CHARACTERISATION OF THE DEEP AQUIFERS OF SOUTH AFRICA – THE BUSHVELD IGNEOUS COMPLEX, CRYSTALLINE BASEMENT ROCKS AND DOLOMITE FORMATIONS

NISHEN GOVENDER

Submitted in fulfilment of the requirements for the degree

Magister Scientiae in Geohydrology

in the
Faculty of Natural and Agricultural Sciences
(Institute for Groundwater Studies)
at the
University of the Free State

Supervisor: Dr. Francois Fourie
Co-supervisor: Mrs. A. Matthews

January 2019

DECLARATION

I, Nishen Govender, hereby declare that the dissertation hereby 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.

Nishen Govender

31 January 2019

ACKNOWLEDGEMENTS

I would hereby like to express my sincere gratitude to all who have motivated and helped me in the completion of this dissertation:

- Dr Francois Fourie, for his guidance and support during this period.
- My wife Marianna for motivating me to finalise this dissertation.
- The Water Research Commission for funding this project.

TABLE OF CONTENTS

CHAPTER 3 GEOLOGY AND HYDROGEOLOGY OF SOUTH AFRICA 28

CHAPTER 4 : COMPARISON OF SHALLOW AQUIFER SYSTEMS AND IDENTIFICATION OF POTENTIAL DEEP AQUIFER SYSTEMS 50

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
BCA	Basement Crystalline Aquifers
BIC	Bushveld Igneous Complex
BICDP	Bushveld Igneous Complex Drilling Project
CGS	Council for Geoscience
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DEP	Department of Environmental Protection
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
GA	General Authorisation
IGS	Institute for Groundwater Studies
IWRM	Integrated Water Resource Management
KZN	KwaZulu-Natal
L/min	litres per minute
L/s	litres per second
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
NWA	National Water Act
PASA	Petroleum Agency of South Africa
PGE	Platinum Group Elements
RGS	Rashoop Granophyre Suite
RLS	Rustenburg Layered Suite
RSA	Republic of South Africa
SABS	South African Bureau for Standards
SANS	South African National Standards
TDS	Total Dissolved Solids
TMG	Table Mountain Group
USGS	United States Geological Survey
WRC	Water Research Commission
WRI	World Resources Institute

CHAPTER 1:
INTRODUCTION

1.1 GENERAL INTRODUCTION

Water is considered to be a basic human right and each individual has a right to a potable water source. However, South Africa is considered to be a developing country and water infrastructure, particularly in rural areas, is unfairly distributed. A possible solution to this issue is the development of groundwater abstraction boreholes. In rural communities, isolated from the city centres, a borehole may be an important potable water source. Other water sources in the area could include dams and rivers, should these be located within close proximity to a rural village. However, in recent times, South Africa has experienced a major drought which resulted in a decrease of surface water levels and severe water restrictions were imposed. In some areas, where there were boreholes feeding into the local municipal system, these were found to be highly effective in combating the effects of the drought.

Groundwater has become the focal point in recent times; however, much emphasis is placed on the shallow aquifer system. The increase in the population and water demand has lead town planners to identify alternative sources of water. In this regard, the focus has been placed on groundwater sources to ease the demand pressure. However, the reliability of shallow aquifers may not be sufficient. In this regard, the deeper aquifer systems may have the potential to meet the water demands.

Limited information is available for deeper aquifer systems; this is attributed to the escalated costs and challenges associated with installing deep production boreholes.

If groundwater aquifers are the future solution to major supply-demand, then identification of protection measures should be in place to ensure the survival of these important water sources. In terms of deep borehole drilling, this has been done on a large scale particularly by the mining companies; however, the emphasis of such drilling operations was aimed at identifying geological formations and not collecting important hydrogeological data.

This research project entails the identification and characterisation of potential deep aquifers in South Africa, focussing on important geological units found in the eastern parts of the country, namely: the Bushveld Igneous Complex, crystalline basement rocks, and dolomitic formations. In addition, the activities that could potentially impact on these aquifers are identified and measures to protect the deep groundwater resource are discussed. A basic classification system for deep aquifers is also developed.

1.2 AIMS AND OBJECTIVES

The aim of this investigation is to characterise the potential deep aquifer systems of South Africa in terms of their geohydrological properties. The study focuses on deep aquifer systems that occur in the eastern parts of the country, specifically a) the Bushveld Igneous Complex, b) crystalline basement rocks and c) the dolomite formations of South Africa. To achieve the aim of the investigation, the following objectives were identified:

- To review the available literature relevant to the potential deep aquifer systems,
- To identify potential deep aquifer systems in South Africa,
- To characterise the potential deep aquifer systems based on the available geohydrological information,
- To identify activities that could potentially have detrimental impacts of the deep aquifer systems and to propose measures to prevent or limit such impacts, and,
- To develop a classification system for the deep aquifer systems.

1.3 RESEARCH METHODOLOGY

Deep aquifer systems discussed in this dissertation will focus on basement crystalline aquifers (BCA), the Bushveld Igneous Complex (BIC), and dolomite formations. To understand the deep aquifers, at a minimum, the following will need to be carried out:

i. **Identify possible deep aquifers in South Africa** - Any available information on this topic would need to be reviewed and areas, where there are potential aquifers, will need to be identified. This will be discussed in the literature review section as Chapter 2;

ii. **Define the depth at which an aquifer can be considered as “deep” from an international and local context** - Any available information that relates to potentially deep groundwater aquifers will need to be considered and a defining depth for local South African context will need to be established. This will be discussed in Chapter 2;

iii. **Identify existing aquifer systems and determine the groundwater quality** - A thorough literature review of existing aquifer systems would need to be carried out and information identified in Chapter 2 will be utilised to further understand aquifer systems. Understand the geology and hydrogeology of these aquifer systems. Use existing laboratory information to confirm water quality results of different aquifer systems. This will involve a thorough investigation into the water quality of mines, rivers, dams, boreholes and wells. These will be discussed in Chapter 3 and 4;

iv. **Identify structures that contribute to the groundwater flow** - Review all existing information and identify geological structures that assist with the increase in groundwater flow potential. How the structures originate and where they are most likely found and the associated rock types. This is discussed in Chapter 3;

v. **Identify the origin/source of these groundwater aquifers** - Review existing information and identify the likely source of the deep groundwater aquifers which will be discussed in Chapter 4;

vi. **Do thermal springs provide an insight into the water quality of deep groundwater aquifers** – Review existing information on thermal springs and correlate their importance to the deep aquifer flow regimes. Identify if these thermal springs can provide details on the inferred water quality and specific origin depths which is discussed in Chapter 5;

vii. **Characterisation of deep aquifer systems** - Analyse all available data on the shallow aquifer system and identify potential characteristics that may be suitable for deep aquifer systems. Identification of basic characteristics of the deep aquifer systems. This will be discussed in Chapter 6.

viii. **Mining activities** - Can the deep underground mines provide adequate information for understanding deep groundwater aquifers - How does the water quality of mines assist with the water quality information for deep aquifers.

ix. **What are the potential threats to these deep groundwater aquifers** – How do human activities such as mining negatively affect the groundwater quality of deep aquifers and their flow regimes. Provide possible solutions to mitigate these impacts, which is discussed in Chapter 7.

1.4 DISSERTATION STRUCTURE

This dissertation discusses various aspects of the shallow and deep aquifer systems; the structure is as follows:

- Chapter 1 provides a general introduction to groundwater systems and geohydrological terminology.
- Chapter 2 comprises a review of existing deep groundwater information within South Africa with particular emphasis on crystalline basement aquifers, Bushveld Igneous Complex aquifers and dolomite aquifers.
- Chapter 3 focuses on detailed descriptions in terms of geology and hydrogeology of the crystalline basement, Bushveld Igneous Complex and dolomite aquifer systems.

- Chapter 4 provides a basic comparison of the above shallow aquifer systems and provide an identification of areas in which deep aquifer systems may occur.
- Chapter 5 focuses on the available information on deep aquifer systems.
- Chapter 6 focuses on the characterisation of deep aquifer systems and inferring hydrogeological characteristics based on the shallow aquifers.
- Chapter 7 provides solutions for protecting the deep aquifer systems.
- Chapter 8 utilises all information to establish a classification system for the development of deep groundwater aquifers.

CHAPTER 2:
LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will provide a brief introduction to groundwater aquifers and the fundamentals of groundwater. Emphasis will be placed on the differentiating depths between shallow and deep aquifer systems at both local and international levels. In order to evaluate the potential characteristics of the deep aquifer system, we need to first understand the mechanisms of the shallow aquifer system.

2.1.1 General Definition of Aquifers

Our basic understanding of an aquifer is a geological formation that is porous and permeable enough to allow adequate water to flow through and/or be stored for sufficient water supply. Aquifers are classified into four subcategories, as follows:

- Confined aquifers,
- Semi-confined aquifers, and
- Aquitards.

A confined aquifer is a permeable geological formation that is constrained at the top and bottom by impervious layers (aquitards). The hydrostatic pressure within the aquifer is generally greater than the atmospheric pressure.

A semi-confined aquifer is a permeable geological formation that is either constrained at the top or bottom by an impervious layer.

An aquitard is a low permeable geological formation that allows fluids to move through at slow rates.

An aquiclude is an impervious geological formation that does not allow fluids to pass through.

2.1.2 Deep Groundwater Fundamentals

Deep groundwater aquifers will have similar characteristics to that mentioned in Section 2.1.1. Considering that limited information is available on the deep aquifer system, all available information will be discussed in the following subsections: groundwater flow patterns, inferred regional groundwater quality, inferred groundwater depths and porosity and permeability of deep aquifers.

2.1.2.1 Groundwater Flow Patterns

Groundwater flow patterns vary between the different aquifers, a confined aquifer system will have a different flow to an unconfined aquifer system. In terms of a confined aquifer, our understanding is that the hydraulic conductivity of the aquifer will be higher than the confining layers.

According to Davis (1969) and Freeze and Cherry (1979) in Fitts (2002), the hydraulic conductivity values of common geological material varies significantly. The difference in variations of hydraulic conductivity with aquifers is a result of the difference in fracture width and frequency. Table 2-1 is a summary extracted from Fitts (2002) showing the different hydraulic conductivities within common geological materials.

Table 2-1: Hydraulic conductivities of common geological materials (from Fitts, 2002)

Material	**Hydraulic conductivity (K, cm/s)**
Gravel	10^{-1} to 100
Clean Sand	10^{-4} to 1
Silty Sand	10^{-5} to 10^{-1}
Silt	10^{-7} to 10^{-3}
Glacial till	10^{-10} to 10^{-4}
Clay	10^{-10} to 10^{-6}
Limestone and Dolomite	10^{-7} to 1
Fractured Basalt	10^{-5} to 1
Sandstone	10^{-8} to 10^{-3}
Igneous and Metamorphic Rocks	10^{-11} to 10^{-2}
Shale	10^{-14} to 10^{-8}

According to Fitts (2002), groundwater flow velocities in basalts and carbonate rocks can be particularly high if there is a high degree of fracturing (basalts) and dissolution cavities (dolomites). Typically groundwater is recharged from high lying areas and enters the aquifer system and discharge at the surface again in low lying areas.

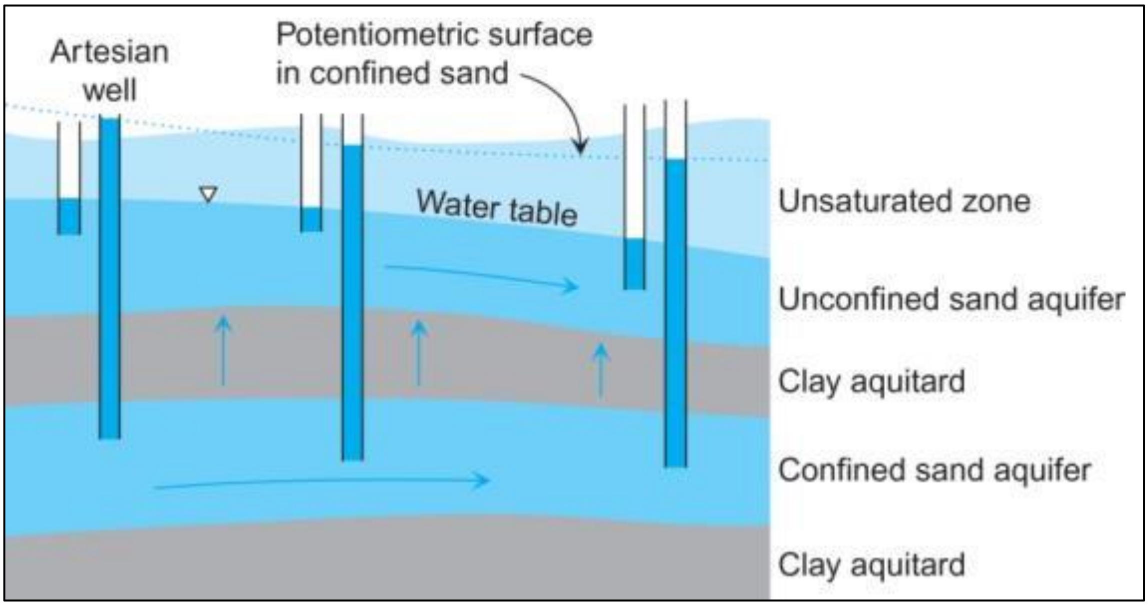

Figure 2-1: Vertical cross-section through an unconfined aquifer and a confined aquifer, with a confining layer separating the two (Fitts, 2002)

Groundwater within the aquifer will have two types of flow either laminar or turbulent flow. Laminar flow has high viscous forces and low velocities and momentum, whilst turbulent flow has chaotic eddies which can be illustrated in Figure 2-2.

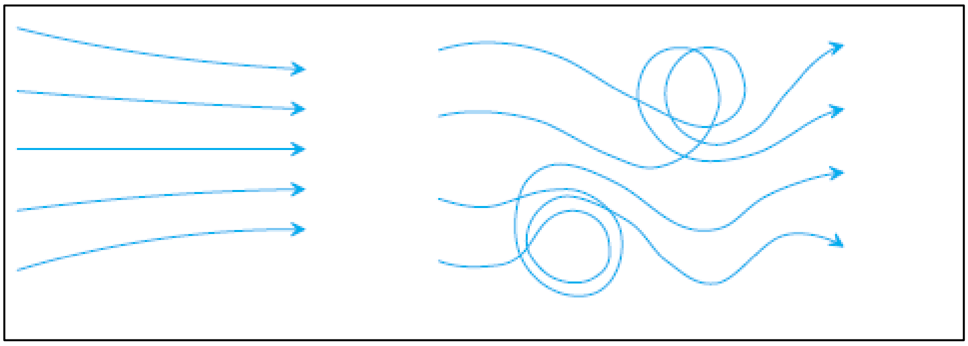

Figure 2-2: Illustration of laminar flow (left) and turbulent flow (right) (Fitts, 2002)

Analysing flow in fractured bedrock is typically problematic due to the following reasons: Flow occurs along fractures, distribution and properties of bedrock differ throughout, impossible to determine width and roughness of fractures.

2.1.2.2 Recharge and Discharge

Groundwater is constantly flowing, and recharge areas are typically associated with highlands or inland areas. Groundwater is typically recharged by seepage activity into the aquifer after a rainfall event or discharge from a surface water source. According to Fitts (2002), groundwater flow within the subsurface is dependent on the hydraulic conductivity of the aquifer. In areas in which hydraulic conductivity is high, groundwater will flow parallel to layer boundaries as opposed to low conductive areas in which groundwater will flow perpendicular to the layer boundaries and move through the shortest route. Figure 2-3 is a conceptual visualisation of groundwater flow patterns within the subsurface.

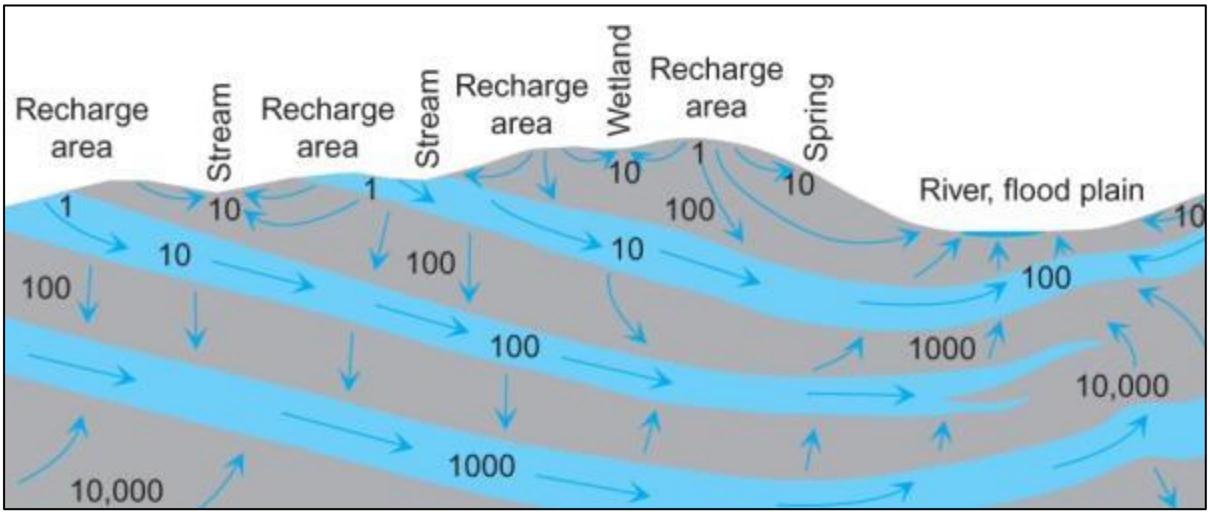

Figure 2-3: Vertical cross-section showing groundwater recharge and discharge areas in a hypothetical setting. Arrows show the direction of flow, and numbers indicate the residence time of groundwater in years. Lighter shading indicates aquifers and darker shading indicates aquitards (Fitts, 2002)

In Figure 2-3 it can be observed that the shallow groundwater flow patterns are variable, however, with an increase in depth the flow patterns appear to be uniform. In Figure 2-3 the deeper groundwater flow patterns or regional groundwater flow is towards the river/floodplain. The groundwater flow is also dependent on the hydraulic properties of the aquifer.

Freeze and Witherspoon (1967) in Fitts (2002) carried out various numerical simulations to outline the effects that heterogeneity has on groundwater flow patterns.

2.1.2.3 Water Table and Potentiometric Level

In layman's terms, water table and/or potentiometric level are basically the water level within the aquifer. Theoretically, a water table is associated with an unconfined aquifer and potentiometric level is associated with a confined aquifer. Our basic understanding of groundwater flow is that water will always move from a higher hydraulic head to lower hydraulic head. By determining the hydraulic heads in an area, we can easily determine the inferred groundwater flow pattern.

2.1.2.4 Surface and Groundwater Interaction

Water can be discharged either from the aquifer to a surface water body or vice versa. An aquifer that discharges into a surface water body would be regarded as a gaining stream and a surface water body that discharges into an aquifer would be regarded as losing stream. Surface and groundwater interaction will also depend on the hydraulic head of the area, if the hydraulic head of the aquifer is higher than the surface water body, water will move towards the surface water body and vice versa.

2.1.2.5 Regional Groundwater Flow

Current investigations comprise the assessment of the shallow groundwater condition, therefore, the shallow groundwater flow. However, as we understand, groundwater can occur at great depths and over lengthy periods. Person and Baumgartner (1995) identified that down to depths of approximately 6 km, the rock permeability is higher at depths greater than 6 km. Figure 2-4 provides a visualisation of the movement of groundwater through the subsurface. When the groundwater flow correlates to the local topography, we refer to this phenomenon as "*Topography Driven Flow*".

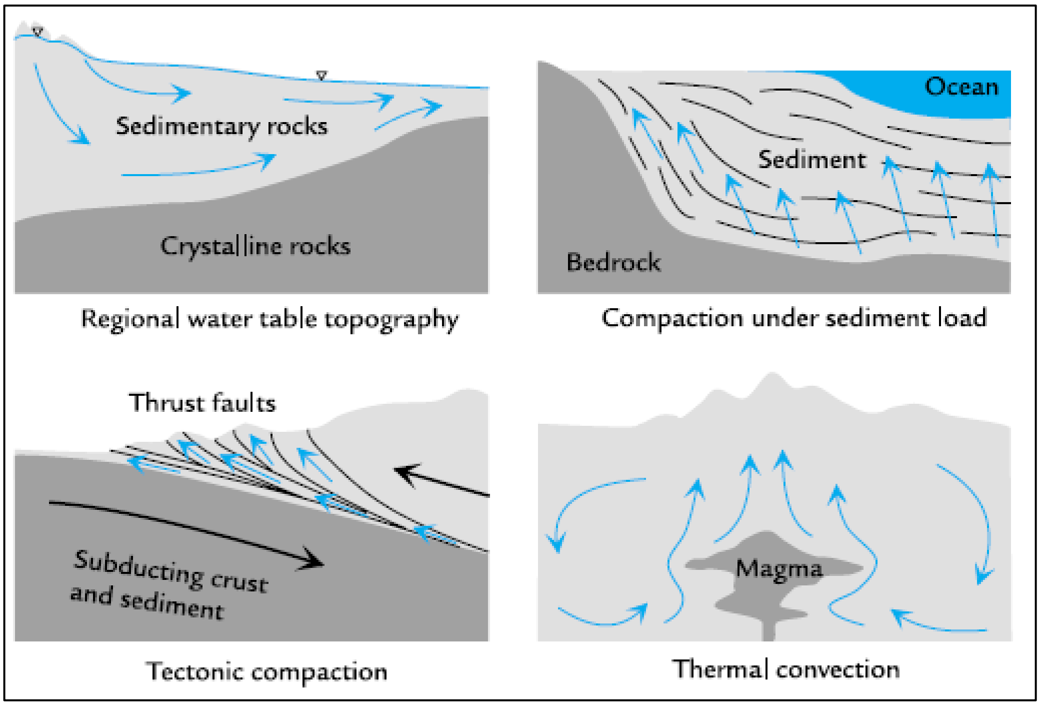

Figure 2-4: Typical illustration of the groundwater flow in different geological environments

2.1.2.6 Compaction of Sediments

The groundwater flow rates in these areas are dependent on the overburden pressures and fast sedimentation rates (Fitts, 2002). In areas, typically oceanic environments, the continuous deposition of sediments increases the pressure at the base, which forces the groundwater out of the deeper layers into the less pressurised layers (refer to Figure 2-4).

2.1.2.7 Tectonic Compaction

Compaction can also be caused by tectonic plate boundaries (Fitts, 2002). Consider a sedimentary basin along a plate boundary, the sedimentary basin will be subjected to extension geological forces which will result in tectonic deformation. The fluids within the basin will be forced out of the highly pressured areas and move along fractures, similarly to that of sedimentation compaction (refer to Figure 2-4).

2.1.2.8 Thermal Convention

Fluids are also circulated within the crust by magma flows from deep beneath the earth's surface. Convection flow is one cause of fluids migrating to the surface, this is when the heated less dense magma rises. It should also be noted that the magma contains fluids and chemical reactions near the magma chamber create these fluids and change the surrounding pressures (Fitts, 2002).

2.1.3 Deep Groundwater Quality and Circulation Depths

The groundwater quality at great depths is typically associated with an increase in dissolved solids as identified by Fitts (2002). There are several reasons for the increase in dissolved solids as outlined by Fitts (2002). Groundwater within the deep aquifers resides for millions of years which allows adequate time for complete dissolution reactions, typically of which are not found in shallow groundwater systems. Seawater is usually trapped within the marine sediments that are exposed to sedimentation loads. There is also an increase in pressure and temperature with depths and these type of environments allow for complete dissolution of mineral. Due to the large scale flow paths within the deep aquifers, the water will at some point interact with highly soluble minerals with high salt content.

Crustal flow mechanisms are responsible for migrating the fluids to areas of lower pressure and temperatures, where these fluids are allowed to precipitate and form secondary structures such as veins within the host rock.

Research conducted by Laaksoharju *et al.* (1995) on a deep borehole in Sweden. Based on the laboratory test results, they concluded that the upper 800 m of the aquifer comprise a groundwater recharge region as the saline content of the water was low and at depths greater than 1 000 m the saline content increased. Based on these findings, there was an indication of potentially potable water sources down to a depth of at least 1000m.

2.1.4 Secondary Porosity, Permeability and Circulation Depths

According to Viljoen et al (2010), the sedimentary rocks within the sedimentary basins in South Africa have been subjected to metamorphism and have low primary porosity. However, in areas where there are structural defects such as faults and fractures, these basins will have an increase in secondary porosity (Viljoen *et al.,* 2010). It is understood that permeability and porosity decrease with an increase in depths below the surface. Rosewarne (2002) provides a theory that due to an increase in overburden pressures, the fractures at depth close.

The above theory may not always be applicable, there are certain areas within the Table Mountain Group (TMG) in which circulation depths are at approximately 2 000 m. Rosewarne (2002), provides a simple explanation for this, the quartzite sandstone bedrock of the TMG fractured easily under the pressures provided by the development of the Cape Fold Belt. The groundwater quality is also low in dissolved solids which do not allow for the development of secondary mineral depositions within the fractures. Not all areas of the TMG contained groundwater at deep circulation depths, Lin *et al.,* (2007) carried out an interpretive investigation on an 800 m borehole drilled into the TMG. Lin *et al.,* (2007) identified four significant fracture zones. These zones comprise highly hydraulically active fractures to low/no hydraulic activity. It was observed that down to depths of 150 m below ground level (mbgl) the fractures were hydraulically active (highly), between 150 and 400 mbgl, the fractures were of medium hydraulic activity. At depths greater than 400 mbgl the fractures had the least hydraulic activity and greater than 570 mbgl, there was no hydraulic activity. These provide an indication that not all the TMG lithologies have hydraulic activity at depth.

2.1.5 Deep Groundwater Data

Deep groundwater has been described in terms of deep sedimentary basins and where aquifers can occur at depths up to 3000 mbgl (Alley *et al.,* 2013). In order to obtain information on deep groundwater aquifers, typical field methodologies for shallow aquifer systems cannot be solely used. Alley *et al.* (2013) indicate that the typical water level data, hydraulic conductivity and multiple borehole aquifer tests that are carried out on the shallow aquifer cannot provide insight into the deep aquifers. Instead, information of deep aquifer systems would require pressure data, intrinsic permeability and single well drill stem tests. Thus, the terms and methods used by petroleum geologists will now have to be used by hydrogeologists to characterise deep aquifer systems. A list of data to be collected during the assessment of deep aquifer systems proposed by Tsang and Niemi (2013) are core samples, geophysical logs, pore pressures, temperatures, chemistry, rock mechanical stress, permeability, storativity, thermal conductivity and porosity.

2.1.6 What is Considered to be Deep Groundwater?

Based on research carried out by various authors, the division between shallow and deep groundwater aquifers can vary from 100 m to 1000 m, depending on which part of the globe you are situated.

Tsang and Niemi (2013) and Pimentel and Hamza (2014) considered deep groundwater to be at depths greater than 1000 mbgl. The consideration is based on a principle that as overburden stresses increase the residual porosity become lower. In local geological settings, Van Wyk (2013) considered a depth of 300 m to be a sufficient divide between shallow and deep aquifer systems.

An alternative depth of 100 m was considered as a divide between deep and shallow aquifers by Pieterson and Parsons (2002). Based on an analysis of groundwater chemistry from various boreholes ranging between 100 m to 250 m, Reddy and Nagabhushanam (2012) considered a depth of 100 m as a boundary. Castany (1981) identified that there are three possible vertical zones when dealing with aquifer systems. The first zones are considered to be local flow system and are restricted to a depth of 100 m, the second zone is the regional flow system and extends to depths of 300 m and the deep aquifer system flow zones are considered to be at depths greater than 300 m.

Drake *et al.* (2015) considered a depth of 500 m to a suitable divided between shallow and deep groundwater. Boreholes that were drilled to depths in excess of 400 m were used in Drake *et al.* (2015) analyses and based on sulphur isotope fractionation, an interim depth of 400 m to 500 m was considered to be suitable. In local content, research done by Murry *et al.* (2015) identified that shallow groundwater can occur down to a depth of 500 m within the Karoo Supergroup groundwater flow systems. Table 2-2 provides a summary of the groundwater divide depths.

Table 2-2: Summary of depths proposed to define “deep” aquifers

Author(s)	Depth (m)
Tsang and Niemi (2013)	1 000
Pimentel and Hamza (2014)	1 000
Van Wyk (2013)	300
Pieterson and Parsons (2002)	300
Reddy and Nagabhushanam (2012)	100
Castany (1981)	300

2.1.7 Definition of Groundwater for South Africa

As discussed in previous sections, the definitive depth for deep and shallow groundwater various significantly with no distinctive depth, Table 2-2 provides a summary of this. The distinction between shallow and deep groundwater from a local context should consider the environments and conditions of the country. Examples of these criteria would be, exploitation depths of groundwater, groundwater quality, aquifer type and depth to groundwater.

2.1.7.1 Groundwater Exploitation Depths

Groundwater investigations for the Karoo aquifers were typically confined to the upper 100 m to 150 m below surface, with rare boreholes being drilled to 300 m (Vermeulen, 2012). Vermeulen (2012), sourced information from approximately 2 323 boreholes from the National Groundwater Archive (NGA) and identified that only 93 boreholes (4%) were drilled deeper than 100 m. Woodford and Chevallier (2002), analysed 67 boreholes within the Victoria West area and identified that approximately 73% of water strikes were encountered within the first 100 m, however, the average borehole depths were 200 m. At the time of their investigation, a depth of 200 m would be considered a deep aquifer, however, in order to define the appropriate depth for deep aquifer systems in South Africa, a thorough analyses of the existing boreholes would need to be compiled.

Based on experience with drilling groundwater boreholes, usually water strikes were encountered within the top 120 m, Table 2-3 provides a summary of a few boreholes drilled around South Africa based on investigations carried out by Geosure (Pty) Ltd.

Table 2-3: Location of boreholes and general groundwater strike depths

Location	Water Strike Depth mbgl (Aquifer Yield L/s)	Geology
Umzimkhulu - KwaZulu-Natal	62 (2)	Sandstone
Melmoth - KwaZulu-Natal	97 (3)	Sandstone
Mtubatuba - KwaZulu-Natal	86 (4)	Shale
Taung - North West	85 (0.8)	Quartz Porphyry
Umzimkhulu - KwaZulu-Natal	92 (2.5)	Shale
Skeerpoort - Northwest	30 (3.5)	Aeolian sediments
Kranskop - KwaZulu-Natal	88 (0.7)	Granite

2.1.7.2 Groundwater Quality

Due to the insufficient information on deep aquifer systems, Murray *et al.* (2015) proposed the use of isotopes and gases to identify deep groundwater circulations within the Karoo basin. There are more than 87 thermal springs in South Africa with temperatures ranging from 25°C to 64°C (Diamond and Harris, 2000) and the groundwater from these springs may provide an insight into the chemical components of the groundwater at depth. Considering the insufficient depths of current Karoo boreholes, these springs may be a source for further chemical investigations as the groundwater is inferred to be sourced from greater depths due to their temperature.

2.1.7.3 Aquifer Types

Deep groundwater flow regimes were identified by Van Wyk (2013) based on deep borehole drilling. Van Wyk (2013) identified potentially deep artesian aquifer systems and their characteristics. A list of the potential deep aquifer flow systems is the TMG, Karoo Supergroup and hot springs within the Karoo Supergroup. Many authors in the past have indicated the importance of understanding the geology for the identification of deep groundwater systems. For such reason, an understanding of deep basin geology is a requirement to understand the deeper aquifer systems in South Africa. Scheiber-Enslin *et al.* (2015) developed a new geological map of the Karoo Basin utilising geophysical methods. Research by Viljoen *et al.* (2010) identified that various sedimentary basins that have from the Archaean Eon cover a vast landscape of South Africa and these basins will be helpful in assisting with the identification of potential deep groundwater aquifer systems.

2.1.8 Deep Groundwater in South Africa

2.1.8.1 Introduction to Underlying Geology and Hydrogeology

The geological map of the Republic of South Africa developed by the Council for Geoscience to a scale of 1:1000 000, provides an indication that majority of the surface is covered by sedimentary rock units which have been intruded and extruded by igneous rocks and altered to form metamorphic rocks. According to McCarthy and Rubidge (2005), there are two main sedimentary basins in South Africa, namely, the Karoo and Cape basins which are estimated to form around Cambrian to Jurassic time (510 to 160 million years ago).

The groundwater in South Africa is stored within these two sedimentary basins and depth to exploitable groundwater varies across the country. Referring to Figure 2-5, the depth of groundwater across the country varies between 17 mbgl to 35 mbgl in the east and southeast, to greater than 35 mbgl in the west to northwest.

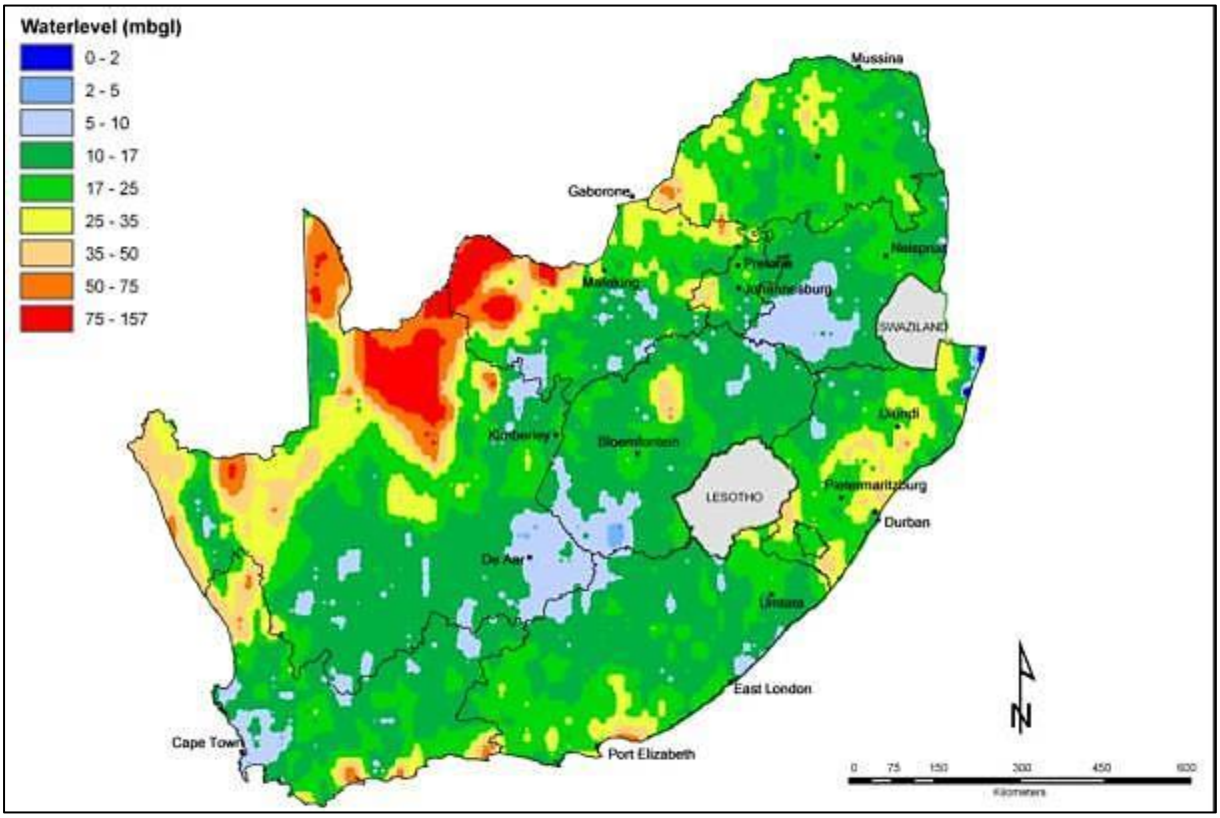

Figure 2-5: Groundwater level map of South Africa, prepared by the Department of Water Affairs (2010)

Considering the depths to exploitable groundwater in Figure 2-5, and the depth identified for potential deep groundwater aquifer, this would indicate that the map only provides an indication of the shallow groundwater system. Aquifer classification map series was developed by the Department of Water and Forestry (DWAF) in the early 1990s to a scale of 1:500 000. These hydrogeological maps depicted the underlying hydrogeology of the area and the anticipated yields which have been designated into for groups from a to d (Table 2-4 refers). Assuming that the shallow aquifers have similar properties to the deeper aquifers, consideration could be given to using the DWAF classification system to infer hydrogeological characteristics of the deeper aquifer system.

The classification of aquifers systems as depicted in Table 2-4, comprise the following:

- Intergranular,
- Fractured,
- Karst, and,
- Intergranular and fractured.

Intergranular aquifer (designation a) comprise unconsolidated sedimentary deposits such as that along the coastal areas. These aquifers generally have yields in the range 0.5

litres/second (L/s) to 2.0 L/s. According to Nel *et al.* (2014), these aquifers have transmissivity values in the range 4 m^2/day to 70 m^2/day and storage coefficients in the range 7% to 25%.

Fractured aquifers (designation b) form as a result of discontinuities, such as faults, fractures and joints, in hard bedrock. These form the primary porosity in which groundwater moves through. According to Nel *et al.* (2014), these aquifers have transmissivity values in the range 7 m^2/day to 1 320 m^2/day and storage coefficients in the range 0.0002% to 2%.

Karst aquifers (designation c) form as cavities, occur in dolomite areas and are considered to be high yielding aquifers. According to Nel *et al.* (2014), intrusive dykes form impermeable or low permeable barriers that restrict the flow of groundwater and as such create different compartments within these cavities. In addition, these aquifers have transmissivity values in the range 800 m^2/day to 8 000 m^2/day and storage coefficients in the range 1% to 25%.

Intergranular and fractured aquifers (designation d) display properties of a multi-porous aquifer system. According to Nel *et al.* (2014), these are commonly found in granite, dolerite and sandstone areas. Hydrogeologists target areas that are known to have a high degree of fracturing to establish a good groundwater supply. According to Nel *et al.* (2014), these aquifers have transmissivity values in the range 0.5 m^2/day to 150 m^2/day and storage coefficients in the range 0.003% to 7%.

The aquifer group is differentiated further based on their approximate yields, i.e. b1 to b4, as depicted in Table 2-4.

Table 2-4: Aquifer classification based on groundwater yields (DWA, 2010)

Description of Aquifer	**Estimated Groundwater Yield (L/s)**				
	0-0.1	**0.1-0.5**	**0.5-2.0**	**2.0-5.0**	**>5.0**
Intergranular			a3		
Fractured	b1	b2	b3	b4	
Karst			c3		
Intergranular and Fractured	d1	d2	d3	d4	

A potential source of deep groundwater in South Africa may be identified within the hot springs (thermal). According to Van Wyk (2013), hot springs usually occur along faults and/or dykes and the groundwater brought to the surface is heated by geothermal forces. This may potentially indicate deep groundwater circulation. Kent (1949) suggests that the thermal water in the Karoo is derived at great depths below the surface and this may be confirmed based on the temperature of the water. Kent (1949), identified that the average temperatures of the thermal springs range from 26°C to 57.2°C and considering a hydrothermal gradient of 3°C for every 100 m increase in depth below surface (Demlie and Watkeys, 2011), this would suggest that the circulation depths of the thermal spring water is in the range 860 m (26°C) to 1 906 m (57.2°C).

According to Smith (1964), various groundwater exploration projects were carried out within the Kalahari basin to identify potential groundwater sources at depths greater than 300 mbgl. The boreholes were subsequently drilled to approximate depth in the range 441 mbgl to 652 mbgl, with saline water being encountered between depths of 137 mbgl and 426 mbgl. The lithologies of the Dwyka Group and Nama Group, including basement granites, were encountered in these boreholes.

2.1.9 Case Studies from South Africa

Three case studies from South Africa will be discussed in this section, namely Johannesburg, West Rand and Rustenburg. However, concentration will be given to the Witwatersrand area, as this is where the deepest gold mines are situated and have the potential to provide adequate information on potential deep underground aquifers.

2.1.9.1 Surface and Groundwater Interaction in Johannesburg

Johannesburg, "*The city of gold*" has some of the countries deepest gold mines with depths reach as far as 3 200 mbgl. Johannesburg has approximately 650 mm of rainfall a year and has a semi-arid climate. Due to the increase in mining activities in the area, the groundwater quality has deteriorated to acid mine drainage. According to McCarthy (2010), the broader geology of the Witwatersrand area comprises shale, quartzite, conglomerate, dolomite and various igneous intrusions and extrusions. The general dip of the strata in the area is between 20° to 80°. Figure 2-6 provides an illustration of the general geological setting of Johannesburg.

