CHARACTERISATION OF THE DEEP AQUIFERS OF SOUTH AFRICA – THE KAROO SUPERGROUP AND TABLE MOUNTAIN GROUP

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DECLARATION

I, NWABISA MAKIWANE, hereby declare that the dissertation submitted by me to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State in fulfilment of the degree of Magister Scientiae, is my own independent work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

I furthermore cede copyright of the dissertation and its contents in favour of the University of the Free State.

Nwabisa Makiwane

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LIST OF ACRONYMS AND ABBREVIATIONS

AKGT	Agulhas-Karoo Geophysical Transect
AMD	Acid Mine Drainage
API	American Petroleum Institute
ARD	Acid Rock Drainage
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BEDD	Blikhuis Experimental Deep Drilling
BIC	Bushveld Igneous Complex
BIF	Banded Iron Formation
BMA	Beattie Magnetic Anomaly
CAPP	Canadian Association of Petroleum Producers
CBM	Coalbed Methane
CCP	CO_2 Capture Project
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CFB	Cape Fold Belt
CGS	Council for Geoscience
CGWB	Central Ground Water Board
CIMERA	Centre of Excellence for Integrated Mineral and Energy Resource Analysis
CMM	Coal Mine Methane
COM	Chamber of Mines
COC	Chain of Custody
CRIP	Continuous Retraction Injection Point
CSIR	Council for Scientific and Industrial Research
CTL	Coal-to-Liquid
DACC	Drilling and Completions Committee
DAGEOS	Deep Artesian Groundwater Exploration for Oudtshoorn Supply
DBG	Deep Biogenic Gas
DE	Department of Energy

DEA	Department of Environmental Affairs
DEP	Department of Environmental Protection
DM	Department of Mines
DST	Department of Science and Technology
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EO	Earth Observation
ERT	Electrical Resistivity Tomography
FDEM	Frequency-Domain Electromagnetic
GA	General Authorisation
GAO	General Accounting Office
GIPIP	Good International Petroleum Industry Practices
GTL	Gas-to-Liquid
GUI	Graphical User Interface
ICDP	International Continental Drilling Programme
ICSU	International Council for Science
IEA	International Energy Agency
IEAEP	International Energy Agency Environmental Projects
IGC	International Geothermal Center
IGS	Institute for Groundwater Studies
IHFC	International Heat Flow Commission
IPCC	Intergovernmental Panel on Climate Change
IRP	Industry Recommended Practice
ISO	International Organization for Standardization
IWRM	Integrated Water Resource Management
KARIN	Karoo Research Initiative
KGEG	Karoo Groundwater Expert Group

KZN	KwaZulu-Natal
L/min	litres per minute
L/s	litres per second
MCSA	Media Club South Africa
MDEQ	Michigan Department of Environmental Quality
MoPNG	Ministry of Petroleum and Natural Gas (India)
MRPDA	Mineral Resources and Petroleum Development Act
m/s	metres per second
m/d	metres per day
m^3	cubic metres
Mm^3	Million cubic metres
m^3/h	cubic metres per hour
mbgl	metres below ground level
mg/L	milligrams per litre
NEMA	National Environmental Act
NGA	National Groundwater Archive
NGS	National Groundwater Strategy
NOGA	Norwegian Oil and Gas Association
NRC	National Research Council (USA)
NRF	National Research Foundation
NWA	National Water Act
NWRS	National Water Resource Strategy
OES	One Environmental System
OGP	Oil and Gas Producers
PASA	Petroleum Agency of South Africa
PGE	Platinum Group Elements
PSAC	Petroleum Services Association of Canada
PWV	Pretoria-Witwatersrand-Vereeniging
RDM	Resource Directed Measures
RGS	Rashoop Granophyre Suite

RLS	Rustenburg Layered Suite
RSA	Republic of South Africa
SACCCS	South Africa Centre for Carbon Capture and Storage
SABS	South African Bureau for Standards
SANS	South African National Standards
SDC	Source Directed Control
SOEKOR	Southern Oil Exploration Corporation (Suidelike Olie-Eksplorasie Korporasie)
TDS	Total Dissolved Solids
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
TNF	Tritium Zero Limit (Tritium Null Flache)
UAA	Uitenhage Artesian Aquifer
UKEA	United Kingdom Environmental Agency
UKOOG	United Kingdom Onshore Operators Group
UCG	Underground Coal Gasification
USEPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USSEC	United States Securities and Exchange Commission
VLF	Very Low Frequency
WCELRF	West Coast Environmental Law Research Foundation
WGA	Western Governors' Association
WRC	Water Research Commission
WRI	World Resources Institute

CHAPTER 1:
INTRODUCTION

1.1 BACKGROUND

South African water resources are under increasing stress and the country is likely to face significant water shortages in the not too distant future. Population growth combined with climate change and continued economic development will put further stress on water resources and infrastructure (CSIR, 2010).

Groundwater forms an important component of fresh water resources. The pressure on surface water resources in response to increasing water supply demands has increased the importance of groundwater, not only in South Africa but the world. As it stands, South Africa's water supply is further threatened by deteriorating water quality in rivers and dams, a drought epidemic and the contamination of soil-rock-groundwater systems.

Numerous studies have demonstrated that the quality of water resources is predominantly affected by anthropogenic activities (Davies & Day, 1998). However, according to McCarthy (2011) ecological problems can arise from both anthropogenic and natural activities, such as the geological characteristics of that particular catchment. All these issues have focussed the attention onto deeper geohydrological systems. So while shallow groundwater resources are currently used for water supply, deeper groundwater resources have become a focus point as future water source.

The focus on deep groundwater aquifers is furthermore driven by new developments such as shale gas development, the injection of brine into deep aquifers, and geothermal energy, to mention a few. All these developments require deep groundwater information. However, there is very limited data available to characterise deep groundwater systems in South Africa. While investigations at large depths within the Earth's subsurface have already been taking place for decades, these investigations were not focused on characterising groundwater, but rather geological formations, oil exploration and gathering data for climate reconstructions. As a consequence valuable hydrogeological data was disregarded. Thus the absence of deep groundwater data is not due to the lack of deep boreholes, but rather the absence of hydrogeological data collected from those boreholes. For example, the mining industry in South Africa has installed numerous deep core boreholes for geological investigations and reserve estimations, but hydrogeological data such as hydraulic conductivities are either not measured or the data is not made available.

1.2 AIMS AND OBJECTIVES

The principal aim of this research project is to characterise deep groundwater systems belonging to the Karoo Supergroup and Table Mountain Group (TMG) and use these characterisations to better understand deep-seated aquifer systems. A further aim of the project is to identify and describe activities that may impact the quantity and quality of the groundwater in deep aquifer systems, and describe approaches for the protection of this deep groundwater resource.

The objectives of the study are to:

- Study the available information on deep aquifer systems in the Karoo Supergroup and TMG,
- Consolidate the available deep groundwater data,
- Assess the potential deep groundwater resources of the Karoo Supergroup and TMG,
- Characterise the deep aquifers in terms of their physical and hydraulic properties, and
- Investigate technologies, procedures and legislation to protect deep aquifer systems.

1.3 RESEARCH METHODOLOGY

This project is predominantly desktop-based research and involves the identification, collection and processing of information and data on deep aquifer systems in the Karoo Supergroup and TMG. Various sources were consulted:

- Journal articles and conference papers relevant to this study.
- Databases containing data on the deep aquifer systems, including the database of the International Heat Flow Commission (IHFC), the Pangea database, a database on deep boreholes at the Council for Geoscience (CGS), and the National Groundwater Archive (NGA) of the Department of Water and Sanitation (DWS).
- Reports relevant to this research project, including reports on the SOEKOR and KARIN boreholes drilled to great depths in the Karoo Supergroup.
- Information on the locations and depths of deep opencast and underground mines intersecting the Karoo Supergroup. Information on the occurrence of deep groundwater could potentially be obtained from these mines.

After the review of national and international literature on deep groundwater systems was conducted, an assessment of the potential deep groundwater systems in South Africa was done by considering the known geology and geohydrology of the different rock formations that occur in the country. The collected data and information was analysed and evaluated to characterise the deep aquifer systems in the Karoo Supergroup and TMG in terms of various physical and chemical parameters:

- Lithology (rock type)
- Occurrence (depth)
- Physical dimensions (thickness, lateral extent)
- Aquifer type (fractured, granular, double porosity)
- Saturation level (saturated, unsaturated)
- Heterogeneity and degree of isotropy
- Formation properties (porosity, pore size distribution, bulk density, mechanical properties)
- Hydraulic parameters (hydraulic conductivity, storativity, transmissivity, specific yield, permeability)
- Pressurisation (confined, unconfined, artesian)
- Yield
- Groundwater quality (inorganic parameters, organic parameters)
- Aquifer vulnerability and susceptibility

After the characterisation of the deep aquifer systems, current and possible future activities that may impact the quality and quantity of deep groundwater resources were identified. This was followed by a discussion of the technologies, procedures and legislation that can be implemented to protect the deep aquifer systems.

1.4 STRUCTURE OF DISSERTATION

This dissertation comprises seven chapters:

Chapter 1 serves as an introduction, defining groundwater and its role in South Africa. In this chapter the aims and objectives of the study are stated and the research methodology described.

Chapter 2 is a literature review in which deep groundwater concepts are discussed. In this chapter available literature relevant to deep aquifers are analysed. First, the depths at which aquifers may be considered to be "deep" are investigated. Followed by a discussion of the circulation depths and water quality of deep groundwater. Then the collection of deep groundwater data and the characterisation of deep groundwater systems are described, after which a summary is given of the geophysical methods that may be used to delineate deep aquifer systems. This is followed by a discussion of the evidence for deep groundwater systems in South Africa. Lastly, both national and international case studies of deep aquifer systems are presented.

Chapter 3 discusses potential deep aquifers in the Karoo Supergroup and TMG by considering the different lithologies that constitute these geological units in terms of their potential to store and transmit groundwater.

Chapter 4 focuses on identifying sources that contain data and information on the geohydrological conditions of the deep aquifer systems.

Chapter 5 characterises the potential deep groundwater resources of the Karoo Supergroup and TMG.

Chapter 6 investigates and discusses the various activities that may impact deep aquifers in the Karoo Supergroup and TMG.

Chapter 7 is the concluding chapter in which the results of the study are summarised and discussed, and recommendations for future studies are made. Some procedures and legislation applied to protect the deep aquifer systems will also be discussed.

CHAPTER 2:
LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter a review of the available literature relevant to deep aquifers is presented. The chapter starts by investigating the depths at which aquifers may be considered "deep", followed by a discussion on the circulation depths and water quality of deep groundwater. Then the collection of deep groundwater data and the characterisation of deep groundwater systems are described, where after a summary is provided of the geophysical methods that may be used to delineate deep aquifer systems. This is followed by a discussion of the evidence for deep groundwater systems in South Africa. Lastly, both national and international case studies of deep aquifer systems are presented.

2.2 DEFINING DEEP

Over the years there have been numerous views and discussions concerning the distinction between shallow and deep aquifer systems, taking into account the current hydrogeological knowledge. The description of deep groundwater is usually subjective and undecided, with the dividing depth between shallow and deep a moving target. There is no commonly standardised or agreed upon depth distinction between shallow and deep groundwater (Alley *et al.*, 2013). A description of the various definitions used for "deep" groundwater systems follows.

2.2.1 Various definitions of "deep" aquifers

Numerous depths, ranging from 100 m to 1 000 m, have been recommended for the divide between shallow and deep groundwater. The authors Reddy and Nagabhushanam (2012), Zektser and Everett (2004), Pietersen and Parsons (2002), Seiler and Lindner (1995) and Castany (1981) established a boundary between shallow and deep groundwater at a depth of 100 m. While exploring chemical and isotopic seismic precursory signatures in deep groundwater Reddy and Nagabhushanam (2012) considered boreholes from 100 m to 250 m deep. Zektser and Everett (2004) evaluated the groundwater resources on a global perspective, and the generally reported average depth of boreholes was 100 m.

Castany (1981) considered vertical zoning of groundwater and described three zones based on flow systems: local, regional and global. Castany (1981) defined the upper zone as the zone of the subsurface aquifers (where local flow systems reach depths of 50 m to 100 m), followed by the zone of intermediate aquifers (with regional flow systems in confined aquifers reaching depths of 200 m to 300 m), and lastly the zone of deep aquifers (with large scale flow systems where vertical mixing is predominate). Castany (1981) indicated that the groundwater for human consumption is limited by the increase in mineralisation with depth. Two case studies were considered and the limiting depths for groundwater production given was 1 000 m in the Paris Basina and 2 000 m in the northern Sahara Basin (Castany, 1981).

An additional divide between shallow and deep groundwater is set at 300 m, as seen in work by van Wyk (2013), González-Ramón *et al*. (2013), Mejías *et al*. (2008) and Umvoto (2005). Mejías *et al*. (2008) makes a distinction between shallow and deep groundwater in their methodology of hydrogeological characterization of deep carbonate aquifers as potential reservoirs of groundwater and applied to an aquifer in Spain. Mejías *et al*. (2008) as cited in Anton-Pacheco *et al*. (2005), explains that the definition of deep aquifer includes different types of aquifers, namely “unconfined aquifers with water tables deeper than 300 m, confined aquifers whose top lies below 300 m, and those aquifers that due to their hydraulic properties require deep boreholes and the application of specific techniques for study”. From a South African perspective van Wyk (2013) and Umvoto (2005) characterised deep groundwater as below 300 m.

Murray *et al*. (2015), Drake *et al*. (2015), González-Ramón *et al.* (2013) and Bouri *et al*. (2008) refer to a divide of shallow and deep groundwater at 400 m to 500 m below the ground surface. Drake *et al*. (2015) investigated sulphur-isotope fractionation in groundwater (in fractured crystalline rock) in boreholes greater than 400 m in depth. Murray *et al*. (2015) refer to shallow groundwater above 500 m in the Karoo groundwater systems while discussing preferential flow paths that potentially link deep and shallow systems. González-Ramón *et al*. (2013) scrutinized exploited aquifers in southern Spain, where the lower aquifer is between 300 m to 700 m. Bouri *et al*. (2008) makes a distinction between shallow and deep groundwater at 500 m, with shallow groundwater defined from 50 m to 500 m, and deep groundwater defined from 500 m to 3 500 m. They estimate deep groundwater temperatures based on a geothermal study on the thermal waters of Southeast Tunisia, with a focus on the integration of surface and subsurface data and geothermometric calculations (Bouri *et al*., 2008).

Pimentel and Hamza (2014) and Lippmann-Pipke *et al*. (2013) considered deep groundwater to be at a depth of 1 000 m. Pimentel and Hamza (2014) indirectly gave this distinction while discussing the use of geothermal methods in outlining deep groundwater flow systems in Paleozoic basins of Brazil. While analysing deep fracture water in search of microbial communities Lippmann-Pipke *et al*. (2011) considered “shallower fluids” or groundwater in the gold mines of the Witwatersrand Basin to a depth of 1 km.

2.2.2 The various perspectives on deep groundwater according to related disciplines

Local and worldwide knowledge has revealed that the progress of initial investigation into deep groundwater principles can be backed by the analysis of disciplines related to deep groundwater. As a starting point the fundamental concepts used in the geothermal, carbon capture and storage, and petroleum industries were reviewed.

2.2.2.1 Geothermal industry

Geothermal energy is the heat energy contained within the Earth, however, the term "geothermal" is most commonly used to define that part of the Earth's heat that can potentially be recovered and exploited (Dickson & Fanelli, 2003). Water is needed as the medium to transport this heat from deep hot zones to or near the surface and presently restricts the conditions at which geothermal energy can be collected. Geothermal energy is divided into shallow and deep geothermal systems.

According to the International Geothermal Centre (IHC) (2015) the depth threshold for shallow geothermal energy is 400 m, and geothermal systems below this depth are considered deep. Deep geothermal energy differs from shallow geothermal systems in that deep boreholes are required to extract the geothermal energy and the energy can usually be used without additional heat pumps (Stober *et al*., 2014). Stober *et al.* (2014) defined shallow geothermal energy as the geothermal heat extracted from shallow depths, normally down to a depth of 150 m and to a maximum depth of 400 m. Stober *et al*. (2014) defined deep geothermal energy as geothermal energy extracted from depths of more than 400 m and temperatures exceeding 20°C. However, Stober *et al*. (2014) stated that it is becoming common practice to reserve the term "deep geothermal" for energy extracted from depths greater than 1 000 m and temperatures greater than 60°C.

2.2.2.2 Carbon capture and storage industry

Viljoen *et al*. (2010) defined geological storage of CO_2 as the injection of man-made CO_2 into underground formations so that it becomes trapped in the pore spaces of the sedimentary rock. It has been determined that a burial depth of at least 800 m is needed to achieve a high enough temperature and pressure for CO_2 to occur in the supercritical phase (IPCC, 2005; as cited by Viljoen *et al.* 2010). Thus, when considering deep saline aquifers for carbon storage, the divide between deep and shallow is 800 m.

2.2.2.3 Petroleum industry

High temperature and pressure, which occur at depths, are required for the production of oil and gas. Oil and gas reservoirs are traditionally found deep in the Earth's subsurface. However, they can move to the surface through porous media or get trapped by impermeable geological layers. In a summary of the deep wells and reservoirs in the United States, "deep" oil production wells were defined as wells drilled to a depth of 4 572 m or more (Dyman & Cook, 2001). According to Vermeulen (2012) oil is generated at temperatures and pressures found between 1.5 km and 5 km, while gas is generated between 3 km and 6 km. Vermeulen (2012) suggests that the depths of the target geological formations for hydraulic fracturing in South Africa is between 3 000 m to 5 000 m. Figure 2. 1 A relative representation of the depth of oil wells in feetof the depths (in feet) of some boreholes drilled in the search for oil.

Unconventional gas can be defined as gas resources that were not always accessible but with recent advancements in technology and understanding, it can now be exploited. By this definition all unconventional gas could be classed as "deep", thus the exploration of unconventional gas will serve to extend what is considered deep.

Recent developments in technology have directed petroleum production to offshore resources, i.e. deepwater oil and gas. According to the CEO of Oil and Gas UK, there is no agreed upon industry definition of what constitutes deepwater for oil and gas production (Dragani & Kotenev, 2013).

2.2.3 Revision of the term "deep" with technological advancements

As technology progresses and allows for more accessible methods for deep drilling, the depth at which groundwater is considered deep will inevitably increase. When deepwater drilling started over 30 years ago in the North Sea, depths of 150 m would have been considered deepwater. Currently deepwater is defined as depths greater than 400 m, with drilling of ultra-deepwater becoming common at depths greater than 1 500 m (Dragani & Kotenev, 2013). A similar trend is seen in groundwater development, with geothermal resources, geosequestration, and hydrocarbon migration and production driving the development of these technologies (Commander, 2010).

There are also technological advances in fields other than drilling that will advance deep groundwater development in the future. Hartnady *et al*. (2008) discussed emerging science and technology for deep groundwater resource assessment with an emphasis on the application of modern Earth Observation (EO) and space-geodetic methods. These new technologies will serve to improve the exploration, development and management of groundwater within deep artesian basins (Hartnady *et al*. (2008).

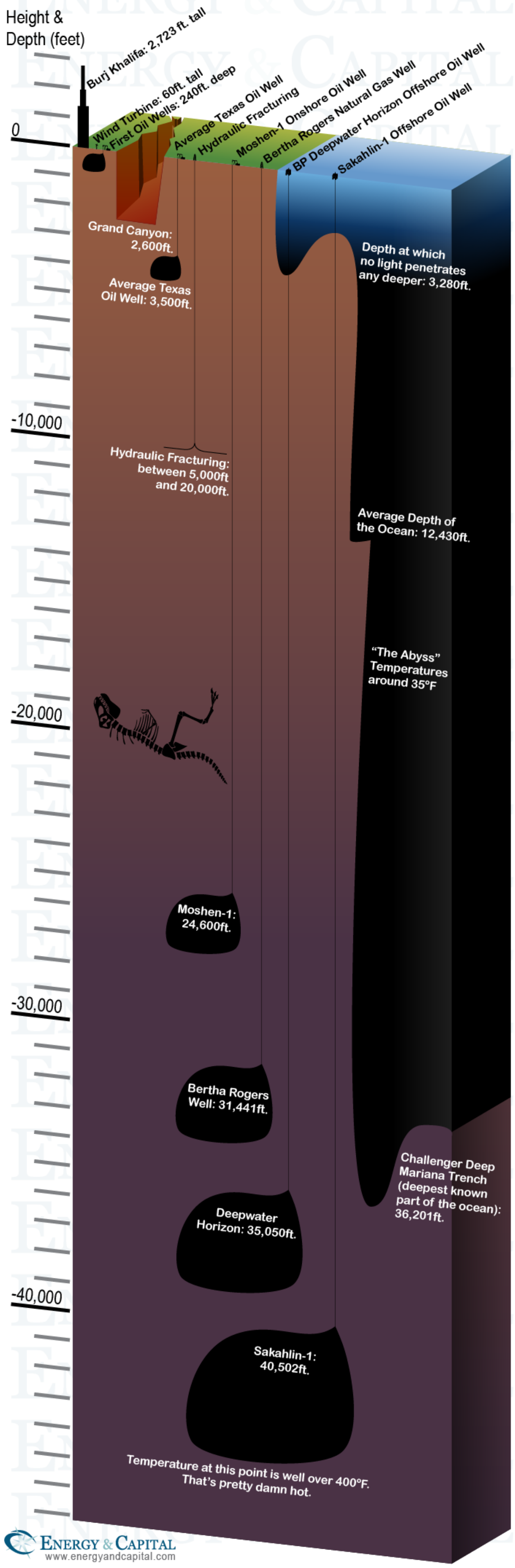

Figure 2. 1 A relative representation of the depth of oil wells in feet

2.2.4 Depth-independent definitions of "deep groundwater"

According to Commander (2010) the term deep groundwater is ambiguous, with some referring to groundwater below alluvial systems and others to groundwater below the depth to which groundwater is presently allocated and licenced. There are areas where the depth of deep groundwater will be controlled by the data and understanding of these systems. Commander (2010) acknowledges that the knowledge of deep groundwater is uneven over specific areas. In these areas the realisation of deep groundwater will diverge from the norm due to the lack of knowledge. The arid-zone Canning and Officer Basins in Australia, which are largely unexplored for groundwater, is an example of where deep groundwater is unknown. Groundwater conditions in these areas are largely interpreted from petroleum exploration well data, particularly stratigraphic and electric logs.

Alternatively groundwater quality can also be used to define the depth of deep groundwater. The Laxemar deep borehole in Stockholm, Sweden was investigated by Laaksoharju *et al*. (1995) by means of chemical analyses. The research indicated that the groundwater compositions consisted of two distinct groupings: one shallow to intermediate sodium-bicarbonate type to a depth of 1 000 m, and the other a calcium-chloride type of deep origin (Laaksoharju *et al*., 1995). Based on the results from this study the divide between shallow and deep groundwater could be based on groundwater quality, which reflected the divide between different flow systems.

2.2.5 Definition of "deep groundwater" for South African aquifers

As stated previously, the definition of deep groundwater is typically subjective and ambiguous with the dividing depth between shallow and deep a moving target. There is no commonly agreed upon or standardised depth distinction between shallow and deep groundwater (Alley *et al.*, 2013). South Africa is no exception. However, the definition applied to South Africa should take into consideration the environments and conditions specific to the country. Defining the divide between shallow and deep groundwater may include definitions based on: depth to current groundwater exploitation, groundwater quality (chemical determinands), unconfined versus confined, unknown areas/depths, and the groundwater below alluvial aquifers. These components will be investigated to aid in the generation of a representative definition of deep groundwater for South Africa.

2.2.5.1 Depth to current groundwater exploitation

According to geohydrological investigations performed by Vermeulen (2012), Karoo aquifers were traditionally restricted to the upper 100 m of the subsurface. Developments in drilling equipment has increased the average depth of drilling to 150 m, but boreholes deeper than 300 m are still uncommon in the Karoo.

Information on the depths of boreholes was extracted from the NGA in 2008 and analysed. The analyses indicated that only 4% of the 2 323 boreholes were drilled deeper than 100 m (Vermeulen, 2012). In the vicinity of Victoria West 67 boreholes were analysed by Woodford and Chevallier (2002). Their analyses found that the average depth of these boreholes was 206 m, but 73% of all the water strikes occurred within the top 80 m of the subsurface. If the definition of deep groundwater used is based on the current depth of groundwater exploitation, then these values become important (Commander, 2010).

An up-to-date account of the average depth of groundwater boreholes in South Africa would serve as a sound foundation to define deep groundwater in South Africa. The current project aims to further investigate the depths of boreholes in the country to assist in the definition of deep aquifer systems.

2.2.5.2 Groundwater quality (chemical determinands)

Murray *et al.* (2015) recently conducted a study to investigate the use of chemistry, isotopes and gases as indicators of deeper circulating groundwater in the main Karoo Basin. The use of chemical constituents was considered an alternative indicator due to the lack of suitable boreholes for sampling the deep formations targeted for shale gas development in South Africa (Murray *et al.*, 2015). A number of determinands, including temperature, was analysed and their ability to differentiate deep from shallow groundwater was assessed. Table 2. 1 provides a summary of the results.

Table 2. 1 Success rate and prioritisation of different determinands for identifying deep groundwater. A 100% success rate means that all the determinands listed meet the criteria set (Murray *et al.*, 2015)

Group	Success Rate	Determinands
Group 1	100% success rate	^{14}C, $\delta^{18}O$, fluoride, %sodium, magnesium, uranium, alkalinity
Group 2	>75% success rate	Boron, vanadium, lithium, $\delta^{11}B$, $^{36}Cl/Cl$, ^{222}Radon, H_2S
Group 3	50-75% success rate	Sodium, pH, tritium, nitrate, temperature, ^4He, $^3He/^4He$, CH_4
Group 4	< 50% success rate	$^{87}Sr/^{86}Sr$, $\delta^{13}C$, rare earth elements, other trace elements

Historically tritium concentrations have also been used to define deep groundwater based on residence times. Goldbrunner (1999) defined deep groundwater as groundwater that has a residence time of greater than 50 years, as indicated by the absence of anthropogenic tritium. Tritium Zero

Limit (TNF) is the depth at which tritium concentrations become unmeasurable. At this depth the water ages exceed 50 years and quickly increases in age over short depth ranges to ages of several thousand years (Seiler & Lindner, 1995). This TNF is met at an average groundwater depth of between 40 m and 100 m in Germany where the groundwater resources are not overexploited (Seiler & Lindner, 1995).

2.2.5.3 Unconfined vs confined

Netili (2007) quoted a groundwater specialist stating that shallow and deep groundwater systems are commonly referred to as unconfined aquifer and confined aquifers, respectively. The unconfined aquifer is often considered the shallow aquifer as it forms the uppermost system in a multiple-aquifer system, while confined aquifers are typically considered deep aquifers (Netili, 2007).

The classification of unconfined and confined aquifers can be used to support the definition of deep groundwater. Van Wyk (2013) discussed southern African pre-cretaceous deep groundwater flow regimes from a geological perspective of deep artesian (confined) systems. Van Wyk (2013) evaluated an amount of potential deep flow systems in terms of their geohydrological characteristics, which was acquired from deep drilling results. A list of prospective deep flow systems were identified, namely: the Table Mountain Group (TMG) sandstones, the Karoo Supergroup in Southern Africa, and hot springs in Karoo environments of Southern Africa (Van Wyk, 2013). These confined systems were investigated in this study to assist in defining deep groundwater in South Africa.

According to Diamond and Harris (2000) there are over 87 thermal springs in South Africa, ranging in temperature from 25°C to 64°C. Groundwater quality from these thermal springs should be considered in defining the depth of deep groundwater in South Africa, especially due to the present scarcity of suitable deep boreholes for groundwater testing.

Van Wyk (2013) and others have emphasized the importance of understanding the underlying geology for identifying deep groundwater systems. Consequently an emphasis on understanding the deep basin geology of South Africa will be incorporated into this study. Scheiber-Enslin *et al.* (2015) developed a new depth map of the Main Karoo Basin by using geophysics. This map, along with supplementary geological mapping for other areas, will be used to better define the deep geology of South Africa, giving insight into the deep aquifer systems. According to Viljoen *et al.* (2010) South Africa has a number of sedimentary basins covering most of the land surface, ranging in age from the Archaean to the present. These basins were investigated by Viljoen *et al.* (2010) to determine their carbon storage potential. The delineation of these basins will be used in the current project to assist in the evaluation of deep aquifer potential.

2.2.5.4 Deep groundwater as groundwater below alluvial/weathered aquifers

Studies conducted in Australia suggest that there can be differentiated between shallow and deep groundwater based on the depth to alluvial/weathered aquifer (Commander, 2010). However, South African land surface consists mainly of hard rock (Shahin, 2003), and the main Karoo Basin aquifers, which only developed after the rocks were formed, are prone to faulting, fracturing and the intrusion of dolerite bodies (Vermeulen, 2012). For this reason, the definition based on the alluvial aquifers' thickness is not an option for South Africa.

2.2.5.5 Unexplored depths

Commander (2010) presented an alternative definition of deep groundwater: groundwater that is unknown or unexplored. Where there is no current groundwater information below a certain depth for a specific area the definition of deep will be restricted to the depth below the current understanding. Data listed in the National Groundwater Archive (NGA) shows that most boreholes in South Africa have depths of less than 300 m, with only approximately 0.4% of the boreholes exceeding this depth.

2.3 DEEP GROUNDWATER QUALITY AND CIRCULATION DEPTHS

A groundwater chemistry investigation on the Laxemar deep borehole in Stockholm was conducted by Laaksoharju *et al*. (1995). The authors formed the hypothesis that the upper 800 m of the bedrock at Laxemar lies within a groundwater recharge area. This hypothesis was based on the groundwater quality: in the upper 800 m low saline brackish water was found, but below 1 000 m a highly saline groundwater was observed. Based on this hypothesis the quality of deep groundwater and the related degree of use as a potential water supply source was directly related to circulation depths.

Deep groundwater contains high levels of dissolved solids for several reasons (Fitts, 2002). Evidence of the high concentration of dissolved minerals in deep groundwater can be seen in the formation of veins and ore deposits (Fitts, 2002). These features are formed by mineral-rich deep groundwater being driven upwards due to the driving mechanisms discussed. As these fluids rise they encounter lower pressures and temperatures, causing some of the dissolved minerals to precipitate (Fitts, 2002).

The residence times in deep groundwater is typically longer, allowing mineral dissolution reactions to approach equilibrium, which is not usually reached in shallow groundwater systems due to the shorter residence times. Additionally, temperature and pressure increases with depth, which causes the solubility of many common minerals to also increase with depth. The flow paths of deep groundwater are long, thus increasing the probability of intersecting highly soluble minerals (Fitts, 2002).

2.4 DEEP GROUNDWATER DATA

Hydraulic data for deep flow systems is expensive and requires different field testing strategies and methods than the traditional techniques used to characterise shallow groundwater (Alley *et al*., 2013). The high cost of deep drilling should encourage the exploitation of alternative means of data collection, such as available for deep mineral exploration, geothermal exploration and deep oil and gas exploration.

According to Alley *et al.* (2013) deep groundwater is discussed in terms of deep sedimentary basins where aquifers can transpire at depths greater than approximately 3 000 m. They suggest that the characterisation of deep groundwater flow requires the use of pressure data instead of the traditional water level data, intrinsic permeability instead of the conventional hydraulic conductivity, and single-well drill-stem tests instead of multiple-well aquifer tests (Alley *et al.* 2013). In essence, to characterise deep groundwater flow hydrogeologists will need to acquire some of the concepts and skills that petroleum engineers use to characterise deep oil reserves. Tsang and Niemi (2013) suggested the use of tracer testing methods, including single-well injection-withdrawal tests. These measurements involve different techniques and approaches that require a carefully planned testing strategy to ensure the optimal sequence of testing, so as to not interfere with each other or influence the drilling procedure (Tsang & Niemi, 2013).

In a discussion of the issues and research needs for deep geohydrology, Tsang and Niemi (2013) also listed the typical data to be obtained from a deep borehole. In addition to geophysical logs and core samples, data to be collected includes pore pressure, temperature, fluid chemistry, rock mechanical stress, local permeability, storativity, thermal conductivity and porosity.

2.5 GEOPHYSICAL METHODS FOR DEEP AQUIFER DELINEATION

For decades surface geophysical methods have been used to successfully and economically explore groundwater resources (Hasbrouck & Morgan, 2003). The summary of geophysical methods by Hoover *et al*. (1995) is simplified in Table 2. 2. Only the methods with an appropriate depth of investigation should be considered for future investigations of deep groundwater. According to the summary by Hoover *et al*. (1995) the most applicable methods for deep groundwater investigations would be gravity, seismic, electrical and electromagnetic methods.

In recent years geophysical methods are being applied to explicitly explore deeper groundwater resources on an international scale. The application of deep geophysical methods on the South

African landscape is investigated, however, the scope of these applications is scarce. In the following sections, only the Karoo Supergroup and Cape Supergroup areas are discussed.

The American Society for Testing and Materials' (ASTM) guideline for selecting surface geophysical methods describe different conditions/features that could potentially be investigated, with an indication of appropriate geophysical methods for that specific condition/feature (Table 2. 3). For investigating the depth to bedrock or depth to water table, the seismic and ground-penetrating methods are most appropriate. For the identification of rock layers, the seismic (reflection) method is most appropriate. However, for the identification of fractures and faults, the very low frequency electromagnetic (VLF EM) method is most appropriate (McGinnis *et al*., 2011).

Table 2. 2 Summary of geophysical methods, characteristics and general depth of investigation (taken from Hoover *et al*., 1995)

Method	Relevant physical property	Typical source of anomaly	Depth of investigation
Gravity	Density	Rock density contrasts	All
Magnetic	Magnetic susceptibility and revenant magnetization	Magnetic susceptibility and revenant magnetization contrasts	Surface to Curie isotherm
Gamma-ray	Quantity of K, U, Th	K, U, Th contrasts	Upper 50 cm
Seismic refraction/reflection	Velocity of P and S waves	Structures of velocity layer contrasts	All
Thermal (borehole/remote sensing)	Thermal conductivity/inertia	Thermal flux or conductivity variations	Hole depth (borehole) or 5cm (remote sensing)
Electrical (direct current resistivity)	Resistivity	Lateral or vertical changes in the Earth's resistivity	2 km
Electromagnetic methods	Conductivity (inverse of resistivity)	Lateral or vertical changes in the Earth's conductivity	Shallow (10 – 100 m) Intermediate (1 km) Deep (10 km)
Remote sensing	Spectral reflectance	Changes in spectral reflectance	Surface only

Table 2. 3 Selection of geophysical methods for common applications (ASTM D 6429-99). Black boxes indicate primary methods while grey boxes represent secondary methods (McGinnis *et al*., 2011)

	Seismic		Electrical		Electromagnetic							
	Refraction	Reflection	DC Resistivity	SP	Frequency Domain	Time Domain	VLF	Pipe/Cable Locator	Metal Detectors	Ground-Penetrating Radar	Magnetics	Gravity
Natural geologic and hydrologic conditions												
Soil/unconsolidated layers												
Rock layers												
Depth to bedrock												
Depth to water table												
Fractures and fault zones												
Voids and sinkholes												
Soil and rock properties												
Dam and lagoon leakage												
Inorganic contaminants												
Landfill leachate												
Saltwater intrusion												
Soil salinity												
Organic contaminants												
Light, nonaqueous phase liquids												
Dissolved phase												
Dense nonaqueous phase liquids												
Manmade burial objects												
Utilities												
Drums and USTs												
UXO												
Abandoned wells												
Landfill and trench boundaries												
Forensics												
Archeological features												

*ASTM International. "Standard Guide for Selecting Surface Geophysical Methods." ASTM D6429–99, Philadelphia, Pennsylvania: American Society for Testing and Materials. 2006.

2.6 HISTORICAL EVIDENCE FOR DEEP AQUIFERS IN SOUTH AFRICA

Van Wyk (2013) described the evidence for deep groundwater flow regimes in South Africa. The exploration of gold and diamonds in South Africa increased significantly in the 19th century and large volumes of water was required for steam powered locomotives. Hence, the Cape Government

Railways initiated investigations for potential groundwater supply sources. Between 1893 and 1913 numerous projects were carried out to explore the potential for deep artesian wells (van Wyk, 2013). Twenty-seven boreholes were drilled to depths in the range of 183 mbgl to 1 103 mbgl, however, there is only data available for four of them. This data is presented in Table 2. 4.

Table 2. 4 Borehole IDs, depths to water strikes and groundwater yields of boreholes drilled by the Cape Government Railways (van Wyk, 2013)

BOREHOLES (ID)	DEPTH TO WATER STRIKE (mbgl)	YIELD (L/s)
Leeu-Gamka	366	4
Camdeboo	> 244	0 (no water)
De Aar	> 497	0 (no water)
Matjesfontein	458	1.2

Only minor water strikes were encountered at depths greater than 100 m (van Wyk, 2013). The borehole drilled to a depth of 1 085 mbgl within the Swartkops River Valley encountered various water strikes with a total yield of 13 L/s and a temperature of 54^{o}C.

According to van Wyk (2013) hot springs in South Africa and Namibia mainly occur along faults and/or dykes and where geothermal heated water is brought to the surface. This provides evidence of deep groundwater flow circulation. Kent (1949) suggested that the thermal water within the Karoo is sourced at significant depths beneath the ground surface. The temperatures of hot springs in South Africa vary from 26^{o}C to 57.2^{o}C (Kent, 1949). Considering that the hydrothermal gradient is approximately 3^{o}C per 100 m, these temperatures suggest circulation depths of approximately 200 m to 1 200 m.

In the 1960s the Department of Mines (DM) funded exploration projects to depths greater than 300 mbgl for groundwater sources within the Kalahari Basin (Smith, 1964). Saline groundwater was encountered down to depths in the range of 137 mbgl to 426 mbgl, with final borehole depths in the range of 441 mbgl to 652 mbgl. The geological formations encountered within these boreholes were the Dwyka Group, Nama Group and basement granites (van Wyk, 2013).

During the 1960s the Southern Oil Exploration Corporation (SOEKOR) drilled numerous boreholes for hydrocarbon exploration. The drilling results showed that the Karoo Supergroup was between 2 035 m and 5 288 m thick at the various drill sites (van Wyk, 2013). Saline groundwater was encountered at depths greater than 1 500 mbgl in some of these boreholes. Some of the deep boreholes were artesian, indicating that the deep aquifer systems were pressurised.

From the previously mentioned examples it appears that deep aquifers are most likely to occur in sedimentary basins, primarily within sandstone formations. Deep aquifer systems are likely to be associated with folded geological formations in which the water will occur in the host rock and fractures. Natural springs may provide an insight into the quality and type of water facies within the deeper aquifer systems.

2.7 INTERNATIONAL CASE STUDIES ON DEEP AQUIFERS

2.7.1 Introduction

In this section an international case study involving deep sedimentary aquifer systems is described. The deep groundwater system of the Monterey County in the Salinas Valley in California is explored.

