IMPLICATIONS OF THE GEOLOGICAL STRUCTURE OF THE QOQODALA
DOLERITE RING COMPLEX FOR GROUNDWATER DYNAMICS

By

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I declare that **Implications of the geological structure of the Qoqodala dolerite ring complex for groundwater dynamics** is my own work, that it has not been submitted for any degree or examination in any other tertiary institution, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

O.L Nhleko

Signed ................................

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# TABLE OF CONTENTS

**TABLE OF CONTENTS** ........................................................................................................ iii
**ABSTRACT** ....................................................................................................................... v
**ACKNOWLEDGEMENTS** .................................................................................................. vi
**LIST OF FIGURES** ......................................................................................................... vii
**LIST OF TABLES** ........................................................................................................... xi
**LIST OF PLATES** ........................................................................................................... xi

**CHAPTER 1. INTRODUCTION** ......................................................................................... 1
  1.1 BACKGROUND ........................................................................................................... 1
  1.2 AIMS AND OBJECTIVES ......................................................................................... 2
  1.3 SELECTION OF THE STUDY AREA ..................................................................... 2

**CHAPTER 2. GENERAL DESCRIPTION OF STUDY AREA** .............................................. 4
  2.1 GEOGRAPHICAL SETTING .................................................................................. 4
  2.2 CLIMATOLOGY ....................................................................................................... 5
  2.3 GEOLOGICAL SETTING ....................................................................................... 7
    2.3.1 REGIONAL GEOLOGY .................................................................................. 7
    2.3.2 GEOLOGY OF THE QOQODALA AREA ...................................................... 11
  2.4 HYDROGEOLOGY .................................................................................................... 17
  2.5 WATER NEEDS AND SUPPLY ........................................................................... 18

**CHAPTER 3. PREVIOUS WORK ON FRACTURED-ROCK AQUIFERS ASSOCIATED WITH SILLS** ................................................................................................................. 22
  3.1 DOLERITE SILLS AND RING AQUIFER SYSTEMS ............................................. 22
  3.2 GAPS IN KNOWLEDGE IDENTIFIED .................................................................. 24

**CHAPTER 4. METHODOLOGY** ....................................................................................... 26
  4.1 GEOLOGY, STRUCTURE AND SELECTION OF EXPLORATION PROFILE .......... 26
    4.1.1 GEOLOGICAL MAPPING AND BOREHOLE SITING ................................. 26
    4.1.2 GEOLOGICAL CROSS-SECTIONS ......................................................... 27
    4.1.3 FRACTURE MAPPING ............................................................................... 27
    4.1.4 SELECTION OF EXPLORATION DRILLING PROFILE ......................... 27
  4.2 EXPLORATION DRILLING ....................................................................................... 28
    4.2.1 DRILLING AND MONITORING ................................................................. 28
    4.2.2 BOREHOLE LOGGING ............................................................................ 29
ABSTRACT

The rural community of Qoqodala in the Eastern Cape is challenged by numerous social problems, worsened by the application of ad hoc, non-sustainable water schemes. This research investigates the possible role of groundwater from fractured-rock aquifer systems in addressing the problem of the provision of good quality and sustainable water supplies for Qoqodala. The fundamentals of the National Water Act # 36, of 1998 are recognised in this research.

Previous hydrogeological work on fractured aquifer systems was confined to the more arid western region of the Karoo and needed to be expanded into the wetter eastern Karoo where Qoqodala is situated.

The research involved the structural analysis of a pilot site across a specific dolerite ring, and the analysis of the groundwater flow dynamics thereof. The structural analysis included geological mapping, interpretation of satellite imagery, fracture mapping, exploration drilling, borehole logging, geological cross-sections and geophysical profiling. Assessment of the groundwater flow dynamics was done using video imaging, geophysical logging and aquifer testing.

The practical aspects included the drilling of eleven exploration boreholes, of which three were pump tested and injection tests performed. Pump testing and subsequent monitoring revealed two aquifers; a shallow (unconfined) and deep (confined) aquifer system. Monitoring and video logging showed vertical water movement within the boreholes (upwards and downwards) and laterally within the aquifers which followed the local topography. Water pumped out of the boreholes during tests caused either lateral movement of water within the aquifers, or water loss from the shallow aquifer to the bottom aquifer, showing that drilling had linked the deep and shallow aquifers.

The Qoqodala dolerite ring complex is made-up of induced compartmentalisation of the rock mass, leading to various fractured-rock aquifers. The aquifers are characterised by different fracture connectivity and local recharge. Long- and short-term pumping rates from the three pump-tested boreholes indicate that the linked aquifer system is sustainable. Recharge to the system was only observed in Aquifer II, it is not clear how the other aquifers are being recharged. It is thus highly recommended that further research and monitoring be carried-out before the aquifer can be exploited.
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LIST OF FIGURES

Figure 1: Locality map showing the simplified geology in the study area and the position of WMA 12 (highlighted in pink in the insert). Map compiled using 1: 250 000 geological data.

Figure 2: Mean Annual Precipitation, evapotranspiration and deficit/surplus pattern distribution throughout the Karoo Basin (Chevallier et al., 2001) compiled from data supplied by the Computing Centre for Water Research.

Figure 3: Mean Annual Precipitation distribution map of Queenstown and surrounding area. Map compiled using data from the Computing Centre for Water Research.

Figure 4: Simplified Lithostratigraphy of the Karoo Supergroup compiled from the 1: 1 000 000 geological map of South Africa. The area inside the square shows the greater study area for the WRC project No.1238 (same as in figure 2); the drill site is located northeast of Queenstown.

Figure 5: Simplified cross-section of the Eastern Karoo basin from Queenstown to the Drakensberg, showing the relations between the Jurassic Drakensberg flood basalts and the dolerite intrusions forming the roots and feeders of the system (After Chevallier et al., 2001).

Figure 6: Morpho-tectonic model of the dolerite sill and ring complex of the Queenstown area, showing the stacking and box-like intrusion of the dolerite (Chevallier et al., 2001).

Figure 7: Landsat 7 image (bands RGB321, true colours) of the Qoqodala study area northeast of Queenstown, showing the saucer-shaped dolerite rings. Bonkolo Basin (commercial farming) shows green segmented areas in the flat plains, and Vaalbank (traditional communal farming) is characterised by barren lands shown in light blue.

Figure 8: Geological map of the dolerite intrusions (sills, rings and dykes) compiled from various sources (Qoqodala study area covers four 1: 50 000 topocadastral sheets).

Figure 9: Cross-sections across the four map sheets (see figure 8 for location). Borehole logs from Rural Support Services’ report were used to calibrate the sections. The exploration drill site of the present study is shown on section B-B”. Different vertical scales are used to better illustrate the geometry of the dolerite intrusions.

Figure 10: Lithostratigraphic profile of the Burgersdorp Formation at Nonesi’s Nek, on the eastern rim of Bonkolo basin (Adapted from Hancox, 1998).
Figure 11: Social implications tied to water needs in rural settlements of the former Transkei homeland: Piped water availability.

Figure 12: Chevallier et al.’s (2001) hydro-morpho-tectonic model of a Karoo dolerite sill and ring complex showing the relation between deep and shallow fractured aquifers.

Figure 13: Seamless geological map compiled from four 1:50 000 digitized geological field maps, showing the prominence of the northwest and northeast structural trends.

Figure 14: Fractures mapped from Landsat 7 satellite image. The dolerite rings and sills (in pink) are wrapped over the image.

Figure 15: Three viewpoints of the Qoqodala exploration drill site; A is a picture of the drill site taken from the top of the adjoining ring. B shows the exact positions of the boreholes. C is an Aster image of the same area, also showing the boreholes.

Figure 16: The first step of data processing on graph paper: The geology and the corresponding elevations have been captured next to the boreholes. Only 8 boreholes had been drilled at this stage.

Figure 17: The digitized boreholes showing the correlation between lithologies, for the Qoqodala exploration drilling cross-section.

Figure 18: Geological cross-section of the Qoqodala dolerite ring, showing the boreholes lithologies and water strikes. A and B refer to observation points described during downhole geophysical logging.

Figure 19: The positions of the different sized transmitter and receiver loops with respect to the boreholes, showing the 28 stations of the TDEM profiling.

Figure 20: The two geo-electrical cross-sections from TDEM showing the resistivity (Ohm) of major lithologies and water-saturated layers for shallow (A) and greater (B) depth.

Figure 21: The final product of TDEM profiling incorporated with borehole logging in order to get the geometry of the dolerite, and to show layering of the dolerite sills.

Figure 22A: Geophysical logs for borehole BH1 at 55.1 m. Video image shows water movement and bacteria being sucked into the fracture.

Figure 22B: The geophysics of borehole BH1, highlighting the 176.1 m depth water strike. The sonic log indicates fracturing, while the video recording does not, neither in the sandstone nor the dolerite above. No water movement detected.

Figure 23A: The geophysics of borehole BH5 at depth 36.1 m. The sonic log and the other geophysical logs are in agreement with the fracturing noted on the
video recording. Fractures may be obscured by bacteria in borehole water.

Figure 23B: Note that the fracture indicated on the video image at 172.7 m in borehole BH5, is not clearly supported by the sonic and the water quality logs.

Figure 24A&B: Geophysical data for borehole BH7, depicting the depths of interest at 48 m and 264 m respectively.

Figure 25A&B: Geophysical results from borehole BH9, at depths 40 - 46 m and 112 - 120 m respectively. Note the anomaly at 44 m and 116 m.

Figure 26: Local groundwater movement within boreholes, and the corresponding temperatures. Water occurrences at the intersected fractures and water strikes add to the complexity of the groundwater flow dynamics.

Figure 27: The nine ‘steps’ of the step-drawdown test for borehole BH11, extracted from Aquimon database (software developed by A. Woodford).

Figure 28: A) The effect of the constant discharge test on Borehole BH11 and the surrounding boreholes 9 and 10. B) The graphical drawdown effects during pump testing. Analysis performed by A. Woodford in Chevallier et al., 2004a and 2004b.

Figure 29: Step-drawdown test results for borehole BH7 showing start and finish water levels, as well as the start of the recovery after the test. Data extracted from Aquimon database (software developed by A. Woodford).

Figure 30: A) The effects of the constant discharge test on borehole BH7 and the surrounding boreholes. B) The graphical drawdown effects during pump testing. Analyses performed by A. Woodford in Chevallier et al., 2004a and 2004b.

Figure 31: The summarised nine ‘steps’ of borehole BH1 for the step-drawdown test. Graph extracted from Aquimon (software developed by A. Woodford).

Figure 32: A) The effect of the constant discharge test on borehole BH1 and the adjacent boreholes. B) The graphical drawdown effects during pump testing. Analyses performed by A. Woodford in Chevallier et al., (2004a and 2004b).

Figure 33: The positions of the packer into each borehole during the injection tests, with respect to the water strikes intersected during drilling.

Figure 34: Water level response in borehole BH5 due to injection in borehole BH1.

Figure 35: Water level response in borehole BH7 due to injection in borehole BH1.

Figure 36: Water level response in borehole BH10 due to injection in borehole BH10A.

Figure 37: Water level response in borehole BH 7 due to injection in borehole BH10A.
Figure 38: Water level monitoring of the Boreholes BH1, Bh1A, BH1B, BH4 and BH5 (southwestern compartment) over a three year period, starting on 9 December 2002. Data for figure extracted from Aquimon (software developed by A. Woodford).

Figure 39: Water level monitoring of the boreholes BH7, BH8, BH9, BH10 and BH11 (northeastern compartment) over a three year period, starting on 9 December 2002 for boreholes BH7, BH8 and BH9 and on 7 March 2003 for borehole BH 10 and 24 June 2003 for borehole BH11. Data for figure extracted from Aquimon (software developed by A. Woodford).

Figure 40: Water level measurements for boreholes BH5 and BH7 for the monitoring done using divers (after aquifer testing). The water level fluctuations are viewed with the corresponding rainfall period to see the effect thereof.

Figure 41: Natural and 'Induced' Groundwater flow pattern of the Qoqodala drill site (After Chevallier et al, 2004b).
LIST OF TABLES

Table 1: Hydrological data of the exploration boreholes in Qoqodala (from Chevallier et al., 2004a and 2004b).

Table 2: The results of the injection test, showing the depth and location of the packer and the rate of injection.

LIST OF PLATES

Plate 1: The Burgersdorp Formation at Nonesi’s Nek, northeast of Queenstown. The succession is characterised by a 50 m thick middle sandstone marker shown in the foreground. The red line corresponds to the cross-section in Figure 10.

Plate 2: A protected spring in Luxeni village, situated on the southeastern rim of the Qoqodala ring structure. The spring occurs in the foothills, and is mainly used for household purposes. Photo taken by Luc Chevallier.
CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The South African water policy (National Water Act No. 36, 1998) states that every household should have access to clean water by 2020. Poverty alleviation and the sustainable use of natural resources are high priorities for the Department of Water Affairs and Forestry (DWAF). However access to clean potable water and sanitation is a difficult challenge, especially in rural areas. The Transkei, a former homeland that now falls under the Mzimvubu to Keiskamma Water Management Area (WMA) No. 12, has the highest level of underdevelopment and poverty in South Africa. This area has problems such as land degradation, insufficient and non-sustainable ad hoc water schemes, as well as social problems such as unemployment. The population is widely scattered and the development of infrastructure such as a water scheme is not easy due to large distances between city centres and settlements.