There have been three types of groundwater occurrences identified by Abiye *et al.* (2011) in the Johannesburg area, namely:

- Near-surface within the weathered geological profile,
- Fractures, dykes and shear zones, and,
- Dolomite cavities.

A conceptual geological cross-section of the Johannesburg area, prior to mining activities, was created by McCarthy (2010) to indicate the type of fractured aquifer system (Figure 2-7 refers). McCarthy identified that these fractures have formed due to various geological processes and are the potential pathways in which groundwater may be transported through the subsurface. According to McCarthy (2010), these fractures can occur for hundreds of metres and any pollution sources at the surface may seep into the subsurface and cause deterioration of the subsurface.

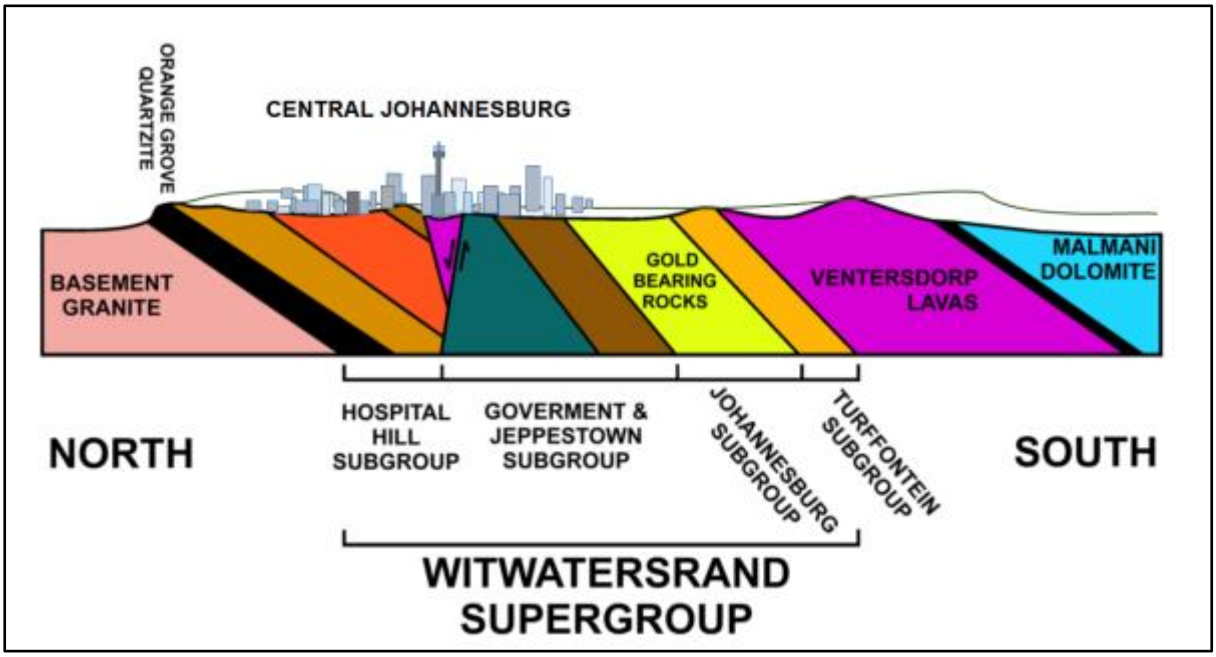

Figure 2-6: Simplified geological cross-section of Johannesburg from north to south (Wikipedia, 2016)

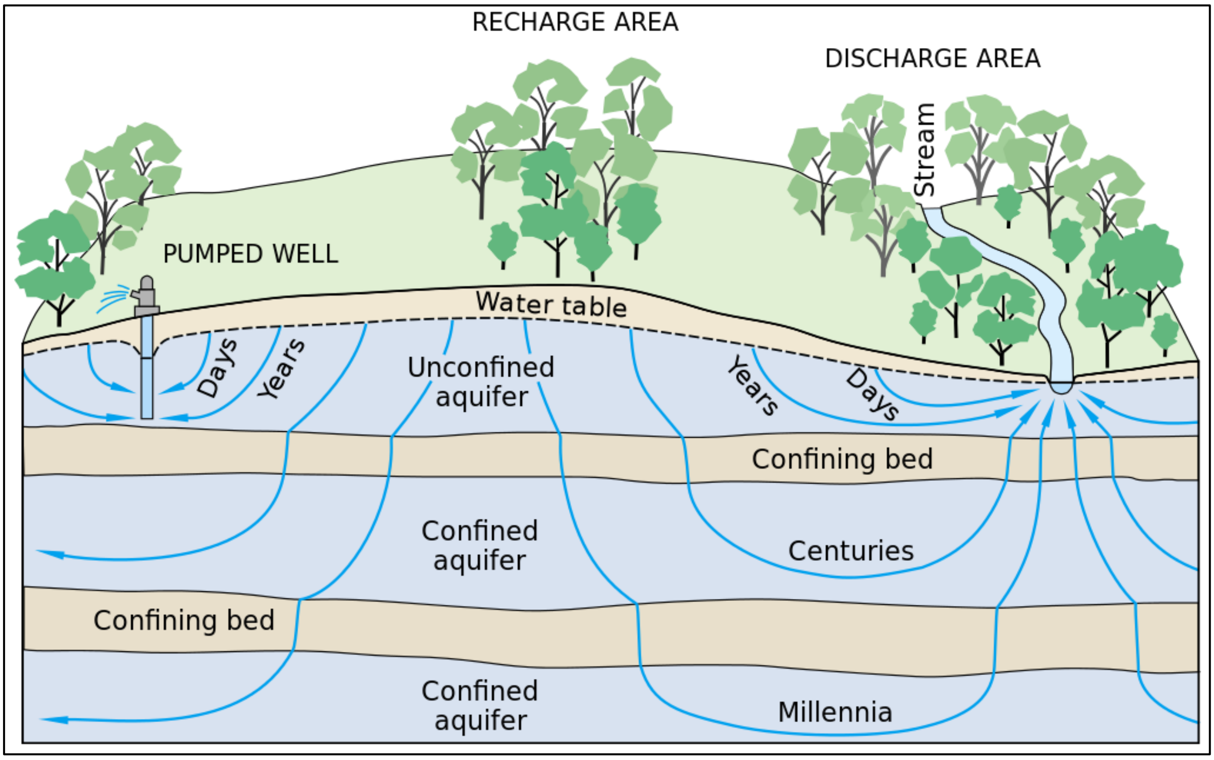

Figure 2-7: Flow of groundwater prior to mining activities (USGS, 2015)

2.1.9.2 Dolomite Karst Aquifers of the West Rand

The deep gold mines of the West Rand are overlain by a thick sequence of highly fractured dolomite bedrock and karst aquifers. Hydrogeological data collected by Scheader *et al.* (2014), identified that the largest karst aquifer can be found in the Malmani subgroup.

During the initial mining years, it was assumed that due to the depth of mining activities, the karst aquifers would not pose a threat. However, in the summer of 1968, the Driefontein mine was flooded by the overlying karst aquifers, this was a result of the intersection of the Big Boy Fault during the mining advance. At this point, it was then recommended that dewatering activities take place within the mine to prevent any future incidents.

Figure 2-8 illustrates the highly fractured and weathered dolomite rock to a depth of approximately 90 mbgl. Referring to Figure 2-8, the storativity at these depths is relatively high (10%) because of the weathering and the fine grain size in this unit which results in a higher porosity. Beneath this layer, the cavernous dolomite occurs which extends to a depth of approximately 200 mbgl and has a relatively low storativity of 2%. Total volumes of water stored within the dolomite sequence are estimated to be in the range 663 to 2 200 million cubic metres (Mm^3).

The transmissivity in these dolomite rocks differ widely and has been estimated to be in the range 1 000 m^3/d to 25 000 m^3/d. Schrader *et al.* (2014) estimated the hydraulic conductivity in boreholes to be in the range 7x10^{-5} metres/second (m/s), 3.1x10^{-4} m/s for the upper 200 m, and 2.9x10^{-6} m/s and 1.0x10^{-5} m/s for the deeper aquifers (refer to Figure 2-9). The storativity and transmissivity of the aquifer generally decrease with depth.

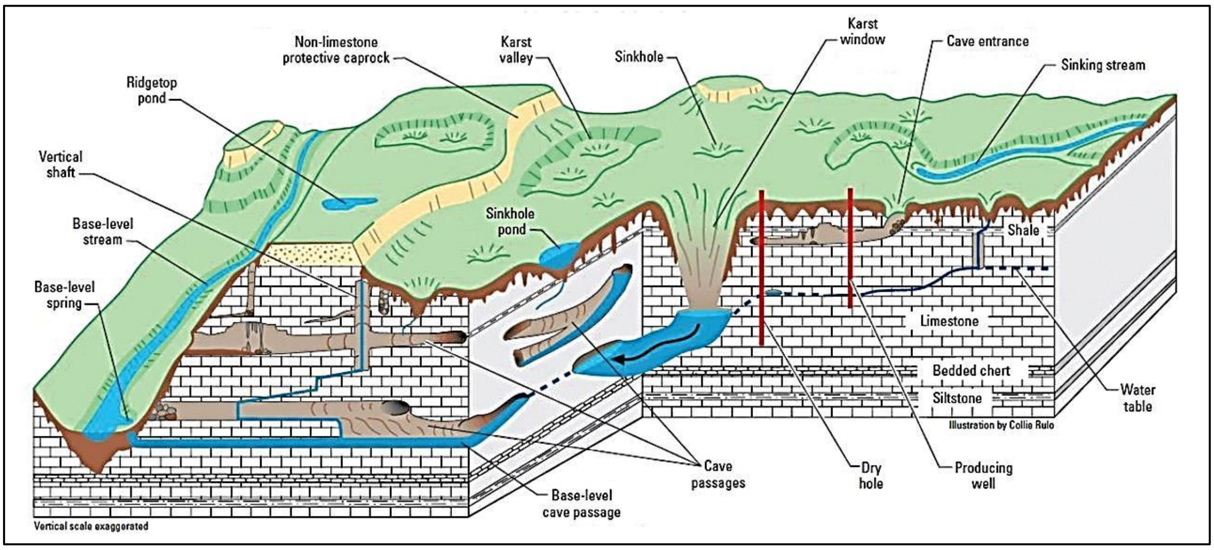

Figure 2-8: A schematic cross-section through the deep karst aquifers showing the dolomite zones (Taylor *et al.*, 2008)

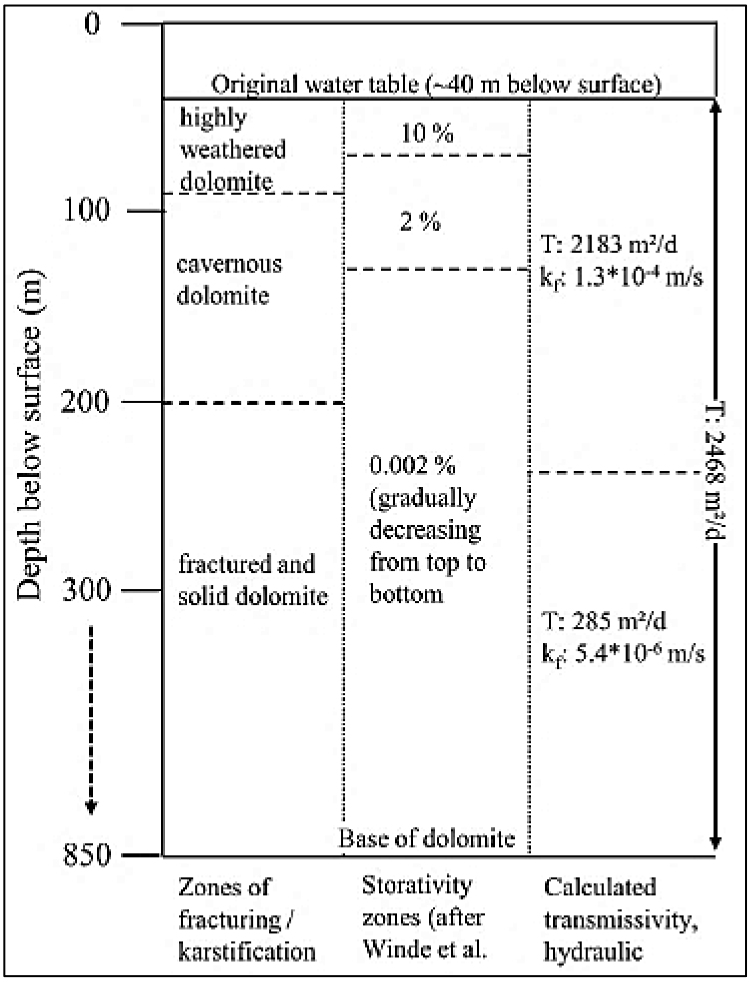

Figure 2-9: Calculated values for transmissivity and storativity in relation to the zones of fracturing (Schrader *et al.*, 2014)

2.1.9.3 Groundwater in the Bushveld Complex

Rustenburg forms the hub of the mining activities within the Bushveld Igneous Complex (BIC). The geology of the BIC comprises felsic to ultramafic rocks and rich in platinum group elements (PGE). Mining activities within the BIC comprise opencast and deep underground mines.

Hydraulic activity within the BIC is dependent on the interlinked fracture networks (Titus *et al.*, 2009). Titus *et al.* (2009) subdivided the BIC aquifers into two distinct groups, Group 1 is a shallow intergranular aquifer and Group 2 being a deeper fractured aquifer system. Local contractors within the area indicate that all boreholes are typically drilled to 50 mbgl and rarely deeper. Group 1 intergranular aquifers can be regarded saprolitic rocks or highly weathered rocks. Within the BIC Titus *et al.* (2009) identified that the deeper aquifer comprises highly fractured norite, anorthosite and pyroxenites in which the hydraulic activity is dependent on the fractures network. Various chemical tests were carried out on representative groundwater samples and according to Titus *et al.* (2009), three facies occur within the BIC.

- Mg-Ca-HCO_3 for the shallow aquifer.
- Mg-Ca-HCO_3-CL for the alluvial aquifers.
- Na-CL for deeper aquifers.

The groundwater results in Titus *et al.* (2009) study showed similarities with the surface water and groundwater chemistry which could indicate surface-groundwater interaction. Groundwater chemistry identified that the deeper aquifer system classified as Na-Ca-Cl with total dissolved solids (TDS) values in the range 350 mg/L to 1000 mg/L. The increase in TDS may be due to the increase in residence time beneath the surface. According to Titus *et al.* (2009), the chemical analysis of the shallow aquifer showed variations than uniformity within the deeper aquifer. Figure 2-10 provides an illustration of the grouping of the different aquifers in the form of a piper diagram.

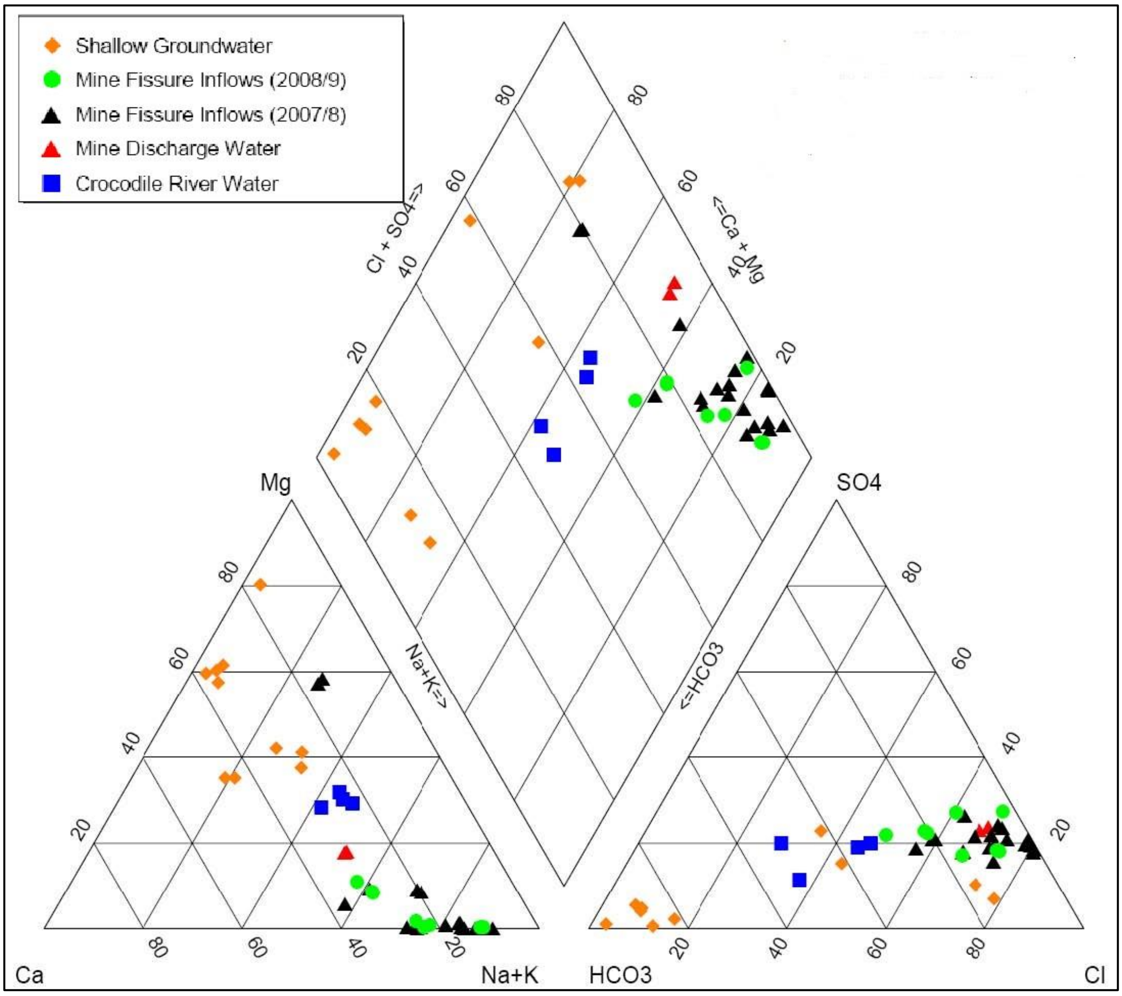

Figure 2-10: Piper diagram depicting shallow groundwater as well as deep mine fissure inflows (from Titus *et al.*, 2009)

Various hydraulic parameters within the aquifer are summarised in Table 2-5 after Titus *et al.* (2009).

Table 2-5: BIC aquifer characteristics (Titus *et al.*, 2009)

Aquifer Type	Transmissivity (m2/day)	Storativity	Abstraction Rate (L/s)	Porosity	Conductivity
Shallow Anomalies	3 to 8	10^{-3} to 10^{-4}	0.5 to 1.0 2	Varying	Varying

2.1.10 Protection of Deep Groundwater

2.1.10.1 Impacts of Mining on Physical Geohydrology

Mining activities may be carried out in two ways either underground or surface mining. The Witwatersrand mines are typically underground mines that are developed deep within the earth surface. Surface mines are either opencast or open pit mine and are large excavations at the surface, such as the Sishen Mine in Northern Cape. During mining, large volumes of in-situ material are removed from the ground which has a direct effect on the void ratio and permeability. There are many different mining methods, however, two that are commonly used in South Africa are Bored and Pillar and Longwall Mining. According to Younger (2004), bord and pillar method is a network of interconnected pathways and pillars. Pillars a generally left unmined to support the overburden material. During the advancement of mines, dynamite is used to create new areas for exploration and these results in an increase in fractures within the subsurface which could create additional fractures and increase the void ratio. The blasting can also lead to destabilisation of overburden rock, thus the pillars provide additional support. According to Younger (2004), the bord and pillar method is understood to be the most cost-effective mining method.

The longwall method comprises the excavation of a 250 m wide and 1 000 m long trench and is usually done in coal mining areas. In this mining method, hydraulic support is used to stabilize the overburden roof.

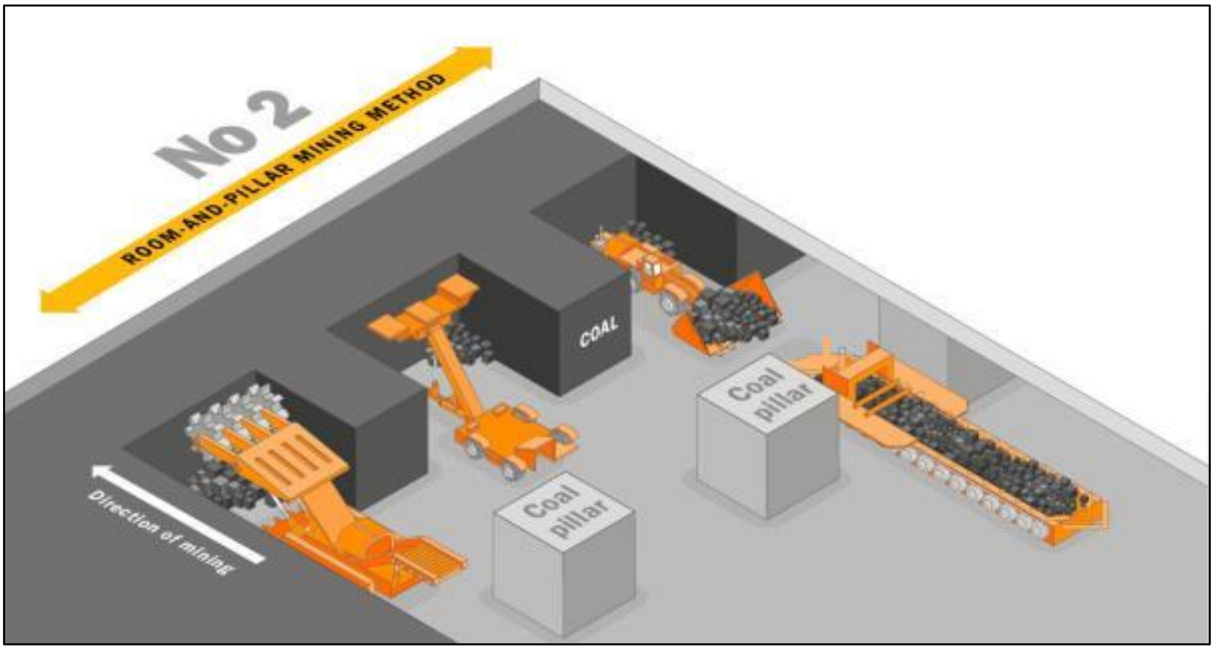

Figure 2-11: Bord and pillar method of mining (https://ar2016.evraz.com/business-review/coal, 2019)

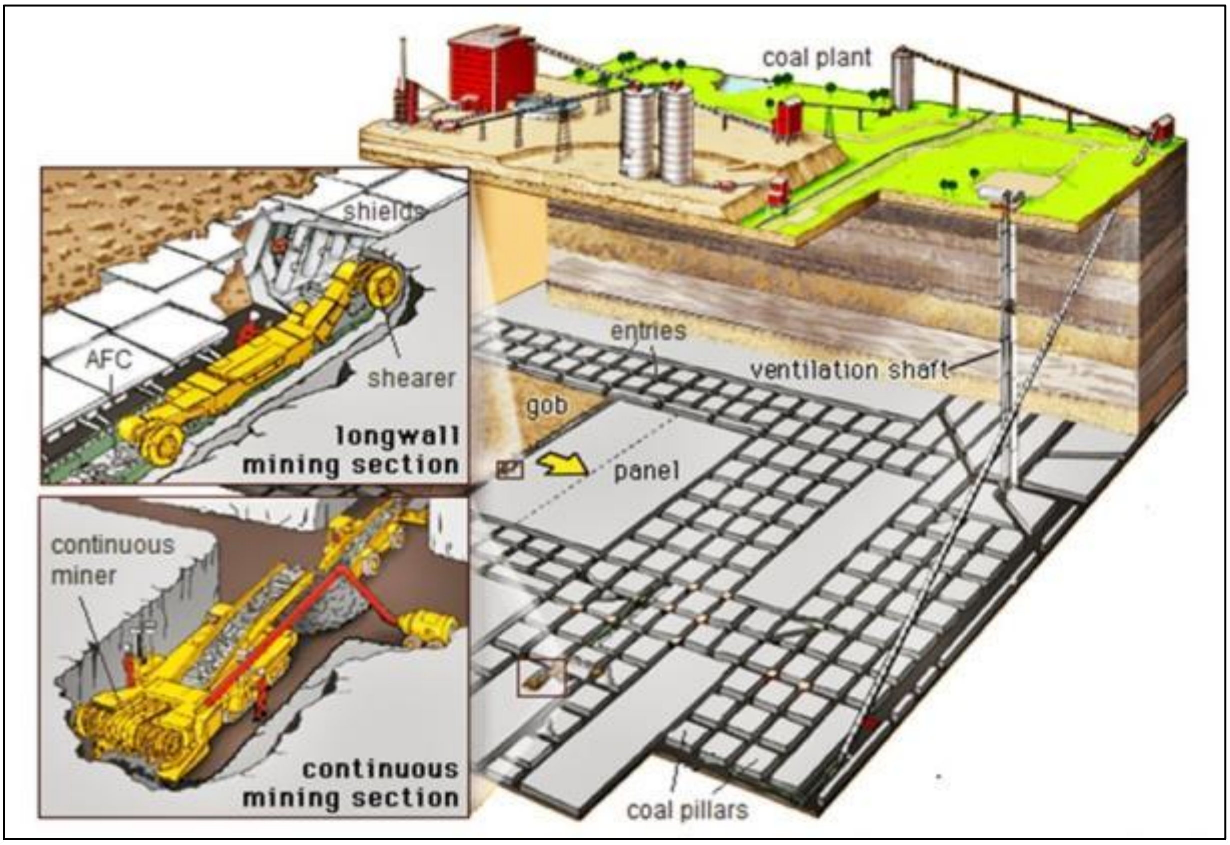

Figure 2-12: Longwall method of mining (www.britannica.com, 2019)

Surface mines comprise at least eighty percent of mining operations and involved the removal of overburden material and mining the ore deposits (Younger, 2004). The open pits are then backfilled with waste rock once the mining activity is completed. There is two types of surface mine, an open pit mine and an opencast mine, Open pit mine is basically the removal of overburden material and stockpiling in an area, whereas, open cast mine is done in stepped benches. According to Younger (2004), the benches are approximately 18 m to 45 m wide and 9 m to 30 m in height.

According to Younger (2004), more than 400 million tonnes of mine waste is generated annually and is either stored in stockpiles or tailings dams. Stockpiling usually has unconsolidated sediments and are considered to be heterogenic and have different flow rates. A zone within the stockpile known as the "cobbly zone" is regarded as the free draining zone and has high porosity and is the unsaturated zone of the stockpile. The fine-grained zone of the stockpile has the least porosity and holds the most water. There are preferential flow paths that are created within the stockpile and these facilitate the erosion process within the stockpile. Chemical reactions between water and ore material create a process known as acid rock drainage (ARD), this can either occur within the stockpile or in the mine. The ARD would lead to probable contamination of the groundwater. ARD may only develop is certain mines, particularly those that have a high sulphate/sulphide concentration or sulphate/sulphide is mined as a by-product.

2.1.10.2 Geochemical Processes within the Mine

Geochemical processes are highly active within the mined groundwater and continue to alter groundwater quality (Banks, 2004). Geochemistry of mines water indicates that there is a high acid content with an abundance of salts and toxic metals. According to Banks (2004), mine water varies, where some can be more alkaline than the other and will have a signature of the recharge source. According to Banks (2004), newly recharge groundwater will have the following; an isotopic signature, atmospheric chloride content that decreases with distance from the coast, pollutants from industries such as nitrate, sulphate and a high content of dissolved oxygen. According to Banks (2004), due to the high microbial activity within the subsoil, there is an increase in CO_2 and any groundwater percolating through the subsurface will have a high CO_2 content.

Banks (2004) identified that during interactions between bedrock and groundwater, O_2 and CO_2 are consumed during chemical reactions, the pH increases and base cations are released. Areas situated along the coast will have interaction with sea water and develop a salty (saline) taste. The formation of acids and bases will depend on the chemical reactions that occur within the groundwater. Major rock-forming minerals such as carbonates and silicates consume acids through various chemical reactions.

In South African context, oxidation of pyrite is common as ore deposits and host rock have a high pyrite content. Oxidation of pyrite leads to acidic conditions which cause contamination to the groundwater.

Typical acid and base reactions are shown below:

$CaCO_3 + CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$ (Base reaction - Calcite)

$2FeS_2 + 2H_2O + 7O_2 \leftrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$ (Acid Reaction - Sulphide oxidation).

Natural groundwater has a low concentration of acidic minerals, therefore are seen as more neutral to alkaline (Banks, 2004). Once oxygen enters the mining area and/or stockpile, oxidation reactions occur and acid rock drainage develops. Once oxidation of sulphide occurs, ground pH lowers, sulphate and metal concentrations increase. Numerous studies were carried out by Banks (2004) and are summaries in Table 2-6 and Table 2-7.

Table 2-6: Hydrochemical characteristics of three different metal sulphide mine waters (Banks, 2004)

Determinant	Unit	San Jose Bolivia	Kongens Gruve Norway	Magpie Sough UK
Flow Rate	L/s	8	5.8	-
Temperature	°C	20.8	-	-
pH		1.47	2.7	7.2
Alkalinity	mg/L	0	0	4.28
Chloride	mg/L	32670	-	19
Sulphate	mg/L	8477	901	33
Calcium	mg/L	1780	47.8	98
Sodium	mg/L	17256	-	8
Iron	mg/L	2460	134	<0.0005
Aluminium	mg/L	559	33.1	0.005
Manganese	mg/L	27.4	-	<0.0002
Zinc	mg/L	79.4	36.3	0.074

Table 2-7: Hydrochemical characteristics of four different coal mine waters (Banks, 2004)

Determinant	Unit	Ynysarwed Wales	Dunston Chesterfield	Morlais Wales	Mine No.3 Svalbard
Flow Rate	L/s	30	20	150	0.056
Temperature	°C		9.4	14.2	4.7
pH		4.2	6.3	6.9	8.2
Alkalinity	mg/L	2.76	3.74	6.07	36
Chloride	mg/L	32	26	25	236
Sulphate	mg/L	1554	210	455	7.43
Calcium	mg/L	222	64.5	91.8	15.5
Sodium	mg/L	109	51.4	155	925
Iron	mg/L	180	10.6	26.6	<0.01
Aluminium	mg/L	<0.5	<0.045	<0.01	<0.02
Manganese	mg/L	6.1	1.26	0.93	0.04
Zinc	mg/L	0.061	<0.007	<0.002	0.055

Based on the results of Banks (2004) study provided by Table 2-6 and Table 2-7, the following comments can be given:

- Mine groundwater chemistry various between mines.
- Mines comprising metals have acidic groundwater.
- A recently flooded mine will show aggressive groundwater discharges.
- The higher the metal content the lower the pH and as pH increase, the metal contents will decrease.
- The chloride content in the groundwater is not dependent on the pH.

Banks (2004) made the following conclusion on the formation of aggressive mine waters;

- High pyrite content can be found in mine/spoil material.
- Aggressive water will form in areas of increasing oxygen supply.
- In areas where water discharge is low.
- In mines that have recently flooded, creating an ideal scenario for oxidation and creation of acids.

The data has been plotted in Figure 2-13 and Figure 2-14 to provide a comparison of the results from the two different mines.

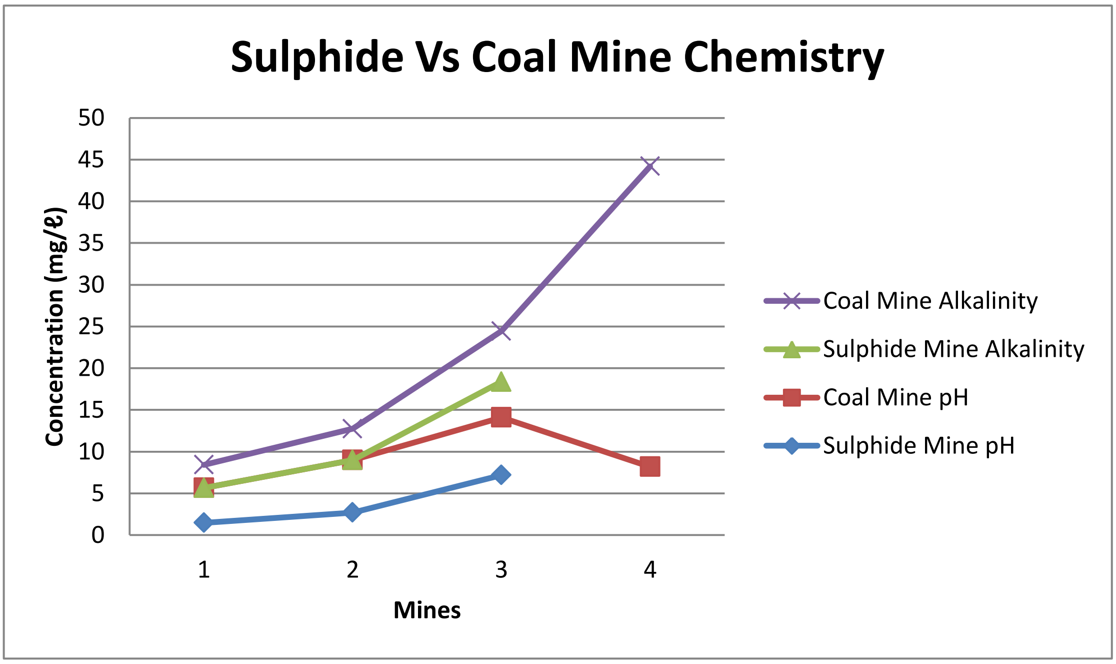

Figure 2-13: Comparison of the chemical constituents of sulphide and coal mines

Figure 2-13 suggests that sulphide mines have a lower pH than the coal mines with groundwater being very acidic. Two of the three sulphide mines have a pH exceeding the lower limit allowed in SANS 241-2015 (pH = 5).

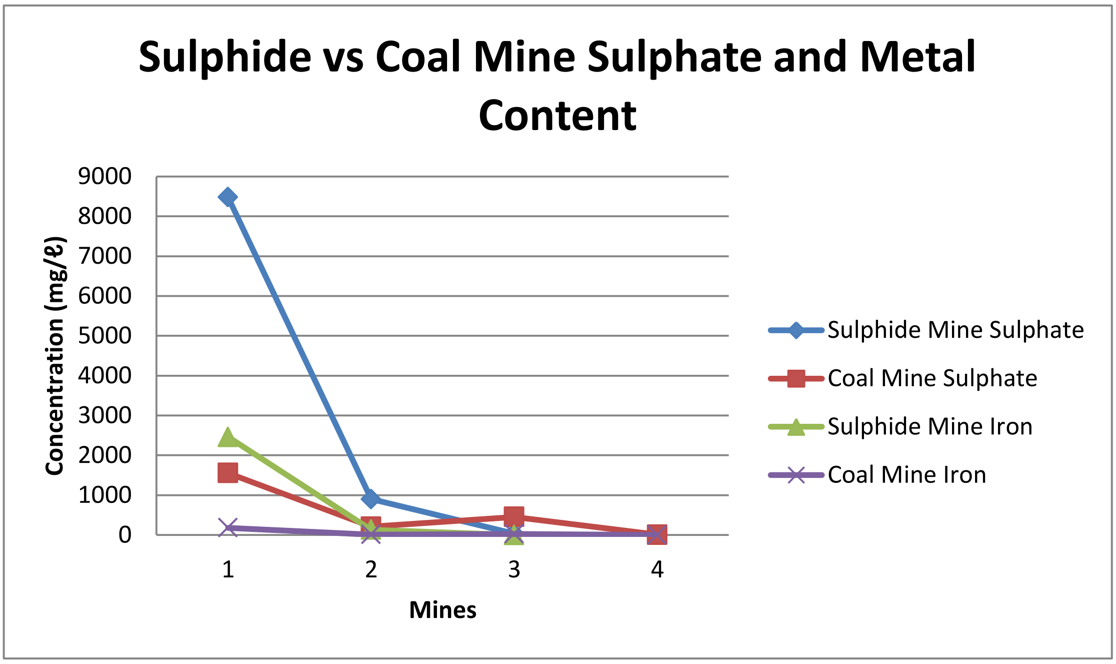

Figure 2-14: Comparison of the sulphate and metal content in the sulphide and coal mines

Figure 2-14 suggests that sulphide mines have high concentrations of sulphate compared to coal mines. Two of the three sulphide mines have sulphate concentrations exceeding the upper limit allowed in SANS 241-2015 (500 mg/L).

In conclusion, mining activities alter the void ratio of the subsurface and allow oxygen to enter the system, thus providing a catalyst for oxidation reactions. Mine water has a high acid content, a high concentration of toxic metals and generally a very low pH, i.e. particularly in areas of high ARD. Newly recharged groundwater is found to have decreasing chloride content away from the coastal areas. The high concentrations of CO_2 within the soil contribute to the elevated concentrations of CO_2 in the groundwater from percolation.

CHAPTER 3

GEOLOGY AND HYDROGEOLOGY OF SOUTH AFRICA

3.1 INTRODUCTION

The geological map of the Republic of South Africa developed by the Council for Geoscience to a scale of 1:1000 000, provides an indication that majority of the surface is covered by sedimentary rock units which have been intruded and extruded by igneous rocks and altered to form metamorphic rocks. According to McCarthy and Rubidge (2005), there are two main sedimentary basins in South Africa, namely, the Karoo and Cape basins which are estimated to form around Cambrian to Jurassic time (510 to 160 million years ago). The groundwater within South Africa is typically contained within these sedimentary basins.

This dissertation will concentrate on three geological units/formations (Figure 3-1 refers):

i. Basement complexes,
ii. The Bushveld Igneous Complex, and,
iii. Dolomite formations.

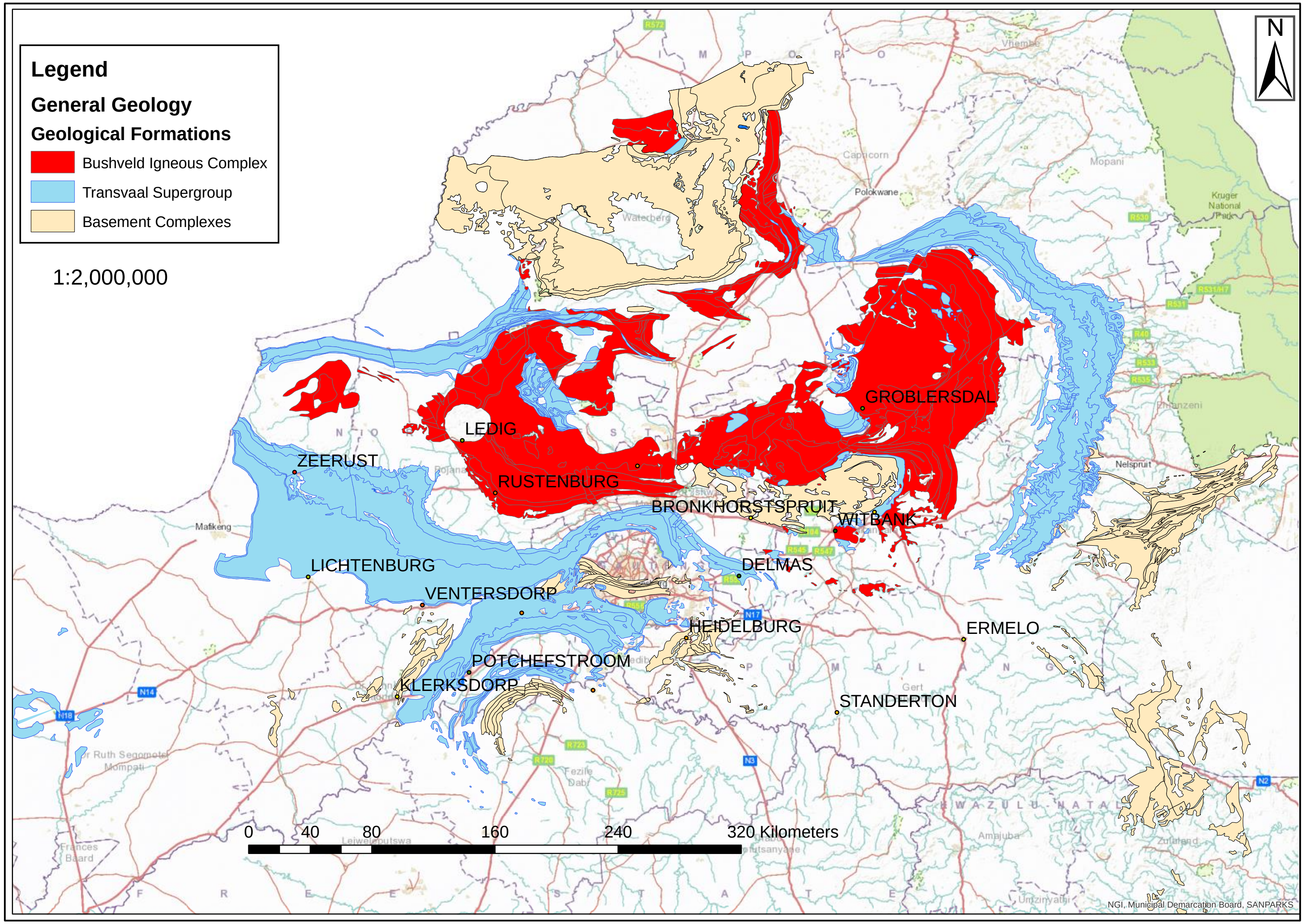

Figure 3-1: Simplified geology of South Africa (Council for Geoscience, 2003)

3.2 CRYSTALLINE BASEMENT GEOLOGY

3.2.1 Introduction

It is understood that majority groundwater is stored within the sedimentary unit within South Africa, however, there are secondary aquifers known as basement rocks which also comprise groundwater. According to Dippenaar *et al.* (2009), most of the basement complexes can be identified at the surface along the northern portions of South Africa. The basement rocks refer to bedrock such as granites, granitoids, migmatites, etc. According to Abiye *et al.* (2011), groundwater supply in the northern portions of South Africa is typically sourced from either crystalline aquifers (basement) or alluvial aquifers.