2.7.2 The deep aquifer system of the Monterey County

As part of a cooperative study with the Monterey County Water Resources Agency (MCWRA) the US Geological Survey drilled Deep Monitoring Well 1 (DMW1) at a site between the coast and several supply wells in the Salinas Valley located in the central coastal area of California. This location was chosen because extensive agriculture and subsequent urbanization has resulted in extensive groundwater development and seawater intrusion within the upper-aquifer system. In 2000 DMW1 was completed to provide basic geologic and hydrologic information about the deep-aquifer system in the coastal region of the Salinas Valley. The monitoring-well site contains four wells in a single borehole:

1. DMW1-1 with depth of over 567 m below land surface in the lower Purisima Formation.
2. DMW1-2 has a depth of approximately 436 m below land surface in the middle Purisima Formation.
3. DMW1-3 has a depth of 323 m below land surface in the upper Purisima Formation.
4. DMW1-4 has a depth of roughly 290 m below land surface in the Paso Robles Formation.

The purpose of the well and related investigation was to assist in resolving several hydrogeological issues regarding the deep-aquifer system that had been previously identified by local agencies (Hem, 1985). These hydrogeological issues include:

1. understanding the continuity or connectivity of the aquifers that constitute the deep aquifer system,
2. examining the age of the sediments that compose the deep aquifer system,
3. analysing the mechanism of recharge and age of ground water in the deep aquifer system, and
4. investigating the relation of water pressures in the deep aquifer system to pressures in the submarine outcrops in Monterey Bay, the presumed source of seawater intrusion.

2.7.3 The deep geohydrology of the Salinas Valley

According to Wagner *et al*. (2000) the Salinas Valley comprises a wide alluvial aquifer system bounded by bedrock mountains and in part by the Zayante-Vergeles Fault zone on the northeast and the fault zone that includes the Seaside and Ord Terrace Faults on the southwest (Figure 2. 2 and Figure 2.3). The aquifer system's alluvial deposits are roughly 610 m thick and composed of river and sand dune deposits from the Holocene and Pleistocene age that are underlain by the Aromas Sand and Paso Robles Formation of the Pleistocene age (Rosenberg, 2001). The Purisima Formation underlies the Paso Robles Formation and the Aromas Sand. The Monterey Formation (shale) of the Miocene age underlies the Purisima Formation and is, in turn, underlain by the granitic basement rocks (Green, 1970). The Monterey Formation and the granitic basement represent the relatively impermeable bedrock that underlies the regional alluvial aquifer systems.

The geohydrology framework of the Marina area deep aquifer system remains unclear and may represent a transition between terrestrial Pleistocene-age sediments deposited in re-incised channels along the ancestral Salinas River and shallow marine-shelf sediments that were aligned with and bounded by the southwestern side of the Marina "Trough". Quaternary-Tertiary undifferentiated sediments, which may be the Paso Robles Formation, outcrop west of the monitoring-well site about 7 km offshore (Wagner *et al*., 2000) at a depth of about 80 m below sea level. Previous researchers described the deep aquifer system as a break at between 365 m and more than 609 m of Pleistocene-age deposits. This description is based on data from the MCWD deep-aquifer system water-supply wells (Hanson & Nishikawa, 1991; as cited by US Geological Survey, 2002).

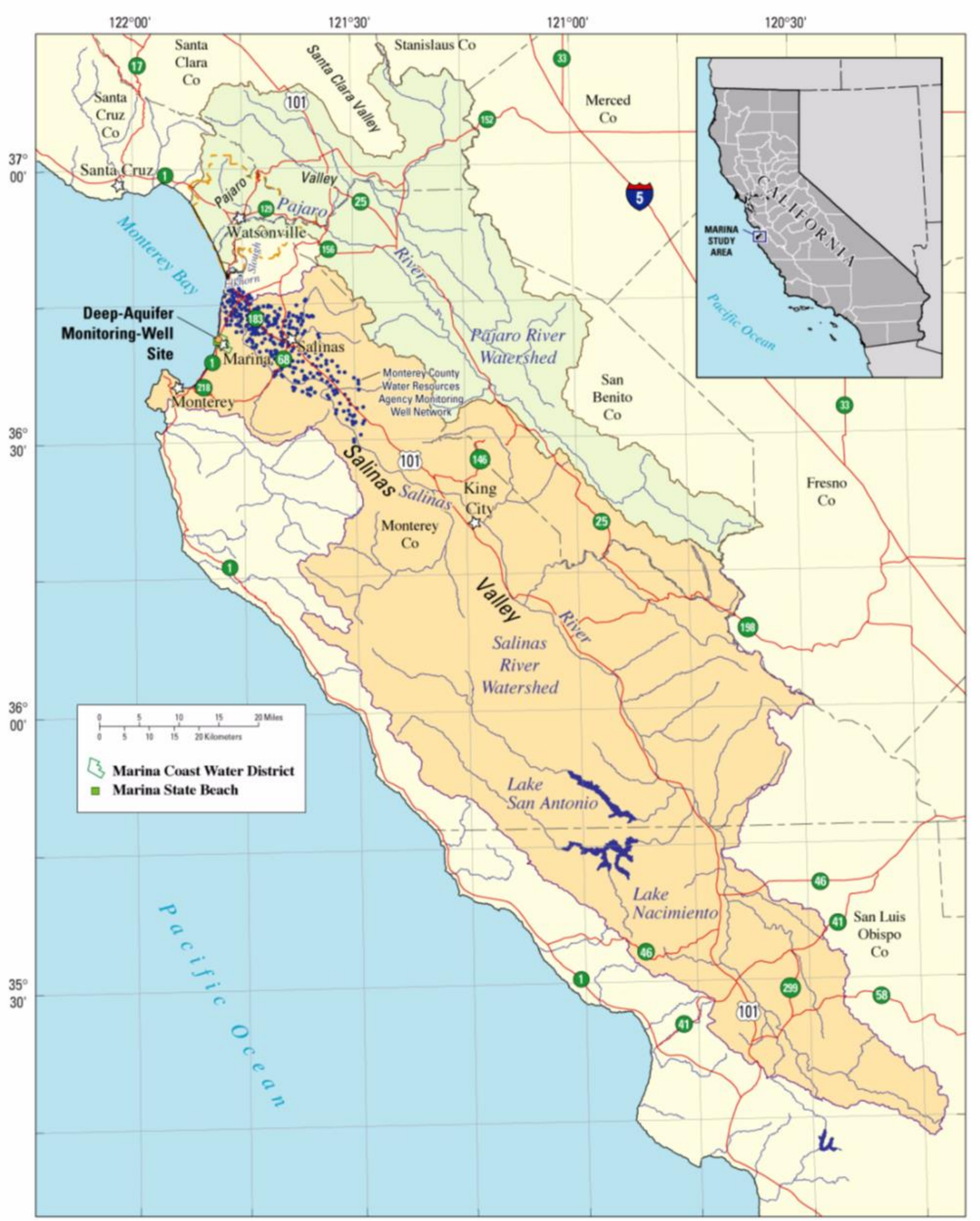

Figure 2. 2 Location of deep aquifer system monitoring-well site in the Salinas Valley at Marina, California (US Geological Survey, 2002)

The water-bearing sediments are grouped into an upper and a deep aquifer system. The upper aquifer system includes the shallow perched aquifer. These deposits may be hydraulically connected to the Paso Robles Formation at the DMW1 site. The Purisima Formation crops out on the southwestern side of the Monterey submarine canyon about 10 km offshore from the monitoring-well site at a depth of about 90 m below sea level (Wagner, 2000). Additional geological investigations, beyond the completion of the DMW1 site, are needed to establish this stratigraphic relation.

2.7.3.1 Investigation approach

During the drilling of 615 m deep multiple-well monitoring site DMW1, drill cuttings were collected at regular intervals and cores at selected depths. Geophysical logs were run after reaching final borehole depth (Hanson, 2001). Fossils contained in the cuttings and cores were used to establish the age of the sediments. Water extracted from cores below 245 m and water sampled from the four monitoring wells were analysed for general water chemistry as well as constituents that would help determine the source, age, and movement of groundwater in the deep aquifers. Each of the wells within the DMW1 borehole was also hydraulically tested to determine selected aquifer properties.

During the study the estimated physical properties and data were combined into a preliminary interpretation of the geohydrology of the DMW1 site. This preliminary interpretation was based on interpretations of the geologic, hydrologic and geochemical conditions of the aquifers at the DMW1 site and correlations to conditions at the nearby MCWD deep aquifer system water-supply wells. Since this study is largely limited to data obtained from one monitoring-well site, no broader or more detailed interpretations of the regional geology and hydrology for the coastal regions of the Salinas Valley form part of the study.

2.7.3.2 Hydrostratigraphy of the DMW1 site

Figure 2. 4 documents the DMW1 site upper aquifer system as a six depth-sequential aquifer system units within non-marine sediments to a depth of 291 m. The upper aquifer system includes the “180-foot” and “400-foot” aquifers within the older valley-fill alluvium and upper Aromas, the shallow perched aquifer in the dune sand, and the “900-foot” aquifer in the lower Aromas and Paso Robles Formation. Although these depth-sequential aquifer system units are referred to as “aquifers” in this study, they are generally heterogeneous collections of fine- and coarse-grained deposits.

The DMW1 site deep aquifer is located within the Purisima Formation. It is acknowledged as those aquifers within mainly marine sediments, extending from a depth of 300 m (the base of the Paso Robles Formation) to more than 615 m. According to mega-fossil identification DMW1 sediments cored from a depth of about 405 m are characteristic of the marine sediments of the Pliocene age Purisima Formation. This is also confirmed by micro-fossil identification. DMW1 site geophysical logs indicate four groups of sediment layers between 300 m and 600 m, representing several depositional and erosional cycles within the Purisima Formation.

The geological and geophysical data collected in this study has led to the identification of 10 hydrostratigraphic units at the DMW1 site (Figure 2.4) that differ from the initial classification by Green (1970).

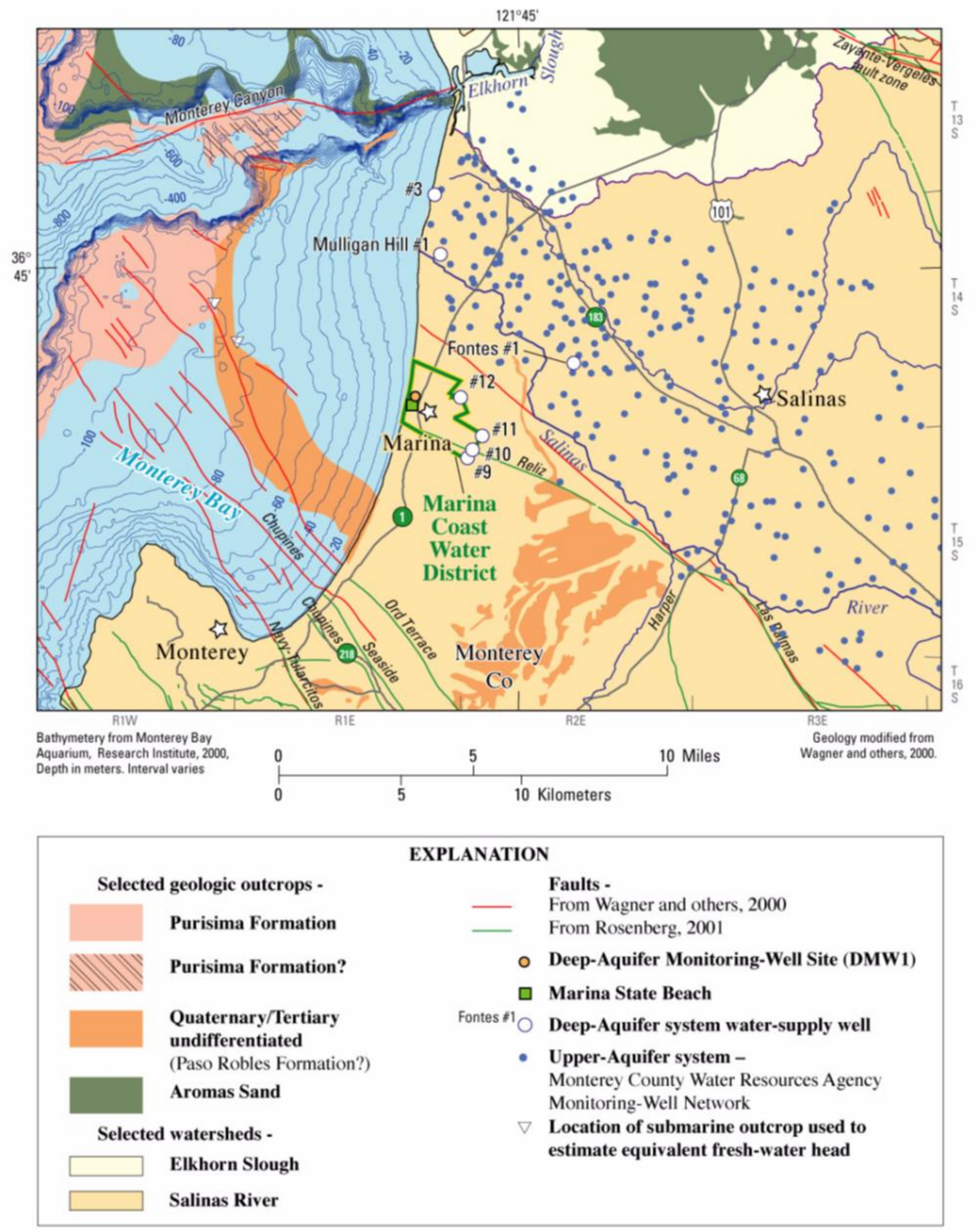

Figure 2. 3 Location of deep aquifer system monitoring-well site and selected water-supply wells, Marina, California (US Geological Survey, 2002)

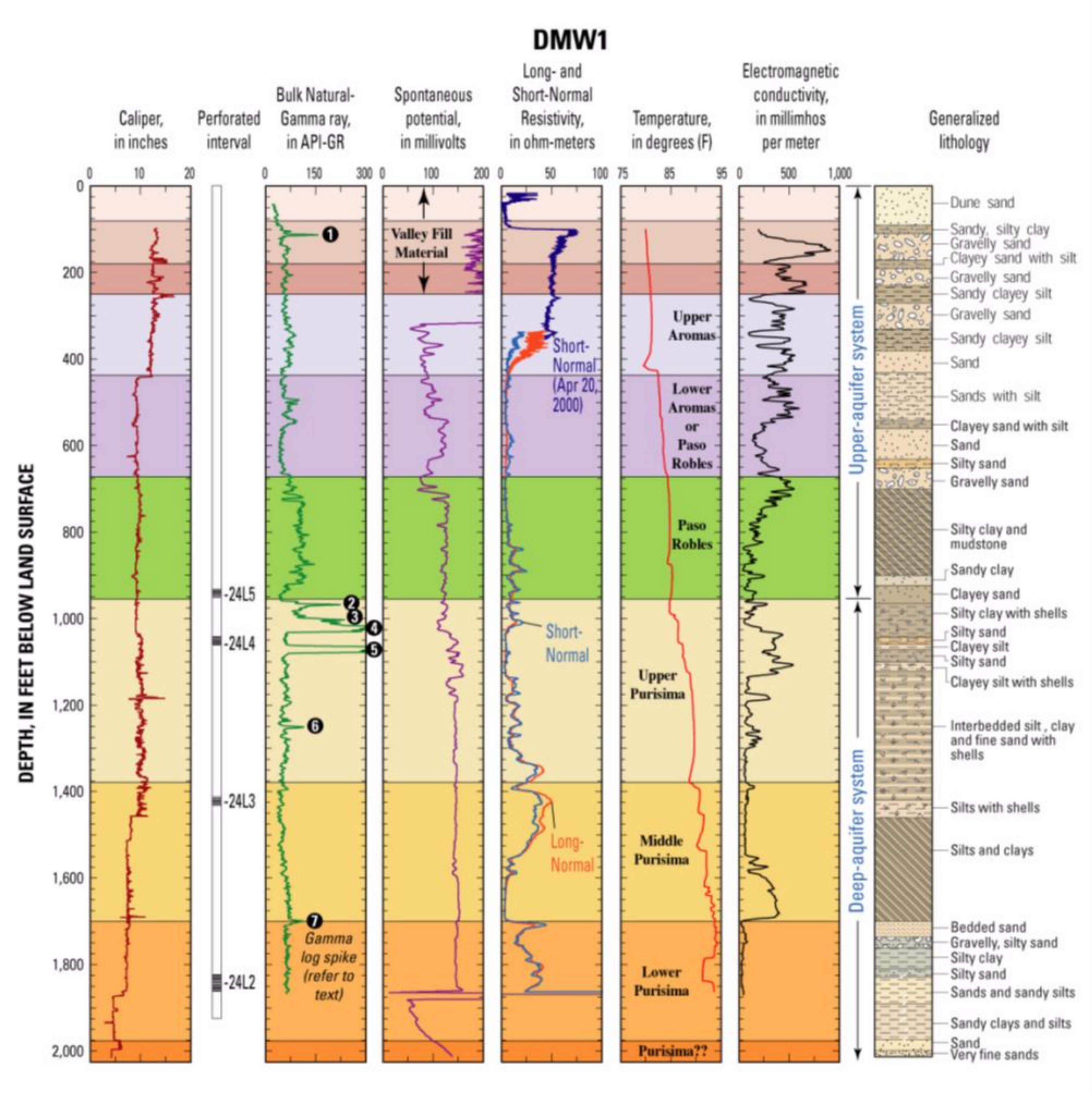

Figure 2. 4 Lithology and geophysical logs for the deep aquifer system monitoring-well site, Marina, California

An interpretation of Figure 2. 4 follows:

UPPER AQUIFER SYSTEM

1. The first 80 ft bls: The dune sands of the Holocene age may represent an extension of the Salinas Valley perched aquifer that is bounded below by the Salinas Valley Aquiclude.

2. From 180 ft bls: The aquifer is made of valley-fill alluvium of the Holocene to Pleistocene age.

3. Between 180 to 250 ft bls: Water-bearing units between the aquifers that may be composed of additional valley-fill alluvium of the Holocene to Pleistocene age.

4. From 250 to 270 ft bls: The aquifer is made up of water-bearing sands and gravels, which may be equivalent to the upper Aromas Sand of the Pleistocene age. The lower fragment of the aquifer is mainly made of water-bearing sands, contains thin basal gravelly sand, and may represent the lower Aromas Sand of the Pleistocene age.

DEEP AQUIFER SYSTEM

1. At depth 955 to 1,380 ft bls: The upper Purisima Formation of the Pliocene age was identified. Water-bearing units are identified at interval 1,030-1,045 ft bls and 1,345-1,360 ft bls in the upper Purisima Formation.

2. From 1,380 to 1,700 ft bls: The middle Purisima Formation is predominantly fine-grained marine deposits. On the basis of the resistivity log (Figure 2.4,

3. At 1,700 to 1,975 ft bls: The lower Purisima Formation is predominantly composed of sands. The deepest monitoring well, DMW1-1, is screened near the middle of this water-bearing unit.

4. 1,990 to 2,012 ft bls: This interval is possibly part of the lower Purisima Formation. The unit is composed of silts and fine-grained sands of dark greenish grey to olive grey colour that may be a water-bearing unit that is separate from unit 9.

In conclusion, the DMW1 monitoring site provides an indication on water levels and aquifer properties of the deep aquifer system. The water levels, water-level differences between aquifers, and connection to offshore comparable freshwater heads are all aspects of pressure within the aquifer system that help assess the potential for seawater intrusion and intraborehole flow in the deep aquifer system.

2.8 NATIONAL CASE STUDIES ON DEEP AQUIFERS

2.8.1 Introduction

In this section four case studies about the occurrence of deep aquifers in the Karoo Supergroup and Table Mountain Group are discussed. These case studies include four deep drilling projects and a study into the potential of deep saline aquifers to act as reservoirs for carbon storage.

2.8.2 The Deep Artesian Groundwater Exploration for Oudtshoorn Supply (DAGEOS) project

Umvoto Africa was contracted in April 2000 to undertake a project on Deep Artesian Groundwater Exploration for Oudtshoorn Supply (DAGEOS). The aim of the DAGEOS project was to secure deep groundwater as a long-term option to augment the water supply to the greater Oudtshoorn Municipality, and/or to contribute to a conjunctive surface-and-groundwater augmentation scheme (Umvoto, 2005). Figure 2. 5 displays the location of the DAGEOS study area.

Key outcomes for the DAGEOS project included:

- Exploring and quantifying the resource potential of deep artesian groundwater in confined TMG fractured rock aquifers within a water-stressed catchment.
- Developing the technical capacity to drill wells deeper than 300 m at selected sites with potentially high water resource yields (>35 L/s or >1 million cubic metres [Mm^3] per year).
- Completing and pump-testing an experimental deep groundwater well (at optimum yield) at one or more sites in order to determine aquifer parameters and prove an environmentally acceptable and sustainable way of adding to the Oudtshoorn municipal water supply.

(Umvoto, 2005)

2.8.2.1 Local Geology and Hydrogeology

Umvoto (2005) studied the structural geology and geometry of the large scale fracturing in the study area by using satellite images and aerial photographs to define target sites for deep drilling. The geohydrological units defined by Umvoto (2005) are summarised in Table 2.5.

According to Umvoto (2005) the Cape Supergroup formations dominate the DAGEOS study area. The Cape Supergroup consists of the TMG, Bokkeveld Group and Witteberg Group. The Peninsula Formation, which constitutes the lower aquifer in the TMG of the Swartberg-Outeniqua region, is topographically dominant and hydrogeologically most important due to its a) wide areal extent in the areas of maximum precipitation and recharge potential, and b) greatest subsurface volume of permeable fractured rock (Umvoto, 2005). The Peninsula Formation forms a thick aquifer. It has an approximate thickness of 550 m in the Cape Peninsula, reaches up to 1 300 m in the Citrusdal region, can be up to 1 500 m within the Cape Fold Belt, and is speculated to be greater than 2 000 m in the Oudtshoorn area (Umvoto, 2005).

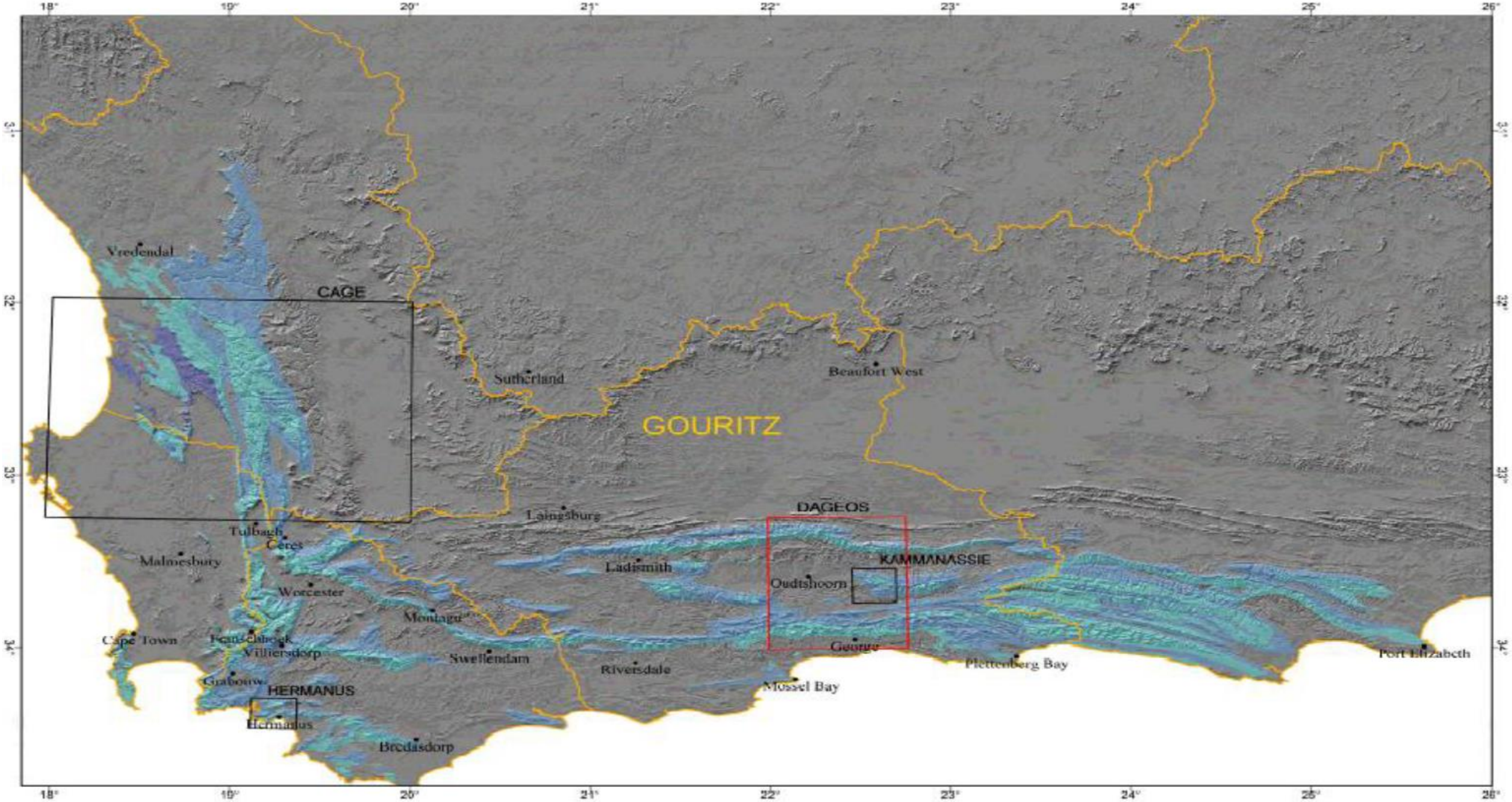

Figure 2. 5 Locality map for the DAGEOS project (Umvoto, 2005)

The Skurweberg Formation within the Nardouw Subgroup of the TMG is also considered a potentially important fractured-rock aquifer. It consists of thick, cross-bedded quarzitic sandstones and can reach thicknesses of up to 400 m in some areas (Theron *et al.*, 1991; as cited by Umvoto, 2005).

The Bokkeveld Group forms an overlying, confining layer to the TMG, with the major unit in this area being shaly strata. It does not form a significant aquifer, except where the intercalated sandstone formations have become fractured and relatively porous. However, this is usually only up to 50 m below the ground surface (Umvoto, 2005).

Table 2. 5 Hydrostratigraphic units of the eastern TMG in the DAGEOS study area. Grey indicates aquitards and white indicates aquifers (Umvoto, 2005)

Superunits	Units	Subunits
	Gydo Mega-aquitard	
Table Mountain Superaquifer	Nardouw Aquifer	Kareedouw Subaquifer
		Baviaanskloof Mini-aquitard
		Skurweberg (Kouga) Subaquifer
	Winterhoek Mega-aquitard	Goudini (Tchando) Meso-aquitard
		Cedarberg Meso-aquitard
		Pakhuis Mini-aquitard
	Peninsula Aquifer	Platteklip Subaquifer? (not yet separately mapped in this area)
		Leeuklip Subaquifer (not yet separately mapped in this area)
	Saldanian Aquicludes	[Kansa Subgroup] [Cape Granite Suite] [Cango and Kaaimans Groups]

From Table 2. 5 it can be seen that Umvoto (2005) conceptualised two main aquifers in the study area, namely the Skurweberg and Peninsula Formations within the TMG. A number of aquitards that form confining layers are also conceptualised (Umvoto, 2005).

2.8.3 The Blikhuis Experimental Deep Drilling (BEDD) project

The study site for the Blikhuis Experimental Deep Drilling (BEDD) project is located roughly 25 km from Citrusdal (Figure 2.6). As part of the project four experimental boreholes were drilled, however, due to technical problems one was abandoned (Hartnady & Hay, 2002a). The drill target was the confined section of the Peninsula Aquifer, which is located along the faulted hinge zone of a major synclinal fold (Hartnady & Hay, 2002). In order to reach the main deep aquifer in the Peninsula Formation one needs to drill through the lower part of the Nardouw Subgroup (Goudini Formation) as well as the underlying Cedarberg and Pakhuis Formations.

The intersection of borehole BH2 with the Nardouw Aquifer indicates that the potentiometric surface of this confined layer is located at 165 m below the ground surface. Only when water strikes were encountered below a depth of 145 m below the ground surface in the Peninsula Aquifer was when the deepest boreholes started flowing. Analysis results also indicates chemical and physical differences between the deeper artesian Peninsula groundwater and the shallower Nardouw groundwater. The Nardouw groundwater is more distinct as it contains a higher Fe content (Hartnady & Hay, 2002a).

Borehole BH2 intersected the Cedarberg-Goudini contact at 160 m. The borehole was terminated at a depth of 304 mbgl, in black carbonaceous shale. BH2 indicated that the Cedarberg Formation was considerably deeper than its regional thickness of 90 m at the BEDD drilling site. Diamond-bit rotary core drilling was later used to deepen the borehole where it intersected the Cedarberg-Pakhuis contact. At 324 mbgl the Pakhuis-Peninsula contact was intersected and at a depth of 349 m a highly fractured Peninsula quartzite was found. Between 349 m and 352 m a few smaller water strikes followed, until a main water strike was intersected at a depth of 360 m. The rest water level in the borehole then rose and led to a slightly artesian BH2 (Hartnady & Hay, 2002a).

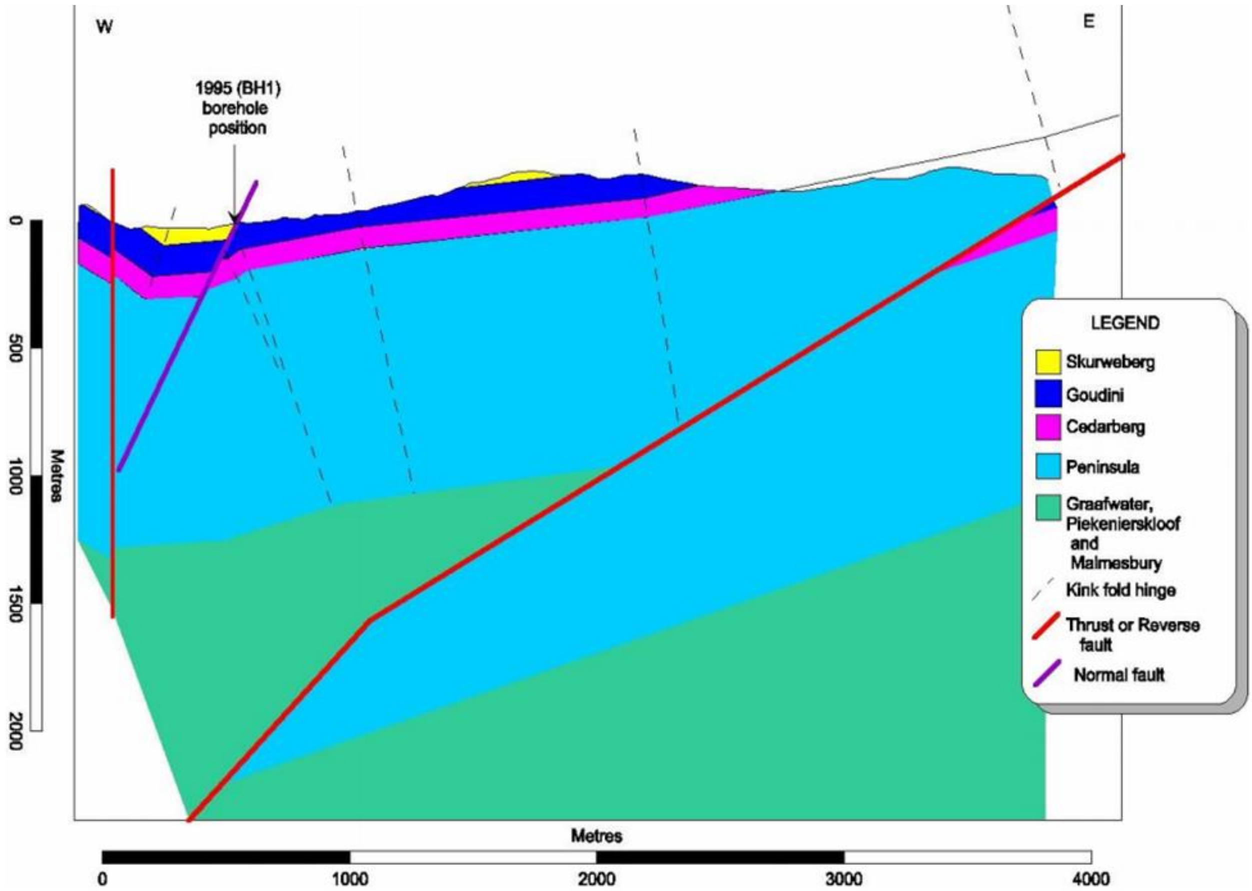

Figure 2. 6. Preliminary geological cross-section through the BEDD project study area (Hartnady & Hay, 2002a)

After casing off all water strikes, drilling below 381 m proceeded at 76 mm diameter using the wire-line method of core retrieval (Hartnady & Hay, 2002a). Further fracture intersections seen between 434 m and 444 m depth resulted in an artesian flow at a rate of 1 to 3 L/min. Another porous zone of sandstone at a depth of 475 m to 485 m was reported by the driller's record (Hartnady & Hay, 2002a). When the borehole reached a depth of 490 m the artesian flow had recovered further to 0.31 L/s. At a depth of 528 m to 544 m a complex fault zone was found where the bedding dips are steepened to become sub-parallel to the borehole core axis. Hartnady and Hay (2002a) reported that below 500 m in the BH2 borehole there has been no notable increase in the artesian flow.

The information gathered from the deep BH2 borehole of the Blikhuis deep drilling project serves to indicate that there could potentially be sufficient amounts of water to be extracted at depths greater than 300 m in the TMG. The common ^{14}C results for BK1 and BK2 and the elevated groundwater temperatures for all these boreholes establish a definite influx of groundwater from a relatively deep flow path into these wells. Additionally, there is the potential for artesian flow from the Peninsula Aquifer. However, the information from borehole BH2 indicating that no substantial flow increased the artesian flow correlates to the conclusions made by Lin *et al.* (2007). Lin *et al.* (2007) analysed an 800 m deep borehole and characterised the fractures into four zones based on the degree to which fractures are hydraulically active. The zones are: (1) high (0-150 mbgl); (2) medium (150-400 mbgl); (3) low (400-570 mbgl); and (4) hydraulically inactive (570-800 mbgl or deeper).

2.8.4 Deep carbon storage in South Africa

Holloway (1996) was the first to identify geological formations (specifically gas and oil reservoirs, saline aquifers and coalbeds) as a possible means to store CO_2 back in 1996. In 2009 deep saline aquifers in sedimentary basins were identified as the best possible storage source for CO_2 by Birkholzer *et al.* (2009). However, the potential effects that storing CO_2 in aquifers might have on the aquifers are not yet clearly understood. Birkholzer *et al*. (2009) mentions changes to the pressures within the strata as a possible effect. Changes to the pressures within the strata may increase the hydraulic head, resulting in saltwater intrusion. The rate at which water moves through geological formations depend on how conductive the aquitard or aquiclude is. Figure 2. 7 illustrates CO_2 being pumped into a deep aquifer under pressure and the resulting saltwater intrusion into the upper aquifer systems.

A numerical model with eight aquifers (approximately 60 m thick) and seven aquitards (approximately 100 m thick) was set up to further investigate this theory (Birkholzer *et al*., 2009). A radius of 50 km was established and effects for a 100 year period (30 years of CO_2 pumping and 70 years after pumping) simulated. The initial temperatures, pressures, salt mass fraction and saline density in Figure 2. 8 clearly indicate that pressure and temperature increases with depth. However, it also illustrates that salt mass fraction and saline density remains constant up to a depth of 540 mbgl, which was the assumed depth of freshwater aquifers (Birkholzer *et al*., 2009).

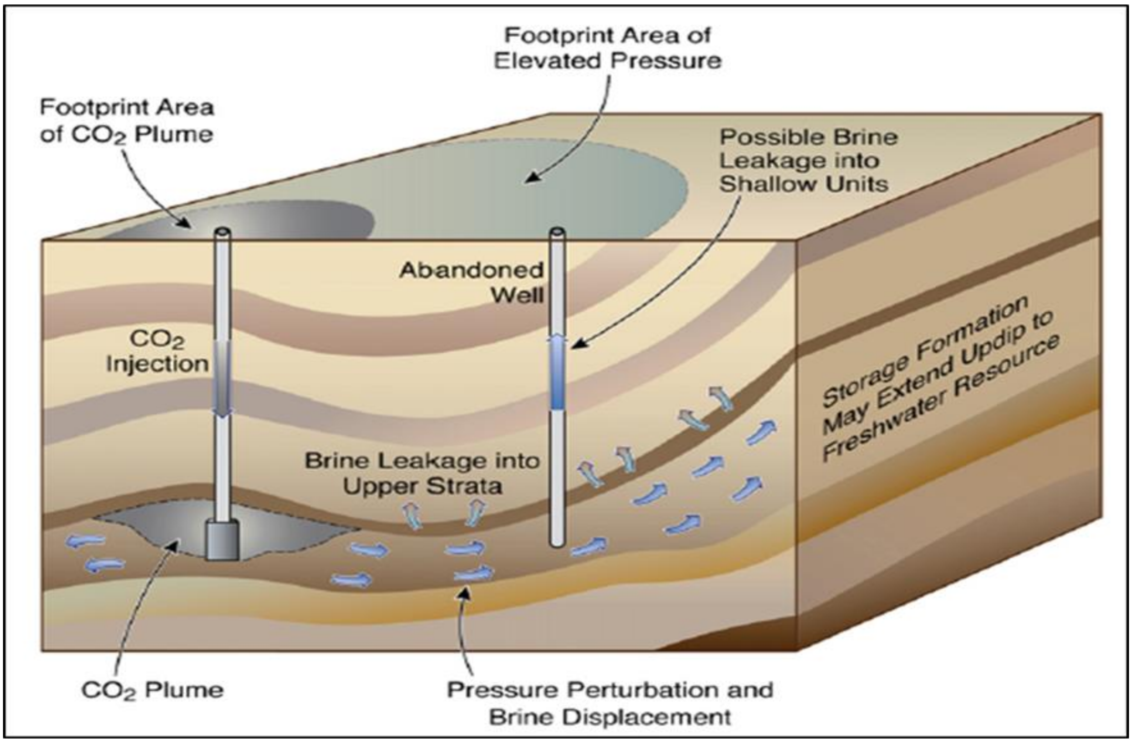

Figure 2. 7 Schematic showing the different regions of influence related to CO_2 storage (Birkholzer *et al*., 2009)

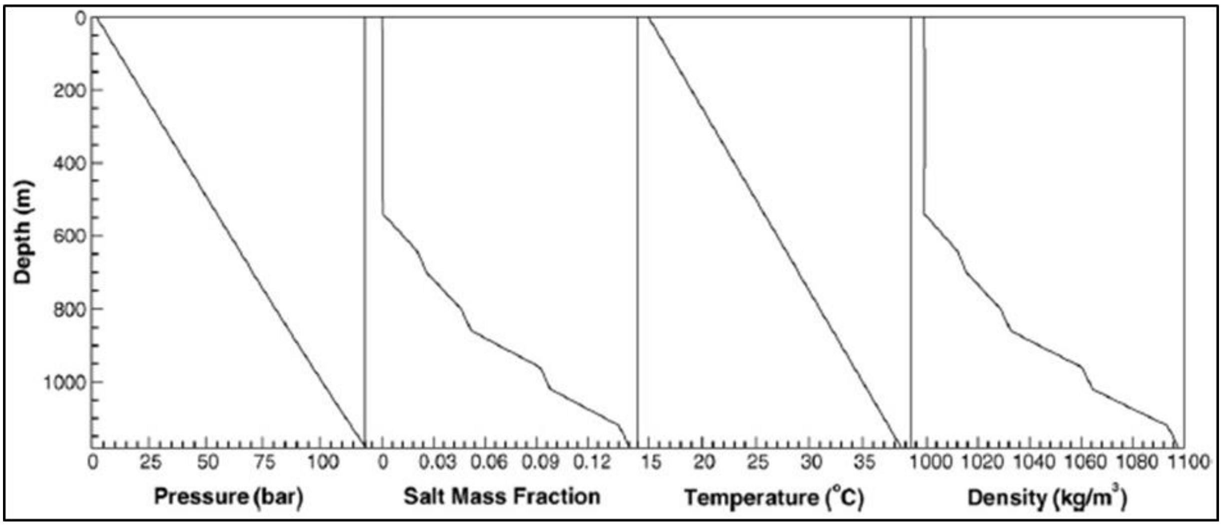

Figure 2. 8 Vertical profiles of pressure, salt mass fraction, temperature and saline density from top of aquifer to storage formation (Birkholzer *et al*., 2009)

Although it may be relatively environmentally safe to store CO_2 at great depths, the zones in which storage will take place need to be studied in great detail since the confining layers play a significant role in the possible contamination of upper freshwater aquifer systems. Geological structures such as faults and shear zones are features typically associated with zones of increased permeability. Such zones could hydraulically link the deeper and shallower aquifer systems. Since groundwater generally decreases with depth (as salinity increases) groundwater from the deeper aquifers could have adverse impacts on the quality of the shallow water resources (Birkholzer *et al*., 2009).

