THE RELATION BETWEEN SOUTH AFRICAN GEOLOGY AND GEOHYDROLOGY

By

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DECLARATION

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I, Paul Lourens, hereby declare that this dissertation, submitted for the degree Master in the Faculty of Natural and Agricultural Sciences, Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa, is my own work and has not previously been submitted by me at another University/Faculty. I declare that all sources cited or quoted are indicated and acknowledged by means of a list of references. I further cede copyright of the thesis in favour of the University of the Free State.

________________________________________

Paul Joël Havemann Lourens
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>BIC</td>
<td>Bushveld Igneous Complex</td>
</tr>
<tr>
<td>BIF</td>
<td>Banded Iron Formation</td>
</tr>
<tr>
<td>CFB</td>
<td>Cape Fold Belt</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>FEDM</td>
<td>Frequency Domain Electromagnetics</td>
</tr>
<tr>
<td>Ma</td>
<td>Million Years</td>
</tr>
<tr>
<td>NNMP</td>
<td>Namaqua-Natal Metamorphic Complex</td>
</tr>
<tr>
<td>RLS</td>
<td>Rustenburg Layered Suite</td>
</tr>
<tr>
<td>TEDM</td>
<td>Time/Transient Domain Electromagnetics</td>
</tr>
<tr>
<td>TMG</td>
<td>Table Mountain Group</td>
</tr>
<tr>
<td>UAA</td>
<td>Uitenhage Artesian Aquifer</td>
</tr>
</tbody>
</table>
## LIST OF UNITS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>degree Celsius</td>
</tr>
<tr>
<td>%</td>
<td>percentage</td>
</tr>
<tr>
<td>A/m</td>
<td>ampere per metre</td>
</tr>
<tr>
<td>cm</td>
<td>centimetre</td>
</tr>
<tr>
<td>cm/s²</td>
<td>centimetre per second squared</td>
</tr>
<tr>
<td>h/d</td>
<td>hour per day</td>
</tr>
<tr>
<td>kg/m³</td>
<td>kilogram per cubic metre</td>
</tr>
<tr>
<td>kHz</td>
<td>kilohertz</td>
</tr>
<tr>
<td>km²</td>
<td>square kilometre</td>
</tr>
<tr>
<td>l/s</td>
<td>litres per second</td>
</tr>
<tr>
<td>m</td>
<td>metre</td>
</tr>
<tr>
<td>mbgl</td>
<td>metre below ground level</td>
</tr>
<tr>
<td>m/d</td>
<td>metres per day</td>
</tr>
<tr>
<td>m²/d</td>
<td>square metres per day</td>
</tr>
<tr>
<td>mgal</td>
<td>milligal</td>
</tr>
<tr>
<td>mg/l</td>
<td>milligrams per litre</td>
</tr>
<tr>
<td>Mg/m³</td>
<td>megagrams per cubic metre</td>
</tr>
<tr>
<td>m³/h</td>
<td>cubic metres per hour</td>
</tr>
<tr>
<td>mm</td>
<td>millimetre</td>
</tr>
<tr>
<td>mm/a</td>
<td>millimetre per annum</td>
</tr>
<tr>
<td>m/s²</td>
<td>metre per second squared</td>
</tr>
<tr>
<td>mS/m</td>
<td>millisiemens per metre</td>
</tr>
<tr>
<td>Nm²/kg</td>
<td>newton metre squared per kilogram</td>
</tr>
</tbody>
</table>
nT  nanotesla
1.1. What is Groundwater

Water within the subsurface occurs in two different zones, namely the saturated and unsaturated zones (Figure 1). The latter occurs directly below the land surface in most areas, containing both water and air. The saturated zone directly underlay the unsaturated zone and all interconnected openings are filled with water (Heath, 1983). Only water within the saturated zone (below water table) is defined as groundwater.

Generally groundwater is of good quality, and can often be put into water supply systems with little or no treatment. Due to the fact that groundwater occurs within the subsurface no evaporation can occur, thus it makes it resistant to droughts and able to supply water even when surface water bodies (dams & rivers) have dried up. For these reasons, groundwater is considered to be a very important resource.

1.2. Groundwater in South Africa

Groundwater in South Africa is the most important source of potable water for rural communities, farms and towns. However, groundwater in South Africa is usually regarded as an unreliable source of water.
The right of people to have access to sufficient water and food (basic services) is enclosed in the Constitution of South Africa through the adoption of a Bill of Rights. Article 27 (1997) of the Bill of Rights states that everyone has the right to have access to:

I. Health care services, including reproductive health care.
II. **Sufficient food and water.**
III. Social security, including, if they are unable to support themselves and their dependants, appropriate social assistance.

Supplying sufficient water to communities in South Africa becomes a difficult task. This is especially true in the semi-arid and arid central regions of South Africa where surface water resources (dams & rivers) are limited or absent and the communities are only depended on groundwater resources (Botha, et al., 1998). Due to a growing population, surface water resources are almost entirely being exploited to their limits. These factors, therefore, increases the demand for groundwater resources and a more efficient management plan for water usage.

For these reasons, the relationship between the geology and geohydrology of South Africa becomes an important tool in locating groundwater resources that can provide sustainable quantities of water for South Africans.

### 1.3. Objectives

No document exists that provides valuable geohydrological information on the geological formations of the whole of South Africa, however, detailed reports and articles exist that focuses on specific areas. The present study therefore has the objective in mind to compile a document that provides valuable geohydrological information on the geological formations of the whole of South Africa.

The information that needed to be gathered includes the following:

I. Geohydrological characteristics of the geological formations of South Africa.
II. Geological formations that are more favourable aquifers and the geological structures to target within these formations that will improve the chances of striking good yielding aquifer systems.
III. Geophysical method or methods to apply in order to locate the different geological structures.
1.4. Methodology

The first step towards achieving the objective was by the collection of available information. The information was then gathered as follows:

I. Travelling to different provinces throughout South Africa to interview experienced geohydrologist (See Acknowledgements). The interviews were conducted to gain valuable information learned by these professionals/individuals through years of experience.

II. Review reports and articles of geohydrological studies conducted throughout South Africa.

After all the information was gathered the following geohydrological characteristics was identified and discussed:

I. Rock and aquifer parameters and behaviour.
II. Aquifer types (primary or secondary).
III. Groundwater quality.
IV. Borehole yields and expected striking depths.
V. Geological target features and geophysical method applied.

1.5. Structure of Thesis

This thesis comprises of six chapters:

- Chapter 1 serves as an introduction, defining groundwater and its role in South Africa. States the objectives of the thesis and how it has been approached.
- Chapter 2 discusses basic groundwater concepts which include the hydrologic cycle, basic groundwater definitions, aquifer types and aquifer classification.
- Chapter 3 discusses the basic principles of the geophysical methods used in South Africa for groundwater exploration.
- Chapter 4 discusses the geology of South Africa in chronological order from youngest rocks to oldest together with its geohydrology.
- Chapter 5 is a short conclusion and discussion in tabular form that summarises the thesis in whole.
- Chapter 6 contains a list of appropriate references.

A list of appendices follows in Chapter 6.
2.1. Hydrologic Cycle

The concept of groundwater can be described by the Hydrologic Cycle (Water cycle). The Hydrologic Cycle is a conceptual model (Figure 2) that describes the storage and movement of water between the biosphere, atmosphere, lithosphere and the hydrosphere (Hubbart & Pidwirny, 2010). The movement of water between these spheres occurs through various stages or processes such as precipitation, interception, runoff, infiltration, percolation, storage, evaporation and transportation.

Water evaporates from the oceans in enormous quantities and falls as precipitation either on land or ocean. The precipitation that falls on land evaporates, is transpired by plants, runs off, or infiltrates into the subsurface. Between these various stages of the Hydrologic Cycle, the water moves between temporary storage areas (Figure 2) which are often called reservoirs (Hubbart & Pidwirny, 2010). The water that infiltrates the soil will slowly move down-gradient (groundwater flow) where it will eventually end up in the ocean reservoirs.
The amount of water that will infiltrate the ground is controlled by various mechanisms which include (Hubbart & Pidwirny, 2010):

- Precipitation rate
- Soil water content
- Surface gradient
- Vegetation

Increased rates of precipitation will generally result in a decrease of water infiltration and an increase in surface runoff. Prior to rainfall, the relative amount of soil water content can dictate the amount of water that soil can hold before saturation. Generally, more water will infiltrate into dry soil than into a wet soil, and more water will run off steeper slopes than of moderate slopes. The presence of vegetation can counter act this process by holding more water than the hill slopes would by themselves (Hubbart & Pidwirny, 2010). Thus these mechanisms will control the amount of water entering the groundwater system. The water that enters the groundwater system, either by the downward percolation of precipitation or surface water and/or lateral migration of groundwater from adjacent aquifers is known as groundwater recharge.

### 2.2. Basic Definitions

Definitions sited in this section are from the Groundwater Dictionary of the Department of Water Affairs, South Africa.

#### 2.2.1.1. Porosity

Porosity is the voids or openings of a rock or soil and is defined as the ratio of the volume of void space to the total volume of the rock or earth material (can be expressed as a percentage). Porosity is an indication of the amount of water in the subsurface, but does not equate to the volume than can be released from storage.

Porosity can be primary, secondary or double (Figure 3):

- **Primary Porosity** is the porosity preserved from deposition through lithification.
- **Secondary Porosity** is the porosity created through alteration of rock, commonly by processes such as fracturing, faulting and dissolution.
- **Double Porosity** is when the porosity of a rock mass is from both primary and secondary porosity.
2.2.1.2. Permeability (k)

Permeability is the ease with which a fluid can pass through a porous medium and is defined as the volume of fluid discharged from a unit area of an aquifer under unit hydraulic gradient in unit time (expressed as m$^3$/m$^2$d or m/d). It is a fundamental property of the porous medium and is dependent of the properties of the saturating fluid. Permeability should not be confused with hydraulic conductivity (see section 2.2.3.1).

Permeability provides an indication of the ease with which a fluid can move through the subsurface.

The larger the pores or fractures through which the water flows, the higher the permeability of that rock. For example, clay is highly porous (well sorted) but its permeability is very low because of the fineness of the clay particles. Coarse sand on the other hand has a lower porosity than clay, but its permeability is high. If both the porosity and permeability is high, then the material will be an ideal aquifer as illustrated in Figure 4.

Figure 3: Illustration of primary, secondary and double porosity.

Figure 4: The relationship between porosity, permeability and aquifer potential.
2.2.2. Aquifers

An aquifer can be defined as a geological unit, or part of it which contains intergranular interstices, or joints and fractures or a system of interconnected joints and fractures capable of transmitting groundwater rapidly enough to directly supply a borehole or a spring (Vegter, 1995). An aquifer can either be confined, semi-confined or unconfined (Figure 5).

An **unconfined aquifer** is an aquifer without an upper confining layer of impermeable or low permeability soil or rock material. The water table is exposed to the atmosphere through a series of interconnected openings in the overlying soil or rock layers and is in equilibrium with the atmospheric pressure, thus the water table is free to fluctuate up and down.

A **confined aquifer** is an aquifer with an upper and lower boundaries marked by confining beds (aquicludes). In other words the groundwater within the geological formation is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

A **semi-confined aquifer** (leaky aquifer) is an aquifer that is partly confined by layers of lower permeability through which recharge and discharge may occur (aquitards). The confined character of these aquifers is often a result of the heterogeneous nature of the subsurface and has a piezometric surface (Figure 5) rather than a water table.

![Figure 5: Illustration of an unconfined and confined aquifer system.](image)

Aquifers can be grouped into two types according to the nature of the openings present. They are as follows.
I. **Primary Aquifer** – an aquifer in which groundwater moves through intergranular spaces formed at the same time as the geological formation (primary openings). These aquifers can yield large quantities of groundwater, but are vulnerable for pollution.

II. **Secondary Aquifer** – an aquifer through which groundwater moves through interstices formed after the geological formation was formed (secondary openings). The secondary openings form as a result of weathering, fracturing, faulting and dissolution.

### 2.2.3. Aquifer Parameters

#### 2.2.3.1. Hydraulic Conductivity (K)

Hydraulic conductivity is the constant of proportionality in Darcy’s Law. It is defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow and expressed in m/d. In other words it is a measure of the ease with which water will pass through the earth’s material.

Hydraulic conductivity should not be confused with permeability. While similar, hydraulic conductivity relates specifically to the movement of water, whereas, permeability considers the properties of the fluid being transmitted (density, viscosity, and temperature) and is relevant to multiphase flow systems which include gas, oil, and water phases.

Hydraulic conductivity provides an indication of the ease with which water moves through the subsurface and is used to calculate rates of groundwater movement.

#### 2.2.3.2. Transmissivity (T)

Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the average hydraulic conductivity and thickness of the saturated portion of an aquifer. In other words it is the measure of the ease with which groundwater flows in the subsurface.

Transmissivity is used to calculate the yield of a borehole, determine the safe yield of an aquifer system and predict groundwater movement.

#### 2.2.3.3. Storativity (S)

Storativity or storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. The storage coefficient is a dimensionless unit.
The size of the storage coefficient depends on whether the aquifer is confined or unconfined (Figure 6). If the aquifer is confined, the water released from storage when the head declines comes from expansion of water and from compression of the aquifer. When the aquifer is unconfined, the predominant source of water is from gravity drainage of the sediments through which the decline in the water table occurs (Heath, 1983). The storativity values of confined aquifers are less than that of unconfined aquifers.

The storativity is a measure of the volume of water stored and released in an aquifer and is used to quantify the safe yield of an aquifer system.

![Figure 6: Illustration of the storativity of unconfined and confined aquifer systems (Heath, 1983).](image)

### 2.3. Aquifer Classification

The Department of Water Affairs classified the aquifers South Africa into four classes when they developed the 1: 500 000 Hydrogeological Geological Maps. The aquifers are classified as follows:

- Intergranular (Class A)
- Fractured (Class B)
- Karst (Class C)
- Intergranular and Fractured (Class D)

**Intergranular** describes aquifers associated either with loose and unconsolidated formation such as sands and gravels (primary aquifer), or with rock that has weathered to the extent where its primary structure is that of loose or only partly consolidated material (secondary aquifer). Under these circumstances, water is stored in and transmitted through the intergranular voids that render the material porous and permeable.
**Fractured** describes aquifer associated with generally hard and compact rock formations in which fractures or joints occur that are capable of both storing and transmitting water in useful quantities.

**Karst** describes aquifers associated with carbonate rocks (dolomite or limestone) in which groundwater is predominantly stored in and transmitted through cavities and/or fractures.

**Intergranular and fractured** describes aquifers in which the intergranular interstices serve primarily as a storage and water is transmitted mainly through the fracture-type interstices. This is a common feature for many South African aquifers.
In this chapter, the geophysical methods that are being used in South Africa for locating groundwater resources are discussed, to provide a basic understanding of how each method operates. The most commonly and widely used geophysical methods in South Africa are:

I. Magnetics
II. Electromagnetics
III. Resistivity (Electric)
IV. Gravity

Seismic and aerial geophysical surveys are often used in geohydrological investigations. Aerial geophysics refers to magnetic, gravimetric and electromagnetic measurements taken from the air via an airplane equipped with geophysical measurements. Aerial geophysics is useful to cover large areas and to obtain a regional overview of the presence of geological structures. The seismic method is briefly discussed in section 3.1.

**3.1. Magnetic Method**

The magnetic method is possibly the geophysical tool that is mostly used by South African geohydrologist to locate groundwater resources, as it is an easy-to-operate geophysical tool.

Many rock formations contain magnetic minerals and will have a magnetic field of their own. The magnetic fields of these rock formations are superimposed on the large-scale magnetic field of the Earth (Milsom, 2003; Ernstson, 2006b), in other words it will give rise to an anomaly in the Earth’s magnetic field. Thus by using the magnetic properties of rocks one can delineate rock formations that show a magnetic anomaly. Figure 7 illustrates the basic idea of magnetic anomalies of different rock formations.