Crystalline aquifers are problematic in terms of identifying a suitable classification class, as they tend to have variable characteristics (Dippenaar *et al.,* (2009). From experience with such aquifers, typically hand pumps were identified in such areas, in which a preliminary conclusion can be made that these are low yielding aquifer systems. Wright E.P. (1992) identifies potential constraints for the development of crystalline aquifers as a potable source:

- The high rate of dry boreholes drilled into these aquifers.
- The risk for pollution from the shallow aquifers due to potentially high permeability rate.
- Low primary storativity.

During the Archaean period, there were four significant granitoid intrusions in South Africa according to Robb *et al.* (2006), i.e. eastern and southeastern Kaapvaal Craton, north-eastern Kaapvaal Craton, central Kaapvaal Craton and south-western Kaapvaal Craton. According to Robb *et al.* (2006), the oldest bedrock identified within the Kaapvaal Craton is the banded tonalitic gneiss complex which formed approximately 3.6 billion years ago. The term basement refers to any hard crystalline bedrock that has formed during the Precambrian age (Dippernaar *et al.,* 2009). According to Ky (1992), the basement rocks may be identified in South Africa by archaean cratons, metamorphic rocks situated in mobile belts and anorogenic intrusions.

3.2.2 Limpopo Belt

3.2.2.1 General Geology

One of the identified basement complexes in the Limpopo Belt situated along the northern portion of South Africa (Figure 3-2 refers), eastern Botswana and southern Zimbabwe

(Kramers *et al.,* 2006). According to Lourens (2013), the Limpopo Belt has been subdivided into three different zones, Southern Marginal Zone, Central Zone and Northern Marginal Zone (Figure 3-3 refers) and are all characterised by high-grade metamorphism and shear zones.

According to Lourens (2013), the aquifers within the Limpopo Belt can be regarded as intergranular and fractured and have developed as a result of structural activity within the belt. The groundwater is concentrated along the secondary fractures.

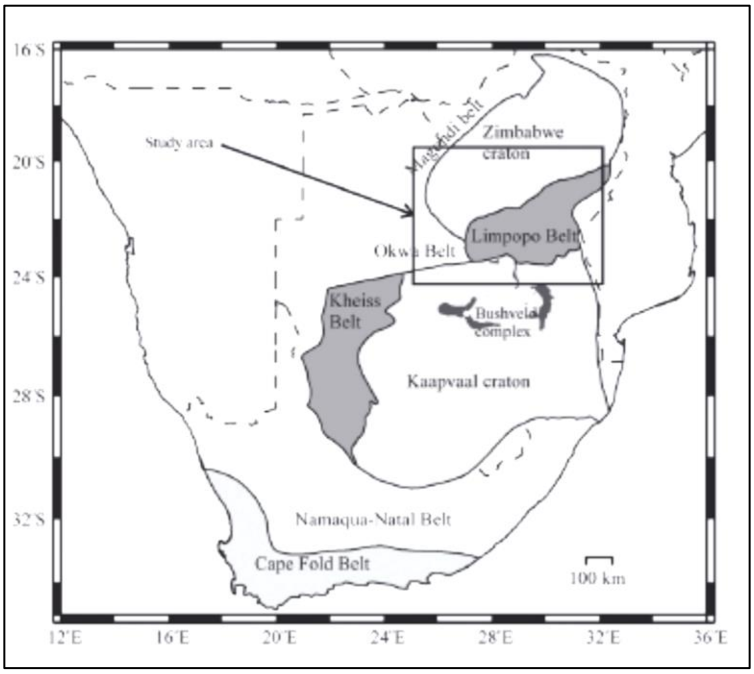

Figure 3-2: Location of the Limpopo belt in southern Africa (Gore *et al.*,, 2009)

3.2.2.2 Hydrogeological Characteristics

The aquifers within the Limpopo Province are concentrated along the upper weathered zone and have limited groundwater potential due to the impermeable clay membranes (Lourens, 2013), however, these can act as a recharge source to the lower fractured aquifer. Lourens (2013) identified that there are potential deep groundwater flow systems within the Limpopo belt which can be supported by the occurrence of thermal springs in the area. The main geological unit within the Limpopo Belt is the schists in which the thermal springs are located. Based on a study carried out by Dhansay *et al.* (2014), a single thermal spring site was selected to identify the geothermal potential in the Limpopo area and the result identified a spring that was approximately 70°C and that circulated at a depth of approximately 2 000 m.

In terms of groundwater quality, Vegter (2001) identified poor groundwater conditions. A total of 750 groundwater samples were analysed by Vegter (2001) and greater than half of the tested samples classified as poor groundwater in terms of potable quality. A conclusion was made by Lourens (2013) that the Limpopo belt is a low yielding aquifer with poor groundwater quality. However, if there is significant fracturing, a high yielding aquifer may be encountered, for example, an isolated case was identified in which boreholes drilled into a major fault encountered a yield of approximately 25 L/s.

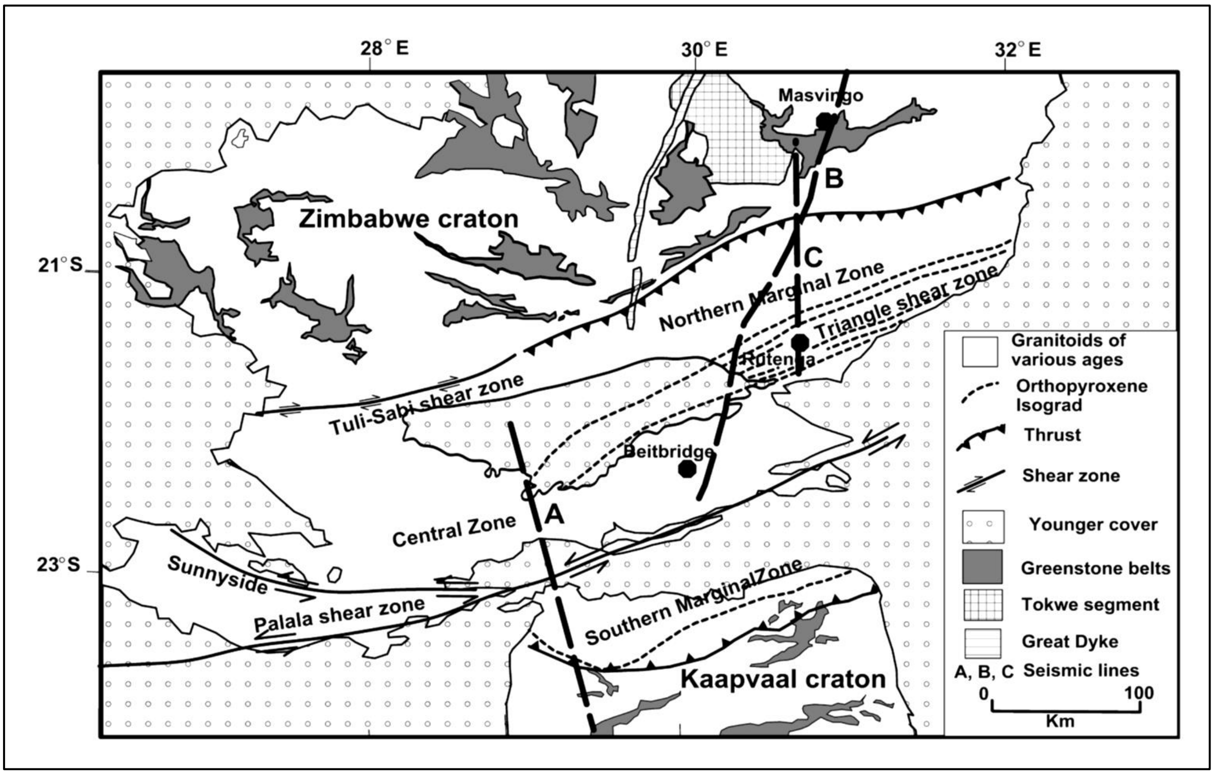

Figure 3-3: Limpopo belt showing the three domains (modified from Gore *et al.,* 2009)

3.2.3 Archaean Greenstone Belts

These geological units are considered to be the oldest and can extend to widths in excess of 50 000 m and lengths up 300 000 m that comprise mainly extrusive mafic with minor ultramafic and felsic rocks (Brandle *et al.,* 2006). The Kaapvaal Craton in South Africa is a typical example of archaean complexes and comprise the following belts (Figure 3-4 refers):

i. Barberton Greenstone Belt.
ii. Pietersburg Greenstone Belt.
iii. Murchison Greenstone Belt.
iv. Giyani Greenstone Belt, and
v. Kraaipan Greenstone Belt.

3.2.3.1 Barberton Greenstone Belt

The Barberton Greenstone Belt comprises three subdivisions, Moodies Group, Fig Tree Group and Onverwacht Group. Studies were carried out by Owen and Madari (2009) on the Moodies Group. The Moodies Group is a typical sedimentary sequence that is underlain by schistose and metabasic lavas and intrusions of the Onvewacht Group (Owen and Madari, 2009).

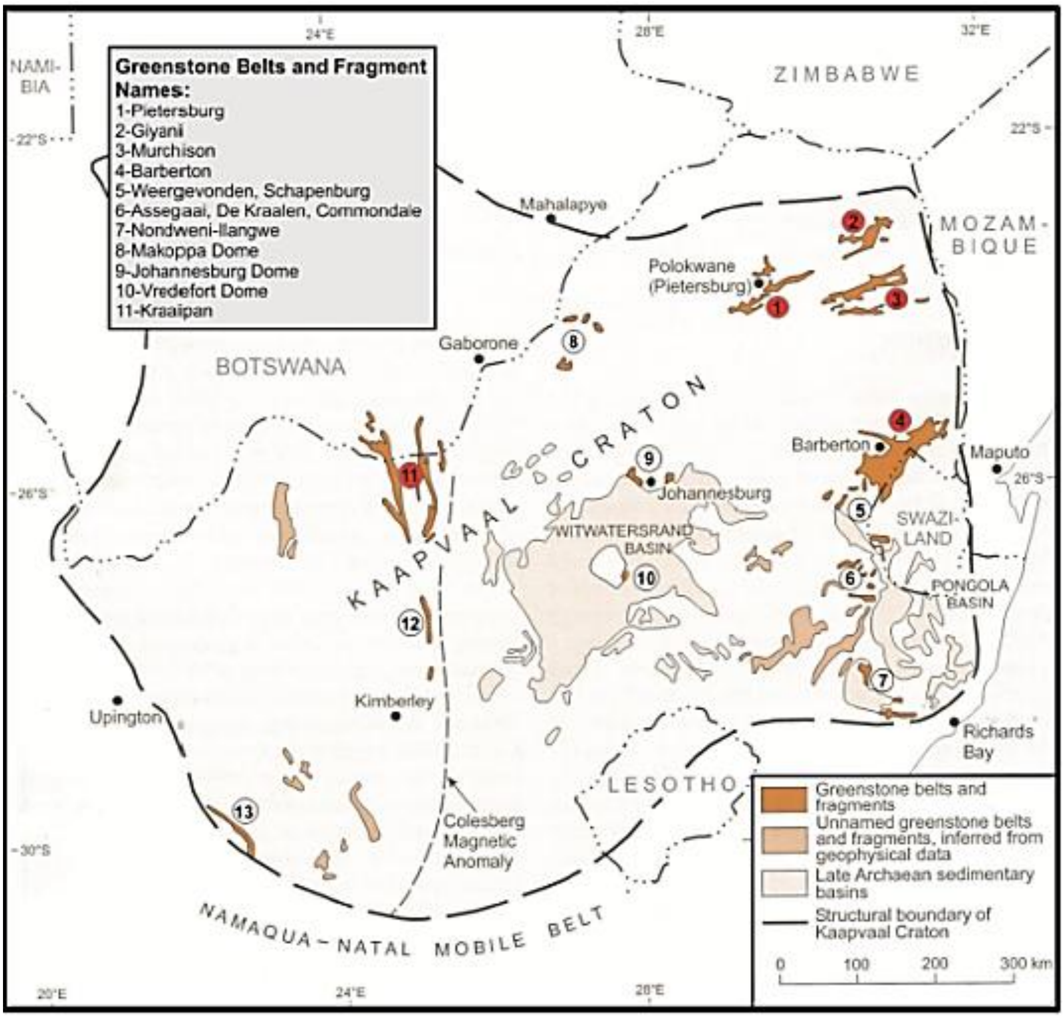

Figure 3-4: Location of the greenstone belts and fragments on the Kaapvaal Craton. Red circles represent important greenstone belts. (Gore *et al.*, 2009)

The Moodies Group was subjected to metamorphism and the development of poor aquifer systems was created (Owen and Madari, 2009). Furthermore, due to the presence of micaceous material within the phyllites, groundwater movement within the aquifer is limited as these materials hinder groundwater movement. The rocks within the Barberton Greenstone Belt are considered to be high impermeable, however, the development of secondary features increase the permeability of the host rocks (Lourens, 2013). Sami *et al.* (2002) analysed a total of 64 boreholes and identified that more than 50% of these were declared to be dry. The remainder of the boreholes encountered yields in the range 0.1 L/s to 0.5 L/s, and in terms of the DWA aquifer classification systems, this would be regarded as a low yielding aquifer system. There was also a correlation between groundwater strike and depth of strike, and Sami *et al.* (2002), identified that shallower strikes had greater groundwater yields.

The metasedimentary rocks of the Barberton Greenstone Belt have undergone significant folding which has resulted in an increase in secondary porosity and could lead to a potential increase in groundwater movement. The aquifers within this unit are dependent on the secondary development of fractures that increase the potential for groundwater activity.

3.2.3.2 Pietersburg Greenstone Belt

This greenstone belt is located near Polokwane and is approximately 20 km in width and 125 km in length (Brandle *et al.,* 2006). The greenstone belt is comprised of a thick sequence of volcanic rocks which is overlain by terrigenous sediments of the Uitkyk Formation (Brandle *et al.,* 2006).

According to Lourens (2013), the important units in terms of hydrogeological significance within the Pietersburg Greenstone belt is the Mothiba, Eersteling and Zandrivierspoort Formations. Due to the clay content within the bedrock, the permeability decreases with an increase in weathering. In terms of groundwater quality, the Greenstone belt is associated with generally good potable quality within isolated areas in which fluoride content exceeding allowable limits. According to Lourens (2013), these aquifers can be regarded as moderate to high yielding and boreholes drilled into this sequence had yields of at least 2 L/s.

3.2.3.3 Murchison and Giyani Greenstone Belts

Murchison and Giyani Greenstone belt is located along the north-eastern part of the Kaapvaal Craton. The hydrogeological characteristics of this aquifer are similar to that of the Pietersburg Greenstone belt, however, the groundwater is high in nitrates. In terms of electrical conductivity (EC), the groundwater samples were found to be between 70 mS/m to 300 mS/m (Lourens, 2013). According to Lourens (2013), these aquifers can be classified as low to moderate yielding, with the Murchison Greenstone having yields up to 8 L/s and Giyani Greenstone aquifer up to 21 L/s.

3.2.3.4 Kraaipan Greenstone Belt

The Kraaipan Greenstone Belt is located in Botswana in a north-northwest trend (Brandl *et al.,* 2006). Van Dyk and Kisten (2006), analysed 257 boreholes and approximately 91% of the boreholes were identified as dry. Lourens (2013) concluded that the Kraaipan

Greenstone belt aquifer is low yielding. There were isolated areas in which high yields were encountered along contact zones with granitic rocks.

3.2.3.5 Summary

It can be concluded that the meta-sedimentary rocks of the Archaean Greenstone Belts are both intergranular and have secondary porosity, in which the porosity has been decreased due to metamorphism (Owen and Madari, 2009). The overall classification of Archaean Belt can be low to moderate yielding.

3.2.4 Archaean Granites and Gneiss

Figure 3-5 shows the location of the granitoid and gneiss intrusions within the Kaapvaal Craton. According to Lourens (2013), the Archaean granites may be divided into the Pietersburg Plateau and Lowveld regions.

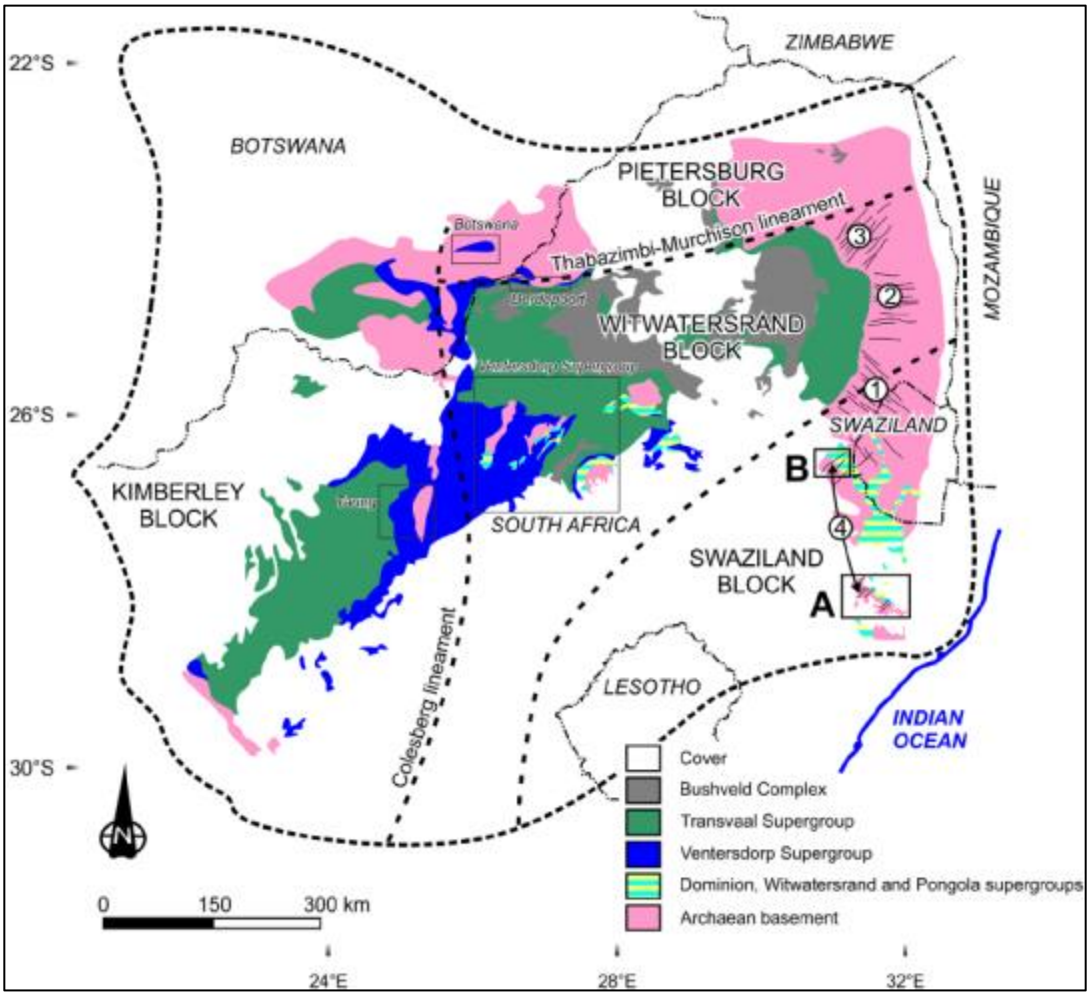

Figure 3-5: Location of Archaean Basement granites on the Kaapvaal Craton (Gumsley *et al*, 2016)

The aquifers found within the Archaean rocks are classified as intergranular and fractured, i.e. double porosity, and are considered in some parts to semiconfined (Lourens, 2013). High permeability and low storativity are associated with fractures and high storage and low permeability for the matrix (Du Toit, 2001). A conceptual model for the Archaean basements was developed by Holland (2011) (Figure 3-6 refers).

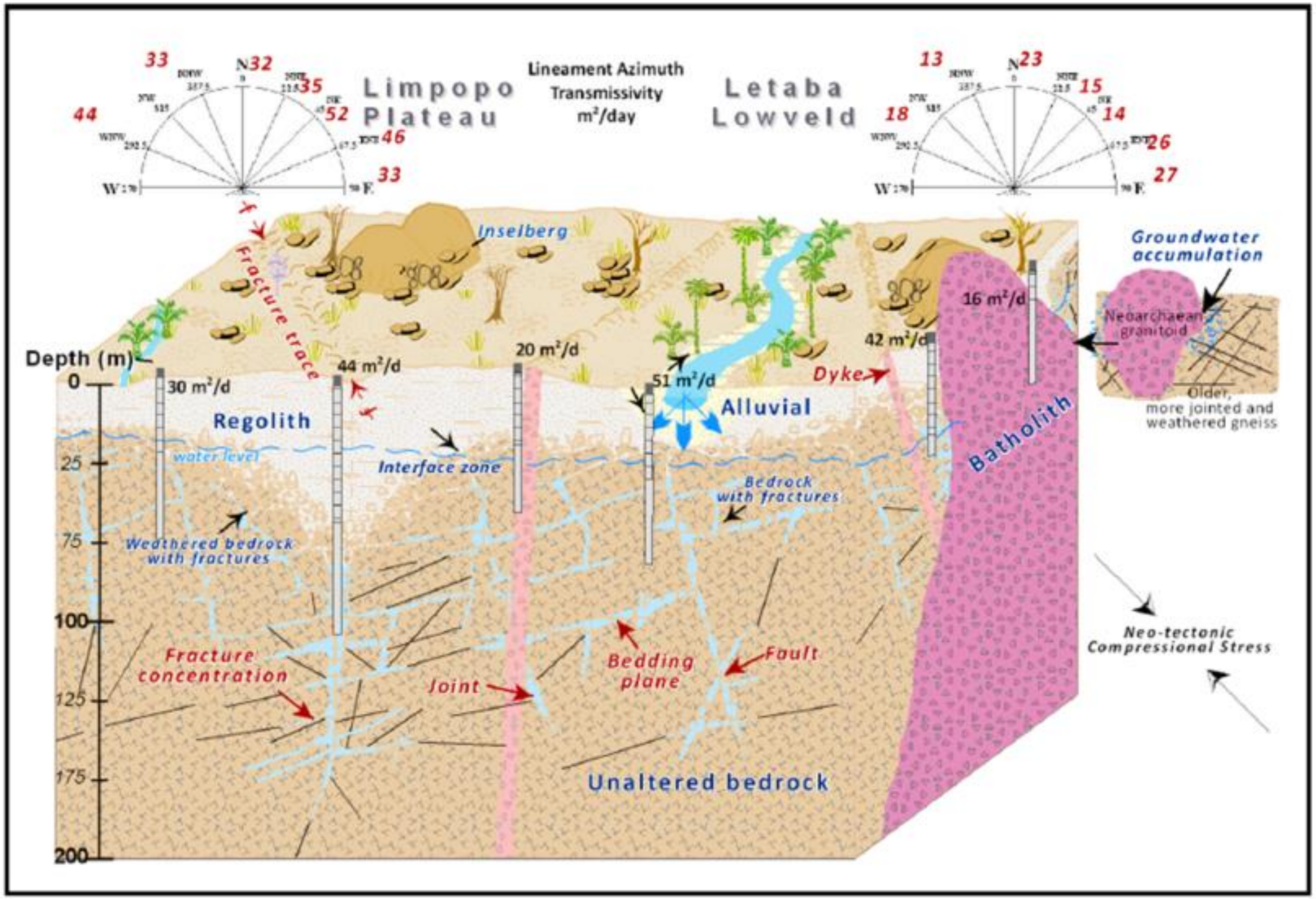

Figure 3-6: Conceptual model of aquifers systems found in the Archaean granites and gneisses of the Polokwane Plateau and Lowveld region (from Holland, 2011; as cited by Lourens, 2013)

Referring to Figure 3-6, the weathered zone can be down to a depth of at least 70 mbgl for the Limpopo Plateau and 20 mbgl for the Lowveld region. Holland (2011), identified that fracture zones may exceed a depth of 120 mbgl in the Dendron and Mogwadi regions. According to Holland (2011), these regions are also known to have high yielding boreholes.

The groundwater quality within the Limpopo Plateau and Lowveld region was found to be relatively good (Lourens, 2013). It should be noted that this analysis in groundwater quality was restricted to the shallow aquifer systems.

In terms of aquifer yields, the Goudplaats-Hout River Gneiss of the Limpopo Plateau is associated with a moderate to high yields of up to 5 L/s (Lourens, 2013). The yields associated with the Lowveld region are low with a maximum yield of 2 L/s (Du Toit and Lelyvel, 2006).

3.2.5 Namaqua-Natal Metamorphic Province

During the formation of the Namaqua Orogeny, a thick sequence of igneous and metamorphic rocks was created, known as the Namaqua-Natal Province (Lourens, 2013) and outcrops in Northern Cape and KwaZulu-Natal Provinces. Namaqua refers to the Cape area and Natal refers to KwaZulu-Natal area (Figure 3-7 refers). Geological investigations indicate that the Natal and Cape sequences are connected by an orogenic belt (Cornell *et al.,* 2006).

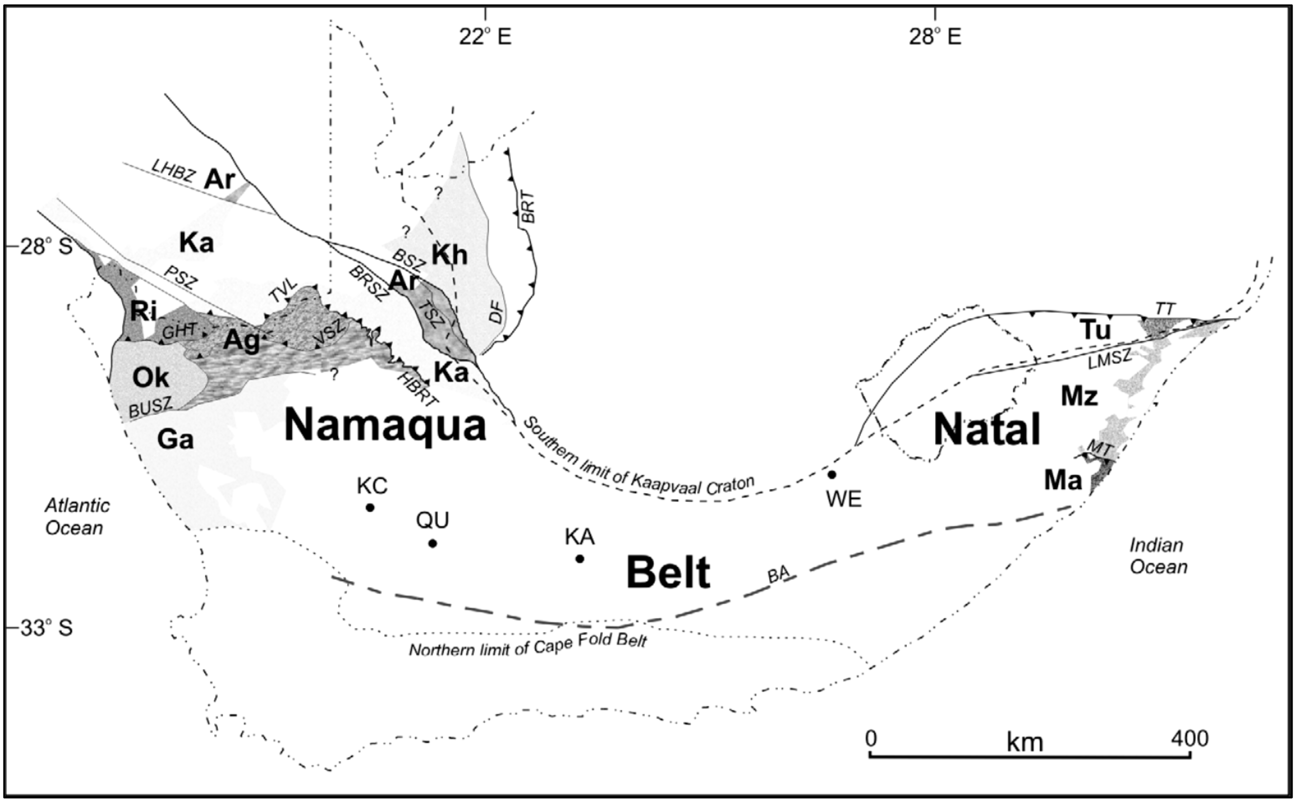

Figure 3-7 Geological setting of the Namaqua-Natal Province (Eglington, 2006)

3.2.5.1 Namaqua Section

3.2.5.1.1 Geology

The Namaqua Sequence is split into different subgroups, Richtersveld Suite, Bushmansland Suite, Kakamas Suite, Areachap Suite and Kaaien Suite (Cornell *et al.,* 2006). The Richtersveld is a volcanic-sedimentary sequence that comprises rhyolites, andesites and gabbro complexes that have been intruded by dyke swarms (Onstott *et al.,* 1986).

Bushmanland comprises a basement complex of granitic rock, supracrustal sequences and intrusive granitic rocks (Cornel *et al.,* 2006). The Kakamas comprises various intrusions with a variation in deformation structures (Lourens, 2013). The lithologies within this group comprise marbles, calc-silicates, sandstones, schists and metapelites that have been intruded by Granites (Lourens, 2013).

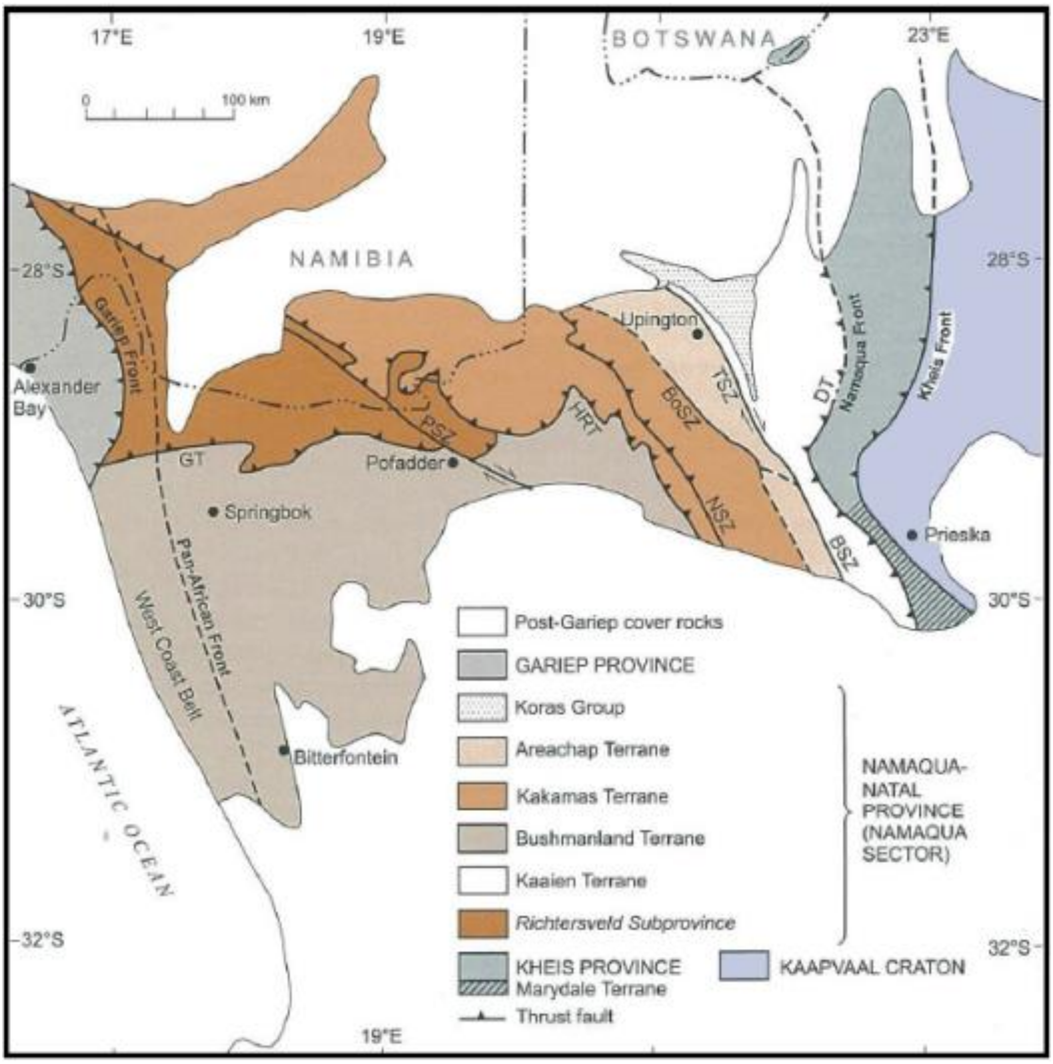

Figure 3-8: Tectonic subdivision of the Namaqua Section of the Namaqua-Natal Province. BoSZ: Boven Rugzeer Shear Zone, BSZ: Brakbosch Shear Zone, DT: Dabep Thrust, GT: Groothoek Thrust, HRT: Hartbees River Thrust, NSZ: Neusberg Shear Zone, PSZ: Pofadder Shear Zone (Cornell *et al.,* 2006)

Areachap comprises mainly migmatites in a meta-volcanic sequence. The Kaaipen comprises quartzites with occasional volcanic layers.

3.2.5.1.2 Geohydrology

According to Friese *et al.* (2009), there have been three aquifer systems identified within the Namaqua-Natal Province, a sandy aquifer, weathered aquifer and fractured bedrock aquifer. According to Pieterson *et al.* (2009), the aquifer systems within this province have formed as a result of the deformation and evolution of the Namaqua Belt, and in addition weathering of bedrock has played a significant role. The rocks within this province are considered to have very low to almost none primary porosity with fracturing formed during the evolution of the belt forming the secondary porosity.

3.2.5.2 Natal Section

3.2.5.2.1 Geology

The Natal Sequence of the province comprises mainly gneisses, granitoids and younger intrusive rocks (McCourt *et al.,* 2006). The Natal sequence is separated into the Margate Suite, Mzumbe Suite and Tugela Suite (Figure 3-9 refers). The Margate Suite is dominated by granitoids and gneisses (McCourt *et al.,* 2006). The Mzumbe Suite is dominated by layered gneisses and migmatites (Lourens, 2013).

3.2.5.2.2 Geohydrology

Groundwater within this section of the province is not as overexploited than the northwestern parts of South Africa. According to Lourens (2013), the Natal section comprises an intergranular and fractured aquifer system. The weathered zoned is defined as the intergranular zone and is associated with high hydraulic conductivity and is usually less than 25 m. The weathered and fractured zones are interconnected via a series of fractures and pore spaces. The aquifer system is considered to be very low yielding with yield typically less than 0.5 L/s.

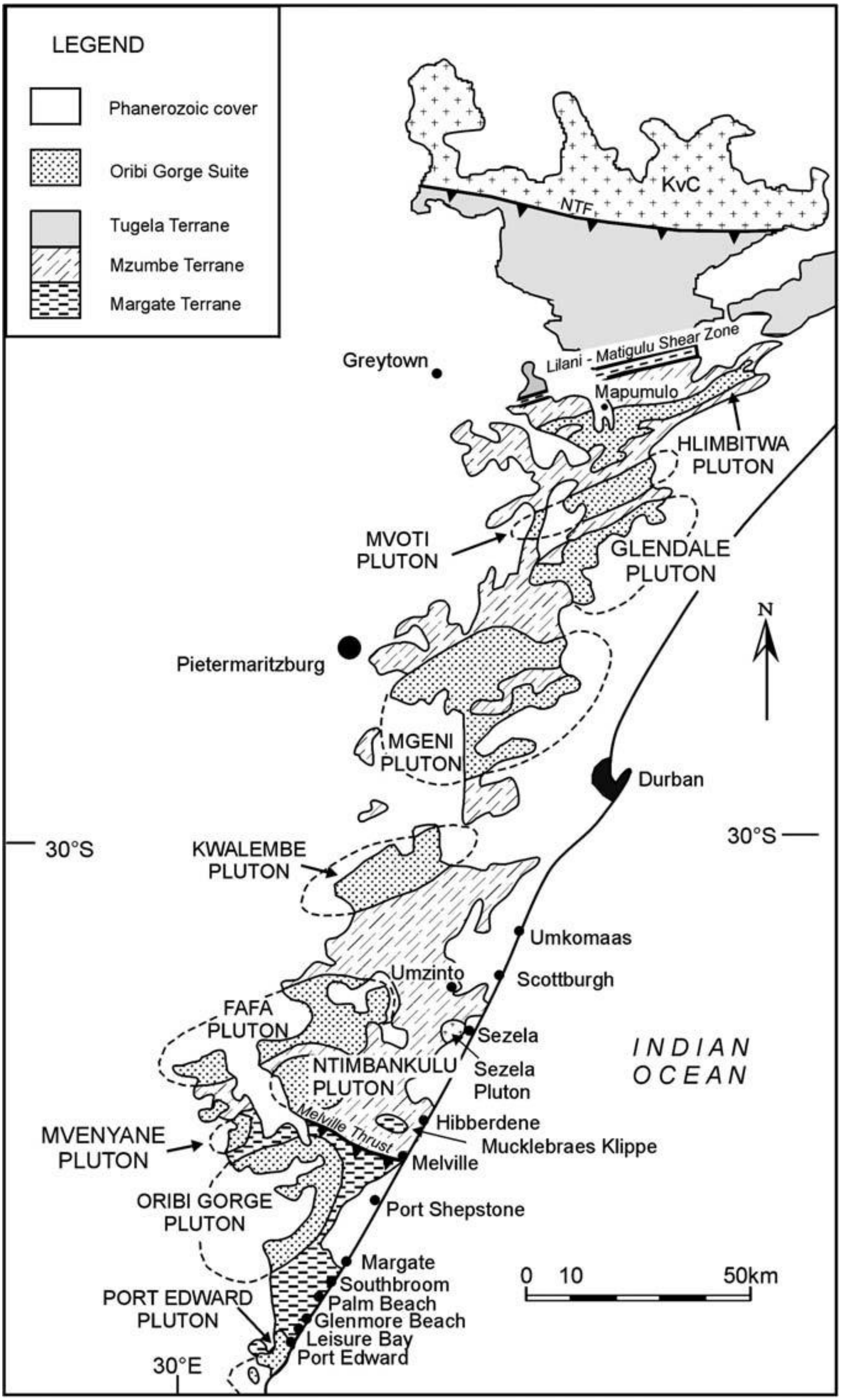

Figure 3-9: Simplified geology map of the Natal Section of the Namaqua-Natal Metamorphic Province (McCourt *et al.,* 2006)

3.3 BUSHVELD IGNEOUS COMPLEX

The Bushveld Igneous Complex (BIC) is the world's largest layered igneous intrusion that stretches across four provinces in South Africa (Figure 3-10 refers). The BIC is divided into three subgroups, namely the felsic upper Rashoop Granophyre Suite, the felsic Lebowa Granites, the mafic Rustenburg Layered Suite and the Rooiberg Group (Cawthorn *et al.,* 2006).