2.8.4.1 Carbon storage in South Africa

Coal-fired power stations produce tonnes of carbon dioxide (CO_2) every year and new methods are required to dispose of this waste by-product. According to Birkholzer *et al*. (2009) the CO_2 may be stored within deep saline aquifers as a potential means of minimising climate change. Viljoen *et al.* (2010) produced a technical report on the geological storage of CO_2 in South Africa. The report focussed on the various large-scale emission point sources of CO_2 in South Africa, the physical properties of CO_2 that affects its storage, the range of possible geological storage types, and previous work done on CO_2 storage in South Africa (Viljoen *et al.*, 2010). Viljoen *et al.* (2010) examined the geological criteria that affects CO_2 storage and how basins could be ranked and assessed to identify the best potential storage.

Viljoen *et al.* (2010) listed the screening criteria used to determine the potential carbon storage. Some of the parameters listed under "other criteria" are geohydrology, salinity of groundwater, size of the basin, thickness, tectonic setting of the basin, lithology of basin (potential of reservoir), fault intensity, dolerite dykes and sills to mention a few.

Geohydrology as a criterion relates to the preference of basins with deep, relatively slow regional long-range flow systems for carbon storage. Shallow and short flow systems or compacted flow negatively influences the CO_2 storage potential of a basin. Again, the identification of deep regional flow systems will assist in identifying deep aquifers (Viljoen *et al*., 2010). Similarly, information on the salinity of groundwater and the accessibility of data could also contribute to the identification and understanding of deep aquifer systems.

Thickness is included in Viljoen *et al*.'s (2010) list because a minimum depth for storage in saline aquifers is anticipated to be approximately 800 mbgl and 300 mbgl for coalbeds. Viljoen *et al.* (2010) thus excluded any shallower basin. On the other hand, if the selected reservoir rocks are too deep it can negatively impact the economic feasibility, as the greater the depth to the injection target the larger the associated costs of drilling (Viljoen *et al.*, 2010). The evaluation of potential storage sites could assist in the identification of aquifers below depths of 300 mbgl to 800 mbgl in South Africa.

Lithology and the associated potential for CO_2 storage reservoirs were evaluated by Viljoen *et al.* (2010). According to them a large, deep, simple, undeformed and layered sedimentary basin with alternating porous sandstone and impervious mudstone is ideal for CO_2 storage (Viljoen *et al*., 2010). In standard oil exploration the reservoir potential of sandstones is classified from poor to very good, as shown in Table 2. 6. This screening criteria could also be useful in identifying deep aquifers that have parameters that would allow for groundwater flow at depths.

Table 2. 6 Porosity and permeability classification for determining reservoir potential for oil exploration (Viljoen *et al.*, 2010)

	Poor	Fair	Good	Very good
Porosity (percent)	10	10-15	15-20	>20
Permeability (mD)	1	1-10	10-100	>100

Fault intensity and the presence of dolerite dykes and sills are used to gauge the appropriateness for carbon storage as these features will enhance the movement of CO_2 back to the surface. However, these features are desirable for groundwater flow at depth. The fractures and dolerite dykes identified as possible problems for carbon storage can thus be used to identify potential deep fractured aquifers (Viljoen *et al*., 2010).

2.8.5 The Agulhas-Karoo geophysical transect

The South African landscape is shaped by the Cape Fold Belt in the south, with the adjacent Cape-Karoo Basin and underlying Precambrian basement. The Inkaba yeAfrica research initiative designed the Agulhas-Karoo Geophysical Transect (AKGT) to examine the deep crustal features using geophysical data. The AKGT consists of two roughly parallel north-south lines that intersect onshore/offshore area (Figure 2.9). Lindeque *et al.* (2011) focusses on a smaller 100 km segment of the larger AKGT line, which covers the Karoo Supergroup transition over the escarpment to the Cape Supergroup (

Figure 2. 9). Geophysical data acquired by Lindeque *et al*. (2011) along the AKGT between 2004 and 2007 within the Inkaba yeAfrica framework includes:

a) Archive data containing surface geology, aeromagnetic data, proximate deep boreholes, teleseismic receiver functions and regional seismic reflection profiles, and

b) line coincident newly acquired high-resolution geophysical data consisting of near vertical seismic reflection data, shallow P- and S-wave velocity data, wide-angle refraction data, high resolution magnetotelluric data and impedance spectroscopy measurements on borehole samples.

Lindeque *et al.* (2011) investigates the collected geophysical data to create the first high-resolution deep seismic reflection profile and deep crustal model through the Palaeozoic-Mesozoic sediments of the Cape-Karoo Basin and its underlying basement, both overprinted in the south by the mid-Phanerozoic Cape Fold Belt deformation.

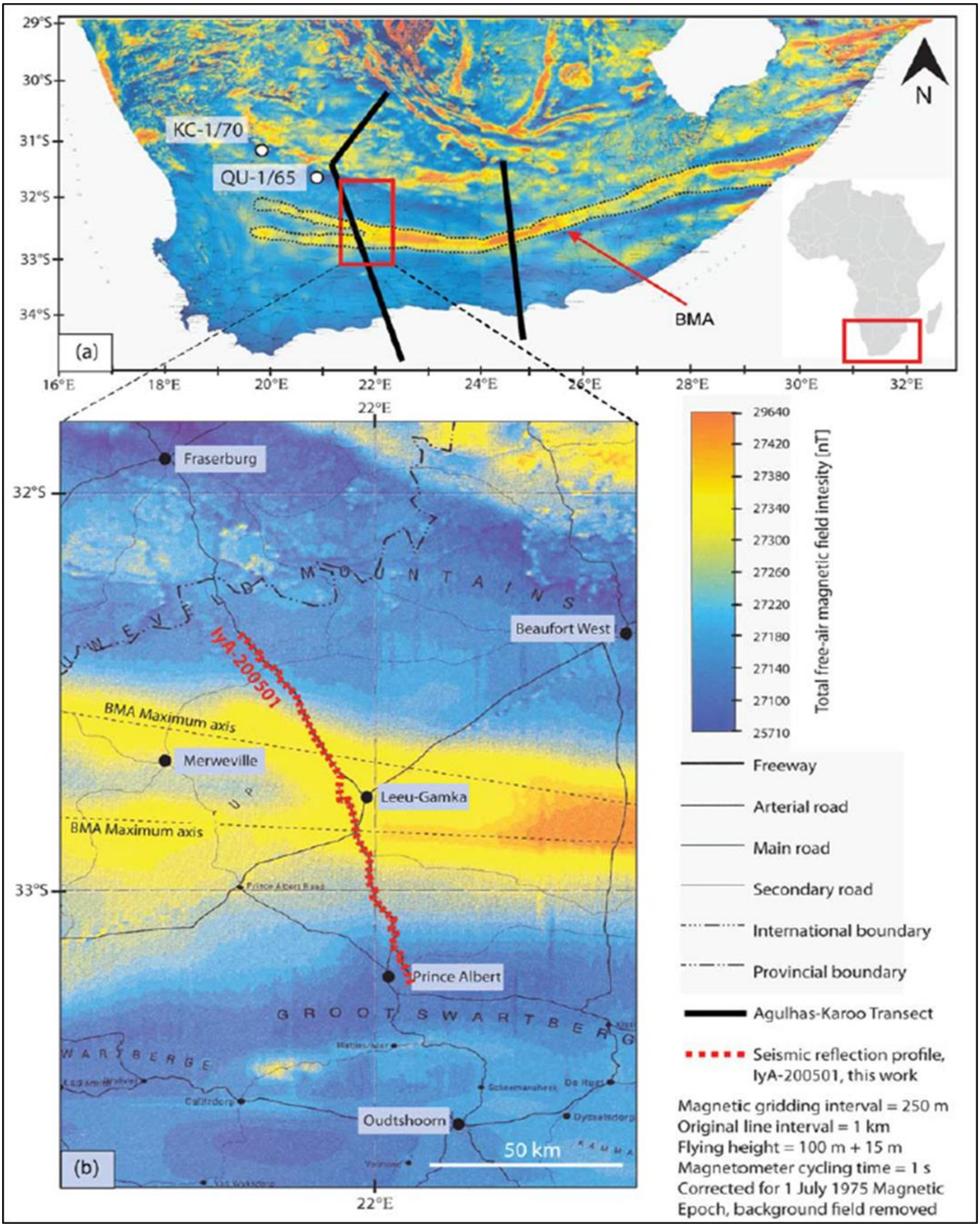
KC-1/70
QU-1/65
BMA
N
(a)
(b)
Fraserburg
Beaufort West
Merweville
Leeu-Gamka
Prince Albert
Oudtshoorn
IyA-200501
BMA Maximum axis
BMA Maximum axis
50 km
Total free-air magnetic field intesity [nT]
29640
27420
27380
27340
27300
27260
27220
27180
27140
27100
25710
Freeway
Arterial road
Main road
Secondary road
International boundary
Provincial boundary
Agulhas-Karoo Transect
Seismic reflection profile, IyA-200501, this work
Magnetic gridding interval = 250 m
Original line interval = 1 km
Flying height = 100 m + 15 m
Magnetometer cycling time = 1 s
Corrected for 1 July 1975 Magnetic Epoch, background field removed

Figure 2. 9 Total field free-air aeromagnetic map showing the western and eastern lines of the Agulhas-Karoo Geophysical Transect (AKGT), the Beattie Magnetic Anomaly (BMA) and the 100 km section used for this study (Lindeque *et al.*, 2011)

Lindeque *et al*. (2011) produced a model differentiating between four components (Figure 2. 10.):

1. Karoo Supergroup (approximately 5 km thick folded and resting para-conformably on wedge of the Cape Supergroup)
2. Wedge of the Cape Supergroup (CSG) (continuous undeformed sub-horizontal, approximately 1.5-10 km thick and resting unconformably on middle crust)
3. Middle crust (approximately 13-21 km, interpreted as Mesoproterozoic Namaqua-Natal Metamorphic Belt (NNMB) crust, and separated by a detachment to the lower crust)
4. Lower crust (highly reflective, approximately 10-24 km thick, interpreted as an older Palaeoproterozoic section of the NNMB or even Archean cratonic basement, and bounded by a 2-5 km thick bottom layer that lies subparallel to a clear Moho interpreted as a mafic under-plate, metasomatic reaction zone, or lower-crust to mantle transition zone)

The Lindeque *et al.* (2011) study does not clearly discuss the potential occurrence of deep groundwater in the study area. However, it has been discovered that thermal springs are found along the Cape Fold Belt due to the deformation and subsequent fracture/fault systems. Cave and Clarke (2003) studied the thermal springs in the Western and Eastern Provinces to determine circulation depths based on geothermometer methods and estimated a maximum circulation depth of 7.4 km at the Warmwaterberg spring (close to the AKGT line). This depth was thought to be extreme by Cave and Clarke (2003), yet the geophysical crustal model indicates that the TMG formations not only extend down to these depths but fractures are also evident at these depths. Figure 2. 11 displays the integrated crustal model produced by Lindeque *et al.* (2011) matched against previous crustal models of Southern Africa by Hälbich (1993), Chevallier *et al*. (2004a) and Lindeque *et al.* (2007), as cited by Lindeque *et al.* (2011).

In conclusion, the integrated crustal model produced by Lindeque *et al.* (2011) gives a more accurate indication of the potential depth of groundwater in the Cape Supergroup and Karoo Supergroup lithologies.

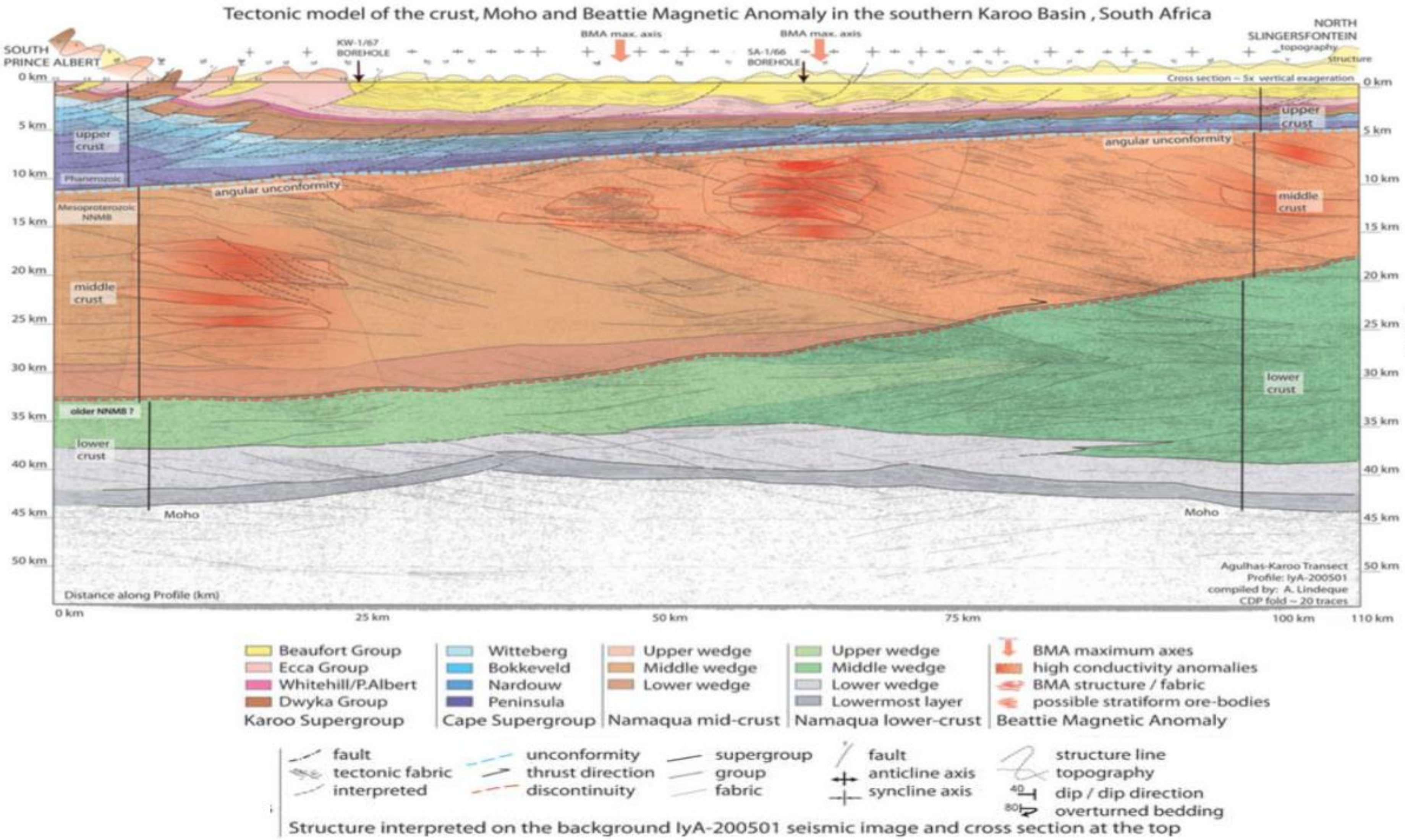

Figure 2. 10. New crustal tectonic model derived from the integration of seismic reflection data, wide-angle refraction data, magnetotelluric measurements, aeromagnetic data, receiver function analyses and existing boreholes as discussed in the text (Lindeque *et al.*, 2011)

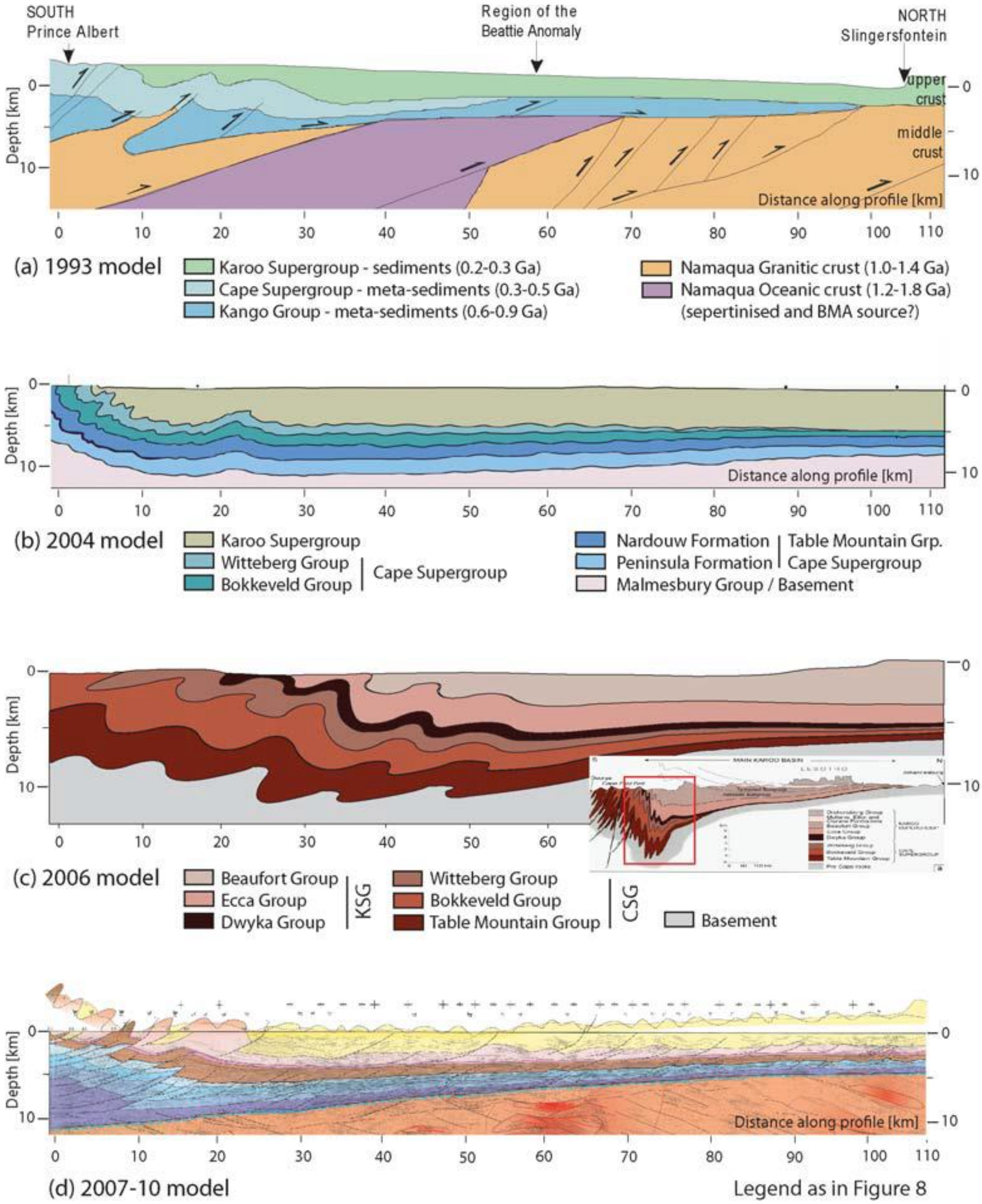

Figure 2. 11 Comparing models of the Cape and Karoo Basins in the upper crust (< 15 km). (a) Hälbich *et al.* (1993) model, (b) Chevallier *et al.* (2004) model, (c) Johnson *et al*. (2006) model, and (d) current model (Lindeque *et al*., 2011)

CHAPTER 3:
POTENTIAL DEEP AQUIFERS IN THE KAROO SUPERGROUP AND TABLE MOUNTAIN GROUP

3.1 INTRODUCTION

The geology of South Africa can be analysed to better facilitate the location of potential deep groundwater aquifers. When investigating potential deep groundwater aquifers within the Karoo Supergroup and TMG the various lithologies that represent these geological units are taken into account, as they influence their potential to store and transmit groundwater. The geohydrological characteristics are based on available information, which is typical for the shallow systems utilised for water supply.

Saggerson and Turner (1992, 1995), as cited in Viljoen *et al.* (2010), found that the rocks in most of South Africa's sedimentary basins are metamorphosed and have little or no primary porosity, only secondary porosity where they have been faulted and fractured (Viljoen *et al.*, 2010). Two prominent examples of deep confined aquifer systems would be the Karoo Sequence and the TMG sandstones.

In this section the basics of aquifer types and porosity are described, followed by a description of the geology and geohydrology in the Karoo Supergroup and TMG. South African geology and geohydrology are divided into Pre-Karoo, Karoo, Mesozoic and Cenzoic Geologies (Table 3.1).

Table 3. 1 South African geology for investigation

Pre-Karoo Geology
• Limpopo Belt
• Archaean Greenstone Belts
• Archaean Granites and Gneisses
• Pongola Supergroup
• Dominion Group
• Witwatersrand Supergroup
• Ventersdorp Supergroup
• Transvaal Supergroup
• Bushveld Igneous Complex
• Waterberg and Soutpansberg Groups
• Namaqua-Natal Metamorphic Province
• Saldania Belt - Malmesburg Group
• Natal Group
• Cape Supergroup
Karoo Geology
• Main Karoo Basin
• Springbok Flats Basin
• Ellisras Basin
• Tshipise and Tuli Basins
• Karoo Dolerite Suite
Post-Karoo Geology
• Mesozoic Geology
• Cenzoic Geology

3.2 THE KAROO SUPERGROUP

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

3.2.1 Location and extent

The Karoo Supergroup (150-320 Ma) is said to cover approximately two thirds of the current land surface of South Africa and comprises a thick sedimentary sequence that has been intruded by numerous dykes and sills (KGEG, 2013a). It extends across South Africa, Botswana and Namibia, with the northwestern part of South Africa forming the Aranos Basin. According to van Wyk (2013) the Aranos basin covers an area of approximately 500 km, comprises mainly of the lower Karoo sediments that is underlain by Nama Group sediments, and is approximately 3 km thick. The Main Karoo Basin is largely undeformed and essentially flat lying with small centripetal dips. The strata are only folded in the south where it was affected by the Cape Orogeny (Figure 3. 1) (Viljoen *et al.*, 2010).

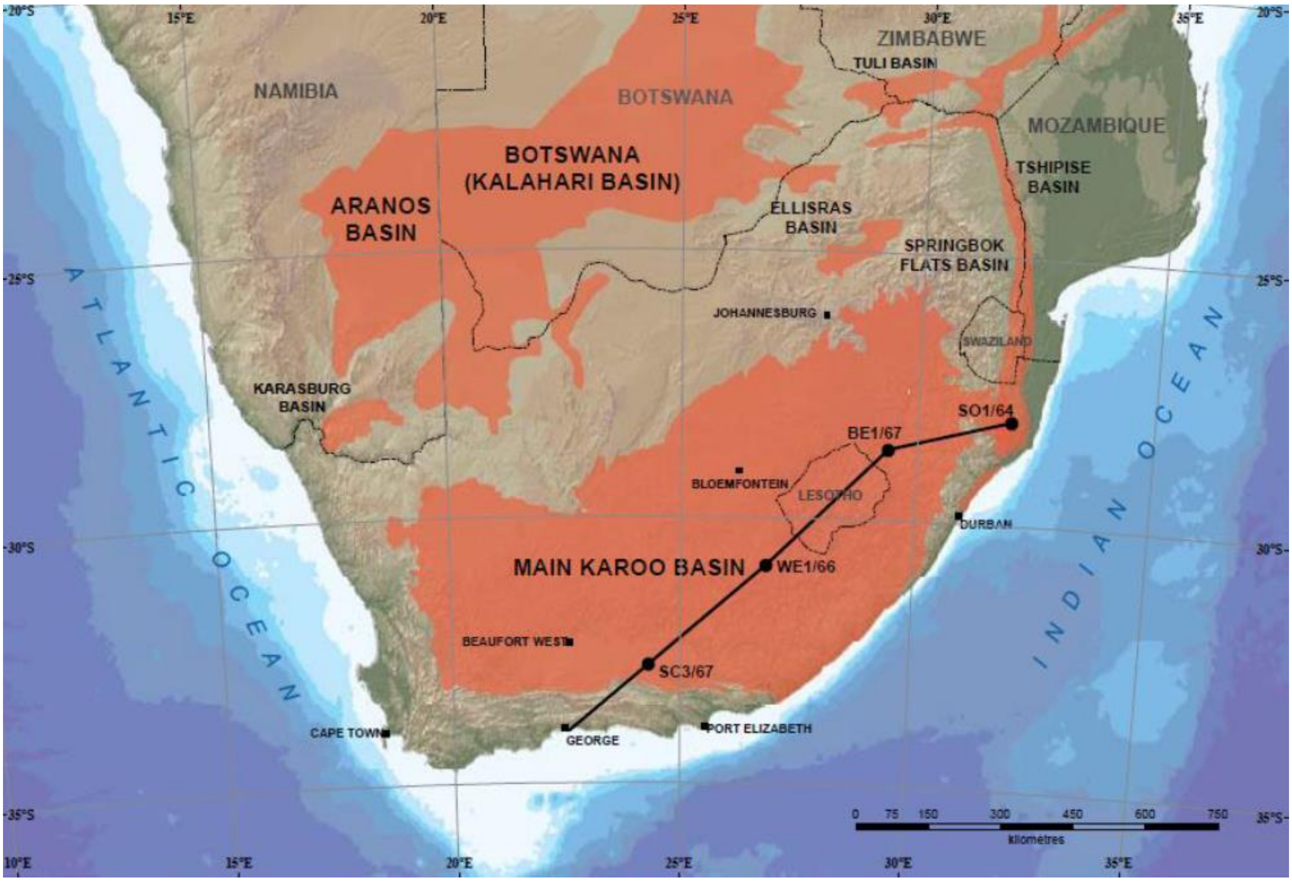

Figure 3. 1 Location of the Karoo basins in South Africa, with the location of a cross-section line through the basin (Viljoen *et al.*, 2010)

3.2.2 Geology

The rocks of the Karoo Supergroup within the Main Karoo Basin are divided into various groups and formations (Lourens, 2013). The main lithostratigraphic units are the Dwyka, Ecca, Beaufort and Stormberg Groups. The lithostratigraphic subdivisions of the Karoo Supergroup are given in Table 3. 2.

The Dwyka Group forms the basal unit of the Karoo Supergroup. It overlies glaciated Precambrian bedrock surfaces along the northern basin margin, the Cape Supergroup unconformably in the south, and the Natal Group and Msikaba Formation in the east (Johnson *et al.*, 2006; Lourens, 2013). The Dwyka Group predominantly consists of diamictite with minor amounts of conglomerate, pebbly sandstone, and mudrock with dispersed stones (Visser *et al*., 1990; as cited by Lourens, 2013). The thickness of the Dwyka Group is 500 m to 800 m in the south, and 100 m to 200 m at the northern margin of the southern facies, from where it is highly variably further northwards (0 m to 600 m) (Du Toit, 1954; Visser *et al*., 1990; as cited by Lourens, 2013).

Table 3. 2 Lithostratigraphic subdivision of the Karoo Supergroup (Lourens, 2013)

		Thickness	Main Rock Types
Lebombo Group		?	Mainly a succession of basaltic and rhyolitic lava flows
Drakensberg Group		>1200 m	Basalt with amygdales
Stormberg Group	Clarens Formation	<300 m	Fine-grained sandstone and siltstone
	Elliot Formation	<500 m	Red-maroon to green mudstones, with interbedded sandstones
	Molteno Formation	<600 m	Alternating sandstone, mudstone and shale, minor coal beds
Beaufort Group		<7 000 m	Mainly grey-green to reddish mudstones, thick river-channel sandstones; beds thin to the north of the central Karoo Basin
Ecca Group		<3 000 m	Dark shales, some sandstone layers and coal seams; deep-water sediment in the south grading to shallow-water sediments in the north
Dwyka Group		<700 m	Unsorted tillite, minor shale; thickest in the south

The Ecca Group is subdivided into 14 formations: the Prince Albert, Whitehill, Tierberg, Skoorsteenberg, Kookfontein, Waterford, Collingham, Vischkruil, Laingsburg, Ripon, Fort Brown, Pietermaritzburg, Vryheid and Volksrust Formations. 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, 1989).

The Beaufort Group covers an area of approximately 200 000 km², reaches a maximum total thickness of roughly 7 000 m in the foredeep of the Karoo Basin, and then thins quickly northwards. The Beaufort Group consists of fluvial-deposited Permo-Triassic rocks and is subdivided into two subgroups, namely the Adelaide and Tarkastad Subgroups (aged ~260 Ma and ~240 Ma respectively) (Catuneanu *et al*., 2005; as cited by Lourens, 2013).

According to Saggerson and Turner (1992; 1995) as cited in Nhleko (2008), geological strata in the Karoo are generally horizontal to very gently dipping, except adjacent and sub-adjacent to the Cape Fold Belt. They comprise of a thick sequence of multiple layers of shale and mudstone with subordinate sandstones and dolerite sills of variable thickness (usually tens of metres but up to 100-200 m). As indicated by Figure 3.2 the rocks of the Karoo Supergroup within the Main Karoo Basin are divided into various groups and formations.

Thick dykes and their contact zones extend for up to hundreds of kilometres (E-W) on surface but their vertical continuation is uncertain. It remains to be proven to what depths single dykes and their contact zones continue uninterrupted. Regional east-west trending "shear" dykes, as well as a number of regional north-west trending "feeder" dykes (e.g. the Middelburg Dyke), probably extend to the base of the Karoo sediments. The thickest sills are associated with the Ecca Group, while nested, saucer-shaped ring structures occur in the Beaufort Group, with individual sill thicknesses of 100 m Nhleko (2008). The Stratigraphy and correlation of the Karoo Supergroup strata in the northeastern part of the main Karoo Basin and the Springbok Flats, Ellisras, Tshipise and Tuli Basins are illustrated in Figure 3.3.

The simplified geological representation of South Africa (Figure 3.4) was used to evaluate the potential for deep groundwater. The geology is sub-divided into pre-Karoo, Karoo, and post-Karoo.

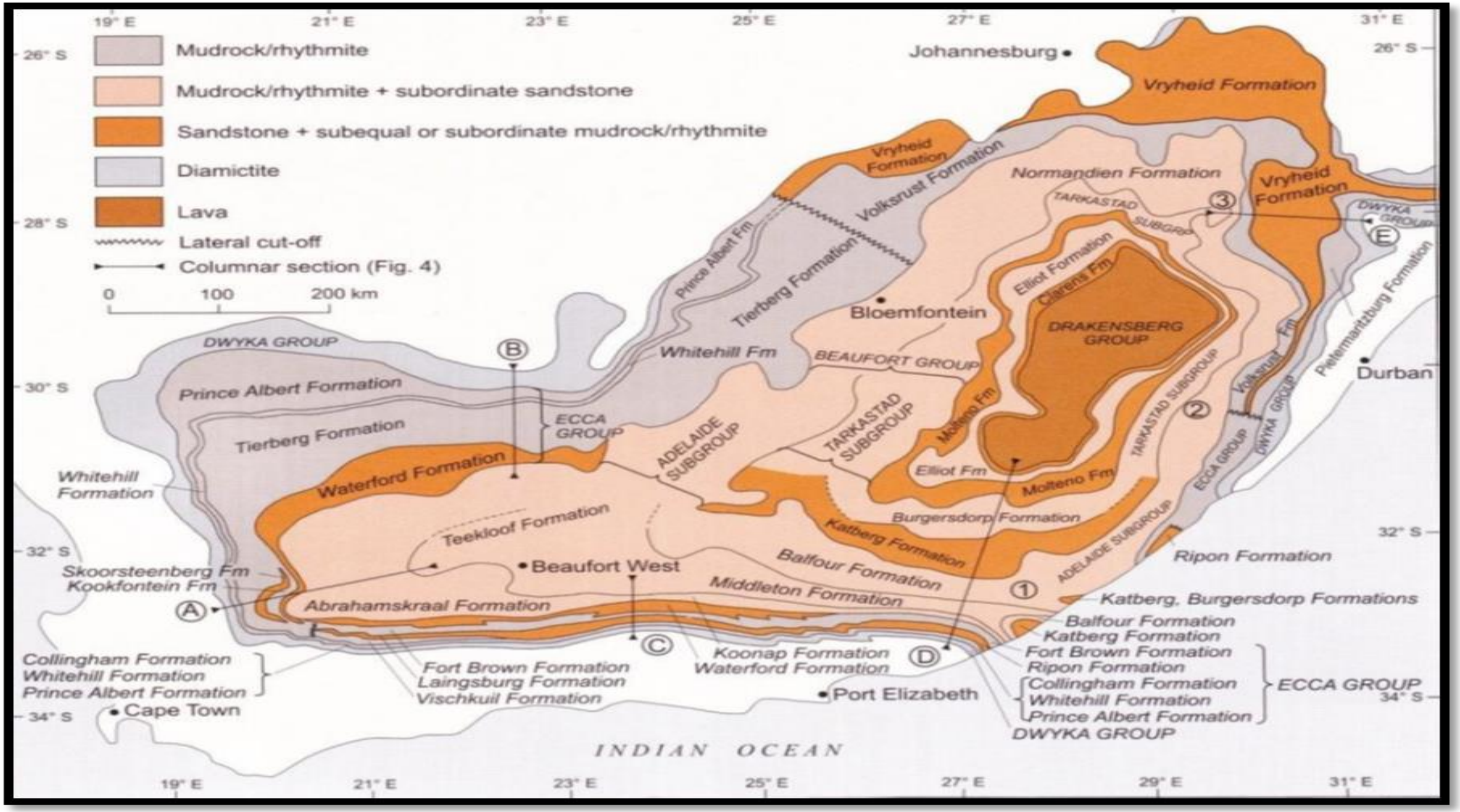

Figure 3. 2 Schematic areal distribution of the lithostratigraphic units of the Karoo Supergroup and location of sections A-E and 1-3 (Johnson *et al.*, 2006)

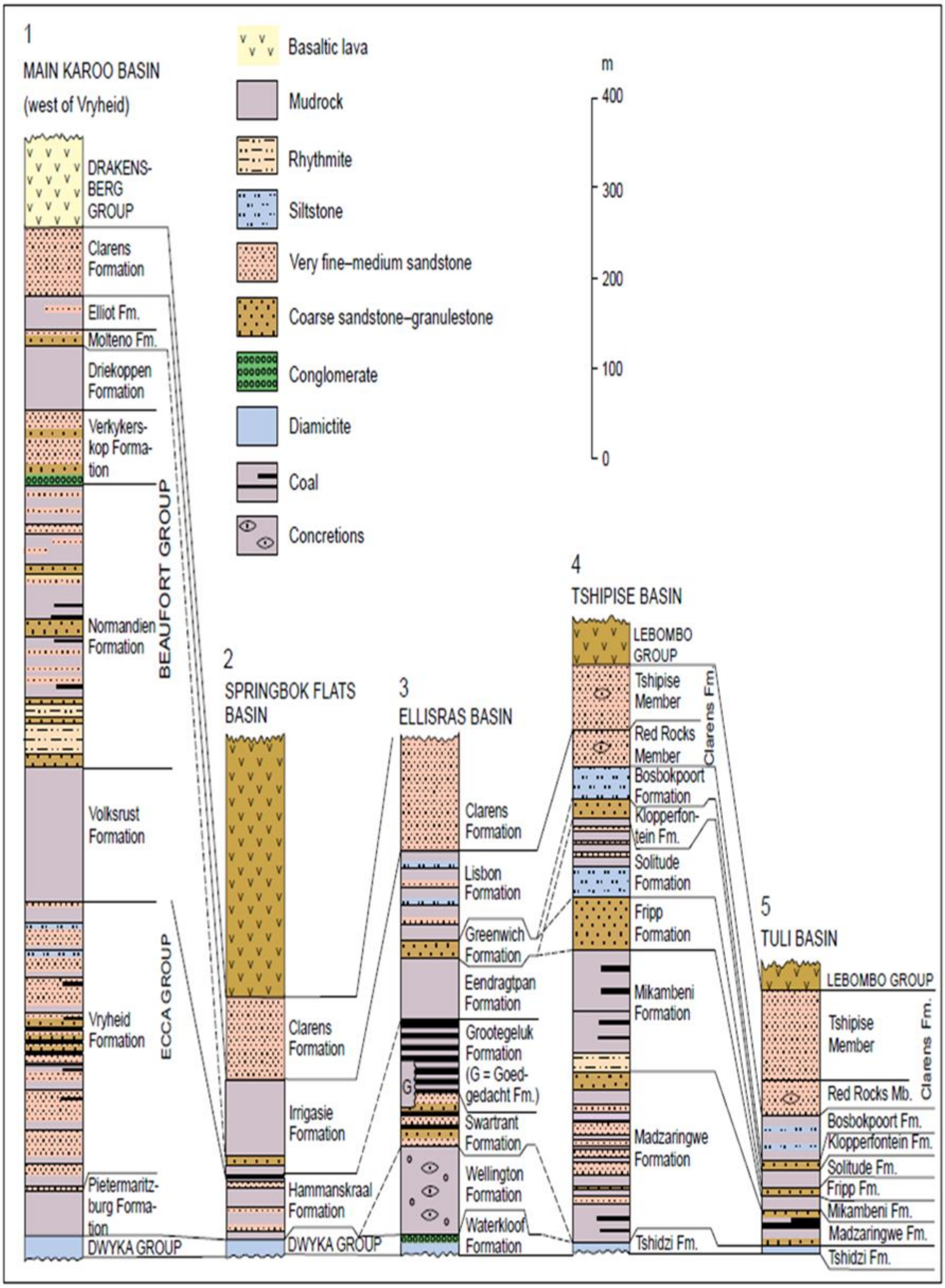

Figure 3. 3 Stratigraphy and correlation of the Karoo Supergroup strata in the northeastern part of the main Karoo Basin and the Springbok Flats, Ellisras, Tshipise and Tuli Basins (Johnson et al., 2006)

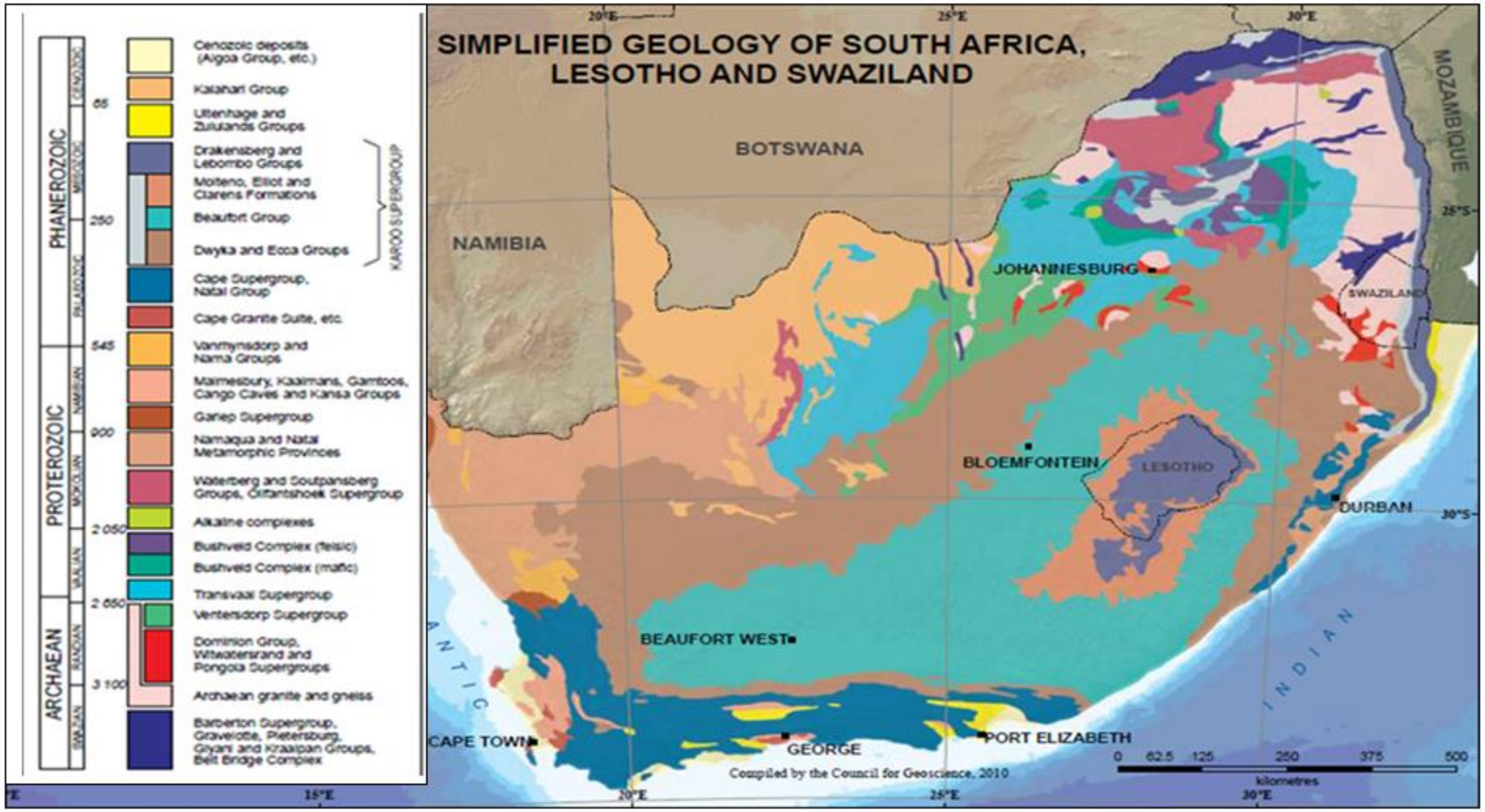

Figure 3. 4 Simplified geology of South Africa (Viljoen *et al*., 2010)

3.2.3 Geohydrology

The majority of comprehensive studies conducted on Karoo hydrogeology are contained in reports by Woodford and Chevallier (2002) and Murray *et al.* (2012). The Karoo Supergroup sediments mainly consist of a combination of sandstones, shales and mudstones from the Beaufort Group. These Karoo sedimentary rocks (such as sandstone and mudstone) have a low permeability. As a result, secondary permeability due to dolerite intrusions is important for groundwater retention and exploitation. The Karoo fractured rock aquifers associated with dolerite intrusion store water in the interconnected fractures that have developed in the surrounding sediment.