Minerals such as magnetite, pyrrhotite, ilmenite and maghemite are the only important naturally occurring magnetic minerals on earth and are widely distributed throughout, whereas magnetite is by far the most common (Roux, 1980). Magnetometers are used to measure the magnetic field.
3.1.1. Basic Principles

The Earth’s magnetic field resembles the field of a large bar magnet situated near the centre of the Earth about one third of the Earth’s diameter and ischant from the Earth’s spin axis (Roux, 1980), as illustrated in Figure 8. The Earth’s magnetic field is generated by electric currents circulating in the liquid outer core of the Earth (Milsom, 2003). The magnetic intensity of the Earth’s magnetic field varies across the globe (Figure 9) and is the greatest at the magnetic poles and least at the magnetic equator (Roux, 1980). In South Africa the magnetic intensity is about 27 000 nT.

The difference between the direction of geographic (true) and magnetic north is known as the magnetic declination (the angle a compass needle deviate from true north) and the angle the Earth’s magnetic field makes with the horizontal component is known as the magnetic inclination (Figure 9 & Figure 10).
Figure 9: Magnetic inclination (continuous lines, value in degrees) and intensity (dotted lines, values in thousand of $\mu$T) of the Earth's magnetic field. The thick continuous line is the magnetic equator (Milsom, 2005).

Magnetic inclination (continuous lines, value in degrees) and intensity (dotted lines, values in thousand of $\mu$T) of the Earth's magnetic field. The thick continuous line is the magnetic equator (Milsom, 2005).
Induced and remanent magnetism are the two magnetisms causing magnetic anomalies in the Earth’s magnetic field. The induced magnetism of a geological body is in the same direction of that of the Earth’s present day magnetic field (Roux, 1980), thus the Earth’s magnetic field is induced into the body, whereas remanent magnetism need not to be in the same direction of the Earth’s magnetic field (Roux, 1980).

The intensity of the Earth’s magnetic field at a particular locality and also the rock’s known magnetic susceptibility will determine the degree of the induced magnetisation (Roux, 1980). The magnetic susceptibility is defined by (Roux, 1980) as the measure of the degree to which a material may be magnetised. The intensity of the magnetisation is given by the following equation:

**Equation 1**

\[ I = kH \]

Where:

- \( I \) = Intensity of magnetisation
- \( k \) = Susceptibility
- \( H \) = Magnetic field intensity

The susceptibility of a material can be either positive or negative and is very small for most natural materials (Milsom, 2003) and the unit of both magnetisation and the magnetic field is ampere per metre (A/m) (Ernstson, 2006b). The susceptibilities of common rocks and ores are given in Table 1.
Table 1: Magnetic susceptibilities of common rocks and ores (Milsom, 2003).

<table>
<thead>
<tr>
<th>Common Rocks</th>
<th>Susceptibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slate</td>
<td>0.001-0.002</td>
</tr>
<tr>
<td>Dolerite</td>
<td>0.01-0.15</td>
</tr>
<tr>
<td>Greenstone</td>
<td>0.0005-0.001</td>
</tr>
<tr>
<td>Basalt</td>
<td>0.001-0.1</td>
</tr>
<tr>
<td>Granulite</td>
<td>0.0001-0.05</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>0.00025-0.01</td>
</tr>
<tr>
<td>Salt</td>
<td>0-0.01</td>
</tr>
<tr>
<td>Gabbro</td>
<td>0.001-0.1</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.00001-0.0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ores</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematite</td>
<td>0.001-0.0001</td>
</tr>
<tr>
<td>Magnetite</td>
<td>0.1-20</td>
</tr>
<tr>
<td>Chromite</td>
<td>0.0075-1.5</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>0.001-1</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.0001-0.005</td>
</tr>
</tbody>
</table>

Some rocks and minerals possess remanent magnetism because of the remanent magnetism of their constituent ferro-magnetic grains and this remanent magnetism may completely dominate the induced magnetism and can be in a different direction to that of the Earth’s magnetic field and can even oppose the Earth’s field (Roux, 1980). The reason why the
Remanent magnetism is in a different direction to that of the Earth’s magnetic field is because the earth’s field was in a different direction when the rocks became magnetised (Roux, 1980).

Remanent magnetism may result from one or a combination of geological processes such as (Roux, 1980):

I. Cooling down of a rock in a magnetic field.
II. Chemical formation or crystallisation in a magnetic field.
III. Magnetic grains tending to be orientated in the direction of the magnetic field during sedimentation.
IV. Reorientation of magnetic grains as a result of great pressure.

### 3.1.2. Diurnal Variations

The Earth’s magnetic field varies with time because of the variation in the direction and strength of solar winds (Roux, 1980; Milsom, 2003). The variations occur mainly during daylight hours (Roux, 1980) and are almost constant during the night but decreases between dawn to about 11 a.m., increases again until about 4 p.m. and then slowly declines to the overnight value (Figure 11 A) (Milsom, 2003). Solar radiation is the cause of upper atmosphere ionization and diurnal curves tend to be directly related to local solar time but crustal conductivity may be more important than time dependency for points up to a few hundred kilometres apart if the amplitude difference is more than 20% (Milsom, 2003).

A violent form of diurnal variation (Figure 11 B) is magnetic storms (Roux, 1980) and is caused by sunspot and solar flare activity (Milsom, 2003). Normally during a solar storm the magnetic field values may change by hundreds of nT, which is followed by a slower, erratic return to normality (Milsom, 2003) and the effects can last hours or for a few days (Roux, 1980; Milsom, 2003). It is advisable not to take readings during magnetic storms and to scrap any readings taken during it.
3.1.3. Instrumentation

Magnetic measurements are carried out by using magnetometers and mechanical magnetometers have completely been replaced, based on physical processes, by electronic instruments (Ernstson, 2006b). Types of magnetometers include:

I. Proton Precession Magnetometer (most common)
II. Fluxgate Magnetometer
III. Magnetic Balance Magnetometer (hardly ever used)
IV. Alkali Vapour Magnetometer

The proton magnetometer (Figure 12) is the most commonly used instrument for magnetic measurements and is composed of a portable sensor (Ernstson, 2006b) containing a low freezing-point hydrocarbon fluid (proton rich) with a coil of copper wire around it (Milsom, 2003). The protons in the fluid act as small spinning magnets and their spin axes are randomly orientated under normal conditions (Roux, 1980). A polarizing current, in the order of and amp or more, is passed through the coil, it creates a strong magnetic field and the spin axes of the protons align in the direction of this field (Roux, 1980; Milsom, 2003). When the current is switched off the spin axes of the protons will realign (precess) to the direction of...
the Earth’s magnetic field (Roux, 1980; Milsom, 2003). The electronic console of the proton magnetometer will output the results as nanoTesla on the digital display.

The other type of magnetometers will not be discussed as they are rarely used by geohydrologists in South Africa.

![Proton Precession Magnetometer](image)

**Figure 12: Proton Precession Magnetometer.**

### 3.1.4. Applications

There are a number of applications for magnetic measurements which include the following:

I. Locating dolerite dykes and sills.

II. Identification of basement faulting and other locations of crustal weakness that may present preferential fluid flow paths.

III. Locating the cause of contaminated groundwater by surveying for buried metallic objects such as hydrocarbon storage tanks, and chemical containers.

The advantages and disadvantages of the magnetic method are given in Table 2.
Table 2: Advantages and disadvantages of the magnetic method modified after Technos Inc. (2004).

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements are relatively easy to make</td>
<td>Susceptible to interference from steel/iron objects</td>
</tr>
<tr>
<td>Does not require intrusive ground contact</td>
<td>Total field measurements susceptible to natural fluctuation in Earth’s magnetic field (a base station must be used to remove natural fluctuations in Earth’s field)</td>
</tr>
<tr>
<td>Carried by hand</td>
<td></td>
</tr>
</tbody>
</table>

Dolerite contains ferromagnetic minerals which formed during the crystallisation of the magma it originated from giving it its magnetic properties. Fe, Mg, and Ca are accessory elements (< 20 %) present within this low silica (40-45 %) magma and during the crystallisation of this magma these accessory minerals will react with each other to form ferromagnetic elements (pyroxene) and Ca-rich plagioclase (Van der Westhuizen, et al., 2000). The crystallisation of these minerals is a function of the magma composition and temperature, as demonstrated by Bowen’s Reaction Series (Figure 13).

Figure 13: Bowen’s Reaction Series demonstrating the formation of minerals during magma crystallisation.
Dolerite dykes and sills are important geological structures in the exploration of groundwater resources. As a dolerite intrudes into the Earth’s crust, the heat (900-1200 °C) of the magma will cause a zone of contact metamorphism within the host rock, along the sides of the intruded body (Van der Westuizen et al., 2000). Joint and fracture formation occur in this zone of metamorphism as a result of cooling, resulting in a possible good aquifer system. A dolerite dyke or sill serve as a barrier for groundwater flow and water accumulates in this zone of contact metamorphism known as the baked zone, resulting in a possible good aquifer system (Van der Westuizen et al., 2000).

3.2. Electromagnetic Method

Electromagnetic methods are able to measure the electric conductivity of the subsurface (McNeill, 1980; Technos Inc., 2004). Electric conductivity is a function of soil and rock type, and permeability, as well as the composition of fluids that fill the pore spaces (McNeill, 1980). The values are given in mS/m and these values are not generally very diagnostic on their own, but rather how they relate spatially (Technos Inc., 2004).

All electromagnetic methods are based on the fact that time electromagnetic radiation of the subsurface will cause electric currents to flow (IGS, [n.d.]). Electromagnetic methods thus induce currents into the subsurface which are time-varying in nature and give rise to time-varying magnetic fields (IGS, [n.d.]; Christiansen et al., 2006) which is then measured on the surface by induction coils.

Electromagnetics can be implemented using one of the following techniques:

I. Frequency Domain Electromagnetics (FDEM)
   - Measure the electrical conductivity of soil and rock by measuring the magnitude and phase of an induced electromagnetic current (Technos Inc., 2004).

II. Time/Transient Domain Electromagnetics (TDEM)
   - Measure the electrical conductivity of soil and rock by inducing pulsating currents in the ground with a transmitter coil and monitoring the decay of the induced current over time with a separate receiver coil (Technos Inc., 2004).

2.3.1. Basic Principles

2.3.1.1. Electromagnetic Induction

The best possible way to explain electromagnetic induction is by illustrations. In Figure 14 (A), a momentary current is observed in the ammeter when the magnet is moving or if the
brass disk is spinning while the magnet is stationary (Kostlin & Van Zijl, 1985). This phenomenon is stated by Faraday’s Law, which states that “a time-varying magnetic field sets up a circulating electric field”. The magnet can also be replaced by a coil as seen in Figure 14 (B).

Current flow can be induced in another coil without any physical contact (Figure 14 C). In Figure 14 (C) a momentary current is observed in the ammeter connected to coil No. 2, when the resistance of the rheostat is decreased quickly, thus increasing the current of the electromagnet and if the current of the electromagnet is quickly decreased the ammeter needle moves in the opposite direction (Kostlin & Van Zijl, 1985). From this example it is clear that only an alternating current can induce current flow in another coil without physical contact.

Figure 14: Experimental set-ups to illustrate basic principles of electromagnetic induction modified after (Kostlin & Van Zijl, 1985).

The question is why it is possible to create a current in another coil without physical contact. The coil with the alternating current creates a time-varying magnetic field as stated by Ampere’s law. The magnetic field can visually be represented by lines of flux and the density of this flux at any given point is a measure of the strength of the magnetic field also
known as the magnetic induction whereas the magnetic flux is a measure of the total size of the magnetic field through a specified area (Kostlin & Van Zijl, 1985). Thus if the number of field lines cutting through a surface changes with time, then the magnetic flux through the surface changes with time, and a circulating electric field is induced (IGS, [n.d.]). The current only exist when there is a closed circuit but the electromotive force (emf; voltage) that drives the current is present even if the circuit is broken in coil No. 2 (Figure 14 C) (Kostlin & Van Zijl, 1985). Thus any conducting material will have an induced emf if it intersects time-varying magnetic flux lines.

There are three distinct ways in which an emf can be induced in a circuit (IGS, [n.d.]):

I. If the magnetic field is time-dependent.
II. If the surface size of the circuit is time-dependent.
III. If the orientation of the circuit changes with respect to the direction of the magnetic field.

There is a time-lag between the applied voltage and the current or in other words a phase shift (IGS, [n.d.]). The current lags behind the voltage by a factor given in the equation below:

Equation 2

\[ \varphi = \tan^{-1}\left(\frac{\omega L}{R}\right) \]

Where:

- \( L \) = Self-inductance
- \( R \) = Resistance
- \( \omega = 2\pi f \) (f = frequency)

The importance of this phase shift between the voltage and the current is that the secondary magnetic field is out of phase and lags \( \pi/2 \) radians behind the primary magnetic field (Kostlin & Van Zijl, 1985; IGS, [n.d.]).

### 2.3.1.2. Electromagnetic Induction Measurements

**Frequency Domain**

When performing an electromagnetic survey, currents are induced (known as eddy currents) into subsurface conductors (Kostlin & Van Zijl, 1985) by creating a time-varying magnetic field (primary field) with a transmitter loop. The eddy currents set up their own magnetic field (secondary field), as discussed above, and the secondary field is then superimposed on the
primary magnetic field and can be detected by a receiver coil (induction coil) (Kostlin & Van Zijl, 1985).

The electromagnetic response of geological bodies will be different from that in circuits. The reason for this is that the induced current is not restricted to a single path as in a circuit unit but rather in all directions when considering the 3-dimensional aspect of geological bodies and thus the effects of attenuation with depth of penetration (skin depth concept) need to be considered (IGS, [n.d.]).

The secondary magnetic field response is smaller than the primary magnetic field at the receiver coil, thus it is necessary to get rid of the primary field.

When comparing the in-phase and quadrature (out-off-phase) components (Figure 15) of the response function (frequency is kept constant) it is possible to qualitatively estimate the conductivities of geological bodies (Kostlin & Van Zijl, 1985). Bodies with medium conductivity will give in-phase and quadrature anomalies of the same order, whereas with good conductors the in-phase component dominates and vice versa for poor conductors (Kostlin & Van Zijl, 1985).

Choosing the correct frequency is very important. If the frequency is too low the anomalies will be small and if it is too high the anomalies will be large (Kostlin & Van Zijl, 1985) which will make it virtually impossible to distinguish between a good and moderate conductor (Kostlin & Van Zijl, 1985; Milsom, 2003) as the quadrature field is very small at high frequencies (Milsom, 2003).

![Figure 15: The behaviour of the response function of a vertical loop conductor with changing response parameter. Curves for complex targets would have the same general form (Milsom, 2003).](image-url)
**Time/Transient Domain**

The TDEM method uses a direct current (Christiansen et al., 2006). The current is pulsed through the transmitter loop and thus creating a primary magnetic field (Bean & Pipes, 1997) which induces eddy currents (secondary current) into the subsurface, creating a secondary magnetic field which is then measured during the time off (Fitterman & Stewart, 1986). The primary field is absent while measuring (Christiansen et al., 2006). Figure 16 illustrates the basic measuring principle of the TDEM method, where A shows the current in the transmitter loop, B is the induced emf in the ground, and C is the secondary magnetic field measured at the receiver loop.

The induced secondary current in the subsurface show a characteristic decay which will generate a decaying magnetic field (secondary), where the time varying rate of change in the magnetic field is measured by the receiver coil (Kostlin & Van Zijl, 1985). The initial magnitude of the electric current is independent of the conductivity structure (resistance) of the subsurface but the decay rate is direct proportional to the resistance. Thus, measurements from poor conductors have initial high amplitudes and decay rapidly and vice versa for good conductors (Kostlin & Van Zijl, 1985) as illustrated by Figure 17.