New sources of sustainable water supply need to be investigated in order to address the needs of the population, especially in rural areas. South Africa is among the world leaders in surface water resource management, but groundwater resources are nonetheless underutilised. Surface water needs to be treated before use and is vulnerable to drought, while groundwater has the potential to address most of the requirements for water supply in rural areas. Infrastructure development for groundwater delivery is less costly as opposed to that for surface water, making it ideal for dispersed rural settlements. Furthermore, in most cases groundwater does not usually require treatment before use whereas surface water need to be treated.

Fundamental to groundwater exploitation is the need for refined targeting of boreholes, because of the often low yields of the aquifers. The Water Research Commission (WRC) and the Department of Water Affairs and Forestry, have for the past 20 years supported intensive hydrogeological research, in Karoo fractured-rock aquifers in particular (Vandoolaegehe, 1980a and 1980b, Botha et al., 1998; Woodford and Chevallier, 2002a). Karoo dolerite intrusions (dykes, sills and rings) have been associated with high groundwater yields. Often these intrusions are deep, and develop into extensive fractured-rock aquifer systems that form successful drilling targets.

This research forms part of a Water Research Commission project, WRC No. 1238 (Chevallier et al., 2004a). It was co-sponsored by the Department of Water Affairs and Forestry who provided exploration drilling and aquifer testing, the Council for Geoscience
who provided extensive geological mapping, structural analysis and remote sensing applications, and NorskHydro and Volcanic Basin Petroleum Research, in Oslo. The participation of the latter formed part of a bilateral agreement between South Africa and Norway, and provided financial and technical assistance for aquifer testing.

1.2 AIMS AND OBJECTIVES

The chief aim of this project is to investigate the groundwater flow dynamics of the various fractured-rock aquifers (deep and shallow) associated with Karoo dolerite ring complexes in the Qoqodala area (northeast of Queenstown in the Eastern Cape Province). Groundwater associated with deep structures can be of strategic importance in water supply schemes for scattered rural settlements. Where the yield of the deep groundwater system is found to be higher than the shallow groundwater, the sustainability needs to be proven. The dynamics of the system i.e. geometric, structural and flow relation between deep, and shallow aquifers, must be investigated in order to understand its sustainability during abstraction.

The project has two objectives:

(i) Structural analysis of a pilot site across a specific dolerite ring by means of field mapping, satellite image interpretation, fracture mapping, exploration drilling, borehole logging, geophysical profiling, and geological cross-sections across the intrusion.

(ii) Assessment of the groundwater flow dynamics of the fractured-rock aquifer associated with dolerite intrusion, using video camera, geophysical logging, the results of pump tests and injection tests.

1.3 SELECTION OF THE STUDY AREA

The density of dolerite intrusions in the Eastern Karoo Basin is particularly high (Woodford and Chevallier, 2002b). The study area, the Qoqodala dolerite ring system, was selected during the course of WRC project No. 1238 (Chevallier et al., 2004a) for which a local pilot site was required to test the relations between groundwater associated with dolerite rings, springs and ecosystems. In terms of groundwater research more has to be done in the eastern region of the Eastern Cape Province, where the water needs are extreme (Vandoolaeghe, 1980a).
The Great Kei catchment, located in the Eastern Karoo was deemed ideal due to its wetter climate, the occurrence of dolerite intrusions and the many springs that are present (they form an important part of the water supply for the local community) (Gibson, 2003).

The study on the Qoqodala dolerite ring complex is primarily based on an exploration drill site situated between two villages, Manelspoort and Lalini, alongside the road from Qoqodala to the Zingqutu settlements (northeast of Queenstown). This particular site was chosen because of easy accessibility and the need for water supply in the area.

The study area was also selected on the basis of previous work and scientific knowledge already acquired:

- Du Toit showed the complex structural nature of dolerite intrusions. He proposed several models based on his field observations and mapping (Du Toit, 1905 and 1920) and proposed a mechanism of emplacement.

- The Karoo stratigraphy of the region has been well investigated, mapped and documented. Several profiles of the Tarkastad Subgroup (Karoo stratigraphy) have been described, especially the Burgersdorp Formation (see section 2.3.1) (Hancox, 1998).

- Several groundwater investigations on dolerite intrusions have been carried-out in the area in the past. High yields and sustainable groundwater potential have been shown by exploration drillings by Smart (1998), Rural Support Services (1994) and Vandoolaeghe (1980a).
CHAPTER 2. GENERAL DESCRIPTION OF THE STUDY AREA

2.1 GEOGRAPHICAL SETTING

The Qoqodala study area falls within the Water Management Area (WMA) No. 12, in the Eastern Cape Province (Figure 1). Within the WMA an initial area covering four 1: 50 000 sheets around Queenstown was selected. These sheets are Queenstown (3126DD), Vaalbank (3126DB), Bolotwa (3127CC) and Lady Frere (3127CA). The specific geographic location of the drill site is 26 km northeast of the town of Queenstown.

Figure 1: Locality map showing the simplified geology in the study area and the position of WMA 12 (highlighted in pink in the insert). Map compiled using 1: 250 000 geological data.
2.2 CLIMATOLOGY

The Karoo region receives summer rainfall, with the exception of the southeastern region which receives rainfall throughout the year. Figure 2 shows the mean annual precipitation, evapotranspiration and deficit/surplus pattern throughout the Karoo region. Although general estimates are shown for the different climate parameters, the broader study area (indicated by the box) shows a higher annual evapotranspiration rate than the annual precipitation. A deduction that the study area is a dry-land is thus made (Computer Centre of Water Research (CCWR)).

Mean annual precipitation ranges from 300 to more than 1000 mm, in the western and eastern Karoo regions respectively. There is a direct correlation between elevation above sea-level and rainfall; the higher elevation areas receive more rain (Smart, 1998). Queenstown’s topography ranges from 800 to 1200 m, and Qoqodala is in the 1200 to 1600 m range, as seen on the 1: 50 000 topographic maps.

The dolerite rings may be large scale features forming topographical highs, and controlling morphology. Consequently they receive more rainfall than the flatter inner part of the ring system (topographic lows). This situation is applicable to Qoqodala settlement where the mean annual precipitation map shows that Qoqodala receives between 600 and 800 mm, while Queenstown receives between 400 and 600 mm (Figure 3). Qoqodala ring settlement receives orographic rainfall due to the surrounding dolerite ring, and it is also at a higher elevation than Queenstown that receives normal seasonal rainfall and is located away from the dolerite rings.

The study area has a mean annual temperature of 15°C. During winter nights temperatures can drop to below zero, and rise to more than 40°C during summer days. Frost characterises most winter mornings, with the occasional light snowfall (Smart, 1998).

The relative aridity coupled with the steep slopes present in the study area promotes land degradation.
Figure 2: Mean Annual Precipitation, evapotranspiration and deficit/surplus pattern distribution throughout the Karoo Basin (Chevallier et al., 2001) compiled from data supplied by the Computing Centre for Water Research.
2.3 GEOLOGICAL SETTING

2.4.1 REGIONAL GEOLOGY

The region of the Great Kei catchment covers part of the Karoo basin underlain by the Triassic (245-208 Ma) continental sediments of the Beaufort Group (Karoo Supergroup) that were later intruded by the Jurassic dolerite intrusions (sills, dykes and ring complexes) (Figure 4) (Visser, 1984).

The Karoo sediments cover more than half of South Africa and have been deposited from Late Carboniferous (310 Ma) to Mid Jurassic (185 Ma) period, as a foreland basin of the Cape Fold Belt (CFB) Orogeny. Sedimentation within the basin occurred through cycles of orogenic loading and unloading in the CFB. Episodes of subsidence and increase in accommodation structure adjoining the fold belt correlate to episodes of uplift and a decrease in accommodation structure away from the thrust belt (Catuneanu et al, 1998).
The Cape Orogeny has deformed the southern margin of the basin severely, while the interior away from the CFB was gently folded (Cole, 1992). Sub-horizontal beds with a slight 5 ° dip northwards are observed in the study area (north of Queenstown) (Johnson et al., 1997).

The main Karoo Basin stratigraphy and evolution are well documented by Cole (1992), Veevers et al. (1994) and Johnson et al. (1997). The Karoo Supergroup is made up of up to 12 000 m of sedimentary strata filling the southern part of the basin, and is capped by 1 400 m of basaltic lava now outcropping in the Drakensberg (Cole, 1992 and Johnson, 1991) (Figure 5). The succession is subdivided into the extensive Dwyka Group (tillites), the Ecca Group (marine shales), the Beaufort Group (mudstone, siltstone and sandstone), Molteno Formation (sandstone and mudstone), Elliot Formation (sandstone and mudstone) and Clarens Formation (sandstone and siltstone).

During the Late Carboniferous to Early Permian period, glacial processes deposited the Dwyka Group sediments. These rocks are the basement of the Karoo Supergroup and consist mainly of diamicrite (predominantly tillites) and other rock types related to glacial processes (Cole, 1992).

The Permian Ecca Group (245-286 Ma) is characterised by appreciable lateral facies that change at the scale of the basin. It consists of shales, siltstones, mudrocks and sandstones that were deposited in a rapidly downwarping foreland basin through submarine fans and turbidites, as well as pro-deltas and deltas. Numerous plant fossils, especially *Glossopteris*, are found in the Ecca Group (Visser, 1984).

The Beaufort Group consists of the Adelaide and Tarkastad Subgroups (aged ~260 Ma and ~240 Ma respectively). The Adelaide Subgroup comprises bluish-grey mudstones with alternating grey sandstones (fine-to-medium grained). The mudstones represent a flood plain depositional environment, while lateral migration of meandering rivers is considered to be responsible for the deposition of the sandstone. (Johnson et al., 1997; Cole, 1992)

The Tarkastad Subgroup consists of the lower 700 m thick sandstone-rich (>30 %) Katberg Formation and the overlying 700 m thick mudstone-rich Burgersdorp Formation (Hancox, 1998).

The Molteno Formation (Late-Triassic age) consists of medium-to fine-grained pale sandstones and pale olive mudstones. Fine-to medium-grained sandstones and predominant greyish-red mudstones make up the Elliot Formation (late Triassic to early
Jurassic). The middle Jurassic Clarens Formation consists of well-sorted wind-blown, fine-grained sandstone and siltstone (Johnson et al., 1997).

The Karoo basalts extruded at the top of the Karoo Supergroup sediments during the Mid-Jurassic (183 Ma) period (Duncan et al., 1997). This extensive magmatic activity is recorded in Southern Africa, Antarctica, Western Australia and Tasmania, and is associated with the early stages of Gondwanaland break-up. The basalts are thought to originate from large mantle plumes. The total volume of the emplaced magma covers several million km$^3$, making it one of the largest flood basalt outpourings in the world. On the Southern African continent alone an estimated 10 million km$^3$ of magma was extruded (White, 1997).

Dolerite dykes, sills and rings of the Karoo represent the roots and the feeders of the Drakensberg volcanism (Figure 5). They are very common in the study area and control the geomorphology of the landscape. These geological structures were first mapped by Du Toit (1905, 1920). The dykes, sills and rings form a complex, interconnected network that can possibly be attributed to one magmatic event (Chevallier and Woodford, 1999).

![Figure 4: Simplified Lithostratigraphy of the Karoo Supergroup compiled from the 1: 1 000 000 geological map of South Africa. The area inside the square shows the greater study area for the WRC project No.1238 (same as in figure 2); the drill site is located northeast of Queenstown.](image)
Figure 5: Simplified cross-section of the Eastern Karoo basin from Queenstown to the Drakensberg, showing the relations between the Jurassic Drakensberg flood basalts and the dolerite intrusions forming the roots and feeders of the system (After Chevallier et al., 2001).

Flat lying dolerite sills (40 to 80 m thick) are well developed within the Ecca Group and at the base of the Beaufort Group, while saucer-shape dolerite rings are more common in the upper part of the succession i.e. Beaufort Group, Molteno and Elliot Formations (Chevallier et al., 2001).

The dolerite rings of the Queenstown area result from a complex interaction of flat sills and inclined sheets, leading to a box-type pattern in cross-section (Figure 6). This type of structural pattern was also identified in Victoria West and Loxton, and has been proven to be conducive to the occurrence of deep fractured-rock aquifers (Chevallier et al, 2001).

Figure 6: Morpho-tectonic model of the dolerite sill and ring complex of the Queenstown area, showing the stacking and box-like intrusion of the dolerite (Chevallier et al., 2001).
2.3.2 GEOLOGY OF THE QOQODALA AREA

The morphology in the study area is characterised by coalescing dolerite rings. The Landsat 7 satellite image (Figure 7) shows that the dolerite rings strongly influence the morphology and the drainage system of the region. The satellite image encompasses four 1: 50 000 topocadastral maps and includes the settlements of Qoqodala, Zingqutu, Vaalbank (the biggest settlement to the north of Qoqodala) and Bonkolo (Figure 7). The first three settlements are part of the former Transkei homeland where communal lands are characterised by sparse vegetation and bare soil as opposed to the lush vegetation seen in the area of the commercial farming in the former South Africa (Bonkolo basin).
Figure 7: Landsat 7 image (bands RGB321, true colours) of the Qoqodala study area northeast of Queenstown, showing the saucer-shaped dolerite rings. Bonkolo Basin (commercial farming) shows green segmented areas in the flat plains, and Vaalbank (traditional communal farming) is characterised by barren lands shown in light blue.
A geological map of the dolerite intrusions was compiled at the scale of 1: 50 000 from existing field sheets (Council for Geoscience archives), aerial photographic interpretation, satellite image (Landsat 7) analysis and field work (Figure 8).