3.3.1 Geology

3.3.1.1 Rustenburg Layered Suite

An important formation within the BIC is the Rustenburg Layered Suite (RLS) which comprising mainly of differential magmatic layering with rock types norite, gabbro, anorthosite, dunite, pyroxenite and diorite (Crawthorn *et al.,* 2006). According to Cawthorne *et al.* (2006), the Rustenburg layered suite (RLS) of the BIC is divided into three limbs, i.e. northern, eastern and western limbs that are approximately 9km thick and covers an approximate length of 370km east to west and 200km north to south (Figure 3-11 refers). The RLS is divided into five zones:

- Upper zone,
- Main zone,
- Critical zone,
- Lower zone; and,
- Marginal zone.

According to Eriksson *et al.* (1995), the RLS comprises mineral-rich marker reefs such as the Merensky Reef within the Critical Zone, Thornhill pyroxenite layers within the Main Zone and the Magnetite Layer with the Upper Zone.

3.3.1.2 Lebowa Suite

This suite comprises different layers of granites which have been differentiated based on radiometric dating and chemical analysis (Lourens, 2013). The granites within this sequence are the Nebo, Verena, Klipkloof, Bobbejankop, Lease, Balmoral and Makhutso Granites (Lourens, 2013) which occur as two semicircles within the BIC.

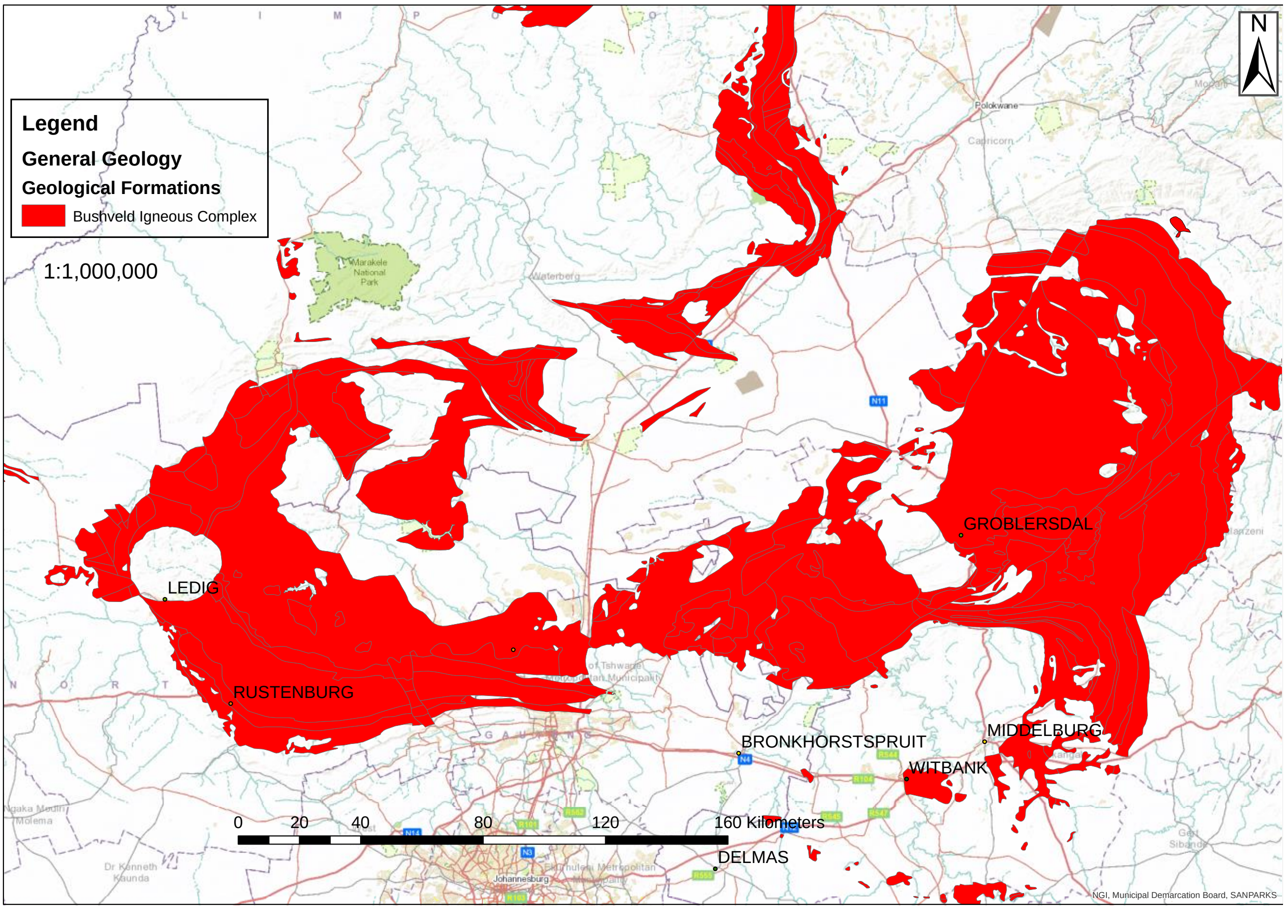

Figure 3-10: Simplified geology of South Africa indicating the location of the Bushveld Igneous Complex

3.3.1.3 Rashoop Granophyre Suite

This suite comprises entirely of Granophyre rock which is subvolcanic by origin and has an abundance of quartz and alkali feldspars as inclusions. According to Lourens (2013), this unit is divided into three different units based on textural variations and are classified as either magmatic or metamorphic.

3.3.1.4 Rooiberg Group

There is a thick volcanic sequence above the RLS which is known as the Rooiberg Group and occurs in areas up to 100 000 km^2. The Rooiberg Group is subdivided into four formations according to Crawthorn *et al.* (2006), with the Dullstroom forming the base, Damwal, Kwaggasnek and the top comprising the Schrikkloof Formation.

The Dullstroom Formation is a 400 m thick volcanic sequence that comprises basalts and dacites (Lourens, 2013). Investigations by Buchanan *et al.* (2004) identified that this volcanic sequence is interbedded with poorly sorted sandstone units.

Above the Dullstroom Formation, the other three formations comprise mainly siliceous extrusive rocks. The Rooiberg Group according to Buchanan *et al.* (2004), comprises mainly magmatic activity and is typically fine-grained with phenocrysts, porphyroblast and amygdales and are rich in manganese and iron hydroxides which have formed as a result of groundwater activity within fractures.

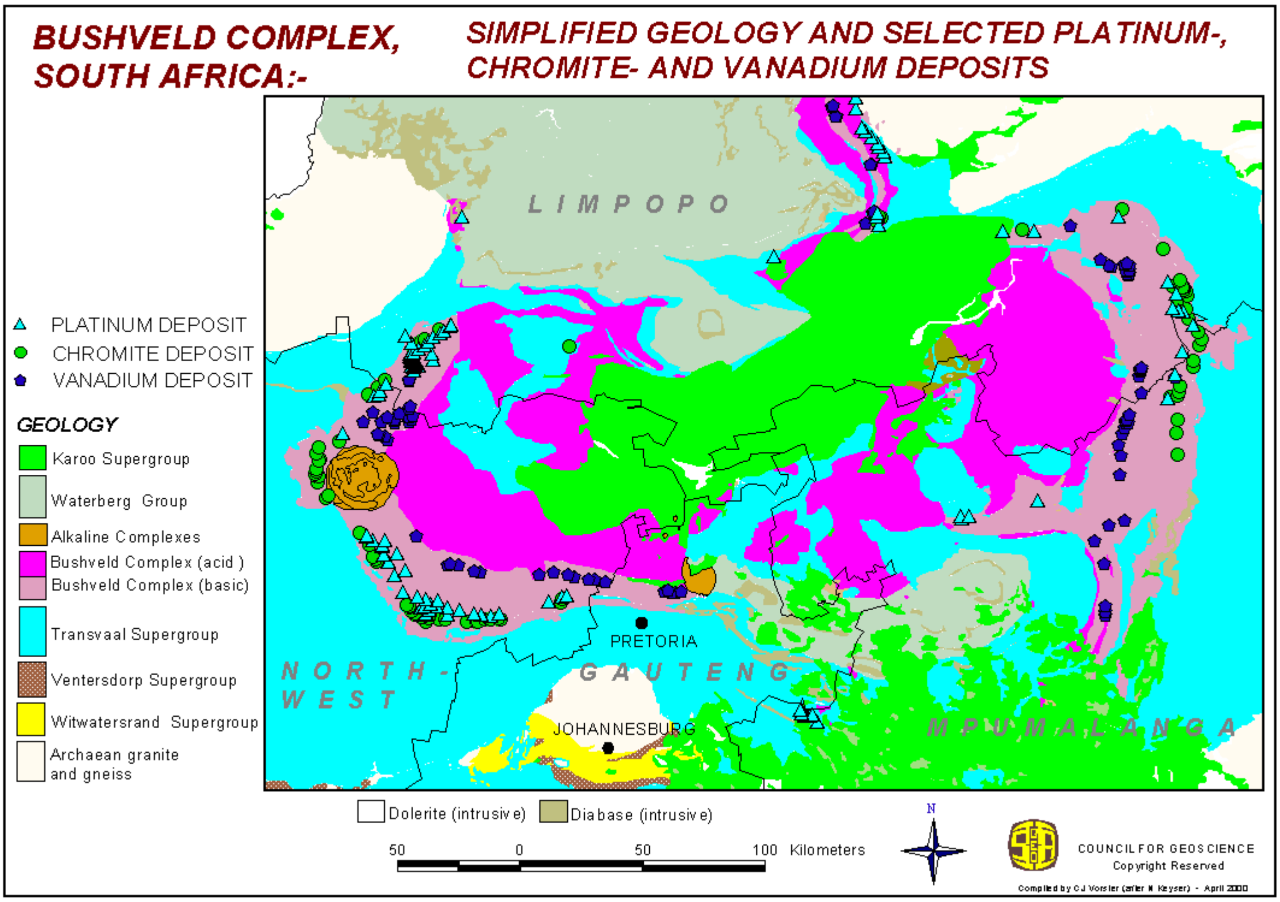

Figure 3-11: Simplified geology of the Bushveld Igneous Complex (Council for Geoscience, 2000)

3.3.2 Tectonic Setting of the BIC

The BIC is situated in the northeastern portion of the Kaapvaal craton and was created during an intracratonic and anorogenic event. The formation of the BIC was controlled by crustal scale structures that had trends east-northeast to west-southwest and north-northwest to south-southeast (Kinnard, J.A., undated). These structures are seen as the Thabazimbi Murchison lineament, Magaliesburg-Barbeton lineament and the Palalazoetfontein fault. According to Hayhoe (2013), the BIC has experienced some disruptions along the western limb which occurred during the formation of the Rustenberg fault. Aeromagnetic images (Figure 3-12 refers) provides an indication of faults and dykes within the BIC. According to Hayhoe (2013), there are two major faults within the BIC, a 2 600 m long sub-vertical trending in a northeast to southwest direction and a 1 600 m long sub-vertical fault trending in an east to west direction.

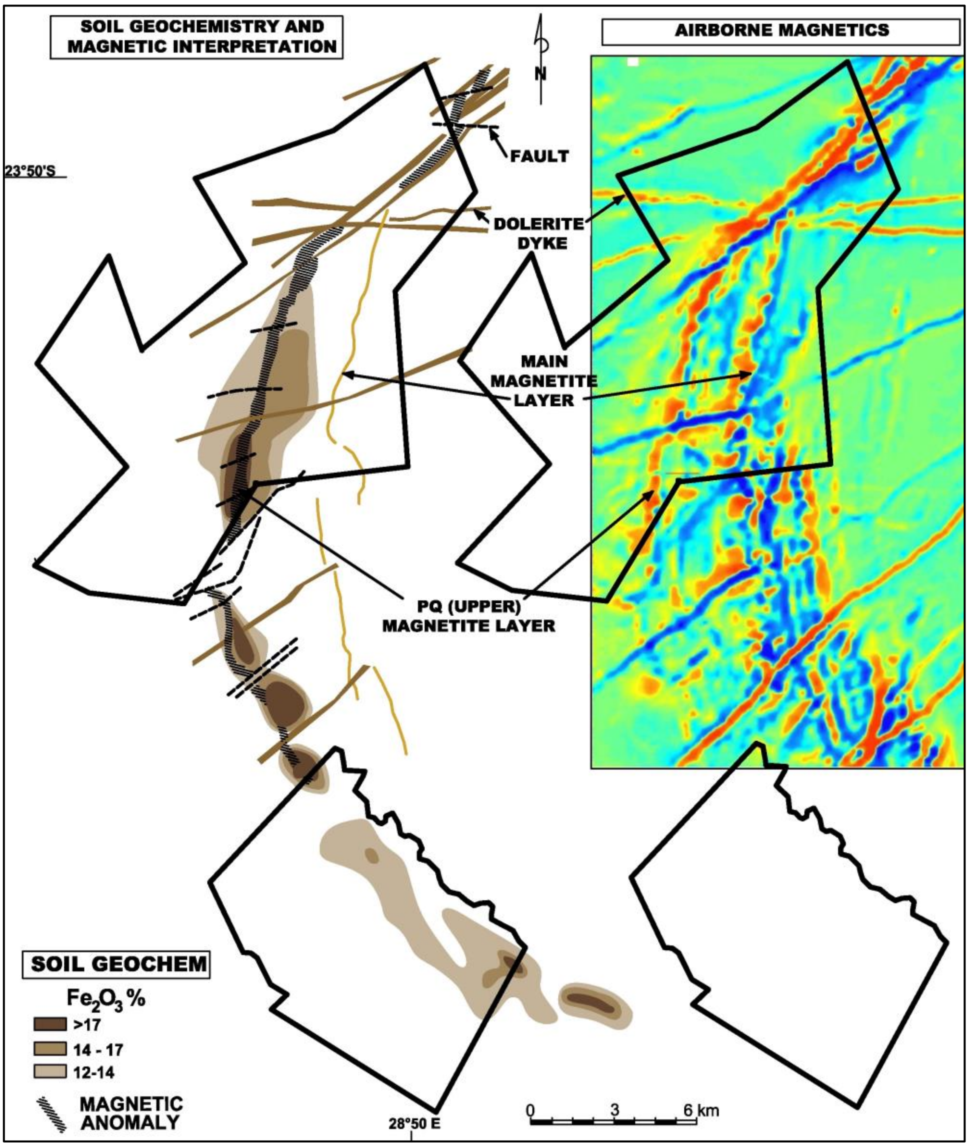

Figure 3-12: Aeromagnetic image of the BIC indicating the faults and dykes using geophysics (Hayhoe, 2013)

3.3.3 Geohydrology

Lourens (2013) classified the aquifers of the BIC as crystalline fractured and intergranular aquifer systems, with the intergranular aquifer limited to the weathered zone that ranges in thickness from 12 m to 50 m. Below the weathered zone, the unweathered, fractured aquifer zone extends to a depth where fractures are closed due to the pressure from the overlying rocks.

The aquifers of the BIC can be regarded as a low- to moderate-yielding, with the majority of boreholes yielding less than 2 L/s, but some areas where yields are greater than 5 L/s (Lourens, 2013). The Rooiberg Group, Rashoop Granophyre and Lebowa Granite Suites have borehole yields generally less than 2 L/s, but the RLS appears to be associated with higher-yielding aquifers that may be classified as a moderate- to high-yielding (Barnard, 2000). The yields of the boreholes in the RLS generally range from 0.5 L/s to 5 L/s, with a maximum measured yield of 25 L/s.

The BIC has abundant deposits of platinum group elements (PGE) and chromium, which has led to numerous mining activities to extract these resources (Cawthorn, 2010). Data collected in these mines have allowed for some characterisation of the groundwater systems within the BIC. Titus *et al.* (2009) characterised the shallow groundwater and mine fissure inflows for the BIC. A two-layer aquifer model was developed to describe the groundwater regime in the BIC on a regional scale. The model consists of an upper shallow, weathered bedrock aquifer system (intergranular aquifer), and a deeper fractured, bedrock aquifer (Titus *et al.,* 2009).

The deeper fractured aquifer consists of an unweathered bedrock matrix that has a low hydraulic conductivity. The effective hydraulic conductivity of the deeper aquifer is controlled by fractures and mine voids (Titus *et al.,* 2009). Groundwater flows through interconnected fracture systems with the potential for rapid vertical inflow from the upper weathered aquifer, as well as great depths along interconnected conductive zones. Initial groundwater quality data have indicated that groundwater from the deeper fractured aquifer is chemically and isotopically different to groundwater from the shallow aquifer. A longer, slower groundwater flow system appears to occur at depth.

DWA (2011) investigated the norite and gabbro lithologies of the BIC that lie within the Olifants Catchment. This investigation confirmed the regional scale groundwater regime described by Titus *et al.* (2009), where groundwater occurs in an upper weathered aquifer and a deeper fractured aquifer. Measured borehole yields from this area range from 0.5 L/s to 2 L/s, with higher yields found along dyke contacts (DWA, 2011). The average depth of boreholes drilled into the BIC within the Olifants catchment ranges from 30 mbgl to 80 mbgl (DWA, 2011). The limited depth of groundwater boreholes in the BIC has hindered the understanding of the deeper groundwater flow systems.

3.4 DOLOMITE AQUIFERS

3.4.1 What is a Dolomite Aquifer?

Dolomite as a rock has a low permeability, however, dissolution of the bedrock creates cavities which are known as dolomitic karsts. According to DWAF (2006), rain waters dissolves atmospheric carbon dioxide and create a weak acid that infiltrates beneath the surface along fractures and dissolves the dolomitic/limestone host rock. Over a period of time karsts start to develop within the dolomitic rock. Groundwater collects within these karsts and although dolomite maybe an impermeable rock, the groundwater moves via a series of fractures.

The Dolomites at the surface are considered to have a higher rate of dolomite cavities developing than dolomites at depth. This is possibly due to their extensive interaction with atmospheric conditions particularly that of acidic rainwater. However, dolomite cavities may still develop at depth particularly along or near areas close to dykes, faults and fractures that have free-flowing groundwater. Dykes, in particular, are impermeable features that compartmentalise dolomite aquifers.

3.4.2 Occurrence of Dolomites in South Africa

According to Naidoo (2014), there have been four karstification periods in South Africa, which where during the following periods, Pre-Pretoria Group (~1.95 Ga), Pre-Waterberg Group (~1.7 Ga), Pre-Karoo Supergroup (before the formation of the Dwyka Group) and the recent Tertiary period in which the Malmani Group rocks where exposed at surface. The main dolomite formations in South Africa are located within the Chuniespoort and Ghaap Groups (Table 3-1 refers).

Table 3-1: Summary of dolomitic sediments of the Cape and Transvaal Supergroups, youngest to oldest (DWAF, 2006)

Supergroup	Group	Member	Formation	Thickness (m)	Description
Malmani Dolomite					
Transvaal	Chuniespoort	Malmani	Eccles	380	Chert rich, dark coloured dolomite with stromatolites and oolitic bands. Chert content increases to top.
			Lyttelton	150	Chert free, dark coloured dolomite with large stromatolitic mounds
			Upper Monte Christo	258	Chert rich dolomite
			Middle Monte Christo	162	Chert rich dolomite
			Lower Monte Christo	275	Chert rich dolomite
			Oaktree	200	Chert poor dolomite with interlayered carbon rich shale towards the base
			Black reef	30	Basal conglomerate and quartzite with interlayered carbon rich shale.
Ghaap Plateau Dolomite					
Griqualand West	Ghaap Group	Campbell Rand			Coarse recrystallized dolomite with interbedded chert, prominent chert at base
					Dolomite, limestone and chert with interbedded shale
		Schmidtsdrif	Monteville		Dolomite, stromatilitic limestone interbedded with shale
			Clearwater		Shale and siltstone with interbedded dolomite
			Boomplaas		Oolithic stromatolitic dolomite with interbedded quartz, shale and flagstone

3.4.2.1 Chuniespoort and Ghaap Groups

The dolomite formations within the Chuniespoort Group is confined to the Malmani subgroup, which is differentiated into Oaktree (oldest), Monte Christo, Lyttelton, Eccles and Frisco (youngest) Formations (SACS, 1980). The Chuniespoort Group formed within the Transvaal Basin and overlies the Black Reef Formation.

The dolomite Formation within the Ghaap Group is confined to the Campbell Subgroup and formed within the Griqualand West Basing and overlies the Vryburg Formation. According to Eriksson *et al.* (1995), the Campbell Rand Subgroup and the Malmani Subgroup are correlated and formed around a similar time interval. These units comprise thick sequences of dolomites and limestone that are interbedded with chert, shale and stromatolites.

3.4.2.2 Geohydrology of Chuniespoort and Ghaap Groups

According to Lourens (2013), dolomite rocks, particularly those of the Chuniespoort and Ghaap Groups are considered to be the most important aquifers in South Africa. These aquifers are considered to be the highest yielding aquifers. These aquifers are however subdivided into different compartments by the presence of impermeable dykes.

The primary porosity of carbonate rocks is usually very low, however, due to the creation of secondary fractures and cavities that have formed as a result of dissolutions, the secondary porosity is very high, therefore, these aquifers are regarded as karst systems.

According to Schrade *et al.* (2014), the storativity at depths less than 90 mbgl is relatively high at 10% which is a result of higher porosity due to the weathering and the fine grain sizes. Beneath this layer comprises the cavernous dolomite that extends to a depth of approximately 200 mbgl and has a relatively low storativity of 2%. According to various authors cited in Schrade *et al.* (2014), the total volume of water stored within this dolomite is estimated to be in the range 663 million cubic metres (Mm^3) to 2200 Mm^3. They have also identified that the transmissivity in these dolomite rocks differ widely and is estimated to be in the range 1 000 m^3/day to 25 000 m^3/day. Schrade *et al.* (2014) calculated hydraulic conductivity in boreholes to be in the range $7x10^{-5}$ metres/second (m/s) to $3.1x10^{-4}$ m/s for the upper 200 m and $2.9x10^{-6}$ m/s to $1.0x10^{-5}$ m/s for the deeper aquifers.

According to various authors in Naidoo (2014), the storativity of dolomites is typically in the range 1% to 20%, transmissivity between 10 m^2/day to 30 000 m^2/day, a storativity coefficient of 0.0001% to 0.1% and storage of up to 12 000 million m^3 of water. According to Foster (1988), the highest transmissivity values were that of boreholes that were drilled into the Eccles Formation, where approximately 18 out of 30 boreholes (60%) had transmissivity values greater than 100 m^2/day.

Foster (1988) identified that the chert rich formation is more fractured and have a higher degree of dissolution than the chert poor horizons. Foster (1988) further identified that in areas were boreholes intersected paleo karst units had higher transmissivities, as much as 11 575 m^2/day. Typically it was identified that high transmissivity areas were associated with zones within close proximity to a dyke. Research by Kafri and Foster (1989) identified that transmissivity values up to 50 000 m^2/day were common to dolomite aquifers.

According to Lourens (2013), the dolomite aquifers of the Ghaap Group are moderate yielding and have yields in the range 0.5 L/s to 2 L/s with some boreholes encountering yields of at least 5 L/s. The Chuniespoort Group has higher yields than the Ghaap Group, with yields in boreholes at least 5 L/s and a maximum yield of 126 L/s (Lourens, 2013). According to Foster (1989), average yields for boreholes drilled into the Malmani Subgroup, particularly Oaktree, Monte Christo, Lyttelton and Eccles Formation, were in in the range 4.5 L/s to 64 L/s. Some boreholes drilled into the Monte Christo Formation yielded up to 64 L/s, whilst the Lyyelton and Eccles Formations yielded up to 29 L/s. It was also identified that borehole drilled near dykes had an increase in groundwater potential.

Lourens (2013) identified that the electrical conductivity within these karst aquifers is in the range 55 mS/m to 397 mS/m, which are an indication of generally good groundwater quality. However, due to the high permeability of the karst system, the groundwater is vulnerable to contamination from surface sources.

Thus, the dolomite formations within the Chuniespoort and Ghaap Groups are considered to be good aquifers for drilling of boreholes, particularly in areas where karstification and intrusions have occurred (Lourens, 2013).

3.4.2.3 Recharge of Dolomite Aquifers

According to DWAF (2006), recharge in dolomite aquifers is mainly by rainfall and can range between 0% to 50% of mean annual precipitation. (MAP). The unusual recharge rates are due to the different permeability rates of the dolomite units. Higher permeability is typically associated with karst aquifers and lower permeability with solid dolomite bedrock.

Kafri and Foster (1989) estimated that the recharge to the Malmani Dolomites was 25% of MAP using the chloride mass balance method and various authors calculated recharge rates to be in the range 2.5% to 28% of MAP.

3.4.2.4 Groundwater Quality

According to DWA (2006), groundwater from dolomite aquifers has a significant fingerprint of Calcium-Magnesium Bicarbonate ($Ca(Mg)$-HCO_3) waters. In addition, Ca^{2+} is usually at a higher concentration in dolomite groundwater than Mg^{2+}. In 1946, Bond carried out a study in which twenty-two groundwater samples were collected from various dolomite aquifers in the Transvaal and Northern Cape Province and laboratory analyses showed that concentrations of solid elements were typically between 200 to 300 parts per million (ppm) and in arid areas as much as 750 ppm and pH was typically consistent around 7.8. The concentration of solids within the groundwater was at least 87% of Ca and Mg, 4.6% Chloride (Cl), 1.6% Sulphate (SO_4) and traces of Fluoride (F). According to Kafri and Foster (1989), total dissolved solids (TDS) concentrations are typically around 500 mg/L for pure dolomite groundwater and greater concentrations for contaminated groundwater.

CHAPTER 4:
COMPARISON OF SHALLOW AQUIFER SYSTEMS AND IDENTIFICATION OF POTENTIAL DEEP AQUIFER SYSTEMS

4.1 INTRODUCTION

This chapter first describes the aquifer characteristic of the shallow manifestations of the three aquifer systems discussed in this dissertation. Although the deep aquifer systems are likely to differ from their shallow counterparts, an understanding of the shallow aquifer systems may allow insight into some of the expected characteristics of the deep aquifer systems. Next, potential deep aquifer systems of the three types discussed in this dissertation are identified by considering the geological and geohydrological characteristics of the rock units that may host these aquifer systems.

4.2 COMPARISON OF SHALLOW AQUIFER SYSTEMS

Table 4-1 provides a summary of the hydrogeological characteristics of each aquifer system based on the information identified in this dissertation.

The basement complexes and BIC have similar types of bedrock, i.e. they have formed from igneous intrusions/extrusions, and are considered as crystalline bedrock. These rocks are usually associated with very low primary porosities and have low hydraulic conductivities. Boreholes drilled into these bedrock aquifers, typically yield volumes less than 1L/s. There are instances in which borehole had yields greater than 1 L/s, but these were in areas that have a high fracture network and/or are located close to fault zones. The boreholes have double porosity, i.e. they are intergranular and fractured.

The dolomite aquifer formed in a carbonate-rich sedimentary environment such as the Transvaal and Griqualand West Basins. These rocks have low primary porosity and hydraulic conductivities. However, the development of dissolution cavities (karst) and fractures increase the porosity and hydraulic conductivity. The karsts have significant volumes of water and boreholes drilled, typically have high yields, usually greater than 5 L/s.

The primary porosity of these aquifers are considered to be low and groundwater is usually encountered when there are secondary structures such as faults, fractures, contact zones, etc. The degree of fracturing and weathering of bedrock generally decreases to depths in excess of 100 m. This is possibly a result of the overburden rocks that forces the closure of any fractures with the geological profile. With a decrease in fracture frequency, there is usually a decrease in groundwater potential. Furthermore, aquifers at a depth generally receive less recharge that the shallow aquifers.

In terms of water quality, Table 4-2 provides a summary of groundwater samples from the different aquifers. Three groundwater samples per aquifer are compared to obtain a basic understanding of the typical groundwater conditions of the shallow aquifer systems. Three basement complex samples are collected from schools in KwaZulu-Natal province, BIC groundwater samples are collected from Impala Platinum Mine in the North West Province and Dolomite samples are collected from Quarry Site in Delmas in Mpumalanga Province.

In terms of groundwater quality, pH, sulphate, TDS and alkalinity contents have been plotted on Figure 4-1 to Figure 4-3 to illustrate the typical groundwater ranges for each aquifer type and have been referenced according to SANS 241-2015 for Drinking Water.

The pH concentrations fall within the SANS 241 required limits with the exception of a single sample from the BIC. The pH values for the BIC are not consistent and have a range of values. Similarly, the basement aquifers have a slight deviation with the pH but not a significant one. The only consistent pH value is within the Dolomite aquifers which are approximately pH of 8 as shown in Figure 4-1.

The TDS concentrations for the different aquifers, particularly the basement and BIC aquifers have a range of concentrations from 100 to 950 mg/L as shown in Figure 4-2. The dolomite aquifers have relatively consistent TDS values in the range 100 to 200 mg/L.

Sulphate concentrations with the aquifers have a significant variation. The BIC aquifer has sulphate values in the range 10 to 1 000 mg/L as shown in Figure 4-3. The basement aquifers have sulphate content in the range 1 to 100 mg/L with dolomite aquifers have a consistent range of less than 10 mg/L.

Table 4-1: Comparison of the different shallow aquifer systems

Description	Basement Complexes	Bushveld Igneous Complex	Dolomite
Lithology	The rock types associated with these type of aquifers are granites, migmatites, geisses, etc. Typically bedrock which extruded during the Precambrian and Cambrian Era.	The rock types associated with these type of aquifers are gabbros, norites, anorthosites, etc. The BIC is associated with a spectrum of rocks that range from utramafic to felsic.	These type of aquifers are associated with dolomite/limestone bedrock that is rich in carbonates. There are two typical basins in which these aquifer form in South Africa, the Transvaal and Griqualand West Basin.
Occurrence	Typically occur down to depths in excess of 8km and are the founding horizons for many ancient sedimentary basins. An example is that of the Natal Structural and Metamorphic Province in KwaZulu-Natal	The BIC is localised within the north western and north eastern parts of South Africa, particularly around Northwest, Gauteng, Limpopo and Mpumalanga Provinces	Dolomite aquifers are typically encountered in the Northern Cape, Northwest, Gauteng, Limpopo and Mpumalanga Provinces.
Aquifer Type	These are considered to be secondary aquifers and groundwater is stored and/or moves through fractures in the bedrock, hence, can be regarded as fractured aquifer systems. These rocks are usually associated with low porosities.	These are considered to be secondary aquifers and groundwater is stored and/or moves through fractures in the bedrock, hence, can be regarded as fractured aquifer systems. These rocks are usually associated with low porosities.	These type of aquifers are considered to be secondary aquifers which groundwater is stored and/or moves through fractures and dissolution cavities. Typical feature with dolomites is the development of karst.
Hydraulic Parameters	Primary hydraulic conductivities of unfractured basement rocks are expected to be low, however, if fractured, these aquifers can have a high hydraulic conductivity.	Primary hydraulic conductivities of unfractured rocks are expected to be low. However, when fractured these aquifers can have high hydraulic conductivities.	Primary hydraulic conductivities, transmissivities and storativities of dolomite bedrock is poor. However, if there is a presence of cavities (Karsts) and dissolution networks, the hydraulic properties are high.
Inferred Yield	The yields for basements aquifers are considered to be very low. Even if fractured, these aquifers at depth will receive very low recharge, thus, volumes of groundwater are expected to be low. Yield are typically less than 1L/s.	The yield for these type of rocks is expected to be low to moderate. The degree of fracturing is expected to decrease with an increase in depth, therefore, limited recharge can be expected with an increase in depth. Yield are typically less than 2L/s.	The yield of these aquifers is anticipated to be very high and in some areas boreholes obtained yields of at least 60L/s.
Inferred Groundwater Quality	The groundwater quality of these aquifers is expected to be good. Chemicals within the groundwater may have different concentrations depending on the chemistry of the host bedrock.	The groundwater quality within these type of aquifers is expected to be poor and have a high concentration of TDS. Due to mining activities within these areas, AMD is expected to contaminate the groundwater.	The groundwater quality of these type of aquifers are considered to be very good, however, due to mining activities these aquifers maybe polluted with AMD.

Table 4-2: Summary of groundwater quality results for the different aquifer systems in South Africa

Determinant	SANS 241	Siyathuka School in Pongola KwaZulu-Natal Province	Makhapha School, Pinetwon District, KwaZulu-Natal Province	Senzokhule School, Pinetwon District, KwaZulu-Natal Province	Impala Mine in Rustenburg, Northwest Province (MWG 18-04)	Impala Mine in Rustenburg, Northwest Province (MWG 18-02)	Impala Mine in Rustenburg, Northwest Province (MWG 18-06)	Delmas Quarry, Mpumalanga Province Pedra 1	Delmas Quarry, Mpumalanga Province, Pioneer 3	Delmas Quarry, Mpumalanga Province ES 16 BH1D
Bedrock Type		Basement Granite	Basement Granite	Basement Gneiss	BIC Gabbro	BIC Gabbro	BIC Gabbro	Dolomite	Dolomite	Dolomite
pH	5 to 9.7	7.6	8.2	6.9	9.8	8.3	7.7	7.9	7.8	7.8
TDS	<1200	123.5	546	468	782	360.1	929.5	115.05	117	206
EC (mS/m)	<170	19	84	72	120	55.4	143	17.7	18	33.6
Sodium (mg/L)	<200	12	93	85	211	127	73	2	2	
Potassium (mg/L)	NS	0.9	-	-	<1.0	<1.0	<1.0	1	0.9	1.1
Calcium (mg/L)	NS	13	40	29	19	4	99	16	15	3.5
Magnesium (mg/L)	NS	6.7	27	14.4	<2	<2	99	10	11	18
Fluoride (mg/L)	<1.5	0.01	1.1	0.1	0.5	4	0.2	-	-	
Nitrite (mg/L)	<0.9		0.1	0.1	-	-	-	-	-	
Nitrate (mg/L)	<11	2.6	4.07	9.74	0.2	0.2	31	4.4	5.3	10
Chloride (mg/L)	<300	12	64	85	84	39	126	4	5	14
Sulphate (mg/L)	<500	1.75	26	18.6	409	26	66	4	5	4
Alkalinity (CaCO3)	NS	65	264	139	48	196	444	72	60	128
Source		Geosure (Pty) Ltd	Engeolab (Pty) Ltd		SLR Global Environmental Solutions			Jones and Wagner (Pty) Ltd		

NS - Not Specified   - Results not available

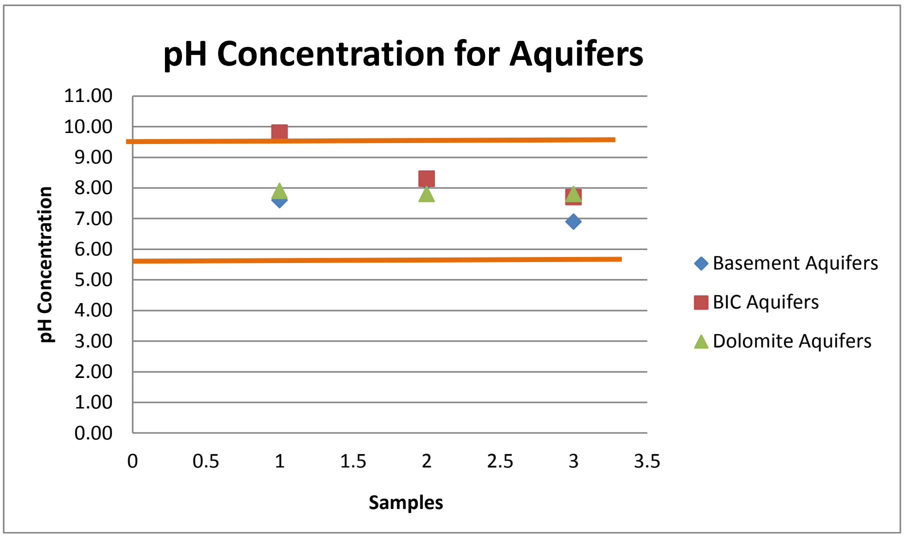

Figure 4-1: Comparison of pH values for different aquifer systems (orange lines correspond to the SANS 241-2015 limits)

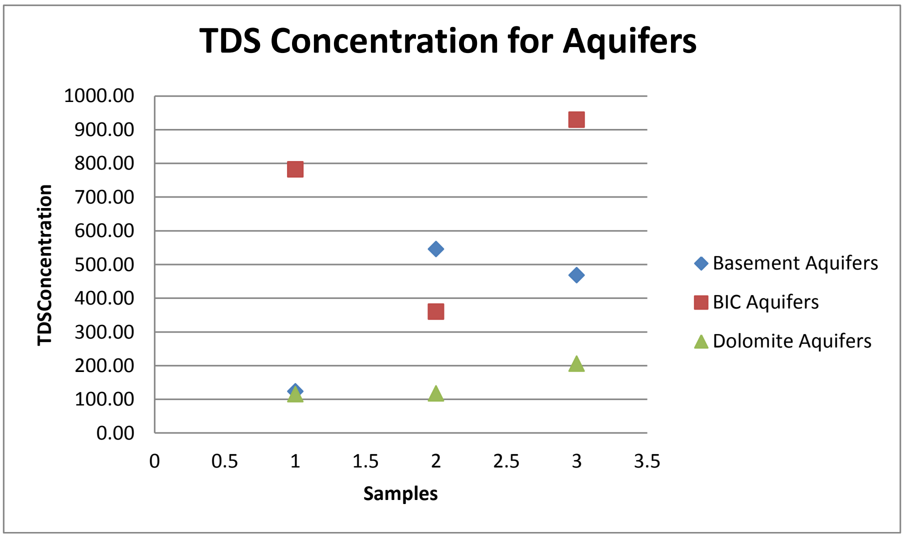

Figure 4-2: Comparison of TDS concentrations for the different aquifer systems

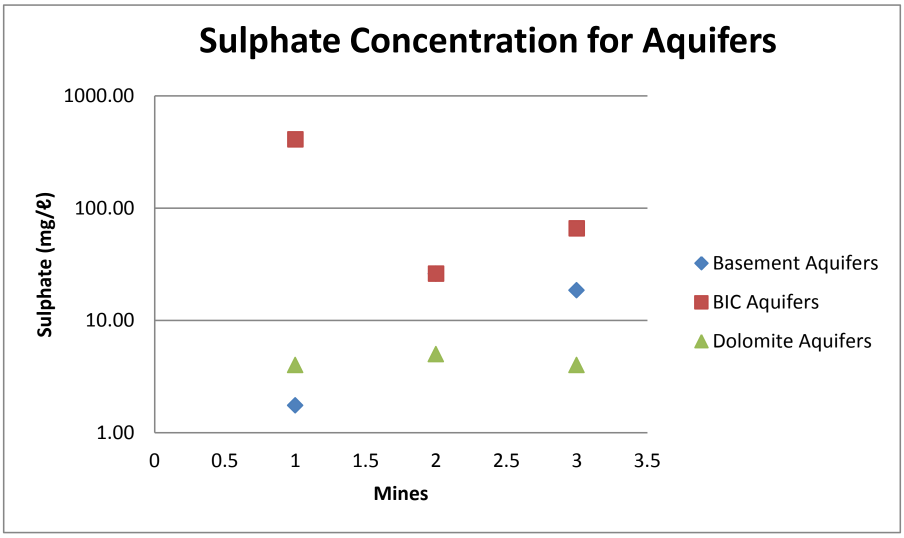

Figure 4-3: Comparison of sulphate concentrations for the different aquifer systems

Although only three samples from each aquifer system were compared, the results correspond to the literature review and the following comments can be made:

- The groundwater quality of the basement and dolomite aquifers is considered to be good.
- The groundwater quality of the BIC aquifers is considered as poor groundwater.
- The pH values of the basement and dolomite aquifers are relatively constant, whilst the pH values of the BIC aquifers vary.
- The TDS concentrations for the BIC aquifer are significantly greater than for the basement and dolomite aquifers.
- The TDS concentrations for the dolomite aquifer are generally consistent between 100 and 200 mg/L, which is a good indication of fresh water.
- The sulphate concentrations are the greatest for the BIC aquifers and the lowest for the dolomite aquifers.

Based on the information identified thus far, a possible classification of potential deep aquifer zones can be discussed.

4.3 POTENTIAL DEEP AQUIFERS

Areas in which there is a potential for deep aquifer systems in South Africa will be briefly described here based on available information.

4.3.1 Identified Potential Deep Aquifers

Based on the current data collected, the main potential deep aquifers are identified for further investigation. A ranking system is implemented, using ranks from 1 – 4:

Rank 1 shows a positive indication for deep groundwater systems

Rank 2 shows some indication for deep groundwater systems

Rank 3 shows a neutral indication for deep groundwater systems

Rank 4 shows a negative indication for deep groundwater systems

4.3.1.1 Geological Groups

Rank 1 Geological Groups

- Limpopo Belt

The occurrence of thermal springs within the Limpopo Belt serves as an indication of long, deeper groundwater flow systems.