The dolerite intrusives in the Karoo Supergroup play a major role in the occurrence and movement of groundwater. During the intrusion of dolerites intensive fracturing formed in the older Karoo Supergroup sediments, and it is these fractures that are commonly targeted in groundwater exploration (Vandoolaeghe, 1980). During intrusion local sediments were baked, with veins of calcite and quartz introduced. Shallow fractured aquifers (30 to 60 m) in the weathered zone can only yield sufficient water for local supply (Vandoolaeghe, 1980). These fractured aquifers possibly correspond to a set of horizontal fractures that develop close to the surface as a result of stress off-loading (Chevallier & Woodford, 1999). Alluvium and other quaternary deposits are poorly developed, except west of the Karoo Supergroup (Vandoolaeghe, 1980).

3.2.4 Karoo dolerites and their relation to deep aquifer systems

Around 183 Ma Jurassic, Karoo volcanics intruded the Karoo sediments and demonstrated significant tectonic complexity. The interrelated network of these intrusions comprise of dykes and sills, making it difficult to single out any specific intrusive event. For example, a single dyke can be the source of more than one sill, or one sill can originate from numerous dykes. It therefore appears that numerous fractures were intruded by magma concurrently and the dolerite network acted as a shallow reservoir (Murray *et al.*, 2015).

Over the years there have been detailed investigations aimed at characterizing water occurrences (depth and yield) or defining the storativity of a specific fracture system on dolerite ring aquifers in the Karoo (Woodford & Chevallier, 2002b). The structure of the Karoo dolerite rings have long been something of a mystery and until recently very little was known about their geometry.

Figure 3.5 shows the components of a ring complex intrusion with a combination of dyke and sill intrusives, enhanced permeability at contacts and groundwater occurrence and levels. The Karoo is comprised of sedimentary rocks that have a low permeability. As a result, secondary permeability due to dolerite intrusions is significant for groundwater retention and exploitation. Karoo fractured rock aquifers connected with dolerite intrusion store water in the interconnected fractures that have established in the surrounding sediment (Chevallier *et al*., 2001). These complex hydrogeological systems have not been fully investigated by means of fracture interconnectivity and groundwater flow dynamics.

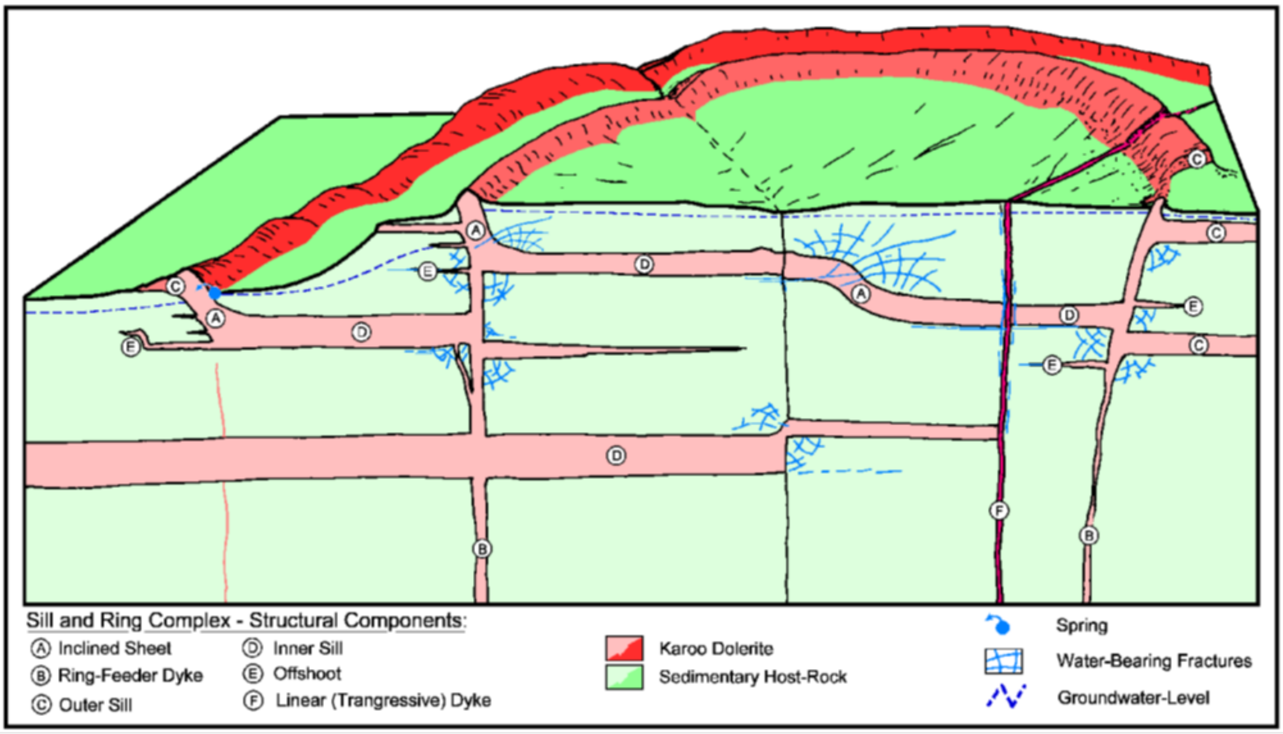

Figure 3. 5 Hydro-Morphotectonic Model of a Ring Complex (Chevallier et al., 2001)

According to Woodford and Chevallier (2002) not much is known about the extension of the fractures and their aperture. There seems to be a number of limited lateral extensions (with an aperture of not more than 1 mm for some) that would not serve as the main storage unit of groundwater. It is assumed by Chevallier *et al.* (2001) that 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 fractured medium is generally dictated by the fracture dimension, orientation and connectivity (Odling, 1993). The water-yielding fractures in the Karoo aquifers appear to be too sparsely spread to satisfy connectivity requirements, however, others may have sufficient lateral extension and be spaced closely enough to sustain a specific discharge.

Chevallier *et al.* (2001) identified three major types of fracturing associated with sill and ring complexes:

1) Sub-horizontal fractures in curved portions of a sill that are filled with calcite in the western and eastern parts of the Karoo.

2) Vertical thermal columnar jointing, which is well developed in flat-lying sills.
3) Fractures parallel to the strike of the intrusion that are common in inclined dolerite sheets.

The association between shallow and deep-seated aquifers or between aquifers occurring on each side of a dolerite intrusion has not been recognised.

3.3 THE TABLE MOUNTAIN GROUP

According to the 1:1000 000 geological map of the Republic of South Africa published by the Council for Geoscience, South Africa is predominantly covered at surface by sedimentary rocks with abundant igneous intrusions and extrusions and metamorphic rocks. According to Johnson *et al.* (2006), two major sedimentary basins have been identified, namely the Karoo and Cape sedimentary basins. These primarily formed the stratigraphic sequence known as the Karoo Supergroup and Cape Supergroup. Johnson *et al.* (2006) identifies the Cape Supergroup to be older than the Karoo Supergroup. McCarthy and Rubidge (2005) indicate that these basins formed roughly 150-160 million years ago.

The TMG was subject to ductile deformation approximately 230 million years ago, which resulted in the folding sedimentary layers. According to van Wyk (2012) two projects, namely Blikhuis and Blossoms (where boreholes were drilled to depths of 860 mbgl and 650 mbgl) intercepted these high water pressurised zones and water levels rose to approximately 8 mbgl and 76 mbgl. The TMG is associated with a thick (approximately 50 m to 120 m) shale (Cederberg Formation) confining layer above and below the sandstones (van Wyk, 2013). The TMG aquifers form a special case due to a number of factors. For example, the main lithology consists of fairly uniform, brittle quarzitic sandstones that fractures readily under pressure and the continental-scale orogeny that formed the Cape Fold Belt provided sufficient levels of stress to produce widespread and deep fracturing. Additionally, the groundwater quality is usually acidic and low in dissolved solids, which lessen the likelihood of deposition of minerals that could block fractures. The sandstones are also predominantly composed of silica, which lessens the likelihood of weathering products that could also block fractures (Rosewarne, 2002).

3.3.1 Location and extent

The TMG has a deposit area of 248 000 km² and a thickness that varies from approximately 900 to 4 000 m (Figure 3.6). These rocks have an outcrop area of approximately 37 000 km² along the west and south coast of South Africa (Lin, 2008). The vast distribution of the TMG leads to great variability in its geohydrological properties, resulting in an uneven distribution of groundwater occurrences in the TMG area (Jia, 2007).

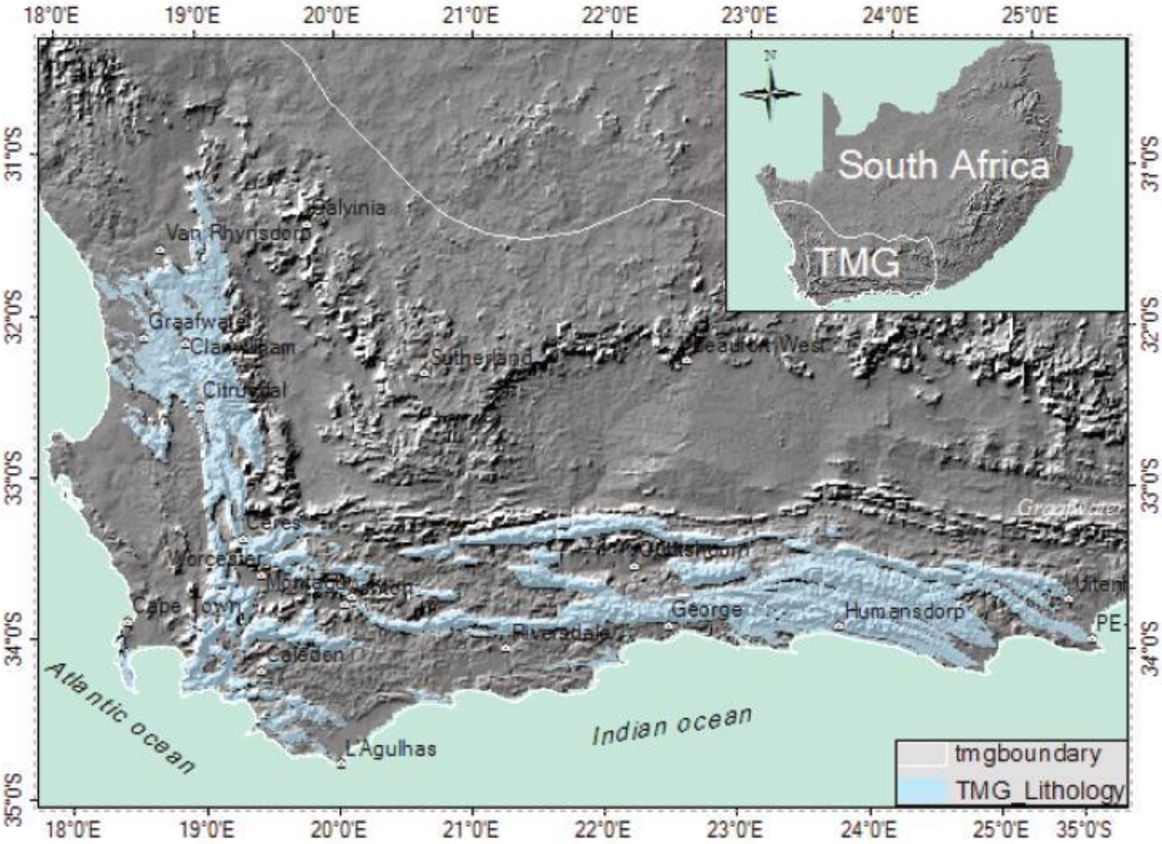

Figure 3. 6 Distribution of the deposit area and outcrops of the TMG in South Africa (Jia, 2007)

3.3.2 Geology

TMG is a group of rock formations within the Cape Supergroup rock sequence. The sediments of the Cape Supergroup were deposited in a shallow marine environment, as well as in a braided fluvial environment (Wu, 2005). The Cape Supergroup (Figure 3.7) is divided into three main groups that are lithologically distinctive and show lateral continuity throughout the length of the Cape Supergroup (Lourens 2013). In ascending order they are:

1. Witteberg Group
2. Bokkeveld Group
3. Table Mountain Group

The TMG is the lowest geological unit of the Cape Supergroup. It mostly consists of quartz arenites, shales and siltstone, with minor conglomerate and a thin diamictite unit. The TMG is divided into the Nardouw and Peninsula Subgroups (each consisting of various formations) and further subdivided into six lithostratigraphical units, namely the Piekenierskloof, Graafwater, Peninsula, Pakhuis, Cedarberg Formations and the Nardouw Subgroup, which contains the Goudini, Skurweburg and Rietvlei Formations (Thamm & Johnson, 2006).

The Piekenierskloof and Graafwater Formations extend from Lamberts Bay, east- and southwards to Piket Mountain (Visser, 1989). The Piekenierskloof Formation consists of course-grained sandstone, conglomerate and minor mudrock where the conglomerate layer is confined to the base of the formation in the northeastern part (Thamm & Johnson, 2006). The sandstone is predominantly whitish in colour.

The Graafwater Formation signifies the area between Graafwater and Piekenierskloof but narrows out toward the east and the south (Visser, 1989). The base of the Graafwater Formation consists of purple shale with quartzite and clay pebble conglomerate, which is then followed by reddish and white, fine-grained sandstone and quartzite with reddish siltstone, shale and clay pebble conglomerate (Visser, 1989). Trace fossils (Thamm & Johnson, 2006), wave ripple and cross bedding are common sedimentary features within the Graafwater Formation (Visser, 1989).

The Peninsula Formation comprises of quartz arenite with minor shale and conglomerate (Thamm and Johnson, 2006). Cross bedding is a characteristic sedimentary feature, indicating a source region from the northwest (Visser, 1989).

The Pakhuis Formation consists of diamictite, pebbly sandstone and mudrock with drop stones, all of which host facetted, striated, and polished clasts (Thamm & Johnson, 2006). The clasts include quartz, chert, quartzite, jasper and hornfels (Visser, 1989). It has an average thickness of 40 m and disappears in the area of the Swartbergpas (Visser, 1989).

The Cedarberg Formation, also known as the Cedarberg Shale Formation (Figure 3.8), forms a persistent negative-weathering marker and consists of dark shale at its base, which coarsens upward into siltstone (Thamm & Johnson, 2006). The thickness of the formation varies from 50-120 m (Thamm & Johnson, 2006).

The Nardouw Subgroup occurs along the whole of the Cape’s folded series and reaches a maximum thickness of 1 200 m close to Citrusdal in the western part of the basin, but thins rapidly northwards (Thamm & Johnson, 2006). The Nardouw Subgroup consist of quartzitic sandstones (Thamm & Johnson, 2006), which is divided into the lower Goudini Formation, the middle Skurweberg Formation and the upper, laterally equivalent Rietvlei and Baviaanskloof Formation.

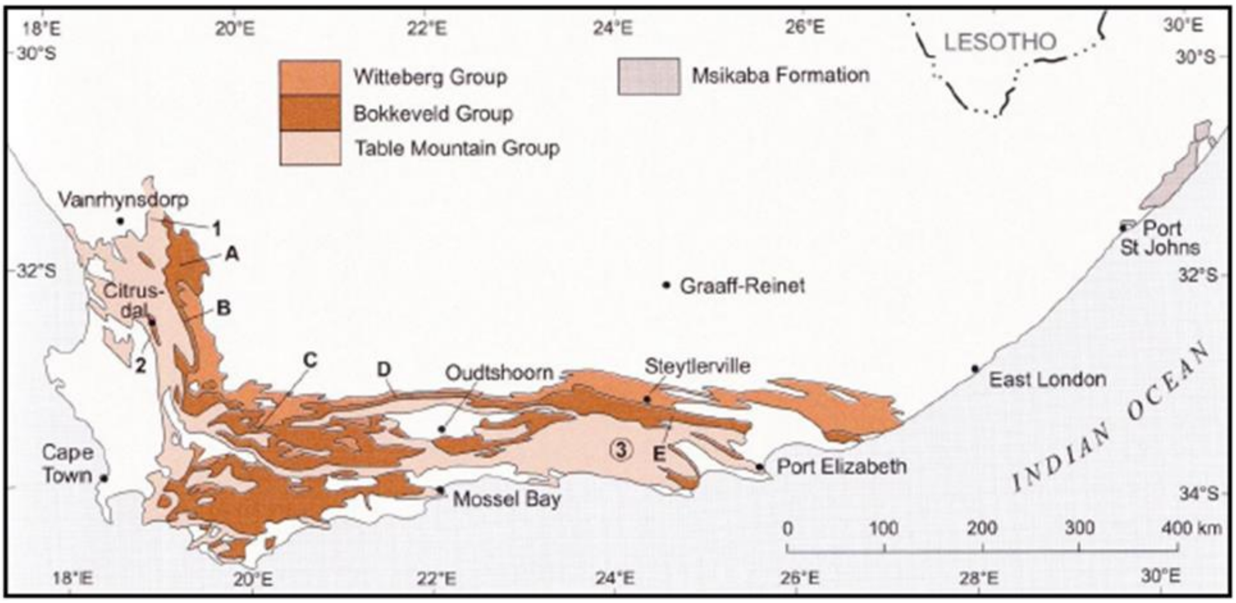

Figure 3. 7 Distribution of the Cape Supergroup, indicating section lines of Table Mountain Group (1-3) and Bokkeveld Group (A-E) (Thamm & Johnson, 2006)

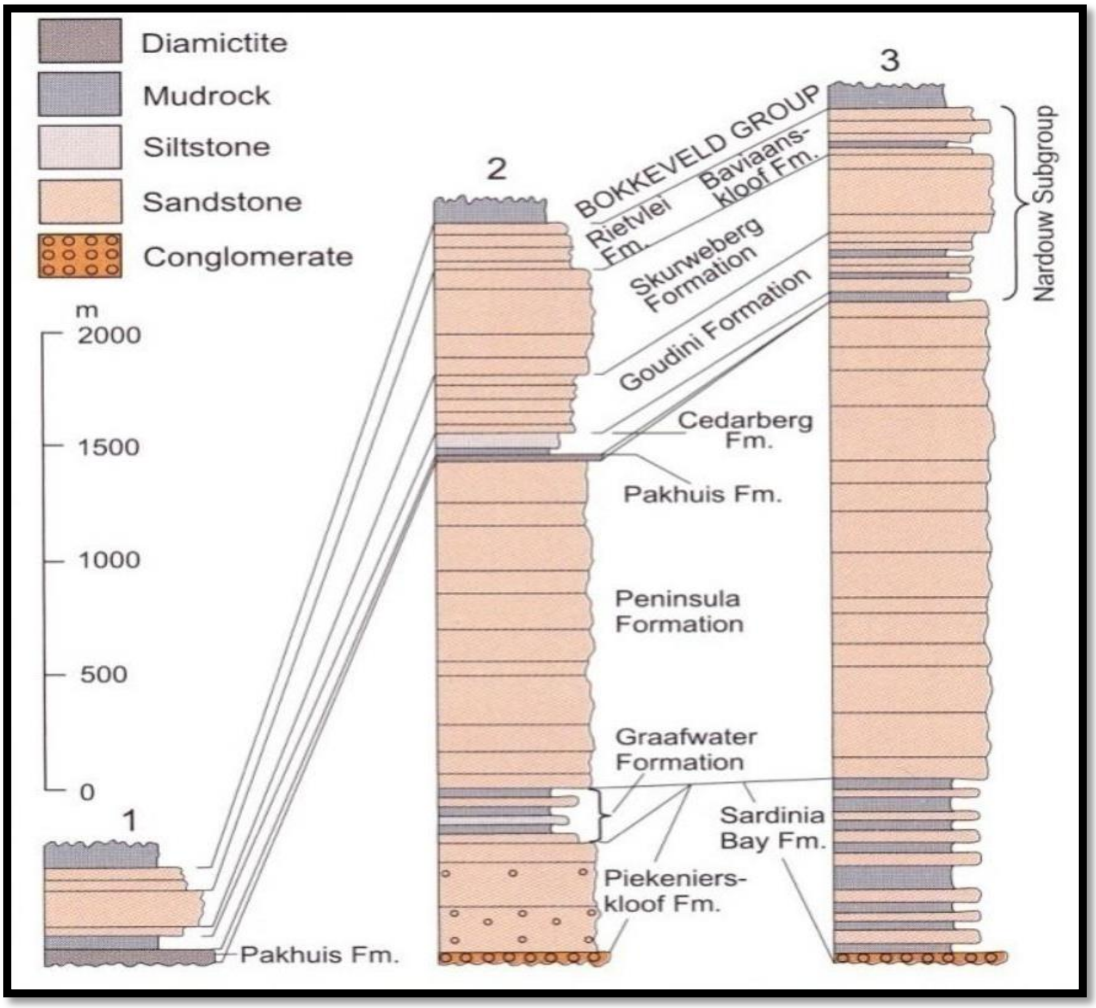

Figure 3. 8 Representation of sections (1-3) of the Table Mountain Group (Thamm & Johnson, 2006)

3.3.3 Geomorphology of the TMG

Between 280 and 235 Ma the South American and African continents collided to form part of Pangaea, giving rise to the Cape Fold Mountains (Aston, 2007). The associated compressional forces resulted in widespread deep fracturing throughout the TMG with larger faults running for tens of kilometres (Hartnady & Hay, 2002b).

Regionally the TMG occurs in the form of mountains, wave-cut plains and intermountain drainage basins. The modern landform patterns of the TMG area largely resulted from quaternary processes, including crust heaves, and physical and chemical erosions. These processes have led to the formation of the rolling landscapes with a topographical elevation of approximately 200 to 1 700 mamsl. The mountain peak can reach elevations of 1 900 to 2 250 mamsl in the Hex River Mountain, 1 500 to 2 000 mamsl along Langeberg, and 1 700 to 2 000 mamsl on the Swartberg Mountains (Jia, 2007; Lin, 2008).

Compared to overlaying argillaceous rock formations and the underlying basement rocks, the geomorphologic patterns of the TMG are characterized by the sharp mountains with steep slopes and thin or even no soil covers over its outcrops (Jia, 2007; Lin, 2008).

3.3.4 Geohydrology

From a geohydrological point of view the TMG rocks represent a multi-porous medium, essentially consisting of two major components, namely (i) fractures and (ii) inter-fracture "blocks" or rock matrix. In general the fractures act as the more permeable conduits for groundwater movement, while the matrix blocks form the main storage unit or reservoir (Duah, 2010). The matrix may be either permeable or impermeable. However, the rock mass may contain many fractures of different scales and is thus expected to have its own secondary porosity. TMG rocks are therefore generally considered to form dual porosity, fractured-rock aquifer systems (Duah, 2010).

The TMG aquifer is classified as a semi-confined aquifer since it is phreatic in some areas but confined below an impermeable layer in other areas. The installation of groundwater abstraction boreholes in the TMG aquifer often requires drilling through a confining layer (Aston, 2007). Some boreholes in the TMG have free-flowing artesian conditions, confirming that the aquifer is confined and under positive pressure.

The formations making up the TMG differ widely in their ability to store and transmit water. The sandstones of the Nardouw and Peninsula Subgroups generally act as aquifers, while the shale layers in these subgroups act as aquitards (Aston, 2007). Two main aquifer systems have been identified in the TMG, namely the Nardouw aquifer and the Peninsula aquifer. The Nardouw aquifer consists of two sub-aquifers (the Rietvlei and Skurweberg sub-aquifers) separated by the Verlorenvalley mini-aquitard. The Peninsula aquifer is separated from the Nardouw aquifer by the Winterhoek mega-aquitard, which consists of the Goudini, Cedarberg and Pakhuis meso-aquitards. The Peninsula aquifer itself is subdivided into two sub-aquifers, namely the Platteklip and Leeukop sub-aquifers (Blake *et al.*, 2010).

The extraction of groundwater from the Nardouw aquifer is mainly for farm water supply. The deeper Peninsula aquifer requires deeper drilling and has been exploited to a lesser extent (TMGA Alliance, 2016). However, the Peninsula aquifer is thought to have a greater potential for bulk abstraction than the Nardouw aquifer (Rosewarne & Weaver, 2002). It is much thicker but, more importantly, has a lower shale content and faults are therefore expected to remain open to great depths (Rosewarne & Weaver, 2002).

Extensive deep groundwater reserves have been reported in the fractured rock aquifers of the TMG. Rosewarne (1998) (cited in Smakhtin *et al*., 2001) quoted groundwater storage estimates of approximately 50 000 Mm^3 and annual recharge as high as 2 000 Mm^3. However, a more detailed investigation of a section of the aquifer system suggested a much lower annual recharge volume of approximately 260 Mm^3 (Smakhtin *et al*., 2001). Weaver and Talma (2000) suggested that within a radius of 200 km from Cape Town the total volume of groundwater stored in the TMG aquifer may be as high as 66 000 Mm^3 with an annual recharge of approximately 2 600 Mm^3/year.

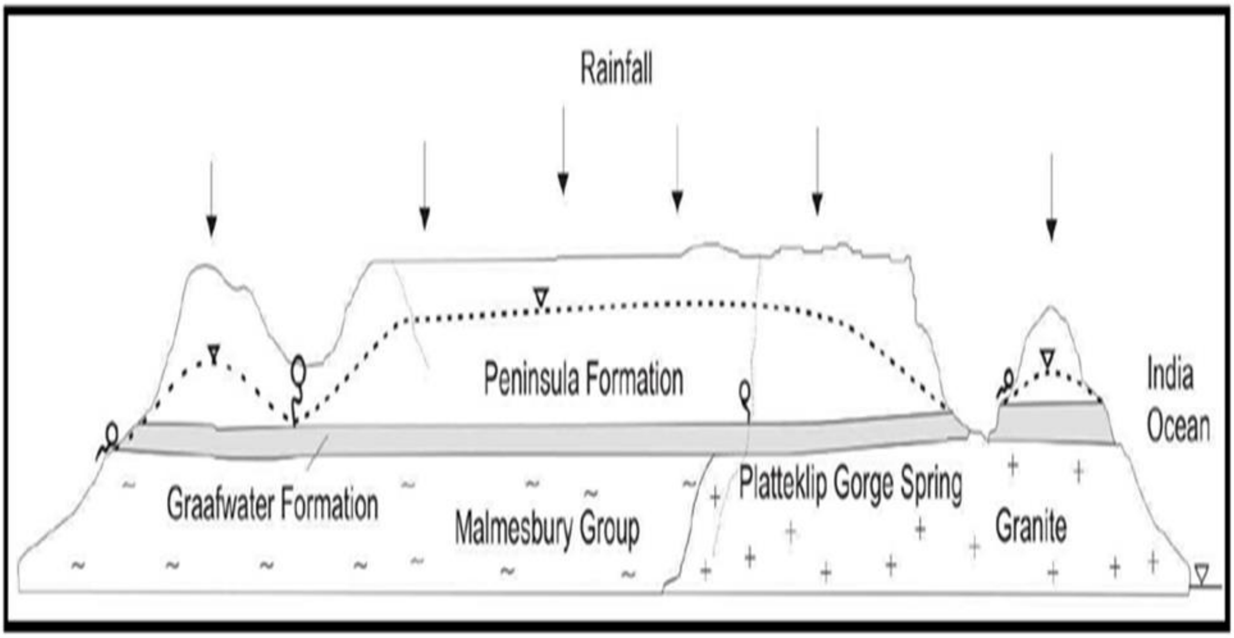

Figure 3. 9 An example of a horizontal strata aquifer in Table Mountain, Cape Town (Xu *et al.*, 2007d)

Lourens (2013) classified the TMG as being associated with secondary aquifer systems where secondary porosity features control groundwater movement. The TMG aquifers can be divided into four categories, namely horizontal strata, folded strata, fracture zone and composite aquifer systems (Xu *et al.*, 2007; as cited by Lourens, 2013). According to Viljoen *et al.* (2010) very good fracture porosity is created where folding and faulting are present.

The TMG is characterised by an abundance of springs (Meyer, 2001; as cited by Lourens, 2013). Meyer (2001) and Kotze (2002), as cited by Lourens (2013), identified three types of springs within the TMG: shallow springs emanating at perched water tables, lithologically-controlled springs (due to the presence of inter-bedded aquitards), and fault controlled springs.

3.4 POTENTIAL DEEP AQUIFERS

Potential deep aquifer systems in South Africa are discussed in terms of the identified geological divisions, thermal springs and depth of fracturing influence.

3.4.1 Potential deep aquifers in the TMG

The Cape Supergroup shows a positive indication for deep groundwater systems. The main groundwater intersections within the TMG aquifer are at depths of greater than 100 mbgl and borehole yields have been found to increase with depth. This characteristic goes against conventional structural geological theory, which states that joint/fracture openings close with increasing depth due to the pressure of the overlying rock mass. However, there are special cases where this conventional theory does not apply. For example, circulation depths of up to 2 000 m have been found in the TMG aquifers (Rosewarne, 2002). Since deep groundwater circulation has been confirmed within the TMG, the TMG constitutes a potential deep aquifer system.

Lin *et al.* (2007) analysed a deep borehole in the Graafwater area in the Western Cape to determine fracture network characteristics of the TMG. The analysed borehole was 800 m deep and Lin *et al.* (2007) divided it into four zones based on the degree to which fractures are hydraulically active. The zones are 1) high (0 mbgl to 150 mbgl), 2) medium (150 mbgl to 400 mbgl), 3) low (400 mbgl to 570 mbgl), and 4) hydraulically inactive (570 mbgl to 800 mbgl or deeper).

Lin *et al*. (2007) stated that the top of the hydraulically inactive fracture zone clearly indicated that groundwater flow could not take place below a depth of approximately 570 m. However, this analyses was based on a single borehole and Lin *et al.* (2007) concluded that the depth model of groundwater circulation developed was not necessarily applicable to all areas of the TMG rock aquifers.

Considering that deep groundwater generally occurs below the traditionally exploited weathered zone (shallow aquifers), the occurrence and distribution of fracturing in the deeper formations is paramount in the investigation of potential deep aquifers. The key to delineating future deep groundwater resources will be determining:

- the depth to the fractured aquifer (i.e. below the extent of weathering),
- the depth to which fractures remain open (in different geological mediums), and
- the methods to accurately locate such fractured aquifers.

3.4.2 Potential deep aquifers in the Main Karoo Basin

The occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding-plane fractures. It is not certain if these bedding-plane porosities are also present at depth, but it has been reported that water was struck at a depth of 3 700 mbgl in borehole SP 1/69 intersecting Dwyka diamictite near East London (Lourens, 2013).

Main Karoo Basin (south and southwestern Karoo)

It was found that weathered and fractured zones associated with faulting and folding are confined to the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines formed due to folding have characteristic open joints and fractures. While these structures are seldom dry when drilled, the groundwater quality may be problematic.

Main Karoo Basin (central Karoo)

The presence of a warm water spring in Aliwal North (Molteno Formation) indicates that deep circulating groundwater systems are present in this area.

Tshipise and Tuli Basins

The presence of thermal springs, with a maximum water temperature of 59°C to 60°C, provides evidence for deep circulating groundwater in the Tshipise Basin. These warm springs are associated with some of the major faults.

Dwyka Group (as a whole)

The Dwyka Group is considered to act as an aquitard rather than an aquifer, as the diamictite and shales have very low hydraulic conductivities and virtually no primary voids. However, where the Dwyka Group is significantly fractured, high yields have been measured. Unfortunately, the occurrence of zones of extensive fracturing is rare and could be related to the tendency of fractures/joints within the Dwyka Group to be mineralised (kaolinised), which decreases the potential yield.

Ecca Group, Beaufort Group and Stormberg Group (as a whole)

All the Groups are considered to be associated with low-yielding aquifer systems but higher yields have been obtained in fold, fault and joint structures where favourable recharge conditions exist.

Drakensberg and Lebombo Groups

The Drakensberg and Lebombo Groups were classified as hosting intergranular and fractured aquifer systems. A characteristic feature of the Drakensberg Group is the numerous low-yielding springs emerging in elevated areas. The basalts (Letaba Formation) of the Lebombo Group are classified as hosting low- to moderate-yielding aquifer systems.

Springbok Flats Basin

The northeastern and southwestern sub-basin has a maximum thickness of approximately 700 m and 1 000 m respectively. The basin is underlain by rocks of the BIC.

3.4.3 Thermal springs as indicators of deep groundwater flow

Thermal springs are the surface occurrences of water heated geothermally and therefore represents water that circulates deep in the Earth's crust. Thermal springs are thus likely to provide useful information on the geohydrological conditions of deep aquifer systems.

Thermal springs develop when surface water descends into the earth and gets heated by either the geothermal gradient in the Earth's crust or by the presence of shallow magma chambers. The water is heated and returns along preferential pathways, such as faults and fissures, to the surface of the Earth. Thermal springs are either of volcanic or meteoric origin. The flow rate of a thermal spring is determined by the size of the aquifer, extent of recharge, aquifer storage capacity, and transmissivity and discharge capacity of both the aquifer and conduit through which the water rises to the surface (LaMoreaux & Tanner, 2001).

3.4.3.1 Thermal springs of volcanic origin

According to Scheffel and Wernert (1980) thermal springs occur in volcanic areas where reservoirs of molten or slowly cooling magma lie close to the surface and have heated the rocks above. The water is heated as it flows through cracks in the rocks, and if the passage of the water to the surface is unobstructed the heated water continuously bubbles up to the surface to form a thermal spring.

3.4.3.2 Thermal springs of meteoric origin

Thermal springs of meteoric origin are formed due to the effect of geothermal gradient rather than volcanic activity. Temperature increases with increasing depth. Cold water from rain, rivers or lakes may descend along a fault to a depth of several kilometres. This underground water is heated due to the geothermal gradient of 2.5-3°C per 100 m, which causes it to expand and rise up another fault, creating a convection system (Hoole, 2001; LaMoreaux & Tanner, 2001). Figure 3.10 illustrates diagrammatically how meteoric and volcanic hot springs are formed.