Three cross-sections were drawn across the study area (Figure 9) with the aid of existing geological field maps. Their locations were chosen so as to include borehole information collected by Rural Support Service (1994). The sections show the structural interference (ring within ring system) and cross cutting of the dolerite sills, rings and dykes. An inclined sheet can feed more than a single ring system. In accordance with the model of Chevallier et al. (2001) saucer-shaped dolerite rings consist of an inner flat-lying sill (60 m thick), an inclined sheet (up to 120 m thick) and an outer sill (also 60 to 80 m thick). Thin dolerite offshoots (10 to 20 m thick) are also very common.

The Qoqodala study area is essentially underlain by the mudstones and sandstones of the Burgersdorp Formation that belongs to the (240 Ma) Tarkastad Subgroup. The Burgersdorp Formation is well exposed at Nonesi’s Nek, on the eastern rim of the Bonkolo ring, where about 500 m of the succession is exposed (Figures 10). The Burgersdorp Formation in the Queenstown-Lady Frere area has a thickness of 700 m and the mudstones make up 70 to 80% of the sediments, whereas the sandstone can reach thicknesses of 10 m (Hancox, 1998; Groenewald, 1996).

A laterally extensive 50 m thick sandstone bar occurs in the middle of the succession and is referred to as the middle marker (Groenewald, 1996; Hancox, 1998). It is easily identifiable in the field (Plate 1) and occurs at an elevation of 1100 m. It could have a very significant importance from the hydrogeological view point (different permeability, porosity, fracture density) if it has a large regional extension.

A similar sandstone bar was found at the same elevation in the Qoqodala exploration drilling profile (see section 5.1.2).
Figure 8: Geological map of the dolerite intrusions (sills, rings and dykes) compiled from various sources (Qoqodala study area covers four 1: 50 000 topocadastral sheets).
Figure 9: Cross-sections across the four map sheets (see figure 8 for location). Borehole logs from Rural Support Services’ report were used to calibrate the sections. The exploration drill site of the present study is shown on section B-B". Different vertical scales are used to better illustrate the geometry of the dolerite intrusions.
Figure 10: Lithostratigraphic profile of the Burgersdorp Formation at Nonesi’s Nek, on the eastern rim of Bonkolo basin (Adapted from Hancox, 1998).
Plate 1: The Burgersdorp Formation at Nonesi’s Nek, northeast of Queenstown. The succession is characterised by a 50 m thick middle sandstone marker shown in the foreground. The red line corresponds to the cross-section in Figure 10.

2.4 HYDROGEOLOGY

The Karoo Supergroup sediments in the study area are mainly sandstones, shales and mudstones of the Beaufort Group. During intrusion of dolerites, intensive fracturing formed in the older Karoo Supergroup sediments, and it is these fractures that are frequently targeted in groundwater exploration (Vandoolaeghe, 1980a). However, sedimentary rocks of the Beaufort Group are seldom targeted for large groundwater schemes in the study area, due to their lack of primary porosity and permeability (Woodford and Chevallier, 2002a). During intrusion, local sediments were baked, with veins of calcite and quartz introduced. Shallow fractured aquifers in the weathered zone (30 to 60 m) can only yield sufficient water for local supply (Vandoolaeghe, 1980a, 1980b). These fractured aquifers probably correspond to a set of horizontal fractures that develop close to the surface as a result of stress off-loading (Chevallier et al, 1999).

Alluvium and other quaternary deposits are poorly developed, except west of Queenstown in the Swart Kei River sub-catchment (Vandoolaeghe, 1980b). Here the mean saturated
thickness of the alluvial aquifer is 8 m and can yield a maximum of 5 ℓ/s. Unfortunately, heavy abstraction due to irrigation has resulted in a piezometric depression.

Groundwater yields associated with dolerite intrusions are higher than those from sedimentary rocks, and the boreholes in the former are statistically more successful (Smart, 1998). Yields from sedimentary rocks are generally less than 1 ℓ/s, whereas yields greater than 5 ℓ/s are found in areas associated with dolerites. The incidence of high yielding boreholes in the 3 - 10 ℓ/s range is relatively high in the Queenstown area, and has been estimated at greater than 15 % (Smart, 1998).

Dolerite dykes are usually preferred drilling targets because their secondary permeability is increased due to shrinkage joints that developed during cooling of the intrusion, and because they act as conduits for groundwater flow (Woodford and Chevallier, 2002b). Dolerite sill and ring complexes have, however, seldom been targeted. However Vandoolaeghe (1980a and 1980b) and Rural Support Services (1994) report the presence of water-bearing fractures near dolerite sheets/sills.

Agricultural irrigation requirements in the Queenstown area are high and thus make it a major focus for groundwater abstraction. The surrounding rural communities, excluding commercial farms, use little groundwater (Smart, 1998). These rural dwellings are scattered and located far from the water source. About 40 000 to 80 000 m³/km² of groundwater can be harvested from the area northeast of Queenstown. This is the maximum sustainable abstraction volume according to Smart (1998).

Springs and seeps form an important source of water for communities in the study area. They can occur at different elevations along dolerite rings, commonly at the base of the slope. According to the survey conducted during the project, the communities situated in the foothills rely to a large extend on these springs and even use them for stock watering. Numerous springs, seeps and wetlands are located at higher altitude and correspond to perched water tables. They occur along fractures, which are characterised by the incidence of thick grass, in contrast to the surrounding indigenous Karoo shrubs (Gibson, 2003).
2.5 WATER NEEDS AND SUPPLY

About 14% of the South African national population is found within the Eastern Cape Province, where only a third of that population live in urban centres. The study area (a rural settlement) experienced intense overgrazing that has resulted in increased runoff and erosion, resulting in the formation of dongas. People rely mostly on non-perennial springs, dirty run-off and hand-pump boreholes (drilled ad hoc) for water. These methods however, appear generally unsustainable. Commercial farming utilising irrigation and municipal water supply rely, on groundwater (Vandoolaeghe, 1980a).

Rural Support Services (1994) drilled several successful boreholes, some of which are used for water supply. These boreholes were drilled close to the inclined sheet of the Qoqodala structure (Figure 9 and 10). Due to drilling time constraints, the boreholes could not be drilled deep enough to investigate possible deeper aquifers (more than 300 m).

Water supply in urban areas such as nearby Queenstown, and the townships, is from the surrounding Waterdown and Bonkolo dams. About 96% of households in Queenstown have piped water compared to 0.4% in dwellings 15,000 m to the north. Similar trends were also observed for sanitation. Unemployment and illiteracy add to the poverty factor (Chevallier et al, 2004a). Figure 11 shows piped water availability statistics associated with poverty in rural settlements. More than 70% of the population does not have access to piped water, including the people of Qoqodala especially around the drill site. During a hydrocensus (June 2002 to March 2003) conducted in and around Qoqodala settlement, none of the households had piped water (Chevallier et al., 2004).

Smart (1998) postulated that a person living in a rural area requires 25 ℓ of water daily, while a person living in an urban area is assumed to require 200 ℓ. This water requirement only applies to personal use and does not extend to stockwatering and irrigation, and is therefore somewhat anomalous.

Over the years, the two main dams in the area (Bonkolo and Xonxa) have become highly silted-up and are thus only good for irrigation (Shand, 1999). The same applies to river water, especially during the rainy season. Rainwater captured in roof gutters is a popular form of obtaining clean drinking water for domestic use.

The hydrocensus (June 2002 to March 2003) shows that there are no proper sustainable, reliable water schemes for the rural areas and thus the high number of hand pumps. These hand pumps were installed by European donors and are not properly maintained. There are
generator operated boreholes as well. Maintenance, in the form of provision of diesel for the running of the generator, of these boreholes is the responsibility of the community. This task is however proving to be expensive for these poor communities and therefore water supply is erratic.

Plate 2: A protected spring in Luxeni village, situated on the southeastern rim of the Qoqodala ring structure. The spring occurs in the foothills, and is mainly used for household purposes. Photo taken by Luc Chevallier.
Figure 11: Social implications tied to water needs in rural settlements of the former Transkei homeland: Piped water availability.
CHAPTER 3. PREVIOUS WORK ON FRACTURED-ROCK AQUIFERS ASSOCIATED WITH SILLS

3.1 DOLERITE SILLS AND RING AQUIFER SYSTEMS

Karoo sedimentary rocks such as mudstone and sandstone have a low permeability. As a result, secondary permeability due to dolerite intrusions is important for groundwater retention and exploitation. Karoo fractured-rock aquifers associated with dolerite intrusion store water in the interconnected fractures that have developed in the surrounding sediment.

The structure of the dolerite rings of the Karoo have long been something of an enigma and until recently very little was known about their geometry. The Water Research Commission has been sponsoring research into Karoo dolerite sill and ring systems for a period of 16 years. Good water yielding capacity has been associated with dolerite dykes (Woodford and Chevallier, 2002b), and fractured sedimentary rocks above the sills (Botha et al., 1998; Burger et al., 1981). However, dolerite ring-sill complexes have often been overlooked, due to access difficulties and the requirement for deep drilling into this hard rock.

Exploration drilling on dolerite rings has been carried out at various places in the Karoo Basin: Williston, Vanwyksvlei, De Aar, Calvinia, Phillipolis, Graaff-Reinet, Middleburg, Victoria West, and Queenstown (Botha et al. 1998; Chevallier et al., 2001; Woodford and Chevallier, 2002a; Vandoolaeghe, 1980a and 1980b; Rural Water Services, 1994). The fracture-forming nature of Karoo dolerite rings and sills is responsible for the presence of deep-seated fractured aquifers (Chevallier et al., 2001). An increase in yield with depth was noted in the Western Karoo, which could mean that fractures with a higher yield exist at greater depth in the complex part of the intrusive system.

In-depth studies were also carried out by Burger et al. (1981) and Botha et al. (1998) in the Central Karoo showing that exploration drilling targeting the shallower weathered zone can be related to a system of fractures developed above sills. At the University of the Free State’s campus site, extensive research was carried out on experimental aquifer testing showing the connectivity of these shallow fractures (between 20 and 40m) supporting the presence of a generalised zone of numerous shallow water interceptions (Burger et al., 1981; Botha et al., 1998).

The characteristics of various types of groundwater occurrences associated with dolerite sills and rings (depth, size, and fracture pattern) were summarised by Chevallier et al.
(2001) in their hydro-morpho-tectonic model (Figure 12). The model integrated all the results from exploration drillings carried out on dolerite intrusions. The vertical stacking of the various “saucer-shaped” ring systems has lead to the development of aquifers at different stratigraphic levels. Inclined sheets (forming the ring and fed by regional dykes) have generated dense fractured systems responsible for deep (and possibly confined) aquifers.

The junction between the inclined sheet and the sills is the most fractured part of the system (Figure 12). The intersection between a dyke and a sill represent another structural target. The extension of aquifers at the base of sills is not known although exploration drilling and pump testing in Victoria West has shown that these fractures can extend for several hundred of meters (Chevallier et al., 2001).

Fractures developed at the top of shallow sills are more in agreement with the laccolith model of Burger et al. (1981). However their extension does not seem to exceed an area with a radius greater than 100 m (Botha et al. 1998).

Figure 12: Chevallier et al.’s (2001) hydro-morpho-tectonic model of a Karoo dolerite sill and ring complex showing the relation between deep and shallow fractured aquifers.

Cumulative yields measured during deep drilling (250 m) are often found to reach 20 ℓ/s and more. However pump tests done on the Victoria West sites showed the highly variable
nature of the yield capacity and the heterogeneous nature of the deep fractured-rock. The limited extent of some of the fractured systems is indicated by the slow recovery rate of some of the boreholes. This in line with what is commonly found in the Karoo dolerite aquifers where dry boreholes and high-yielding boreholes can be drilled within relatively short distances of one another (Chevallier and Woodford, 1999).

3.2 GAPS IN KNOWLEDGE IDENTIFIED

Previous work done on dolerite ring aquifers in the Karoo has been aimed at characterizing water occurrences (depth, and yield) or defining the storativity of a specific fracture system. However, the sustainability of these complex hydrogeological systems has not been fully investigated by means of fracture interconnectivity and groundwater flow dynamics (which are important for future abstraction and water supply studies).

The extension of the fractures and their aperture is not previously known. Some of them seem to be of limited lateral extension with an aperture of not more than 1 mm, and cannot serve as the main storage unit of groundwater. The sandstone and mudstone must therefore serve as the main storage unit and the fractures act as conduits for water to move from the sedimentary matrix to the borehole being pumped.

The flow in a fully fractured medium is largely controlled by the fracture dimension, orientation and connectivity (Odling, 1993). While some of the water-yielding fractures in the Karoo aquifers seem to be too sparsely distributed to satisfy connectivity requirements, some others might have sufficient lateral extension and be closely spaced to sustain a specific discharge.