Figure 16: Basic measuring principle of the TDEM method. Assumed, that the receiver coil is located in the centre of the transmitter loop for the graphs of the induced emf and the secondary magnetic field (Christiansen et al., 2006).
When the primary current is switched off (early time), the secondary current is near the surface, and the measured signal reflects primarily the conductivity of the top layers but at later times (late time) the current will run deeper in the ground, and the measured signals here will contain information about the conductivity of the lower layers (Christiansen et al., 2006). Thus the measurements obtained are a function of depth, and is known as depth sounding. The current progresses through the subsurface as an expanding “smoke ring” (Milsom, 2003) as illustrated in Figure 18.
2.3.2. Instrumentation

Electromagnetic instruments commonly used are as follows:

I. FDEM (Figure 19):
   - EM-34
   - EM-31
   - EM-38

II. TDEM:
   - EM-47
   - EM-57

![Figure 19: FDEM electromagnetic instrumentation.](image)

The instrument most commonly used by geohydrologists of South Africa in groundwater exploration is the EM-34. For this reason the EM-34 will be discussed in more detail.

The EM-34 is a portable, two men, frequency domain system. It makes use of two coils (loops), where one is the transmitter coil and the other one the receiver coil. This instrument uses frequencies of 0.4, 1.6, and 6.4 kHz with spacings of 40, 20 and 10 m respectively (Milsom, 2003).
Coil configurations for maximum-and minimum-coupling is illustrated by Figure 20. For the EM-34, the horizontal and vertical co-planar is the preferable coil configuration to achieve coupling with subsurface structures. When the coils are horizontal in relation with the ground surface, then the magnetic dipole is vertical (hence the term vertical dipole) and if the coils are vertical in relation to the ground surface, then the magnetic dipole is horizontal (horizontal dipole) (Milsom, 2003). Thus the horizontal, co-planar configuration is used to detect vertical structures within the subsurface and vice versa for the vertical, co-planar configuration. The penetration depth of the horizontal dipole is about half of that of the vertical dipole (Milsom, 2003). The approximate depths of penetration for the FDEM instruments are given in Table 3.

Table 3: Approximate depth of bulk conductivity measurement of the FDEM instruments (Technos Inc., 2004).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Coil Spacing (m) (vertical dipole)</th>
<th>Maximum Depth of Measurement (m) (70% response)</th>
<th>Depth of Maximum Response (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM-38</td>
<td>1</td>
<td>1.5</td>
<td>0.4</td>
</tr>
<tr>
<td>EM-31</td>
<td>3.7</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>EM-34</td>
<td>10</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>EM-34</td>
<td>20</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>EM-34</td>
<td>40</td>
<td>60</td>
<td>16</td>
</tr>
</tbody>
</table>
2.3.3. Applications

There are a number of applications for electromagnetic measurements which include the following (McNeill, 1980):

I. Mapping of geological structures that are associated with preferred fluid pathways such as faults, fractured bedrock, contact zones etc.
II. Detecting cavities in carbonate rocks.
III. Mapping pollution plumes in groundwater.
IV. Locating gravel deposits.
V. Mapping of saline intrusions.
VI. Locating conductive mineral deposits (Christiansen et al., 2006).
VII. Locating pipes and metallic-type conductors such as steel tanks.
VIII. Determining the depth and thickness of geological conductive layers (Technos Inc., 2004).

The advantages and disadvantages of both the FDEM and TDEM are given in Table 4.
Table 4: The advantages and disadvantages of both the FDEM & TDEM (Technos Inc., 2004).

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FDEM</strong></td>
<td>Measurements are relatively easy to make</td>
<td>Limited vertical resolution</td>
</tr>
<tr>
<td></td>
<td>Provide excellent lateral resolution with profiling</td>
<td>Susceptible to interference from nearby metal pipes, cables, fences, vehicles and induced noise from power lines</td>
</tr>
<tr>
<td></td>
<td>Does not require ground contact</td>
<td>Effectiveness of electromagnetic measurements decreases at very low conductivities</td>
</tr>
<tr>
<td></td>
<td>Provides measurements with depths ranging from 1.5 m to 60 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continuous data may be acquired to depths of 15 m with hand-carried or vehicle-mounted equipment.</td>
<td></td>
</tr>
<tr>
<td><strong>TDEM</strong></td>
<td>Good lateral and vertical resolution</td>
<td>Deeper measurements require a large transmitter coil (300 × 300 m or more) for which space may not be readily available</td>
</tr>
<tr>
<td></td>
<td>Depth range of approximately 6 m to 900 m</td>
<td>Susceptible to interference from nearby metal pipes, cables, fences, vehicles and induced noise from power lines</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effectiveness of electromagnetic measurements decreases at very low conductivities</td>
</tr>
</tbody>
</table>
3.3. Resistivity Method

Resistivity measurements are carried out by recording the electric potential (voltage) from a current input into the ground, thus collecting information on the resistivity ability of the subsurface (Moller et al., 2006). The resistivity of the subsurface is a complicated function of porosity, permeability, ionic content of the pore fluids, and clay mineralization (GEOVision, 2001). The resistivity method is capable of mapping both low and high resistive formations and therefore a valuable tool for vulnerability studies (Sorensen et al., 2005).

The resistivity data are commonly expressed as apparent resistivity (Moller et al., 2006) which is the ratio of the measured potential to the theoretical potential at a given point (Kunetz, 1966; Van Zijl, 1985) and is also the resistivity that would have been obtained if the object was homogenous (Van Zijl, 1985).

Resistivity methods in geohydrology are commonly used for sounding and profiling (GEOVision, 2001). Sounding is when the distribution of electrical resistivity with depth is studied by progressively increasing the depth of investigation and profiling is when the lateral distribution of electrical resistivity is studied by an electrode array for which the depth of investigation remains constant (Van Zijl, 1985).

3.3.1. Basic Principles

The resistance of a length of wire in a circuit is a familiar concept. According to Ohm’s law the resistance (R) of a wire for direct current (DC) is equal to the potential difference (ΔV) between the ends of the wire, divided by the intensity of the current (I) that flows in the wire (Equation 3).

Equation 3

\[ R = \frac{\Delta V}{I} \]

The resistance of a length of wire (Figure 21) is proportional to its length (L) and inversely proportional to its cross-sectional area (A) (Van Zijl, 1985). From Equation 3 and the Equation in Figure 21, the following equation can be derived:

Equation 4

\[ \Delta V = I \left( \rho \frac{L}{A} \right) \]

Where \( \rho \) = resistivity
All rocks conduct electricity and this is mainly due to the presence of mineralised water in pore spaces and fissures (electrolytic conductivity), and some mineral deposits also have conductivity values comparable to those of metals (metallic conductivity) (Kunetz, 1966).

Resistivity determination is done by inducing a known current into the earth between two current electrodes, A and B, by conserving the resulting potential distribution by means of potential difference measurements between two potential electrodes, M and N, and by comparing this potential with that caused by the same current in a homogenous isotropic earth (Van Zijl, 1985). In a homogenous earth (halfspace), the current flow radially out from the current source and the arising equipotential surfaces run perpendicular to the current flow lines and form half spheres (Figure 22a), but in the common situation with both a currents source and a current sink the current flow lines and equipotential surfaces become more complex (Figure 22b) (Moller et al., 2006). Earth materials in the subsurface are heterogeneous and thus will the current flow lines and the equipotential surfaces be far more complex as the current flow lines will bend at boundaries, where the resistivities change (Figure 23).

The resistivity measurements made in the field are expressed as apparent resistivities ($\rho_a$). The apparent resistivity formula (Figure) is as follows:

**Equation 5**

$$\rho_a = K \frac{V_{MN}}{I}$$

Where: $V_{MN} =$ measured potential

$K =$ geometric factor
The geometric factor can be expressed as follows:

**Equation 6**

\[ K = 2\pi \left( \frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} \right)^{-1} \]

Figure 22: Simplified current flow lines and equipotential surfaces arising from (a) a single current source and from (b) a set of current electrodes. A & B are the current electrodes and M & N are the potential electrodes (Moller et al., 2006).

Figure 23: Current flow lines for (a) two-layer ground with lower resistivity in upper layer, (b) two-layer ground with higher resistivity in upper layer (Milsom, 2003).
3.3.2. Field Techniques

3.3.2.1. Sounding and Profiling

Sounding are applied where the ground is assumed to be horizontal or near horizontal (Ernstson & Kirsch, 2006a; Moller et al., 2006), as the sounding curves can only be interpreted using a horizontally layered earth (Moller et al., 2006). The spacing between the current electrodes is increased after each measurement, thus increasing the depth of investigation (Figure 24) (Ernstson & Kirsch, 2006a; Moller et al., 2006). The stepwise measured apparent resistivities are plotted against the current electrode spacing in a log/log scale and interpolated to a continuous curve, called a sounding curve (Figure 24) (Ernstson & Kirsch, 2006a). Due to practical and methodical advantages, the Schlumberger array is mostly used for resistivity soundings (Ernstson & Kirsch, 2006a).

Profiling is done by moving the electrodes laterally across the surface while the electrode spacings stay constant (Herman, 2001), thus moving the electrode array as a whole.

![Figure 24: Apparent resistivity measurements with increased current electrode spacing leading to increased penetration depths of the injected current. Results are compiled in the sounding curve (Ernstson & Kirsch, 2006a).](image)

3.3.2.2. Electrode Arrays

To carry out resistivity measurements of the subsurface one will at least need four electrodes, two current electrodes and two potential electrodes (Kostlin & Van Zijl, 1985). The electrodes can be placed in different configurations, the term array is used. The most common electrode arrays are shown in Figure 25.
Figure 25: The most commonly used electrode arrays. A & B are current electrodes and M & N are the potential electrodes. Modified after, (Moller et al., 2006).

The geometrical factors of the different arrays are given below (Ernstson & Kirsch, 2006a):

Equation 7

\[ K_{SCHLUMBERGER} = \frac{\pi}{MN} \left( \frac{AB}{2} \right)^2 \]

Equation 8

\[ K_{POLE-DIPOLE} = \frac{2\pi}{MN} \left( \frac{A0}{2} \right)^2 \]

Equation 9

\[ K_{WENNER} = 2\pi a \]

Where: \( a = \) distance between electrodes

In the Schlumberger array the potential electrodes are closely spaced and fixed to the centre of the array and the current electrodes move outwards after each measurement during sounding, giving rise to the geometrical factor in Equation 7 (Ernstson & Kirsch, 2006a).

Theoretically, in the pole-dipole array, also known as the Halfschlumberger array, the current electrode is placed to infinity with zero contribution to the potential electrodes, giving rise to the geometrical factor in Equation 8 (Ernstson & Kirsch, 2006a).

In a Wenner array, all four electrodes have to be moved when increasing the spacing during a sounding (Ernstson & Kirsch, 2006a). The spacing between all four electrodes remain identical (AM=MN=NB). Thus giving rise to the geometrical factor in Equation 9.
In the dipole-dipole array the current electrodes and the potential electrodes in each case are closely spaced to form a current dipole and a potential dipole. Sounding is done by keeping the current dipole fixed and moving the potential dipole and the geometric factor is then calculated from Equation 6 (Ernstson & Kirsch, 2006a).

All of these electrode arrays used do have their advantages and disadvantages (Table 5).

**Table 5: Advantages and disadvantages of the, Wenner, Schlumberger, and Dipole-dipole arrays (Van Zijl, 1985; Herman, 2001).**

<table>
<thead>
<tr>
<th>Array</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wenner</td>
<td>Potential electrode spacing increases as current electrode spacing increases, less sensitive voltmeters required.</td>
<td>All four electrodes must be moved to acquire each reading.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can be more susceptible to near-surface, lateral variation in resistive. These near-surface lateral variations could potentially be misinterpreted in terms of depth variations in resistivity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In general, interpretations based on DC soundings will be limited to simple, horizontally layered structures.</td>
</tr>
<tr>
<td>Schlumberger</td>
<td>Need to move the two current electrodes only for most readings, decreasing time of sounding.</td>
<td>Because the potential electrode spacing is small compared to the current electrode spacing, for large current electrode spacings, very sensitive voltmeters are required.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effects of near-surface lateral variations in resistivity are reduced.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In general, interpretations based on DC soundings will be limited to simple, horizontally layered structures.</td>
</tr>
<tr>
<td>Dipole-dipole</td>
<td>Less labour intensive than Wenner and Schlumberger arrays</td>
<td>Poor lower resolution obtained from its signal along with the relative lack of theoretical support for the analysis of the signal obtained.</td>
</tr>
</tbody>
</table>
3.3.2.3. Instrumentation

Multichannel resistivity instruments are becoming the norm today, rather than single channel resistivity meters. The multichannel resistivity instruments can take continuous vertical electrical soundings, which combines both profiling and sounding, so that 2D data coverage along a profile is obtained (Moller et al., 2006).

With a multichannel resistivity instrument a large number of electrodes are placed on a line at equal distance and connected to a switching unit and the resistivity meter by multicore cables, a build in computer then controls which electrodes are used as current and potential electrodes (Moller et al., 2006).

Figure 26: Multichannel resistivity instrument (UAV Survey Inc., 2009).

3.3.3. Applications

There are a number of applications for electromagnetic measurements which include the following (GEOVision, 2001; Technos Inc., 2004; Geopotential, 2007):

I. Determine the depth and thickness of geological strata.
II. Mapping of geological structures that are associated with preferred fluid pathways such as faults, fractured bedrock, contact zones etc.
III. Mapping of saltwater intrusion and contaminant plumes.
IV. Detecting cavities in carbonate rocks.
V. Locating buried wastes (e.g. landfill sites).
VI. Detecting sand and gravel deposits (palaeo-channels).

The advantages and disadvantages of the resistivity method are given in Table 6.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good vertical resolution.</td>
<td>Time consuming and expensive.</td>
</tr>
<tr>
<td>Depth range of up to 60 m (200 feet).</td>
<td>Susceptible to interference from nearby metal fences, buried pipes, cables, etc.</td>
</tr>
<tr>
<td>Various electrode configurations are available.</td>
<td>Effectiveness decreases at very low resistivity values.</td>
</tr>
<tr>
<td></td>
<td>If the surface is highly conductive it may not be possible to collect data below the top layer, as the data are influenced by near surface conductors.</td>
</tr>
</tbody>
</table>

### 3.4. Gravity Method

The gravity method is the best established method in applied geophysics (Gabriel, 2006). Differences in rock density produce small changes in the Earth’s gravity field that can be measured using portable instruments known as gravity meters also known as gravimeters (Milsom, 2003).

#### 3.4.1. Basic Principles

The gravity method is based on Newton’s gravitational laws. Newton’s laws of gravitation define the gravitational force ($F$) between two point masses as follows (Gabriel, 2006; Lowrie, 2007):
Equation \(10\)

\[
F = -G \left( \frac{m_1 m_2}{r^2} \right) = m_2 a
\]

Where:

\(m_1\) = mass of body 1 (earth)

\(m_2\) = mass of body 2 (falling body)

\(G\) = gravitational constant = \(6.67 \times 10^{-11}\) Nm\(^2\)/kg\(^2\)

\(r\) = distance between centre of mass of the two bodies

\(a\) = acceleration of the bodies

When applying gravitational measurements, we are not concerned with the gravitational forces but rather the gravitational acceleration (\(g\)) (Lowrie, 2007). Thus during a gravity survey we are measuring the gravitational acceleration at a specific point. Thus we can rewrite Equation 10 as follows:

Equation \(11\)

\[
g = \frac{G m_1}{r^2}
\]

The gravitational acceleration is measured in milligal (mgal; gal = cm/s\(^2\)) as the changes in acceleration of gravity is very small for geological structures (Lowrie, 2007). The Earth’s gravity field is almost the same as that of a sphere having the same average radius and total mass but increases slightly towards the poles (Milsom, 2003; Lowrie, 2007). This variation (0.5%) in the gravity field occurs because of the Earth’s rotation and flattening and the Earth’s average value of gravity is about 9.80 m/s\(^2\) (980 000 mgal) (Lowrie, 2007).