- Transvaal Supergroup

The carbonate rocks of the Chuniespoort and Ghaap Groups represent an important aquifer system in South Africa. It was found that the storativity of the dolomites decreases with increasing depth. A decrease in storage from approximately 9.1% at a depth of 61 mbgl to 1.3% at a depth of 146 mbgl was observed.

Rank 2 Geological Groups

- Archean Greenstone Belts

Groundwater within this geological group is dependent on the secondary porosity and permeability of the bedrock, such as fractures and dyke intrusions. There are areas in which low yield have been encountered at depth.

- Archaean Granites and Gneisses

This group is classified to have a double porosity aquifer system (intergranular and fractured), this system is considered to be structurally controlled and may be of a semi-confined nature. Fractured within this group may exceed a depth of 120 mbgl. These aquifers typically exceed the expectation of similar crystalline aquifers as identified in the Limpopo area.

- Bushveld Complex

Groundwater flow within this aquifer system is mainly between interconnected fractures at various depths. Chemical analysis carried out on groundwater samples indicates that the shallow and deep aquifer systems are isotopically different and indicate longer residence time for the deeper aquifer system.

- Namaqua-Natal Province

In areas that are highly fractured, there is a potential for high yielding aquifers.

Rank 3 Geological Groups

No rank for the geologies in this dissertation.

Rank 4 Geological Groups

No rank for the geologies in this dissertation.

4.3.1.2 Thermal Springs

According to LaMoreaux and Tanner (2001), the flow rate of thermal springs is determined by the aquifer size, recharge rate, storage capacity of the aquifer, and storativity of both aquifer and fracture in which the water is transported. It is understood that thermal springs may originate in areas of recent volcanic activity or meteoric water flow through fractures in bedrock. In South Africa, thermal springs originate in an area where there are geological structures and high temperatures encountered are due to geothermal gradients (Kent, 1949). There are a total of 83 thermal springs in South Africa, of which 9 are considered to be an artesian system.

In areas where there has been a potential for deep groundwater aquifers, indications regarding deep groundwater flows have been identified in areas of thermal springs. Depending on the temperature of thermal springs, an assumed groundwater origin depth may be adopted. In order to refine the search for potential deep aquifer systems, thermal springs need to be researched further.

4.3.1.3 Depth of fractures

Murray *et al.* (2000) stated that more than 90% of South Africa's groundwater occurs within hard-rock, fractured aquifers. Other authors have also 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.

The porosity and permeability of bedrock will decrease with an increase in depth and due to the overburden pressures, the fractures at depth may close. A study carried out by Lin *et al.* (2007) identified that there are four hydraulic zones within the bedrock:

- High hydraulic zone down to at least 150 mbgl.
- Medium hydraulic zone down to at least 400 mbgl.
- Low hydraulic zone down to at least 570 mbgl.
- Hydraulically inactive zone down to the final depth of the borehole at 800 mbgl.

Based on the research of Lin *et al.* (2007), the potential for groundwater below a depth of 570 mbgl is considered to be very low. This may be an isolated case as Rosewarne *et al.* (2002) identified groundwater within the Table Mountain Group to a depth of at least 2000 mbgl. The presence of groundwater here may be due to the brittle deformation of the bedrock during a continental scale orogeny.

Deep aquifer systems are located a significant distance from the shallow overexploited aquifers and additional research is required to identify these aquifer systems. One of the main initiatives is to identify the fracture depths and depths to which fractures remain open.

CHAPTER 5: AVAILABLE DEEP AQUIFER INFORMATION

5.1 INTRODUCTION

In this chapter, available information regarding deep groundwater aquifers will be discussed, as follows:

1. Council for Geoscience (CGS) database in which more than 5 000 boreholes greater than 300 m are available.
2. Boreholes from the National Groundwater Archive (NGA) from the Department of Water and Sanitation (DWS).
3. Groundwater information from thermal springs.
4. Bushveld Igneous Complex Drilling Project (BICDP).

The objective of this chapter is to identify basic hydrogeological information based on available deep groundwater data. The following will need to be identified at a minimum:

- Location (GPS coordinates)
- Geological information, and,
- Geohydrological information (groundwater quality, groundwater quantity, and depth of aquifers).

5.2 BOREHOLES FROM THE COUNCIL FOR GEOSCIENCE

Borehole information sourced from the CGS is derived from the energy and mining sectors. It should be noted that there is limited hydrogeological information available. Basic information such as borehole ownership name, the location of the borehole, date of borehole exploration, and borehole depth. Additional information was available for boreholes drilled within coal mines as these comprised basic water analysis.

The total number of boreholes existing within the CGS records with depths greater than 300 m is 5 221. Based on a statistical analysis, as shown in Figure 5-1, approximately 48.6% of boreholes were drilled to 400 m in depth, 26.5% were drilled to 500 m in depth, 12.9% to 700 m in depth with the remaining 12% drilled to depths greater than 700 m in depth. Figure 5-2 shows the distribution of CGS boreholes within South Africa, as can be identified, the majority of the boreholes are within the northeastern portion of the country.

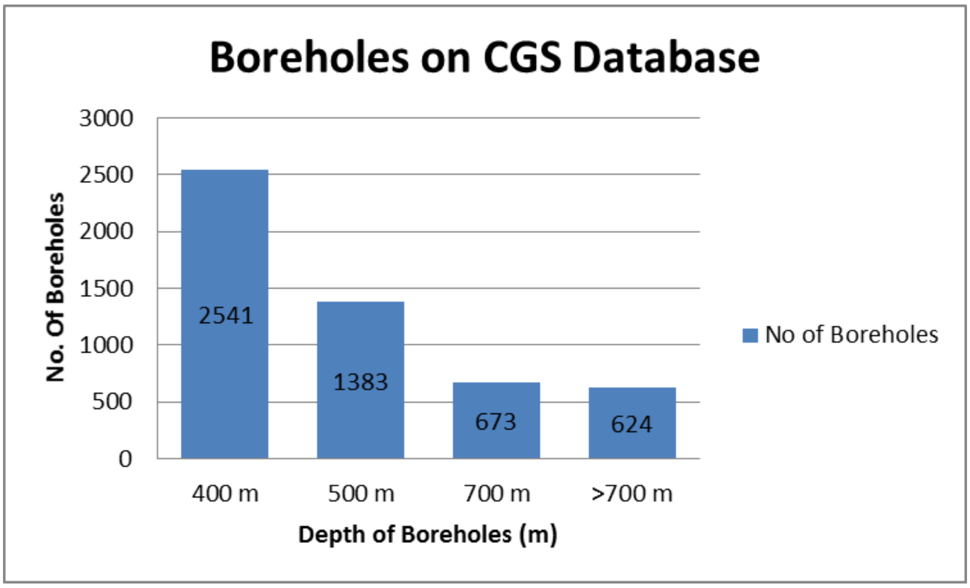

Figure 5-1: Depth distribution of boreholes with depths exceeding 300 m in the CGS database

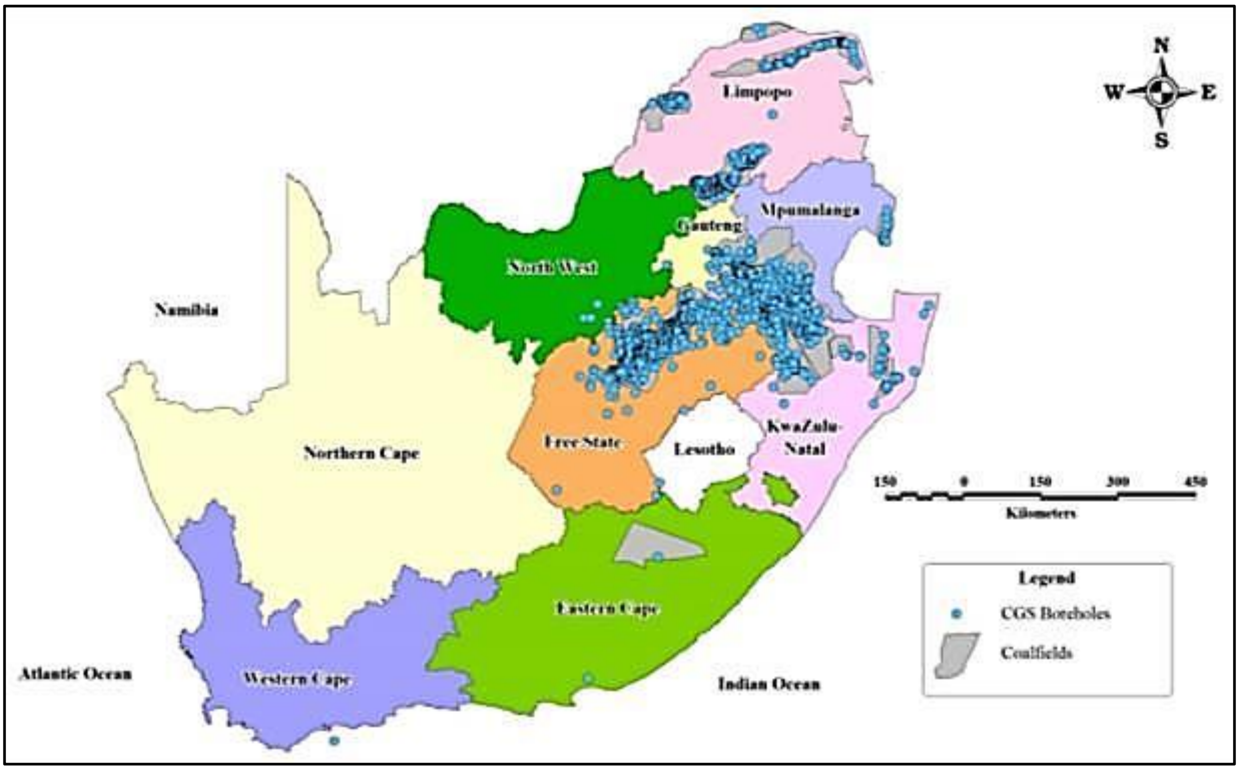

Figure 5-2: Distribution of boreholes with depths greater than 300 m in the CGS data

BOREHOLES WITHIN THE NATIONAL GROUNDWATER ARCHIVE

The NGA database is helpful tools developed by the DWS to assist hydrogeologists in South Africa to identify existing groundwater data. There is insufficient information within the NGA database to assist with identifying hydrogeological characteristics of boreholes greater than 300 mbgl. The NGA database was developed with the aim to promote sustainable groundwater use in South Africa. On 04 March 2016, existing information from the NGA was extracted and the database comprised 253 441 boreholes. However, only 0.5% (1 116) were drilled to depths in excess of 300 m. The distribution of boreholes within South Africa are shown in Figure 5-3.

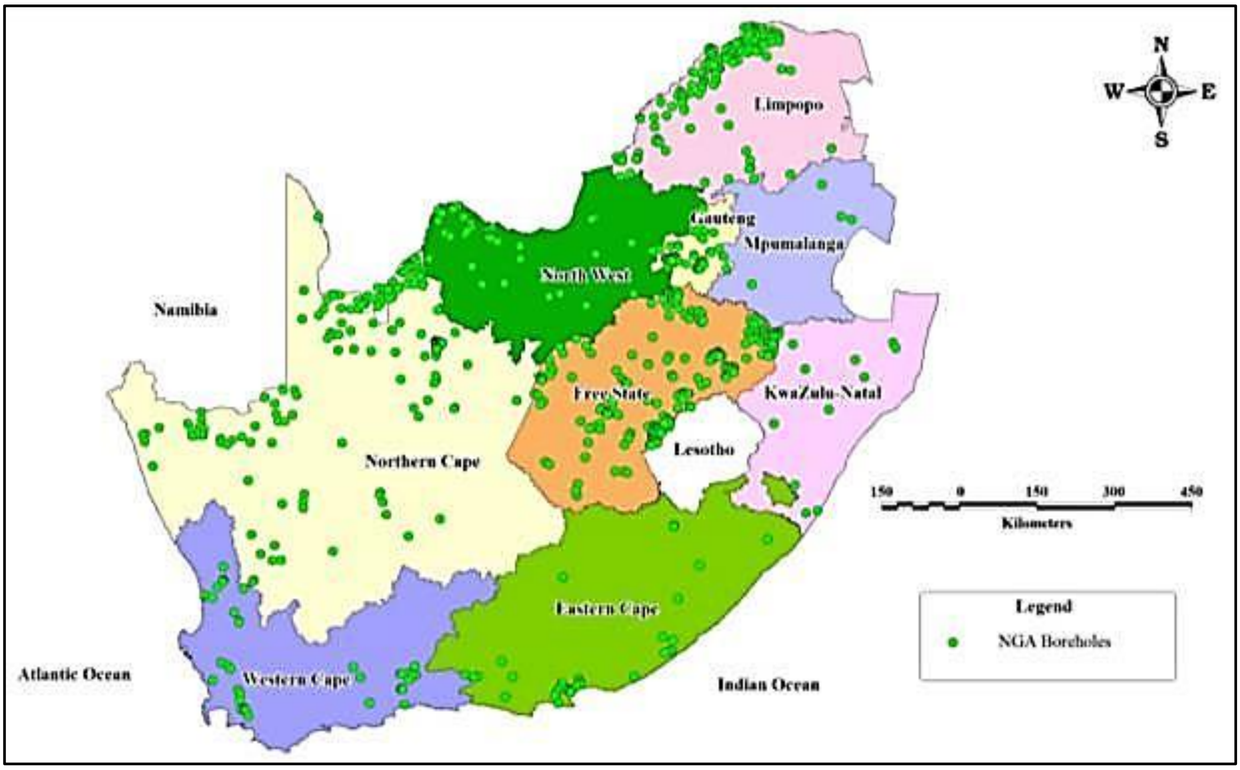

Figure 5-3 Distribution of boreholes with depths greater than 300 m in the NGA

5.4 THERMAL SPRINGS IN SOUTH AFRICA

5.4.1 Introduction

As mentioned in earlier Chapters, thermal springs are geothermally heated groundwater that originates from a great depth below the surface. Due to the potential circulating depth, analysis of groundwater samples from these springs may provide information on the groundwater quality at depth. Thermal springs may be of two origins volcanic or meteoric.

5.4.1.1 Thermal springs of volcanic origin

Thermal springs develop within close proximity to slow cooling magma reservoirs that are located close to the surface and heat the host bedrock. Thermal springs form when groundwater is heated as it migrates through the fractures within the bedrock. Eventually, the groundwater makes its way to the surface and develops into a thermal spring.

5.4.1.2 Thermal springs of meteoric origin

Meteoric thermal springs are associated with geothermal gradients instead of volcanic activity. Water from rain, rivers and lakes migrate down beneath the earth’s surface through various fractures/openings and extend to for several kilometres. This underground water is then heated by a geothermal gradient with temperatures of approximately 3°C for every 100 m. The heated groundwater expands and rises along another fracture set, creating a convection system. Figure 5-4 shows a typical setting for volcanic and meteoric thermal springs.

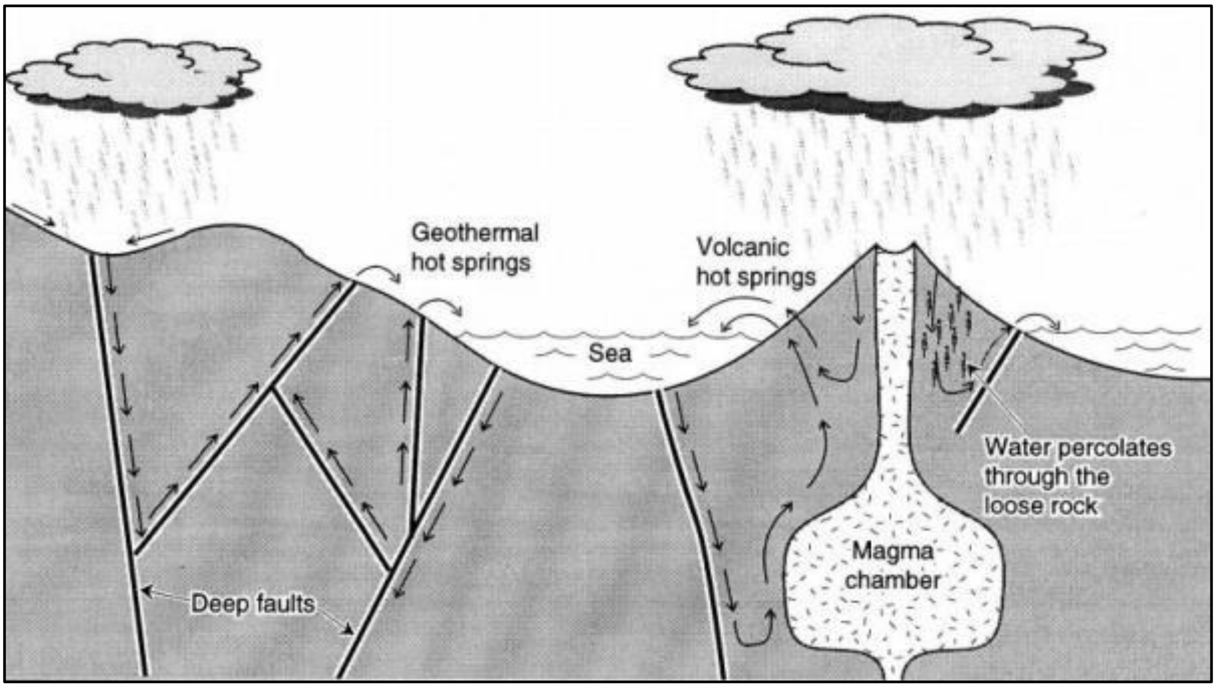

Figure 5-4 Diagrammatic representation of the origin of thermal springs (Higgins and Higgins, 1996)

The origin of thermal springs in South Africa is considered to be meteoric as there is no known area that is volcanically active. According to Witcher (1981), there are a few conditions that are associated with thermal springs, such as, heat source, recharge source, circulation framework and discharge mechanism. Based on research, the hottest geothermal spring in South Africa is located within the Limpopo Province and is situated along the Nzhelele Fault, which is considered to be a geologically active area. The name given to the spring is Siloam and is approximately 67.5°C.

5.4.1.3 Distribution of thermal springs in South Africa

A total of 87 thermal springs have been identified within South Africa, of which only 34% are developed into relaxation resorts (Hoole, 2001). Kent (1952), Boekstein (1998) and Hoole (2001) identified that majority of the thermal springs in South Africa are concentrated in the Limpopo and Western Cape provinces. Evidence suggests that the springs are located within a 400km wide strip of land from the west to the northeast of South Africa (Figure 5-5 refers). According to Demlie and Watkeys (2011), the thermal springs throughout KwaZulu-Natal are a result of various geological structures.

Considering South Africa is situated in areas of no recent volcanic activity, various studies have provided a conclusion that the thermal springs form as a result of groundwater activity emanating from deep geological structures such as faults, folds and dykes which are preferential flow paths for groundwater. The heated groundwater is then transported to the surface along these flow paths.

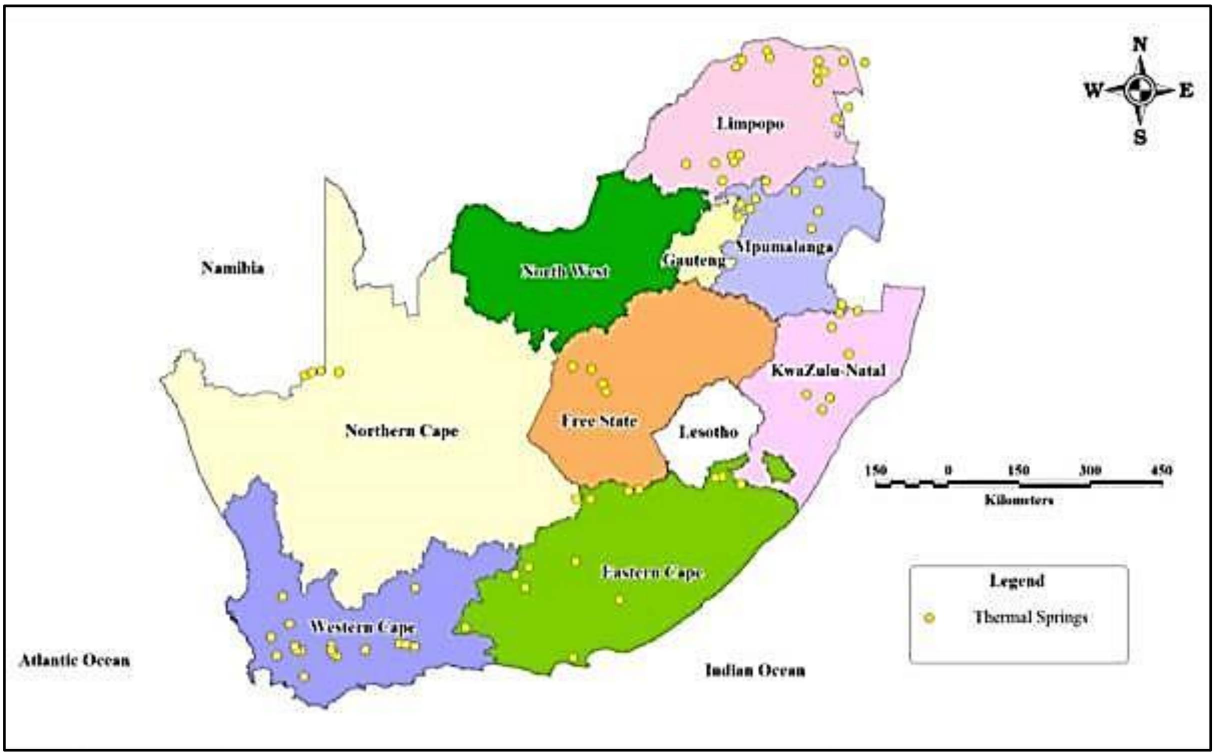

Figure 5-5 Distribution of thermal springs in South Africa (after Baiyegunhi *et al.*, 2014)

5.4.1.4 Information on the hydrochemical characteristics of water from thermal springs

According to Kent (1949), the groundwater chemistry of thermal springs do not correlate with the constituents of the surface geology, but rather the geology at depth, however, this is not always the case. Kent (1949) devised a classification scheme for thermal springs that differentiated them by their respective temperatures. These classifications are as follows:

- 25°C to 37°C - Warm Springs,
- 38°C to 50°C - Hyperthermic (hot), and,
- >50°C - Scalding.

Bond (1946) distinguished thermal springs based on their chemical concentrations and can be seen in Table 5-1 below.

Table 5-1: Classification of thermal water according to Bond (1947)

Class	Water	Chemical Composition
A	Highly mineralised chloride-sulphate water	TDS >1 000 mg/L; Cl > 270 g/kg; SO4 > 50 g/kg
B	Slightly saline chloride water	TDS 300-500 mg/L; Cl > 270 g/kg; SO4 < 3 g/kg
C	Temporary hard carbonate water	TDS < 800 mg/L; pH >7.6
D	Alkaline sodium carbonate water	TDS < 1 000 mg/L; Na2CO3 or NaHCO3>150 mg/L
E	Pure water	TDS <150 mg/L; pH<7.1

5.4.1.5 Thermal Springs of KwaZulu-Natal

According to Demlie and Watkeys (2011), there are approximately five thermal springs throughout KwaZulu-Natal (KZN). Table 5-2 provides an indication of the basic attributes for the springs as indicated by Demlie and Watkeys (2011).

Table 5-2: Temperature of thermal springs throughout KZN

Spring Name	Location	Temperature (°C)	Altitude (mamsl)
Black Mfolozi	Ulundi	37	560
Lilani	Greytown	40	622
Natal Spa	Paulpietersburg	41	940
Shushu	Kranskop	51	217
Warmbad	Paulpietersburg	31	878

As indicated in Table 5-2, the temperatures of the springs vary, from 31°C to 51°C. According to Demlie and Watkeys (2011), thermal springs usually occur in volcanically active areas, however, South African thermal springs are unique in that they occur in a tectonically stable region. According to Demlie and Watkeys (2011), the thermal springs throughout KwaZulu-Natal are a result of various geological structures. Figure 5-6 adapted from Demlie and Watkeys (2011), provides a basic illustration of the locality of the hot springs.

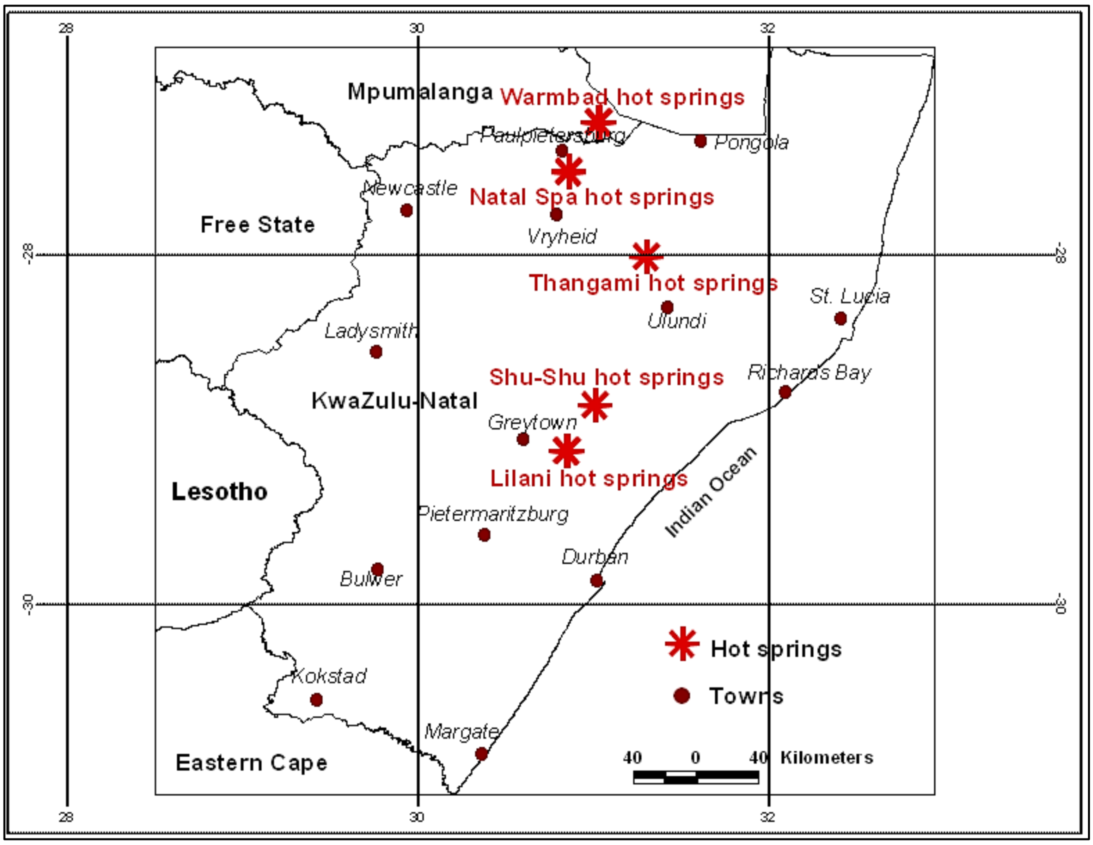

Figure 5-6: Locality plan of the thermal springs in KwaZulu-Natal (Demlie and Watkeys, 2011)

Geologically the thermal springs are in the area that is underlain by pre-Karoo igneous and metamorphic rocks and Karoo sedimentary rocks. According to the Council for Geoscience

1:250 000 geological map series for these areas, the following information regarding geology can be summarised for each hot spring:

- **Lilani:** Geology in the area comprises of gneiss, schist and granulite bedrock that is situated adjacent to a south-west to northeast trending fault.
- **Shu-Shu:** Geology in the area comprises of diorite, granite, schist and amphibolite that is situated on a south west to north east thrust fault.
- **Black Mfolozi:** Geology of the area comprises of tillite bedrock of the Dwyka Group.
- **Natal Spa:** Geology of the area comprises of granite bedrock.
- **Warmbad:** Geology of the area comprises of tillite basalt and rhyolite bedrock that have been intruded by Jurassic age dolerite.

From a geological perspective, all five springs are situated within the Natal Structural and Metamorphic Complex. The area is associated with numerous folds and faults that are considered as planes of weakness within the stratigraphic sequence, hence, preferential flow paths for fluids. These fractures are known to originate at great depths beneath the earth's surface.

According to Demlie and Watkeys (2011), a 3°C change per 100 m depth is considered applicable for geothermal gradients in South Africa. Based on the identified temperatures of the thermal springs the approximate origin depth may be calculated. Table 5-3 provides an indication of the temperature and depth of origin.

Table 5-3: Temperature and water origin depth of the thermal springs

Spring Name	Temperature (°C)	Depth of Origin (mbgl)
Black Mfolozi	37	1 235
Lilani	40	1 335
Natal Spa	41	1 370
Shushu	51	1 700
Warmbad	31	1 035

According to Demlie and Watkeys (2011), the temperature is only an estimate and the actual temperature at depth can only be determined by drilling boreholes into the aquifer. Demlie and Watkeys (2011) collected water samples and analysed for various chemical elements, only the pH, electrical conductivity (EC) and total dissolved solids (TDS) were discussed in detail. Table 5-4 provides an indication of the water quality parameters.

Table 5-4: Water quality results for the springs

Spring Name	Temperature (°C)	pH	TDS (mg/L)	EC (mS/m)
Black Mfolozi 1	36.53	8.64	319	0.638
Black Mfolozi 2	34.05	8.67	317	0.635
Lilani 2	40	9.22	219	0.438
Lilani 3	38.7	9.18	218	0.436
Lilani River	17.63	7.8	82	0.163
Natal Spa	40.73	9.07	172	0.343
Natal Spa Borehole	22.01	6.41	120	0.24
Bivane River	18.16	8.06	48	0.095
Shu-Shu	51	7.7	789	1.554
Warmbad 1	30.1	9.67	139	0.278
Warmbad 2	31.2	9.56	141	0.278
SANS 241-2015 Range		5.0 to 9.7	1200	170

Referring to Table 5-4, the following comments can be made:

- The average temperature of the water is 32.74°C with minimum and maximum values of 17.63°C and 51°C;
- Average pH of the water is 8.54 with minimum and maximum values of 6.41 and 9.67 respectively;
- Average TDS of the water is 233.09 mg/L with minimum and maximum values of 48 mg/L and 789 mg/L; and
- Average EC of the water is 0.436 mS/m with minimum and maximum values of 0.095 mS/m and 1.554 mS/m.
- Referring to Table 5-4, spring classification by Bond 1947, based on the TDS values all the springs except Shu-Shu classify as Class B, which indicates slightly saline chloride water.

According to the South African National Standards (SANS) for drinking water (SANS 241), the water samples fall within the recommended limits for safe drinking water. Figure 5-7 to Figure 5-9 provide a graphical representation of the water quality results, the solid green line represents the SANS 241 allowable limits.

Nonetheless, based on these three basic parameters, the water in the area can be considered as pristine. Hence, it can be considered that the water quality at depths greater than 1 000 mbgl in this area is pristine.

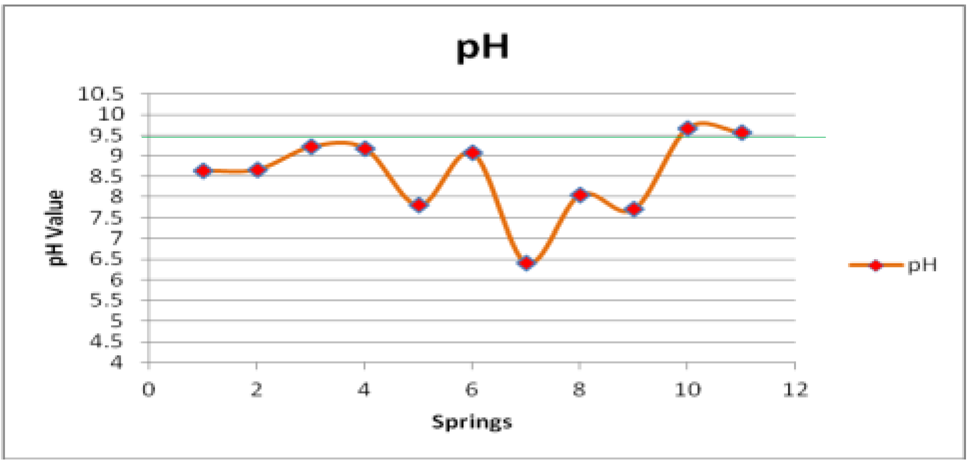

Figure 5-7: pH results of the water from the spring sites

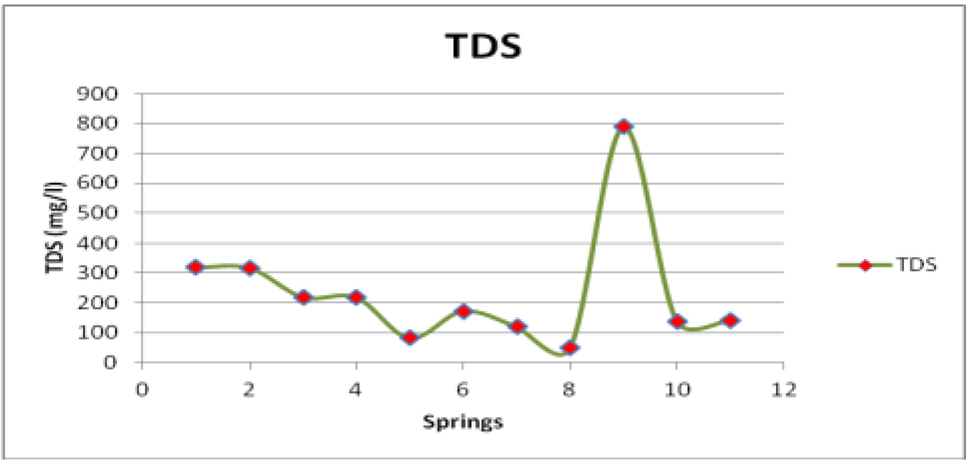

Figure 5-8: TDS results of the water from the spring sites

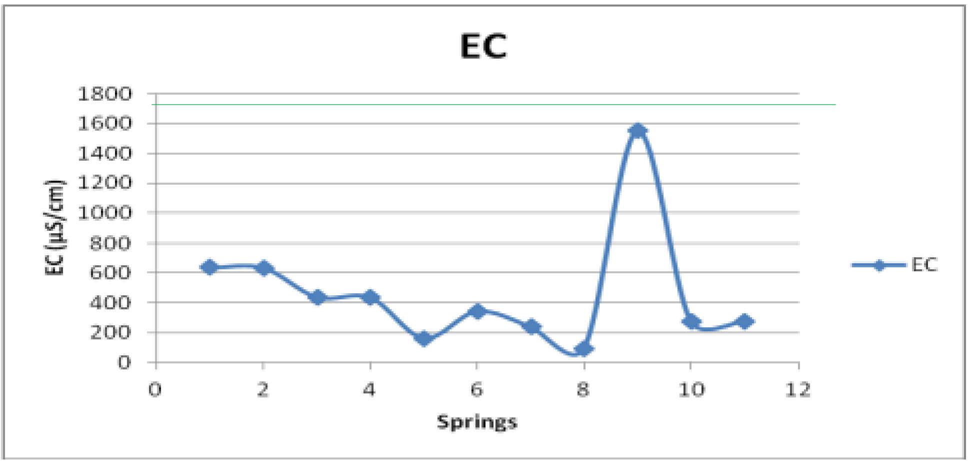

Figure 5-9: EC results of the water from the spring sites

5.4.1.6 Thermal Springs in Limpopo Province

According to Kent (1949), 24 thermal springs are situated within the Limpopo Province, with the majority being located in the Waterberg area (Figure 5-10 refers).

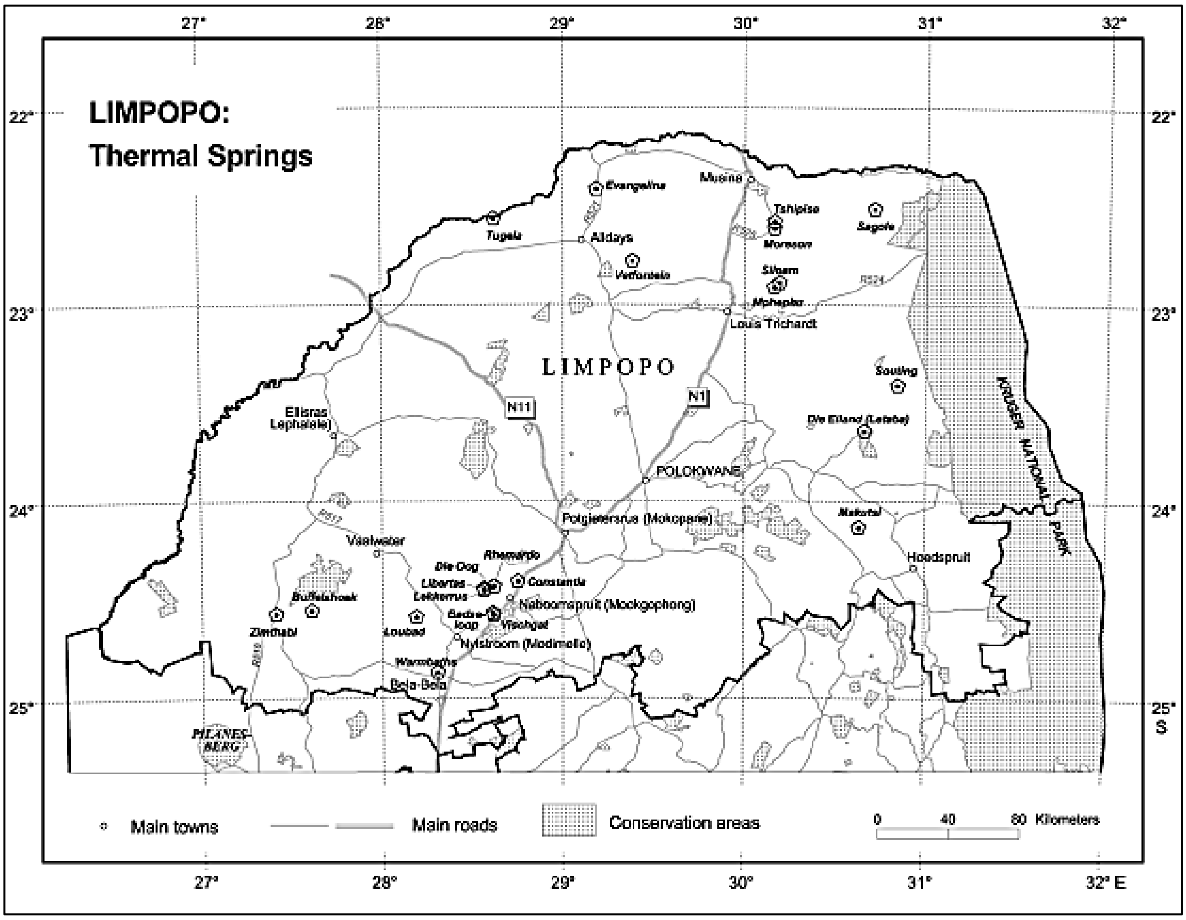

Figure 5-10: Location of thermal springs in Limpopo Province (Olivier *et al.,* 2008)

According to Kent (1949), there are three known geological formations in which the thermal springs are situated, namely Rooiberg felsites, Bushveld granites and Waterberg sandstones. According to Olivier *et al.* (2008), these geological formations are known to be highly fractured, faulted and have been intruded by dykes through which the water flows.

Table 5-5, extracted from Olivier *et al.* (2008), provides an indication of some of the thermal springs within the Limpopo Province and their associated geological structures through which the water flows.

Table 5-5: Thermal springs in Limpopo Province and associated geological structures (Olivier, 2008)

Spring Name	Geological Structure
Warmbaths (Bela-Bela)	Intersection of two post-Permian faults in Waterberg system.
Loubad	Diabase dyke in sandstones in the Waterberg system.
Buffelshoek	Diabase dyke as a barrier on artesian slope of Bushveld granite.
Vischgat	Post-Karoo fault in Bushveld granite.
Die Oog	Diabase dyke along post-Karoo fault in Rooiberg felsites.
Welgevonden/Rhemardo	Diabase dyke along post-Karoo fault in Rooiberg felsites.
Lekkerrus	Diabase dyke along post-Karoo fault in Rooiberg felsites.
Libertas	Diabase dyke along post-Karoo fault in Rooiberg felsites.