The relationship between shallow and deep-seated aquifers, or between aquifers occurring on each side of a dolerite intrusion, has not been established. The depth of the groundwater circulation is another matter that is still to be established. The Hopefield boreholes, west of Queenstown, were drilled at the junction between a sill and an inclined sheet. The depth and yields of the water strikes suggested the presence of three open sub-horizontal fractures cross-cutting the dolerite sill, creating possible connection between each side of the inclined sheet (Chevallier et al, 2001).

The role of lithology and lithological discontinuities in the hydraulic property of the medium has not been fully assessed. About 20 to 30 percent of the Burgersdorp Formation is made up of sandstones. The sandstones are lenticular in shape and can stretch for a few hundred
metres to a few kilometres before pinching out. The middle sandstone marker is of special
importance since it extends regionally over several tens of kilometers and could play a role
in the overall hydraulic connectivity.

The need for a full structural investigation of a dolerite ring and the hydraulic property of the
associated fractured aquifer was therefore identified.
CHAPTER 4. METHODOLOGY

The methodology for the research involved a series of steps that included:
- geological mapping and site selection
- exploration drilling
- geophysical profiling
- aquifer testing

4.1 GEOLOGY, STRUCTURE AND SELECTION OF EXPLORATION PROFILE

4.1.1 GEOLOGICAL MAPPING AND BOREHOLE SITING

The drill site in Qqodala was selected according to the fulfilment of the following criteria; 1) water needs for the community, (2) prominent dolerite ring system conducive for fractured-rock aquifer, (3) and accessibility to the inclined sheet of the ring, where groundwater has been proven to occur in large quantities (Rural Support Services, 1994). The exploration drill site was chosen based on the hydro-morphotectonic model of Chevallier et al. (2001) (Figure 12).

The first step to the research involved a desktop study that included gathering of existing data. The Council for Geoscience had in its archives 1: 50 000 scale geological field sheets, two of which were hard copies while the other two were only available in the form of scanned copies. The hardcopies were later scanned and a seamless geological map compiled through digitizing.

Aerial photographs and satellite imagery (Landsat 7) were used to supplement the available geological data, especially to get more details on the dolerite intrusions. This method involved stereographic interpretation, and two 1: 50 000 hardcopy maps were produced. These maps were vectorised and later captured into GIS format. The vectorised maps were then combined with two 1: 50 000 digitized maps (from scanned maps) to make one complete seamless geological map (Figure 13). The final geological map was verified in the field, where information about lithological contacts and dips was attained.
4.1.2 GEOLOGICAL CROSS-SECTIONS

Several regional cross-sections of the study areas were drawn in order to understand the relationship between the various dolerite sill and ring systems. These cross-sections were made using:
- field geological maps of 1: 50 000 scale
- aerial photographic interpretation
- borehole logs supplied by Rural Support Services (1994). The location of these existing boreholes is shown in Figure 8.

4.1.3 FRACTURE MAPPING

Dolerite intrusions and the sediments of the surrounding Burgersdorp Formation are strongly fractured and these fractures represent potential groundwater paths. Mapping of fractures is therefore an important phase in groundwater exploration and drilling.

Fractures are defined as discrete lines corresponding to an identified open fissure. These structural features/lines are limited to where there is outcrop. Fractures of the study area were captured on screen through digitizing using satellite imagery (Figure 14). This exercise required the use of a combination and alternation of satellite images (Aster and Landsat 7) as well as hillshade images generated from 50 m resolution DEM (Digital Elevation Map created from 1: 50 000 topographic contour maps). This process of combining and alternating images allowed for better definition of the topography, so as to see and map the fractures better.

The digitizing was done on screen at a scale of 1: 200 000. This information was later incorporated with the geological map for further analysis (Figure 14). Although these structural features were mapped at a different scale to the geology, in figure 14 the map is set at a scale of 1: 250 000.

4.1.4 SELECTION OF EXPLORATION DRILLING PROFILE

The aim of the exploration drilling was to investigate a prominent dolerite sill/ring system conducive to potential fractured-rock aquifers at various depths. The profile was chosen after the desk study (map information, cross-section, and fracture pattern) and several field reconnaissances.
The exploration drill site is characterized by:
- a thick inclined sheet that is structurally complex and is fractured at depth (following the
  hydro-morphotectonic model of Chevallier et al., 2001; Figure 12).
- the possibility of an inner sill at a depth deeper than 90 m (according to previous drilling
  results in Qoqodala by Rural Support Services, 1994).
- the presence of regional fracturing.

4.2 EXPLORATION DRILLING

4.2.1 DRILLING AND MONITORING

Percussion air rotary drilling carried-out by the Department of Water Affairs and Forestry
commenced in March 2002 and ended in June 2003. A total of twelve boreholes (varying
from 100 to 300 m in depth) along the profile were drilled (Figure 17) with a cumulative total
drilling depth of 2655 m. A site survey was conducted by the Department of Water Affairs
and Forestry (DWAF) of the Port Elizabeth branch, where the boreholes’ positioning and
altitude were captured. This data complemented hand data recorded from GPS (Global
Positioning System) and the topographical map data.

During drilling, blow yields and water strikes were recorded; however the corresponding
water samples were not taken. This oversight was due to the absence of technical staff to
supervise the entire drilling process. As a result the only groundwater chemistry information
available is EC (Electrical Conductivity) and pH, captured for boreholes BH1, BH4, BH5,
BH7, and BH8 (Table 1). This geochemistry data was recorded using a combined EC/pH
meter and represents the mixed water (not from known specific depths) in the boreholes.

Water levels were recorded after drilling had started when groundwater monitoring
commenced (in March 2002). The water levels were at first recorded manually using a
dipmeter. In July 2003 two divers (electronic piezometric measuring devices) were installed
in two selected boreholes, BH5 and BH7, on each side of the inclined sheet that appeared
to have a very strong influence on the hydrodynamics of the fractured aquifers. Monitoring
with divers stopped in May 2004. Manual monitoring with dipmeters carried-on although
now on an irregular basis (once every two to three months).
4.2.2 BOREHOLE LOGGING

Borehole logging of the drill chips was conducted by two scientists in the field after each borehole had been drilled. The final borehole logs for the entire exploration site are given in Annexure 1. The following parameters were recorded:
- lithology (rock type, colour, grain size)
- nature of contact between sediment and dolerite (sharp or mixed)
- mineralization (calcite)

The geological information from the borehole logs was incorporated into a profile and a cross-section was compiled. The cross-section was first hand-drawn and later captured digitally using ArcGIS software (Figures 17 and 18).

4.2.3 DOWN-HOLE INVESTIGATION

Down-hole survey involves lowering different probes down the boreholes and capturing the data, which is used to generate curves. The probes are suspended on a wire and reeled off down the borehole when logging begins (Spaans, 1995). WELCAD software was used to capture and display the data.

Two types of down-hole investigations were conducted in boreholes BH1, BH 5, BH 7, BH8 and BH9 by DWAF (system operated by Barry Venter). The investigation included video camera logging and geophysical logging.

The general geology and construction of the boreholes was verified through video logging. Groundwater movement within the boreholes and fractures were identified. The video camera revealed new data on the lithology and the contact between sediment and dolerite. Information captured through video logging was incorporated into the cross-section (Figure 26).

The camera was equipped with a light (for visibility) and a compass to determine fracture orientation. Boreholes BH7, BH8 and BH9 were video recorded on the 18 December 2002, boreholes BH1, BH4 and BH5 were recorded on the 17 December 2002, and boreholes BH1A, BH1B, BH10A and BH11 were recorded between the 15 and the 17 September 2003.
Geophysical logging was conducted on the same boreholes. It included water quality, sonic, gamma, density, resistivity; caliper and neutron logging. The water quality survey included oxygen content, pH, temperature, pressure and conductivity (Pailett, 1993).

4.3 GEOPHYSICAL PROFILING

The profile along the drill site was further assessed using the constraints of a Time Domain Electromagnetic survey, where a total of 28 stations were established. The survey was carried out during March 2003 by Terra Sounding and Analytical Ltd.

A, “Tsickl” 5 component instrument, equipped with receiver and transmitter loops was used. Two square receiver loops of 1 x 1m, 625 m² and 6400 m² effective areas respectively, were used and positioned at the center of the transmitter loop. Two transmitter loops of 100 x 100 m and 200 x 200m size were used at the stations.

The 200 x 200m transmitter loops were only used at three stations, where the ground is relatively flat; the study area being on uneven ground and not enough space was available (river on the one side, the dolerite ring on the other side).

The smaller receiver loop of 625 m² effective size returns information from 25 to 400 m maximum depths, while the large receiver loop of 6400 m² effective size is capable of reaching deeper than 600 m.

By switching the transmitter coil on, a steady current is transmitted by induction to the earth’s subsurface. A series of current pulses is separated by periods of current cut-off, resulting in primary and secondary magnetic fields. The induced eddy current from the primary magnetic field (caused when the transmitter is first switched-on) causes a decaying magnetic field at the surface. This is the secondary field, generated when the primary field is off and can then be measured. Measurements of the rate of decay for the secondary magnetic field provide a means of detecting subsurface conductive bodies and estimating their conductivity (Figures 19 and 20) (Bennet and Ross, 1978).

Interpretation of data was performed by comparing and adjusting mathematical data/ model with the field data and further incorporating the available geological data. The field signal is translated from Apparent Longitudinal Conductivity (ALC) into the resistivity of the geological formations. An increase in ALC indicates a horizon of low resistivity, i.e. water saturated sediments or just sedimentary rocks, depending on the amount of increase.
These are easily put in a cross-section for further interpretation of layered structures (Figure 21) (Keys and Mac Cary, 1971; Keys, 1990).

4.4 AQUIFER TESTING

Two types of aquifer testing (Figures 28 to 33) were performed, namely: pump test and injection test.

4.4.1 PUMP TEST

Three boreholes; BH1, BH7, and BH11 were selected for pump testing based on the criteria: type of fractured medium; possible types of confining conditions; depth of aquifer(s) in relation to the dolerite; and depth of borehole.

The aquifer pump test was subcontracted by DWAF to Hippo Contractors from Bloemfontein. The test was conducted from 27 June 2003 to 22 July 2003, and involved a step-drawdown test, a 72-hours constant discharge test, and the respective water level recovery in each borehole. The step-drawdown test comprises of 9 steps of 60 minutes duration, and a varied pumping rate (from 1 to 15 ℓ/s).

After each aquifer test water levels were allowed to recover, before continuing with the next test. After the step-drawdown test, the 72-hours constant discharge test followed. The pumping rates for constant discharge tests varied for each borehole: BH11 was pumped at 10 ℓ/s, BH7 at 12 ℓ/s, and BH1 at 15 ℓ/s.

During the testing nearby boreholes as well as the two springs in the vicinity were monitored for water level fluctuation.

All the data from the exploration drilling was captured into Aquimon, a hydrogeological software designed by A. Woodford, for further processing and analysis.

4.4.2 INJECTION TEST

An injection test was performed so as to gain information on the fracture connectivity and flow dynamics within the zone of intersection of the inclined sheet and outer sill of the Qoqodala dolerite ring-complex. This test was carried out on boreholes BH1 and BH10A;
located on either site of the dolerite’s inclined sheet. For monitoring purposes divers were inserted in BH5, BH7 and BH1B on the 16 September 2003 and hand measurements were used for the rest of the boreholes. The injection test however was performed on the 17 and the 18 September 2003.

A single-packer hydraulic-fracture rig and an 8 000 ℓ reservoir tank (supplied by the Department of Water Affairs and Forestry) were used at each borehole. In borehole BH1 the packer was set at 139.5 m for 2 injections, and in borehole BH10A the packer was set at four different elevations (see Figure 34). In all cases the water was injected below the packer and the injection varied from 5 to 60 bars (the pressure on the packer) depending upon the transmissivity (obtained from pump test data) and the degree of connectivity of the fractures being tested (Chevallier et al., 2004b).

The results of the injection test were captured in Aquimon (Table 2 and figures 35 to 38) as part of the monitoring programme.
CHAPTER 5. RESULTS AND DISCUSSIONS

5.1 STRUCTURAL ANALYSIS

5.1.1 GEOLOGICAL MAPPING

The compiled and updated 1: 50 000 geological map of the Queenstown area (Figure 13) shows the box-like structure of the thick and extensive dolerite rings and the predominance of two major structural trends northwest-southeast and northeast-southwest clearly shown by dolerite dykes (Figure 14). Although the dykes cross-cut each other no clear age relationships could be discerned. The map also shows that dykes can cut through rings but are in turn cut by rings. It leads to the conclusion that all dolerites (dykes, sills) intruded at approximately the same time.

Figure 13: Seamless geological map compiled from four 1:50 000 digitized geological field maps, showing the prominence of the northwest and northeast structural trends.

Fracture mapping from satellite imagery also shows the two major northwest and northeast structural trends (Figure 14). The dolerite rings are intensely fractured, more so than the sills. A zone of northwest-trending fractures is particularly well developed on the
southwestern rim of the Qoqodala ring. This area was selected as a target for exploration drilling and is a suitable place to investigate the fracture network at depth along dolerite rings, and the implication for local groundwater flow dynamics.

Figure 14: Fractures mapped from Landsat 7 satellite image. The dolerite rings and sills (in pink) are wrapped over the image.