Gravity anomalies only occur when there is a density contrast in the Earth (Lowrie, 2007) which means that a gravity survey will only be useful if there are a high enough density contrast between the geological bodies being investigated. A geological body with a higher density than the host rock will have a positive density contrast and a body with a lower density than the host rock will have a negative density contrast (Lowrie, 2007). Density ranges for some common rocks and ore minerals are shown in Table 7.

### 3.4.2. Factors Affecting the Gravitational Acceleration

The factors that affect the gravitational acceleration can be grouped into two categories as follows (Gretchen, n.d.):
I. Time Dependent Variations
   - Instrument Drift: Changes in the observed acceleration caused by changes in the response of the gravimeter over time.
   - Tidal Effects: Changes in the observed acceleration caused by the gravitational attraction of the sun and moon.

II. Spatial Dependent Variations
   - Latitude Variations: Changes in the observed acceleration caused by the ellipsoidal shape and the rotation of the earth.
   - Elevation Variations: Changes in the observed acceleration caused by differences in the elevations of the observation points.
   - Topographic Effects: Changes in the observed acceleration related to topography near the observation point.
   - Slap Effects: Changes in the observed acceleration caused by the extra mass underlying observation points at higher elevations.

3.4.3. Instrumentation

Gravity measurements are measured by using gravity meters also known as gravimeters which are spring systems. These systems or gravimeters use zero-length main springs (Figure 27), in which the tension in the spring is proportional to its actual length (Milsom, 2003). Looking at the setup in Figure 27, the gravitational acceleration is measured by the measuring spring by observing how much the spring deforms and the zero-length spring “backs off” a constant weight so that the measuring spring can respond to small changes in the gravity field (Milsom, 2003). The setup in Figure 27 is not the exact setup of actual gravimeter but rather a basic setup of how gravimeters work.

Types of gravimeters include (Figure 28):

I. Sodin
II. Worden
III. Scintrex
IV. LaCoste-Romberg
Figure 27: Basic setup of a gravimeter. Measurements are made by rotating the dial, which raises or lowers the measuring spring to return the mass to a standard position (Milsom, 2003).

Figure 28: Gravimeters; (a) Sodin Type 410-T, (b) Worden, (c) Scintrex CG5 Autograv, (d) Lacoste-Romberg.
Table 7: Densities of common rocks and ore minerals (Milsom, 2003).

<table>
<thead>
<tr>
<th>COMMON ROCKS</th>
<th>Mg/m$^3$</th>
<th>ORE MINERALS</th>
<th>Mg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td>1.4 – 1.65</td>
<td>Sphalerite</td>
<td>3.8 – 4.2</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>2.5 – 2.6</td>
<td>Galena</td>
<td>7.3 – 7.7</td>
</tr>
<tr>
<td>Wet sand</td>
<td>1.95 – 2.05</td>
<td>Chalcopyrite</td>
<td>4.1 – 4.3</td>
</tr>
<tr>
<td>Gneiss</td>
<td>2.65 – 2.75</td>
<td>Chromite</td>
<td>4.5 – 4.8</td>
</tr>
<tr>
<td>Coal</td>
<td>1.2 – 1.5</td>
<td>Pyrrhotite</td>
<td>4.4 – 4.7</td>
</tr>
<tr>
<td>Granite</td>
<td>2.5 – 2.7</td>
<td>Hematite</td>
<td>5.0 – 5.2</td>
</tr>
<tr>
<td>Chalk</td>
<td>1.9 – 2.1</td>
<td>Pyrite</td>
<td>4.9 – 5.2</td>
</tr>
<tr>
<td>Dolerite</td>
<td>2.5 – 3.1</td>
<td>Magnetite</td>
<td>5.1 – 5.3</td>
</tr>
<tr>
<td>Salt</td>
<td>2.1 – 2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>2.7 – 3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>2.6 – 2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gabbro</td>
<td>2.7 – 3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartzite</td>
<td>2.6 – 2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peridotite</td>
<td>3.1 – 3.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4.4. Applications

There are a number of applications for gravity measurements which include the following (Technos Inc., 2004):

I. Identify karst features (sinkholes etc.).
II. Characterize stratigraphic thickness and structure.
III. Locating gravel deposits.
IV. Identify man-made structures (tunnels and mines)

The advantages and disadvantages of the resistivity method are given in Table 8.

Table 8: The advantages and disadvantages of the gravity method (Technos Inc., 2004).

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides a means to characterize conditions in geologic and cultural</td>
<td>Data acquisition is relatively slow compared with other geophysical methods.</td>
</tr>
<tr>
<td>environments, where other geophysical method may fail.</td>
<td></td>
</tr>
<tr>
<td>Data can be interpreted to provide estimates of depth, size and the nature</td>
<td>Irregular topography will produce artefacts in the data unless accounted for</td>
</tr>
<tr>
<td>of the anomaly.</td>
<td>in the processing.</td>
</tr>
<tr>
<td>Can be used inside buildings and structures.</td>
<td>Local sources of vibrations, wind, storms, and distant earthquakes can produce interference.</td>
</tr>
</tbody>
</table>

3.5. Seismic Method

The seismic method will only be briefly discussed as it is rarely used in South Africa in locating groundwater resources.

3.5.1. Basic Principles

The seismic method entails the input of an acoustic energy into the subsurface by an energy source such as a sledge hammer impacting a metal plate, weight drop, vibrating source or an explosive charge (GEOVision, 2001a). The acoustic energy propagates through the subsurface in the form of acoustic waves. These waves are then reflected (seismic reflection) or refracted (seismic refraction) at every boundary between rocks of different types or other geological structures such as faults. The response of the reflected or refracted sequences is received by geophones placed on or near the surface (Chaubey, 2007).

Chaubey (2007) describes the seismic reflection and refraction methods as follows:
**Seismic Reflection** – waves travel downward initially and are reflected at some point back to the surface, the overall path being essentially vertical (Figure 29). It’s basically a more sophisticated version of echo-sounding used in submarines, ships and radar systems.

**Seismic Refraction** – principal portion of the wave-path is along the interface between two layers and hence approximately horizontal (Figure 29). The travel times of refracted wave paths are then interpreted in terms of depth to subsurface interfaces and the speeds at which the wave travels through the subsurface within each layer.

Both the seismic reflection and refraction wave paths depend on the elastic parameters of the layered subsurface and the attitudes of the layers.

![Figure 29: Seismic reflection versus seismic refraction.](image)

### 3.5.1. Applications

There are a number of applications for gravity measurements which include the following (GEOVision, 2001a):

I. Map bedrock and basement topography.
II. Map faults in sedimentary and basement rocks.
III. Evaluate rock properties.
IV. Map buried palaeo-channels.
V. Map lateral continuity of geological layers.

The advantages and disadvantages of the seismic methods are given in (Table 9).
**Table 9: The advantages and disadvantages of the seismic methods (Chaubey, 2007).**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect both lateral and depth variations in a physically relevant parameter (seismic velocity).</td>
<td>Amount of data collected in a survey can rapidly become overwhelming.</td>
</tr>
<tr>
<td>Can produce detailed images of structural features present in the subsurface.</td>
<td>Data is expensive to acquire and the logistics of data acquisition are more intense than other geophysical methods.</td>
</tr>
<tr>
<td>Can be used to delineate stratigraphic and in some instances depositional features.</td>
<td>Data reduction and processing can be time consuming, require sophisticated computer hardware, and demand considerable expertise.</td>
</tr>
<tr>
<td>Response to seismic wave propagation is dependent on rock density and a variety of physical (elastic) constants. Thus, any mechanism for changing these constants (porosity &amp; permeability changes, compaction, etc.) can in principle be delineated.</td>
<td>Equipment for the acquisition of seismic observations is, in general, more expensive than equipment required for the other geophysical surveys.</td>
</tr>
<tr>
<td>Direct detection of hydrocarbons, in some instances, is possible.</td>
<td>Direct detection of common contaminants present at levels commonly seen in hazardous waste spills is not possible.</td>
</tr>
</tbody>
</table>

3.6. Applying Geophysics in South Africa

3.6.1. Borehole Siting

Borehole siting involves the identification of geological targets that are preferred pathways for groundwater flow and accumulation. Geological target identification should involve the following:

I. **Desktop study** – involves the examination of geological maps, aerial photographs and satellite images of the hydrogeological area of interest. This is done to identify targets that are the most promising for drilling targets.
II. **Site Assessment** – involves a field visit of the features indentified in the desktop study confirming their existence. Do a proper geological examination of the structures identified and their related features. Conduct a hydrocensus to gather historical information, gathering information on which geological target tends to be more successful when drilled. Then prioritise possible drilling sites.

III. **Geophysics** – apply only when additional information is acquired or when geological target features are not visible on surface.

### 3.5.2. What Geophysical Method to Use

Table 10 provides a summary of the geophysical methods used in South Africa and where to apply it according to the geological unit and their related target feature.

It is clear that the magnetic method is the method of choice when targeting dolerite dykes or sills except for the dykes associated with the BIC. Electromagnetics is occasionally used in conjunction with the magnetic method to delineate dolerite dykes.

The electromagnetic and resistivity methods are the methods of choice when identifying unconsolidated deposits and highly fractured zones within the rocks of South Africa. The gravity method is only applied in the rocks of the Transvaal Supergroup in conjunction with the electromagnetic method to identify highly fractured and karstic zones.

### 3.5.3. Short Overview of the Interpretation of Geophysical Graphs

#### 3.5.3.1. Magnetic Method

The interpretation of the magnetic method graphs are summarised from Paver *et al.* (1943). The magnetic method is mainly used to delineate dykes and sills, faults where these involve displacements of magnetic formations and contacts between rocks of different magnetic properties. Magnetic graphs can be simplified so that little knowledge is required to interpret them.

Different types and structures of magnetic bodies will result in different forms of anomaly curves. The most common curves to be encountered in groundwater exploration will be discussed below and illustrated in (Figure 30):

I. **Normal Magnetic Dyke Anomaly** – most common form of anomaly (Figure 30 A & E), symmetrical in shape (north-south striking dyke). The nanoTesla value reaches a maximum over the centre of the dyke. When the top of the dyke is near the surface (Figure 30 A), the slope of the curve is steep. As the thickness of the of the overburden increases (Figure 30 E), the maximum value decrease in value,
increases in nanoTesla values occur at greater distances from the dyke, and the curve tend to flatten out.

Table 10: Summary of the geophysical methods applied according to the geological units of South Africa. Where A is the primary method of choice and B the secondary method of choice.

<table>
<thead>
<tr>
<th>Geological Units of South Africa</th>
<th>Geological Target</th>
<th>Geophysical Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Magnetics</td>
</tr>
<tr>
<td>Coastal Cenozoic Deposits</td>
<td>Unconsolidated Deposits</td>
<td></td>
</tr>
<tr>
<td>Karoo, Ventersdorp &amp; Witwatersrand &amp;</td>
<td>Dolerite/Diabase Dykes or Sills</td>
<td>A</td>
</tr>
<tr>
<td>Natal, Waterberg &amp; Soutpansberg Groups</td>
<td>Fracture/Fault Zones (weathering)</td>
<td>A</td>
</tr>
<tr>
<td>Cape Supergroup Malmesbury Group</td>
<td>Fracture/Fault Zones (weathering)</td>
<td>A</td>
</tr>
<tr>
<td>Bushveld Igneous Complex</td>
<td>Dolerite/Diabase Dykes or Sills</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Fracture/Fault Zones (weathering)</td>
<td>A</td>
</tr>
<tr>
<td>Transvaal Supergroup</td>
<td>Karst Zone (Cavities)</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>Dolerite/Diabase Dykes or Sills</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Fracture/Fault Zones (weathering)</td>
<td>B</td>
</tr>
<tr>
<td>Namaqua-Natal Metamorphic Province</td>
<td>Unconsolidated Deposits</td>
<td>A</td>
</tr>
<tr>
<td>Archaean Granites &amp; Gneisses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Archaean Greenstone &amp; Limpopo Belts</td>
<td>Dolerite/Diabase Dykes or Sills</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Fracture/Fault Zones (weathering)</td>
<td>A</td>
</tr>
</tbody>
</table>
II. *Reversed Magnetic Dyke Anomaly* – some dykes show a reversed polarity and appears as negative anomalies (decrease in nanoTesla) (Figure 30 D). This phenomenon are associated with the Pilansberg phase of the Bushveld Igneous Complex.

III. *Double-peaked Anomaly* – generally associated with comparatively thick dykes (Figure 30 C). This is due to the existence of two like magnetic poles near the flanks of the dyke, often the result of the concentration of magnetite towards the flanks. The double-peaked anomaly may be either positive or negative.

IV. *Asymmetrical Magnetic Dyke Anomaly* – some comparatively thin dykes, striking east-west, develop unlike magnetic poles at the two faces and give an asymmetrical anomaly (Figure 30 I), in which a maximum is observed over one flank and a minimum over the other.

V. *Dipping Dykes* – the dip of a dyke can be obtained from a study of its magnetic curve. If the curve is symmetrical, the dyke may be presumed vertical (Figure 30 A & E), but if asymmetrical, the dyke will be dipping away from the side which gives the steeper flank to the curve (Figure 30 B). This is not always the case, small finite dykes, both the poles are effective at the surface, different curve will be obtained, in which the direction of dip will be toward the steeper flank.

VI. *Sills* – anomalies produced by an inclined or undulating sill are represented by a maximum value where the sill is nearer to the surface. The magnetic curve may indicate the position of the sill, but errors occasionally occur due to irregular dispersion of magnetite through the body; for example, the anomalies given by a horizontal sill with decreasing magnetite content, and a dipping sill of uniform magnetite content may be represented by similar curves.

VII. *Magnetic Contacts* – where geological formation consisting of rocks of different magnetic characteristics are in proximity to one another by reason of faulting (G & H), plutonic intrusions, volcanic lava extrusion (F), or normal sedimentation on an igneous base, the magnetic anomalies observed are represented by curves which bear a simple straight-forward relationship to the form of the structure concerned.
Figure 30: The most common magnetic graphs encountered in groundwater exploration. Modified after Paver et al. (1943).
3.5.3.2. Electromagnetic Method

The interpretation of the electromagnetic method graphs are summarised from Payne (2004). The electromagnetic method as a quick, simple and effective method of locating fractured or highly weathered zones. It is also used to locate vertical dykes.

Where the groundwater conductivity and rock type are fairly uniform, lateral variations in apparent ground conductivity are considered to be caused by changes in the mineralogy, porosity, or degree of saturation of the rock. High clay content, high porosity and a high degree of saturation, increase the conductivity of the rock.

Figure 31 illustrates anomalies obtained from electromagnetic traverses over fracture and weathered zones, and a vertical dyke. The conductivity responses to the fracture and weathered zones is characterised by a high electrical conductivity in both the vertical and horizontal dipole modes relative to background levels, and a higher conductivity for the vertical dipole than for the horizontal dipole.

The electromagnetic conductivity meter responds to highly conductive vertical dykes in a manner which is significantly different from its response to other subsurface features. In the case of Figure 31 the meter does not show the true ground conductivity, but instead displays a conductivity response curve which indicates a vertical dyke. The curve is characterised by very low or negative anomalies over the dyke and relatively high values at a distance of one half the coil spacing away from the dyke. In many instances, the signature response for a vertical dyke has been important because it indicates false negative and exaggerated positive readings.
Figure 31: Electromagnetic horizontal and vertical dipole responses for fracture and weathered zones, and a vertical dyke. Modified after Payne (2004).
3.5.3.3. Resistivity Method
The interpretation of resistivity graphs is somewhat complicated. It is advisable to consult experienced geophysicists when applying the resistivity method. Geophysicists generally conduct inverse modelling on the data obtained during a resistivity survey. These are then represented as 2-D inverse model resistivity sections (Figure 32).

![Inverse model resistivity sections of dolomites intruded by dykes.](image)

3.5.3.4. Gravity Method
The interpretation of the gravity method graphs are summarised from Mariita (2007). The measurement of gravity provides information about densities of rocks within the subsurface. There is a wide range in density among rock types, and therefore geologists can make inferences about the distribution of strata. Anomalies in the earth’s gravitational field result
from lateral variations in the density of subsurface materials and the distance to these bodies from the measuring equipment (Figure 33 A).