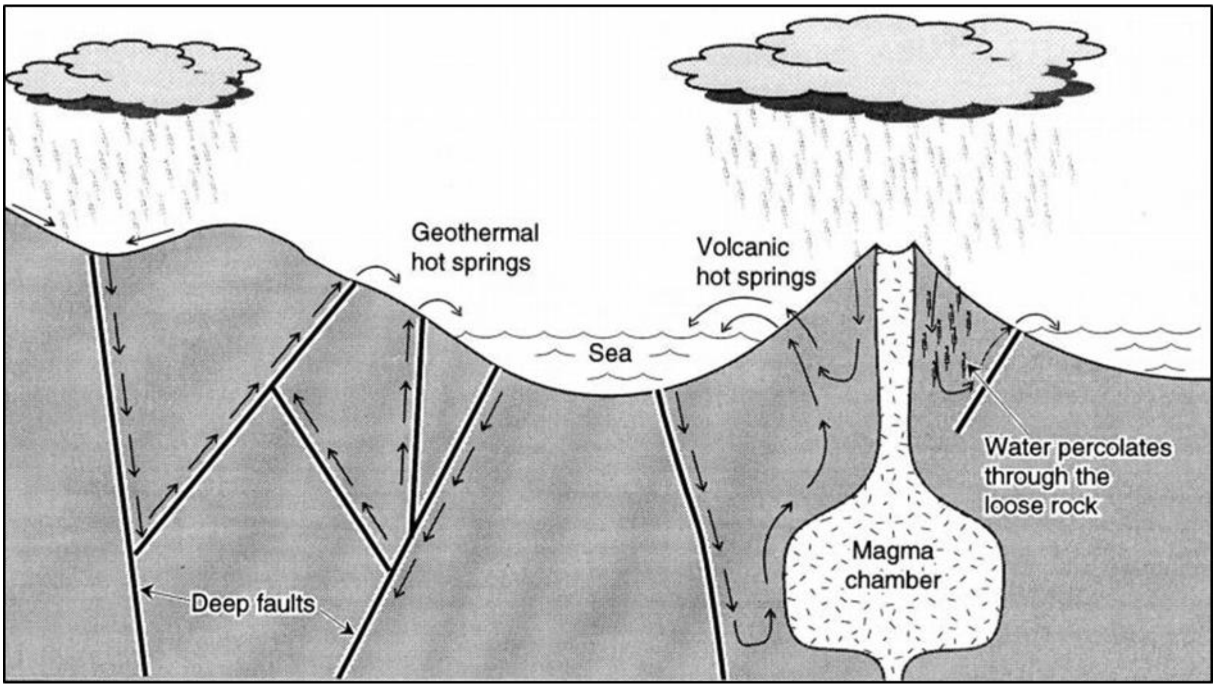

Figure 3. 10 Diagrammatic representation of the origin of thermal springs (Higgins & Higgins, 1996)

3.4.3.3 Distribution of thermal springs in South Africa

South Africa has 87 known thermal springs (Hoole, 2001; Olivier *et al.*, 2010; Tuwani, 2011), of which more than 30 are run as resorts (Boekstein, 1998). However, the exact number of thermal springs in the country is not known. According to Kent (1952) the majority of thermal springs in South Africa are confined to a broad band (approximately 400 km wide) that extends across more than half of the country, starting at Piketberg in the Western Cape through KwaZulu-Natal, the Free State and Gauteng, up to the Soutpansberg in the Limpopo Province. Information extracted from maps by Kent (1949), Boekstein (1998), Hoole (2001) and Baiyegunhi *et al.* (2014) indicate that Limpopo and the Western Cape province are the most richly endowed with thermal springs (Figure 3.11).

Since there is no evidence of recent volcanic activity in South Africa, geological studies have shown conclusively that the origin of each individual thermal spring can be attributed to the local presence of deep geological structures (such as fractures, folds, faults and dykes) that provide a means for the circulation to depth and return of the heated waters to the surface. The secondary permeability of the rocks are very important for South African hot springs, as it is not only responsible for the formation of the fractured rock aquifers hosting the spring water but also provides preferential flow paths for the hot water to reach the surface.

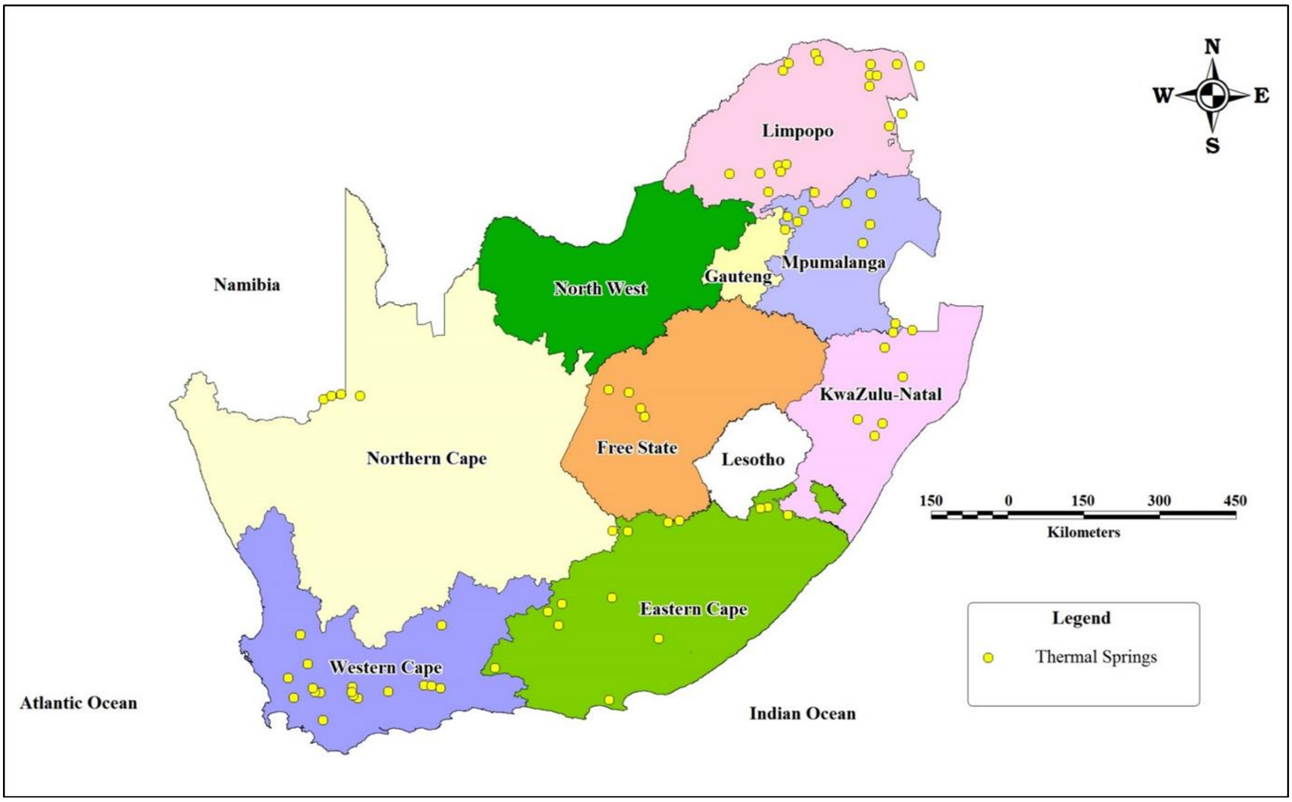

Figure 3. 11 Distribution of thermal springs in South Africa

Due to the lack of recent volcanic activity it is generally assumed that all thermal springs in South Africa are of a meteoric origin (Rindl, 1936; Kent, 1949). According to Witcher (1981), thermal springs originate from a combination of special conditions. These conditions are:

- a heat source,
- a recharge source,
- a circulation framework or storage reservoir, and
- a discharge mechanism.

The hottest geothermal spring in South Africa is Siloam in the Limpopo Province. Siloam is situated on the Nzhelele Fault in a relatively active geological area. Before 2000 the water temperature was significantly lower in the area. However, after a period of tremendous heavy rain, the Siloam hot spring emerged with a water temperature measuring 67.5°C.

CHAPTER 4: DATA SOURCES FOR DEEP AQUIFERS IN SOUTH AFRICA

4.1 INTRODUCTION

This chapter focuses on identifying data sources that contain information on the geohydrological conditions of various deep boreholes, springs and mines (Figure 4.1). Although some of these data sources contain only limited information this chapter aims to consolidate the available data on deep aquifers and deep groundwater conditions in South Africa. Various confirmed and potential sources of data on deep aquifers and groundwater conditions were identified during this investigation.

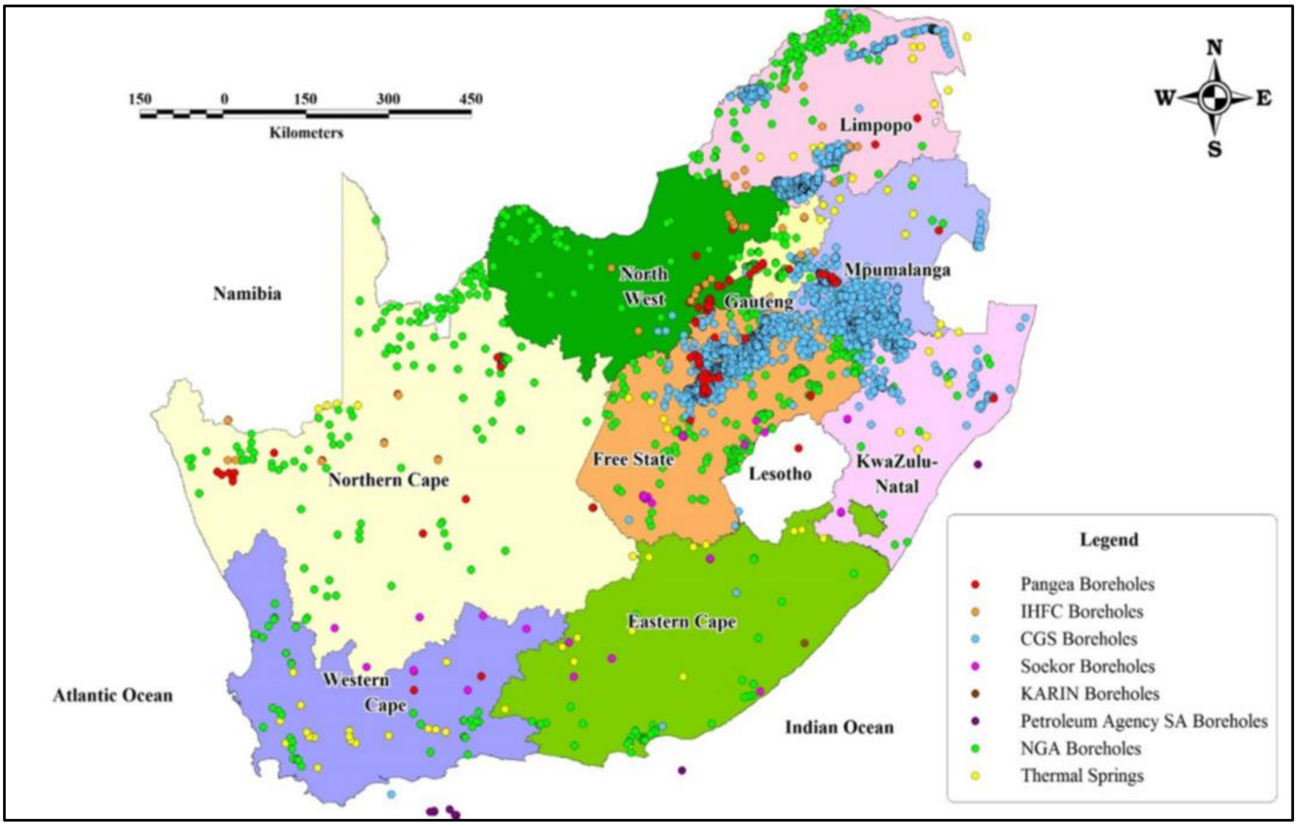

Figure 4. 1 Map illustrating the various locations for data consolidation

4.1.1 Boreholes in the National Groundwater Archive

The National Groundwater Archive (NGA) is a web-enabled database managed by the Department of Water and Sanitation (DWS). It allows the capturing, viewing, extraction and modification of groundwater-related data. The database was developed as part of the DWS' obligation to manage and develop the water resources (including groundwater) of South Africa in a sustainable and equitable manner. Access to groundwater data is becoming increasingly important for projects aimed at providing water to rural and urban communities, as well as agricultural use.

At the time when the NGA was accessed (4 May 2018) it contained information on 264 232 groundwater sites in South Africa, including information on 253 441 boreholes, 5 drains, 1 661 dug wells, 13 mines, 436 seepage ponds, 12 sinkholes, 8 047 springs and 617 well points. Of the 253 441 boreholes in the database, 1 116 have depths equal to or in excess of 300 m. The depth distribution of the boreholes with depths exceeding 300 m is shown in Figure 4.2.

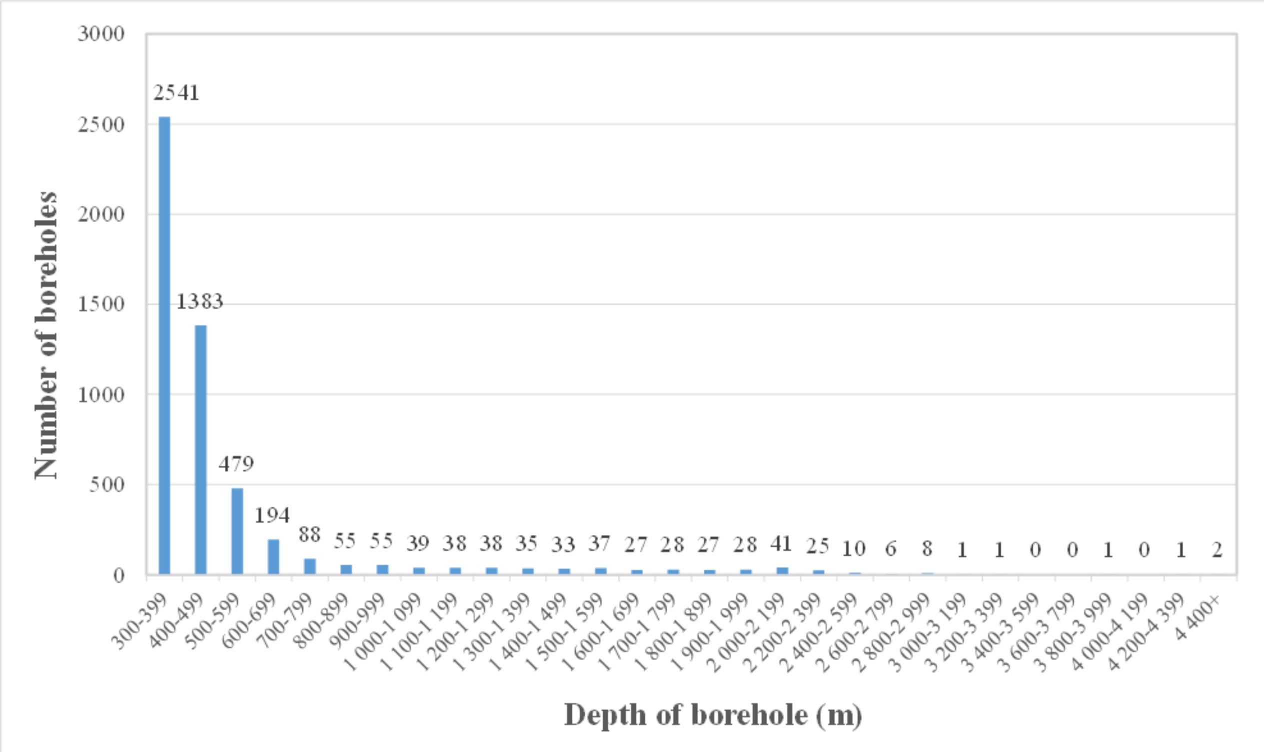

Figure 4. 2 Depth distribution of boreholes with depths exceeding 300 m in the NGA

Most boreholes have depths in the 300 to 399 m range, while similar numbers of boreholes are seen for the other depth ranges. The locations of these deep boreholes are shown in Figure 4.3. No boreholes with depths in excess of 1 000 m are listed in the NGA. Deep boreholes are seen to occur in all the provinces of South Africa, with particularly dense distribution in the northern parts of Limpopo, the Northern Cape Provinces, and eastern parts of the Free State.

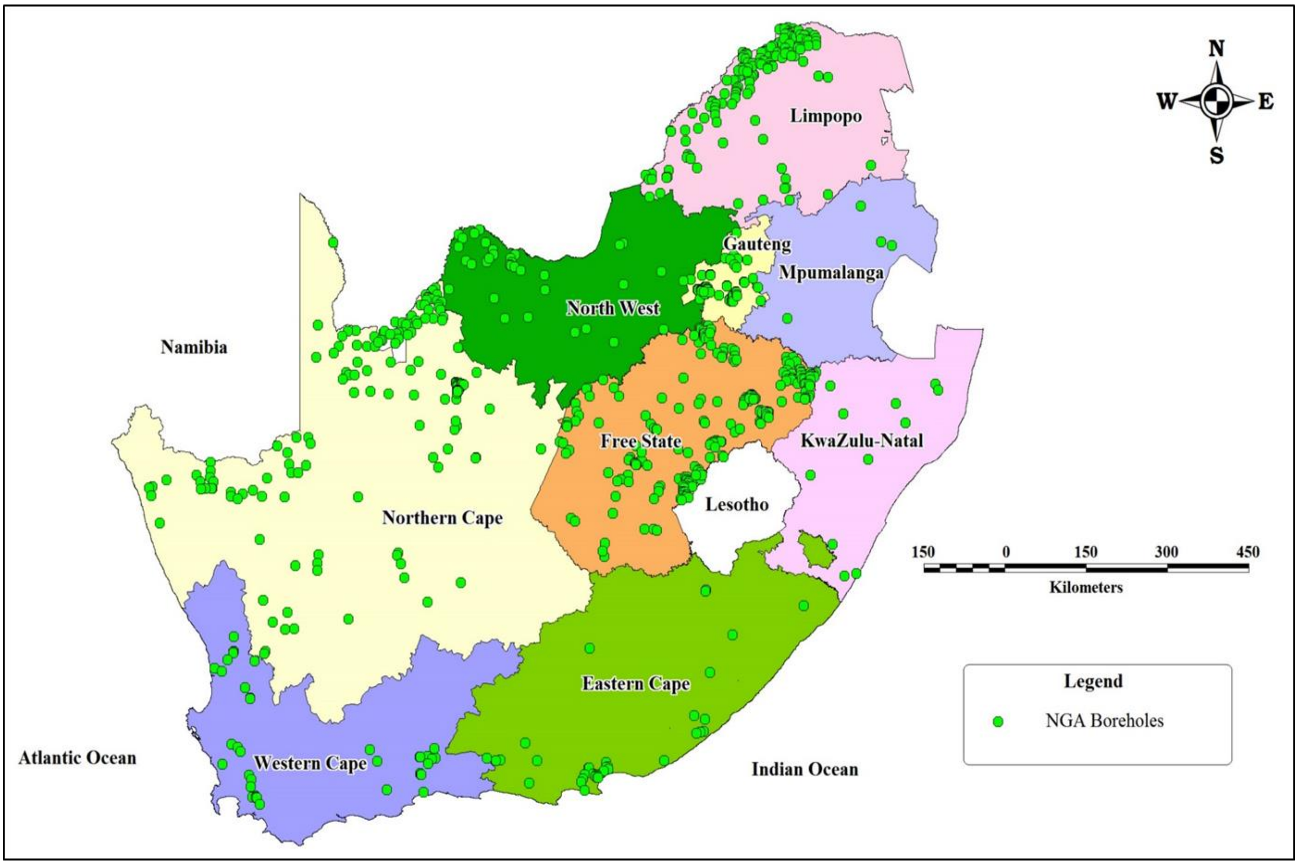

Figure 4. 3 Distribution of boreholes with depths greater than 300 m in the NGA

4.1.2 The SOEKOR boreholes

During the period 1965 to 1975 Southern Oil Exploration Corporation (SOEKOR), now known as PetroSA, drilled 25 deep boreholes (depths in excess of 2 000 m) as part of an oil and gas exploration programme (Vermeulen, 2012; Swana, 2016). These boreholes were installed at locations where the Karoo Supergroup rocks were thought to be potentially favourable for oil and gas production. The distribution of the SOEKOR boreholes is shown in Figure 4.4.

KGEG (2013a) summarised the available information on the SOEKOR boreholes. This includes information on:

- borehole construction (depth and diameter),
- borehole logs (geological, chromato, gamma, neutron, density, sonic, electric and caliper),
- water strikes (depth and flow rate), and
- groundwater quality (information from only two samples taken during 2012 and 2013).

Figure 4.5 shows the profile of SOEKOR deep boreholes (west to east) used to constrain horizons picked in SOEKOR seismic data. Not all the above information is available for all SOEKOR boreholes. For some boreholes the information is limited to the depth of the borehole accompanied by a brief description of the lithologies intersected Table 4.1.

Figure 4. 4 Locations of the SOEKOR boreholes

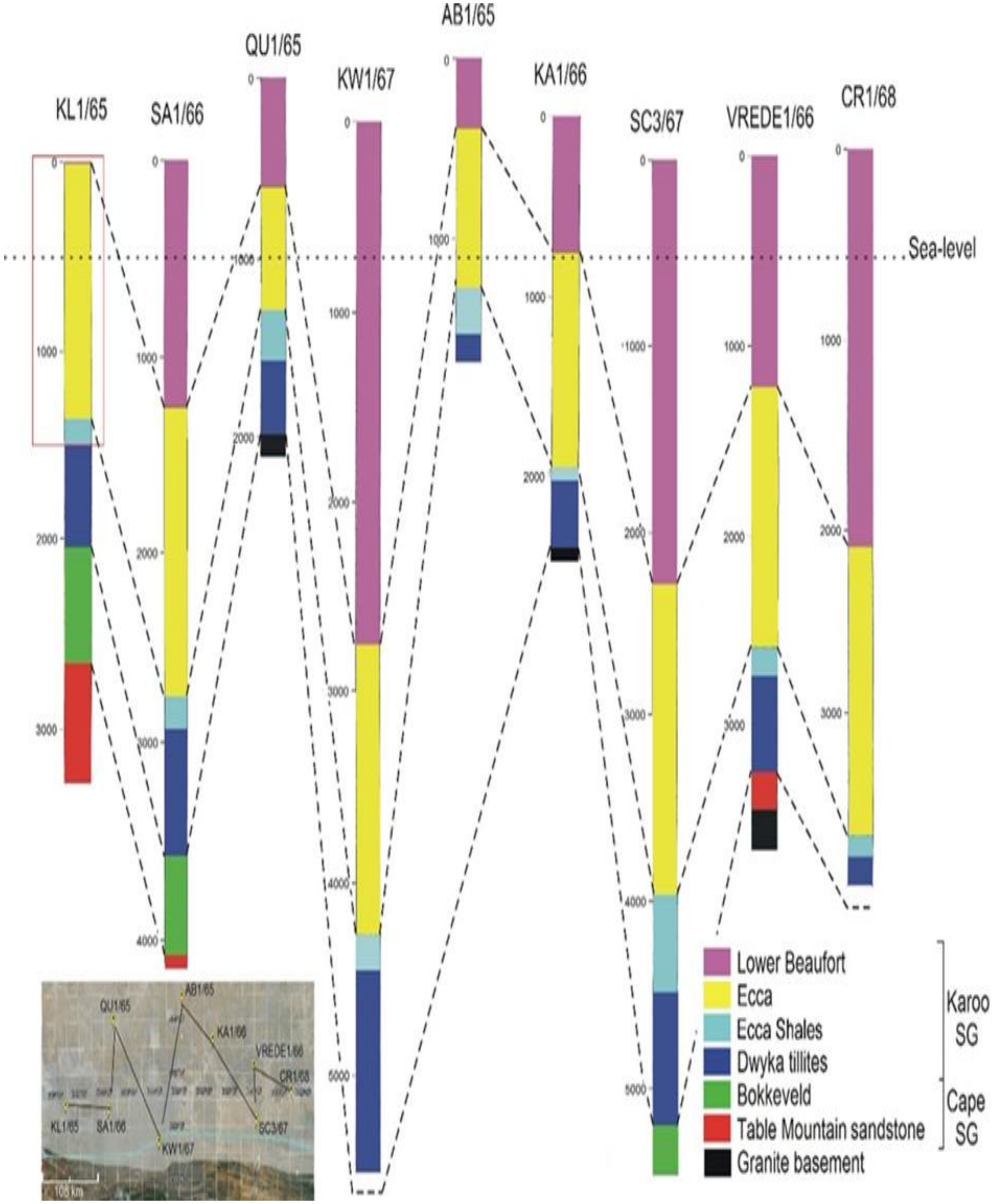

Figure 4. 5 Stratigraphic succession of the main sedimentary units intersected by SOEKOR boreholes on either side of the dolerite line

Table 4. 1 Information on the SOEKOR boreholes

Borehole #	Company	Farm/Location	Nearby Town	Latitude (°S)	Longitude (°E)	Elevation (mamsl)	Depth (m)
AB1/65	Soekor	Abrahamskraal		-31.80161	22.61749	1 415	2 311
AD1/68	Soekor/Geological Survey	Addo		-33.58500	25.66472		
BE1/66	Soekor			-28.35045	32.09979		
BE1/67	Soekor			-28.67707	29.38693	1 151	
CK1/68	Soekor	Commandokraal		-33.52194	25.69667		2 115
CL4/68	Soekor/Sterrenberg Mynbou	Clocolan	Clocolan	-28.88788	27.55409		897
CO1/67	Soekor	Colchester		-33.68667	25.79222		>914
CR1/68	Soekor/Karroo Petroleum	Cranemere	Pearston	-32.48547 -32.48528	25.00871 25.00917	793	4 658
EL1/67	Soekor/Geological Survey	Elandsnek	Utrecht	-27.48056	30.45000	1 675	585
FI1/72	Soekor	Ficksburg Municipality	Ficksburg	-28.89371 -28.89333 -28.89385	27.84771 27.84806 27.84869	1 572	1 911
GL1/67 (GLEN1/67)	Soekor	Klipfontein	Bloemfontein	-28.95258 -28.95222	26.33377 26.33417	1 280	1 198
GSO1/67	Soekor/Geological Survey			-28.58278	29.38333		
GSO14	Soekor	Schietnek	Newcastle	-28.11000	29.69056	1 411	646
JA2/75	Soekor	Jackhalsdraai	Utrecht	-27.43472 -27.44816 -27.44770	30.18167 30.18347 30.18142	1 753	647
KA1/66	Soekor	Karreebosch		-32.01354	23.42586	1 036	2 469
KL1/65	Soekor	Klipdrift		-32.61688 -32.61861	20.45352 20.45383	729	3 370
KW1/67	Soekor	Klein Waterval		-32.98434	22.33611	969	
LA1/68	Soekor	Olney		-29.08564	27.48047	1 614	
MA1/69	Soekor	Matatiele		-30.32279	28.76773		
ME1/72	Soekor			-28.18750	29.27917		1 060
NA1/69	Soekor	Nanaga	Paterson	-33.55944	25.95167	1085?	2 063
OL1/69	Soekor	Olyvenbosch		-32.00024	19.86043	542	1 219
OM1/73	Soekor			-27.83333	29.51667		973
PA1/68	Soekor		Paterson	-33.47278	25.89222		
QU1/65	Soekor	Quaggafontein		-31.82662 -31.82792 -31.82639	21.43827 21.44253 21.43889	1 261	329
SA1/66	Soekor	Sambokkraal	Merweville	-32.66964 -32.65017 -32.66944	21.32856 21.33345 21.32917	741	4 169
SC3/67	Soekor	Schietfontein	Aberdeen	-32.77379 -32.77361	24.29952 24.30000	792	6 401
SP1/69	Soekor	Springfontein		-33.00433	27.76298	237	
SS1/73	Soekor	Sans Souci	Harrismith	-28.10417	29.44833	1 704	304
SW1/67	Soekor/Geological Survey	Swartberg		-30.15447	29.26635	1 682	
TK1/75	Soekor			-27.44306	30.31889		304
UV2/75	Soekor	Uitval	Utrecht	-27.51111 -27.51159	30.34444 30.34420	2 100	1 027
VR1/66 (VREDE1/66)	Soekor	Uitkomst	Vrede	-32.22441	24.21281	875	3 839
WE1/66	Soekor	Weltevrede		-30.89804 -30.89722	26.83988 26.84056	1 532	3 746
WI1/72	Soekor	Wittekrans		-28.70872	27.68854	1 695	1 520
ZE1/71	Soekor	Ntabankulu	Maputa	-27.07083	32.68583	73	1 900
ZF1/72	Soekor	Native Reserve		-27.21528 -27.21582	32.59694 32.59659	81	1 921
ZH1/74	Soekor	Nyalazi	Mtubatuba	-28.20722 -28.20716	32.40083 32.40063	34	973

4.1.3 Boreholes in the database of the IHFC and Pangaea

Two main databases were drawn upon to create this initial framework on deep boreholes, namely the International Heat Flow Commission (IHFC) and Pangaea, a data publisher for earth and environmental science that forms part of the International Council for Science (ICSU). The International Heat Flow Commission (IHFC) database (http://www.heatflow.und.edu/data.html) contains 48 boreholes located in South Africa for which temperature gradient data is available. The temperature database was originally assembled to determine the historical heat flow of the Earth but now serves as a good indication of where deep boreholes are located, their depth and the temperature of the groundwater at these locations.

Data from climate reconstruction investigations are considered to supplement the current framework of deep boreholes. The climate reconstruction data consists of temperature gradients, temperature profiles and heat flow rates. The presence of temperature data at these depths is indicative of the existence of deep boreholes, from which data could potentially be collected without having to drill new deep boreholes at those locations.

The distribution of the deep boreholes contained in the Pangaea and IHFC databases across South Africa is shown in Figure 4.6. The IHFC boreholes are clustered within the Limpopo and North West Provinces, while the deep boreholes on the Pangaea database has a smoother distribution across South Africa with a few boreholes in each province. However, there are dense clusters of boreholes within the Free State, Gauteng, North West and Mpumalanga Provinces of South Africa. The coordinates of the boreholes and the recorded temperature data are compiled in Appendix A and Appendix B.

The IHFC database lists the location of 39 boreholes with depths greater than 300 m. The depths of these boreholes range from 300 m to 800 m, with an average depth of 532 m. The depth distribution of the Pangea and IHFC boreholes with depths exceeding 300 m is shown graphically in Figure 4.7 and Figure 4.8.

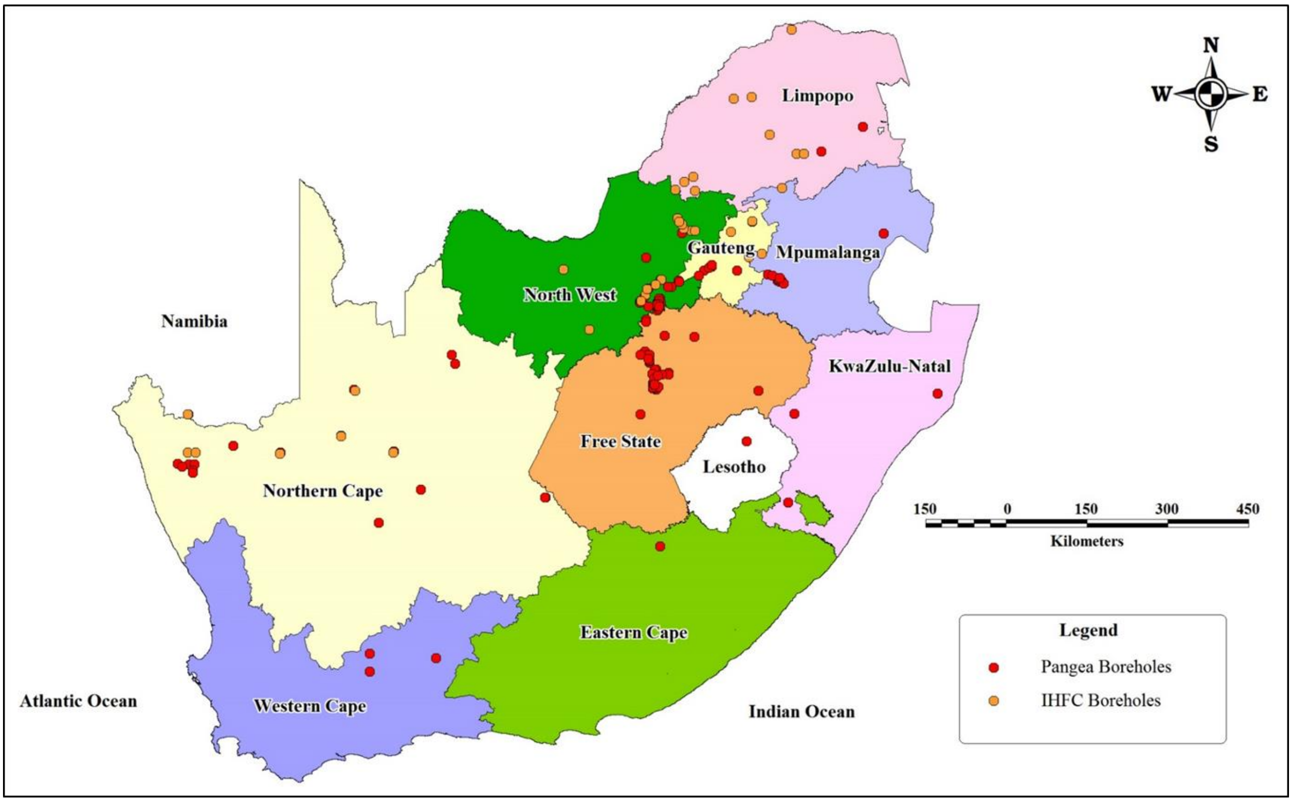

Figure 4. 6 Distribution of boreholes with depths greater than 300 m in the IHFC and Pangea databases

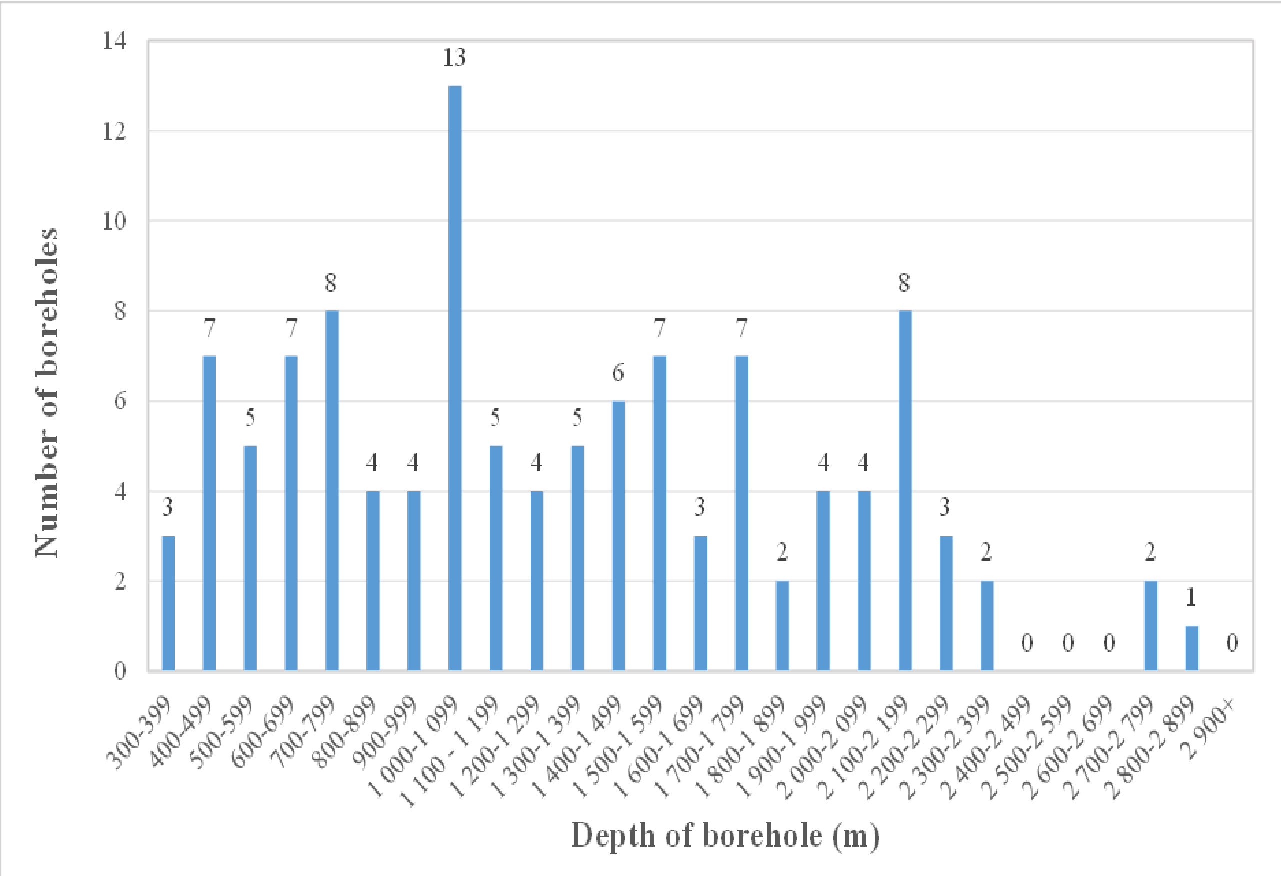

Figure 4. 7 Depth distribution of boreholes with depths exceeding 300 m in the Pangaea database

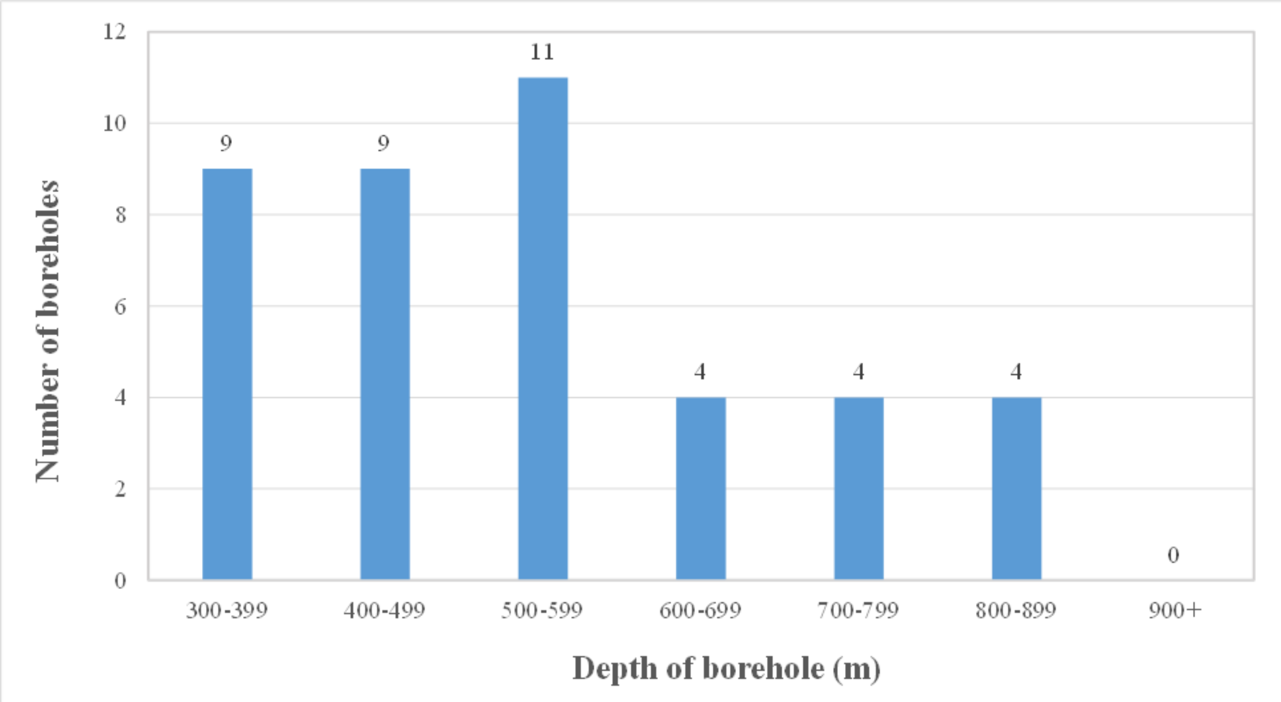

Figure 4. 8 Depth distribution of boreholes with depths exceeding 300 m in the IHFC database

4.1.4 Boreholes in the database of the Council for Geoscience (CGS)

The Council for Geoscience (CGS) maintains a database of borehole information received from the mining and energy sectors. The database includes information on the mining/energy company for whom the borehole was drilled, date of installation, and borehole depth and coordinates. In addition, the results of coal analyses performed on samples from some of the boreholes drilled during coal exploration are also listed in the database. The coal analyses include water content analyses.