The drill site is situated in a valley cutting through the dolerite ring (Figure 15) and drained by a perennial river. The site is flanked by two intensely fractured mountains that also receive high rainfall. This location is thus also ideal for local groundwater recharge. Several springs, seeps and wetland are also found along the dolerite ring at various altitudes (bottom of slope).
Figure 15: Three viewpoints of the Qoqodala exploration drill site locality; A is a picture of the drill site taken from the top of the adjoining ring. B shows the exact positions of the boreholes. C is an Aster image of the same area, also showing the boreholes.
A total of 9 deep boreholes were drilled by DWAF along the profile to depths varying from 180 to 280 m. Boreholes BH2 and BH3 were shallow (less than 30 m) and were subsequently abandoned due to drying-up. For water table monitoring purposes, boreholes BH1A and BH1B were drilled on either side of borehole BH1, and further selected as possible abstraction points.

5.1.2 GEOLOGICAL SECTION AT THE DRILL SITE

After every borehole was drilled, rock chips were studied in the field and borehole logs were compiled. The results of the logging are given in Appendix I, and the hydrogeological data summarized in Table1. Although the water quality was not tested in the lab, the EC and pH values show that the groundwater at the drill site falls within the allowed standards for drinking water (DWAF, DH and WRC, 1998).

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<th>Borehole field No.</th>
<th>Depth (m.bgl)</th>
<th>WL (m.bgl)</th>
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The log of each borehole was first plotted on graph paper (Figure 16). The elevation of each borehole, as well as the nearby springs and river were accurately surveyed by DWAF. All this information was represented in the form of profiles. These hand drawn profiles were then captured digitally using ArcGIS (Figure 17). The geological cross-section of the drill site was compiled using lithological lateral correlations. A lot of the mudstone and shale packages form thin layers and are difficult to correlate over large distance. Thick sandstone packages form extensive bars that can be followed laterally and allow to constrain the correlation.
Figure 16: The first step of data processing on graph paper: The geology and the corresponding elevations have been captured next to the boreholes. Only 8 boreholes had been drilled at this stage.
Figure 17: The digitized boreholes showing the correlation between lithologies, for the Qoqodala exploration drilling cross-section.
The compiled cross-section based on borehole logs (rock chips) and lithological correlation is shown on Figure 17. The massive Qoqodala dolerite intrusion (measuring about 150 m at its thickest part) is the main lithological body, cross-cutting sedimentary rocks such as sandstone, mudstone and shale.

The Qoqodala dolerite ring complex displays the saucer-shape geometry postulated by Chevallier et al. (2001) (see Figure 12). The inner sill is very deep, and its base was not intersected by the exploration boreholes. The inclined sheet has a thickness of 150 m which is considered to be unusually thick. A structural complexity was noted in boreholes BH4 and BH5; south of the inclined sheet were frequent and thin layers of dolerite and sediment which seem to indicate multiple inter-fingering of dolerite with the sediment. The dolerite ring also shows two outer sills of about 80 m in thickness, one forming the relief at surface and the second one at elevations of between 1120 and 1200 m. The latter sill is at the same elevation as the one forming the base of the Zingqutu and Bonkolo rings, and could be part of an extended regional structure (see section B-B″ of Figure 9).

The Qoqodala cross-section is also characterised by 100 m thick sandstone bar with lenses of shale. The sandstone lies between elevation 1250 and 1150 (above the inner sill) and below 1150 m (south of the inclined ring). It therefore appears to have been displaced by the intrusion of the inclined dolerite sheet. This thick sandstone is a regional marker and could be correlated to the middle Burgersdorp sandstone outcropping at similar elevation at Nonesi's neck (Groenewald, 1996) (see Figure 10 and Plate 1).

Several water strikes were recorded during drilling and are reported on the cross-section together with the cumulative blow yield (Figure 18). They were intersected at various levels and could have different origins:

- possible extensive fracture at the base of the sill,
- structural complexity behind the inclined sheet
- lithological contacts

The large number of water strikes is not uncommon in Karoo dolerite context and usually indicates high yielding fractured-rock aquifer system, the sustainability of which still has to be investigated.
Figure 18: Geological cross-section of the Qoqodala dolerite ring, showing the boreholes lithologies and water strikes. A and B refer to observation points described during downhole geophysical logging.
5.1.3 GEOPHYSICAL PROFILING

The Time Domain Electromagnetic Survey was instrumental in further constraining the cross-section, especially to depths that could not be reached by drilling.

TDEM survey was done alongside the exploration profile. The position of the transmitter and receiver loops is shown on Figure 19. The transmitter loops had a size of 100x100m, and two receiver loops of different sizes (effective areas of 625 and 6 400 m²) were used for different depth penetration (up to 400 and 600 m respectively). The large loops seen in figure 19 are for the 200x200 m transmitter loops, in order to obtain information for clastic sedimentary rocks expected at shallow depth. Two profiles for shallow and greater depths are shown in Figure 20. The two resultant geo-electrical cross-sections, show major lithological boundaries and water-saturated layers at shallow and great depths.

Figure 19: The positions of the different sized transmitter and receiver loops with respect to the boreholes, showing the 28 stations of the TDEM profiling.
Figure 20: The two geo-electrical cross-sections from TDEM showing the resistivity (Ohms) of major lithologies and water-saturated layers for shallow (A) and greater (B) depth.
The dolerite is characterised by high resistivity (around 2000 Ohms). A layer of medium resistivity (around 700 ohms) seems to indicate another dolerite sill at a depth between 700 and 750 m.

Possible water-saturated layers, characterised by a rapid change in resistivities, have been detected at several places and would be indicative of various aquifers: shallow aquifer above the inner sill in the sandstone, deep aquifer just above the inner sill and intermediate aquifer (possibly fractured) south of the inclined sheet.

The structural cross-section has been further constrained with the TDEM results as shown on Figure 21, with a step in the shape of the inner sill and the presence of an even deeper sill.

Figure 21: The final product of TDEM profiling incorporated with borehole logging in order to get the geometry of the dolerite, and to show layering of the dolerite sills.
Geophysical profiling, and Time Domain Electromagnetics specifically, has proven to be a very useful tool to complement the borehole logging. A clearer interpretation of the geological boundaries and especially the detection of the lower dolerite sills were achieved. Another important observation is that the possible water-saturated zones do not always correspond to water strikes, like the one just above the inner sill. They might correspond to matrix aquifer and not fractured aquifer.

5.1.4 DOWN-HOLE INVESTIGATION

Four boreholes (BH1, BH5, BH7 and BH9) were chosen for down-hole investigation, in order to study the role played by fractured systems on the water flow or movement at depth. Two of the boreholes are located behind the dolerite inclined sheet (BH1 and BH5) and two are located in front of the sheet (BH7 and BH9). The investigation included:

- a camera survey
- a series of physical parameters measured with the probe (the list of parameters is given in the methodology).

Borehole logging using the video camera enabled visual verification for the logging from drill chips. Every borehole was fitted with a steel casing up to the weathered zone, to avoid the borehole collapsing especially during pump testing. The water within the borehole was found to be either clear or turbid. Clear water indicates a deep source/origin, while turbid water indicates a shallow origin from the upper aquifer.

Bacterial colonies are commonly present in borehole water. The distinguishing characteristic of the bacteria is a pinkish mass of no specific shape or size. This particular bacterium is only present in nutrient-rich and oxidizing environments. The bacterium was noted on the video recording attaching itself to the steel casing, and increasing in density towards the bottom of the casing. Other favourable environments for the bacterium were permeable fractures, and they would also settle on big horizontal fractures.

From the drift direction of the bacteria water movement in the borehole was found to be either up or down. Inflow and outflow of water was noted at open fractures, shown by bacteria being sucked in or blown out of the fractures. However when the water was clear, water flow direction was shown by rock flakes/flour (from the massive dolerite). Rock flour comprises bits of fine material that comes off the surface of the rocks after drilling. These visual aids contributed to the ultimate flow pattern of water within the aquifer.
Rock flour and bacteria settled at the bottom of the borehole and started filling it up, changing the borehole depth determined during drilling. Also formed after and during drilling are u-shaped induced fractures. However, these fractures were only noted on massive rock formations such as dolerite and were not open.

**Borehole BH1**

Two observation points (A at 55 m and B at 176 m in Figure 18) were found informative.

At 55 m the lithology is mudstone with lenses of sandstone, with large open and horizontal fractures well exhibited on the geophysical logging (Figure 22A). A 1.8 l/s water strike was intersected at this depth. The video recording shows bacteria disappearing into the fracture at 55.1 m, meaning that the borehole is possibly losing water or this movement could be an indication of lateral water movement within the aquifer.

At 176 m (at the contact of the sediment and the base of the sill) the lithology is sandstone mixed with dolerite, with joints running in a north-south direction. The rock is laminated (bedding) but without apparent horizontal openings; however a cumulative 17 l/s water strike was intersected and the strong signals from the sonic and geophysical logs implying fracturing (Figure 22B).

**Borehole BH5**

The hole was found to be skew when the video was inserted, and the extensive fracturing had offset loose rocks.

Two observation points (A at 36 m and B at 172 m in Figure 18) were found informative.

At 36 m (below the base of the upper outer sill) the lithology consists of interfingered mudstone, sandstone and dolerite. There are many open fractures, confirmed by the geophysical logs (Figure 23A). A 8.5 l/s water strike was intersected, yet no apparent water movement was noted on the video. The bacteria have settled on the fractured surfaces. However, according to the oxygen content of the water quality logs, there is a deficiency of oxygen at this depth that could indicate water circulation.

At 172 m (at the contact of the sediment and the bottom of the lower outer sill) the sandstone is heavily fractured (northeast fracture trend). A 16 l/s cumulative water strike was intersected. Water movement, illustrated by bacteria, is seen to be moving into the
open fracture located at this depth. This water movement could be an indication of lateral movement within the aquifer or that the borehole is losing water. The oxygen content ($O_2$ %) of the water is noted to be decreasing confirming water circulation indicated by outflow of water from the borehole. The gamma log and the attenuated sonic signal validate the fracturing seen on the video (Figure 23B).

**Borehole BH7**

Two observation points (A at 48 m and B at 264 m on the cross-section of Figure 18) were found informative.

At 48 m (near surface of the inclined sheet) the lithology consists of fractured dolerite. The fracturing is however not extensive or continuous (laterally or vertically) and a water strike of 0.2 ℓ/s was intersected. The presence of this fracture is shown by a break in the sonic waves, a slight increase in the gamma and resistance logs as well as a decrease in the short- and long-normal logs (Figure 24A). This fracture is filled with calcite in places, and is not open. There are few floating bacteria in the clear water and the general water movement within the borehole is upwards.

At 264 m (near the base of the inclined sheet) the lithology is still dolerite. The video shows an undisturbed solid rock formation. The long-normal, short-normal and resistance logs show a degree of fracturing (a decrease in the amplitude) that is also reflected by the sonic log. However the fracture is not well established on the gamma log (Figure 24B). There are no changes in the water quality sensors thus disagreeing with the implied fracturing. A cumulative water strike of 10 ℓ/s was intersected.

**Borehole BH9**

Two observation points (A at 44 m and B at 115 m in Figure 18) were found informative.

At 44 m, the lithology is sandstone with lenses of shale and horizontal jointing noted on the video recording. There are a lot of bacteria in the turbid water, however they appear to be floating rather than moving. A 2.5 ℓ/s water strike was intersected. From the other geophysical recordings, only the sonic log reflects this jointing. The water quality curves at this depth are all stable (Figure 25A).

At 115 m, fracturing is suggested by the sonic log (Figure 25B). A series of subvertical joints and cracks occur at the base of the thick sandstone (the Burgersdorp sandstone).
There is a slight increase in the oxygen content curve. The increase in oxygen content could imply that the fractures are open and receiving freshwater or indicating bubbles in circulating water. A cumulative 10 ℓ/s water strike was intersected.
Figure 22A: Geophysical logs for borehole BH1 at 55.1 m. Video image shows water movement and bacteria being sucked into the fracture.
Figure 22B: The geophysics of borehole BH1, highlighting the 176.1 m depth water strike. The sonic log indicates fracturing, while the video recording does not, neither in the sandstone nor the dolerite above. No water movement detected.
Figure 23A: The geophysics of borehole BH5 at depth 36.1 m. The sonic log and the other geophysical logs are in agreement with the fracturing noted on the video recording. Fractures may be obscured by bacteria in borehole water.
Figure 23B: Note that the fracture indicated on the video image at 172.7 m in borehole BH5, is not clearly supported by the sonic and the water quality logs.
Figure 24A&B: Geophysical data for borehole BH7, depicting the depths of interest at 48 m and 264 m respectively.
Figure 25A&B: Geophysical results from borehole BH9, at depths 40 - 46 m and 112 - 120 m respectively. Note the anomaly at 44 m and 116 m.
Figure 26: Local groundwater movement within boreholes, and the corresponding temperatures. Water occurrences at the intersected fractures and water strikes add to the complexity of the groundwater flow dynamics.
5.2 PUMP TESTING

Three boreholes; BH1, BH7 and BH11 were pump tested in July 2003 for a total duration of five days. The boreholes were chosen so that there would be monitoring holes on either side. The field operations were controlled by the author, pump test analyses performed by A. Woodford, and the results were fully reported in the WRC project report (Chevallier et al., 2004a).

