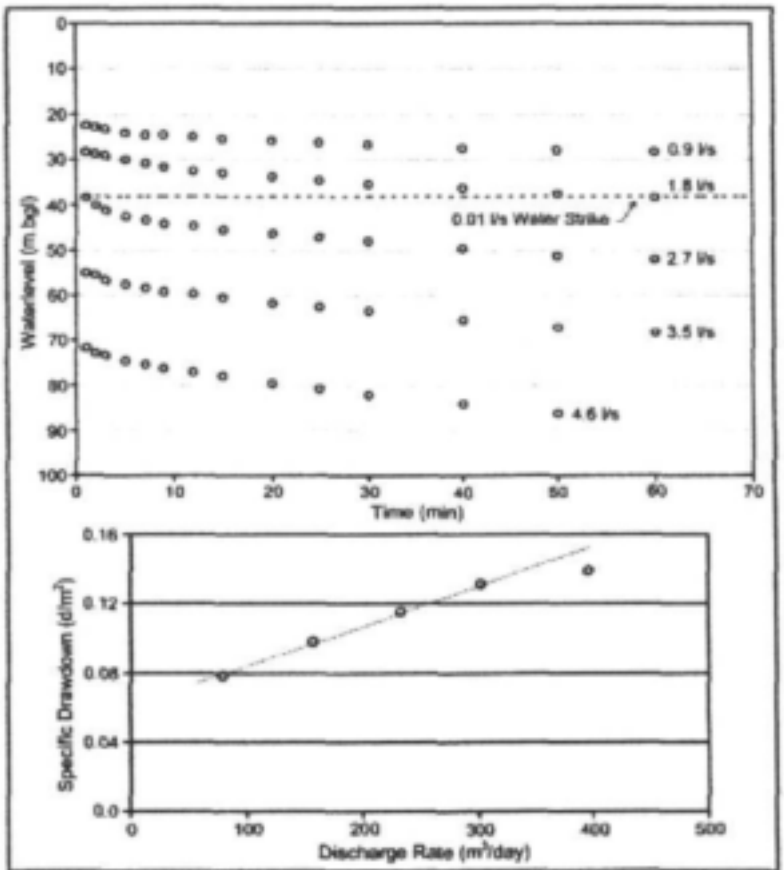



Figure K: *Borehole G40199 – Step-Drawdown Test*

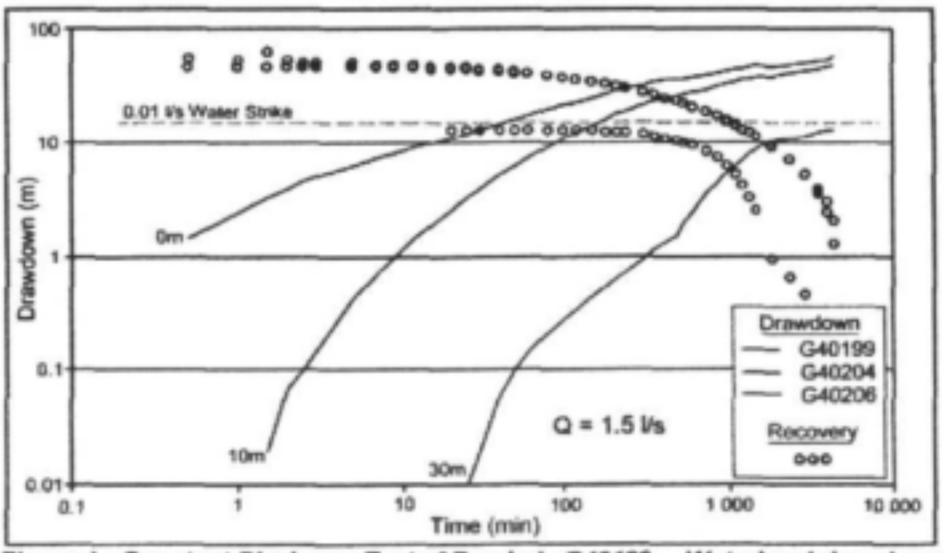



Figure L: *Constant Discharge Test of Borehole G40199 – Waterlevel drawdown and Recovery*

**SITE 8 – Borehole G46017**

The production borehole, G46017, is drilled into fractured sediments overlying an inner sill, and some 100m from a 9m wide dolerite dyke (**Figure 66**). A 6-stage step-drawdown test was conducted on borehole G40199, where the discharge rate was varied between 5.9 and 29.6 l/s (**Table A & Figure M**). During the test a significant water-bearing fracture (6 l/s) located at 15 m.bgl was partially dewatered during the $4^{th}$ step at a discharge rate of 20.4 l/s. This resulted in an upward deflection of the specific drawdown – discharge graph after the $4^{th}$ step and hence a non-linear curve was fitted to the data. In the Karoo, this inflection point commonly marks the lower limit of the more porous 'weathered-fractured' zone, wherein the majority of the groundwater is stored in these shallow aquifers.