The gravity method is not readily applied for groundwater exploration in South Africa (except karst regions) due to the fact that its time consuming and expensive. It is advisable to consult other geophysics data such as magnetic.

All known gravitational effects not related to the subsurface density changes should be removed before the data can be interpreted. A qualitative examination of a grid of gravity values, contour maps or gravity profiles can determine the lateral location of any gravity variation or one can perform a more detailed analysis in order to quantify the nature (dept, geometry, density) of the subsurface feature causing the gravity variations. To determine the latter, the anomaly of interest (residual) should be removed from the remaining background anomaly (regional). Then the residual gravity anomaly is modelled to determine the depth, density and geometry of the anomaly’s source. Gravity modelling is generally the last step in gravity interpretation. Figure 33 B illustrates a 2-D gravity model.

![Figure 33: A) Illustrations showing the relative surface variation of the earth’s gravitational acceleration over geological structures; B) 2-D gravity model, the solid line is the calculated gravity values due to the model and the stars are the observed data. Modified after Mariita (2007).](image)
CHAPTER 4: GEOLOGY & GEOHYDROLOGY

Vegter (2001) divided South Africa into 64 groundwater regions (Figure 183, Appendix A) by considering the type of fracturing (primary or secondary), lithostratigraphy, physiography, and climate. The subdivisions, proposed by Vegter (2001) are fundamentally geological and not geohydrological as the delineation of hydrogeological units requires an establishment of groundwater divides and flow paths.

The subdivision of the groundwater regions by Vegter (2001) are as follows:

A. Regions consisting mainly of primary water-bearing formations. Hard-rock formations underlying primary water-bearing formations may act in places as aquifers. This include the following formations:
   i. Regions composed of Tertiary-Quaternary formations.

B. Regions consisting mainly of secondary water-bearing formations. Fluvial deposits are included. Regions have been classified further into principal rock type and erathem/system. These regions has been subdivided into groundwater regions on the basis of both lithostratigraphy and physiography and is classified according to the main type of water-bearing hard-rock as follows:
   B1 Crystalline metamorphic and igneous
      i. Swazian and Mokolian crystalline rocks.
   B2 Intrusive
      i. Bushveld complex regions.
   B3 Extrusive
      i. Ventersdorp and Karoo lava regions.
   B4 Sedimentary
      i. Regions composed of Vaalian strata.
      ii. Regions composed of Vaalian-Mokolian strata.
      iii. Regions composed principally of Mokolian strata.
      iv. Regions composed principally of Namibian strata.
      v. Regions composed of Ordo-Devonian strata.
      vi. Regions composed of Carbo-Triassic strata.
   B5 Composite

Regions have been classified as composite where no major rock type is predominant, several major lithostratigraphic units are involved, and where more extensive primary aquifers than alluvial deposits are present (Vegter, 2001).
The main lithostratigraphic units of South Africa (Figure 34 & Figure 184 – Appendix A) are discussed separately, together with its geohydrological characteristics. These units are discussed in chronological order, from the most recent Cenozoic age deposits (section 4.1), ending with the oldest Archaean age deposits (section 4.16 to 4.18).

Figure 34: Stratigraphy of South Africa (Johnson et al., 2006).
4.1. Coastal Cenozoic Deposits (0 – 55 Ma)

4.1.1. Location and Extend
The Coastal Cenozoic deposits developed extensively along the coastal plain of South Africa (Figure 35). These deposits are generally thin overall, due to the buoyancy of this passive coastline over the past 60 million years of erosional events triggered by at least two pulses of epeirogenic uplift, except within offshore extensional rift basins and major river mouths (Roberts et al., 2006).

4.1.2. Geology

4.1.2.1. Lithostratigraphy
The Coastal Cenozoic deposits include the following groups:

I. Maputaland Group
II. Algoa Group
III. Bredasdorp Group
IV. Sandveld Group
V. West Coast Group

Maputaland Group
The Maputaland Group extends from the border of Mozambique southwards to the Durban area (Figure 35). The group is bounded by the monoclonal Lebombo Mountains in the west and the Phongolo and Mkhuze River valleys (Porat & Botha, 2008). The Maputaland Group can be divided into seven formations (Figure 36 & Figure 37) (Roberts et al., 2006). From the top to the bottom they are:

- Sibayi Formation
- KwaMbonambi Formation
- Isipingo Formation
- Kosi Bay Formation
- Port Durnford Formation
- Umkwelane Formation
- Uloa Formation
Figure 35: Distribution of coastal Cenozoic deposits in South Africa (Roberts et al., 2006).
Figure 36: Maputaland geology map, showing the distribution of its geological formations. Modified after Porat & Botha (2008).

Figure 37: Idealised composite section of the Maputaland Group (Roberts et al., 2006).
The Uloa Formation consist of a thin basal conglomerate overlain by a 2-3 m thick coquina succession (Wright, Miller, & Cooper, 2000). The average thickness of the Uloa Formation is about 10 m with a maximum of 35 m at the Richards Bay coastal plain (Roberts et al., 2006). The Umkwelane Formation that rest upon the Uloa Formation, or Cretaceous sediments, consists of cross-bedded calcarenites/aeolianite of up to 25 m in thickness (Roberts et al., 2006; Wright et al., 2000). The surface of the Umkwelane Formation is extensively karstified with a thick overlying mantle of Berea-type red sand which may be up to 50 m thick (King, 2003).

The Port Durnford Formation rests unconformably on either the Cretaceous sediments or the Uloa and Umkwelane Formations (Roberts et al., 2006). The thickness of the Port Durnford Formation is approximately 20 m, consisting of flat lying, but locally slumped mudrock, calcarenites and sandstone with a distinctive, discontinuous lignite horizon (King, 2003). Mammalian fossils are common (Porat & Botha, 2008).

The Kosi Bay Formation consists of unconsolidated aeolian sands with localised calcarenites and the weathering of the formation has progressed sufficiently to form Berea-type red sand in certain localities (King, 2003).

The Isipingo Formation consists of basal aeolianite that contain oyster beds within karst potholes in certain localities, and calcified beach and dune deposits (Roberts et al., 2006).

The KwaMbonambi Formation consists of yellowish red, grey and white dune sand that is reworked material of the Kosi Bay Formation (Roberts et al., 2006). The KwaMbonambi Formation occurs extensively over most of the inland portions of the Maputaland Coastal Plain with a thickness of up to 10 m (King, 2003).

Sibayi Formation generally overlies the Isipingo, Port Durnford and Kosi Bay Formations (Roberts et al., 2006) and consists of stacked calcareous and siliceous sand units (King, 2003; Roberts et al., 2006). The sand units is separated by organic-rich palaeosols, or the sands are rubified and decalcified to a depth of several metres (Roberts et al., 2006) and attains a maximum thickness of 182 m along the coastal barrier dune in Maputaland (King, 2003; Roberts et al., 2006).
**Algoa Group**

The Algoa Group extends from Oubosstrand eastwards to East London (Figure 35). The group unconformably overlies the Cape Supergroup, Karoo sediments, or Uitenhage Group (Le Roux, 1990). The Algoa Group can be divided into six formations (Figure 38):

- Schelm Hoek Formation
- Nahoon Formation
- Salnova Formation
- Nanaga Formation
- Alexandria Formation
- Bathurst Formation

![Generalised composite section of the Algoa Group](image)

*Figure 38: Generalised composite section of the Algoa Group (Roberts et al., 2006).*
The Bathurst Formation extends eastwards from Oubosstrand to East London as isolated patches with a thickness that varies from 1-20 m, but generally it is less than 10 m (Maud & Partridge, 1990). Consist of a soft marine limestone overlain by a pebbly coquina (Roberts et al., 2006).

The Alexandria Formation attains a maximum thickness of 18 m and consists of a basal conglomerate/bed of oyster shales, overlain by interbedded calcareous sandstone, pebbly coquina and thin conglomerates with the sandy upper part containing horizontally bedded as well as planar and through cross-bedding structures (Roberts et al., 2006).

The Nanaga Formation consists of coastal palaeo-dune fields, with medium-grained, cross-bedded, calcareous sandstones and calcretes up to 250 m thick (Roberts et al., 2006). It occurs extensively in the northern hinterland of Algoa Bay and along the coast to west of Port Elizabeth (Roberts et al., 2006).

The Salnova Formation varies in thickness from 1.6-6.5 m and consists of calcareous sand, sandstone, conglomerate and coquina (Roberts et al., 2006). The Salnova Formation is occasionally disconformably overlain by the Nahoon Formation (Le Roux, 1989). The Nahoon Formation attains an average thickness of 15 m and varies from 6-60 m consisting of calcareous sandstone with interbedded palaeosols and occasionally very thin calcrete layers and with large-scale aeolian cross-bedding (Le Roux, 1989).

The Schelm Hoek Formation consists essentially of unconsolidated windblown calcareous sand, occurring in coastal dunefields with intercalated Strandloper middens and poorly developed palaeosols and soil horizons at certain localities (Illenberger, 1992).

**Bredasdorp Group**

The Bredasdorp Group occur along the coast from Plettenberg Bay westwards to Hermanus (Figure 35). The group unconformably overlies the Uitenhage Group or the Cape Supergroup Strata (Malan, 1989). The Bredasdorp Group is divided into five formations (Figure 39):

- Strandveld Formation
- Waenhuiskrans Formation
- Klein Brak Formation
- Wankoe Formation
- De Hoopvlei Formation

The Wankoe Formation forms the bulk of the Bredasdorp Group consisting of prominent ridges of calcified dune sand outcrops (Malan, 1989). The Klein Brak and Waenhuiskrans
Formations occupy a narrow strip along the present coastline where the Strandveld Formation is represented by recent dunes adjoining the present coast (Malan, 1989).

The Bredasdorp Group consists essentially of limestone, calcarenite, calcirudite, conglomerate, coquinite, sandstone and calcareous sand (Malan, 1989).

![Diagram of geological formations](image)

**Figure 39:** Generalised composite section of the Bredasdorp Group (Roberts et al., 2006).

**Sandveld Group**

The Sandveld Group extends northward from Cape Hangklip in the south to Elands Bay (Figure 35). The group overlies a variety of pre-Mesozoic basement rocks and is thickest in structurally and lithologically controlled basement depressions (Roberts et al., 2006). The Sandveld Group can be divided into 7 formations (Figure 40):

- Witzand Formation
- Springfontyn Formation
- Velddrif Formation
- Langebaan Formation
- Varswater Formation
- Prospect Hill Formation
• Elandsfontyn Formation

The deposits of the Sandveld Group can generally be correlated with those of the Bredasdorp Group (Roberts et al., 2006). The Sandveld Group essentially consists of quartzose sands, gravel, clay, lignite, calcareous aeolianites, bioclastic-silicilastic aeolianites which is mantled by hardpan calcrite and coquina (Roberts et al., 2006).

Figure 40: Generalised composite section of the Sandveld Group, showing lateral interrelationships of units (Roberts et al., 2006).
West Coast Group
The West Coast Group (Namaqualand Coast) extends from Elands Bay in the south to the mouth of the Orange River at Alexander Bay. The group is divided accordingly

I. Neogene deposits
   • Aeolian deposits
   • Curlew Strand Formation
   • Alexander Bay Formation

II. Early post-Gondwana deposits

The early post-Gondwana deposits are fluvial palaeo-channel deposits that are kaolinised in places consisting of conglomerates, overlain by partly silicified marine sand, clayey sand, clay and carbonaceous material containing plant fossils, topped by calcareous and ferruginous pedocretes (Roberts et al., 2006).

The Alexander Bay Formation consists of three marine units namely:
   • Hondeklip Bay Member (30 m package)
   • Avontuur Member (50 m package)
   • Kleinsee Member (90 m package)

Each of the above members consists of basal gravels that contain diamonds, followed by shoreface sand deposits (Roberts et al., 2006). The deposits of the Alexander Bay Formation is followed by high-energy beach deposits of the Curlew Strand Formation, comprising of calcified to unconsolidated sandy to gravelly deposits, similar to those inhabiting the coast today (Roberts et al., 2006).

The Alexander Bay and Curlew Formation deposits was accompanied by synchronous aeolian deposits, comprising of rubified, consolidated to semi-consolidated, quartzose sands, rich in heavy minerals and feldspathic in parts (Roberts et al., 2006). These deposits have not yet been formally assigned to stratigraphic units.

4.1.3. Geohydrology
The Coastal Cenozoic aquifers of South Africa are all classified as primary aquifers.

4.1.3.1. Maputaland Group (Zululand Aquifer)
The Maputaland Aquifer System is the largest primary coastal aquifer system in South Africa and has the potential to yield large and reliable quantities of water (Rawlins & Kelbe, 1991). Several large lakes, some of which have a direct connection to the ocean while others are isolated from the ocean, occur along this stretch of land and form an integral part of this
delicate ecosystem (Meyer, et al., 2001). The St. Lucia Wetland Park (Nature Reserve) that is situated within this coastal aquifer effectively protects this coastal region from exploitation (Steyl & Dennis, 2010).

**Geohydrological Characteristics of the Maputaland Group**

The aquifers within the Maputaland Group are confined or semi-confined with generally shallow groundwater levels (King, 2003). The uppermost stratigraphic formations form the main unconfined aquifers, that promote rapid recharge and strong interactions with the wetlands within the Maputaland Group region (Mkhwanazi, 2010). There are little variation in the grain size distribution and porosity between the Holocene cover sands, the aeolian sands and the Port Durnford Formation (Meyer et al., 2001) which implies that there should be a relatively consistent permeability throughout the sequence.

The coastal dunes form a separate aquifer system and are the source of numerous fresh water springs occurring along the beach in the uMhlathuze Municipal region (Golder Associates, 2004). The Uloa Formation behaves very similar to a karstic aquifer due to its carbonate content (King, 2003).

The primary aquifers are linked to the estuaries and coastal lakes within the Maputaland Group region through direct seepage and via local streams and rivers which also form part of the tidal system (Mkhwanazi, 2010).

**Borehole Yields**

Groundwater intersections within the Maputaland Group Aquifer are commonly less than 10 mbgl in low lying areas, and 50% of existing boreholes have water levels less than 15 mbgl (King, 2003).

The shallow aquifers within the Holocene deposits is generally low yielding (<0.5 l/s) (Mkhwanazi, 2010). The Uloa Formation is the highest yielding aquifer in the region with yields of up to 15 l/s (King, 2003), but the formation is not continuous and has a limited extend (Meyer et al., 2001; Mkhwanazi, 2010). Yields of up to 20 l/s for the Uloa Formation have been recorded where the thickness of the formation exceeds 20 m (Mkhwanazi, 2010). According to Schapers (2011) the Isipingo Formation is also a high yielding aquifer with yields up to 14 to 16 l/s (50-60 m³/h).

In the Durban region, groundwater levels are shallow, generally between 2 and 7 mbgl and according to King (2002) yields in excess of 50 l/s have been reported.
4.1.3.2. Algoa Group

As geohydrology information on the Algoa Group is limited, most of the information is from Meyer (1998) unless otherwise stated.

Geohydrological Characteristics of the Algoa Group

According to the SRK Consulting and Eskom Report (2007) the Algoa Group is classified as a major aquifer of high vulnerability and is therefore of high groundwater potential.

The basal conglomerate of the Alexandria Formation is an important groundwater bearing formation within the Algoa Group. The water is concentrated within the basal conglomerate as water seeps rapidly through the highly porous, sandy calcareous material to the contact with the underlying, usually impervious pre-Algoa rocks, from where it moves in the conglomerates seawards, frequently emerging as springs near sea-level. Build-up of groundwater levels seldom occurs because of the high permeability of the conglomerate and therefore a water interception in the conglomerate is likely to be the true piezometric level. The high permeability of the basal conglomerate makes the Algoa Group Aquifer system unique.

The groundwater flow direction is to the south with discharge along the beaches and rocky outcrop into the ocean (SRK Consulting & Eskom, 2007).