The CGS database contains information on 5 221 boreholes with depths exceeding 300 m. The depth distribution of these boreholes is shown in Figure 4.9. The boreholes of the CGS database have been identified to be clustered on and around the coalfields of South Africa.

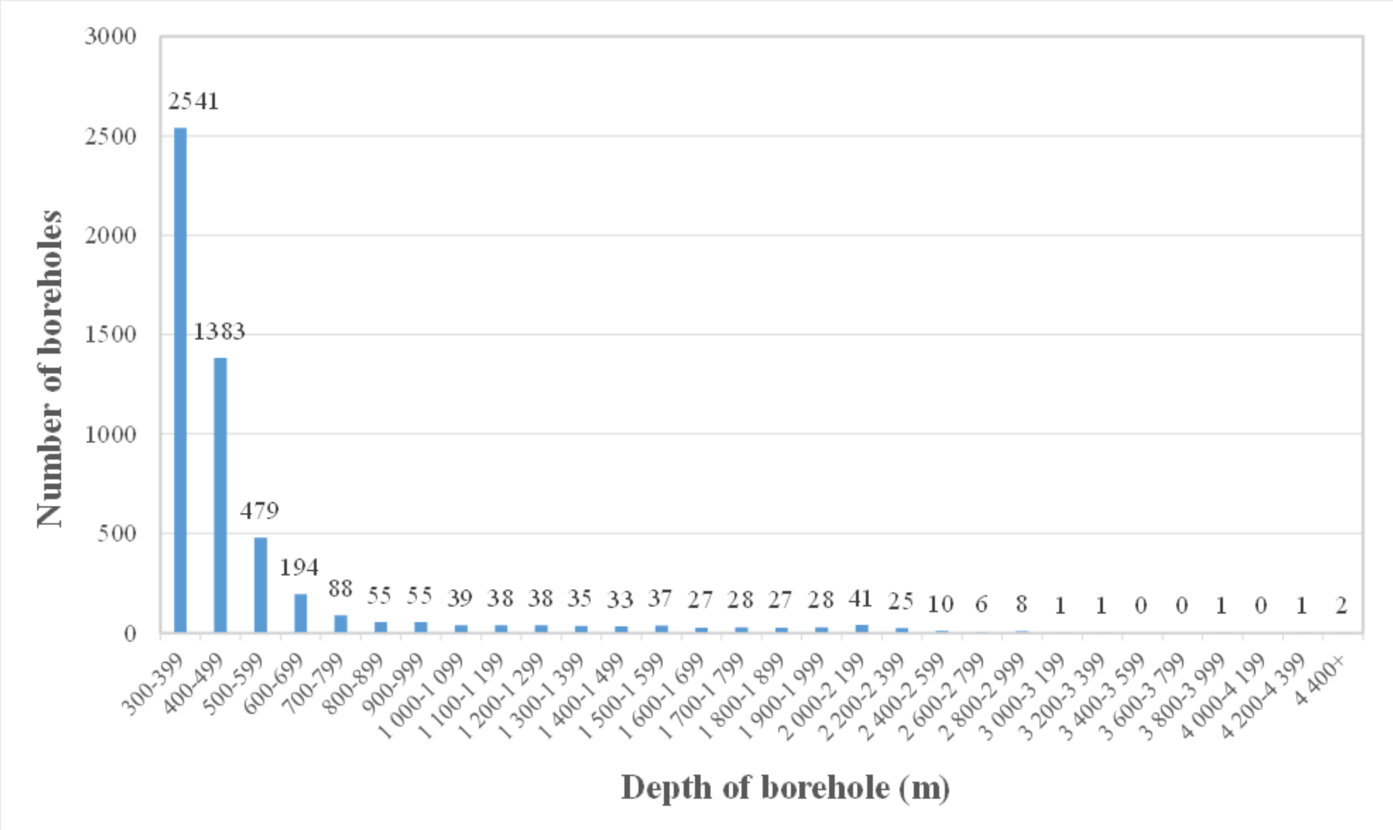

Figure 4. 9 Depth distribution of boreholes with depths exceeding 300 m in the CGS database

4.1.5 The KARIN boreholes

The Karoo Research Initiative (KARIN) is an academic contribution to geoscientific research in South Africa. The KARIN project entails the installation of two deep core boreholes in the southern parts of the Karoo Basin. The main aim of the project is to improve the understanding of the stratigraphy and basinal settings of potential shale gas reserves in the Karoo Basin south of the dolerite line. The project also had the characterisation of the geohydrological conditions and water quality of the deep aquifer systems as one of its objectives (de Kock *et al*., 2016a, b).

The two core boreholes were drilled by Geoserve Exploration Drilling (Pty) Ltd during the latter half of 2015. As shown in Figure 4.10 Borehole KFZ-01 was drilled on the farm Zandfontein, approximately 85 km northeast from Ceres in the Western Cape and to a depth of 671 m. Borehole KWV-01 is located approximately 10 km east of the town Willowvale in the Eastern Cape and drilled to a depth of 2 353.5 m.

Borehole KZF-01

Borehole KZF-01 was drilled in the Tankwa Karoo, south of the Karoo Large Igneous Province, near the town of Ceres. The borehole is located at a topographic elevation of 510 mamsl and was drilled vertically to a final depth of 671 m. Core from the borehole was recovered with an average core recovery of 97.5%. Geophysical well logging was conducted after drilling. Groundwater samples were collected, both at surface and selected depths within the borehole and submitted for chemical analyses.

Borehole KWV-01

Borehole KWV-01 was drilled near the town of Willowvale in the Eastern Cape Province. The borehole was drilled in an area with abundant dolerite intrusives to allow comparison with the results of borehole KZF-01, which was drilled in a dolerite-free area. KWV-01 was drilled vertically to a depth of 2 353 mbgl. Geophysical well logging was conducted after drilling.

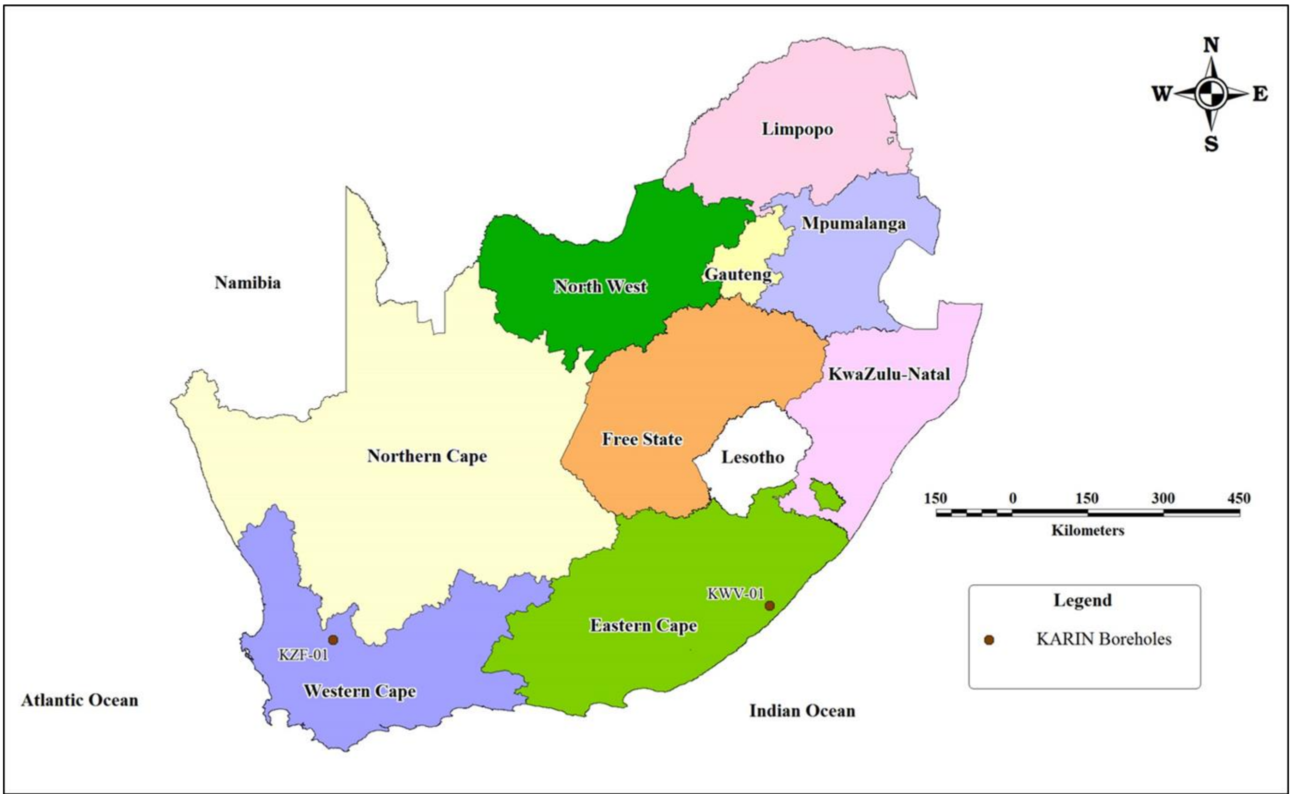

Figure 4. 10 Locations of the two KARIN boreholes

4.1.6 Boreholes in the database of the Petroleum Agency of South Africa

The Petroleum Agency SA promotes the exploration of onshore and offshore resources of oil and gas, as well as the optimal development of these resources on behalf of the government of South Africa. The agency also regulates exploration and production activities. It acts as the custodian of the national petroleum exploration and production database.

The database currently contains information on 598 exploration and production wells, both onshore and offshore. The distribution of the onshore and offshore boreholes in the database is shown in Figure 4.11 Information on these wells may be ordered using the Storefront Web Mapping

Application (https://geoportal.petroleumagencysa.com/Storefront/Viewer/index.htm) on the agency's website.

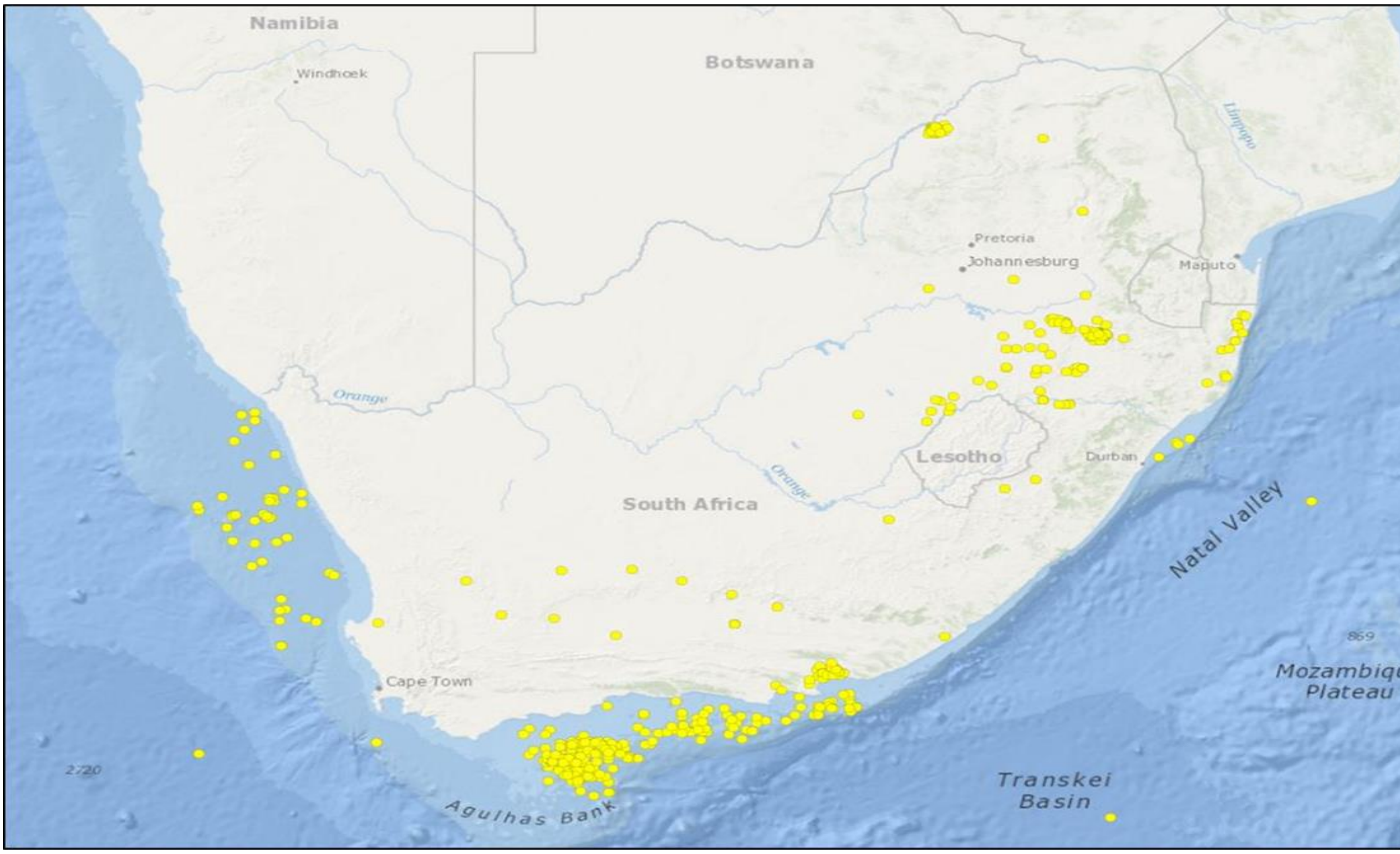

Figure 4. 11 Distribution of onshore and offshore boreholes in the database of the Petroleum Agency SA

The depths of only 13 offshore boreholes are listed in the database of the Petroleum Agency SA. These boreholes have depths ranging from 2 443.4 m to 3 548.5 m. The positions of these boreholes are shown in Figure 4.12. Eleven of the boreholes occur to the south of Mossel Bay and were probably drilled during exploration for the Mossgas fuel-from-gas project. One borehole is located southeast of Port Elizabeth, approximately 60 km from the shore, while another occurs south of Richards Bay, approximately 30 km from shore.

Numerous reports may be ordered from the website for each of the 13 boreholes. Some of these reports are likely to contain valuable information on the aquifer systems intersected during drilling. The 13 boreholes with depth information are listed in Table 4.2. Also listed in the table are some of the reports available for each borehole, as well as the costs of these reports.

Although information on borehole depth is explicitly listed in the database for only these 13 boreholes, it is very likely that depth information on the other boreholes in the database is also available in the various reports compiled for these boreholes. Unfortunately, to ascertain whether such information is available would require the purchase of these reports.

Table 4. 2 Reports available for the deep boreholes in the database of the Petroleum Agency SA

Name/ Number	Longitude (°E)	Latitude (°S)	Depth (m)	Nearest City / Town	Available Reports	Cost (R)
Jc-D1	31.80843	-29.39672	2 888.00	Richards Bay	Geophysical Survey of the Rhino Drill Site	120.00
					Interpretation of Fluid Inclusion Stratigraphy	30.00
					Intermediate Survey	120.00
					Final Drilling Report	100.00
					Geophysical Log	0.00
					Environmental Close Out Management Programme	100.00
					End of Well Report	100.00
					Waveform Slowness Analysis Results	0.00
					Environmental Management Programme Report	50.00
					Geochemical Analysis of Ten Rock Extracts	30.00
					Well Plan	100.00
					Description of Sidewall Cores	30.00
					Final Geological Report	300.00
					Geochemical Analysis of Samples	30.00
					Statigraphic Reconstruction	100.00
					Drilling	600.00
Hb-Q1	26.31084	-34.26289	3 548.50	Port Elizabeth	End of Well Report	100.00
					Well Drilling Close Out Report	100.00
					Petrophysical Evaluation	0.00
					Well Report	100.00
					Drilling Programme	100.00
					Geological Well Completion Report	300.00
F-BE1	22.12559	-34.97216	2 559.70	Mossel Bay	End of Well Report	180.00
					Drilling Well Completion Report	100.00
					Geological Well Completion Report	300.00
F-AD01P	22.09705	-34.96309	2 725.80	Mossel Bay	Drilling Programme	100.00
E-BF01PZ1	21.71210	-34.91439	2 529.75	Mossel Bay	Well Installation Report	100.00
					Completion and Well Testing Report	30.00
					Drilling Well Completion Report	100.00
					Petroleum Engineering Report	30.00
E-AR02P	21.53840	-35.19910	2 514.55	Mossel Bay	Geophysical Log	0.00
E-BT01P	21.49777	-35.23359	2 550.98	Mossel Bay	Geochemistry Data and Summary Report	30.00
					Petrography Core Analysis and Interpretattion Report	30.00
E-H2	21.71502	-34.90437	2 830.30	Mossel Bay	Completion and Well Testing Report	30.00
					Drilling Programme	100.00
					Well Completion Report	0.00
					End of Well Report	100.00
					Drilling Well Completion Report	100.00
					Geophysical Log	0.00
E-M01P	21.63407	-34.91917	2 563.40	Mossel Bay	End of Well Report	100.00
					Completion and Well Testing Report	30.00
E-M03P	21.65096	-34.91630	2 596.40	Mossel Bay	Geophysical Log	0.00
					Drilling Well Completion Report	0.00
E-AR03P	21.53990	-35.20467	2 443.40	Mossel Bay	No Report Available	
E-M02P	21.63489	-34.91912	2 569.40	Mossel Bay	No Report Available	
F-AH02P	22.00067	-34.87946	2 577.00	Mossel Bay	No Report Available	

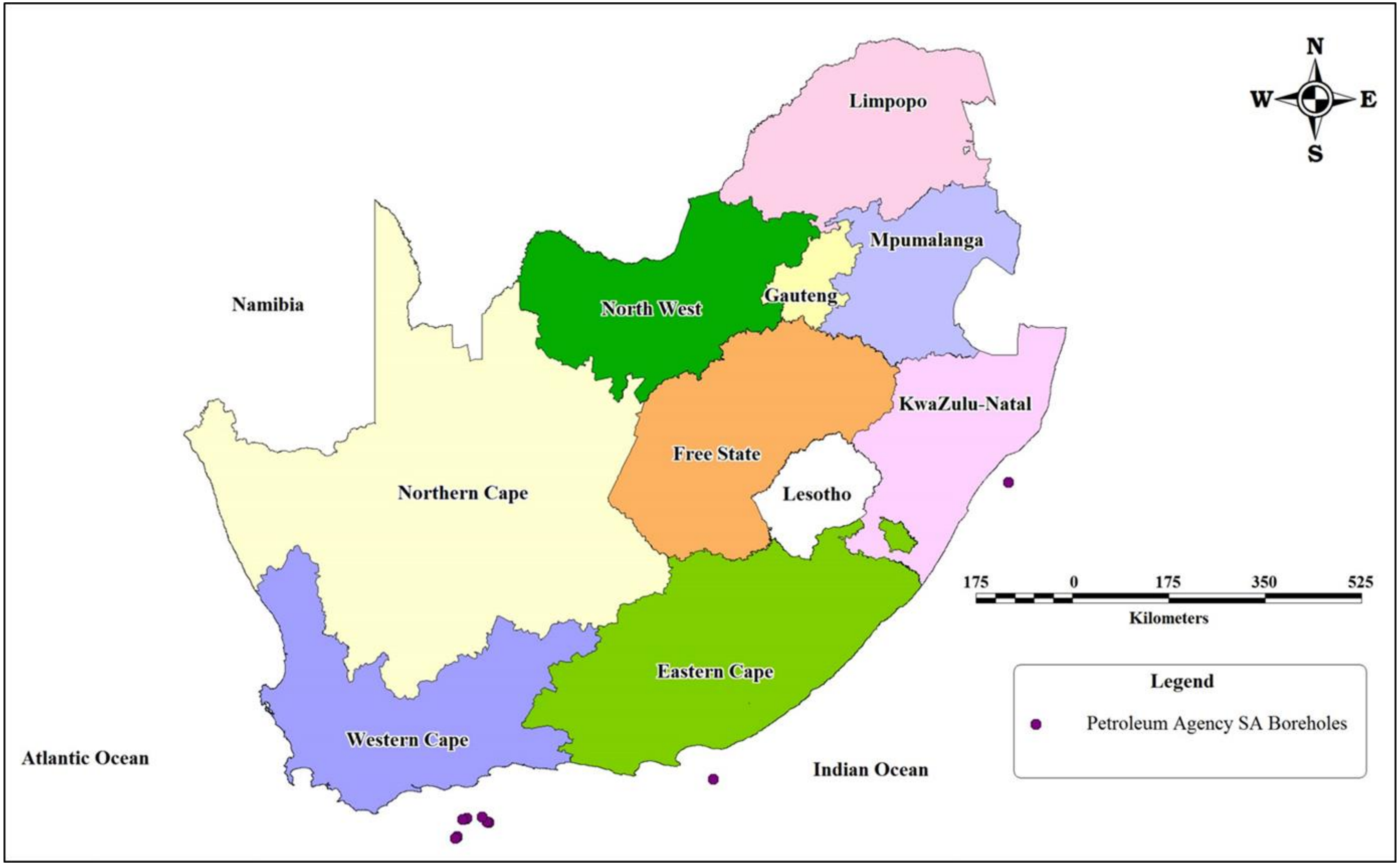

Figure 4. 12 Distribution of boreholes with depths greater than 300 m in the database of the Petroleum Agency SA

4.1.7 Thermal springs

There is very limited research conducted on the thermal springs of South Africa. Most research on these springs was done in the 1950s (Olivier *et al.*, 2008). According to Olivier *et al.* (2008) South Africa has an abundance of thermal springs, with the majority located in the Limpopo Province.

Thermal springs are known to originate in areas with recent volcanic activity or from meteoric water flowing through fractures in bedrock (LaMoreaux & Tanner, 2001). LaMoreaux and Tanner (2001) stated that the flow rate of a thermal spring is determined by the size of the aquifer, extent of recharge, aquifer storage capacity, and the transmissivity and discharge capacity of both the aquifer and conduit through which the water rises to the surface.

South Africa is not situated in an area that has experienced any recent volcanic activity. Instead, the country's thermal springs are linked to geological structures such as faults and folds (Kent, 1949). Kent (1949) identified 74 thermal springs and 9 thermal artesian wells in South Africa. Kent (1949) further devised a classification scheme for thermal springs based on the recorded water temperatures:

- Warm springs (25°C-37°C)
- Hyperthermic (hot) spring (38°C-50°C)
- Scalding spring (>50°C)

Figure 4.13 shows the location of springs in South Africa classed from cold to thermal types, and the approximate location of the AKGT lines. It has been established that thermal springs are found along the Cape Fold Belt due to the deformation and the resulting fracture/fault systems. Cave and Clarke (2003) studied the thermal springs in the Western and Eastern Provinces to determine circulation depths based on geothermometer methods, and estimated a maximum circulation depth of 7.4 km at the Warmwaterberg spring (close to the AKGT line). This depth was thought to be extreme by Cave and Clarke (2003), yet the geophysical crustal model indicates that the TMG formations not only extend to these depths but fractures are evident at these depths as well.

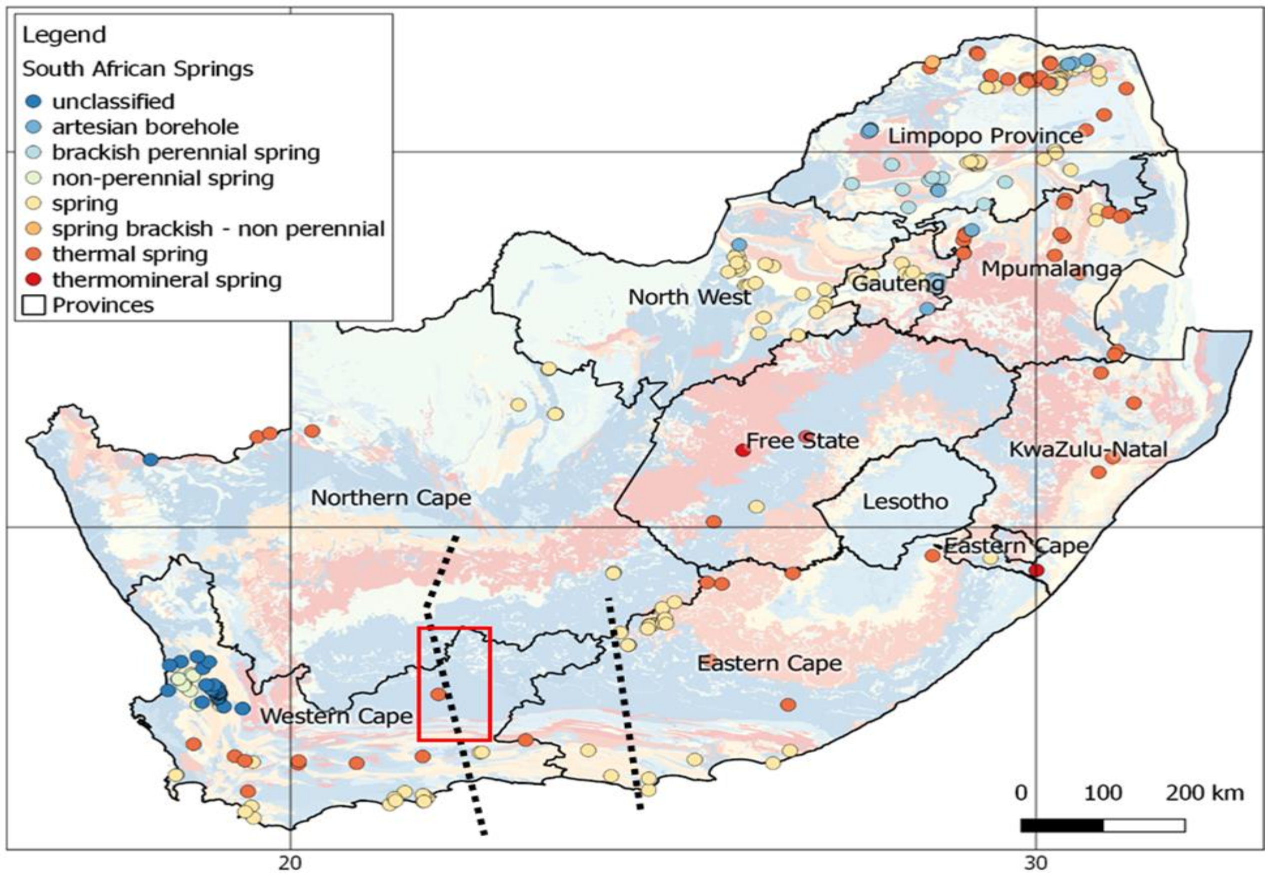

Figure 4. 13 Springs in South Africa, classed from cold to thermal types, indicating the approximate location of the AKGT lines

4.1.8 Deep mining

South African deep mines could potentially provide plenty of information and data regarding the deep aquifer systems intersected by mining. This information can be obtained from a variety of mining activities (including exploration drilling, mine dewatering, geophysical surveys and direct access to the rock formations left exposed by these mining activities) and could lead to a deeper understanding of aquifer conditions and deep groundwater.

4.1.8.1 Exploration drilling

Usually core boreholes are drilled during the exploration drilling phase on a grid above the ore body of interest. The cores retrieved during this process are then examined for mineral content, as well as secondary geological features (e.g. fissures, faults, and weathering) and stratigraphic contacts.

Even though the cores are not originally studied to gain insight into the properties of the aquifers intersected by drilling, they could potentially provide a wealth of information on the deep geohydrology near the mine. The various types of geohydrological information that the cores may contain include:

- The depth of aquifers intersected by drilling. Stratigraphy data could help determine which layers could possibly act as aquicludes, aquifers and aquitards.
- The secondary porosity of intersected aquifers, e.g. factors such as fractures, faults, fissures, joints, etc.
- Proof of groundwater flow. Fracture weathering and mineral leaching indicates whether or not groundwater movement takes place.
- The occurrence of mineralisation. The possibility exists that mineralisation influences groundwater quality, e.g. if the host rock contains pyrite it could lead to acidic conditions that could in turn result in the mobilisation of trace metals.

4.1.8.2 Borehole logs

Borehole logging refers to the process whereby the chemical, physical, and structural properties of penetrated geological formations are measured. Normally this is achieved by using a wireline cable to lower logging tools into a borehole. Borehole logging is a means of providing not only information on rock strata’s physical properties, but also information regarding the groundwater within the borehole.

Core boreholes at mines are often the target of geological borehole logging. While borehole logging is typically used to obtain information about mining operations, it may also provide information that could help describe the aquifer systems that are intersected by the core boreholes. Geohydrological information that borehole logs could contain include:

- The groundwater quality,
- The porosities of the geological units intersected by the core boreholes,
- The groundwater salinity present at different depths in the borehole,
- The occurrence and orientation of fractures, and
- The speed and direction of groundwater flow.

4.1.8.3 Ground and airborne geophysics

Even though geophysical investigations at mines are aimed at mineral exploration, it can also be valuable for groundwater exploration. In order to better understand the structural geological factors that influence deep aquifer systems, current geophysical data may be reinterpreted or reprocessed. This data can not only define the vertical and lateral extents of the aquifers, but also estimate the groundwater quality in the aquifer systems.

4.1.8.4 Deep opencast mining

Even though opencast mines are rarely deeper than 300 m, there are a few that do exist. One if these is the 898 m deep open pit that can be found at Phalaborwa Copper. These mines could also potentially contain information on deep aquifer systems.

4.1.8.5 Underground coal mining

South Africa has 19 coalfields. They are predominantly located in the Limpopo, Mpumalanga, Free State, and KwaZulu-Natal provinces (Figure 4.14). However, fewer coal deposits can also be found in the Gauteng, Eastern Cape provinces and North West provinces (Jeffrey, 2006). Usually, coal seams are close to surface and quite thick, which means more cost effective mining. In South Africa roughly 25% of bituminous coal is located less than 50 m below surface; the rest are below depths of 200 m (Eberhard, 2011). However, Waterberg Coalfield seams can be found at depths of up to 400 m, and Springbok Flats Coalfield seams at depths surpassing 1 000 m (Jeffrey, 2006). Roughly 50% of South African coal mining is done by way of underground mining. The 2015 DMR database on South African mining operations lists 59 underground coal mines. These mines usually occur up to depths of approximately 200 m below the surface, but it is possible that some are deeper, providing access to deep aquifer systems.

4.1.8.6 Mine dewatering

Mine dewatering makes provision for effective mining and assures that mining personnel is safe. It is usually done at underground as well as both opencast mines. The rate of groundwater removal needed in order to dewater the mines directly measures the rate of groundwater inflow, and as a result also the yields of the aquifers intersected by these mines.

Besides providing information on the yield of groundwater at a specific mine, mine dewatering can also provide valuable insight on the groundwater quality. The groundwater removed from mines is used for a variety of purposes, including domestic and irrigation use, road wetting to suppress dust, and process water at plants and refineries. Before groundwater can be used for these various purposes, the quality of this water needs to be determined. For this reason mines perform sampling and chemical analyses on a regular basis. This information regarding the water quality is usually kept in databases at the mine.

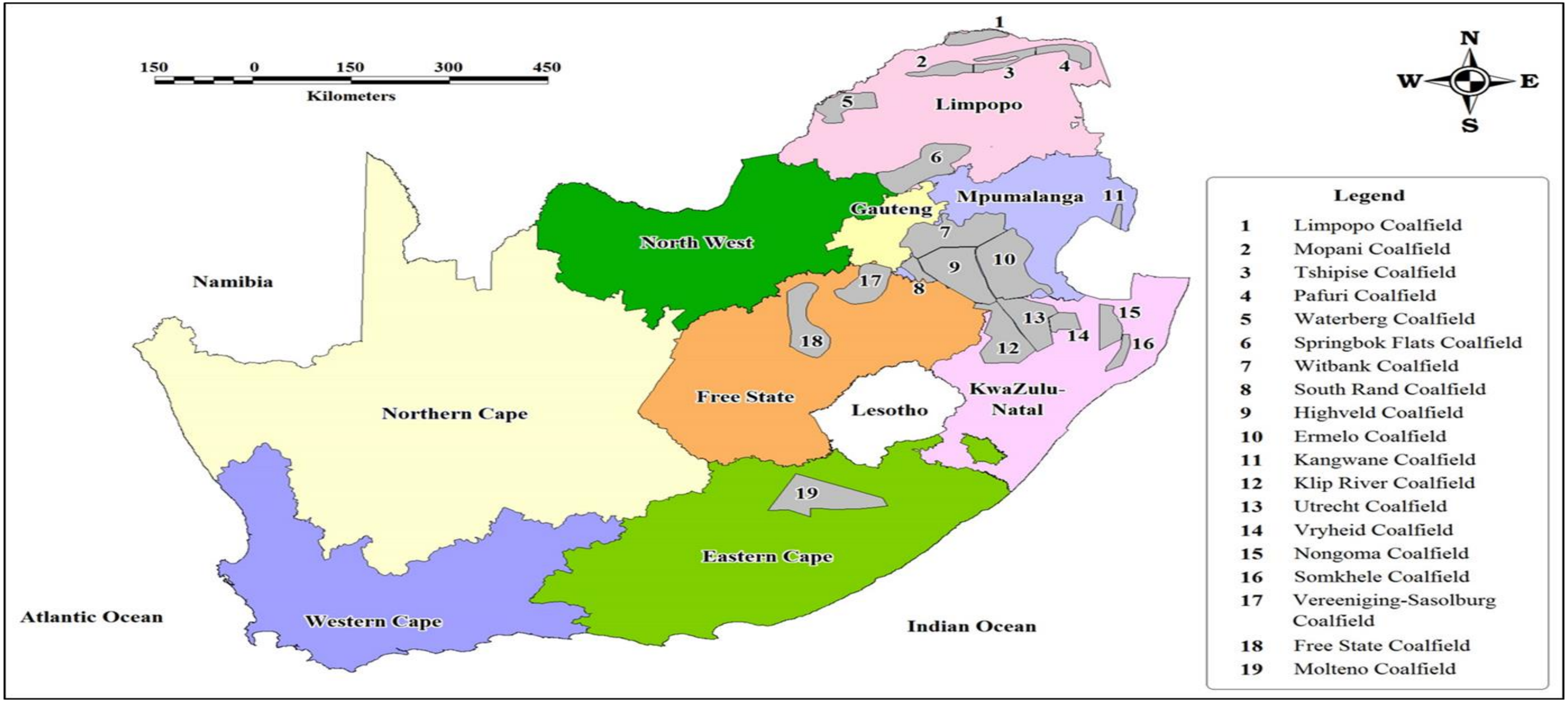

Figure 4. 14 Coalfields of South Africa

CHAPTER 5:
CHARACTERISATION OF THE DEEP AQUIFERS OF THE KAROO SUPERGROUP AND TABLE MOUNTAIN GROUP

5.1 INTRODUCTION

The potential sources of information were cross-examined to gain information on the deep aquifer systems and characterise them in terms of their physical and hydraulic properties, as well as the groundwater quality expected from these aquifers. Not all of the potential sources yielded useful information. The IHFC and Pangaea databases mostly contain information on temperatures and heat production in deep boreholes. The database of the CGS also contains very little information relevant to the deep aquifer systems, although the results of water content analyses performed on rock samples from deep boreholes are listed. The Petroleum Agency of South Africa did not respond to requests for access to the reports on the deep exploration boreholes included in their database.

Aquifers may be classified in terms of various physical and chemical parameters. To characterise the deep aquifers in South Africa the classification systems commonly used in the field of geohydrology may be used as reference:

- Lithology (rock type)
- Occurrence (depth)
- Physical dimensions (thickness, lateral extent)
- Aquifer type (fractured, granular, double porosity)
- Saturation level (saturated, unsaturated)
- Heterogeneity and degree of isotropy
- Formation properties (porosity, pore size distribution, bulk density, mechanical properties)
- Hydraulic parameters (hydraulic conductivity, storativity, transmissivity, specific yield, permeability)
- Pressurisation (confined, unconfined, artesian)
- Yield
- Groundwater quality (inorganic parameters, organic parameters)
- Aquifer vulnerability and susceptibility

The TMG sandstones and Karoo Sequence are two prominent examples of deep confined aquifer systems. The TMG was subject to ductile deformation approximately 230 million years ago, which resulted in the folding sedimentary layers. The Karoo Supergroup extends across South Africa, Botswana and Namibia, with the northwestern part of South Africa forming the Aranos Basin. The Aranos Basin can be considered a typical artesian flow model, comprising mainly Dwyka Group and Ecca Group sediments with the Nossob Formation (sandstone) at the base (van Wyk, 2013). The Nossob Formation (thickness ~20 m) represents the base and stratigraphically lower pressurised formation of the two main artesian to semi-artesian sandstone formations in the Aranos Basin. With the abovementioned assessment it appears that deep aquifer systems are likely to be associated with folded geological formations in which the water will occur in the host rock and fractures. Natural springs may provide insight into the quality and type of water facies within the deeper aquifer systems.

5.2 THE KAROO SUPERGROUP CHARACTERISATION

5.2.1 Introduction

Groundwater from weathered and fractured rock aquifers is an important resource for local communities who rely on the aquifers for their domestic, livestock and irrigation water supply. The Karoo Basin is an arid area of South Africa, occupying approximately a third of the country's land surface and consisting of a thick sequence of sedimentary rocks intruded by dolerite dykes and sills (KGEG, 2013b) (Figure 5.1). Although the shallow aquifers (<300 m depth) in this basin are relatively well understood (Woodford & Chevallier, 2002), groundwater occurrence in the deeper Karoo formations, as well as the characteristics of the deep aquifer systems are largely unknown.