A 3-day constant-discharge test was conducted at a discharge rate of 20.2 l/s and a maximum drawdown of 18m was attained after 72 hours of pumping (**Table B & Figure N**). The 6 l/s water-bearing fracture was dewatered after 80 minutes of pumping. The waterlevel recovery curves in boreholes G46017 and G46016 are almost identical after 10 minutes, yet the drawdown curves are offset from one another. A similar waterlevel response is, however, to be expected as both boreholes intercepted the same high-yielding fracture and thus the greater drawdown in the pumped well is ascribed to 'borehole losses' and turbulent flow in this borehole. Reasonable hydraulic parameters were estimated from the waterlevel drawdown and recovery data using the Theis Method (Kruseman & de Ridder, 1994) for extensive, confined, porous aquifers (**Table H**). It is interesting to note that the 9m wide dyke separating the pumping borehole from observation borehole G46018, some 410m away, does not act as a 'impermeable barrier' to groundwater flow and a maximum drawdown of 1.1m was recorded. The waterlevels recovered positively within 3 days of pump shutdown, but this is more related to the fact that the CD test was commenced prior to the full recovery of the waterlevels following the completion of the step-drawdown test (i.e. the CD-test started with a 2m waterlevel deficit – **Table B**)

Table H: *Borehole G46017 – Aquifer Transmissivity and Storativity Values*

| Borehole Number | Distance (m) | Drawdown Transmissivity ($m^2$/day) | Drawdown Storativity | Recovery Transmissivity ($m^2$/day) |
|---|---|---|---|---|
| G46017 | 0 | 55 | - | 109 |
| G46016 | 100 | 85 | $2.20 \times 10^{-4}$ | 126 |
| G46018 | 410 | 330 | $8.81 \times 10^{-4}$ | - |
| Average | | 157 | $5.51 \times 10^{-4}$ | 117 |

**Conclusion**

The pumping-tests clearly exhibited the highly variable yield capacity and heterogeneous nature of Karoo fractured-rock aquifers. In general, the aquifers associated with the Victoria West dolerite ring-complex are confined to semi-confined with an average bulk storativity value of $4 \times 10^{-4}$ and a transmissivity that varies from 1 to 300 $m^2$/day.

The aquifer-tests confirm the findings of this research project, that specific morpho-tectonic structures within dolerite ring-complexes represent major water-bearing features in Karoo fractured-rock aquifers. The tests also indicate that the intersection of the ring feeder-dykes with other intrusions, i.e. inner and/or outer sills and other transgressive dykes that represent more hydraulically extensive zones of intense fracturing.