Borehole BH11

A 9 step-drawdown test was performed for a maximum abstraction of 15 ℓ/s, and the results are displayed graphically in Figure 27. The final pumping rate at 15 ℓ/s dewatered the borehole very rapidly and depleted the upper fractured aquifer, especially the fracture occurring at 55.1 m. Only borehole BH9 (closest to the pumped borehole) responded to the pumping. The estimated optimum short-term pumping rate for Borehole BH11 is 6 ℓ/s. During the 72- hour constant discharge at 10 ℓ/s (864 m³/day) the water level in borehole BH11 declined by 22.5 m (Figure 28). Three days after the test, the water level recovered to less than a metre (1 m) short of the original water level. The estimated long-term sustainable yield of borehole BH11 is 90 000 m³ per annum (2.8 ℓ/s), providing there is no abstraction from any other nearby production boreholes tapping the same aquifer.

Figure 27: The nine ‘steps’ of the step-drawdown test for borehole BH11, extracted from Aquimon database (software developed by A. Woodford).
Figure 28: A) The effect of the constant discharge test on Borehole BH11 and the surrounding boreholes 9 and 10. B) The graphical drawdown effects during pump testing. Analysis performed by A. Woodford in Chevallier et al., 2004a and 2004b.

Borehole BH 7

The results of the 9 step-drawdown test are presented in Figure 29. At 12 ℓ/s pumping rate (eighth step) the borehole starts to be dewatered. The optimum short-term pumping rate was estimated to be 4 ℓ/s. The 72-hours constant discharge shows a narrow and deep depletion cone inside the dolerite ring, which would indicate poor water circulation in the
massive dolerite characterised by few open high yielding fractures (Figure 30). However, the water level in borehole BH4 (situated on the northern side of the inclined sheet) dropped by 1.4 m during the pump test. This suggests an artificial connection created by drilling through the base of the sill. After the 72-hours constant discharge at 12 ℓ/s pumping rate (1 037 m³/day), water level recovery was within less than 2 m of the rest water level. Dewatering from the base of the sill could be indicated. The long-term sustainable yield for borehole BH7 is estimated at 62 000 m³ per annum (1.9 ℓ/s), provided there is no abstraction from any other nearby production boreholes tapping the same aquifer.

Figure 29: Step-drawdown test results for borehole BH7 showing start and finish water levels, as well as the start of the recovery after the test. Data extracted from Aquimon database (software developed by A. Woodford).
Figure 30: A) the effects of the constant discharge test on borehole BH7 and the surrounding boreholes. B) The graphical drawdown effects during pump testing. Analyses performed by A. Woodford in Chevallier et al., 2004a and 2004b.

Borehole BH1

The results of the 9 step-drawdown test are presented in Figure 31. The drawdown curve shows a steady decrease of water level and a slow dewatering of this large upper aquifer. An estimate of 8 ℓ/s was determined for the short-term pumping rate. During the 72 hour constant discharge test at a rate of 15 ℓ/s (1 296 m³/day), monitoring boreholes BH4, BH1A and BH1B all responded to the pumping (Figure 32) indicating a good connectivity between fractures of the upper aquifer. However, the water level recovery was slow in all monitored boreholes but recovered better in the pumped borehole. This could be due to faster recharge through the granular alluvial paleochannel next to the river at this locality (see geological cross-section of figure 20). A long-term sustainable yield estimate of 68 400 m³
per annum (2.1 ℓ/s) was obtained for borehole BH1, provided there is no abstraction from any other nearby production boreholes tapping the same aquifer.

Figure 31: The summarised nine ‘steps’ of borehole BH1 for the step-drawdown test. Graph extracted from Aquimon (software developed by A. Woodford).
Figure 32: A) The effect of the constant discharge test on borehole BH1 and the adjacent boreholes. B) The graphical drawdown effects during pump testing. Analyses performed by A. Woodford in Chevallier et al., (2004a and 2004b).

Summary

The three tested boreholes were chosen because they represent different aquifer environments i.e. above the inner sill, in the inclined sheet and south of the inclined sheet:

- The upper fractured aquifer above the inner sill (represented by borehole BH11) has an average transmissivity value of 163 m²/day and an average storativity value of 5.5 x 10⁻⁵. The high transmissivity value indicates that the porous aquifer medium is permeable. There is good connectivity with water circulation between fractures situated at least 150 m apart. However, these fractures do not appear to be very open and do not allow water to circulate
freely at high pumping rates (i.e. 15 ℓ/s). Local recharge, probably from rainfall, appears to be significant and the aquifer recovers fairly well after being pumped at 10 ℓ/s.

- The inclined sheet (represented by borehole BH7) shows poor fracture connectivity and becomes dewatered at high pumping rates. However, the borehole recovers fairly well after an abstraction of 12 ℓ/s; this could be due to the artificial recharge from the bottom of the sill and connection with the borehole south of the inclined sheet. The hydraulic parameters of this aquifer include an average transmissivity value of 152 m²/day and an average storativity value of 5.2 x 10⁻⁴.

- The aquifer below the upper outer sill (south of the inclined sheet and represented by borehole BH1) is characterised by wide open fractures with good connectivity. The water circulates freely even at the high pumping rate of 15 ℓ/s. However, the recharge of this fractured aquifer is slow (due to the impermeable dolerite) except at one location, where the river recharges a paleo-alluvial channel. The hydraulic parameters of this aquifer included an average transmissivity value of 94 m²/day and an average storativity value of 1.8 x 10⁻⁴.

The water level decline noted during the constant discharge test for all three boreholes indicates the general semi-confined nature of Karoo fractured aquifers. Karoo fractured aquifers have a dual porosity. This implies that during pumping, water is first released through large fractures, then from a network of micro-fractures.

5.3 INJECTION TEST

Down-hole investigation and pump testing have shown that fractures occurring at the bottom of dolerite sills are well developed, open and have fairly good connectivity. The Qoqodala ring /sill system was judged a good site to test fracture connectivity at the base of sills.

During the period 17 to 18 September 2003, injection-type tests were conducted on boreholes BH1 and BH10 in order to test the fracture system below the 80 m thick deep outer sill, and below the upper 10 m thick inner offshoot.

In borehole BH1 the packer was placed in the middle of the sill in order to isolate the bottom of the intrusion (Figure 33). In borehole BH10 the packer was placed at several levels in order to test the connectivity inside the inclined sheet, at the bottom of the offshoot and at the top of the inclined sheet.
Electronic water level measuring devices (in this case two divers) were used for monitoring the boreholes’ water level fluctuation during the injection tests. Red fluorescent dyed water (about 1000 m$^3$) was injected into boreholes BH1 and BH10 and down-hole video recording was used for visual monitoring in observation boreholes. The nearby river was also used to monitor the influence of surface water in recharging local fracture systems.

Figure 33: The positions of the packer into each borehole during the injection tests, with respect to the water strikes intersected during drilling.

All the information pertaining to the injection test, especially the testing itself is summarized in Table 2.
## Table 2: The results of the injection test, showing the depth or location of the packer and the rate of injection.

<table>
<thead>
<tr>
<th>Borehole No.</th>
<th>Date / Time Commencement Test</th>
<th>Duration of Test (min)</th>
<th>Depth of Inflatable Packer (m.bgl)</th>
<th>Ave. Rate of Injection (ℓ/s)</th>
<th>Ave. Injection Pressure (bar)</th>
<th>Approx. Volume Injected (m³)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH1</td>
<td>17/09/2003 – 08h55</td>
<td>17.70</td>
<td>139.5</td>
<td>5.5</td>
<td>-</td>
<td>5,840</td>
<td>Response observed in BH 5 at 09h00. Divers installed in boreholes BH5, BH7 and BH1B.</td>
</tr>
<tr>
<td>BH1</td>
<td>17/09/2003 – 14h39</td>
<td>21.5</td>
<td>139.5</td>
<td>5.6</td>
<td>5.5</td>
<td>7,261</td>
<td>Divers installed in boreholes BH5 and BH7, as well as above packer in BH1.</td>
</tr>
<tr>
<td>BH10A</td>
<td>18/09/2003 – 13h44</td>
<td>10.0</td>
<td>109.5</td>
<td>0.25</td>
<td>40.0</td>
<td>151</td>
<td>Divers inserted in boreholes BH5, BH7 and BH10.</td>
</tr>
<tr>
<td>BH10A</td>
<td>18/09/2003 – 14h43</td>
<td>5.0</td>
<td>79.5</td>
<td>0.23</td>
<td>-</td>
<td>70</td>
<td>Divers inserted in boreholes BH5, BH7 and BH10.</td>
</tr>
</tbody>
</table>

**Notes:**
- 16 Sept at 13h50, water level in borehole BH 5 rose by 26 cm due to testing of injection equipment.
- A sodium fluorescent red dye was mixed into the water injected into borehole BH1 and DWAF’s down-hole video camera was inserted in borehole BH5; however no dye was detected in borehole BH5.

After testing, divers were left in boreholes BH5 and BH7 to record the recovery of the system and monitor the induced (artificially) flow between the two aquifers.

During the injection tests in borehole BH1 the packer was set at 139 m within the Zingqutu outer sill, where approximately 13 100 m³ of red sodium-fluorescent coloured water was injected into the high-yielding fracture system at the base of this sill (at 176 m). The piezometric levels in boreholes BH5 and BH7, situated 300 and 483 m away, rose by 0.40 m and 0.04 m, respectively (Figures 34 and 35). This confirms the continuity of the fracture system at the base of the sill and the inclined sheet that extends from BH1 through to boreholes BH4, BH5 and BH7.

The water level in borehole BH1B, situated some 57 m away from borehole BH1, did not respond to the injection tests as this borehole does not penetrate the fracture system at the base of the outer sill. A down-hole video camera installed in borehole BH5 during the injection tests did not detect the red dye. This indicates that the fracture zone is too large and wide and that the dye was diluted or that the water was diverted to another fracture system (like the regional northwest structures mapped on Figure 14).
Figure 34: Water level response in borehole BH5 due to injection in borehole BH1.

Figure 35: Water level response in borehole BH7 due to injection in borehole BH1.
Four phases of injection were conducted in borehole BH10A, where the packer was set at 109.5 m, 79.5 m, 67.5 m and 55.5 m (Table 2). The first two injection tests, where the packer was set at 109.5 m and 79.5 m, showed that the inclined dolerite sheet is poorly fractured and of very low permeability. The injections tests conducted with the packer set at 67.5 m and 55.5 m showed a positive water level response in boreholes BH10 and BH7. These boreholes are situated 10 and 156 m, respectively from the injection borehole (Figures 36 and 37) and a water level rise of 0.31 and 0.16 m respectively was registered. This confirms the presence of two permeable fracture zones or formations, one at the top of the thin offshoot and the inclined sheet, and another one at the base of the thin offshoot going into the inclined sheet.

Borehole BH5 did not show any significant variation during the injection into borehole BH10A, with only a 0.04 m difference from the background reading. During the third phase of the injection test into borehole BH10A the water level rose by 0.29 m, a possible indication that water was by-passing the packer set at 67.5 m.

Figure 36: Water level response in borehole BH10 due to injection in borehole BH10A.
5.4 WATER LEVEL MONITORING

Water level monitoring started in December 2002 after the drilling of boreholes BH5, BH4 and BH1 (drilled during July to September 2002) respectively. All boreholes were monitored using a dip meter for over three years (2002 to 2005) on an irregular basis, including the aquifer testing and the recovery thereof. Divers were also installed in boreholes BH5 and BH7 during injection tests in September 2003 and were kept in the holes for five months after the test. Monitoring was instituted so as to study the response of the water levels in the two structural systems, i.e. the domains south and north of the inclined sheet. This was done in the hope of seeing equilibrium in the water loss and a recovery of the system with a return to a more ‘natural’ flow.

The results of the monitoring are shown separately on two diagrams (Figures 38 and 39), since Aquimon can only accept a limited number of boreholes to be represented at the same time on the same graph. Thus, Figure 38 shows all the boreholes involved in the southwestern structural compartment, i.e. south of the inclined sheet and Figure 39 is showing the northeastern compartment (north of the inclined sheet).
Figure 38: Water level monitoring of the Boreholes BH1, Bh1A, BH1B, BH4 and BH5 (southwestern compartment) over a three year period, starting on 9 December 2002. Data for figure extracted from Aquimon (software developed by A. Woodford).

Figure 39: Water level monitoring of the boreholes BH7, BH8, BH9, BH10 and BH11 (northeastern compartment) over a three year period, starting on 9 December 2002 for boreholes BH7, BH8 and BH9 and on 7 March 2003 for borehole BH10 and 24 June 2003 for borehole BH11. Data for figure extracted from Aquimon (software developed by A. Woodford).
It is noted that the two aquifers were being dewatered, the one faster than the other. The southwestern compartment was dewatering faster (with a maximum water level drop of 17.73 m in borehole BH1, recorded from 9 December 2002 to 4 February 2005) than the northeastern compartment (with a maximum water level drop of 2.23 m in borehole BH9, recorded from 9 December 2002 to 25 November 2003).

**Southwestern compartment (south of the inclined sheet)**

The dewatering in the southwestern compartment was seen on the video recording where water was coming out of the upper fractures. The dewatering is a result of an artificial link created by drilling between the upper and the lower aquifer (below the sill). It is also noted that the water level did not recover satisfactorily after the pump test.