The available information on deep geohydrology is limited and sparsely distributed across the basin (KGEG, 2013b). One source of information on the deeper aquifer systems are the deep SOEKOR boreholes drilled during the 1960s and 1970s (discussed in chapter 4). Thermal springs (Section 3.4.3) also allow insight into deep aquifer conditions. Thermal springs in the Karoo Basin (e.g. at Aliwal North) suggest groundwater circulation to depths of approximately 1 000 m and possibly deeper, as the groundwater is likely to cool somewhat during its upward flow. Recent drilling exercises of the Karoo Research Initiative (KARIN) also provides useful information on deep aquifer systems.

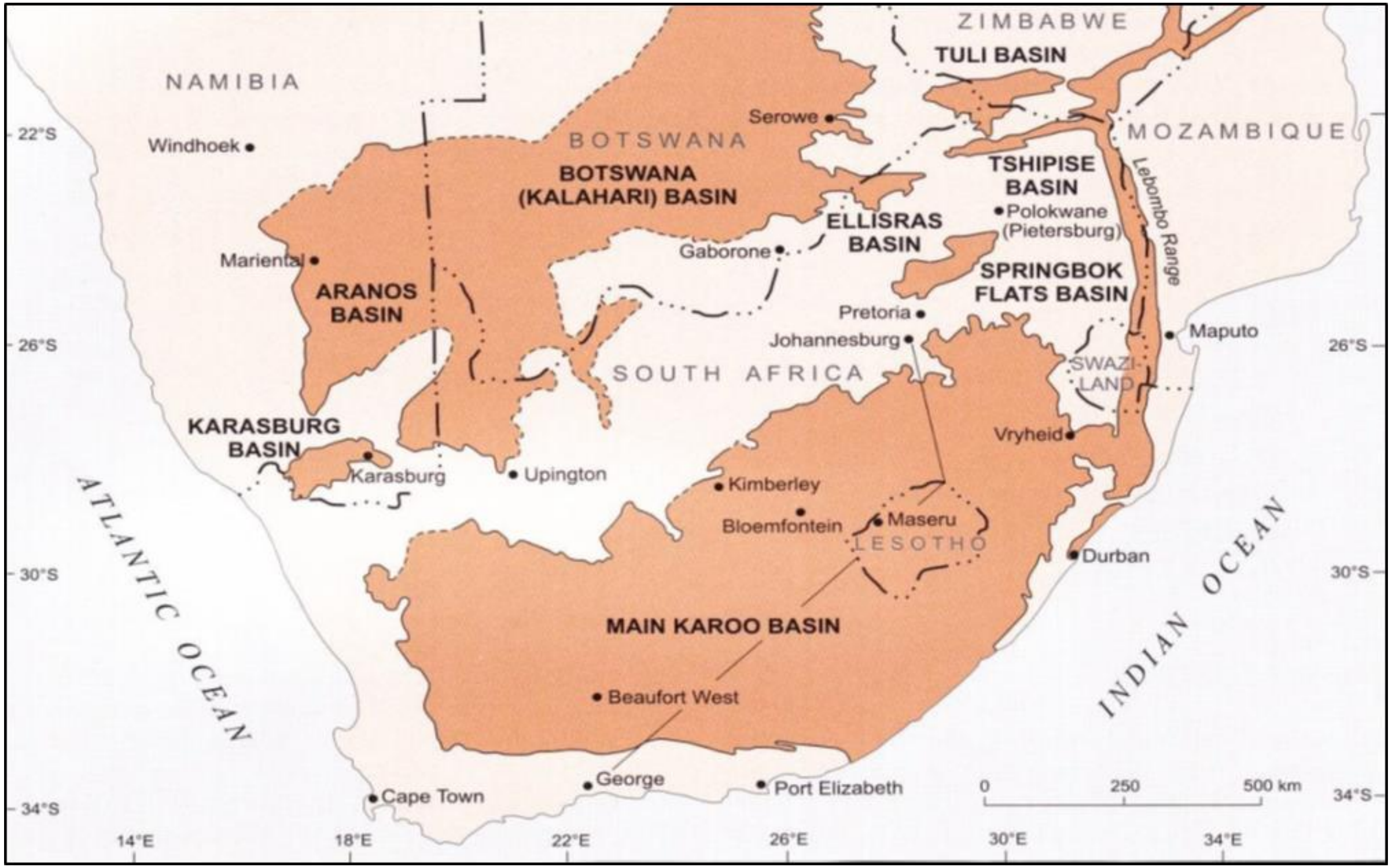

Figure 5. 1 Location and distribution of the Karoo Basin in South Africa and adjacent territories (Johnson et al., 2006)

A schematic cross-section through the Main Karoo Basin from George in the south to Fraserburg in the north is shown in Figure 5.2. The cross-section illustrates that free-flowing artesian conditions are expected for deep boreholes below the Great Escarpment, while sub-artesian conditions are expected on the Great Escarpment (KGEG, 2013b). In addition, the cross-section also shows the possible connection between the deep Karoo aquifers and Cape Supergroup in the southern parts of the cross-section. It also shows that deep circulation of groundwater through the formations of the Karoo and Cape Supergroups is expected to occur along preferential flow paths, such as fault zones. These fault zones may extend from the Cape Supergroup to the Karoo Supergroup. Recharge of the deep aquifer system may also occur along such fault zones, although the deep aquifer systems may also be recharged by slow percolation through the matrices of the rocks.

The dolerite intrusives in the Karoo Supergroup play a major role in the occurrence and movement of groundwater (Figure 5.3). The high pressures and heat that reigned during intrusion caused alteration of the intruded host rock. Van Wyk (1963) speculated that the high permeability of the dyke contact zones is a result of shrinkage joints developed during cooling of the intrusion. The fracture-forming nature of Karoo dolerite rings and sills is responsible for the presence of deep-seated fractured aquifers (Chevallier *et al.*, 2001).

Dolerite dykes are vertical to sub-vertical intrusives associated with near linear zones of relatively higher permeability in directions parallel to their strikes. The dykes may also act as semi-impermeable to impermeable boundaries for groundwater flow in directions perpendicular to their strikes (Woodford & Chevallier, 2002).

The Karoo dolerite sills and ring-complexes have the same geographical distribution as the dolerite dykes and are by far the most common type of intrusion in the Karoo Basin. A hydro-morphotectonic model of the dolerite sill- and ring-complexes was developed by Woodford and Chevallier (2002) (Section 3.2.4)

5.2.2 Description of the Karoo Supergroup deep aquifer systems

The Karoo Supergroup aquifer system is discussed according to various physical and chemical parameters.

Lithology

The Karoo Supergroup consists of different sedimentary rocks that are intruded by dolerites from the Jurassic Period. The intrusion of dolerite led to the formation of fractured zones in the host rock. The deep Karoo aquifers are expected to be fractured rock aquifers, occurring in the sedimentary rocks of the Beaufort, Ecca and Dwyka Groups.

Formation properties

Due to compaction the primary porosities of the sedimentary rocks forming part of the aquifer systems are probable to be very low. Although the porosities are low, the sedimentary rock matrices are expected to act as the main water storage units. The fractures, by contrast, are expected to create localised zones with very high secondary porosities.

Occurrence

The deep fractured rock aquifers could potentially occur anywhere within the Karoo Basin, but are more expected where dolerite intrusives caused secondary porosity in the form of fractures. Fault zones may similarly be associated with deep fractured aquifer systems in the Karoo rocks.

Aquifer type

The aquifer systems are likely of the double-porosity type, entailing rock matrix in which secondary porosity was developed through fracturing.

Physical dimensions

The vertical extents of the deep fracture zones are expected to be very limited (a few metres at most) Hartnady and Hay, 2002. However, the sedimentary rocks hosting the fractures are likely to act as the main storage unit for the water. These sedimentary rocks therefore form part of the aquifer system. The thickness of the saturated sedimentary rock is therefore likely to define the vertical extent of the aquifer systems, while the lateral extent of the aquifer systems is likely to be related to the lateral extent of the interconnected fracture systems.

Heterogeneity and isotropy

The aquifer systems are expected to be highly heterogeneous in the vertical direction due to the large difference in the hydraulic properties of the water-bearing fractures and rock matrix. The aquifer systems are also likely to be inhomogeneous and anisotropic in horizontal directions due to the expected irregularity of the fracture networks and the presence of impermeable dolerite intrusives.

Saturation level

The deep fractured rock aquifers are expected to be under positive pressure, and therefore likely to be fully saturated.

Hydraulic parameters

The hydraulic conductivities of the sedimentary rock matrices forming part of the aquifer systems are expected to be very low. Due to their expected low porosities, the sedimentary rocks are also likely to have low storativities. The fractures, by contrast, are likely to have very high hydraulic conductivities.

Aquifer vulnerability and susceptibility

Xu et al., (2007) defined groundwater vulnerability as the tendency or probability of contaminants to reach a specified point in the groundwater system after introduction at some location above the uppermost aquifer. The large depths of the aquifers propose that these aquifers are not very vulnerable to contaminants deriving from human activities at surface. If used as a source of water, these aquifers may, however, be vulnerable to over-exploitation since little information is available on their rates of recharge and hence the sustainable abstraction rates that can be employed.

Water quality

The Karoo Supergroup groundwater is generally brackish (saline), especially along the coastal zones, with EC values often exceeding 300 mS/m. EC values tend to decrease inland. The quality of groundwater improves in fractures or jointed zones of the Dwyka Group, where significant groundwater movement and turnovers take place, with EC values ranging between 25 and 200 mS/m (Meyer, 2001). However, groundwater quality is expected to deteriorate with depth as the salinity is likely to increase due to slow movement and longer residence times, leading to greater dissolution of constituent minerals.

Pressurisation

The aquifer systems are expected to be under positive pressure, even if the pressurisation of some of the systems is not high enough to give rise to free-flowing artesian conditions.

Yield

Due to compaction and the closure of fractures (as a result of the large depths of burial) the yield of the deep fractured aquifers is expected to be low.

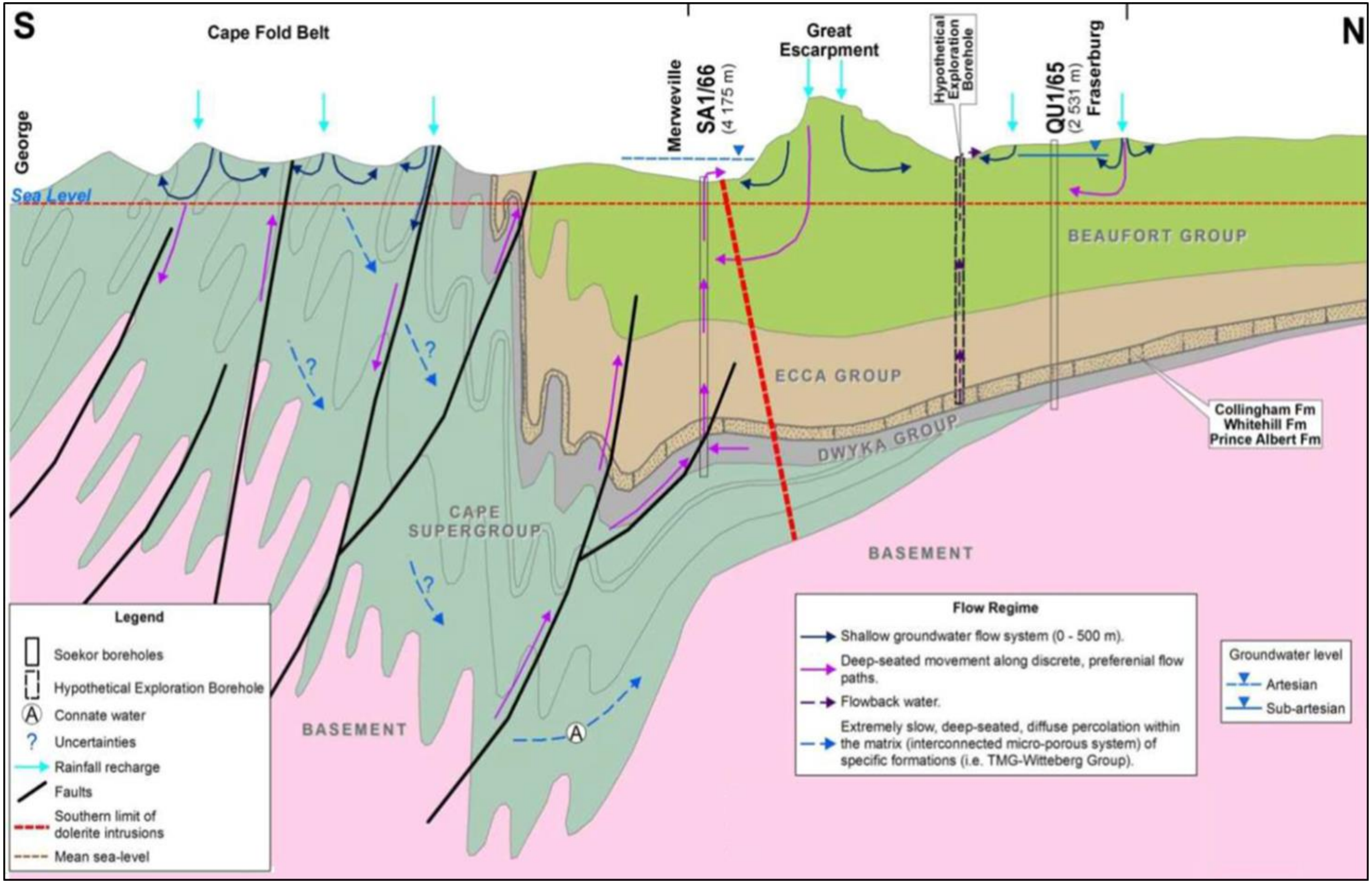

Figure 5. 2 Schematic cross-section through the Main Karoo Basin (KGEG, 2013b)

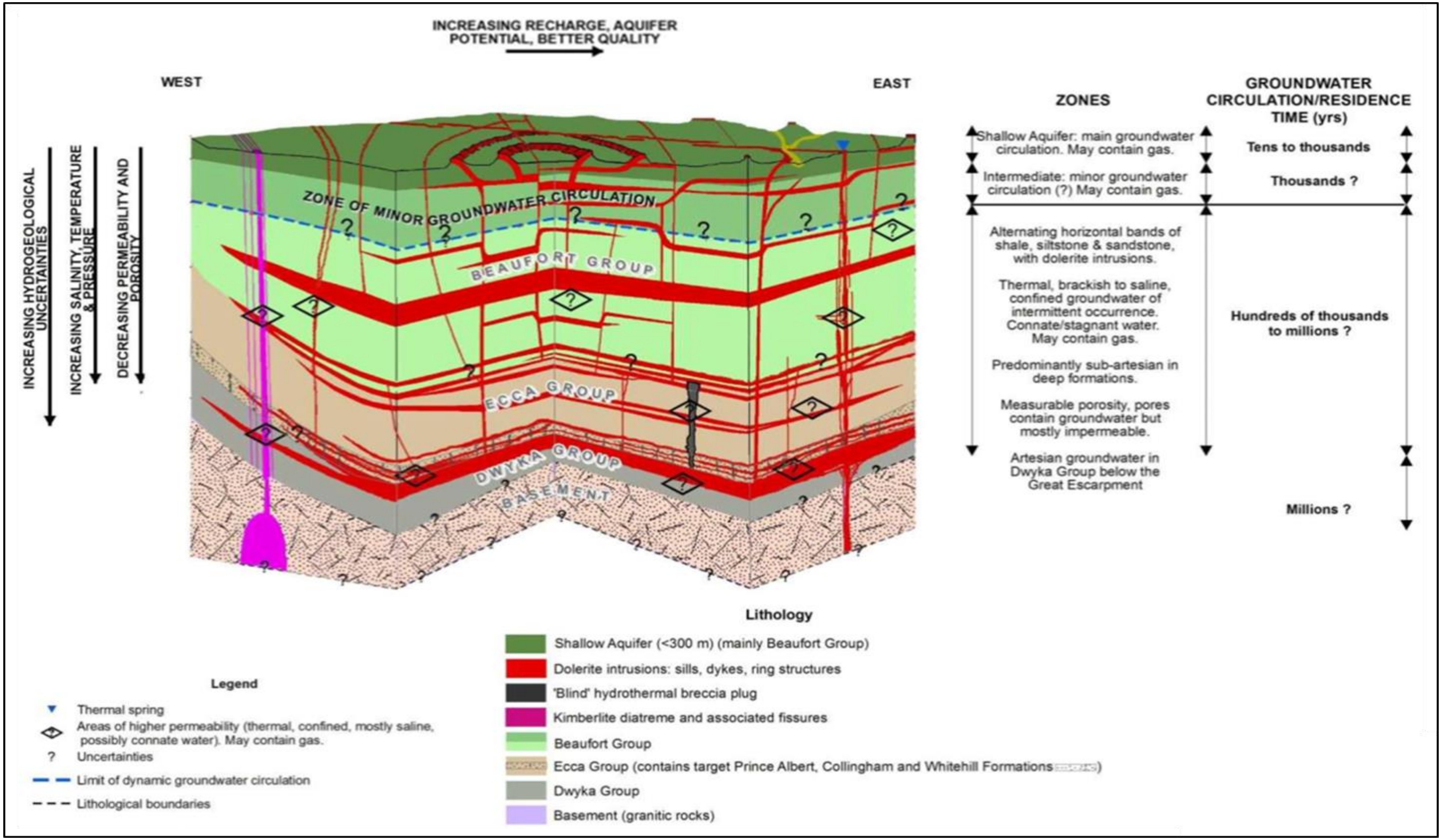

Figure 5. 3 Conceptual geohydrological model for the deep Karoo formations (adapted from KGEG, 2013b)

5.3 THE CHARACTERISATION OF DEEP AQUIFERS IN THE TABLE MOUNTAIN GROUP

5.3.1 Introduction

The TMG aquifer is a secondary aquifer with water stored within (and moving through) extensive deep fractures that have formed in the brittle, otherwise impermeable sandstone. The TMG sandstones are resistant to weathering and form the backbone of the Cape Fold Mountains. The Cape Fold Mountains form huge catchment areas, draining into major river systems. TMG fractured rocks form a regional aquifer with the potential to be a major water source in the Western and Eastern Cape Provinces of South Africa (Wu, 2005). It is estimated that the TMG has a deposit area of 248 000 km^2 and a thickness that varies from approximately 900 to 4 000 m (Lin, 2008). These rocks have an outcrop area of approximately 37 000 km^2 along the west and south coast of South Africa (Jia, 2007). The vast distribution of the TMG leads to great variability in its geohydrological properties, resulting in an uneven distribution of groundwater occurrences in the TMG area (Jia, 2007).

From a geohydrological point of view the TMG rocks represent a multi-porous medium, essentially consisting of two major components, namely (i) fractures and (ii) inter-fracture rock matrix. In general, the fractures act as the more permeable conduits for groundwater movement, while the matrix blocks form the main storage unit or reservoir (Duah, 2010). The matrix may be either permeable or impermeable. However, the rock mass probably contains many fractures of different scales and is thus expected to have its own secondary porosity. TMG rocks are therefore generally considered to form dual porosity, fractured rock aquifer systems (Duah, 2010).

The TMG aquifer is classified as a semi-confined aquifer since it is phreatic in some areas, but confined below an impermeable layer in other areas. The installation of groundwater abstraction boreholes in the TMG aquifer often requires drilling through a confining layer (Aston, 2007). Some boreholes in the TMG have free-flowing artesian conditions, confirming that the aquifer is confined and under positive pressure.

Table 5.1 illustrates the Stratigraphy of the Cape Supergroup. The formations making up the TMG differ widely in their ability to store and transmit water. The sandstones of the Nardouw and Peninsula Subgroups generally act as aquifers, while the shale layers in these subgroups act as aquitards (Aston, 2007). According to Blake et al. (2010) two main aquifer systems have been identified in the TMG, namely the Nardouw and Peninsula aquifer. The Nardouw aquifer consists of two sub-aquifers (the Rietvlei and Skurweberg sub-aquifers), separated by the Verlorenvalley mini-aquitard. The Peninsula aquifer is separated from the Nardouw aquifer by Winterhoek mega-aquitard, which consists of the Goudini, Cedarberg and Pakhuis meso-aquitards. The Peninsula aquifer itself is subdivided into two sub-aquifers, namely the Platteklip and Leeukop sub-aquifers (Blake et al., 2010).

Table 5. 1 Stratigraphy of the Cape Supergroup (Jia, 2007)

Supergroup	Group	Subgroup	Formation	Thickness (m)	Lithology
Karoo				7 000	Basin sedimentary sequence (Permian to Cretaceous)
Cape	Witteberg	Lake Mentz	Waaipoort	340	Shale, siltstone, thin sandstone
			Floriskraal	80	Sandstone, siltstone, shale and grit
			Kweekvlei	200	Shale
		Weltevrede	Witpoort	850	Quartzitic sandstone, minor siltstone
			Swartruggens	300	Siltstone, mudstone and thin-bedded sandstone
			Blinkberg	15-90	Thick-bedded quartzitic sandstone
			Wagendrift	135-165	Siltstone, sandy shale, mudstone and lithic sandstone
	Bokkeveld	Traka	Karoopoort	40	Siltstone, sandy shale and minor mudstone
			Bidohn Adolphspoort	1 000	Siltstone, shale, sandstone
			Klipbokkop/Karies	1 200	Shale
			Wuppertal	26	Sandstone, siltstone
		Bidouw	Waboomberg	200	Siltstone, shale
		Ceres	Boplaas	100	Sandstone
			Tra-Tra	350	Shale, siltstone
			Hex River	70	Sandstone, siltstone
			Voorstehoek/ Swartkrans	300	Shale, siltstone
			Gamka	200	Sandstone, siltstone
			Gydo	600	Shale, siltstone
	Table Mountain	Nardouw	Rietvlei/ Baviaanskloof	300	Feldspathic quartz arenite
			Skurweberg/Kouga	500	Quartz arenite
			Goudini/Tchando	400	Brown-weathering arenite, minor siltstone, shale
			Cedarberg	50-150	Silty shales and shaly siltstone
		Peninsula	Pakhuis	70	Fluvio-glacial tillite, folded diamicite, quartz arenite and thin-bedded quartzitic sandstone
			Peninsula	1 500	Largely thick-bedded, coarse-grained quartz arenite
			Graafwater	25-65	Thin-bedded sandstone, siltstone, shale and mudstone
			Piekenierskloof	10-150	Quartzitic sandstone with coarse-grained to gritty zones and rudites
Basement	A suite of moderately to lightly metamorphic Precambrian sedimentary rocks, and Cape Granite Suite.				

Although extensive deep groundwater reserves have been reported in the fractured rock aquifers of the TMG, many farmers extract groundwater from the Nardouw aquifer for their farm water supply. Rosewarne (1998) (cited in Smakhtin *et al.*, 2001) quoted groundwater storage estimates of approximately 50 000 mm^3 and annual recharge as high as 2 000 mm^3. However, a more detailed investigation of a section of the aquifer system suggested a much lower annual recharge volume of approximately 260 mm^3 (Smakhtin *et al.*, 2001). Weaver and Talma (2000) suggested that within a radius of 200 km from Cape Town the total volume of groundwater stored in the TMG aquifer may be as high as 66 000 mm^3 with an annual recharge of approximately 2 600 mm^3/year.

5.3.1 Characteristics of the deep TMG aquifers

The Table Mountain Group aquifer system is discussed according to various physical and chemical parameters.

Lithology

The deep TMG aquifers are found in the Nardouw and Peninsula subgroups. The rocks in which the aquifers occur are predominantly fractured sandstone and quartz arenites.

Formation properties

The primary porosities of the sedimentary rocks forming part of the aquifer systems are expected to be very low. Secondary porosity due to fracturing of the brittle sandstone is responsible for the water storage and transmission. Fractured zones are expected to be associated with very high secondary porosities.

Occurrence

The TMG aquifers occur in the coastal areas of the Western and Eastern Cape.

Aquifer type

The aquifer systems are likely of the double-porosity type, entailing rock matrix in which secondary porosity was developed through fracturing.

Physical dimensions

The TMG rocks occur in an area with a surface area of approximately 248 000 km^2. Due to the folding of the Cape Supergroup rocks the aquifers extend from surface to depths in excess of 1 000 mbgl. The total volume of the aquifer system is large and it has been estimated that up to 50 000 mm^3 of groundwater is stored in the TMG aquifers.

Heterogeneity and isotropy

The aquifer systems are expected to be highly heterogeneous due to the large difference in hydraulic properties of the water-bearing fractures and the rock matrix. The folding of the rocks of the Cape Supergroup is likely to add to the heterogeneity and anisotropy of the aquifer systems.

Saturation level

The deep fractured rock aquifers are expected to be under positive pressure, and therefore likely to be fully saturated.

Hydraulic parameters

The hydraulic conductivities of sedimentary rock matrices forming part of the aquifer systems are expected to be very low. Due to their expected low porosities the sedimentary rocks are also likely to have low storativities. By contrast the fractured zones are likely to have very high hydraulic conductivities. Groundwater storage in the fractured aquifers is likely to occur in the highly fractured zones.

Aquifer vulnerability and susceptibility

The large depths of the TMG aquifers suggest that they have low vulnerabilities to contaminants deriving from human activities at the surface. However, the folding of the rock of the Cape Supergroup means that deep aquifers may be extended to surface where such aquifers could be exposed to surface contaminants. The complex nature of the fracture networks in the TMG aquifers suggest that abstraction at a specific location could have impacts on groundwater availability at another. Many surface ecosystems depend on discharge of groundwater from the TMG aquifers.

Water quality

Groundwater from the TMG aquifers is known to be of very high quality due to the inert nature of the matrix. EC values as low as 4 mS/m have been measured for a production borehole at the base of the Skurweberg, while EC values in the pristine mountain catchments are typically below 10 mS/m (Rosewarne, 2002). TMG rock matrices are very inert and do not contribute much to the mineral content of the groundwater in the aquifers. As a result the macro-chemical character of the groundwater is determined more by the character of the precipitation than by mineralogy of the rock through which it percolates (Rosewarne, 2002). Groundwater from the TMG aquifers is generally of the Na-Cl type, reflecting the fact that precipitation generally derives from frontal systems in the Atlantic and Indian Oceans.

Elevated iron and manganese concentrations are sometimes observed in TMG groundwater. These concentrations are due to iron and manganese compounds sometimes being associated with the joints and fractures within the TMG rocks. Low pH values are also common in the TMG aquifers due to the lack of buffer minerals in the TMG rocks. The acidic conditions may cause mobilisation of the dissolved iron and manganese minerals (Rosewarne, 2002).

Yield

The yield of the deep fractured aquifers is expected to be very high, although borehole yield varies because it depends on the openings available in the rock mass. Where a particularly good fracture system exists, yields of up to 100 L/s can be obtained.

Hydraulic conductivity, transmissivity and storativity

The TMG rock matrix is expected to have a very low hydraulic conductivity due to the low primary porosity of the TMG rocks. Rosewarne (2002) suggested negligible hydraulic conductivities for unfractured TMG rocks and very high hydraulic conductivities for fractured TMG rocks. The author mentioned a number of studies in which the hydraulic conductivity of the TMG formations was found to range between 0 and 1.73 m/d. The means values of the hydraulic conductivity for the Nardouw and Peninsula aquifers were between 0.07 and 0.26 m/d.

Rosewarne (2002) also listed transmissivity values obtained by various authors for the TMG aquifers and outcrops. He concluded that transmissivities in the order of a few hundred m^2/d are associated with productive fractures zones. Various authors have suggested storativity values for TMG rocks ranging from less than 1E-04 to 1E-02. Rosewarne (2002) concluded that a storativity value of 1E-02 is a fair estimate for the bulk storativity of the Nardouw and Peninsula Formations.

5.4 CHARACTERISTICS OF DEEP AQUIFERS DERIVED FROM THERMAL SPRINGS

South Africa lacks geohydrological data from deep boreholes to directly measure and characterise deep groundwater aquifers. In light of this restriction, an alternative option is the analyses of water emanating from thermal springs. The heat required to warm the water above the ambient groundwater temperatures can only come from the geothermal gradient at greater depths than the typical regional groundwater flow system, making thermal springs the most readily available source of information to characterise deep groundwater.

5.4.1 Location and type

As previously stated, thermal springs are either from volcanic or meteoric origin (Figure 5.4). Since South Africa has not experienced any volcanic activity recently, the origin of thermal springs are linked to geological structures such as folds and faults (Kent, 1949; LaMoreaux & Tanner, 2001).

For a country with no record of recent volcanic activity, South Africa has quite a large number of thermal springs (Kent, 1949). Kent (1949) identified approximately 74 thermal springs and 9 thermal artesian wells in South Africa (Figure 5.5). Geological studies relates each individual thermal spring's origin to deep geological structures (i.e. fold, fault, dyke or fracture) that allows for the circulation of groundwater to great depths, as well as the return of the heated water to the ground surface. Most of the thermal springs in South Africa is located in valleys or low-lying areas, another indication of their meteoric nature. Sufficient rain is a requirement for the development of springs, confining South African thermal springs to areas with an annual rainfall of more than 254 mm (Kent, 1952).

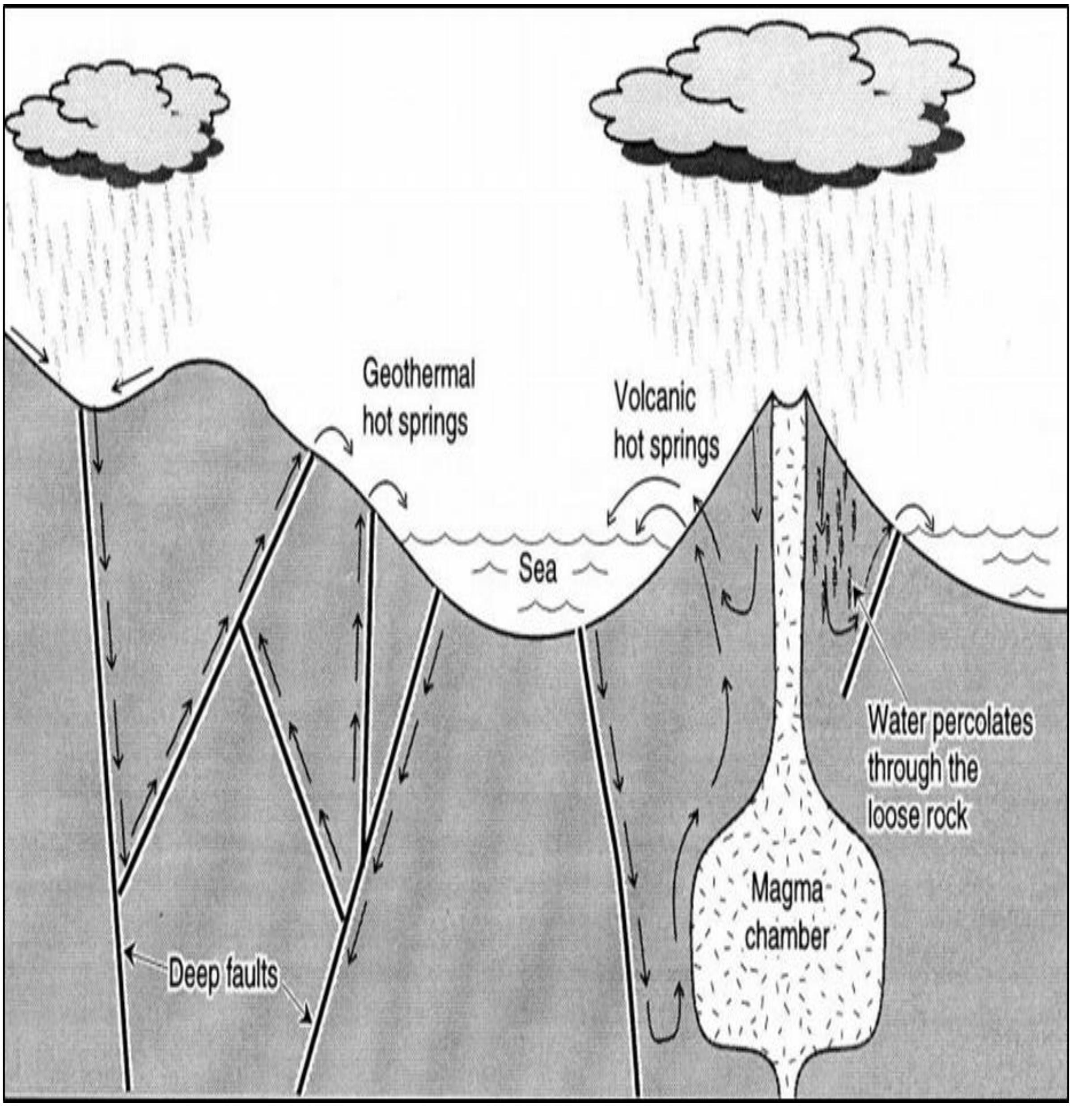

Figure 5. 4 Main types of springs: volcanic springs associated with a magma body, or geothermal (meteoric) springs associated with deep circulating groundwater in faults and fractures

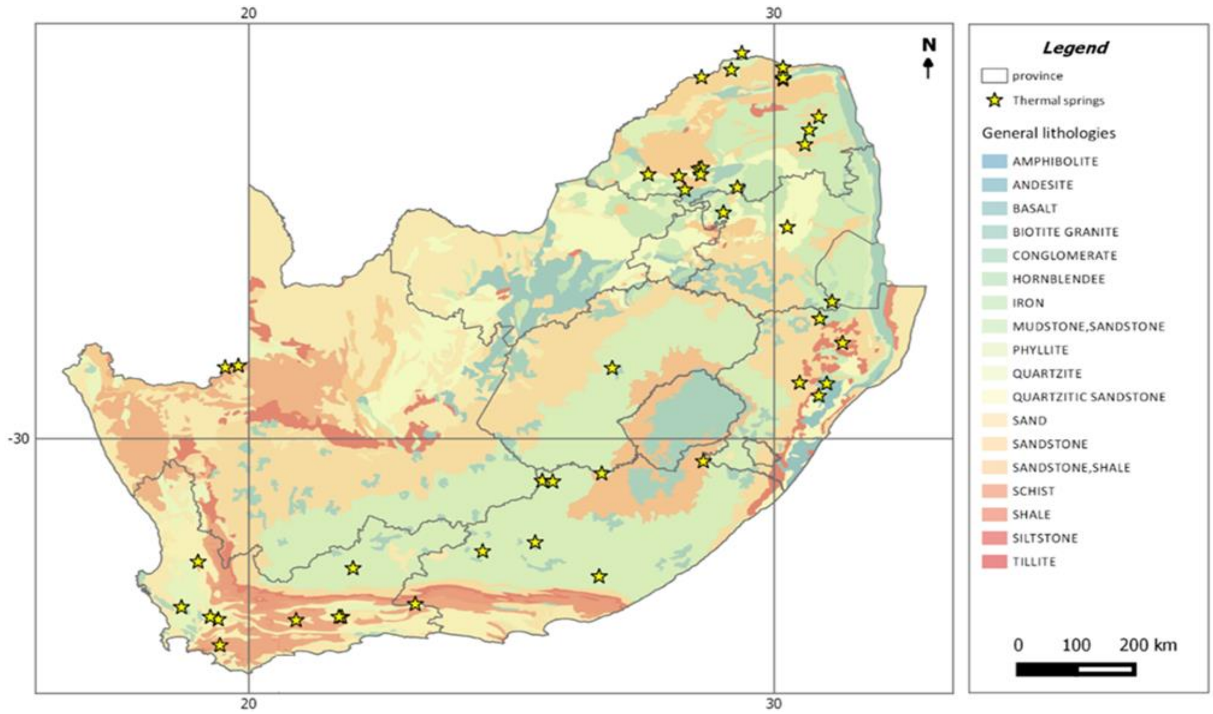

Figure 5. 5 Location of thermal springs in South Africa, as identified by Kent (1949)

5.4.2 Chemical indictors of deep groundwater

Murray *et al.* (2015) used thermal spring water samples to identify indicators of deep groundwater flow in the Main Karoo Basin. Specific determinands were identified that can be used to characterise and differentiate between shallow and deep groundwater. They provided a provisional guide on the limits for these determinands, which can be used to differentiate between deep and shallow waters in future studies. Additionally, Murray *et al.* (2015) reported what they believed to be the most reliable determinands that could be used for future monitoring programmes.

Murray *et al.*'s (2015) results could be extrapolated to other areas of South Africa. By sampling the thermal springs in other areas and using the recommended determinands the deep groundwater within these areas can be characterised. This could potentially help delineate the extent of aquifers, as springs with similar characteristics could intersect the same deep aquifer system. Figure 5.5 indicates the thermal springs in South Africa, including those identified by Kent (1949). Whilst the area investigated by Murray *et al.* (2015) is delineated in a grey circle, the red circles indicate areas where thermal springs are close in proximity (potentially intersecting the same deep aquifer) and the determinands identified by Murray *et al.* (2015) could be applied. Future studies aiming to characterise deep groundwater aquifers should apply Murray *et al.'s* (2015) approach in order to define the indictor ranges for thermal springs in South Africa and in turn use them to analyse the connections and extent of potential deep aquifers.

5.4.3 Circulation depths of deep groundwater

In a number of the identified potential deep aquifers the indication of deep groundwater flow systems is a thermal spring. Geothermometers, using data from thermal springs, have been tested by Cave and Clarke (2003) to trace deep groundwater flow. Geothermometers can be used to assess the circulation depth of thermal spring water based on the principle relationship between temperature and depth below the Earth's surface (geothermal gradient), and the relationship between the composition of a solution in contact with a mineral assemblage and the temperature of the system.

Geothermometers can be grouped into two main categories, namely silica and cation geothermometers. Silica geothermometers are based on temperature-dependent variations in the solubility of individual silica minerals such as quarts, chalcedony and amorphous silica. Cation geothermometers make use of temperature-dependent exchange reactions with hydrothermal minerals such as clays and feldspars that fix the ratios of dissolved cations according to the equilibrium temperature.

Cave and Clarke (2003) experienced challenges in applying geothermometers in South Africa due to their poor performance in lower-enthalpy geothermal environments. It was concluded that cation geothermometers are unsuitable for the South African geological environment, however, silica geothermometers were applied with moderate success in the quartzitic TMG, as well as hot springs in the Western and Eastern Cape. Geothermometers could also be used to compare samples in the same geological setting and draw conclusions about their relative depths and ages, and in this way potentially delineate deep aquifer systems.

5.4.4 Characteristics of water from thermal springs

The waters from the majority of thermal springs in South Africa do not reflect the surface geology. The chemical characteristics of thermal waters are largely determined by the rocks through which the hot water circulates. It is not always straightforward to match the composition of thermal spring waters to the geological formations known to occur in the area of the spring (Kent, 1949).