The coastal sands, otherwise known as the Schelm Hoek Formation, which consists of aeolian sands, is also an important groundwater bearing formation within the Algoa Group.

The groundwater quality of the Algoa Group is essentially potable with EC values generally less than 300 mS/m. If drilling extends into the underlying formations, it is possible that the more brackish water from the underlying formations can contaminate the water within the Algoa Group. Sodium and chloride often exceed the maximum recommended limits.

Borehole Yields

Borehole yields within the Schelm Hoek Formation vary between 0.10-15 l/s. The majority of yields within the Schelm Hoek Formation vary between 0.5-5 l/s. The majority of boreholes in the rest of the Algoa Group have yields less than 0.5 l/s, but higher localised yields do exist.
4.1.3.3. Bredasdorp Group

Geohydrological Characteristics of the Bredasdorp Group

The aquifers of the Bredasdorp Group are unconfined as the water table forms the upper boundary (SRK Consulting & Eskom, 2007). The basal conglomerate of the De Hoopvlei Formation (Figure 41) is the most important formation, as groundwater mainly occurs within this formation (Meyer, 2001).

The Bredasdorp Group aquifers share the same characteristics of that of the Algoa Group Aquifers. Water also seeps relatively rapidly through the generally porous material to the underlying, mostly impervious pre-Bredasdorp beds; where it moves in the De Hoopvlei conglomerate to lower lying outlet points and hardly any build-up of groundwater levels take place (Meyer, 2001).

The groundwater EC values of the Bredasdorp Group are generally less than 150 mS/m, but sodium and chloride might occasionally exceed the maximum recommended limits (Meyer, 1999; Meyer, 2001). Thus groundwater from the Bredasdorp Group is generally potable.

Borehole Yields

The borehole yields within the Bredasdorp Group ranges between 0.1-8 l/s with the majority of yields less than 0.1, but yields of more than 15 l/s have been reported (Meyer, 1999). Calcrete horizons from Hermanus eastwards to Mossel Bay can have yields of 10-20 l/s if the boreholes have been properly constructed (Weaver, 2011).

Figure 41: Semi-consolidated calcareous sand overlies the basal conglomerate of the De Hoopvlei Formation (Bredasdorp Group) near Still Bay. Impervious shale of the Bokkeveld Group underlies the conglomerate (Meyer P. S., 1999).
4.1.3.4. Sandveld Group

Hydrogeological Units
According to Meyer (2001) the Sandveld Group Aquifer can be divided into four main hydrogeological units (Figure 42) as follows:

I. Cape Flats Unit – extending from False Bay to Melkbosstrand.
II. Silwerstroom-Witzand Unit – Atlantis area.
III. Grootwater Unit – Yzerfontein area.
IV. Berg River Unit – Saldanha area:
   a. Adamboerskraal Aquifer Unit
   b. Langebaan Road Aquifer Unit
   c. Elandsfontyn Aquifer Unit

A 2.5 km “buffer zone” was declared along the coastline of the Grootwater Unit (Subterranean Government Water Control Area), where no abstraction of groundwater is permitted, in order to protect the groundwater quality further inland (Meyer, 2001). A part of the Berg River Unit, in the Saldanha area, was also declared as a Subterranean Government Water Control Area (Meyer, 2001).

Geohydrological Characteristics
The groundwater levels of the Sandveld Group are generally shallow (2-5 mbgl) throughout and are also vulnerable to contamination (Conrad et al., 2004).

The Cape Flats Unit can be divided into two different aquifers. The two aquifer systems are the Witzand-Springfontyn Formation aquifer and the Varswater Formation aquifer. The Witzand-Springfontyn aquifer is generally unconfined to semi-unconfined and possesses a degree of heterogeneity and anisotropy due to vertical and lateral grain size gradation and the occurrence of sandy clay and clayey sand lenses (Vandoolaeghe, 1989). The Varswater Formation aquifer forms the major aquifer wherever the above sediments of the Witzand and Springfontyn formations are relatively thin or altogether absent (Vandoolaeghe, 1989). Groundwater within the Cape Flats Aquifer flows in a westerly direction towards Zeekoevlei, and a southerly direction towards Monwabisi/Mnandi (Eskom, 2010).

The groundwater of the Silwerstroom-Witzand Unit, also known as the Atlantis Aquifer System, flows westwards to south-westwards where it discharges along the coast in areas where the aquifer dips below sea level (Tredoux & Cain, 2010). This aquifer unit is heterogeneous as the composition of the lithology varies throughout the unit, even over short distances (Bredenkamp & Vandoolaeghe, 1982). The silt content of the sands plays a
fundamental role in the development of production boreholes, where the silt content is generally less than 3% production wells can be developed (Vandoolaeghe & Bertram, 1982).

Figure 42: Map of Aquifer type and yield of the Berg Water Management Area. The main Hydrogeological units of the Sandveld Group also indicated; the Berg River Unit is divided into two aquifers namely the Langebaan Road (northern limb) & Elandsfontein (Southern Limb) Aquifers. Map modified after (DWA, [n.d.])
The **Grootwater Unit** basically consists of two aquifer systems, an upper and lower aquifer system (Timmerman, 1985a; Baron, 1990). The upper aquifer, situated in the sediments of the Springfontyn and Langebaan Formations, is generally unconfined but silty and peaty horizons give rise to semi-unconfined or semi-confined conditions. The lower aquifer, situated in the quartzose sand layer of the Varwater Formation, is semi-confined due to the presence of a capping layer of fine silty sand. A large portion of the lower aquifer system is situated below sealevel (Timmerman, 1985a). Recharge normally takes place by direct infiltration from precipitation and also runoff directly along the piedmont of the granite hills and the river courses predominantly during the wintertime (Timmerman, 1985a).

The aquifer systems of the **Berg River Unit**, consists of two aquifers, separated by a clay layers. Sand and gravel of the bottom part of the Elandsfontyn Formation constitute the basal confidence to semi-confined aquifer system and the sediments of the Varwater, Langebaan and Springfontyn Formations constitute the upper unconfined to semi-unconfined aquifer system (Timmerman, 1985b). The Lower aquifer of the Langebaan Road Aquifer Unit can be considered as a confined aquifer with groundwater qualities generally better than the unconfined aquifer above the clay layer (Du Plessis, 2009).

The groundwater EC values of the Sandveld Group vary between 30 and 250 mS/m and determinants seldom exceed maximum recommended limits (Meyer, 2001), thus the groundwater is generally potable. Densely populated regions are of concern, regarding the vulnerability of these aquifers to pollution as nitrate levels substantially exceed maximum allowable limits (Meyer, 2001). One such region that is polluted to an extent is the Cape Flats Unit (Smart, 2011).

**Borehole Yields**

Borehole yields within the Sandveld Group ranges between 0.1 and 5 l/s with the majority of boreholes yielding 0.5 l/s or less and about 30% yielding 2 l/s and more (Meyer, 2001). Production boreholes within the Cape Flats Unit with the thickest recorded post-Miocene deposits, yields the highest quantities of water (Vandoolaeghe, 1989).

A study done by Timmerman (1985c) on Cenozoic sediments on part of the coastal plain between the Berg River and Eland’s Bay indicated that it should be possible to establish boreholes within the Elandsfontyn Formation with yields up to 30 l/s and in the post-Miocene deposits with yields between 10 and 15 l/s. This was established by considering the aquifer thickness, hydraulic characteristic and blow yields of boreholes drilled.
4.1.4. Locating Groundwater Resources

4.1.4.1. Target Formations and Geological Features

The target formations of the Cenozoic coastal deposits are:

I. Maputaland Group (Schapers, 2011; King, 2002; 2003)
   a. KwaMbonambi Formation
   b. Isipingo Formation
   c. Uloa Formation (very limited extend)

II. Algoa Group (Meyer, 1998)
   a. Alexandria Formation
   b. Coastal Sands (Schelm Hoek Formation)

III. Bredasdorp Group (Meyer, 2001)
   a. De Hoopvlei Formation

IV. Sandveld Group
   a. Cape Flats Unit
      i. Witzand-Springfontyn Formations
      ii. Varswater Formation
   b. Silwerstroom-Witzand Unit
      i. Witzand-Springfontyn-Langebaan Formations
      ii. Varswater Formation
   c. Grootwater Unit
      i. Springfontyn-Langebaan Formations
      ii. Varswater Formation
   d. Berg River Unit
      i. Springfontyn-Langebaan-Varswater Formations
      ii. Elandsfontyn Formation

V. West Coast Group

Specific target features within the various formations include the following:

I. Coarse-grained sands
II. Conglomerates
III. Palaeo-channels

A good saturated thickness is acquired for the features above to be able to yield good quantities of groundwater (Parsons, 2011b). An increase in the saturated thickness will lead to a more improved aquifer system (Schapers, 2011; Parsons, 2011b). According to Weaver
(2011) at least 15-50 m of cover material is required to have a decent, sustainable aquifer within the Bredasdorp Group.

The favourable sand and gravel drilling targets of the Elandsfontyn Formation are restricted to the palaeo-channels of the Berg, Kulders, and Groen Rivers and is the most important aquifer within the Langebaan Road Aquifer unit with a thickness of up to 60 m (Timmerman, 1985b).

The preferred geophysical methods used to detect these features are:

I. Electromagnetics
II. Resistivity

4.2. The Kalahari Group (0 – 70 Ma)

4.2.1. Location and Extend
The Kalahari Group is situated in the centre of southern Africa (Figure 43). The uppermost aeolian unit extends continuously from the Northern Cape to 2° north of the equator, where the older units can be fairly widely traced from South Africa across Botswana and into Namibia (Partridge et al., 2006). In South Africa the Kalahari Group is situated in the Northern Cape adjacent to the Botswana and Namibia borders (Figure 44). The Kalahari Group forms a tectonic as well as a morphological basin that is filled with several metres of unconsolidated sandy deposits of Cenozoic age (De Vries et al., 2000).

4.2.2. Geology

4.2.2.1. Lithostratigraphy
The Kalahari Group is divided into six formations which displays a considerable lateral variation and not all of the formations are present everywhere (Figure 45) (Partridge et al., 2006). The formations are as follows:

- Gordinia Formation (Kalahari Sands)
- Obobogorop Formation
- Mokalanen Formation
- Eden Formation
- Budin Formation
- Wessels Formation
Figure 43: Distribution of the Kalahari Group in southern Africa (Partridge et al., 2006).

Figure 44: Isopach map showing the thickness and distribution of the Kalahari Group sediments in South Africa (Partridge et al., 2006).
Figure 45: Generalised section of the Kalahari Group (Partridge et al., 2006).

Wessels Formation
The Wessels Formation forms the base of the Kalahari Group and consists of clayey poorly sorted gravel (SACS, 1980). This formation is better developed and thicker in some of the deeper palaeo-valleys but does not always exist in the areas where the Kalahari Group is at its thickest (Partridge et al., 2006).

Budin Formation
The Budin Formation consists of red and brown calcareous clays interbedded with gravel (Visser, 1989) and is widely distributed within the deeper pre-Kalahari channels (Partridge et al., 2006). The Budin Formation outcrops just north-east of Kuruman along the Moshawen River (Visser, 1989).
Eden Formation
The Eden Formation consists mainly of red or brown poorly consolidated sandstones with thin pebble beds occurring locally (Partridge et al., 2006). This Formation outcrops west of Severn along the Moshawen River (Visser, 1989).

Mokalanen Formation
The Mokalanen Formation consists of calcretes which can be divided into a sandy limestone and overlying conglomerates with a calcareous matrix (Partridge et al., 2006).

Obobogorop Formation
The Obobogorop Formation consists of pebble and boulder clasts that eroded away from the Dwyka tillite (Partridge et al., 2006).

Gordinia Formation
The Gordinia Formation consists of red aeolian sands (white in areas) with rounded quartz grains coloured by a thin coating of haematite and is up to 30 m thick (Partridge et al., 2006).

4.2.3. Geohydrology

Geohydrological Characteristics
The Kalahari Group forms more or less a closed basin with an internal groundwater drainage system. The Kalahari Group consist mainly of unconsolidated material and for this reason it can be considered as a primary aquifer system. The underlying rocks of the Karoo Supergroup (also called the palaeo-floor of the Kalahari Group or Karoo landscape) play an important role in locating groundwater in the Kalahari Group. The storage of the clayey gravels of the Kalahari Group is an order higher than that of the underlying secondary aquifer (Karoo Rocks), but due to their clay content, the permeability is lower.

Groundwater is generally intercepted within the lowest formations of the Group which are the Wessels, Budin and Eden Formations (Van Wyk, 1987; 2011). The geohydrological characteristics of these formations are as follows (Van Wyk, 1987):

- **Wessels Formation**: Has a good aquifer potential, but is restricted to thin deposits in palaeo-drainage channels. The groundwater is usually saline due to direct contact with the saline Karoo interface that is often associated with a high clay content.
- **Budin Formation**: Has a low permeability due to the high clay content. Clay and gravel layers within the Formation, occasionally serve as aquifers.
- **Eden Formation**: Has a good aquifer potential. In places the formation is situated above the regional groundwater level.
Recharge of the Kalahari aquifer system is relatively limited. The recharge mechanisms of the aquifer are as follows (Dziembowski & Appelcryn, 1987):

I. Direct recharge from rain.
   - Only when rainfall is higher than normal (low rainfall region).
II. Flooding of river systems.
   - Flooding of the river systems present in the Kalahari Group sediments. An example is the high rise in borehole water levels during the flooding of the Kuruman River Valley 1973 to 1976 (Van Wyk, 2011).
III. Groundwater infiltration from surrounding areas.
   - Groundwater originates from where pre-Kalahari rocks outcrop on surface.

The groundwater quality of the Kalahari aquifer system is relatively complex. Van Wyk (1987; 2011) reported that the water quality vary both vertically and horizontally. The EC values can increase two or more fold within a metre in depth and in profile. EC values varies from 60 to 30 000 mS/m and the central areas of palaeo-channels are generally more saline than the outer parts (young water mixing with old salts) (Van Wyk, 2011). Fresher water obtained in areas where significant leaching of groundwater occurs.

Borehole Yields
The borehole yields within the Kalahari Group sediments generally vary between 0.2 and 1 l/s (Van Wyk, 1987; Dziembowski & Appelcryn, 1987), but there are areas where higher yields can be obtained. Information provided from drillers by Van Wyk (1987), indicates that yield tends to increase with depth but the salinity usually increase as well. Van Wyk (2011), claims that good yielding boreholes can be obtained from approximately 8 m of saturation, but clay layers can have a negative effect.

North of Vryburg, boreholes drilled into palaeo-valleys or channels have yields of up to 20 l/s, but these high yields are obtained at great depths of approximately 200 mbgl. According to Van Wyk (2011) boreholes drilled near the town of Rietfontein, Northern Cape Province, targeting the central zone of the Rietfontein Lineament (striking north to northeast) have yields of up to 15 l/s with good quality water (EC 100 to 120 mS/m) as there is significant leaching of groundwater. The boreholes drilled at the outside zone of the Rietfontein Lineament have significantly lower yields (1 to 2 l/s) with more saline quality water (400-500 mS/m). In the Kuruman River Valley, yields of up to 9 l/s were obtained, but the reasons for these higher yields were that the underlying secondary aquifer system was also penetrated (Dziembowski & Appelcryn, 1987).
The groundwater levels of the Kalahari aquifer system generally varies between 40 and 50 mbgl, but there are areas where water levels varies between 120 and 180 mbgl and even water levels of up to 250 mbgl exist (Van Wyk, 2011). According to Van Wyk (2011), there are areas where the water level is approximately 2 m above the palaeo-floor (either Ecca or Dwyka rocks) that exist as a yellow clay that is easily identified when drilled into.