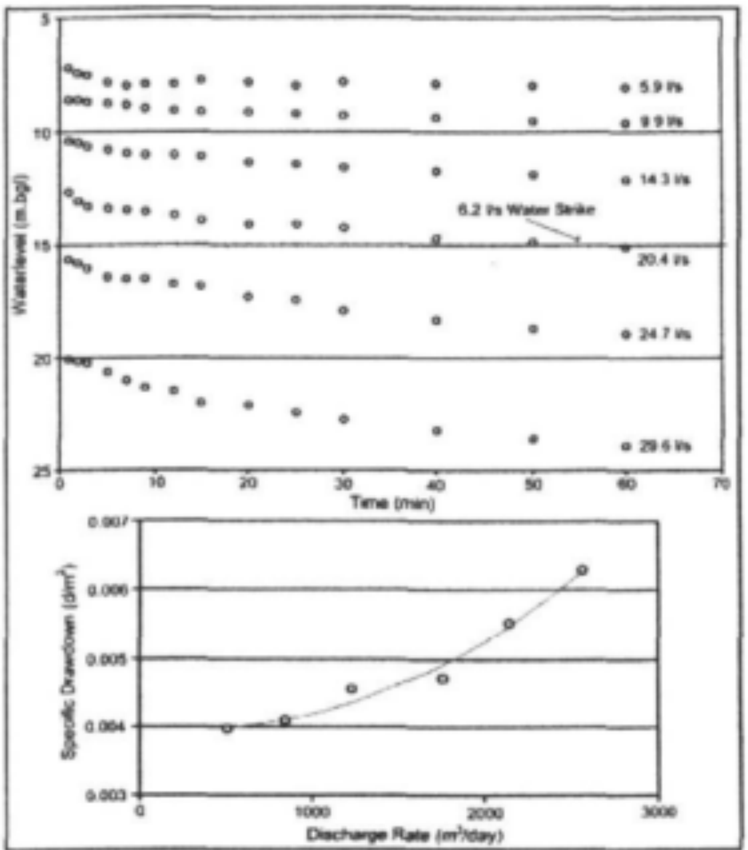



Figure M: *Borehole G46017 – Step-Drawdown Test*

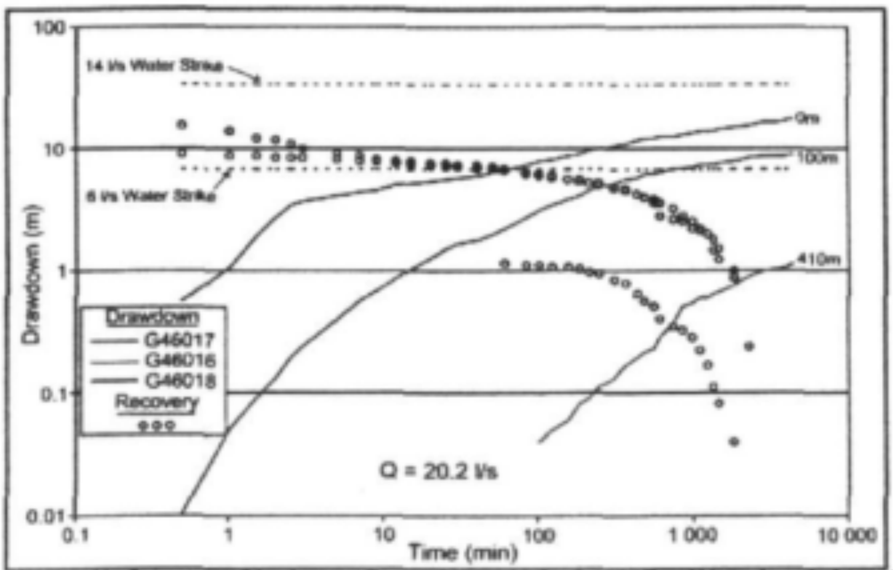



Figure N: *Constant Discharge Test of Borehole G46017 – Waterlevel drawdown and Recovery*

# ADDENDUM 2: ARCHIVING THE DATA

*Several original documents were used during the course of the project and several data sets were created*

## GEOLOGICAL MAPS

### Paper copies

The 1 / 250 000 maps of Victoria West, Middelburg and Queenstown have been published and can be obtained from the Council for Geoscience.

The 1 / 50 000 field maps of the study area are kept at the Council for Geoscience, Port Elizabeth branch office. They can be consulted and copies can eventually be acquired by contacting the Director of the Branch Office.

### Digital data

The sills of the regional study area and the local study area were captured at 1 / 250 000 and 1 / 50 000 scale respectively. Both products are archived at the Council for Geoscience as an Arc View project.

## GEOLOGICAL CROSS SECTIONS AND FIELD OBSERVATIONS

The various cross sections were drawn and captured at the Council for Geoscience, Bellville, where they can be consulted.

Further field information can also be obtained from the Council for Geoscience, Bellville or Port Elizabeth.

## DIGITAL TERRAIN MODELING

The regional Digital Elevation Model was built from raw data purchased from the Chief Surveyor General: Surveys and Land Information. The data set is in Arc/Info grid format and can be used with Arc/View 3 D analyst. The data can be consulted at the Council for Geoscience, Bellville.

The local Digital Terrain Modeling was created from digital vector data purchased from Chief Surveyor General: Surveys and Land Information. It can be consulted either at the Council for Geoscience, or at Toens and Partners in Arc/Info grid format.

## REMOTE SENSING

The Landsat satellite scenes WRS 173 - 82, 172-82 covering the Victoria West area were purchased during the Water Research Commission project 653.

The Landsat satellite scene WRS 171 – 82 was bought for the present project.

The Landsat satellite scene WRS 170 - 82 was bought by the Department of Water Affairs and Forestry in Bellville.

The above-mentioned images are archived at both Council for Geoscience and Toens and Partners. However, the respective purchasers hold the copyright.

## MAGNETIC SURVEY

The magnetic field and magnetic fabric were obtained from the Geophysics Department of the Council for Geoscience in Pretoria. The data can be consulted at Bellville Office. The magnetic field data set is in vector format (contour line), the magnetic fabric in raster format (.ers).

The High Resolution Airborne Data is archived in the Geophysics Department of the Council for Geoscience in Pretoria. Digital data includes: line number, fiducial, x, y, laser altimeter, GPS height, as well as the raw, leveled and micro-leveled magnetic data. The spectrometer data is supplied as a separate file. All grids are either in ER Mapper, Geosoft, Geopak, Surfer or USGS grid format.

## HYDROSENSUS

Hydrocensus data covering the regional study area is kept in the National Ground Water Data Base held at the Directorate geohydrology: Department of Water Affairs and Forestry, Bellville.

## BOREHOLE LOGS

The descriptions of the 37 borehole logs have been captured on the National Data Base of the Directorate Geohydrology: Department of Water affairs and Forestry in Bellville.

## AQUIFER TEST

The field data and results of the aquifer test (interpretation only given in addendum 1) are stored in excel format and archived at the Directorate Geohydrology, Department of Water Affairs and Forestry, Bellville.

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