Various studies have been conducted on the hydrochemical characteristics of South African thermal springs water. Kent (1949) listed and discussed the results of chemical analyses performed on the waters from several thermal springs occurring in different geological formations across South Africa. Olivier *et al.* (2008, 2010, 2011) presented the results of chemical analyses performed on the waters from thermal springs in the Limpopo Province. Tshibalo and Olivier (2010) and Tshibalo (2011) listed and discussed the results of hydrochemical analyses performed on waters from the Sagole thermal spring in the Vhembe District of the Limpopo Province. Boekstein (2012) described the hydrochemistry of thermal springs in the Western Cape. Zonker *et al.* (2013) discussed the association between the geochemical characteristics of thermal springs in the Limpopo Province and algal diversity. Samod (2015) discussed the trace element concentrations in geothermal springs and their impact on soil and vegetation. The author focused on the Siloam and Tshipise thermal springs in the Limpopo Province.

CHAPTER 6:
ACTIVITIES THAT MAY HAVE AN IMPACT ON DEEP AQUIFERS

6.1 INTRODUCTION

In this chapter activities that may have an impact on deep aquifer systems in South Africa are identified and the potential effect of these activities on deep groundwater resources are described. The shale gas exploration rights awarded to mining corporations are shown in Figure 6.1. The following activities that could potentially have an impact on the quality and quantity of our deep groundwater resources are discussed:

- Deep mining
- Deep fossil fuel production
- Unconventional deep fossil fuel production

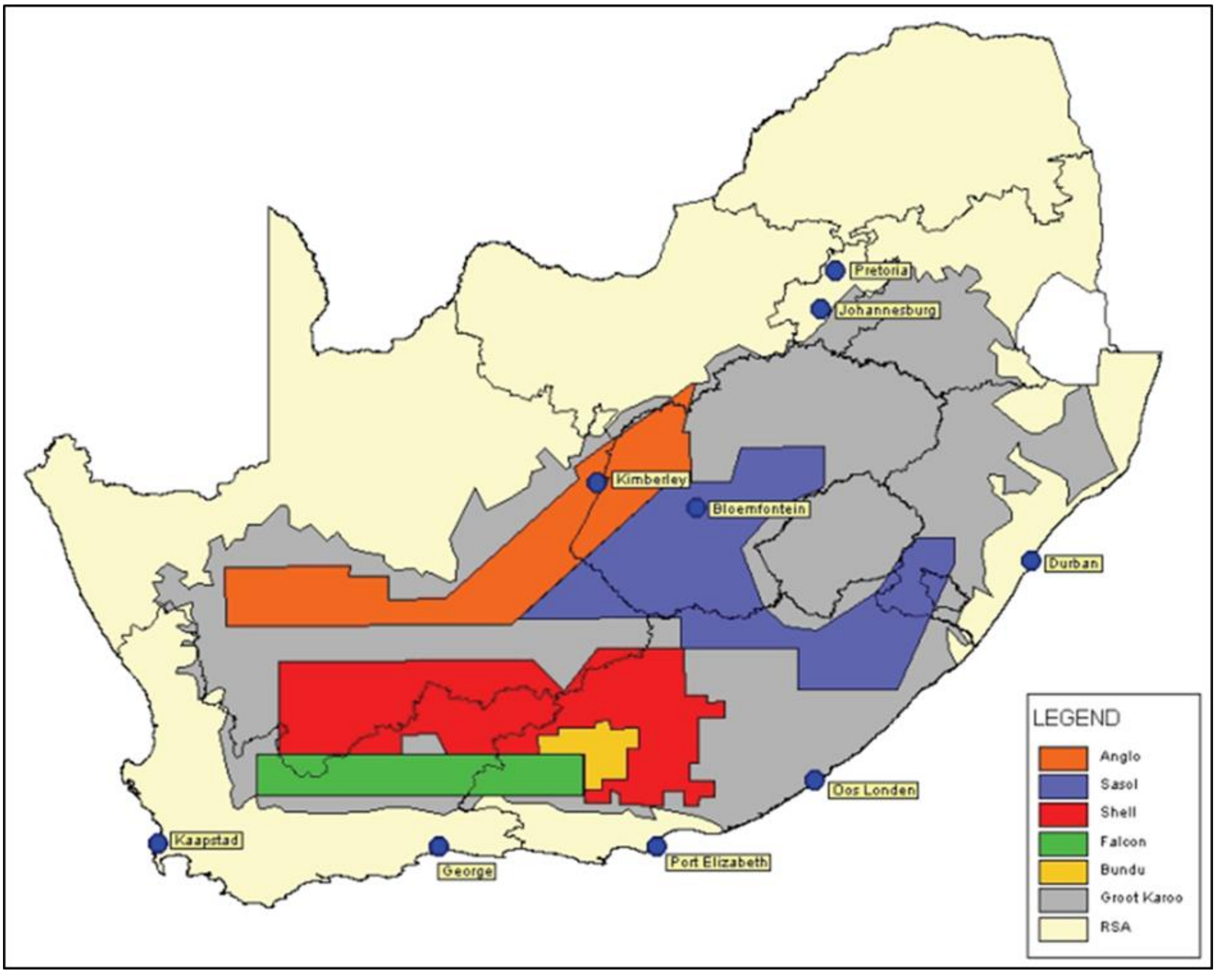

Figure 6. 1 Shale gas exploration rights in South Africa (Steyl et al., 2012)

6.2 DEEP MINING

South Africa is one of the world leaders in mining due to its wealth of mineral resources. Based on the GDP value the country is estimated to have the fifth largest mining sector. Not only does it hold the world's largest manganese and platinum group metals (PGMs) reserves and some of the largest gold, chromite, diamonds, ore and vanadium reserves, but South Africa is also a major producer of coal.

South African deep underground mining activities include:

- mines deeper than 3 900 m that extract uranium and gold from various South African goldfields,
- diamond mines at various locations in the northern and central parts of South Africa with depths up to 1 097 m,
- (potential) deep coal mining in the Springbok Flats and Waterberg Coalfields, and
- the extraction of PGMs, cobalt, gold, chrome, nickel , copper and silver from depths up to 3 585 m in the Bushveld Igneous Complex.

Even though underground mining is usually used to mine below depths of 300 m, there are a few opencast operations that extract ore from depths deeper than 300 m.

Mining removes material from the below the earth surface, which directly influences geological units in terms of permeability and void ratio. There can be distinguished between two types of mining activities: deep mines (underground) or opencast mines (surface). Deep mines, such as the Witwatersrand mines, occur at different depths beneath the surface with rock and soil overburden. Opencast mines, such as the Northern Cape Sishen mine, are open excavations left exposed at the surface.

The two common types of deep mining methods are bord-and-pillar mining (Figure 6.2) and longwall mining (Figure 6.3). Bord-and-pillar mining uses interconnected pathways (roads) and pillars (Younger, 2004) to prevent collapse. The pillars prevent collapse by supporting the weight of the mine roof. Rock blasting during mining operations destabilises the overlying rock by causing more rock fractures. The pillars thus provide additional support by stabilisation the overlying rock unit. This is the least costly deep mining method.

The longwall method is usually carried out in coal mining and involves mining along a horizontal section that is at least 250m wide and 1 000 m long. In this case hydraulic roof supports are used to hold up the roof of the mine once the material is extracted.

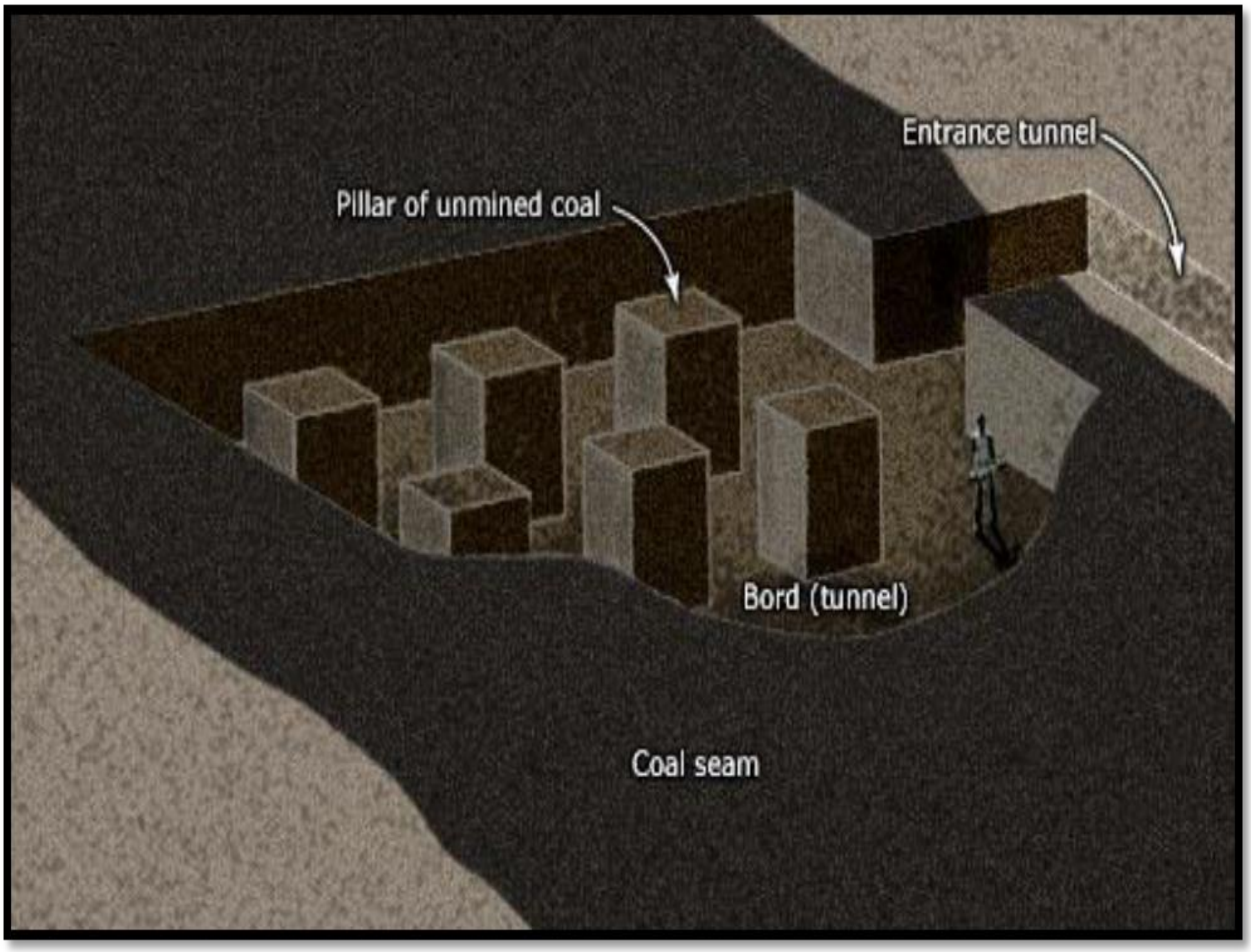

Figure 6. 2 Bord-and-pillar mining method (http://www.teara.govt.nz/en/diagram/7445/bord-and-pillar-mining)

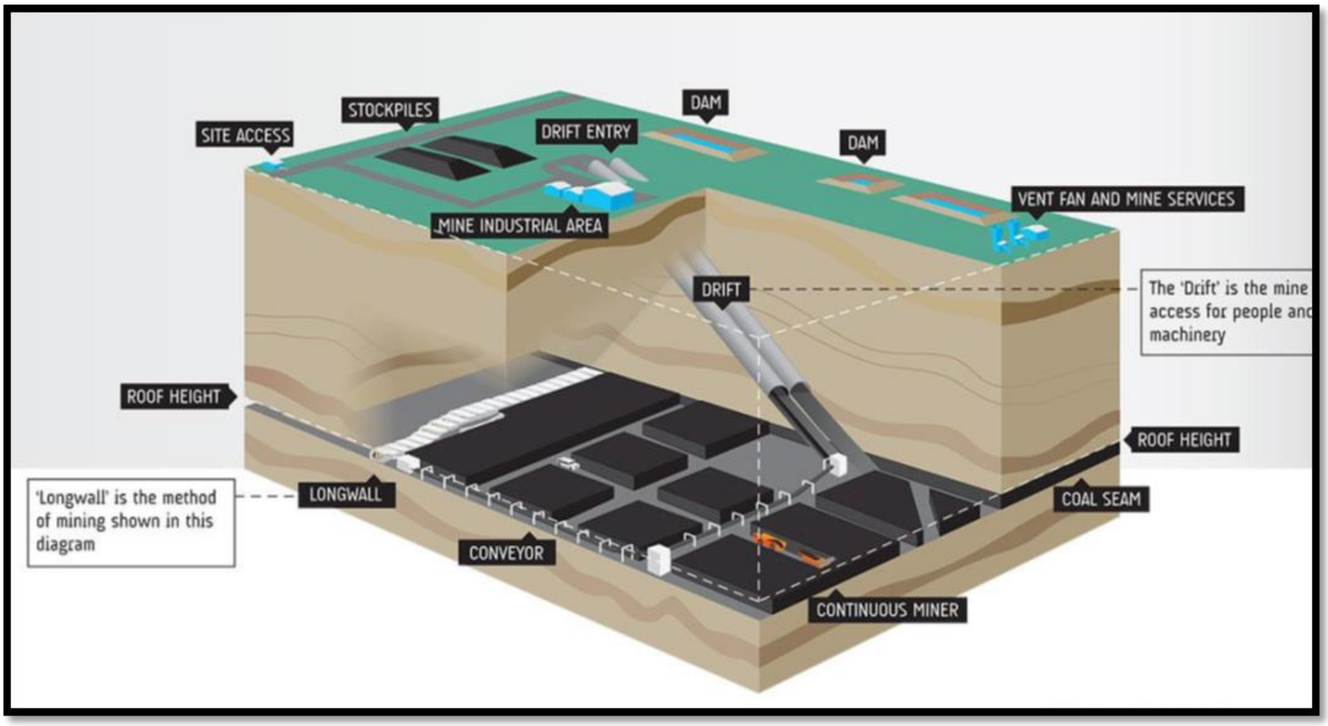

Figure 6. 3 Long wall method of mining (www.springsurecreekproject.com.au)

According to Younger (2004) surface mines comprise at least 80% of mining operations. This involves stripping away the overburden and only mining the ore body, which is then backfilled upon completion of the mining exercise. In South Africa there are commonly two types of surface mines, i.e. open pit and opencast mines. An open pit mine involves the removal of overburden and stockpiling in a disposal area. Open pit mining is typically done in stepped benches approximately 18 m to 45 m wide, and each mined bench is separated by a 9 m to 30 m high in-situ rock layer (Younger, 2004). An opencast mine is similar to an open pit mine, but the overburden material removed is directly backfilled into the adjacent mined out panels (Younger, 2004).

6.2.1 Potential impacts of mining on deep-aquifer systems

Mining activities could impact the environment negatively during not only the exploration and operational phases, but also during decommissioning and after mine closure (Bianchini, 2016). The exploration mining phase usually impacts the environment at shallow depths, while deep exploration drilling might also impact deep aquifer systems. During the typical operational mining phase large quantities of host rock and ore are removed from the subsurface. In order to extract the minerals the ore is processed and the host rock discarded as waste. Where mining activities intersect deep aquifers the quality and quantity of groundwater may be impacted. Where an aquifer is intersected by mining activities the groundwater will often seep into the underground spaces that are created when mining. To safely continue mining this water has to be removed from the mines. This process is referred to as mine dewatering.

6.2.2 Impacts on groundwater quality

As mentioned above, extracting ore and host rock from deep mines may impact the quality of intersecting aquifer groundwater. Blasting activities could potentially raise the nitrate concentrations in groundwater. In fact, groundwater with elevated nitrate concentrations are generally linked to mining activities. The specific salts that affect groundwater quality is dependent on the chemical composition of the ore and host rock, but increased calcium, sodium, magnesium, sulphate and chloride concentrations are found in most deep South African mines.

In addition, when minerals rich in sulphide (such as pyrite) mixes with oxygenated water acidic conditions may arise, which leads to acid mine drainage (AMD) (McCarthy, 2010). In most cases AMD leads to the serious degeneration of quality of groundwater. These acidic conditions caused by AMD may in turn lead to the mobilisation of trace metals in groundwater. Trace metals most often associated with AMD include barium, arsenic, cadmium, mercury, lead and selenium.

Deep aquifer groundwater quality may also be affected by contaminants resulting from mining activities. Mining machinery lubricants and fuel as well as workforce sewerage could potentially contaminate and have an impact on deep aquifer groundwater quality. The type of groundwater contamination may also result from the specific ore that is being mined in the deep mines, e.g. radioactive contamination is most often found at mines that extract gold and uranium.

6.3 DEEP OIL AND GAS PRODUCTION

Natural oil and gas originates from ancient marine organisms who died and whose bodies were buried beneath layers and layers of sediments. Millions of years' intense pressure transforms these decomposed bodies into oil and gas. Oil and gas is traditionally abstracted by drilling wells. Traditional oil and gas production can be done either onshore or offshore. Since natural gas deposits were discovered in the Southern Cape coast in 1969 more than 45 million barrels of crude oil have been extracted from these fields.

6.3.1 Potential impacts of conventional oil and gas production on deep aquifer systems

Deep aquifer groundwater may impacted during the exploration, production, decommissioning and post-closure phases of traditional oil and gas production. If deep freshwater aquifers are intersected during exploration drilling they could be contaminated by formation water from the deep petroleum deposits and deeper fossil water. Fossil water can be high in salt loads, and contain naturally occurring radioactive material (NORM) and a variety of heavy metals (USEPA, 2011; Clark & Veil, 2009). In addition, fluids and wastewater from the wellbore may enter the deep freshwater aquifer systems during exploration drilling if well integrity is not maintained.

Traditional oil and gas extraction methods are likely to contaminate deep aquifer systems with a variety of pollutants. These include petroleum hydrocarbons, organic compounds, salts and heavy metals (Allen *et al.,* 2016). Oil fields generally hold large quantities of saline water. According to Allen *et al.* (2016) water that has already been in contact with crude oil is usually contaminated with heavy metals, hydrogen sulphide, hydrocarbons and boron. Water-related impacts are dependent on multiple factors, such as the amount and type of fossil fuel, physical and geological conditions, extraction methods used, and the regulatory requirements.

Well integrity is equally as important during the production phase since similar impacts could occur during the production phase. E.g. if leakages occur during the production phase, deep aquifer systems may be impacted by the petroleum product that is being pumped to surface. Since large amounts of oil and gas will travel along the well to the surface for extended periods of time during production, failing well integrity could have severe impacts on deep aquifer systems.

If deep aquifers are contaminated by organics during the exploration and production phases they could be impossible to rehabilitate, both from an economic and physical perspective. Some long-term organic contaminants can never be removed from aquifer systems as they absorb to the soil particles. This is as a result of sorption processes being nonlinear, spatially heterogeneous, and potentially limited to the sorbent material inside soil particles by solute diffusion (GAO, 2010; NRC, 2012). Nonlinear and/or rate-limited desorption may contribute to plume persistence over time.

6.3.1.1 Approaches to Protect Deep Aquifers

Since the greatest risk of impacts on the deep aquifer system are associated with the installation and integrity of wells, technologies focussed on limiting the potential these impacts are mostly related to well integrity.

6.3.1.1.1 Technologies and actions to minimize impacts

The Mineral and Petroleum Resources Development Act 28 of 2002 prescribe standards and practices to ensure the safe exploration and production of petroleum. A well risk identification and assessment is a preliminary requirement in the Mineral and Petroleum Resources Development Act 28 of 2002. The well design should be informed by the risk assessment and constructed, equipped, commissioned, operated, modified, maintained, suspended and decommissioned in a manner which provides for the control of the well at all times. It is required to prevent:

a) the migration of petroleum and other fluids into any other formation except the targeted formation,

b) the pollution of water resources, and

c) risks to health and safety of persons from the well or anything in the well, or in strata to which the well is connected.

This International Standard provides requirements, recommendations and methods for the testing of thread compounds intended for use on threaded casing, tubing, line pipe connections, and rotary shouldered connections. The tests outlined are used to evaluate the critical performance properties and physical and chemical characteristics of thread compounds under laboratory conditions. Well construction is required to be performed according to current industry standards published by the American Petroleum Institute (API). The casing thread compound and its use must conform to the current API RP 5A3, which is as follows.

a) A casing installed must have a minimum yield pressure designed to withstand at least 1.2 times the maximum pressure to which the casing may be subjected during drilling, production or hydraulic fracturing operations.

b) The minimum yield pressure must be based upon engineering calculations as listed in the API "TR 5C -3 Technical Report on Equations and Calculations for Casings, Tubing and Line Pipe used as Casing and Tubing, and Performance Properties Tables for Casing and Tubing ".

Additionally, the Mineral and Petroleum Resources Development Act 28 of 2002 prescribe procedures for conductor, surface, intermediate, and production casing, centralisers, cement requirements and compressive tests, casing string tests, formation pressure integrity tests, blowout prevention, pressure testing of blowout prevention equipment, and well examination.

Furthermore, the environmental impact assessment, operations and management, and well suspension and decommissioning are also covered in the Mineral and Petroleum Resources Development Act 28 of 2002.

6.4 UNCONVENTIONAL OIL AND GAS PRODUCTION

Unconventional oil and gas production refers to fossil fuels extracted using techniques other than those routinely used. The distinction between conventional and unconventional oil and gas production changes over time, as technologies that were once considered unconventional find broad application and become conventional. The unconventional technologies described in this section should therefore be seen as unconventional only because they are relatively new at the present time.

In South Africa unconventional fuel is currently produced from:

- coal conversion to liquid fuel at Sasol's CTL plants,
- PetroSA's gas conversion to liquid fuel at the Mossel Bay GTL Plant,
- coalbed methane extraction, and
- underground coal gasification.

6.4.1 Coalbed methane

Coal bed methane (CBM) is a form of natural gas that is extracted from coal beds. Since coal bed methane is both generated and stored in coal beds, coal acts as the source as well as the reservoir rock. The methane is produced by microbial (biogenic) or thermal (thermogenic) processes. Coal's large surface area means that it can hold enormous volumes of methane. Coal seams have large internal surfaces, allowing them to store six to seven times more gas than a rock in a conventional sandstone gas reservoir with the same volume. CBM presents itself in three states: as a free gas, gas dissolved in the water in coal, and gas adsorbed onto the solid coal surface (Petroleum Agency SA, 2013a). The adsorption capacity of coal increases with depth, meaning that deeper coal seams contain more methane than shallow seams (Xaba & Jeffrey, 2002). For optimal CBM production coal beds should be buried at depths in excess of 200 m at least, but preferably greater than 600 m (Petroleum Agency SA, 2012a).

6.4.1.1 Potential impacts of coalbed methane extraction on deep aquifers

CBM extraction may impact both the quality and quantity of the deep aquifer groundwater. Coalbeds act as local or regional aquifers in some areas (USGS, 2000). Coalbed pressure is reduced by removing groundwater, which may result in the dewatering of the deep aquifer. Deep aquifer systems may be impacted in several ways. These include the seepage of contaminated water and gas through the fractures along the space that surrounds the well. Well integrity is therefore extremely important to prevent the contamination of deep aquifer systems. Using injection wells to dispose of produced water in the subsurface directly impacts the quality of aquifer groundwater.

Hydraulic fracturing, used to increase the degree of fracturing on coal seams, may introduce more contaminants, i.e. fracking fluid into the deep aquifer systems. Fracking fluids contain chemicals that are highly toxic, volatile, water soluble, and highly mobile (MBM, 2010).

6.4.2 Shale gas

South Africa has roughly 11 trillion cubic metres (tcm) of shale gas reserves (EIA, 2013). Even though no shale gas has been extracted in South Africa yet, there is a possibility that future energy demands may require the exploitation of this resource. Many multinational gas and oil corporations submitted their applications for shale gas exploration permits to the Petroleum Agency of South Africa (PASA) in 2009 and 2010 (Bosman, 2011). Figure 6.1 indicates the shale gas exploration rights that were awarded to these corporations. The exploration areas cover approximately 150 000 ha (almost 40%) of the South African surface area.

In South Africa the Karoo rock formations are thought to be the most suitable for shale gas extraction:

- the Whitehill Formation (Cape region), and
- the Prince Albert Formation (Cape region).

(Steyl *et al.*, 2012)

The formation of most interest for shale gas development is the Permian-age Whitehill Formation of the lower Ecca Group. It contains an organic-rich, thermally mature black shale unit (Kuskraa *et al.*, 2013). The depth of the potential shale gas horizon in the Main Karoo Basin varies between approximately 1 000 m in the west and approximately 3 450 m in the east of the basin.

6.4.2.1 Potential impacts of shale gas extraction on deep aquifer systems

Using hydraulic fracturing to develop shale gas can lead to the contamination of the deep groundwater resources through:

1) deficiencies in the well casing or cement, which can lead to the unintended movement of liquids or gases along the outside of the production well or out of the production well and into the deep aquifer systems,

2) movement of gases or liquids through geological formation from the production zone, and

3) (after production) the migration of contaminants associated with the hydraulic fracturing process along geological structures (faults, dykes) and along compromised casings due to the artesian and sub-artesian conditions in the Karoo.

(USEPA, 2006; Birol *et al.*, 2012; Krupnick *et al*., 2014; van Tonder *et al*., 2013)

Well integrity and the presence of geological structures that may act as preferential pathways for contaminant migration are therefore the main concerns when considering the potential impacts of hydraulic fracturing on deep aquifer systems. It should, however, be taken into account that the deep aquifer systems in the Karoo Basin are expected to contain highly saline water. This water would likely require treatment prior to use. The impact of contaminants on the water quality may therefore be a lesser concern.

Apart from the impact of contaminants on the quality of deep groundwater resources, the quantity of water may also potentially be impacted. Deep aquifer systems are known to be pressurised, with artesian or sub-artesian conditions reported at all deep boreholes intersecting these aquifer systems. Where artesian conditions occur, problems with well integrity may cause water from deep aquifers to flow into the well or annulus and be released at surface, thereby dewatering the aquifers.

CHAPTER 7:
CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

As formerly revealed in the Literature review, the definition of deep groundwater is subjective and ambiguous, with the dividing depth between shallow and deep being an inconsistent mark. There is no commonly agreed upon or standardised depth distinction between shallow and deep groundwater. The recommend definition of “deep” that can be implemented in South Africa is from 300m deep.

The results of the research project shows that only limited information on the deep aquifer systems of South Africa is available. Our understanding of the deep aquifer systems is therefore limited at present. There are, however, clear indications that the deep groundwater systems could in future form part of South Africa’s water supply, particularly during periods of water stress.

The occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding- plane fractures. Groundwater was struck at a depth of 3 700 mbgl in a borehole near East London. Weathered and fractured zones, associated with faulting and folding, occur in the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines formed due to folding have characteristic open joints and fractures, and these structures are seldom dry when drilled. The presence of a hot water spring in Aliwal North (Molteno Formation), indicates the presence of deep circulating groundwater systems.

The main groundwater intersections within the Table Mountain Group (TMG) occur at depths of greater than 100 mbgl, and borehole yields have been found to increase with depth. Deep groundwater circulation has furthermore been confirmed within the TMG. For these reasons, the Table Mountain Group is identified as having a high potential for deep aquifer systems.

According to the KGEG (2013b) conceptual model of the deep Karoo formations, based on published geological maps and cross-sections, as well as a review of the available literature. The following generalisations best describe the deeper Karoo formations:

- The thickness of the Karoo sedimentary rocks increases from north to south across the Main Karoo Basin,
- Thermal springs in the Karoo Basin (e.g. at Aliwal North) suggest groundwater circulation to depths of approximately 1 000 m and possibly deeper as the groundwater is likely to cool somewhat during its upward flow,

- Groundwater salinity and age increase with depth due to slow movement and longer residence times, leading to greater dissolution of constituent minerals, and,
- The sedimentary rocks are intruded by dolerite sills and dykes leading to compartmentalisation of the subsurface.

Based on the available information, the expected characteristics of the deep TMG aquifers are classified as a semi-confined aquifer since it is phreatic in some areas, but confined below an impermeable layer in other areas. The installation of groundwater abstraction boreholes in the TMG aquifer often requires drilling through a confining layer (Aston, 2007). Some boreholes in the TMG have free-flowing artesian conditions, confirming that the aquifer is confined and under positive pressure.

The formations making up the TMG differ widely in their ability to store and transmit water. The sandstones of the Nardouw and Peninsula Subgroups generally act as aquifers, while the shale layers in these subgroups act as aquitards (Aston, 2007). Lin et al. (2007) analysed an 800 m deep borehole and characterised the fractures into four zones based on the degree to which fractures are hydraulically active. The zones are (1) high (0-150 mbgl); (2) medium (150-400 mbgl); (3) low (400-570 mbgl); and (4) hydraulically inactive (570-800 mbgl or deeper). This is an important conclusion that should be used further in your final argument.

Groundwater associated from the TMG aquifers is known to be of very high quality. EC values as low as 4 mS/m have been measured for a production borehole at the base of the Skurweberg, while EC values in the pristine mountain catchments are typically below 10 mS/m (Rosewarne, 2002a). The rock matrices of the TMG are very inert and do not contribute much to the mineral content of the groundwater in the aquifers.

South African geology was sub-divided into pre-Karoo, Karoo, and post-Karoo geologies, and the geological groups under each geological period were analysed for deep groundwater based on the currently available information. The interpretation of thermal springs and the general depth of fracturing is considered and combined in a summary of the identified potential deep groundwater aquifers based on the geological groups.

To assess the potential for deep exploitable aquifer systems within the different geological formations of South Africa, a ranking system was used in which the formations were rated according to their likelihood of hosting, or being associated with deep aquifers. Formations with Rank 1 were considered to show positive indications for the presence of deep aquifer systems, while formations with Rank 2 were considered to show some indications of deep groundwater. Ranks 3 and 4 were assigned to those formations that show neutral or negative indications for deep aquifers.

Considering that deep groundwater generally occurs below the traditionally exploited weathered zone (shallow aquifer), the study of deep fractured zones becomes paramount in the investigation of potential deep aquifers.

The results of the study imply that majority of deep aquifer systems of South Africa are generally fractured hard rock aquifers in which secondary porosity was developed through processes such as fracturing and dissolution. The primary porosity of most of the rocks forming the aquifers is very low. Groundwater flow predominantly takes place along the fractures and dissolution cavities that act as preferential pathways for groundwater migration. The aquifers are generally highly heterogeneous and anisotropic, confined and associated with positive hydraulic pressures. The groundwater quality also usually decreases with depth as the salinity increases.

The TMG is well known for the occurrence of hot springs. These geothermal occurrences provide direct evidence for the deep circulation of groundwater. Since South Africa lacks geohydrological data from deep boreholes to directly measure and characterise the deep groundwater aquifers, an alternative option is the analyses of water emanating from thermal springs. Thermal springs thus form the most readily available source of information to characterise deep groundwater because the heat required to warm the water above the ambient groundwater temperatures can only come from the geothermal gradient at greater depths than the typical regional groundwater flow system.

The occurrence of groundwater in the Karoo rocks is mainly associated with horizontal bedding planes and bedding-plane fractures as sited by Viljoen *et al*. (2010). The porosity thus occurs along the bedding planes and not in the rock itself (Woodford & Chevallier, 2002). Viljoen *et al*. (2010) stated that it is not certain if these bedding-plane porosities are also present at depth because groundwater is mostly prospected in the upper few hundred metres from the ground surface. The Karoo rocks were fractured along bedding planes during episodes of isostatic rebound and erosional unloading due to the difference in elasticity between the various rock units (Botha & Cloot, 2004; as cited by Viljoen *et al*., 2010). The accepted hypothesis is that since there is an increase in overburden pressures with depth, most deep-seated bedding-parallel fractures are closed. However, groundwater was struck at a depth of 3 700 mbgl in Dwyka diamictite in borehole SP 1/69 near East London.

A database containing data relevant to the deep aquifer systems in South Africa was developed during the investigation. The purpose of the database is to collate all the available information on deep aquifers in South Africa into a user-friendly format.

The data captured in the database include all the data on the deep aquifer systems gathered during the current research project. Unfortunately, the data are generally sparse and incomplete at most sites. There are also inconsistencies and contradictions in the data.

At present the database contains data on:

- 5 221 borehole sites from the database of the CGS,
- 1 116 borehole sites from the NGA,
- 123 boreholes ites from the Pangaea database,
- 71 thermal springs,
- 49 borehole sites from the database of the IHFC,
- 38 SOEKOR boreholes,
- 13 borehole sites from the database of the Petroleum Agency SA, and,
- (2) KARIN boreholes.

Activities that could potentially impact on the deep aquifers in South Africa were identified. These are:

- Conventional deep mining,
- Conventional deep oil and gas production,
- Unconventional oil and gas production,
- Carbon capture and storage,
- Groundwater abstraction from deep aquifers for water provision, and,
- Artificial recharge of deep aquifers.

For each of the identified activities, different approaches for the protection of the deep aquifers were considered, including the establishing of baseline conditions prior to the commencement of the activities. The launch of new technologies that could prevent or minimise the potential impacts on the aquifers. As well as the application of regulatory tools, to manage the activities and the development of monitoring programmes and adaptive management strategies.

South African deep underground mining activities include:

- mines deeper than 3 900 m that extract uranium and gold from various South African goldfields,
- diamond mines at various locations in the northern and central parts of South Africa with depths up to 1 097 m,
- (potential) deep coal mining in the Springbok Flats and Waterberg Coalfields, and

Even though underground mining is usually used to mine below depths of 300 m, there are a few opencast operations that extract ore from depths deeper than 300 m.

Mining removes material from the below the earth surface, which directly influences geological units in terms of permeability and void ratio. There can be distinguished between two types of mining activities: deep mines (underground) or opencast mines (surface). Deep mines, such as the Witwatersrand mines, occur at different depths beneath the surface with rock and soil overburden. Opencast mines, such as the Northern Cape Sishen mine, are open excavations left exposed at the surface.

Deep mining activities (e.g. installing shafts and drilling exploration boreholes) provide direct insight into the deep geohydrological conditions. However, since mining companies are more interested in the presence of ore than deep groundwater conditions, geohydrological information has not been collected at the mines. Furthermore, the information gathered by the mines are often treated as confidential or proprietary. A paradigm shift is needed to bridge the perceived divide between the mining and groundwater industry. Collecting information on the deep aquifer systems at mines will not only improve the current state of knowledge on deep groundwater systems, but also generate new knowledge. This will benefit both parties. The groundwater community gets access to the information they need and mining communities gain a better understanding of the deep aquifers, which will allow for the more efficient management of groundwater influx into mines.

The South African legislature relevant to the protection of the deep groundwater resources include: the Constitution, the National Water Act (NWA), the National Environmental Management Act (NEMA) and the Mineral and Petroleum Resources Development Act (MPRDA).

The Constitution of the Republic of South Africa (Act 108 of 1996) (the Constitution) is the supreme law of South Africa and the Bill of Rights. The Constitution with its environmental right is a crucial enactment, as are a number of other acts (discussed below), which regulate the inter-related areas of environmental concern.

The Water Act of 1956 was replaced by the National Water Act (NWA) of 1998 which is considered worldwide to be the best water legislation as it was acknowledged with an international prize. The NWA is the principle legal instrument governing all water resources in South Africa and is based on the principles of equity, efficiency and sustainability. This act is the best legal instrument to insure good governance of groundwater resources.

Groundwater became public water with the promulgation of the National Water Act in 1998.

The National Water Act is the logical legislation with DWS as the leading agent to regulate deep aquifers. The National Water Act 36 of 1998 (NWA) ensures that the nation’s water resources are protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner, for the benefit of all persons and in accordance with its constitutional mandate.

More specifically, Chapter 14 of the NWA (Sections 137 to 145) titled 'Monitoring, Assessment and Information' is particularly relevant to all activities that impact on deep aquifers (conventional deep mining, unconventional oil and gas production production, carbon capture and storage, water abstraction from deep aquifers as well as aritifical recharge). Monitoring, recording, assessing and disseminating information on water resources are critically important for achieving the objectives of the Act. The Minister of Water and Sanitation must establish national monitoring systems and national information systems, each covering a different aspect of water resources, such as a national register of water use authorizations, or an information system on the quantity and quality of all water resources. The Minister must also establish mechanisms and procedures to coordinate the monitoring of water resources after consultation with the relevant organs of state including water management institutions and existing and potential users of water.

Considering that deep groundwater generally occurs below the traditionally exploited weathered zone (shallow aquifers), the occurrence and distribution of fracturing in the deeper formations is paramount in the investigation of potential deep aquifers.

The key to delineating future deep groundwater resources will be determining:

- The depth to the fractured aquifer (i.e. below the extent of weathering),
- The depth to which fractures remain open (in different geological mediums), and,
- The methods to accurately locate such fractured aquifers.

7.2 RECOMMENDATIONS

It is recommended that the general framework proposed in this report be used to protect deep aquifer systems from impacts from various activities. The framework includes actions such as:

- characterising the affected area's geohydrology,
- baseline investigations,
- developing a conceptual geohydrological aquifer systems model,
- identifying all possible impacts of any particular activity on the deep groundwater resources,
- simulating the potential impacts that the activity may have on the deep groundwater system through numerical modelling,
- considering technologies available to avoid or reduce these impacts,

- considering and implementing the best national and international practice guidelines,
- applying existing laws and regulations to protect deep groundwater resources,
- developing new laws and regulations where existing laws and regulations are inappropriate or inadequate,
- implementing a monitoring programme specifically designed to monitor the potential impacts of a particular activity on the deep groundwater system, and
- applying adaptive management strategies to deal with unforeseen impacts that arise from performing a specific activity.

To authorise and promote the geohydrological characterisation of South African deep aquifer systems it is recommended that deep boreholes (designed by geohydrologists specifically for geohydrological investigations) be installed at selected locations. The boreholes should be constructed in such a way that geohydrologists are able to collect comprehensive datasets on groundwater conditions and aquifer parameters. These boreholes could potentially lead to the development of new technologies that can be used to characterise deep aquifer systems.

It is recommended that an organisation be appointed to manage the database to keep it updated as new data become available. This will avoid the creation of several dissimilar versions of the database

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ABSTRACT

This dissertation describes the characteristics of the deep aquifer systems in South Africa as derived from the available data. The study formed part of the larger WRC Project K5/2434 (Characterisation and Protection of Potential Deep Aquifers in South Africa). Literature review of publications relevant to potential deep aquifers in South Africa was done to allow further characterisation of these aquifer systems. This paper focuses on deep aquifers in 1) the Karoo Supergroup and 2) the Table Mountain Group

From the available data the deep aquifer systems were described in terms of the following characteristics: lithology, occurrence, physical dimensions, aquifer type, saturation level, heterogeneity and degree of isotropy, formation properties, hydraulic parameters, pressurisation, yield, groundwater quality, and aquifer vulnerability.

The study's results indicate that the deep aquifer systems of South Africa are generally fractured hard rock aquifers in which secondary porosity was developed through processes such as dissolution and fracturing. Most of the aquifer rocks' primary porosity is very low. Groundwater predominantly flows along dissolution cavities and fractures that act as pathways for groundwater migration. The aquifers are usually anisotropic and highly heterogeneous. The deep aquifers are typically confined and linked to positive hydraulic pressures. As the salinity increases with depth, the groundwater quality decreases. Due to the fact that deep aquifer systems usually occur at large depths, they are typically not vulnerable to contamination from activities at surface or shallow subsurface. They are, however, extremely vulnerable to over-exploitation since low recharge rates are expected.