4.2.4. Locating Groundwater Resources

4.2.4.1. Target Formations and Geological Features

The groundwater quality of Kalahari aquifer system is relatively complex, thus locating good quality water within this aquifer system will be a difficult task. Groundwater is generally intercepted within the lowest formations of the Kalahari Group which are as follows:

I. Wessels Formation
II. Budin Formation
III. Eden Formation

Van Wyk (2011) learned from experience that the best approach in locating groundwater is to map the palaeo-floor (Karoo landscape) of the Kalahari Group to locate palaeo-valleys/channels, using available borehole logs. Also target the boundaries of the Kalahari Basin where current river systems exist, but where the thickness of the Kalahari Group is no more than 180m so that one penetrates areas where significant leaching occurs. The Kuruman River can be used as an example; when drilling into the river channel, good quality water (50-60 mS/m) is intercepted, however, when drilling just outside the river channel, saline water is generally intercepted at the same level below ground as the borehole drilled into the river channel (Van Wyk, 2011). Thus targeting features within the Kalahari Group are:

I. Palaeo-valleys/channels
II. Regional fault systems
III. Current river channels

4.3. The Zululand Group (65 – 115 Ma)

4.3.1. Location and Extend

The outcrop area of the Zululand Group extends in a narrow north-south trending belt from just north of Ndumo towards Mtubatuba in the south (Figure 46). Drilling confirmed the sediments of the Zululand Group extend towards the coastal plain underlying younger
Cenozoic sediments (Shone, 2006). The group is bounded in the west by the volcanic rocks of the Lebombo Group.

4.3.2. Geology

4.3.2.1. Stratigraphy

The Zululand Group is subdivided into three formations (Figure 46). Contemporaneous faulting probably caused variations in the rate of sediment accumulation in this huge depository, with deposits of the Zululand Group being notably thicker in the north and northeast (Shone, 2006).
**Makatini Formation**

The basal Makatini Formation unconformably overlies the volcanic rocks of the Lebombo Group. The formation generally consists of conglomerate (Figure 47) with minor sandstone, siltstone and limestone (Shone, 2006). The pebbles of the conglomerate are volcanic and quartzitic in composition (Visser, 1989).

![Figure 47: Measured sections across the lower part of the Zululand Group in the southern outcrop area (sections 1 to 4) and representative sections of the Makatini and Mzinene Formations (Sections A to C). See Figure 46 for locations of sections. Modified after Shone (2006).](image)

**Mzinene Formation**

The Mzinene Formation is separated from the Makatini Formation by hard-ground and where the Makatine Formation is absent it directly overlies volcanic rocks of the Lebombo Group (Shone, 2006). The base of the Mzinene Formation consists of layer of conglomerate which is followed by glauconitic siltstone with interbedded sandstone (Shone, 2006).

**St. Lucia Formation**

The lithology of the St. Lucia Formation is very similar to that of the Mzini Formation (Figure 47), but separated from the latter by a slight angular unconformity (Shone, 2006). The base of the formation consists of a bored hardground (similar to that of Makatini & Mzinene Formations) which is then followed by a repetitive sequence of bored concretions, shelly
glauconitic sandstones and bioturbated siltstones (Figure 48). Thin clay lenses and thin bands of hard sandy limestone occasionally occur within the siltstones (Mkhwanazi, 2010).

![Figure 48: Typical sedimentary cycle of the St. Lucia formation (Shone, 2006).](image)

### 4.3.3. Geohydrology

**Geohydrological Characteristics**

The sediments of the Mzinene and St. Lucia Formations are extremely poor aquifers as they are regarded as aquicludes (King, 2003). The Makatini formation is the only formation that can be regarded as an aquifer.

The groundwater of the Zululand Group sediments is highly saline with EC values generally higher than 800 mS/m (King, 2003).

**Borehole Yields**

Borehole yields of the few boreholes intersecting the sediments of the Mzinene and St. Lucia Formations generally yields less than 0.4 l/s, whereas yields of up to 0.4 l/s can be obtained within the conglomerate of the Makatini Formation.

### 4.3.4. Locating Groundwater Resources

Due to the limited groundwater potential and poor quality water of the Zululand Group, it is advisable not to target this group for groundwater resources.
4.4. The Uitenhage Group (115 – 170 Ma)

4.4.1. Location and Extend
The Uitenhage Group occurs in half-graben-type basins (Shone, 2006) developed along the southern margin of South Africa from Port Elizabeth to Worcester (Figure 49). It is believed that these basins developed along the margins of the newly formed African continent in response to regional extension associated with the break-up of Gondwana (Shone, 2006). The most important basins are the Algoa, Gamtoos, Oudtshoorn, Mossel Bay and Riversdale Basins, where the Algoa Basin is the largest of them all with a preserved sediment cover of over 3 500 m (Shone, 2006).

Figure 49: Distribution of the Uitenhage Group in South Africa. Modified after Shone (2006).

4.4.2. Geology

4.4.2.1. Lithostratigraphy
The Uitenhage Group can be subdivided into three formations (Figure 50), where all can be recognised within the Algoa Basin and one or two of them in the other basins.
Algoa Basin

The Algoa Basin is the most complex half-graben basin, with fully developed graben structures, horst blocks and diagonal faults (Coega and Commando Kraal Faults) cutting the horsts (Shone, 2006).

The Enon Formation is the lowermost unit of the Uitenhage Group and attains a thickness of 490 m in its type area (east of Kirkwood) (Shone, 2006). The Enon Formation consists of poorly sorted, yellowish to red conglomerates (Visser, 1989) with large sub-rounded pebbles and cobbles (Shone, 2006). Metre-thick lenses of white to buff-coloured silty sandstone of generally limited lateral extend occur within the conglomerates. According to Shone (2006), the Enon Formation is absent over large parts of the basin floor and is interpreted as alluvial piedmont fans.

The overlying Kirkwood Formation attains a thickness of approximately 2 000 m in parts of the basin (Shone, 2006), and forms the lower most unit where the Enon Formation is absent (SACS, 1980). The base of the Kirkwood Formation consists of a non-fossiliferous sandstone unit (Swartkops Sandstone Member) and is followed by dark grey shales, siltstone and minor sandstone (Colchester Shale Member) that is rich in marine fossils (SACS, 1980). The sandstones are medium-to coarse-grained (Shone, 2006).

The Sundays River Formation overlies the Kirkwood Formation and attains a maximum thickness of approximately 1 863 m consisting of grey clays, siltstone and sandstone (SACS,
The sandstones of the Sundays River Formation are fine-to medium-grained and less porous and permeable than the sandstones of the Kirkwood Formation (Shone, 2006).

**Gamtoos Basin**

The Gamtoos Basin covers an area of approximately 650 km². The basin deepens towards the coast where it reaches a thickness of more than 3 000 m (Viljoen *et al.*, 2010).

Only the Enon and Kirkwood Formations are recognised within the Gamtoos Basin, where exposed sections of the Enon Formation exceed 150 m in thickness, thicknesses of up to 2 000 m in borehole samples. The Kirkwood Formation never attains the thickness of that in the Algoa Basin and is only represented by thin, relatively continuous interbeds of ochreous siltstone and sandstone (Shone, 2006).

**Oudtshoorn Basin**

The Oudtshoorn Basin is approximately 1 800 m deep in the central parts of the basin, but the largest part of the basin is less than 800 m deep (Viljoen *et al.*, 2010).

Both the Enon and Kirkwood Formations are present within the Oudtshoorn Basin. The Kirkwood Formation lies in the axial portion of the basin consisting of red and white siltstone and sandstone beds. The Enon Formation consists generally of conglomerates and dips northwards at relatively shallow angels and overlies rocks of the Cape Supergroup. Along the northern boundary of the Oudtshoorn Basin the Enon Formation contains a higher proportion of angular fragments that looks more like breccia (Shone, 2006).

**Mossel Bay and Riversdale Basins**

The Riversdale Basin is approximately 462 m deep, consisting mainly of mudstones and clayed sandstones of the Kirkwood Formation and minor conglomerates and breccias of the basal Enon Formation (large percentage of clay destroying porosity and permeability) (Viljoen *et al.*, 2010).

In the Mossel Bay Basin both the Enon and Kirkwood Formations can be recognised where the Kirkwood Formation also contains subordinate tuff and lenticular conglomerate beds (Shone, 2006).

**4.4.3. Geohydrology**

**Geohydrological Characteristics of the Uitenhage Group**

Most of the geohydrological characteristics of the Uitenhage Group are obtained from studies done on the Uitenhage Artesian Aquifer (UAA), Uitenhage Basin. The name of the aquifer can rather be misleading as it refers to the major aquifer system within the Uitenhage
Basin rather than the aquifer within the Uitenhage Group rocks. The artesian aquifer system is actually situated within rocks of the TMG (TMG Aquifer) underlying the Uitenhage Group rocks (Maclear, 2001) and is geohydrologically subdivided into the Coega Ridge Aquifer (relatively shallow) and Swartkops Aquifer (deep), separated by the Coega Fault (Figure 51). For a detailed discussion on the UAA see Maclear (2001).

Figure 51: Aquifer delineation of the Uitenhage Artesian Aquifer, including cross-sections of the geology and position of boreholes. Modified after Maclear (2001).

The Uitenhage Group can be classified as a secondary aquifer system. The rocks of the Uitenhage Group are dense and have low permeability, thus resulting in limited groundwater potential (Meyer, 1998; 1999). The mudstones of the Kirkwood Formation overlying the Enon Formation acts as an aquitard which results in artesian and sub-artesian conditions within the Enon Formation (Maclear, 2001).

Within the Uitenhage Basin, groundwater from the TMG Aquifer recharges the basal sandstone units of the aquifers within the Kirkwood and Enon Formations by lateral and
vertical pressure leakage to these formations from the bounding quartzite units (Maclear, 2001).

The EC values of the Uitenhage Group are commonly in excess of 300 mS/m where sodium, magnesium, chloride, total alkalinity, sulphate and fluoride regularly exceed maximum recommended and often maximum allowable limits (Meyer, 1989; 1999). Maclear (2001) conducted quality analysis during pumping tests on exploration boreholes within the Uitenhage Group, which showed that there was a decrease in salinity and an increase in acidity as pumping continued. This is considered to be a function of progressively increasing groundwater contributions from the TMG quartzites and decrease in groundwater derived from the Uitenhage Group.

**Borehole Yields**

The Uitenhage Group is generally a low yielding aquifer with poor quality water. Borehole yields rarely exceed 1 l/s and according to Meyer (1998; 1999) the groundwater potential of the Uitenhage Group may be much worse, as information on numerous, unsuccessfully drilled boreholes which have been destroyed, could not be obtained and therefore not used within the borehole yield analysis.

### 4.4.4. Locating Groundwater Resources

#### 4.4.4.1. Target Formations and Geological Features

Groundwater within the Uitenhage Group can occasionally be obtained from interbedded sandstone lenses, but the water within these lenses are almost invariably of poor quality (Meyer, 1999). Due to the limited groundwater potential and poor quality water of the Uitenhage Group, it is advisable not to target this group for groundwater resources and in the case of the Uitenhage Basin to rather target the underlying TMG Aquifer system (deep drilling).

Looking at the geohydrological characteristics of the Uitenhage Group, the Enon Formation and the lower parts of the Kirkwood Formation can occasionally be targeted for groundwater resources, but quality may still be problematic.

### 4.5. The Karoo Supergroup (150 – 320 Ma)

#### 4.5.1. Location and Extend

The Karoo Supergroup covers approximately two thirds of the current land surface of South Africa. In South Africa, rocks of the Karoo Supergroup are preserved in four different basins
and a narrow strip along the Mozambique-South Africa border known as the Lebombo Mountain Range (Figure 52). The Main Karoo Basin covers the largest area of approximately 700 000 km² (Johnson et al., 2006). The sedimentary and volcanic rocks of the Karoo Supergroup, ranges in age from Late Carboniferous to the Early Jurassic (Johnson et al., 1996).

Figure 52: Location and distribution of the Karoo Basin in South Africa and adjacent territories (Johnson et al., 2006).

4.5.2. Geology

4.5.2.1. Lithostratigraphy of the Main Karoo Basin

The Main Karoo Basin constitutes a retro-arc foreland basin and is also situated behind an inferred magmatic arc and associated fold thrust belt produced by a northward subduction of oceanic lithosphere located south of the arc (Figure 53) (Johnson et al., 2006).

The rocks of the Karoo Supergroup within the Main Karoo Basin are divided into various groups and formations (Figure 53 & Figure 54). The main lithostratigraphic units are as follows:

- Drakensberg and Lebombo Groups
- Stormberg Group (Molteno, Elliot & Clarens Formations)
- Beaufort Group
- Ecca Group
- Dwyka Group
Dwyka Group

The Dwyka Group consists predominantly of diamictite (Figure 56) and to a lesser extent of conglomerate, pebbly sandstone, and mudrock with dispersed stones (Visser, Von Brunn, & Johnson, 1990). Along the northern basin margin the Dwyka Group overlies glaciated Precambrian bedrock surfaces and in the south it overlies the Cape Supergroup unconformably/paraconformably, while in the east it unconformably overlies the Natal Group and Msikaba Formation (Johnson et al., 2006).

The Dwyka Group shows distinct lithological differences over the Basin, which led to the recognition of a northern valley/inlet facies and a southern platform facies (Johnson, et al., 2006; Woodford & Chevallier, 2002). The northern facies has a highly variable lithology, low massive diamictite (±20 %) and high mudrock/sandstone (±40 %) content, where the southern facies has a fairly uniform lithology, high massive diamictite (±70 %) and low mudrock/sandstone (±8 %) content (Visser et al., 1990).

The thickness of the Dwyka Group generally increases southwards (Du Toit, 1954) with a thickness of 500-800 m in the south and 100-200 m at the northern margin of the southern facies from where it is highly variably further northwards (0-600 m) (Visser et al., 1990).

The diamictite facies is generally massive, but may be stratified in places (Woodford & Chevallier, 2002). The diamictite is highly compacted, generally clast-rich, with rounded to angular, frequently striated pebbles and boulders up to 2 m across derived from pre-Karoo rocks (Johnson, et al., 2006). The diamictite is blue-greenish in colour (Figure 56) (Du Toit, 1954).

The conglomerate facies ranges from single layer boulder beds to poorly sorted pebble and granule conglomerates (Johnson, et al., 2006).

The sandstone facies consists of either very fine- to medium grained, massive to ripple-laminated, or medium- to coarse grained, trough cross-bedded, immature sandstones (Johnson, et al., 2006).

The mudrock facies consists of dark-coloured, commonly carbonaceous mudstone, shale or silty rhythmites (Johnson, et al., 2006).
Figure 53: Schematic north-south through the Karoo Supergroup in the eastern part of the Main Karoo Basin.
Figure 54: Schematic areal distribution of the lithostratigraphic units of the Karoo Supergroup and location of sections A-E and 1-3 (Johnson et al., 2006).
Figure 55: Generalised lithostratigraphy of the Karoo Supergroup in the Main Karoo Basin (Johnson et al., 2006).

Figure 56: Blue-greenish diamictite of the Dwyka Group.
Ecca Group
The Ecca Group comprises a total of 16 formations which reflects the lateral facies changes that characterise the succession (Figure 54 & Figure 55) (Johnson, et al., 2006). Except for the fairly extensive Prince Albert and Whitehill Formations, the individual formations can be grouped into three geographical areas/zones (Woodford & Chevallier, 2002) for descriptive purposes. The grouping of the individual formations is given in Table 11.