A different response is seen for two groups of boreholes;

**Group A:**
- Borehole BH1 (monitored from 9 December 2002 to 4 February 2005) has a cumulative 17.73 m drop,
- Borehole BH1A (monitored from 24 June 2003 to 4 February 2005) has a cumulative 11.85 m drop,
- Borehole BH1B (monitored from 24 June 2003 to 17 September 2003). Since the last recorded reading from Borehole BH1B the borehole has collapsed and is termed as dry.

**Group B:**
- Borehole BH4 (monitored from 9 December 2002 to 4 February 2005) has a cumulative 12.72 m drop,
- Borehole BH5 (monitored from 9 December 2002 to 4 February 2005) has a cumulative 5.61 m drop.

Borehole BH1 lost water very rapidly soon after drilling and the water table never recovered. Boreholes BH1A and BH1B were drilled mainly for the purpose of the injection test (much later after borehole BH1), but their water level follows the same pattern as borehole BH1. These boreholes are located in an alluvial paleo-channel (see figure 18), which dewater faster than the other geological formations.

Boreholes BH4 and BH5 are located on either side of a spring (refer to figure 18). They were both artesian at the beginning of drilling, but the water table dropped when the drilling in borehole BH4 reached the depth of 97 m (fracture). Borehole BH5 was equipped with a
diver from September 2003 to June 2004. The curve of borehole BH5 shows an increase in
the piezometric level during the period of April to May 2004 (Figure 40). The area had
winter rainfall and thus this response is interpreted as recharge to the aquifer.

Northeastern compartment (north of the inclined sheet)

In the northeastern compartment some boreholes loose water, while some seem to gain
water.

- Borehole BH7 (monitored from 9 December 2002 to 4 February 2005) has lost the most
  water with a drop of 7.17 m,
- Borehole BH8 (monitored from 9 December 2002 to 4 February 2005) has dropped by
  4.92 m,
- Borehole BH9 (monitored from 9 December 2002 to 25 November 2003) has lost the least
  amount of 2.23 m,
- Borehole BH11 on the other hand has gained 0.56 m of water (monitored from 24 June
  2003 to 4 February 2005)
- Borehole BH10 has gained the most by 0.8 m (monitored from 7 March 2003 to 4
  February 2005).

Borehole BH7 was equipped with a diver from September 2003 to June 2004. A water level
increase was noted during the period April to May 2004 (Figure 40). This response is
interpreted as recharge to the aquifer system as a result of the winter rainfall.

Summary of monitoring

Despite operator errors that could have resulted from hand monitoring, it has been shown
that the system is generally losing water. This dewatering is of great concern and implies a
groundwater imbalance caused by drilling. A clear pattern can be seen from the monitoring
where boreholes drilled down to below the sill or the inclined sheet (BH1, BH4, BH5, BH7,
and BH8) all lose water, and boreholes drilled above the sill (BH10 and BH11) gain water or
lose very little (BH9).

The water levels in the aquifer system has thus far not stabilised to give a proper reflection
of the effects of rainfall, although the divers in boreholes BH5 and BH7 showed this
response on a local scale. Throughout the greater Qoqodala aquifer there are several
boreholes that are in operation, and could be influencing the recharge response.
Monitoring in the study area is still continuing on an *add hoc* basis and will have to be intensified if the water is to be used to reliably supply the community. The required monitoring is however now performed by DWAF.

**Figure 40**: Water level measurements for boreholes BH5 and BH7 for the monitoring done using divers (after aquifer testing). The water level fluctuations are viewed with the corresponding rainfall period to see the effect thereof.
5.5. STRUCTURAL MODEL AND GROUNDWATER CONCEPTUAL FLOW PATTERN

Sedimentary rocks of the Beaufort Group are seldom targeted for large groundwater schemes in the study area, due to their lack of primary porosity and permeability (Woodford and Chevallier, 2002a). Undisturbed horizontal primary sedimentary rock aquifers are usually extensive yet shallow, and they also have high porosity and permeability values. According to Plummer and Mc Geary (1996) average sandstones have a porosity of 10 – 20% and a moderate to good permeability. When unconfined, these aquifers are recharged directly and the water level fluctuation is a direct response to recharge. The storage capacity of these aquifers is generally high (due to areal extent) and water movement is generally a response to a change in hydraulic head (Driscoll, 1986).

The study area includes a complex fractured-rock aquifer system as a result of dolerite intrusions, which differ fundamentally to the primary aquifer type described above. Fractured Karoo aquifers are characterised by secondary permeability and porosity of the fractured sedimentary rock medium. The fractures store water and act as a conduit for groundwater flow. Fracture connectivity was proven to exist and was confirmed through injection testing. In fractured-rock aquifers, groundwater can only flow when there is fracture connectivity.

Groundwater flow in the study area is not always under gravitational pull; water is seen moving upwards within boreholes (BH7 and BH8). It can be deduced that in this instance groundwater flow is a result of pressure difference. However, on a broader scale (the entire drill site) groundwater flow is constrained by topography as seen in Figure 41, proven by monitoring and video logging (lateral flow is consistent with a decrease in hydraulic head). Evidence for direct recharge to the drillsite aquifer systems was only observed in the unconfined aquifer, while the deeper, confined aquifers are assumed to be recharged from either a deeper source or through leakage of the aquifers.

The permeability for the fractured aquifer systems was inferred from the bacterial colonies’ attachment to the fractures within the boreholes. Additionally, through pump- and injection testing the aquifer medium of the study area was found to be of dual porosity; during pumping water was first drained from the fracture and then the matrix. According to Plummer and Mc Geary (1996), fractured crystalline rocks have a porosity of 5 -10% and poor permeability. The average transmissivity values obtained from pump testing for all the aquifers systems was found to be more than adequate for industrial, municipal or irrigation purposes (> 124 m²/day).
During drilling in the study area, a spring close to borehole BH5 was dewatered, and an artificial connection between the aquifer systems created. The induced groundwater flow as a result of the artificial connection between ‘systems’ was observed on the video recording (see Figure 41). The springs in the vicinity of the drill site act as the only discharge points, since the drill site aquifer is not being tapped. The dewatered spring later reappeared about 20m below the surface, just above the river surface. During the dewatering stage of the spring the river water level wasn’t affected. This could mean that the spring (assumed perched water table) has no direct link to the river system; however during peak flow the river feeds the groundwater system.

Fractured Karoo aquifers are multi-layered and may be stacked vertically. The layers are normally made-up of shallow aquifers that are unconfined to semi-confined, laterally extensive and less than 30m below static water level. And then there are deep aquifers that are semi-confined to confined, associated with regional structures and are more than 90m below static waterlevel. The deep aquifer in reverse to the upper aquifer has less groundwater storage yet a higher yielding water interception.

The inclined dolerite sheet divides into three structural domains or compartments as seen in the cross-section, including a northwestern compartment south of the inclined sheet, a northeastern compartment north of the inclined sheet, and a compartment below the deep sill. These domains were identified during the pump test.

Water strikes occurred both at lithological contacts and fracture intersections. The fractured sandstone seems to be the most water-saturated lithological unit, and the video camera recording showed it to be the most jointed. Geophysical profiling, subsequent aquifer tests (pump- and injection test) and groundwater monitoring established the following aquifer systems:

Aquifer I: Compartment south of the inclined sheet and between the two outer sills:

The rock mass mainly comprises mudstone interbedded with thin sandstones. The rock is intensely fractured especially adjacent to the dolerite bodies. The fractures are open with very good connectivity, and water moves freely. However, drilling has induced an artificial link between this upper aquifer and the one below the lower sill. Water observed to be emerging from the fractures could be a result of lateral circulation, but also possibly due to water loss from the upper aquifer to the lower aquifer. Borehole BH1 has shown that this
Aquifer (Aquifer I) can be pumped at 15 ℓ/s although the recovery was poor. This puts limitations on the sustainability of the aquifer.

The persistent decline in water level after drilling (see section 5. 4) of all boreholes that penetrate this compartment confirms that the aquifer is dewatering. The major fall occurred when drilling reached the base of the lower sill, at which point the water level suddenly dropped by 4 m. Additionally, boreholes BH4 and BH5 were no longer artesian and a nearby spring dried out.

Aquifer II: Upper compartment north of the inclined sheet

This upper fractured-rock aquifer is about 80 m thick and corresponds to the Burgersdorp Formation’s middle sandstone bar (Plate 1). Fractures are open, but lateral water circulation is not very prominent. A series of permeable subvertical joints and cracks below the sandstone show a potential for water circulation. At a moderate abstraction rate (10 ℓ/s) the aquifer seems sustainable. This aquifer is directly recharged from precipitation more than Aquifer I is, which is more compartmentalised by dolerite intrusion.

Aquifer III: Lower compartment north of the inclined sheet

The lithology is mainly mudstone with interbedded lenses of fine-grained sandstone. The sandstone bars would make good aquifers and targets for drilling. No water strike has been recorded in this compartment (except at the base of the main sandstone). However according to the TDEM profile interpretation; there is a water saturated zone within this compartment at an elevation of 1050 m (Figure 21).

During the drilling of borehole BH9 no evidence was turned up indicating that this aquifer is confined (borehole BH9 was never artesian as would be expected from puncturing the thin offshoot separating the upper and lower aquifers). Since there is a cap (dolerite offshoot) isolating this aquifer (Aquifer III) from the upper compartment, it can be deduced that this aquifer is semi-confined. Borehole BH11 penetrates the inclined sheet and thus a direct link between this aquifer and Borehole 11 can not be established. As a result data from pump testing borehole BH11 can not be used to draw any conclusion about the sustainability or development of this aquifer.
Aquifer IV: Deep aquifer below the main sill

An extensive fractured aquifer lies at the contact between the main sill and the sedimentary rock. Injection tests have shown very good connectivity along the base of the sill. During drilling an artificial connection was established between this aquifer and the upper one (Aquifer II). Water loss was detected in boreholes BH1, BH4 and BH5, observed from water level monitoring (see section 5.5). At the bottom of some of the boreholes (section 5.3) the water was turbid and could have been emerging from a fracture.

Water gain occurs in boreholes BH7 and BH8. The water is turbid, slightly warm (24°C) and moving upwards. This flow direction is confirmed by geophysical data, mainly the increase in temperature and oxygen levels. Through monitoring it was observed that the boreholes recovered quite well after the pump tests, despite being confined by the dolerite. This would support a flow model of dewatering from the base of the sill.

The results and observations of the hydro-structural investigation are synthesized in the model shown in Figure 41.
Figure 41: Natural and ‘Induced’ Groundwater flow pattern of the Qoqodala drill site (After Chevallier et al, 2004b).

Summary

The deep Aquifer IV shows that water circulation can go as deep as 400 m (the top of the deep sill detected from TDEM) below the ground level. The temperature of the water in the boreholes is generally warm (mostly ranging between 18 - 22 °C); this could be an indication that the water circulation is deep (water temperature from geophysical water quality logs).

Dolerite intrusion compartmentalised and isolated the aquifer systems, however drilling induced mixing of groundwater between the different compartments. Groundwater in the study area moves in response to both differences in water pressure (upward movement in boreholes BH7 and BH8) and elevation (as observed on a broader scale). Aquifer III is
usually an ideal target for well development (water-saturated sandstone bar), however this aquifer was not pump-tested and the sustainability thereof is questioned. Recharge to Aquifer III is not clear and the storage capacity (defined in this case by the size of the sandstone bar) does not appear to be adequate for prolonged pumping durations.

The dewatering of the spring during drilling of borehole BH5 indicates a link between the perched water table (spring) and the groundwater system. However since the river level appeared not to be affected, the perched water table is not linked to surface water (the river). However, groundwater monitoring shows that the river feeds the groundwater systems, and not vice versa. The river and Aquifer II appear to be the only water systems that respond to direct recharge almost immediately.

Aquifer II is expected to act like a normal unconfined aquifer in terms of being recharged directly, and discharging to the river. Normal layered sedimentary aquifers are shallow (less than 100 m in depth). Qoqodala dolerite ring complex has proven the presence of a deep fractured aquifer system that has never been investigated before. The complexity of groundwater flow observed in Aquifer II and IV could emphasise the strong control of the inclined sheet on the groundwater flow pattern. The inclined dolerite sheet acts as a watershed, not only for the river but also for groundwater; flow is expected to be down slope.

Injection testing failed to define the flow pattern within the fractures and the calculation of the flow velocity, since the dyed water was not detected in the nearby river or boreholes. However, this test proved that the fractures of the aquifers are not only connected but are permeable since the water injected was drained and at a fairly fast rate. The injection tests into borehole BH1 were for 17 and 21.5 minutes respectively, with average injection rates of 5.5 ℓ/s. The tests for borehole BH10A ranged from 5 to 15 minutes, and the average injection rates were from 0.23 and 3.81 ℓ/s.
CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The objectives of this research as stated in Chapter 1 were as follows:

(i) Structural analysis of a pilot site across a specific dolerite ring in the Queenstown area by means of field mapping, satellite image interpretation, fracture mapping, exploration drilling, borehole logging, geophysical profiling, and geological cross-sections across the intrusion.

(ii) Assessment of the groundwater flow dynamics of each fractured-rock aquifer associated with the dolerite intrusion, using video camera, geophysical logging, pump and injection tests.