According to Olivier *et al.* (2008), faulting and weathering can alter the geology significantly at the surface and the geology identified at the surface at some of the springs comprises the following:

- Warmbaths - Basalt from the Letaba Formation;
- Loubad - Sandstone and trachyte from the Swaershoek Formation;
- Die Oog - Porphyritic rhyolite from the Kwaggasnek Formation.

The geology at the surface is not an indication of the origin of the thermal water. According to Olivier *et al.* (2008), the origin of the thermal water can only be identified once chemical tests are carried out on water samples and the structural geology of the area is known, including geothermal gradients. Taking into consideration the temperatures in the area and classifying them according to Kent (1949), Table 5-6, extracted taken from Olivier *et al.* (2008), provides an indication of the thermal characteristic of the Limpopo Province springs.

Table 5-6: Temperature and water origin depth of the thermal springs (from Olivier *et al.*, 2008)

Spring Name	Temperature (°C)	Classification (according to Kent 1949)
Loubad	30#*	Warm
Buffelshoek	31*	Warm
Vischgat	40#	Hot
Die Oog	40#*	Hot
Welgevonden/Rhemardo	44#*	Hot
Lekkerrus	46**	Hot
Warmbaths (Bela-Bela)	52#* (38**)	Scalding
Libertas	52#* (60**)	Scalding

* Kent, 1949 Hoffmann, 1979 (#) and 2003 (**)

Table 5-7 below extracted from Olivier *et al.* (2008) indicates the chemical composition of the thermal springs in the Limpopo province.

Table 5-7: Chemical composition of thermal springs in Limpopo (Olivier *et al.*, 2008)

Determinant	SABS 1999	SANS 241	Warm Bad	Loubad	Buffelshoek	Vischgat	Die oog	Rhemardo	Libertas
pH	6 to 9	5 to 9.7	8.3	6.81	-	7.07	7.27	7.33	6.98
SAR	NS	NS	-	0.34	-	2.39	1.72	1.62	1.13
TDS	<450	<1200	340	134.18	-	302.85	175.85	179.9	137.9
EC (mS/m)	<150	<170	69	25	-	52	32	34	25
Sodium	<200	<200	132.5	7.87	151.6	55.95	34.21	32.72	21.98
Potassium	<50	NS	2.9	2.9	5.7	6.13	3.62	3.58	3.57
Calcium	NS	NS	13	30.92	27.1	36.13	24.8	25.57	23.02
Magnesium	NS	NS	1.8	6.44	4.7	3.3	3.14	3.28	3.46
Boron	<1.5	<2.4	-	0.04	-	0.06	0.05	0.05	0.05
Fluoride	<1.5	<1.5	11	0.95	6.6	6.54	5.66	5.39	5.95
Nitrite	NS	<0.9	-	0	-	0.12	0	0	<0.1
Nitrate	NS	<11	-	0.59	0	0.68	0.6	0.88	0.41
Chloride	<200	<300	85.2	2.21	138.5	31.7	28.31	28.64	7.24
Sulphate	<400	<500	12.1	2.16	35.1	92.82	12.96	13.68	5.86
Phosphate	NS	NS	<0.2	0	-	0	0	0	<0.2
Carbonate	NS	NS	-	0	-	0	0	0	0
Bicarb	NS	NS	102	161.65	213.3	140.3	125.05	134.2	134
Classification according to BOND			D	E	D	E	E	E	E

NS - Not Specified - Results not available (results are expressed as mg/L)

Olivier *et al.* (2008) compare the chemical results with that of the South African Bureau of Standards (SABS) 1999 (now SANS 241 - 2015), for drinking water. Comparing the results of the water quality from Olivier to SANS 241, the results indicate that Loubad can be regarded at pristine water quality with the other springs having a high concentration of fluoride.

If you consider the thermal gradient change of 3°C per 100 m, based on the temperatures of the thermal springs, the assumed depths of origin are indicated in Table 5-8.

Table 5-8: Temperature and water origin depth of the thermal springs in Limpopo Province

Spring Name	Temperature (°C)	Depth of Origin (mbgl)
Loubad	30	1 000
Buffelshoek	31	1 035
Vischgat	40	1 335
Die Oog	40	1 335
Welgevonden/Rhemardo	44	1 470
Lekkerrus	46	1 535
Warmbaths (Bela-Bela)	52	1 735
Libertas	52	1 735

Referring to Table 5-8 the inferred origin of groundwater occurs from depths in the range 1 000 mbgl to 1 735 mbgl.

5.5 BUSHVELD IGNEOUS COMPLEX DRILLING PROJECT (BICDP)

5.5.1 Introduction

The Bushveld Igneous Complex Drilling Project (BICDP) is a proposed drilling project to collect data from areas that are inferred to be underlain by BIC geology. Currently, the investigation is at planning level and a proposal was submitted to International Continental Drilling Programme (ICDP) in 2017 for funding. The overall aim of the BICDP is to develop a detailed geological model of the BIC.

5.5.2 Target Drilling Sites

The scientific team responsible for heading the BICDP has identified three possible areas to target during the exercise, these areas have been designated Target A to Target C as shown in Figure 5-11. It has been proposed that each borehole should be at least 3 000 m deep and a maximum of 10 000 m deep.

5.5.3 Potential Deep Groundwater Data

Due to the significant costs of drilling, groundwater information for deep aquifer systems is rarely available in South Africa, therefore, a proposal was submitted to the BICDP team to include hydrogeological characteristics during their drilling programme so that a multiple disciplinary phased project can be engaged (Trumbull *et al.,* 2015).

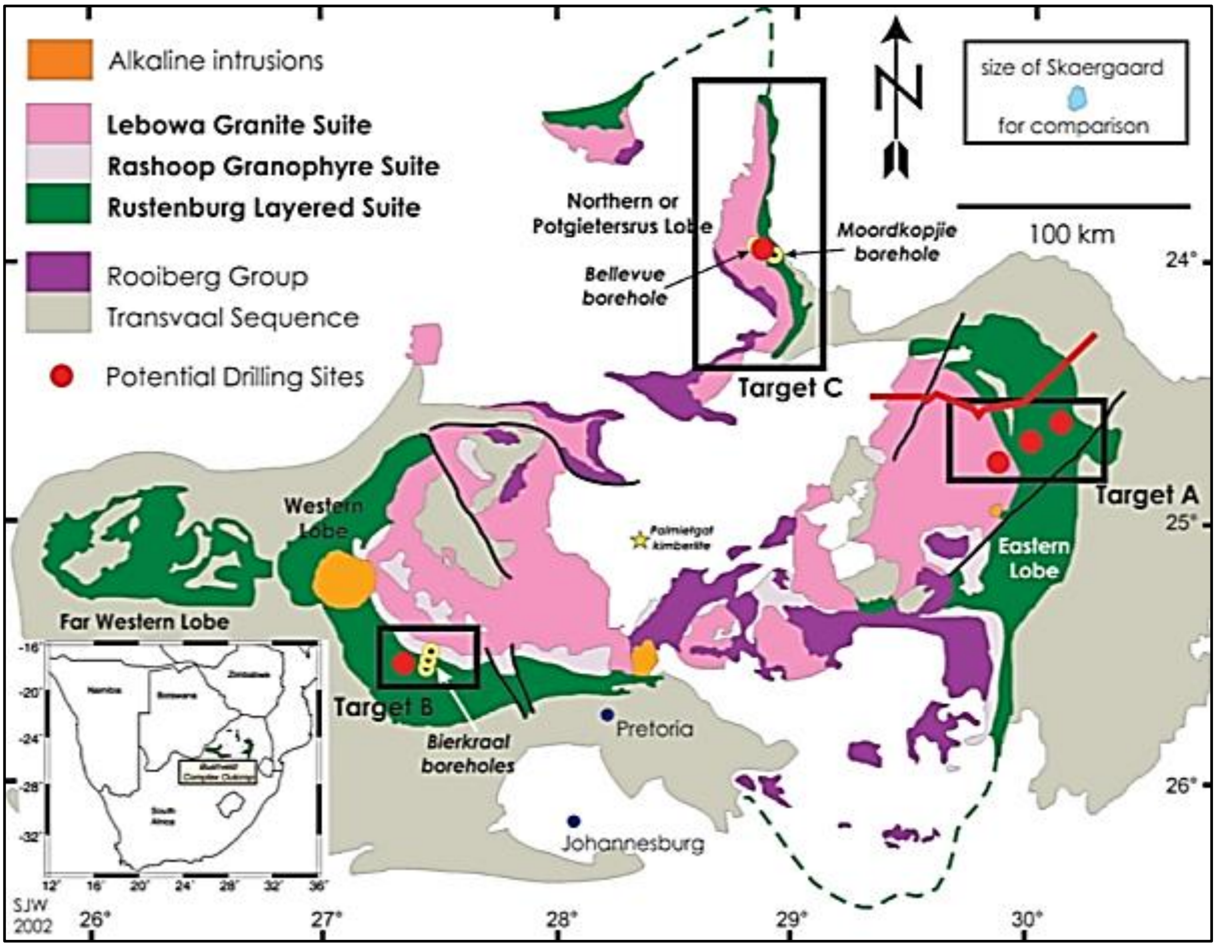

Figure 5-11 A simplified geological map of the Bushveld Igneous Complex with the location of existing reference sections (yellow dots) and possible ICDP targets (red dots) (Trumbull *et al.*, 2015)

The objectives of the hydrogeological aspects of the BICDP are to determine (Trumbull *et al.,* 2015):

- The depth at which groundwater can be encountered.
- Volumes of groundwater available.
- Groundwater Quality.
- Depth at which fractures remain open?
- Is there geothermal potential within the BIC as an alternative energy method?

The potential hydrogeological data from the BICDP will include, at a minimum, geophysical borehole water surveys (fluid temperature, fluid resistivity, etc.), and depth-specific groundwater chemistry. Analysis of hydrogeological data could potentially be realised in the form of a hydrogeological characterisation of geological layers, a description of groundwater chemistry of the BIC, a characterisation of the hydrochemical characteristics as a function of depth in the BIC, a groundwater flow model of the study area, and a simulated geothermal energy model (Trumbull *et al.,* 2015).

CHAPTER 6: CHARACTERISATION OF DEEP AQUIFER SYSTEMS

6.1 INTRODUCTION

In this chapter the literature review will focus on deep aquifers in 1) the basement and crystalline bedrock aquifers, and 2) the Bushveld Igneous Complex 3) dolomite aquifers that could assist with classifying deep aquifer systems.

6.2 AQUIFER CHARACTERISATION

In terms of classifying and characterising deep groundwater aquifer systems in South Africa, typical analogies utilised within the geohydrological field will be referenced. There are numerous parameters (physical and chemical) that would need to be considered when classifying aquifer systems, such as:

- 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), and,
- Aquifer vulnerability and susceptibility.

It should be noted that the above characteristics of aquifer systems particularly that of the deeper aquifer systems are very limited compared to the shallow aquifer systems.

6.2.1 Characterisation of Crystalline Basement Rocks

6.2.1.1 Introduction

Our basic understanding of groundwater in South Africa is that the majority of the groundwater is stored within the sedimentary units. There are also alternative aquifers within South Africa that also store groundwater and these are referred to as secondary aquifers. These secondary aquifers are considered to be crystalline and typically comprise bedrock such as granite, gneiss, migmatites and granitoids. Basement aquifers are generally shallow aquifers that typically have large outcrops at or near the surface and limited information is available on basement aquifers at depths greater than 300 mbgl. This section envisages identifying certain characteristics of deep basement aquifers based on the existing information of the shallow aquifers.

6.2.1.2 Basement Aquifers in South Africa

A typical distribution of the basement aquifer systems within South Africa is given in Figure 6-1. Sedimentary basins that have developed within the country have been subject to metamorphism which is the main reason why a significant portion of South Africa comprises meta-sedimentary basins. These basins are generally 3000 m to 8000 m in thickness and are underlain by basement rocks according to Viljoen et al (2010). Basement rocks are typically encountered at the surface along the northeastern and western parts of the country (Figure 6-1 refers).

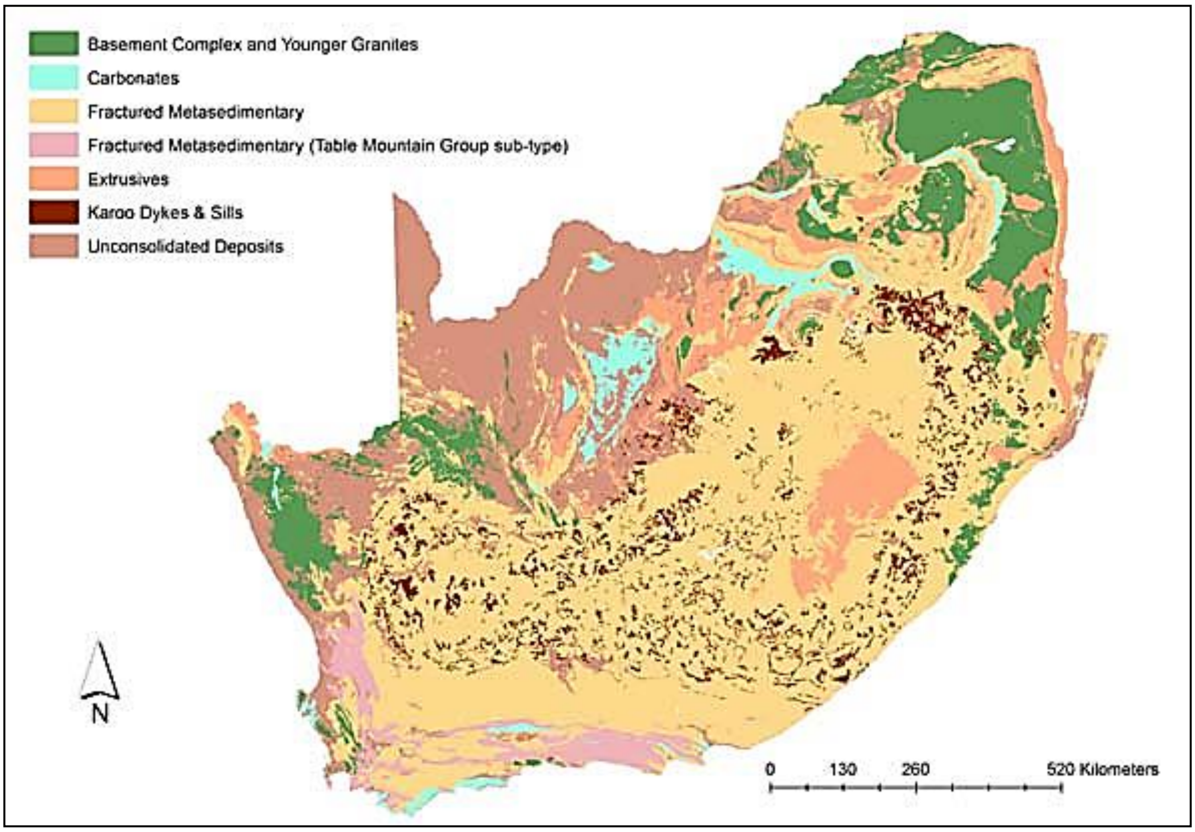

Figure 6-1 Surface distribution of rock types in South Africa (LeMaître and Colvin, 2008)

These type of aquifers are characterised as two-layer systems i.e. weathered material overlies fractures. The area between the lower boundary of the weathered material and the upper boundary of the fractured bedrock is usually the region with the highest permeability and storage capacity and is usually the source of many production boreholes, however, the fractured bedrock is also known to yield sufficient quantities if there an adequate fracture frequency. According to Wright (1992), these aquifer systems are mainly associated with low storativity i.e. less than 1%, which is why these are considered to be poor aquifers systems. It is understood that slightly to unweathered basement rocks will store water within available interconnected fractures that have developed due to regional tectonism (Titus, 2009). It is understood that the permeability and fracture frequency of basement rocks is directly correlated and that the degree of fracturing and permeability will decrease with depth (Wright, 1992).

When investigations are carried out in basement rock terrains, areas of increased fractures, potential dyke zones and zones of high weathering are targeted for exploration. According to Linn (2009), the location of suitable target areas will require a basic understanding of the local geology, geophysical analyses, structural and geological mapping and exploration drilling.

6.2.1.3 Hydraulic Properties of Shallow Basement Aquifers

In terms of hydraulic properties, these basement aquifers are considered to be heterogeneous which have significantly low porosities and permeabilities. The degree of fracturing and permeability with basement aquifers may have significant variations over short distances even though the host material is chemically the same (Titus, 2009).

Hydraulic conductors within basement rocks are limited to structural features such as fractures and fissures (Titus, 2009), whereas zones of intense fracturing are referred to as compound conductors (Gustafson and Krazny, 1994). These structural features are considered to be heterogeneous, i.e. variable fracture frequency, the extent of fracture and connectedness between fractures (Titus, 2009).

Basement aquifers within Zimbabwe and Malawi that were investigated by Wright (1992), have identified that following transmissivities and hydraulic conductivities as given in Table 6-1 and basement aquifers within South Africa are considered to have similar properties.

Table 6-1: Hydraulic parameters in fissured crystalline rocks (modified from Wright, 1992)

Country	Rock Type	Borehole Numbers	Mean Transmissivity (m2/day)	Transmissivity Range (m2/day)	Hydraulic Conductivity Range (m/day)
Zimbabwe	Mobile belt gneiss	228	4.2	0.5-79	0.01-2.3
	Younger Granite	309	3.6	0.5-71	0.01-1.9
	Older Gneiss	392		0.5-101	0.01-2.8
Malawi	Biotite Gneiss	2			0.1-0.2

The hydraulic properties of basement aquifers are summarised in Table 6-1. It can be seen that the transmissivity ranges within the basement aquifers vary significantly from 0.5 m^2/d to 101 m^2/day with hydraulic conductivity ranging from 0.01 m/d to 2.8 m/d. A series of basement aquifers within Limpopo Province was investigated by Holland and Witthuser (2011) and identifies transmissivity values in the range 5 m^2/d to 40 m^2/day.

6.2.1.4 Groundwater Quality within Basement Aquifers

In terms of groundwater quality, these aquifers are considered to have low salinities and neutral to slightly acidic pH values (Clarke, 1985; Holland, 2011), however, according to Holland (2011), in areas of low or limited recharge, salinities are known to be elevated.

Table 6-2 summaries the groundwater quality of a basement aquifer within Malawi (Chimphamba et al., 2009). With reference made to the national groundwater quality standard of Malawi, these samples are considered to classify as good to fair groundwater quality. There are isolated areas in which elevated sulphate and iron concentrations indicate poor quality drinking water. The values have been compared to SANS 241 (2015) for drinking water quality as shown in Table 6-2. Chimphamba et al. (2009) also identified within his study that the aquifers over a short distance were heterogeneous in terms of groundwater quality.

Table 6-2: Common Ranges for chemical and physical parameters of groundwater from basement aquifers in Malawi (modified from Chimphamba *et al.*, 2009) compared to SNAS 241-2015 (South African Standard)

Parameter	Unit	Range	SANS 241-2015 (Guideline)
EC	µS/CM	100 -1000	<170
TDS	mg/L	60 - 600	<1200
Ca	mg/L	10 -100	NS
Mg	mg/L	5 - 50	NS
Na	mg/L	5 -70	<200
K	mg/L	1 - 6	NS
Fe	mg/L	1 - 5	2
HCO_3	mg/L	100 - 500	NS
SO_4	mg/L	5 -1000	<500
CL	mg/L	<20	<300
NO_3	mg/L	<5	<11
Fl	mg/L	<1	<1.5

A study was carried out by Holland (2010) on basement aquifers within the Limpopo Province and it was identified that the chemical parameters fall within the allowable limits of SANS 241 for drinking water. There were isolated anomalies in which some chemical constituents such as nitrate and fluoride were above the allowable limits.

6.2.1.5 Recharge of Shallow Basement Aquifers

Recharge to basement aquifers is governed by the degree of weathering and fracture frequency of the bedrock. It is understood that these aquifers have low storativity potential and exploration drilling within these aquifers may lead to groundwater overexploitation.

Due to the low primary porosities of the basement aquifers, recharge is via a series of structural features such as fractures, faults and dykes. According to Holland (2011), in areas where evaporation is greater than rainfall the aquifers are replenished along preferential flow pathways with the most reliable technique to identify recharge within aquifers is the Chloride Mass Balance method.

According to Nyagwambo (2006), recharge to basement aquifers is typically between 0% to 25% of total rainfall. Due to the heterogeneity of the basement aquifers, these recharge rates vary significantly. Due to the complex flow systems within the aquifers, the estimated recharge may only represent the local recharge and not on a regional scale, which can be misinterpreted for an area (de Vries and Simmers, 2002). Various methods were used by Nyagwambo (2006) to identify recharge rates within crystalline aquifers in Zimbabwe, and the outcome of the investigation identified that recharge rates for crystalline bedrock were between 8% to 15% of the annual rainfall. Holland (2011), identified that recharge to crystalline basement aquifers in the Gauteng area were in the range 0.4% to 4.6% of annual rainfall.

6.2.1.6 Characteristics of Deep Basement Aquifers

Insufficient information is available of the deep crystalline basement aquifers in South Africa i.e. aquifers at depths greater than 300m. However, characteristics from the shallow aquifer systems can be inferred for the deep aquifer system in which similar rock types may occur. The difference with the shallow and deep aquifer system is that the deep aquifer system will not have a weathered profile at depth and the primary storage of groundwater would be within the matrix or fractures. The degree of fracturing is expected to decrease with an increase in depth below the surface. A summary of the characteristics of deep crystalline basement aquifers is summarised in Table 6-3.

Table 6-3: Summary of Deep Crystalline Aquifer Characteristics

Criteria	Description
Lithology	These aquifers occur in fractured basement rocks, such as granites, gneisses and granitoids
Occurrence	Basement rocks are found throughout South Africa and may occur at depths in excess of 8000m under metasedimentary basins. The basement rocks coutcrop along the northern, eastern and western part of South Africa. Deep basement aquifers may occur anywhere in the country. A defining depth for a deep crystalline aquifer system is 300m bgl.
Physical Dimensions	The verticle extend of fractures are expected to be limited. The main storage area within the basement aquifers is the degree of fracturing. The saturate level of the above sedimentary rocks will govern the vertical extent of the aquifer system whilst the lateral extent of the aquifer will depend upon the degree of fracturing.
Aquifer Type	These aquifer systems are considered to be double porosity type systems. The primary porosity is the rock matrix, however, this is anticipated to be low and secondary porosity is related to the fracturing.
Saturation Level	The deep fractured aquifers are likely to be under positive pressure and are assumed to be fully saturated.
Heterogeneity and Isotropy	In terms of vertical profiling, the aquifer is defined as highly heterogeneous, which is due to the degree of fracturing and rock matrix. The horizontal profile of the aquifer is considered to be inhomogeneous and anisotropic due to the irregularity of the fracture networks.
Formation Properties	The primary pososity of the aquifer is expected to be low (<1%), therefore minimal water is expected to be stored within the rock matrix. Secondary porosity is considered to be higher (>1%) and these create localised zones of high prosity within the bedrock.
Hydraulic Parameters	The hydraulic conductivities of the rock matrices ar expected to be low. Due to the low porosities these rocks are likely to have low storatiivities. The fractures within the bedrock will have higher hydraulic parameters. Hydraulic condutivies in the range 0.01 to 2.8m/day. Transmissivities in the range 5-40 m^2/day.
Pressurisation	The aquifer is expected to be under positive pressure. This does not provide an indication that the pressure is sufficient enough to create artesian conditions.
Yield	Although the fractures within the bedrock will have higher hydraulic conductivies than the rock matrix, the yield of the deep aquifers are considerd to be low. The recharge to these aquifers is considered to be low (<1 L/s).
Groundwater Quality	The groundwater quality is expected to be very good. Due to the long residence times an increase in chemical constituents such as flouride may be elevated.
Aquifer Vulnerability and Suceptibility	Due to the depth of these aquifers, the vulnerability to contaminants eminating from human activities is considered to be low. Depending on the volumes of water available, utilisation of these aquifers may lead to overexploitation with limited recharge available.

6.2.2 Characteristics of the Bushveld Igneous Complex Aquifers

6.2.2.1 Introduction

The BIC is a massive crustal emplacement of extrusive and intrusive igneous rocks. The BIC comprises the following volcanic sequences (as discussed in Section 3):

- Upper Rooiberg Group,
- Rustenburg Layered Suite,
- Rashoop Granophre Suite, and
- Lebowa Granite Suite.

The BIC is enriched with platinum, palladium, rhodium, chromium and vanadium ore bodies. A simplified map of the BIC is given in Figure 3-11. The BIC intruded the Transvaal Supergroup along an unconformity between the Magaliesberg quartzites (Eriksson et al., 2007). The thickness of the BIC is approximately 8 km whilst outcrops are known to cover an area of approximately 74 km^2 (i.e. 370 km from east to west and 200 km from north to south).

The subdivisions of the BIC are given in Table 6-4.

Table 6-4: Summary of the Subdivisions of the BIC

Major Unit	Subdivisions
Lebowa Granite Suite	Nebo, Makhutso, Klipkloof, Bobbejaanskop an Verena Granites
Rashoop Granophyre Suite	Stavoren and Diepkloof Granophyres, Rooikop Porphyritic Granites, Zwartberg Pseudogranophyre
Rustenburg Layered Suite	Upper Zone Main Zone Critical Zone Lower Zone Marginal Zone
Rooiberg Group	Schrikkloof, Kwaggasnek, Damwal and Dullstroom Formations

The Critical Zone comprises ultramafic and mafic rocks such as orthopyroxene, harzburgite and chromite layers, feldspathic orthopyroxene, norite and anorthosite. The Critical Zone is the zone rich in mineral deposits. The seams within the Critical Zone have been divided into four groups, Lower Group (LG1-7), Middle Group (MG1-4), Upper Group (UG1-2) and the Merensky reef. According to Kruger (2005), the world's richest platinum deposits occur within the Merensky Reef and UG2 seam. The Critical Zone which is mineral rich has outcrops along the southern parts of the southern limb of the BIC dip towards the north and extends beneath the surface for several kilometres. Underground mines within this area are likely to intersect deep aquifer systems due to mining depths.

The BIC was formed as a result of an intracratonic and anorogenic event along the northeastern portion of the Kaapvaal Craton. The formation of the BIC was governed by three crustal scale structures known as Thabazimbi Murchison lineament, the Magaliesburg-Barbeton lineament and the Palalazoetfontein fault that have a northeast to southwest trend. According to Hayhoe (2013), aeromagnetic surveys along the western limb of the BIC indicate a significant fault and dyke activity. There were two major faults identified along the western limb, a 2 600 m sub-vertical faults and a 1 600 m sub-vertical fault. The general trends of the faults were in an east to west direction.

6.2.2.2 BIC Aquifer in South Africa

A conceptual aquifer model for the BIC comprises a shallow perched aquifer within the regolith overlying a semiconfined, fractured bedrock aquifer, in which the infiltration and flow of groundwater are controlled by the degree of fracturing (Titus et al., 2009). The shallow aquifer within the BIC is associated with a depth not greater than 50 mbgl. The deeper aquifers are associated with highly fractured norites, anorthosites, etc, that have a hydraulic conductivity that is dependent on the degree of fracturing (Titus et al., 2009).

6.2.2.3 Hydraulic Properties of BIC Aquifers including Groundwater Chemistry

In terms of transmissivity, the shallow aquifer has a low to moderate transmissivity between 3 m^2/d to 8 m^2/d, however, there were instances in which aquifer yield tests indicated transmissivities up to 50 m^2/d. Typical borehole yields with the BIC indicates aquifer capabilities of 0.5 L/s to 1 L/s. However, there were isolated anomalies in which abstraction rates of some boreholes yielded as much as 2 L/s (Titus et al., 2009). The shallow aquifer that is located within close proximity to the Brits Graben, comprised transmissivity values up to 285 m^2/d.

The fractured bedrock aquifer system within the BIC is governed entirely by the fracture network. The fractured aquifer has a low porosity but an increased hydraulic conductivity within the fracture network. The aquifer within the BIC is subjected to severe heterogeneity and variations in hydraulic conductivity over a short distance. The fractured aquifer system of the BIC is typically associated with little groundwater (Titus et al., 2009).

The groundwater within the BIC can be divided into two facies (Titus et al., 2009):

- Mg-Ca-HCO_3 - This is typically associated with the shallow aquifer. If there is an alluvial system within close proximity, the water may have an added Cl element which would classify the water as Mg-Ca-HCO_3-Cl facies.
- Na-Cl - This is typically associated with the deep fractured aquifer system in which the groundwater has longer residence times.

A chemical analysis that was carried out on various groundwater samples confirms that the shallow aquifer system has an Mg-Ca-HCO_3 water facies and the deeper fractured aquifer systems have a Na-Ca-Cl water facies with TDS concentrations of up to 1 000 mg/L.

6.2.2.3.1 The UG 2 Aquifer System within the BIC

The main aquifer system within the BIC is the UG2 layer, which is comprised of fractured pyroxenite (Gebrekristos and Cheshire, 2012) and has increased porosity and permeability thatnthe other rocks within the BIC. The zones of higher degrees of weathering and fracturing are restricted to the upper 35 mbgl of the BIC, and will generally decrease with depth (Gebrekristos and Cheshire, 2012). The rock below this zone is less weathered, fractured and are generally low yielding. As most of the groundwater is stored in UG2S, mining activities typically take place between 5 m to 7 m below UG2S.

A conceptual model of the UG2S aquifer system developed by Gebrekristos and Cheshire (2012) is given in Figure 6-2. Three boreholes PD01, PD11 and PD20 were drilled into UG2 aquifer and the results are summarised as follows:

- Borehole PD20 has a yield of 12.8 L/s and intersects the aquifer at a depth of 38 mbgl.
- Borehole PD11 has a yield of 4.4 L/s and intersects the aquifer at a depth of 45 mbgl.
- Borehole PD01 has a yield of 0.7 L/s and intersects the aquifer at a depth of 49 mbgl.

According to Gebrekristos and Cheshire (2012), the following transmissivity values are associated with specific depths:

- 10 m^2/d to a depth of 40 mbgl.
- 1 m^2/d to a depth of 50 mbgl.
- 0 m^2/d to a depth of 80 mbgl.

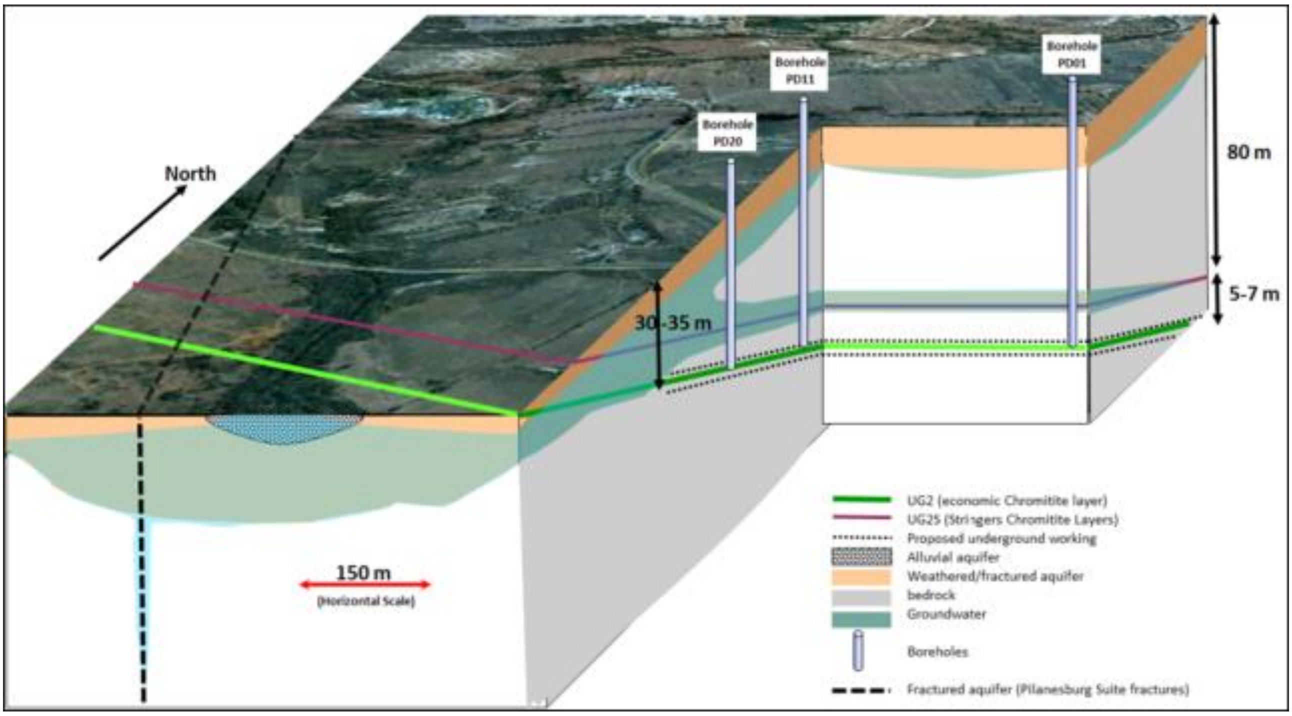

Figure 6-2 Simplified geohydrological conceptual model of the BIC showing the UG2 aquifer associated with the UGS chromitite layer (Gebrekristos and Cheshire, 2012)

6.2.2.4 Aquifer Characteristics

There is limited information available on the deep aquifer systems within the BIC, the characteristics of the shallow aquifer systems are used and comment is made on the potential characteristics of the deeper aquifer system. The potential characteristics are given in Table 6-5.

Table 6-5: Summary of BIC Aquifer Characteristics

Criteria	Description
Lithology	The deep fractured aquifers occur in mafic, ultramafic and felsic rocks of the BIC.
Occurrence	The BIC is very localised and extendeds in northern, northe western and north eastern parts of South Africa. The depth considered for a deep aquifer is 300m bgl.
Physical Dimensions	vertical extent of deep fractures within the BIC are considered to be very limited. Matrices within the rocks comprising fractures are considered to be potential storage units. The thickness of the host rock will determine the thickness of the aquifer system and the length of teh aquifer will be governed by the degree of fracturing.
Aquifer Type	These aquifer systems are considered to be double porosity type systems. The primary porosity is the rock matrix, however, this is anticipated to be low and secondary porosity is related to the fracturing.
Saturation Level	The deep fractured aquifers are likely to be under positive pressure and are assumed to be fully saturated.
Heterogeneity and Isotropy	In terms of vertical profiling, the aquifer is defined as highly heterogeneous, which is due to the degree of fracturing and rock matrix. The horizontal profile of the aquifer is considered to be inhomogeneous and anisotropic due to the irregularity of teh fracture networks.
Formation Properties	The primary porosity is expected to be low (1%) with little water stored within the rock matrix. The secondary porosity structures such as fractures allow for some storage of water.
Hydraulic Parameters	The hydraulic conductivities of the rock matrices ar expected to be low. Due to the low porosities these rocks are likely to have low storativities. The fractures within the bedrock will have higher hydraulic parameters. Storativity 0.15 and hydraulic conductivities between 0.03 to 0.04. Transmissivity values of 3 to 8 m^2/day
Pressurisation	The aquifer is expected to be under positive pressure. This does not provide an indication that the pressure is sufficient enough to create artesian conditions.
Yield	Although the fractured may have high hydraulic conductivities, the yield of the deep aquifer system is considered to be low. The voumes of water available will depend on the size and degree of fracturing. However, recharge to such an area is considered to be low. Yields are typicaly 0.5 to 1.0 l/s.
Groundwater Quality	The groundwater quality is considered to be poor with an increase in NaCl due to longer residence times within the aquifer.
Aquifer Vulnerability and Suceptibility	Due to the depth of these aquifers, the vulnerability to contaminants eminating from human activities is considered to be low. Depending on the olumes of water available, utilisation of these aquifers may lead to overexploitation with limited recharge available.

6.2.3 Characteristics of Deep Dolomite Aquifers

6.2.3.1 Introduction

It is understood the dolomite aquifers form the largest and most important aquifers in South Africa, with the northern parts, particularly Gauteng Province in which there is a 1000 m thick sequence. However, these dolomites overlie some of the most important mineral bearing sequences which contain gold and uranium (Schrader and Winde, 2015). Groundwater influx into mine is not an uncommon phenomenon in South Africa, as mining activities that encounter either faults or fissures that are connected to dolomite aquifers are the main source of the water influx.

One of the negative impacts on mining activities on the groundwater resource is the alteration of groundwater quality. Sulphide rich mineral present within the host rock undergo oxidation reactions and create acid mine drainage which leads to the deterioration of the groundwater. Thus the groundwater is contaminated with sulphide metals, trace metals and radioactive isotopes of Uranium and Thorium. Furthermore, the dewatering of mines has altered the natural groundwater flow levels and directions.

6.2.3.2 Dolomitic Rocks in South Africa

As mentioned in Section 3.4, there have been four karstification periods in South Africa, which where during the following periods, Pre-Pretoria Group (~1.95 Ga), Pre-Waterberg Group (~1.7 Ga), Pre-Karoo Supergroup (before the formation of the Dwyka Group) and the recent Tertiary period in which the Malmani Group rocks where exposed at surface. The main dolomite formations in South Africa are located within the Chuniespoort and Ghaap Groups (Table 3-1 refers).

A distribution of dolomitic rocks at the surface is given in Figure 6-3.

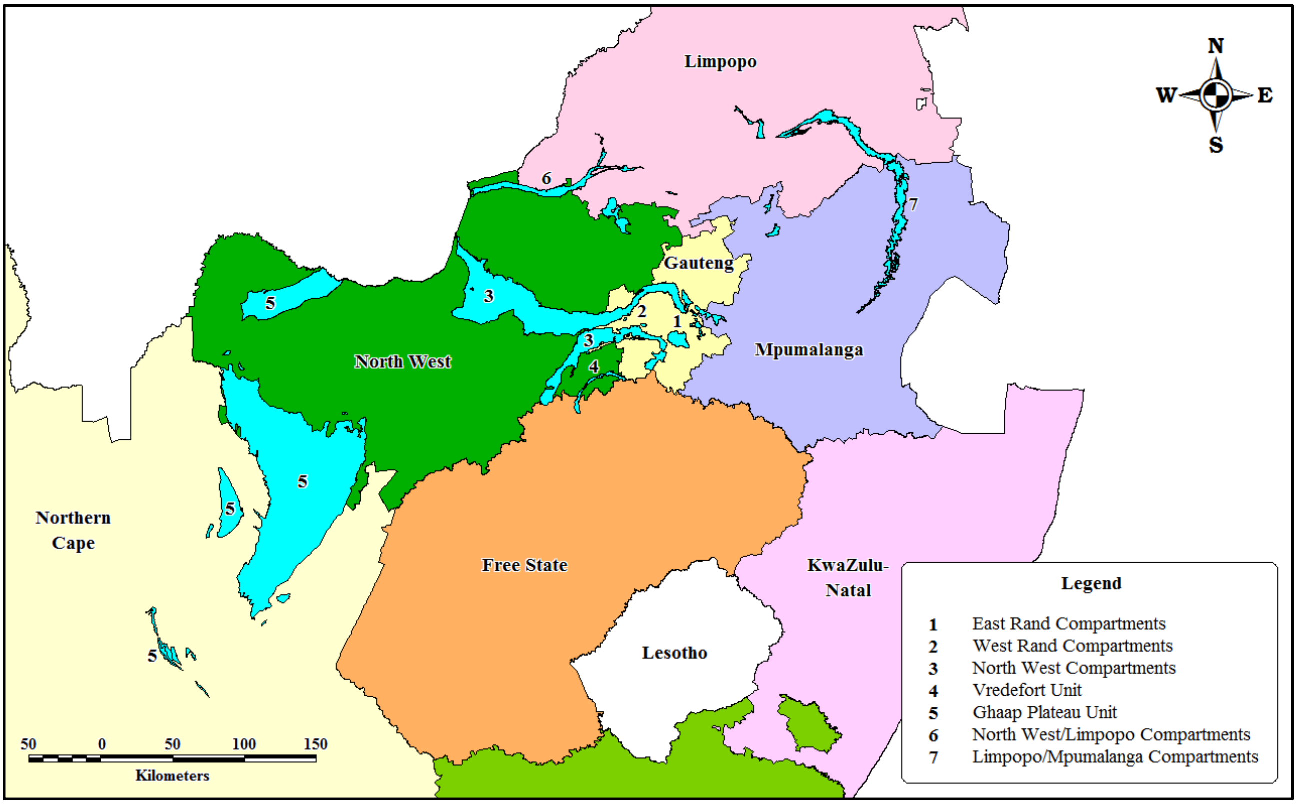

Figure 6-3 **Distribution of dolomite outcrops in South Africa**

The dolomite outcrops in South Africa are mainly grouped according to their location and any structural features. The seven main dolomite units within South Africa are:

- The East Rand Compartments,
- The West Rand Compartments,
- The North West Compartments,
- The Vredefort Unit,
- The Ghaap Plateau Unit,
- The Limpopo/Mpumalanga Compartments, and
- The North West/Limpopo Compartments.

As mentioned in Section 3.4, the dolomite formations within the Chuniespoort Group is confined to the Malmani subgroup, which is differentiated into Oaktree (oldest), Monte Christo, Lyttelton, Eccles and Frisco (youngest) Formations (SACS, 1980). The Chuniespoort Group formed within the Transvaal Basin and overlies the Black Reef Formation.

The dolomite Formation within the Ghaap Group is confined to the Campbell Subgroup and formed within the Griqualand West Basing and overlies the Vryburg Formation. According to Eriksson *et al.* (1995), the Campbell Rand Subgroup and the Malmani Subgroup are correlated and formed around a similar time interval. These units comprise thick sequences of dolomites and limestone that are interbedded with chert, shale and stromatolites.

The dolomites were deposited in three shallow sea environments, Griqualand West Basin, Knaye Basin and Transvaal Basin (Eriksson and Altermann, 1998). These carbonate deposits are known to be the oldest preserved carbonate platforms in the world.

The Griqualand West Basin is subdivided into two areas by the Griquatown fault along the southern portion of the basin. The fault has divided the Griqualand basin in the Prieska carbonate facies and the Ghaap Plateau carbonate facies (Eriksson and Altermann, 1996). The Campbell Rand and Malmani subgroups form the carbonate successions of the Griqualand West and Transvaal basins.

During the meteorite impact which leads to the creation of the Vredefort Dome, the Malmani Carbonate rocks were uplifted and exposed to the surface through erosion. Dolomite bedrock is encountered at significant depths below the surface of the Vredefort Dome, this had lead geologist to consider that the distribution of dolomites beneath the surface is greater than the outcrops.

6.2.3.3 Karst Geohydrology

Dolomite as a rock has a low permeability, however, dissolution of the bedrock creates cavities which are known as dolomitic karsts. According to DWAF (2006), rain waters dissolves atmospheric carbon dioxide and create a weak acid that infiltrates beneath the surface along fractures and dissolves the dolomitic/limestone host rock. Over a period of time karsts start to develop within the dolomitic rock. Groundwater collects within these karsts and although dolomite maybe an impermeable rock, the groundwater moves via a series of fractures. Due to the development of dissolution cavities, the movement of groundwater within dolomite units are considered to be rapid.

A schematic cross-section of a dolomite aquifer which shows the presence of karts is given in Figure 6-4. Cavities within dolomite are typically known to develop close to the surface where there is greater exposure to atmospheric conditions and groundwater. As mentioned in Section 3.4, the cavities may develop deeper within the surface if there are geological structures such as faults and dykes. Water will emanate through these preferential flow paths and aid with the dissolution process.

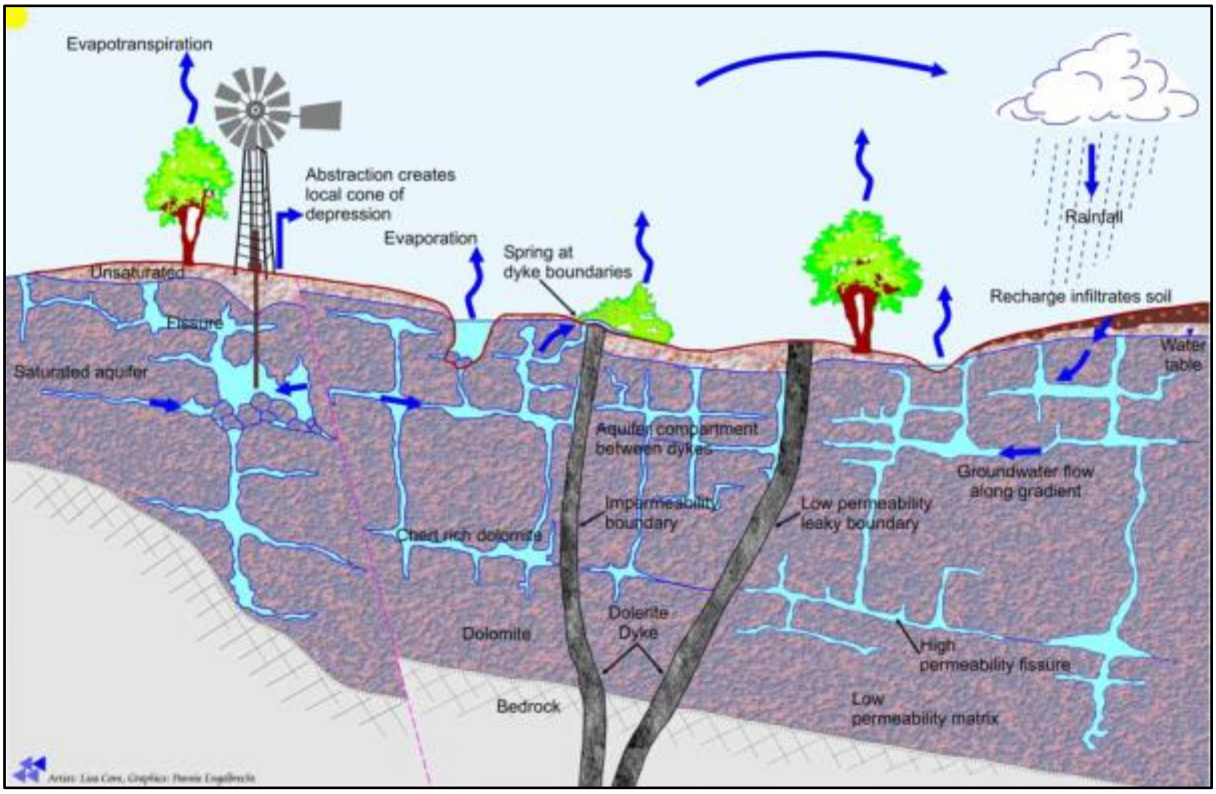

Figure 6-4 **Cross-section through a dolomite aquifer (CSIR, 2003)**

Considering that the dolomite units within South Africa were subjected to four karstification events, this creates the impression that not only is there near surface karstification but palaeokarst environments occur. Palaeokarsts are common along the upper contacts of the Malmani subgroup. According to Foster (1998), the occurrence of palaeokarsts has a major control of the aquifer properties of dolomites.

6.2.3.4 Hydraulic Properties

Carbonate rocks generally have low primary porosity, however, the development of dissolution cavities create larger secondary porosity units. According to Foster (1988), the effective porosity, permeability and storage potential of carbonate aquifers will decrease with an increase in depth from the water table. Porosities within carbonate rocks have been identified to be between 1 % and 20 %.

According to Schrade *et al.* (2014), the storativity at depths less than 90 mbgl is relatively high at 10% which is a result of higher porosity due to the weathering and the fine grain sizes. Beneath this layer comprises the cavernous dolomite that extends to a depth of approximately 200 mbgl and has a relatively low storativity of 2%. According to various authors cited in Schrade *et al.* (2014), the total volume of water stored within the Malmani subgroup dolomites is estimated to be in the range 663 million cubic metres (Mm^3) to 2200 Mm^3. They have also identified that the transmissivity in these dolomite rocks differ widely and is estimated to be in the range 1 000 m^3/day to 25 000 m^3/day. Schrade *et al.* (2014) calculated hydraulic conductivity in boreholes to be in the range $7x10^{-5}$ metres/second (m/s) to $3.1x10^{-4}$ m/s for the upper 200 m and $2.9x10^{-6}$ m/s to $1.0x10^{-5}$ m/s for the deeper aquifers.

According to various authors in Naidoo (2014), the storativity of dolomites is typically in the range 1% to 20%, transmissivity between 10 m^2/day to 30 000 m^2/day, a storativity coefficient of 0.0001% to 0.1% and storage of up to 12 000 million m^3 of water. According to Foster (1988), the highest transmissivity values were that of boreholes that were drilled into the Eccles Formation, where approximately 18 out of 30 boreholes (60%) had transmissivity values greater than 100 m^2/day.

Foster (1988) identified that the chert rich formation is more fractured and have a higher degree of dissolution than the chert poor horizons. Foster (1988) further identified that in areas were boreholes intersected paleo karst units had higher transmissivities, as much as 11 575 m^2/day. Typically it was identified that high transmissivity areas were associated with zones within close proximity to a dyke. Research by Kafri and Foster (1989) identified that transmissivity values up to 50 000 m^2/day were common to dolomite aquifers.

According to Lourens (2013), the dolomite aquifers of the Ghaap Group are moderate yielding and have yields in the range 0.5 L/s to 2 L/s with some boreholes encountering yields of at least 5 L/s. The Chuniespoort Group has higher yields than the Ghaap Group, with yields in boreholes at least 5 L/s and a maximum yield of 126 L/s (Lourens, 2013). According to Foster (1989) average yields for boreholes drilled into the Malmani Subgroup, particularly Oaktree, Monte Christo, Lyttelton and Eccles Formation, were in in the range 4.5 L/s to 64 L/s. Some boreholes drilled into the Monte Christo Formation had yielded up to 64 L/s, whilst the Lyyelton and Eccles Formations had yielded up to 29 L/s. It was also identified that borehole drilled near dykes had an increase in groundwater potential.

Lourens (2013) identified that the electrical conductivity within these karst aquifers is in the range 55 mS/m to 397 mS/m, which are an indication of generally good groundwater quality. However, due to the high permeability of the karst system, the groundwater is vulnerable to contamination from surface sources.

6.2.3.5 Groundwater Quality

Groundwater within dolomite aquifer has a distinct fingerprint, i.e. they classify as bicarbonates. The groundwater is dominated by two major ions Ca^{2+} and Mg^{2+}. The major dissolved elements within dolomite groundwater have TDS concentrations between 100 mg/L to 400 mg/L. A study was carried out by Bond (1946) to identify the groundwater quality of dolomite areas, based on a total of 22 samples, TDS concentrations were identified to be between 200 mg/L to 300 mg/L with isolated anomalies of up to 750 mg/L in arid areas, it was also identified that the pH of the groundwater was relatively consistent. Kafri and Foster (1989) identified that when the TDS concentrations exceeded 500 mg/L, particularly within the Klip River and Natalspruit Basins, these are indicative of groundwater contamination. Dolomite aquifers are vulnerable to pollution due to the ease at which contaminants may enter their aquifer systems (Pieterson et al., 2011) and contamination at the surface could rapidly deteriorate the groundwater.

6.2.3.6 Recharge and Storage

Recharge to dolomite areas shown a drastic variation, during periods of low rainfall recharge maybe 0% of MAP and up to 50% during periods of intense rainfall. The difference in recharge rates is possibly due to the variation is high permeability zones within the dolomite rock. If zones of high permeability are connected to the surface, the recharge to dolomite aquifers will be more rapid.

The CMB method was used by Kafri and Foster (1989), and an estimated recharge of 25% of MAP was identified. In a publication by DWAF (2006), recharge rates for the West Rand dolomite compartments were identified to be between 3.6% and 27.4%. In areas where recharge is not possible by direct rainfall, recharge to dolomite compartments was found to be from springs. Flow rates that have been identified within the West Rand springs indicate flow volumes between 9.2 ML/day to 55 ML/day (Connelly and Ward, 2006). The dolomite compartments in South Africa are estimated to hold a total volume of 5×10^6 ML of groundwater (CSIR, 2003). Schwartz and Midgley (1975) identified that within the Bank Compartment of the West Rand Dolomites a total volume of at least 2.2×10^6 ML is available, which may indicate that the total volume of groundwater stored in dolomite aquifer is greater than 5×10^6 ML.

6.2.3.7 Aquifer Characteristics

There is limited information available on the deep aquifer systems for dolomite compartments, the characteristics of the shallow aquifer systems are used and comment is made on the potential characteristics of the deeper aquifer system. The potential characteristics are given in Table 6-6.

Table 6-6: Summary of Dolomite Aquifer Characteristics

Criteria	Description
Lithology	The main dolomite units were deposits into two basins, the Transvaal and the Griqualand West basin. The dolomites that form part of the Transvaal supergroup are that of the Malmani subgroup and chunniesport group. The dolomites that from part of the sGriqualand West Basin are that of the Campbellrand subgroup and Ghaap Group.
Occurrence	Dolomite outcrops are encounteres along Gauteng, Northern Cape, North West, Limpopo and Mpumalanga provinces. The distribution of dolomites beneath the surface is greater than the dolomites outcropping. Deeper aquifers are considered at depths greater than 300m bgl.
Physical Dimensions	The lateral extent of dolomites is likely to be much larger than the surface distribution of dolomites. The dolomites within the Transvaal Basin are inferred to be greater than 1000m and the Griqualand West Basin, greater than 2000m. The presence of major faults and dykes within the subsurface create positive conditions for the development of dolomite cavities.
Aquifer Type	These aquifers are considered to be double porosity comprising a primary matrix of low porosity and secondary fractures and dissolutions cavities of high porosity.
Saturation Level	The deep fractured rocks are expected to be fully saturated.
Heterogeneity and Isotropy	Due to the variation in the hydraulic properties of the dolomites, these are considered to be highly heterogeneous and anisotopic. The distribution of dissolution cavities is irregular. Dissolution cavities are more common close to the surface.
Formation Properties	Primary porosity of dolomites are considered to be low (1-15%), however, when there are dissolution cavities and fractures, the seondary porosity is considered to be high(20%). It is estimated that the upper 30m of a dolomite sequence will have porosity of 15% and Similar porosities are expected to occur at palaeoakarst environments. Storativity values in teh range 2 - 20%. Hydraulic conductivities 2.9E-6 to 1.0E-5 m/s and transmissivities between 1000 to 25000 m^3/day.
Hydraulic Parameters	In terms of hydraulic conductivity, transmissivity and storativity, these are considered to be low in unweathered and undissolved dolomite bedrock. Higher conductivities, strativities and transmissivities are associated with dissolution cavities.
Pressurisation	If dissolution cavities extend to surface, the pressuremaybe regarded as normal. However, the presence of aquicludes or aquitards between dolomite layers may create a positive hydraulic pressure.
Yield	Dolomites are inferred to have high yielding boreholes. Yields are expected to be up to 60L/s. Similar yields can be expected for paleaokarst dolomite aquifers.
Groundwater Quality	The groundwater quality of dolomite aquifers are very good, however, they a vulnerable to pollution from surface.
Aquifer Vulnerability and Suceptibility	These aquifers are highly vulnerable to contamination from surface. High rates of groundwater migration through dissolution cavities aid the contamination process if these cavities are connected to surface. Deep aquifer would be less vulnerable if their dissolution networks do not extend to surface, however, these maybe susceptable to overexploitation.

CHAPTER 7: PROTECTION OF DEEP GROUNDWATER AQUIFERS

7.1 INTRODUCTION

A list of potential risks to deep groundwater aquifers and approaches to minimise the effects of these risks will be discussed in this chapter. Various activities may contribute negatively to aquifer systems, such activities may include but are not limited to mining, groundwater extraction, and fossil fuel production

The objects of this section will include:

- Identify activities that may negatively impact the quality and quantity of groundwater within the deep aquifer systems of South Africa,
- Identify various approaches that can be implemented to limit the negative impact to the aquifer systems, these may include best practices, regulatory tools and aquifer management,
- Identify existing laws governing the protection of the aquifer systems and identifying gaps within the legal framework and providing suitable solutions.
- Propose a new framework/classification system for deep aquifer systems.

7.2 ACTIVITIES THAT MAY IMPACT DEEP AQUIFER SYSTEMS

A list of activities that may negatively affect the deep aquifer system is provided in this section. The following activities may negatively impact the deep aquifer systems in terms of quality and quantity of groundwater:

- Conventional deep mining, and
- Groundwater abstraction from deep aquifers.

7.2.1 Conventional Deep Mining

There are numerous areas throughout South Africa in which conventional deep mining activities occur, some of these include:

- Deep conventional mining activities within the BIC in which platinum group elements are extracted and mining usually occurs down to depths of at least 3 585 m,
- The deep coal mining activities within the Waterberg and Springbok Flats Coalfields'
- Deep gold mines within the Witwatersrand were mining activities occur down to depths at least 3 900 m,

- Diamond mines in South Africa where mining is carried out to depths at least 1 097 m.

7.2.1.1 Potential Impacts of Mining on the Deep Aquifer System

According to Bianchini (2016), all stages of mining activities (exploration, operation and decommission) have the potential to negatively impact the environment. During the exploration phase of a mining operation, the exploration drilling may affect the environment in a negative way. Usually, the exploration drilling operations are done too shallow depths, however, depending on the depth to high-grade ore material, drilling at greater depths may affect the deep aquifer systems. During the operation stage of the mine, large volumes of in-situ material are removed from the subsurface and stockpiled. The ore is processed and the remainder (waste rock) is stored in stockpiles. These stockpiles are exposed to atmospheric conditions and oxidation reactions may occur, giving rise to acid mine drainage. Groundwater that is encountered during the mining operation drains into these open void spaces and in order to create safe working conditions for mining, the groundwater would have to be removed which is known as mine dewatering.

7.2.1.1.1 Mine Dewatering

There is a safety hazard associated with any underground mining activity and this is the influx of groundwater. In order for a safe working environment to be created the groundwater needs to be removed from the mine and this is known as mine dewatering. Mine dewatering is carried out by installing submersible pumps into a mine and pumping out the water at the surface; depending on the rate of dewatering different pump sizes are used. If the rate of mine dewatering is greater than the rate of recharge to the aquifer, there is a possibility of depleting the aquifer. Due to the low recharge rates of the deep aquifer systems, dewatering activities during the mining operation may deplete the groundwater aquifer.

7.2.1.1.2 Impacts on Groundwater Quality

During the mining operating the extraction of ore and host rock material negatively impact the groundwater quality. Elevated nitrate concentrations are usually identified within the groundwater as a result of the blasting operations. Mining activities are also responsible for the increased salt content of the groundwater. Elements such as sodium, calcium, magnesium, chloride and sulphate are common in deep mines and thus groundwater shows elevated concentrations of these elements.

A common negative impact on groundwater is the development of acid mine drainage (AMD), which usually occurs in areas that have a high sulphate content. AMD creates highly acidic groundwater which allows for the mobilisation of trace metals such as arsenic, barium, lead, etc.

In gold and uranium mines, radioactive contamination of groundwater may occur. The groundwater is negatively impacted by the mining operation, and contamination will depend on the type of chemical/elements used during the mining operation.

7.2.2 Groundwater Abstraction from Deep Aquifers

Groundwater in South Africa has become an integral part of the water supply framework, with many urban and rural areas relying solely on abstraction boreholes. During periods of drought, as South Africa has experienced one this past year, groundwater abstraction boreholes were in urgent demand to supply the local communities.

Generally, in South Africa boreholes are rarely drilled to depths greater than 100 m. Drilling of abstractions boreholes to depths greater than 300 m is considered rare. Therefore, not much information is available for the deep aquifer systems.

Due to the increase in demand for groundwater abstraction boreholes the rate of abstraction is exceeding the rate of groundwater recharge to certain areas, thus the shallow groundwater aquifers are being depleted. Furthermore, dewatering from mines has altered and possibly lowered the groundwater levels which have resulted in certain fracture networks having lower water pressures.

There are known occurrences of aquifers greater than 300 m and are known to have potentially high yields, however, the salinity of the groundwater is considered to be high. These aquifers may be considered as an alternative water supply should the surface water and shallow aquifer systems be unable to meet the minimum demands.

7.2.2.1 Potential Impacts of Abstraction on Deep Aquifer Systems

Should the development of deep groundwater abstraction borehole be implemented, it should be noted that there is a risk for altering the quality and quantity of groundwater at these depths. A concern is that due to the large depths of groundwater occurrence within the deep aquifer system, recharge to the system would be considered as minimal and aquifer may require a long time period to replenish. Therefore, it may not be feasible in terms of environmental impact to utilise these deep groundwater aquifers, however, this solution should only be considered if the demand for water is great and no other source is available.

Another significant impact to the deep aquifer systems is that once the pressure is released from the existing fracture networks the overburden pressures may close the water-bearing fractures as compaction occurs. Furthermore, if compaction of the deep aquifer system occurs, there is a risk for seismic activity. Induced seismicity can lead to the development of secondary fractures within the surrounding rocks. The new fractures may hydraulically connect aquifer systems and if one system has a deteriorated groundwater quality than the other it may affect the quality of the other system.

It is known that as depth increases below the surface the salinity of the groundwater increases, therefore, it is important that the integrity of the abstraction well is maintained to ensure that saline waters do not migrate into the upper shallow aquifers systems where the groundwater quality is better.

The abstraction of groundwater from unconfined aquifers, such as dolomite compartments, may create oxidizing conditions as the groundwater levels lower which may expose ore-bearing host rocks. For example in the Witwatersrand mining areas, a reduction in groundwater levels within the dolomite compartments may lead to gold-bearing rocks exposed and oxidation reactions may occur giving rise to AMD.

7.3 APPROACHES TO PROTECT DEEP AQUIFER SYSTEMS

This section will concentrate on the protection of the deep aquifer systems and the potential approaches that can be engaged. A few approaches that may be considered are:

- Establish baseline conditions for deep aquifer systems prior to commencing any activities that could negatively impact the aquifer,
- Use technologies that could monitor the impact of activities on the aquifer,
- Follow best practice guidelines when engaging in activities that could negatively affect the aquifer,
- Use regulatory tools to enforce compliance of groundwater laws within the country,
- Develop suitable management procedures for the monitoring of the activities that could negatively impact the aquifer.

7.3.1 Establishing Baseline Conditions

Prior to the engagement of any activity that could negatively impact the aquifer a baseline of the aquifer systems of the area needs to be identified. The baseline conditions may consist of understanding the deep aquifer systems and having a baseline of the groundwater quality prior to the commencement of the activity.

7.3.1.1 Understanding the Deep Aquifer Systems

In order to prevent and limit any impacts to the deep aquifer system, from the potential activities, it is imperative that the aquifer is understood properly. In this regard, it is imperative that this is done prior to the commencement of the activities. Due to the depths at which these deep aquifer systems occur, it is not always possible to obtain adequate baseline information.

In order to identify the characteristics of the deep aquifer system a high-level desktop study and field investigation is required.

The desktop study should include but not be limited to:

- A detailed description of the geology and geohydrology that are likely to be encountered by the activities,
- Identification of geological structures such as faults, shear zones that could influence the geohydrology,
- Interpretation of existing geophysical data to identify deep geological structures that may be associated with the aquifer system.
- Identification of thermal springs within close proximity to the site,
- Any available deep groundwater quality information,
- Hydraulic properties of the deep aquifer system, and
- Estimate the groundwater recharge.

Considering that the available information for a particular area may not be adequate. Field investigation will be required to augment the existing information and provide additional information for the aquifer system. Field investigations would include but not limited to:

- A complete hydrocensus of the site to identify any existing water sources,
- The sampling of all groundwater boreholes to identify a baseline groundwater quality,
- Detailed geological mapping of the surface geology to identify any features of geological significance,
- Carry out geophysical surveys to identify deep geological structures,
- Drilling of exploration boreholes to depths in which the proposed activity will be carried out. It is important to record the lithologies encountered and the depths of each groundwater strike,
- If possible, downhole geophysics should be utilised to confirm geological structures,
- The sampling of groundwater for chemical and microbial analyses, and
- Carrying out pumping tests to confirm hydraulic properties of the aquifer.

7.3.1.2 Baseline Monitoring

It is important to understand the groundwater quality of a site prior to any activity is carried out. Both the shallow and deep aquifers systems groundwater quality need to be identified at the outset of a project so that during the project the groundwater quality can be referenced to identify any contamination that may occur over a certain period of time.

In this regard, the DWA has already created “The Best Practice Guideline” (BPG) G3 for water monitoring systems. The BPG should be met as a minimum requirement for environmental and water management plans.

7.3.2 Technologies and Actions to Minimise Effects

In this section technologies particularly related to conventional mining activities will be discussed. Only a broad description of common technologies available for use will be briefly discussed.

Both deep opencast and underground mining negatively impacts the groundwater systems. As discussed in earlier chapters, the mine dewatering affects the volumes of groundwater within the aquifer and the mining activities lead to the deterioration of the groundwater quality.

The implementation of technologies should be done in a way to limit the effects on an aquifer system. Although technologies may be implemented to limit the negative effect of the activities on the aquifer, due to mining being an invasive activity, the negative effect on aquifers is inevitable and technologies would be best suited to minimise the effect.

In order to implement various methods to assist with the groundwater flow within mines, a thorough understanding of the groundwater sources and pathways need to be gained. Mining activities can be planned to avoid geological structures that may contribute to an increase in groundwater activity. Usually, during mining activities, geologist thoroughly maps the subsurface with different methods such as geological mapping, drilling and geophysical surveys. These could be used to aid with the mine design to prevent the intersection of any water-bearing fractures. Although in theory, this may seem like a great proposition in theory, as we understand geology, not every structure will have a linear arrangement and it may be difficult to prevent an intersection with an aquifer body.

The subsurface geology is such that there is a high degree of heterogeneity and anisotropy and groundwater flow into mine is expected. As mentioned, although the best technologies may be used to identify structures, no structure can be accurately delineated and there will be isolated areas in which the mining activity will penetrate a structure which may result in an influx of groundwater. A solution to provide a safe working environment along mining faces is mine dewatering, which is the abstraction of water from the mine. However, the influx of water into a mine is also a way of dewatering the aquifer naturally.

There are two possible ways in which aquifer dewatering can be carried out; 1) the first method is by limiting the influx of groundwater into shafts and pits; and 2) is by recharging the aquifer a certain distance from the point of dewatering, i.e. artificial recharge. A simple technique that may be employed is the grouting of fractures to prevent groundwater flow into mines (Daw and Pollard, 1986). Another method is a grout curtain which may be sprayed onto mine workings to prevent groundwater from entering the mine.

The second solution to aquifer dewatering is to pump groundwater from one part of the mine and replenish the aquifer a certain distance away. However, as mining activities are associated with a contaminant, the groundwater from the mine workings may be of worse quality than the natural groundwater that initially rushed into the mine. This would mean the polluted groundwater would be transferred back into the system, thus, contaminating the groundwater at the point of artificial recharge.

Considering that artificial recharge maybe an appropriate solution, there are ways of treating the groundwater prior to replenishing the aquifer. Various treatment plants can be installed within the mine to purify groundwater, however, these may be expensive to maintain and may not be financially feasible for the mining operation. Alternatively, groundwater that has become acidic may be treated by natural alkaline elements to neutralise the groundwater prior to replenishing the aquifer.

7.3.3 Best Practice Guidelines

Following best practice guidelines ensures that all can be done to minimise the effects of an activity on the groundwater system. The Department of Water and Sanitation of South Africa have developed a series of Best Practice Guidelines (BPGs) particularly for the mining industry

Hierarchy:

- H1 – Integrated Mine Water Management,
- H2 – Pollution Prevention and Minimisation of Impacts,
- H3 – Water Reuse and Reclamation, and
- H4 – Water Treatment.

General:

- G1 – Storm Water Management,
- G2 – Water and Salt Balances,
- G3 – Water Monitoring Systems,
- G4 – Impact Prediction, and
- G5 – Water Management Aspects for Mine Closure

Activities:

- A1 – Small Scale Mining,
- A2 – Water Management for Mine Residue Deposits,
- A3 – Water Management in Hydrometallurgical Plants,
- A4 – Pollution Control Dams,
- A5 – Water Management for Surface Mines, and
- A6 – Water Management for Underground Mines.

Although these BPGs were developed for the mining industry, these applications may still be used for the other activities that may affect the deep aquifer system.

Conventional mining activities in South Africa extend to depths greater than 300 m below surface and the BPGs were developed to ensure the protection of the shallow aquifer system. However, there is a loophole within the current BPGs in that they do not target the protection of deep aquifer systems.

The existing BPGs may be used to protect the deeper aquifer system during conventional mining activities, particularly in areas where the shallow and deep aquifer systems are connected via a series of shafts and tunnels. Although these BPGs may assist with the protection of deep aquifer systems, the current BPGs would need to be revised. The updated revisions would need to include the following at a minimum;

- Rising groundwater levels within abandoned mines and their effect of the groundwater aquifers at depth,
- The structural integrity of geological formations within the mine,
- The effects of oxidation of deep freshwater aquifers,
- Designing the extraction process to minimise the negative effects from the start of new mining endeavours,
- Development of progressive controlled flooding to avoid AMD,
- Updated monitoring procedures for deep mining operations.

Table 7-1: Summary of best practice for deep conventional mining

Best Practice	Action	Reference
Identifying and characterising deep aquifer systems and target mining area	Identify potential aquifers within the mining precinct. Identify geological structures that may interesect the potential aquifers.	Frogtech (2013)
Mapping out Faults and fractures that may serve as preferential pathways	Identification of fractures and faults will identify the preferential pathways for groundwater.	Gibbines and Chalmers (2008)
Monitor groundwater quality in the deep aquifer systems and mining basin	Generate additional information for the development of a geofabric model	Frogtech (2013)
Building a conceptual model	Build a conceptual model from the aquifer characterisation. Supplement the information from geofabric model with realistic groundwater data.	Frogtech (2013)
Integrity of mining basin and associated deep aquifer	Continous groundwater montinoring of the mining area.	Bildstein *et al.* (2010)
Shaft Integrity	Continous monitoring of the shaft for cement degredationa and integrity	Bildstein *et al.* (2010)
Modelling techniques	Use groundwater models to identfy groundwater flow patterns, geochemical processes and redict changes within the aquifer system.	Gibbines and Chalmers (2008)

7.3.4 Regulatory Tools

7.3.4.1 Conventional Mining

The South African government have stringent mining regulation for effects on the groundwater systems. In terms of conventional mining operations the following legislature is in place:

- Regulation 704 (GN R 704) in GG 20119 of 4 June 1999. These regulations are entitled: “Regulations in terms of section 26 of the National Water Act on the Use of Water for Mining and Related Activities aimed at the Protection of Water Resources”.
- GN331 in GG Gazette 37603 of 2 May 2014 (National Norms and Standards for the Remediation of Contaminated Land and Soil Quality in the Republic of South Africa).

The above regulations are specifically for shallow aquifer systems and surface water bodies, there is no legislation for the protection of the deep aquifer systems. In order to mitigate the effects that mining activities have on the deep aquifer systems, new legislation is required and would need to be promulgated urgently.

7.3.4.2 Groundwater Abstraction

South Africa has an excellent National Water Act and Section 21 of the Water Act relates to groundwater licenses for the removal of water from a resource. In this instance, section 21 (a) and 21 (j) is of essence.

Section 21(a) is the removal of water from a resource and section 21 (j) is removing or discharging of water found underground. Currently, there is limited or no groundwater abstraction from boreholes greater than 300 m and should this be required in future, the current water act would need to be revised to include abstraction of groundwater from depths greater than 300 m.

7.3.5 Monitoring and Adaptive Management

Groundwater monitoring of the deep aquifer system is very important, particularly if the objective is to limit the contaminants into the aquifer system. A baseline analysis of the area would need to be carried out prior to the activity occurring and this would need to be followed by a series of monitoring intervals to identify changes in groundwater quality and levels.

The monitoring programme would need to be developed in such a way that the potential impacts are identified at the inception phase of the activity. Thus preliminary rehabilitation procedures can be prepared and should the monitoring programme identify a specific impact, rehabilitation procedures can be followed. The monitoring data should be used for the verification and calibration of groundwater models to identify the contamination levels and plumes within the activity boundary. In addition, monitoring plans may assist with environmental auditing to ensure that the activity is compliant with the regulations.

The monitoring programmes should comprise at a minimum the following:

- The extent of the monitoring network,
- The sampling frequency and methods of sampling,
- Anticipate the type of effects that may occur and prepare rehabilitation procedures
- Identification of main parameters to be analysed,
- The required format of reporting to the relevant authorities,
- The type of environmental auditing that is required and implementations of changes to the monitoring based on updated information.

Depending on the type of activity a list of parameters needs to be identified during the baseline analysis, such that during the activity any changes in groundwater can be easily identified. It is imperative that stringent quality control, quality assurance, criteria to analyse results and data management are in place to ensure that the best practice is carried out to mitigate the effects.

7.4 PROPOSED GENERALISED FRAMEWORK TO PROTECT DEEP AQUIFERS

The following guidelines should be considered when developing an appropriate deep aquifer protection plan:

- Determine the baseline conditions prior to the commencement of any activity,
- Identify the geology and hydrogeology of the area and potential geohydrological structures,
- Develop and geohydrological model of the area,
- Identify all possible impact of the activity,
- Simulate the impacts of the activity on the geohydrological model,
- Using updated technologies to reduce the negative impacts,
- Ensuring the activity is done according to BPGs from South Africa and internationally,
- Implementation of an adequate monitoring programme, and
- Apply adaptive management strategies to solve any unforeseen issues that may arise.

CHAPTER 8: CLASSIFICATION OF DEEP AQUIFER SYSTEMS IN SOUTH AFRICA

8.1 INTRODUCTION

The DWS (previously Department of Water Affairs and Forestry) have developed a basic groundwater classification, which is presented in Table 8-1 in Chapter 2.

Table 8-1: Aquifer classification based on groundwater yields (DWA, 2010)

Description of Aquifer	**Estimated Groundwater Yield (L/s)**				
	0-0.1	**0.1-0.5**	**0.5-2.0**	**2.0-5.0**	**>5.0**
Intergranular			a3		
Fractured	b1	b2	b3	b4	
Karst			c3		
Intergranular and Fractured	d1	d2	d3	d4	

The original aquifer classification system was developed by "*Andiswa Matoti, Julian Conrad and Susan Jones, CSIR, 22 March 1999*". A detailed explanation of aquifer systems in South Africa is provided in Water Research Commission (WRC) research report namely: "*South African aquifer system management classification'; WRC Report No: KV 77/95; Author: Mr Parsons R; Date Published: 12 January 1993*". The original classification system by Parsons was in 1993 and revised classification in 1996, this was more than 20 years ago. In two decades the groundwater regime of South Africa has changed, with more emphasis placed on boreholes as a groundwater source, thus the aquifers in areas are being utilised more than previous years. In the past two years, I have carried out borehole investigation for more than 400 schools on a single project, thus the concern with an increase in groundwater exploitation. It is imperative to develop a new groundwater classification system. On the basis that the shallow aquifer systems have similar characteristics of the deeper aquifers, a proposed new aquifer classification system concept will be developed.

Table 8-2 and Table 8-3 (Parsons, 1995) tabulates the factors that are used to classify groundwater systems.

Table 8-2: Factors used to classify aquifers (modified after Parsons, 1995)

Hydrogeological Characteristics	Water Quality Issues	Usage
Aquifer Material Lithostratigraphic unit Aquifer yield Borehole yield Dept of water table	Current water quality Contamination level Treatment required	Current and Potential usage
Susceptibility	**Integrated Approach**	**Value**
Vulnerability to contamination	Hydraulic relationship with other resources	Social Value Economic Value Environmental Value

Table 8-3: Definitions of aquifer system management classes

Aquifer Type	Description
Sole Source Aquifer	Aquifers that supply more than 50% of water supply to an area for which there are no reasonably available alternative water supplies.
Major Aquifer System	Highly permeable formations with fracturing that have the potential to supply large volumes of water and quality is generally good.
Minor Aquifer System	Potentially fractured aquifers with low volumes of water that are capable of supplying small communities.
Non-aquifer system	These are formations in which no groundwater is stored.
Special Aquifer System	An aquifer that is designated by the Minister of Water and Sanitation.

8.2 PROPOSED LOCAL CLASSIFICATION SYSTEM

The current aquifer system can be used in a regional context, however, at local context, a different aquifer classification should be used and consider site-specific requirements for a given aquifer. The following modified classification system for site-specific requirements using the existing classification system is proposed.

A basic mathematical formula can be used to classify an aquifer, i.e. demand requirements + chemistry.

In order to determine the demand requirements, we need to identify the required supply for the area and similarly use the existing chemistry.

Demand Requirements:

- Aquifer meets demands - Allocate 2 points.
- Aquifer partially meets demands - Allocate 1 point.

- Aquifer does not meet demands – Allocate 0 points.

Chemistry Requirements:

- Within SANS 241-2015 limits – Allocate 2 points.
- Some treatment required – Allocate 1 point.
- Significant treatment required – Allocate 0 points.

Chemistry of groundwater in the area may be sourced from existing information in the area or sourced from the NGA. All chemistry data should be referenced to SANS 241. Table 8-4 provides various calculations used to determine the suitability of an aquifer system at local context.

Table 8-4: A proposed classification system for local context

Demand Requirements	Chemistry	Total	Comments
2	2	4	The aquifer meets the demands and has good chemistry, can be regarded as a good aquifer system.
2	1	3	The aquifer meets the demands and has fair chemistry, can be regarded as a fair aquifer system.
2	0	2	The aquifer meets the demands and poor groundwater chemistry, lots of treatment required, therefore can be regarded as a poor aquifer system.
1	2	3	The aquifer partially meets the demands and has fair chemistry, can be regarded as a fair aquifer system.
1	1	2	The aquifer partially meets the demands and requires treatment of groundwater to a level, therefore can be regarded as a poor aquifer system.
1	0	1	The aquifer partially meets the demands and requires significant treatment of groundwater, therefore can be regarded as a poor aquifer system.
0	2	2	Aquifer does not meet the demands but has good groundwater quality. Does not meet demands, therefore poor aquifer system.
0	1	1	Aquifer does not meet the demands but has fair groundwater quality. Does not meet demands, therefore poor aquifer system.
0	0	0	Aquifer does not meet the demands but has poor groundwater quality, therefore poor aquifer system.

Based on the preliminary analysis in Table 8-4,

Table 8-5 is a summary of the proposed classification system.

Table 8-5: Proposed aquifer classification system results

Aquifer Type	Total	Comments
Good	4	These may be considered as good aquifer systems at local context and have the capacity to supply the community with adequate volumes and clean groundwater.
Fair	3	These may be considered fair aquifer systems as either the demand supply of chemistry may vary slightly and/or provide partial relief to the community.
Poor	<3	These are considered as poor aquifer systems for the area and will have varying groundwater quality.

8.2.1 A Simple Scenario

For discussion purposes, a village in a remote area requires a flow of at least 2 L/s.

For instance, the geological map identified that the site is underlain by a fractured aquifer system with an inferred yield of up to 2.0 L/s, this would mean that the site is underlain by a b3 aquifer system. As a regional context, the aquifer system may be good and indicate potential groundwater, but at local context is this a good aquifer system?

The minimum requirement is 2 L/s and the maximum this aquifer can provide is 2 L/s, the aquifer will be classified based on the proposed aquifer classification system. Aquifer demand is considered to be partial, therefore 1 point and based on chemistry data in the area, all determinants fall within SANS 241, hence 2 points. Based on this information a total of 3 points classifies the aquifer, and according to

Table 8-5, this would be regarded as a fair aquifer system.

Consider if the aquifer in the area according to DWS classification system was a d4, this would indicate that the aquifer has a minimum supply of 2 L/s, which is considered to meet the basic demand. The new total will be 4 and considered to be a good aquifer system for the site and further investigation can proceed.

8.3 AQUIFER FEASIBILITY ASSESSMENT

In Section 8.2 an aquifer classification system was proposed for local context; however, identifying a suitable target area and the inferred depths of drilling can have significant financial implications. The DWS has developed a map which shows approximate groundwater levels within aquifer systems in South Africa.