This project has involved a number of techniques in order to better understand the structure and the lithology of the pilot exploration site as well as the groundwater dynamics. All the techniques made a contribution to the end result, and in a project of this magnitude and complexity none should be excluded.

Main conclusions

The outcomes of the research as per the above objectives are:

The intrusive dolerite ring system is a very complex structure, with an inclined sheet connected to several horizontal sills intruded at various elevations. At least three inner sills and three outer sills were found; through drilling, the shallow ones were intersected and geophysical profiling (TDEM) located a deeper one. The stacked nature and box-type shape of the dolerite rings as postulated by Chevallier et al., (2001) was confirmed. Through understanding the structure, it was possible to suggest a geological control on potential water flow paths.

The fractured medium of the aquifer systems served as a conduit for groundwater flow as well as storage. The high permeability of the fractures was established during pump testing where high transmissivity values were obtained. The high average storativity and transmissivity values confirm the sustainability of the aquifers.
The complexity of dolerite intrusions has induced compartmentalisation of the rock mass, leading to various types of fractured-rock aquifers characterised by different fracture connectivity and local recharge. The geophysical profiling (TDEM) has highlighted water-saturated zones within the compartments, which correspond mainly to the water strikes intersected during drilling.

Within each compartment several open fractures have been intersected by exploration drilling and observed on video recordings and borehole geophysical logging. Some of these fractures have yielded large quantities of water during the pump tests.

The inclined dolerite sheet itself appears to make little contribution to the control of water flow, with very weak drainage from the fractures. This appears anomalous, since the dolerite is intensely fractured and jointed. However, if fractures are numerous, open and possibly connected, lateral drainage of the fractured system to localities elsewhere is possible.

The base of the dolerite sills are highly fractured, forming an important conduit for water circulation. It is speculated that the base of extended sills should be able to provide conduits for water over long distances and contribute to regional flow patterns. The Burgersdorp marker sandstone may play a role in this regard.

Water level monitoring that was carried out over nearly three years has proven to be an essential part in the understanding of the aquifer behaviour and reaction to parameters like: rainfall; artificial links created by boreholes; water abstraction; and the relation between the structure and the groundwater dynamics. Although done intermittently, it proved to be very useful in the understanding of the groundwater dynamics.

Borehole drilling has created an artificial link between shallow aquifers and deep aquifers (especially the one below the sill). Video images show upward and downward movement of water within the boreholes, and water level monitoring has shown constant water decline in some of the boreholes after they reached a certain depth. This induced flow path now links two structural compartments via a combination of boreholes and fractures.

Recharge to the system was only seen in Aquifer II as a response to rainfall. It is not clear though how the other aquifers are being recharged. As a result, the monitoring needs to continue and in-depth research is needed for the area. Discharge within the vicinity of the study area was in evidence when the boreholes lost water as well as in the decline of the water levels during the monitoring period (after the completion of the tests). However, for
the entire Qoqodala aquifer system, discharge occurs in the form of water abstraction from operational boreholes (of which there are several) and several springs found throughout the ring settlement. This abstraction could be interfering with the recharge to the drill site system, although the abstraction boreholes are far from the drill site.

Regardless of the dolerite intrusions, the hydraulic head measured from the boreholes shows a control by topography.

Recommendations for future research

The Qoqodala exploration site is unique as it allows quantification of the relations between the complex fractured aquifers (deep and shallow) linked to multi-intrusive Karoo dolerite systems.

Short-term and long-term pumping rates from the three pump-tested boreholes (BH1, BH7 and BH11) as well as the acceptable water quality, indicate that water can be provided for thousands of people per day (the villages within Qoqodala are estimated to have at most hundreds of people) for personal use as well as irrigation and stock watering needs. It must be stressed though that the system may prove unstable and further research is needed before the aquifers are exploited.

The observed water loss is a matter of concern; water level has been dropping in some boreholes (BH1, BH4 and BH5) since the beginning of drilling in 2003 and was still falling in 2005 at the end of continuous monitoring. It is recommended that the site remain experimental; monitoring should be done without interferences from abstraction.

The site is characterised by complex water-bearing geological structures, the presence of a river, good orographic rainfall that is not constrained by season, springs and wetlands are further favourable factors. A proper groundwater observation site should be created at the exploration site with:

- Monitoring of water level using divers (at least three boreholes)
- Rain gauge
- Stream/river gauge.
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### APPENDIX I

<table>
<thead>
<tr>
<th>DWAF BOREHOLE NO: EC/S10/003 (BH4)</th>
<th>DWAF BOREHOLE NO: EC/S10/004 (BH5)</th>
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<td>Altitude : 1306 m</td>
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<td>0 - 4: Soil (reddish)</td>
<td>0 - 13: Soil (reddish)</td>
</tr>
<tr>
<td>- 21: Totally weathered Dolerite</td>
<td>- 26: Totally weathered Dolerite</td>
</tr>
<tr>
<td>- 25: Dolerite (weathered)</td>
<td>- 32: Sandstone with shale inlayers</td>
</tr>
<tr>
<td>- 30: Sandstone (brownish)</td>
<td>- 50: Sandstone mixed with dolerite intrusions</td>
</tr>
<tr>
<td>- 35: Sandstone (fractured)mixed with shale</td>
<td>- 59: Dolerite</td>
</tr>
<tr>
<td>- 45: Sandstone (solid) inter-layered with shale</td>
<td>- 65: Shale horizon within a dolerite mass</td>
</tr>
<tr>
<td>- 51: Shale</td>
<td>- 84: Dolerite</td>
</tr>
<tr>
<td>- 69: Sandstone (leucocratic)</td>
<td>- 87: Sandstone with shale inlayers</td>
</tr>
<tr>
<td>- 93: Dolerite</td>
<td>- 159: Dolerite</td>
</tr>
<tr>
<td>- 103: Dolerite with sandstone inlayers</td>
<td>- 160: Dolerite with sandstone within</td>
</tr>
<tr>
<td>- 168: Dolerite</td>
<td>- 164: Dolerite</td>
</tr>
<tr>
<td>- 179: Sandstone</td>
<td>- 181: Sandstone</td>
</tr>
<tr>
<td>• Water strike: seepage (25m), 0.94 (26m), 4.10 (32m), 9.8 (66m), 15.0 (96m) &amp; 23.0 (179m)</td>
<td>• Water strike 8.5 (19m), 9.62 (37m), 11.05 (50m) &amp; 16.0 (165m)</td>
</tr>
<tr>
<td>• Total depth: 179</td>
<td>• Total depth: 181 m</td>
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</table>
### DWAF BOREHOLE NO: EC/S10/001 (BH1)

**Latitude:** -31.74125  
**Longitude:** 26.90356  
**Altitude:** 1325 m

0 - 6: Soil (dark-red)  
- 25: decomposed Dolerite boulders  
- 32: Sandstone (decomposed & brownish)  
-43: Sandstone with Dolerite (intensely weathered)  
- 49: Siltstone mixed with mudstone (yellowish, and weathered)  
- 55: Shale with Sandstone (leucocratic) layers  
- 61: Sandstone, fractured (leucocratic)  
- 63: Sandstone and shale horizons  
- 65: Sandstone (leucocratic)  
- 67: Shale/Sandstone (60:40)  
- 79: Shale  
- 85: Shale/Sandstone  
- 92: Sandstone (leucocratic) fractured @89 m  
- 97: Sandstone (leucocratic with greyish horizons)  
- 102: Sandstone (greyish)  
-175: Dolerite (114 -120 m fractured)  
-178: Dolerite/Sandstone  
-181: Sandstone/Siltstone (leucocratic)  
-187: Sandstone (leucocratic), interlayered with dolerite and Siltstone horizons  
- 194: Sandstone with siltstone interlayering  
- 198: Siltstone  
- 199: Sand (fine-grained & unsorted)  
- 205: Shale (black)  
-209: Sandstone (leucocratic) with shale layers  
-211: Sand, fine grained  
-212: Shale (black) with lenses of grey sandstone

**Water strike (ℓ/s):** seepage (26 & 42 blocked by casing), 1.8 (56m), 4.0 (66m), 10.0 (72m), 13.0 (101m), 16.0 (128m), 17.2 (176m) & 38.0 (211m)

**Total depth:** 212 m

### DWAF BOREHOLE NO: EC/S10/002 (BH2)

**Latitude:** -31.7458  
**Longitude:** 26.90400  
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**Borehole BH3**

0 - 2: Soil (reddish)  
- 3: weathered Dolerite  
- 13: clayey Soil & decomposed Dolerite  
- 25: sticky (due to groundwater) Clay layer  
- 31: sandy Clay (poorly sorted river sand, possible buried paleo channel)

- **Water strike seepage (18 m & 31 m)**
- **Total depth:** 31 m

**Borehole BH2**

0 - 2: Soil (reddish)  
- 3: Decomposed Dolerite  
- 15: clayey Soil & decomposed Dolerite  
- 19: sticky (due to groundwater), dark Clay layer

- **Borehole was later sealed and excluded from the research.**
- **Total depth:** 19 m
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<td>-  28: weathered Dolerite</td>
<td>-  34: fractured Mudstone (yellowish)</td>
</tr>
<tr>
<td>-  33: fractured Mudstone</td>
<td>-  41: weathered sandstone with mudstone (brownish) horizons</td>
</tr>
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<td>-  45: weathered Mudstone with Sandstone horizons</td>
<td>-  52: Shale and sandstone (grey) interlayering</td>
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<td>-  51: baked Shale with sandstone interlayering</td>
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<td>-  54: Sandstone (leached brownish) weathered</td>
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<td>-  57: Sandstone (greyish)</td>
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<td>-  70: Sandstone (leached brownish colour) fine-grained</td>
<td>-  69: Shale, undisturbed</td>
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<td>-  90: Shale with sandstone lenses</td>
<td>-  72: Shale with Sandstone (leucocratic) horizon</td>
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<td>-  90: Total depth: 90 m</td>
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<td>- 110: Sandstone (greyish and fine grained)</td>
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<td>Shale (fractured)</td>
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<td>Shale horizon, dark and very fine-grained</td>
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<td>Sandstone (greyish)</td>
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<td>Sandstone with shale interlaying</td>
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<td>Sandstone (leucocratic)</td>
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- Water strike (ℓ/s): 0.5 (18 m), 2.5 (40 m), 10.5 (116 m) & 12.5 (124 m)
- Total depth: 211 m

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<thead>
<tr>
<th>Depth</th>
<th>Material Description</th>
</tr>
</thead>
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<tr>
<td>0 - 5</td>
<td>Soil (&amp; decomposed Dolerite)</td>
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<tr>
<td>11</td>
<td>Decomposed, purplish Mudstone</td>
</tr>
<tr>
<td>19</td>
<td>Mudstone</td>
</tr>
<tr>
<td>24</td>
<td>Yellowish Sandstone with mudstone layer</td>
</tr>
<tr>
<td>30</td>
<td>Sandstone (leucocratic)</td>
</tr>
<tr>
<td>35</td>
<td>Fractured Mudstone with Sandstone lenses</td>
</tr>
<tr>
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<td>greyish Shale</td>
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<td>Sandstone (light brown)</td>
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<td>Sandstone (leucocratic)</td>
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<td>Shale (greyish)</td>
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<td>Dolerite</td>
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<td>Shale with a sandstone horizon</td>
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<td>Shale (baked)</td>
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</tbody>
</table>

- Water strike (ℓ/s): 0.2 (28 m), 1.4 (36 m), 3.2 (54 m), 7.5 (93 m)
- Total depth: 248 m
## INDEX OF DATA

<table>
<thead>
<tr>
<th>DATASET</th>
<th>FIGURE/TABLE NUMBER</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
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<td>Geological Data:</td>
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<td>Lithostratigraphy</td>
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<td>Plate 1</td>
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<td>Dr Stefan Chevrel</td>
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<td>Dolerite Geometry</td>
<td>Figures 6 and 12</td>
<td>Chevallier et al, 2001</td>
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<td>Figure 9</td>
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<td>Author’s own work also published in Chevallier et al, 2004</td>
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<td>Figures 16 and 17</td>
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<td>Author’s own work</td>
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<td>Satellite Imagery:</td>
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<td>Landsat 7</td>
<td>Figure 7</td>
<td>SAC (Satellite Application Centre) published in Chevallier et al, 2004</td>
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<td>Figure 15c</td>
<td>Internet; Author’s own work also published in Chevallier et al, 2004a and 2004b</td>
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<td>Regional MAP distribution</td>
<td>Figure 3, Data from CCWR</td>
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<tr>
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<td>Figure 11, Author’s own work also published in Chevallier et, 2004a</td>
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<td>Figure 22A to 25 A&amp;B, Data from DWAF supplied by B. Venter, processed by Author</td>
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<td>Pump-test data</td>
<td>Figures 27 to 32, Author’s and A. Woodford interpretation, also published in Chevallier et al, 2004a &amp; 2004b</td>
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| Injection test | Figures 33 to 37  
Table 2 | CGS’s internal confidential report |
<table>
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<tr>
<td>Groundwater flow dynamics</td>
<td>Figure 26 and 41</td>
<td>CGS’s internal confidential report</td>
</tr>
<tr>
<td>Monitoring data</td>
<td>Figures 38 to 40</td>
<td>CGS, author’s work unpublished</td>
</tr>
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