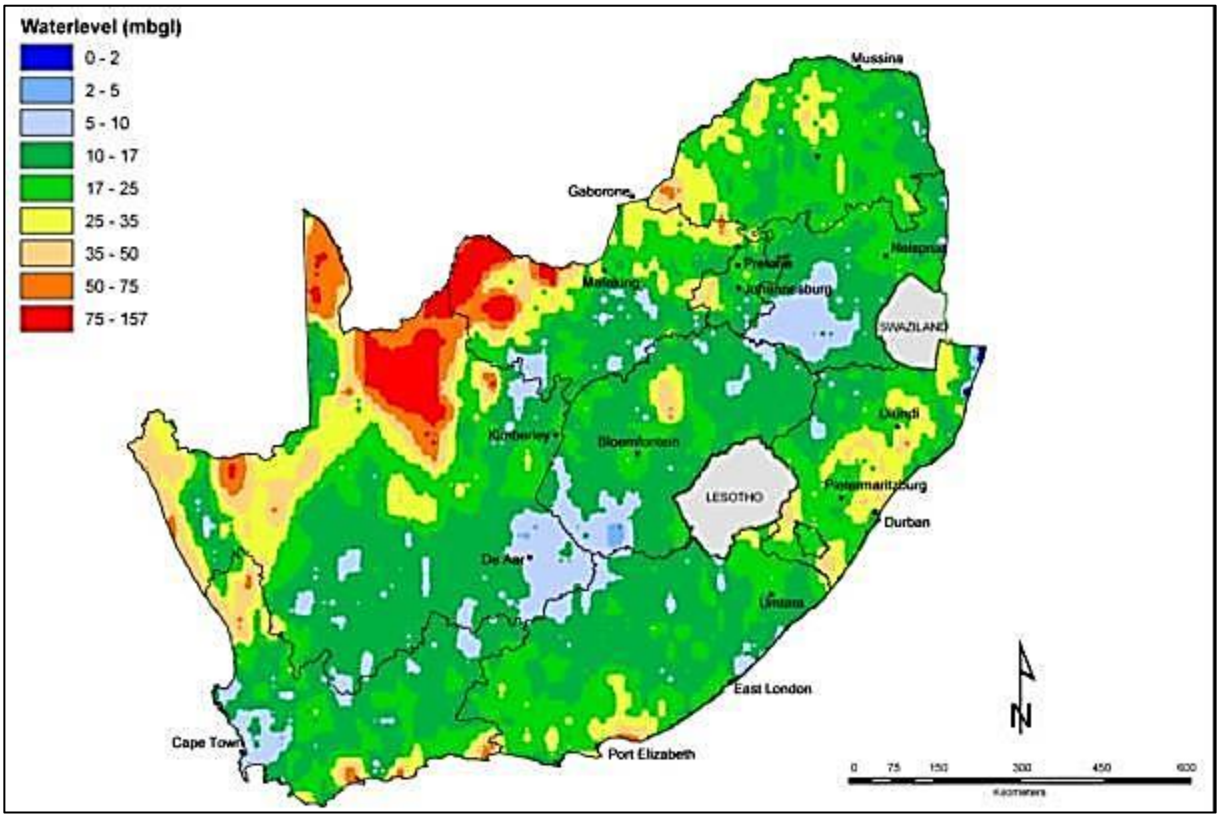

Figure 8-1 Indicative groundwater levels for South Africa (DWA, 2010)

Depending on drilling depth, a points system can also be allocated to determine the feasibility/suitability of drilling the aquifer. In this regard, depending on the aquifer system targeted, i.e. shallow and deep aquifer systems. The differentiating depth for shallow and deep aquifer systems is 300 m. Shallow aquifer systems will target local supplies for farmers, households, etc. Deep aquifer systems will be targeted by municipalities as an alternative source of water should the shallow aquifers in the area not yield sufficient quantities, hence the costs for drilling will be significant. In the context of financially feasible drilling for shallow and deep aquifers, the budget of a farmer maybe R100 000 which is considered as a high financial implication for the farming business, but a budget of R100 000 is considered low for a municipality. In the context of drilling a borehole, the financial feasibility depths may have the same comments but the budget implications are different in context.

Table 8-6: Feasibility of Drilling Aquifers

Drilling Depth (mbgl)	Points	Comments
***Shallow Aquifers**		
<100	2	These are considered to be favourable aquifer systems in which groundwater quality is encountered at shallow depths. Considered a financial feasible aquifer system.
100-149	1.5	These are considered to be moderate depth aquifers and will have an increase in drilling costs. Considered a financially fair aquifer system.
150-199	1	These are considered to be aquifer systems that are associated with significant drilling costs. Considered a financially low feasibility aquifer system.
200-300	0.5	
Deep Aquifer Systems		
300-400	2	These are considered to be favourable aquifer systems in which groundwater quality is encountered at depths between 300 and 400 mbgl. Considered a financial feasible aquifer system.
400-500	1.5	These are considered to be moderate depth aquifers and will have an increase in drilling costs. Considered a financially fair aquifer system.
500-600	1	These are considered to be aquifer systems that are associated with significant drilling costs. Considered a financially low poor aquifer system.
>600	0.5	

*Based on groundwater level depths in Figure 8-1.

Table 8-7 utilised the information provided from

Table 8-5 and Table 8-6 and provides an overall classification for an aquifer feasibility drilling project.

Table 8-7: Feasibility aquifer classification system and local content

Aquifer Type	**Good**	**Fair**	**Poor**
Groundwater Level			
Good	Good Aquifer with adequate supply, good chemistry and feasible drilling depths.	Fair Aquifer with partial supply, good to fair chemistry and feasible drilling depths.	Poor aquifer, does not meet supply demands, but may be associated with good groundwater quality and feasible drilling depths
Fair	Aquifer meets supply demands, may require treatment, drilling depth may be deep.	Aquifer partially meets demands, may require treatment, drilling depth may be deep.	Poor aquifer, may require treatment, drilling depth may be deep.
Poor	Aquifer meets the supply demand, but may require treatment and significant drilling depths	Aquifer partially meets the supply demand, but may require treatment and significant drilling depths	Poor aquifer, but may require treatment and significant drilling depths

Based on the classification in Table 8-7, the results can be concluded as follows;

i. If the aquifer type is good to fair and inferred groundwater level depth is good, these are considered to be feasible situations for the drilling of an aquifer in a specific area, regardless of shallow or deep aquifer systems.

ii. If the aquifer type is good to fair and inferred ground level depth is fair to poor, these are considered to be marginally feasible situations for the drilling of an aquifer in terms of feasibility.

iii. If the aquifer is poor, regardless of the inferred depth to groundwater, these are considered to be the poor situation and should rarely be drilled unless no other solution is permissible.

In order to refine the above local classification system, additional investigations would be required to support the above and develop a more concise classification system.

CHAPTER 9:
CONCLUSIONS AND RECOMMENDATIONS

Based on the research carried out thus far, the following conclusion can be made:

1. South Africa is a water scarce country and with the recent drought experienced, much emphasis was given to groundwater abstraction boreholes to supplement for the water supply.
2. However, the groundwater supply within South Africa is typically restricted to depths less than 120 mbgl and thus limited to the shallow aquifer systems. Rarely are abstraction boreholes drilled to depths greater than 120 mbgl.
3. Depending on which part of the world you are situated, various authors have different defining depths for deep groundwater aquifer systems. Depths range from 100 m to 1000 mbgl. Based on a South African perspective a defining depth of 300 mbgl is considered applicable.
4. The shallow aquifer systems are described as being either fractured, intergranular, karst or intergranular and fractured. In terms is porosity, some aquifer systems have a high degree of primary porosity whilst others have a high degree of secondary porosity. In rocks such as sandstones, primary porosity is usually high and in granite secondary porosities are high. Some rock types have double porosity, i.e. the matrix and fractures are porous enough to store and allow groundwater to move. Assuming that the deep aquifer systems based on similar rock types will have the characteristics of the shallow aquifer system.
5. Considering that much emphasis is placed on the shallow aquifer systems, there is insufficient data available on the deep aquifer systems. Although many mining companies have done exploration drilling to significant depths, hydrogeological information is rarely recorded. Therefore, the characteristics of the deep aquifer systems are inferred based on the behaviour patterns of the shallow aquifer system.
6. This dissertation concentrated on three types of aquifer systems within South Africa, 1) crystalline basement aquifers, 2) Bushveld Igneous Complex and 3) dolomite formations.
7. In summary, the groundwater characteristics of the basement aquifers, Bushveld Igneous Complex and dolomite formations are regarded as secondary aquifers.
8. The crystalline and Bushveld Igneous Complex aquifers formed as a result of either brittle or ductile deformation of the host bedrock. Whilst the dolomite aquifer form as a result of dissolution activities.
9. The degree of weathering and quantity of secondary structures determine the potential and volumes of groundwater that may be stored in a specific aquifer system.

10. Basement and Bushveld Igneous Complex aquifers are considered to be relatively low yielding primary aquifers, however, if the degree of fracturing is high, these aquifers have the potential to yield good secondary aquifer systems.
11. Dolomite aquifers are considered to be the highest yielding aquifers. As a primary aquifer dolomites are low yielding and poor, once dissolution of bedrock occurs and cavities develop large volumes of groundwater may be stored and transmitted and are regarded as the highest yielding secondary aquifer systems.
12. It was also identified that the degree of fracturing within host bedrock generally decreases with depth due to overburden pressures that close openings.
13. Although there is limited information on deep aquifer systems, the shallow aquifer systems are characterised and characteristics of the deep aquifer system are given based on this. This is discussed in detail in Chapter 6.
14. In terms of groundwater quality, the aquifers have varying characteristics; however, a specific signature for groundwater is that an increase in depth will result in an increase in sodium chloride which is particularly due to the long residence time within the aquifers.
15. Based on available information, the best quality of groundwater was identified to be within the dolomite aquifer systems, followed by the crystalline basement aquifer system.
16. Thermal springs have been identified as the best potential source to identify deep groundwater systems and understanding their chemistry.
17. There are many activities that pose a risk to the deep aquifer system, however, for the geologies identified within the study area, conventional mining and deep groundwater abstraction were identified as the two major sources.
18. Conventional mining operations were identified to affect the natural groundwater system by altering the groundwater flow patterns, depleting aquifer systems, contaminating the groundwater supply and disrupting the natural flow of groundwater.
19. Due to the mining activities, aquifers that are intercepted, dewatering of the mine working need to be carried out to create safe working conditions. In this regard, the subtraction of water from the aquifer alters the natural flow and depletes some of the aquifer systems. Furthermore, when groundwater is pumped from one section of the mine and artificially recharges the aquifer at another point, the groundwater that enters the system may be more contaminated, there is a risk from groundwater contamination for the other aquifer system.
20. Emphasis has always been placed on the shallow aquifer system, however, there is limited legislation for the protection of deep aquifer systems. If we consider the legislation for the shallow aquifer system and adapt it for the deeper aquifer systems, regulations can be created for the deep aquifer system.
21. It suggested that the following be carried out for any activity that may affect the deeper aquifer system. A thorough analysis of the aquifer systems within the proposed activity area, this should include both the shallow and deep aquifer system and to the depth in which the activity will be carried out. The use of modern technologies to monitor the effects

of the activity on the environment. Implementing best practice procedures to limit the negative effects on the environments. Implementing laws and legislation and enforcing it on the proposed activities, this would need to be carried out by environmental auditing of the activity.

22. At present, there is insufficient legislation to protect deep aquifer systems and more research needs to be carried out to determine the possible effects of activities and proposed solutions.
23. There is a need to create a new groundwater classification system with particular emphasis on deep groundwater aquifers. A simplified classification system has been proposed in Chapter 8.2.

The following recommendations are provided for additional investigations in order to determine the suitability of deep aquifer systems and classifications:

1. Areas identified as potential deep aquifer systems need to be investigated further using various hydrogeological methods available.
2. Deep groundwater exploration programmes need to be established.
3. Further analysis of thermal springs needs to be considered.
4. Analysis of groundwater samples needs to be collected from deep aquifer systems and analysed to determine groundwater quality.
5. Yield testing of aquifers is advised to confirm approximate yields.

Table 9-1: Summary of the Different Deep Aquifer Systems Discussed in this Dissertation

Criteria	Basement/Crystalline Rock Aquifers	Bushveld Igneous Complex Aquifers	Dolomite Aquifers
Criteria	**Description**	**Description**	**Description**
Lithology	These aquifers occur in fractured basement rocks, such as granites, gneisses and granitoids	The deep fractured aquifers occur in mafic, ultramafic and felsic rocks of the BIC.	The main dolomite units were deposits into two basins, the Transvaal and the Griqualand West basin. The dolomites that form part of the Transvaal supergroup are that of the Malmani subgroup and chunniesport group. The dolomites that from part of the sGriqualand West Basin are that of the Campbellrand subgroup and Ghaap Group.
Occurrence	Basement rocks are found throughout South Africa and may occur at depths in excess of 8000m under metasedimentary basins. The basement rocks coutcrop along the northern, eastern and western part of South Africa. Deep basement aquifers may occur anywhere in the country. A defining depth for a deep crystalline aquifer system is 300m bgl.	The BIC is very localised and extendeds in northern, northe western and north eastern parts of South Africa. The depth considered for a deep aquifer is 300m bgl.	Dolomite outcrops are encounteres along Gauteng, Northern Cape, North West, Limpopo and Mpumalanga provinces. The distribution of dolomites beneath the surface is greater than the dolomites outcropping. Deeper aquifers are considered at depths greater than 300m bgl.
Physical Dimensions	The verticle extend of fractures are expected to be limited. The main storage area within the basement aquifers is the degree of fracturing. The saturate level of the above sedimentary rocks will govern the vertical extent of the aquifer system whilst the lateral extent of the aquifer will depend upon the degree of fracturing.	vertical extent of deep fractures within the BIC are considered to be very limited. Matrices within the rocks comprising fractures are considered to be potential storage units. The thickness of the host rock will determine the thickness of the aquifer system and the length of teh aquifer will be governed by the degree of fracturing.	The lateral extent of dolomites is likely to be much larger than the surface distribution of dolomites. The dolomites within the Transvaal Basin are inferred to be greater than 1000m and the Griqualand West Basin, greater than 2000m. The presence of major faults and dykes within the subsurface create positive conditions for the development of dolomite cavities.
Aquifer Type	These aquifer systems are considered to be double porosity type systems. The primary porosity is the rock matrix, however, this is anticipated to be low and secondary porosity is related to the fracturing.	These aquifer systems are considered to be double porosity type systems. The primary porosity is the rock matrix, however, this is anticipated to be low and secondary porosity is related to the fracturing.	These aquifers are considered to be double porosity comprising a primary matrix of low porosity and secondary fractures and dissolutions cavities of high porosity.
Saturation Level	The deep fractured aquifers are likely to be under positive pressure and are assumed to be fully saturated.	The deep fractured aquifers are likely to be under positive pressure and are assumed to be fully saturated.	The deep fractured rocks are expected to be fully saturated.
Heterogeneity and Isotropy	In terms of vertical profiling, the aquifer is defined as highly heterogeneous, which is due to the degree of fracturing and rock matrix. The horizontal profile of the aquifer is considered to be inhomogeneous and anisotropic due to the irregularity of the fracture networks.	In terms of vertical profiling, the aquifer is defined as highly heterogeneous, which is due to the degree of fracturing and rock matrix. The horizontal profile of the aquifer is considered to be inhomogeneous and anisotropic due to the irregularity of teh fracture networks.	Due to the variation in the hydraulic properties of the dolomites, these are considered to be highly heterogeneous and anisotopic. The distribution of dissolution cavities is irregular. Dissolution cavities are more common close to the surface.
Formation Properties	The primary pososity of the aquifer is expected to be low (<1%), therefore minimal water is expected to be stored within the rock matrix. Secondary porosity is considered to be higher (>1%) and these create localised zones of high prosity within the bedrock.	The primary porosity is expected to be low (1%) with little water stored within the rock matrix. The secondary porosity structures such as fractures allow for some storage of water.	Primary porosity of dolomites are considered to be low (1-15%), however, when there are dissolution cavities and fractures, the seondary porosity is considered to be high(20%). It is estimated that the upper 30m of a dolomite sequence will have porosity of 15% and Similar porosities are expected to occur at palaeoakarst environments. Storativity values in teh range 2 - 20%. Hydraulic conductivities 2.9E-6 to 1.0E-5 m/s and transmissivities between 1000 to 25000 m^3/day.
Hydraulic Parameters	The hydraulic conductivities of the rock matrices ar expected to be low. Due to the low porosities these rocks are likely to have low storatiivities. The fractures within the bedrock will have higher hydraulic parameters. Hydraulic condutivies in the range 0.01 to 2.8m/day. Transmissivities in the range 5-40 m^2/day.	The hydraulic conductivities of the rock matrices ar expected to be low. Due to the low porosities these rocks are likely to have low storativities. The fractures within the bedrock will have higher hydraulic parameters. Storativity 0.15 and hydraulic conductivities between 0.03 to 0.04. Transmissivity values of 3 to 8 m^2/day	In terms of hydraulic conductivity, transmissivity and storativity, these are considered to be low in unweathered and undissolved dolomite bedrock. Higher conductivities, strativities and transmissivities are associated with dissolution cavities.
Pressurisation	The aquifer is expected to be under positive pressure. This does not provide an indication that the pressure is sufficient enough to create artesian conditions.	The aquifer is expected to be under positive pressure. This does not provide an indication that the pressure is sufficient enough to create artesian conditions.	If dissolution cavities extend to surface, the pressuremaybe regarded as normal. However, the presence of aquicludes or aquitards between dolomite layers may create a positive hydraulic pressure.
Yield	Although the fractures within the bedrock will have higher hydraulic conductivies than the rock matrix, the yield of the deep aquifers are considerd to be low. The recharge to these aquifers is considered to be low (<1 L/s).	Although the fractured may have high hydraulic conductivities, the yield of the deep aquifer system is considered to be low. The voumes of water available will depend on the size and degree of fracturing. However, recharge to such an area is considered to be low. Yields are typicaly 0.5 to 1.0 l/s.	Dolomites are inferred to have high yielding boreholes. Yields are expected to be up to 60L/s. Similar yields can be expected for paleaokarst dolomite aquifers.
Groundwater Quality	The groundwater quality is expected to be very good. Due to the long residence times an increase in chemical constituents such as flouride may be elevated.	The groundwater quality is considered to be poor with an increase in NaCl due to longer residence times within the aquifer.	The groundwater quality of dolomite aquifers are very good, however, they a vulnerable to pollution from surface.
Aquifer Vulnerability and Suceptibility	Due to the depth of these aquifers, the vulnerability to contaminants eminating from human activities is considered to be low. Depending on the volumes of water available, utilisation of these aquifers may lead to overexploitation with limited recharge available.	Due to the depth of these aquifers, the vulnerability to contaminants eminating from human activities is considered to be low. Depending on the olumes of water available, utilisation of these aquifers may lead to overexploitation with limited recharge available.	These aquifers are highly vulnerable to contamination from surface. High rates of groundwater migration through dissolution cavities aid the contamination process if these cavities are connected to surface. Deep aquifer would be less vulnerable if their dissolution networks do not extend to surface, however, these maybe susceptable to overexploitation.

REFERENCES

Abiye, T.A., Mengistu, and Demlie, M.B. (2011). *Groundwater resources in the crystalline rocks of the Johannesburg area, South Africa*. Journal of Water Resource and Protection, Vol.3, pp. 98-111.

Alley, W. M., Bair, E. S., and Wireman, M. (2013). *"Deep" groundwater*. Groundwater 51(5), 653-654. http://doi.org/10.1111/gwat.12098.

Baiyenunhi, C., Mupandawana, N.W., Oloniniyi, T.L, and Gwavava, O. (2014) *Characterization of Aliwal North hotspring in the Eastern Cape Province of South Africa, using magnetic, electromagnetic and radiometric methods*. Journal of Engineering, Vol. 4 (12), pp 43-58.

Banks, D. (2004). *Geochemical processes controlling mine water pollution*. Proceedings of the 2nd IMAGE-TRAIN, Advance Study Course, Vienna, 2004, pp. 17-44.

Barnard, H.C. (2000). *An explanation for the 1:500 000 hydrogeological map of Johannesburg 2526*. Department of Water Affairs and Forestry, Pretoria, Johannesburg, RSA.

Bianchini, F. (2016). *Mining industry and his impact on environment and health*. Available at: http://www.source-internatinal.org/wp-content/uploads/2012/11/Mining-impact-on-envronment.pdf [Accessed 18.10.2016].

Bildstein, O., Kervévan, C., Lagneau, V., Delaplace, P., Crédoz, A., Audigane, P., Perfetti, E., Jacquemet, N.M., and Jullien, M. (2010). *Integrative modelling of caprock integrity in the context of* CO_2 *storage: evolution of transport and geochemical properties and impact on performance and safety assessment*. Oil & Gas Science and Technology 2010; 65(3):485-502.

Boekstein, M. (1998) Hot springs holidays: Visitors' guide to hot springs and mineral spa resorts in Southern Africa. Mark Boekstein and Logo Print, Cape Town.

Bond, G.W. (1946). A geochemical survey of the underground water supplies of the Union of South Africa with particular reference to their utilisation in power production and industry. Government Printer, Pretoria.

Brandl, G., Cloete, M. and Anhaeusser, C.R. (2006). *Archaean greenstone belts*. *In:* Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council of Geoscience, Pretoria, 9 – 56.

Castany, G. (1981). *Hydrogeology of Deep Aquifers*. EPISODES, 1981(3), 18-22.

Cawthorn, R.G. (2010). The platinum group element deposits of the Bushveld Complex in South Africa. Platinum Metals Rev 54(4), 205-215.

Cawthorn, R.G., Eales, H.V., Walraven, F., Uken, R., and Watkeys M.K. (2006). *The Bushveld Complex*. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J., (Eds.), *The Geology of South Africa*. Geological Society of South Africa. Johannesburg/Council for Geoscience, Pretoria, 261-282.

Chimphamba, J., Ngongondo, C. and Mleta, P. (2009). *Groundwater chemistry of basement aquifers: a case study of Malawi*. In: Titus, R., Beekman, H., Adams, S. and Strachan, L. (Eds.). *The basement aquifers of southern Africa*. WRC Report No. TT428-09. Water Research Commission, Pretoria, South Africa.

Clark, L. (1985). *Groundwater abstraction from basement complex areas of Africa*. Quarterly Journal of Engineering Geology 18, 25-34.

Coffin, M.F. and Eldholm, O. (1994) Large igneous province: Crustal structure, dimensions and external consequences. Reviews of Geophysics, 32, pp 1-36.

Cornell, D.H., Thomas, R.J., Moen, H.F.G., Reid, D.L., Moore, J.M. and Gibson, R.L. (2006). *The Namaqua-Natal Province*. *In:* Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council of Geoscience, Pretoria, 325 – 380.

CGS (2000). *Bushveld Complex - South Africa-, Simplified Geology and Selected Platinum-,Chromite and Vanadium Deposits*. Council for Geoscience, Pretoria, South Africa.

CGS (2003). *Simplified Geological Map of South Africa, Lesotho and Swaziland* Council for Geoscience, Pretoria, South Africa.

Davis, S.N. (1969). Porosity and permeability of natural materials in flow through porous media, R.J.M De Wiest, ed., Academic Press, New York, 54-89.

Demlie, M.B., and Watkeys, M.K. (2011). Hydrochemical and environmental isotope based study of the thermal springs of KwaZulu-Natal, South Africa. University of KwaZulu-Natal.

Dhansay, T., De Wit, M. and Patt, A. (2014). *An evaluation for harnessing low-enthalpy geothermal energy in the Limpopo Province, South Africa*. S Afr. J Sci.*,* 110(3/4). http://dx.doi.org/10.1590/sajs.2014/20130282.

Diamond, R. E., and Harris, C. (2000). *Oxygen and hydrogen isotope geochemistry of thermal springs of the Western Cape, South Africa: Recharge at high altitude*. Journal of African Earth Sciences, 31(3-4), 467-481. http://doi.org/10.1016/S0899-5362(00)80002-0.

Drake, H., Tullborg, E.-L., Whitehouse, M., Sandberg, B., Blomfeldt, T., and Åström, M. E. (2015). Extreme fractionation and micro-scale variation of sulphur isotopes during bacterial sulphate reduction in deep groundwater systems. Geochimica et Cosmochimica Acta, 161, 1-18. http://doi.org/10.1016/j.gca.2015.04.014.

Du Toit, W. H. (2001). An investigation into the occurrence of groundwater in the contact aureole of large granite intrusions (batholiths) located west and northwest of Pietersburg. Department of Water Affairs, Pretoria, South Africa.

Du Toit, W. H. and Lelyveld, M. (2006). *An explanation of the 1:500 000 general hydrogeological map: Phalaborwa 2330*. Department of Water Affairs and Forestry, Pretoria, South Africa.

DWA (2011). Development of a reconciliation strategy for the Olifants River water supply system. Department of Water Affairs Report no. 04/B50/00/8310/10.

DWAF (2006a). Guideline for the assessment, planning and management of groundwater resources within dolomitic areas in South Africa, Volume 2: process and related activities. Department of Water Affairs and Forestry. Pretoria, South Africa.

Eglington. B.M., (2006).*Evolution of the Namaqua-Natal Belt, southern Africa – A geochronological and isotope geochemical review.* Journal of African Earth Sciences, 46, 93-111

Eriksson, P.G. and Altermann, W. (1998). *An overview of the geology of the Transvaal Supergroup dolomites (South Africa)*. Environmental Geology 36 (1-2), 179-188.

Eriksson, P. G., Hattingh, P. J. and Altermann, W. (1995). *An overview of the geology of the Transvaal Sequence and Bushveld Complex, South Africa*. Mineralium Deposita, Volume 30, pp. 98-111.

Fitts, C. R. (2002). *Groundwater Science*. Academic Press: London. ISBN 0-12-257855-4.

Foster, M.B.J. (1988). Geological control of aquifer properties of the Chuniespoort Group in the Klip River Valley and Natalspruit Basin, Transvaal. Unpublished master's dissertation, Rhodes University, Grahamstown, South Africa.

Freeze, R.A. and Cherry, J.A. (1979). Groundwater, Prentice Hall, Englewood Cliffs, N.J.

Freeze, R.A. and Witherspoon, P.A. (1967). Theoretical analysis of regional groundwater flow:2. Effect of water table configuration and subsurface permeability variation. Water Resources Research, 3(2), 623-634.

Friese, A. E. W., Swartz, H.G., Titus, R., Fielies, A., Davids, S., and Domoney, R. (2006). Geomechanical modeling as a tool for groundwater exploration of fractured rocks aquifers in the Namaqualand region, South Africa. WRC Report No. 1117/1/06. Water Research Commission, Pretoria, South Africa.

Frogtech (2013). *Geological risks of shale gas in Australia*. Project AAS 801. Frogtech Pty Ltd, Australia.

Gebrekristos, R. and Cheshire, P. (2012). *Hydrogeological properties of the UG2 pyroxenite aquifers of the Bushveld Complex*. In Proceedings of the 5th Platinum Conference of the Southern African Institute of Mining and Mettallurgy, 143-152.

Gibbins, J. and Chalmers, H. (2008). *Carbon capture and storage*. Energy Policy 36 (2008) 4317-4322.

Ashley Gumsley, Johan Rådman, Ulf Söderlund & Martin Klausen (2016):U-Pb baddeleyite geochronology and geochemistry of the White Mfolozi Dyke Swarm:unravelling the complexities of 2.70-2.66 Ga dyke swarms across the eastern Kaapvaal Craton,South Africa, GFF, DOI: 10.1080/11035897.2015.1122665To link to this article: http://dx.doi.org/10.1080/11035897.2015.1122665Published online: 08 Jan 2016.

Gustafson, G. and Krásný, J. (1994). *Crystalline rock aquifers: their occurrences, use and importance*. Applied Hydrogeology 2 (2), 64-75.

Hayhoe, M. (2013). *Bushveld minerals initiating coverage*. Fox Davies Resources Specialist Report, dated 21 March 2013.

Higgins, M.D. and Higgins, R. (1996) *A Geological companion to Greece and the Aegean*. Cornell University Press / Duckworth Publishers, Ithaca, NY / London.

Holland, M. (2010). *Groundwater quality in the Limpopo Province basement aquifers and its impact on rural groundwater supply*. In: Proceedings of the XXXVIII IAH Congress. Krakow, Poland. 12-17 September 2010.

Holland, M. (2011). Hydrogeological characterisation of crystalline basement aquifers within the Limpopo Province, South Africa. Unpublished PhD thesis. University of Pretoria, South Africa.

Holland, M. and Witthüser, K. (2009). Factors that control sustainable yields in Archean basement rock aquifers of the Limpopo province. In: Titus, R., Beekman, H., Adams, S. and Strachan, L. (Eds.) (2009). The basement aquifers of southern Africa. WRC Report No. TT428-09. Water Research Commission, Pretoria, South Africa.

Holland, M. and Witthüser, K. (2011). Evaluation of geologic and geomorphologic influences on borehole productivity in crystalline bedrock aquifers of Limpopo Province, South Africa. Hydrogeology Journal 19, 1 065-1 083.

Hoole, R.J. (2001). *The development of Lilani Hot Springs: An analysis of socio-economic and environmental impacts*. Unpublished master's dissertation, University of Natal, Pietermaritzburg, South Africa.

Kafri, U. and Foster, M. (1989). *Hydrogeology of the Malmani dolomite in the Klip River and Natalspruit basins, South Africa*. Environmental Geology and Water Sciences 13 (2), pp 153-166.

Kent, L.E. (1949). The thermal waters of the Union of South Africa and South West Africa. Trans. Geol. Soc. S. Afr. 52, 231-264.

Kent, L. (1952). *The medicinal springs of South Africa*. South African Railways Publishing and Travel Department. Cape Town, South Africa.

Kinnaird, J.A. (2005). *The Bushveld large igneous province*. Review paper, the University of the Witwatersrand. http://www.largeigneousprovinces.org/LOM.htlm [Accessed 17.08.2016].

Kramers, J.D., McCourt, S. and van Reenen, D.D. (2006). *The Limpopo Belt*. *In:* Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council of Geoscience, Pretoria, 209 -236.

Kruger, F.J. (2005) Filling the Bushveld Complex magma chamber: lateral expansion, roof and floor interaction, magmatic unconformities, and the formation of giant chromitite. PGE and Ti-V-magnetite deposits. Mineralium Deposita, 40, 451-472.

LaMoreaux, P.E. and Tanner, J.T. (Eds) (2001). *Springs and bottled water of the World*. Ancient History, Source, Occurrence, Quality and Use, Springer verlag, Berlin.

Lin, L., Jia, H. and Xu, Y. (2007). Fracture network characteristics of a deep borehole in the Table Mountain Group (TMG), South Africa. Hydrogeology Journal 15, 1419 – 1432.

Linn, F. (2009). *Groundwater exploration and development of basement aquifers in Botswana.* In: Titus, R., Beekman, H., Adams, S. and Strachan, L. (Eds.). *The basement aquifers of southern Africa*. WRC Report No. TT428-09. Water Research Commission, Pretoria, South Africa.

Lana, C., Gibson, R.L., Alexander, F.M., Kisters, W., and Reimold, U. (2003). *Archean crustal structure of the Kaapvaal craton, South Africa - evidence form the Vredefort dome*. Earth and Planetary Science Letters, Volume 206, pp. 133-144.

Lourens, P.J.H. (2013). *The relation between South African geology and geohydrology*. Master's thesis, University of the Free State, Bloemfontein, South Africa.

McCarthy, T.S. (2006). *The Witwatersrand Supergroup*. *In:* Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds), *The Geology of South Africa*. Geological Society of South Africa, Johannesburg/Council of Geoscience, Pretoria, 155 – 186.

McCarthy, T., (2010). *The decanting of acid mine water in the Gauteng City Region*, Gauteng City Region Observatory, Johannesburg. September 2010.

McCarthy, T., and Rubidge, B., (2005). The story of Earth and life. A southern African perspective on a 4.6-billion-year journey, Kumba Resources, 332 pp.

McCourt, S., Armstrong, R.A., Grantham, G.H. and Thomas, R.J. (2006). *Geology and evolution of the Natal belt, South Africa*. Journal of African Earth Sciences, Volume 46, pp. 71-92.

Naidoo, V. (2014). *Hydrogeological characterisation of Fountains East and Fountains West karst compartments*. Unpublished master's dissertation. University of Pretoria, Pretoria, South Africa.

Nel, J., Nel, M., Dustay, S., Siwawa, S., and Mbali, S. (2014). *Towards a guideline for the delineation of groundwater protection zones in complex aquifer settings*. WRC Report No. 2288/1/14, Water Research Commission, October 2014.

Nyagwambo, N.L. (2006). *Groundwater recharge estimation and water resources assessment in a tropical crystalline basement aquifer*. Unpublished PhD thesis, Delft University of Technology, Delft, the Netherlands.

Olivier, J., Van Niekerk, H.J. and Van der Walt, I.J. (2008). Physical and chemical characteristics of thermal springs in the Waterberg area in Limpopo Province, South Africa. Water SA, 34(2), 163 – 174.

Onstott, T.C., Hargraves, R.B., Joubert, P. and Reid, D.L. (1986). Constraints on the tectonic evolution of the Namaqua Province I: Palaeomagnetic and Ar/Ar results from the Richtersveld Subprovince. Transactions of the Geological Society of South Africa, Volume 89, pp. 117-142.

Owen, R. and Madari, N. (2009). *Baseline report on the hydrogeology of the Limpopo Basin: country studies from Mozambique, South Africa and Zimbabwe*. WaterNet Working Paper 12. WaterNet, Harare. Retrieved from http://www.waternetonline.ihe.nl/workingpapers/12%20Limpopo%20Hydrogeology.pdf.

Parsons, R. (1995). *South African aquifer management classification*. WRC Report NO. KV 77/95.

Person, M. and Baumgartner, L. (1995). *New evidence for long distance fluid migration within the earth's crust*. Reviews of Geophysics, 33, 1083-1091.

Pimentel, E.T., and Hamza, V.M. (2014). *Use of geothermal methods in outlining deep groundwater flow systems in Paleozoic interior basins of Brazil*. Hydrogeology Journal, 22(1), 107-128. http://doi.org/10.1007/s10040-013-1074-0.

Pietersen, K., Titus, R. and Cobbing, J. (2009). *Effective groundwater management in Namaqualand: sustaining supplies*. WRC Report No. TT 418/09. The Water Research Commission, Pretoria, South Africa.

Reddy, D.V., and Nagabhushanam, P. (2012). *Chemical and isotopic seismic precursory signatures in deep groundwater: Cause and effect*. Applied Geochemistry, 27(12), 23482355. http://doi.org/10.1016/j.apgeochem.2012.08.023.

Rosewarne, P. (2002a). Hydrogeological characteristics of the Table Mountain Group aquifers. In Pietersen, K. and Parsons, R. (2002). A synthesis of the hydrogeology of the Table Mountain Group - Formation of a research strategy. WRC Report No. TT 158/01.

SACS (1980). *Stratigraphy of South Africa (Handbook 8)*. Government Press, Pretoria, South Africa.

Scheiber-Enslin, S.E., Ebbing, J., and Webb, S.J. (2015). *New Depth Maps of the Main Karoo Basin, Used to Explore the Cape Isostatic Anomaly, South Africa*. South African Journal of Geology, 118(3), 225-248. http://doi.org/10.2113/gssajg.118.3.225.

Schrader, A., Erasmus. E., and Winde. F. (2014a). Determining hydraulic parameters of a karst aquifer using unique historical data from large scale dewatering by deep level mining - a case study from South Africa. Water South Africa Vol. 40 No. 3 July 2014.

Smith, P.J. (1964). *Diep Boorgate vir Water op Kruispad, Drieling en Potsepan, Gordonia Distrik*. Geohydrological Report GH 1209, Directorate Geohydrology, Department of Water Affairs, Pretoria, South Africa.

Taylor, Charles J., and Earl A. Greene. (2008). *Hydrogeologic characterization and methods used in the investigation of karst hydrology.* US Geological Survey (2008). Chapter 3 of Field Techniques for Estimating Water Fluxes Between Surface Water and Ground Water, Edited by Donald O. Rosenberry and James W. LaBaugh, Techniques and Methods 4-D2.

Titus, R., Witthüser, K. and Walters, B. (2009b). *Groundwater and mining in the Bushveld Complex*. Proceedings of the International Mine Water Conference, Pretoria, South Africa, 2009, 178 - 184.

Trumbull, R., Veksler, I., Ashwell, L. and Webb, S. (2015). *The Bushveld Igneous Complex Drilling Project (BICDP)*. Unpublished draft ICDP proposal.

Tsang, C.F., and Niemi, A. (2013). *Deep hydrogeology: a discussion of issues and research needs*. Hydrogeology Journal, 21(8), 1687-1690. http://doi.org/10.1007/s10040-013-0989-9

Van Wyk, E. (2013). *Southern African pre-Cretaceous deep groundwater flow regimes: Evidence and drivers*. In: Proceedings of the 13th Biennial Ground Water Division Conference and Exhibition. Durban, South Africa. 17-19 September 2013.

Vermeulen, P.D. (2012). *A South African perspective on shale gas hydraulic fracturing*. In McCullough, Lund, and Wyse (Eds.), Proceedings of the Annual Conference 2012 of the International Mine Water Association (pp. 149-156).

Viljoen, J.H.A., Stapelberg, F.D.J., and Cloete, M. (2010). *Technical report on the geological storage of carbon dioxide*. Council for Geosciences, Pretoria, South Africa. ISBN 978-1-920226-25-1.

Winde, F., Stoch, E.J., and Erasmus, E. (2006). *Identification and quantification of water ingress into mine voids of the West Rand and Far West Rand Goldfields (Witwatersrand Basin) with a view to long-term sustainable reduction thereof*. Final report, Project No. 5512, Council for Geoscience, Pretoria (unpublished). 261 pp.

Witcher, J.C. (1981). *Thermal springs of Arizona*. Field notes from the State of Arizona Bureau of Geology and Mineral Technology. Earth Sciences and Mineral Resources in Arizona, Vol. 11(2).

Woodford, A.C. and Chevallier, L. (Eds) (2002). *Hydrogeology of the Main Karoo Basin: current knowledge and future research need*. WRC Report No. TT179/02. Water Research Commission, Pretoria, South Africa.

Wright, E.P. (1992). *The hydrogeology of crystalline basement aquifers in Africa*. In Wright, E.P. and Burgess, W.G. (Eds.) (1992). *The hydrogeology of crystalline basement aquifers in Africa*. Geological Society, Special Publication No. 66, 1-27.

www.britannica.com (2018)

Younger, P.L. (2004). Impacts of mining on physical geohydrology. Proceedings of the 2nd IMAGE-TRAIN, Advance Study Course, Vienna, 2004, pp 8-16.

ABSTRACT

During periods of drought, as South Africa has experienced recently, groundwater boreholes are explored to identify alternative sources of water. However, much emphasis is placed on the shallow groundwater system with minimal information available on the deep aquifer system. The aim of this dissertation is to identify potential deep aquifer systems in South Africa and characterise their potential as potable water sources. This dissertation concentrates on three types of aquifer systems, the crystalline basement aquifers, Bushveld Igneous Complex and dolomite aquifers. In order to characterise deep aquifer systems, an understanding of basic hydrogeological terminology and characteristics of the shallow aquifer system need to be devised first. The methodology that is required is 1) to determine the defining depth between shallow and deep aquifer systems, 2) identify possible deep aquifer systems in South Africa, 3) identify the groundwater quality of shallow aquifer systems and infer characteristics to the deep aquifer system, depending on the geologies encounters, 4) identify any structures that may contribute to groundwater flow and the origin of the deep groundwater, 5) analyse thermal spring data as they provide an insight into the groundwater quality at depth, 6) characterisation of potential deep aquifer systems, and 7) determine the possible threats to the aquifer systems and provide mitigation procedures to prevent any contamination from occurring.

The defining depth between shallow and deep aquifer systems from a South African perspective is 300 mbgl. Based on the research carried out, all of the above-mentioned aquifer systems are generally classified as secondary aquifer systems in which the groundwater is typically found in fractures and cavities within the bedrock. The volumes of groundwater stored and transported will depend on the degree of fracturing and weathering if the bedrock. The dolomite aquifers in South Africa are considered to be the highest yielding aquifer system. In terms of groundwater quality, the dolomite aquifers have the most pristine groundwater condition of the three, provided that no contamination has occurred. A signature fingerprint with deep groundwater aquifer systems is that the salt content increases with depth, which is possibly due to the long residence time within the aquifer systems. The characteristics of the shallow aquifer system have been inferred to characterise the deeper aquifer systems based on similar geologies. However, the deep aquifer systems are subjected to lower recharge rates than the shallow aquifer system and may be at risk for overexploitation. On the contrary, the deeper aquifer systems are less susceptible to contamination from human activities at the surface. The main identified threat to deep groundwater aquifer systems is from the mining activities, which as we know in South Africa, with mined depth at least 3200 mbgl. The existing legislation that is currently in place focuses more on the shallow aquifer system than the protection of the deep aquifer system. Hence, more investigations are required to develop suitable legislation and tools to manage contamination in deeper aquifer systems.

In conclusions, although there may be potential deep aquifer systems in South Africa, the volumes of groundwater at this stage cannot be determined as there is minimal information available. It is possible that the groundwater at depth comprises a high salt content which may require treatment. It is suggested that more investigations be carried out to determine the volumes of groundwater available within each aquifer system at depth. In this regard, the mining activities and deep drilling projects could assist by collecting hydrogeological information during the exploration and operation phases.