Table 11: The Grouping of the individual formations within the Ecca Group.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Western-Northwestern Zone</th>
<th>Southern Zone</th>
<th>Northeastern Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prince Albert</td>
<td>Prince Albert</td>
<td>Pietermaritzburg</td>
<td></td>
</tr>
<tr>
<td>Whitehill</td>
<td>Whitehill</td>
<td>Vryheid</td>
<td></td>
</tr>
<tr>
<td>Tierberg</td>
<td>Collingham</td>
<td>Volskrust</td>
<td></td>
</tr>
<tr>
<td>Skoorsteenberg</td>
<td>Vischkuil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kookfontein</td>
<td>Laingsburg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waterford</td>
<td>Ripon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fort Brown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Waterford</td>
<td></td>
</tr>
</tbody>
</table>

The Prince Albert Formation is situated at the base of the Ecca Group (Visser, 1989) and is confined to the south-western half of the Karoo Basin (Johnson, et al., 2006). It conformably overlies the Dwyka Group, but locally it unconformably overlies pre-Karoo basement rocks in areas where the Dwyka Group is absent (Cole, 2005). Two facies, southern and northern, can be recognised in the Formation (Johnson, et al., 2006). The northern facies is characterised by greyish to olive-green micaceous shale and grey, silty shale, as well as a pronounced transition from the underlying Dwyka Group glacial deposits. The southern facies is characterised by dark-grey, pyrite bearing, splintery shale, siltstone and the presence of dark coloured chert and phosphatic nodule and lenses. The thickness of the Formation is generally 50-165 m in the Main Karoo Basin, but considerably thicker in the area between Beaufort West and Brandvlei (225-320 m) (Cole, 2005).

The Whitehill Formation consists of black, carbonaceous shale that weathers white, with intermittent chert lenses and pyritic stringers (Visser, 1989; Branch et al., 2007). Towards
the northeast, the lower part of the Formation contains siltstone and very fine-grained sandstone (Johnson, et al., 2006). The shale is generally massive but laminations do occur (Branch et al., 2007). The thickness of the Formation varies from 10-80 m (Johnson, et al., 2006).

The Collingham Formation follows on the Whitehill Formation and is confined to the southern and western margins of the Karoo Basin. The thickness of the Formation is generally between 30 and 70 m and consists of a rhythmic alternation of thin, continuous beds of hard, dark-grey, siliceous mudrock and very thin beds of softer yellowish tuff (Johnson, et al., 2006). There is a distinctive constant chert layer (Matjiesfontein Chert Bed) present in the lower half of the Formation (Johnson, et al., 2006; Visser, 1989).

Figure 57: The Whitehill Formation (arrow) overlain by the Collingham Formation, outcropping in the Laingsburg district, southern part of the Main Karoo Basin. Photo from Catuneanu et al. (2005).

The Vischkuil Formation that overlies the Collingham Formation in the south-western part of the Karoo Basin consists of well developed blue to blue-green shales (Visser, 1989), alternating with subordinate sandstone, siltstone and minor yellowish tuff layers (Johnson, et al., 2006). The middle of the Formation shows a conspicuous, approximately 25 m thick zone of intensely folded and sheared sandstone beds (slide & slumping structures) (Adelmann & Fiedler, 1996). The sandstone beds vary from 0.3-1.5 m (Johnson, et al., 2006) in thickness and tend to thicken towards the east (Visser, 1989). The thickness of the
Formation varies between 200 and 400 m and becomes more arenaceous towards the east, where it grades into the Ripon Formation (Johnson, et al., 2006).

Figure 58: Steeply dipping beds of the Collingham Formation exposed in a road cutting west of Laingsburg, southern part of main Karoo Basin. The yellow beds are altered volcanic tuff interlayered with mudrock. The thick white bed is chert. Photo from Catuneanu, et al. (2005).

The Laingsburg Formation conformably overlies the Vischkuil Formation (Catuneanu, et al., 2002), consisting of four sandstone rich layers separated by thick shale units (Johnson, et al., 2006). The sandstones are fine-to medium-grained (NGuema Mve, 2005; Johnson, et al., 2006). The Formation attains a thickness of 750 m in the Laingsburg area, but thins in a northerly and easterly direction (NGuema Mve, 2005).

The Ripon Formation occurs in the southern regions of the Karoo Basin. The Ripon Formation is the chronostratigraphic equivalent of the Vischkuil and Laingsburg Formations east of the town Prince Albert (Visser, 1989). The Formation consists of poorly sorted, fine-to very fine-grained alternating sandstones and dark-grey shales (SACS, 1980; Johnson, et al., 2006), the sandstones constitutes at least one third of the total thickness (Visser, 1989). The thickness of the Formation is generally between 600 and 700 m, but is over a 1 000 m in the eastern part of its outcrop area (Johnson, et al., 2006).

The Outcrop area of the Fort Brown Formation is confined to the southern region of the Karoo Basin. The Formation consists of rhythmic layered bluish shale with isolated sandstone intercalations (Visser, 1898) and displays an overall coarsening-upward
phenomenon and attains an average thickness of approximately 1 000 m (ranging from 500-1500 m) (Johnson, et al., 2006).

The Waterford Formation overlies the Fort Brown Formation in the southern outcrop area and Kookfontein and Tierberg Formations in the western and north-western outcrop areas (Johnson, et al., 2006) consisting of alternating massive grey, fine-grained, sandstone and shale rhythmite units (Visser, 1989). The Formation is characterised by wave-ripples and ubiquitous ball-and pillow and related structures (SACS, 1980). The thickness of the Formation varies between 200 and 800 m (Johnson, et al., 2006).

The Tierberg Formation occurs in the western and northern regions of the Karoo Basin where it conformably overlies the Collingham Formation (south of 32°E) and the Whitehill Formation (north of 32°E) and grades upward into the Waterford Formation, or where it is absent, into the Adelaide Subgroup of the Beaufort Group (Viljoen, 2005; Johnson, et al., 2006). The Formation consists predominantly of dark grey to greenish grey shale with interbedded siltstone and very- to fine-grained sandstone towards the top of the Formation (Viljoen, 2005) with yellowish tuff beds up to 10 cm thick in the lower part of the succession (Johnson, et al., 2006). The thickness of the Tierberg Formation reaches a maximum of approximately 750 m (Viljoen, 2005) along the western margin of the basin, thinning to about 350 m towards the northeast (Johnson, et al., 2006). The Formation is the chronological equivalent of the Collingham, Vischkuil, Laingsburg, Ripon and Fort Brown Formations in the south of the Karoo Basin (Visser, 1989).

The Skoorsteenberg Formation comprises five sandstone-rich turbidite sequences separated by 20 to 75 m thick intervals of siltstone and mudstone (Van der Werff & Johnson, 2003; Anderson et al., 2004). The sandstones are dark grey in colour and medium- to fine-grained, containing carbonate-rich concretions that weather to a yellow-brown colour (Visser, 1989). The Formation attains a maximum thickness of approximately 200 m (Visser, 1989) where the thickness of the individual turbidite sequences varies between 20 and 60 m (Van der Werff & Johnson, 2003).

The Kookfontein Formation shows a sharp contact with the underlying Skoorsteenberg Formation and grades upward into the Waterford Formation (Johnson, et al., 2006). The Kookfontein Formation consists of dark-grey, rhythmic shale and siltstone with thin interbedded sandstone layers that are similar to that of the Tierberg Formation (Visser, 1989). The rhythmites form minor upward-thickening cycles which becomes more prominent at the top of the Formation where they are up to 15 m thick, and in places capped by a thick sandstone layer (Johnson, et al., 2006).
The Pietermaritzburg Formation shows a sharp contact with the underlying Dwyka Group in the north-eastern part of the Karoo Basin (Johnson, et al., 2006) and consists of dark-coloured, well laminated shales and mudstone, with interlayers of fine-grained sandstone (King, 2002). The Formation attains a maximum thickness of 400 m in the southeast (Johnson, et al., 2006), thinning to less than 100 m (King, 2003) northwards. The upper boundary of the Pietermaritzburg Formation is gradational and is probably best defined as a horizon above which the sand: shale ratio is greater than 0.5 (SACS, 1980).

The Vryheid Formation generally overlies the Pietermaritzburg Formation and is characterised by thick layers of yellowish to white, cross-bedded sandstone with layers of soft, dark-grey sandy shale (Figure 59 & Figure 60) with single layers of coal (Visser, 1989). The Formation attains a maximum thickness of 500 m in the Vryheid-Nongoma area (Section E in Figure 54) from where it thins towards the north, west and south but there is marked variations in thickness in the northern and north-western margins of the Karoo Basin where the Formation rest directly on the uneven pre-Karoo or Dwyka Group rocks (Johnson, et al., 2006).

Figure 59: Sandstone of the Vryheid Formation near the small settlement, Glückstadt, Kwazulu Natal, South Africa.
The Volksrust Formation follows concordant on the Vryheid Formation (Visser, 1989), consisting of grey to black, silty shale with thin, generally bioturbated siltstone or sandstone lenses and beds, especially towards the upper and lower boundaries (Johnson, et al., 2006). The thickness of the Formation varies from 270 m in the south to 170 m in the north (Visser, 1989).

![Image of thin, interbedded, sandy shale layers within the sandstone of the Vryheid Formation.](image)

**Figure 60**: Thin, interbedded, sandy shale layers within the sandstone of the Vryheid Formation.

**Beaufort Group**

The Beaufort Group covers an area of approximately 200,000 km$^2$. It attains a maximum cumulative thickness of approximately 7,000 m in the foredeep of the Karoo Basin, thinning rapidly northwards consisting of fluvial deposited Permo-Triassic rocks (Catuneanu, et al., 2005). The Beaufort Group is subdivided into two subgroups, namely:

- Tarkastad Subgroup
- Adelaide Subgroup

The Adelaide Subgroup is divided into four formations (Figure 61) of which the Koonap, Middleton, and Balfour Formations form part of the proximal facies and the Normandien
Formation that of the distal facies (north-eastern area of the Karoo Basin) (Catuneanu, et al., 1998). The Subgroup attains a maximum thickness of approximately 5 000 m in the south-eastern area of the Karoo Basin and rapidly decreases towards the north to approximately 800 m (Johnson, et al., 2006). The Koonap and Middleton Formations form a single fining-upward unit (Catuneanu et al., 1998) consisting of mudstone and sandstones, where the red mudstones of the Middleton Formation distinguish it from the lower- and upper lying formations (Koonap & Balfour Formations) (Bordy et al., 2011). The mudstones of the rest of the Adelaide Subgroup are generally greenish grey in colour (Catuneanu et al., 1998). The mudrocks of the Adelaide Subgroup are generally massive and blocky weathering except in parts of the Normandien Formation where horizontal lamination is common (Johnson, et al., 2006). The sandstones of the Normandien Formation are coarse-to very coarse grained where the other Formations consist of fine- to very fine-grained sandstones (Johnson, et al., 2006).

The Tarkastad Subgroup is divided into four formations (Figure 61). In the south it comprises of a lower Katberg Formation and an upper Burgersdorp Formation and in the extreme north of a lower Verkykerskop Formation and an upper Driekoppen Formation. The subgroup attains a maximum thickness of nearly 2000 m in the south, decreasing to approximately 800 m towards the middle of its outcrop area and 150 m or less in the far north (Johnson, et al., 2006).

The Katberg Formation consist mainly of sandstone (90% plus) that is fine- to medium-grained with scattered pebbles up to 15 cm in diameter, and light brownish grey or greenish grey in colour (Johnson, et al., 2006). The overlying Burgersdorp Formation consists of alternating reddish mudstones and subordinate light grey sandstones that are fine-grained, moderately sorted, generally subtabular to lenticular in shape, and extend laterally over great distances before pinching out (Johnson & Hiller, 1990). The individual sandstone layers of the Burgersdorp Formation are arranged in upward-finining cycles that can be up to 10 m thick with an average thickness of 2-3 m (Johnson & Hiller, 1990).

The Verkykerskop Formation consists of fine-to very coarse-grained olive brown sandstone with lenses of siltstone and brown-red mudstone and the formation is up to 80 m thick (Johnson, et al., 2006; Kruidenier, 2007). Cross-bedding is a prominent feature of the Verkykerskop Formation (Kruidenier, 2007). The Driekoppen Formation consists of brown-red mudstone with interlayered, fine-grained, reddish sandstone and the formation is up to 70 m thick (Johnson, et al., 2006; Kruidenier, 2007).
Figure 61: Comparative section of the Beaufort Group at localities 1, 2 and 3 on Figure 54. Units thinner than about 7 m, are not shown (Johnson, et al., 2006).
**Stormberg Group**

The Stormberg Group is subdivided into the following three formations:

- Molteno Formation
- Elliot Formation
- Clarens Formation

The Molteno Formation forms the Base of the “Stormberg Group” and consists of alternating medium-to coarse-grained sandstones and dark-grey to bluish sandy shale (Visser, 1989; Johnson *et al*., 2006). The sandstone appears glittery due to secondary quartz overgrowths (Johnson, *et al*., 2006). The Formation represents a wedge-shaped fluvial deposit and attains a maximum thickness of 450 m in the southern outcrop area and decreases towards the north, where it reaches a thickness of less than 10 m (Visser, 1989).

The Elliot Formation conformably overlies the Molteno Formation. The Formation consists of alternating brownish-red and greenish-grey mudstone, siltstone, shale and reddish sandstone (Figure 62) (Visser, 1989). The sandstone units are generally between 6 and 15 m thick but can be up to 22 m thick, where the thickness of the mudstone units typically ranges between 25 and 100 m in the type area (Johnson, *et al*., 2006). The total thickness of the formation reaches a maximum of 500 m in the southern outcrop area, but becomes thinner towards the north (Visser, 1989; Johnson *et al*., 2006). The thick, lenticular sandstone at the base of the Formation is very similar to the sandstones of the underlying sandstones of the Molteno Formation.

The Clarens Formation consists of fine-grained, aeolian sandstone a few hundred metres thick (Figure 63 & Figure 64). Near the base, it is a little more argillaceous, pinkish and in places even deep red, but higher up it is white or yellowish (Visser, 1989). The uppermost part of the formation can consists of minor interlayered basaltic lava flows (Johnson, *et al*., 2006). Bedding is mainly observed at the base and top of the formation and large scale, through cross-bedding occur here and there. The thickness of the formation varies throughout between 300 and 40 m (Visser, 1989).
Figure 62: Sandstone and mudstone of the Elliot Formation in a road cutting on Wolfhuis pass. Smaller photo indicates weathering of the mudstone.

Figure 63: Sandstone of the Clarens Formation taken from the air near Barkly East.
Figure 64: Sandstone of the Clarens Formation forms prominent outcrops in the foothills of the Drakensberg Mountains, such as these at Golden Gate National Park in the Free State Province, South Africa.

Drakensberg Group

The Drakensberg Group covers an area of about 140 000 km² (Visser, 1989) which mostly covers the whole of Lesotho and a part of the Free State, Kwazulu Natal and Eastern Cape Provinces of South Africa.

The Group consists of a series of Basaltic lava flows, with individual flows 3 to 50 m thick (Duncan & Marsh, 2006). The whole succession attains an average thickness of approximately 1 000 m reaching a maximum of 1 400 m in the northwest (Woodford & Chevallier, 2002). The Basalt is dark grey to black with pipe amygdales at the base and ordinary amygdales near the top of individual flows, but the basalt weathers to a chocolate-brown to purplish crust (Visser, 1989).

According to Visser (1989), Woodford and Chevallier (2002) the Drakensberg Group can informally be divided into two formations as follows:

- Lower Barkly East Formation
- Upper Lesotho Formation
The lower Barkly East Formation is 200 m thick and consists of thin flows (Figure 65), is of restricted geographical distribution and diverse geochemical character. The upper Lesotho Formation represents the bulk of the sequences with thick flows (Figure 66) of more uniform composition (Woodford & Chevallier, 2002).

Figure 65: Basaltic lava flows of the lower Barkly East Formation in a road cutting near Barkly East.

Figure 66: Basalt lava of the Drakensberg Group forming rugged walls of the famous Amphitheatre (left and bottom right photos) of the Drakensberg Mountain Range, viewed from the Tugela Falls and Sentinel Hill (top right photo) respectively.
**Lebombo Group**

The Lebombo Group are made up of a few major lava formations. The Group is subdivided into the following formations (Figure 67):

- Movene Formation
- Mbuluzi Formation
- Jozini Formation
- Sabie River Formation
- Letaba Formation
- Mashikiri Formation

![Figure 67: Distribution of the Lebombo Group Formations (Duncan & Marsh, 2006).](image)

The Mbuluzi Formation mainly confined to Swaziland and the Movene Formation is largely confined to Mozambique Border (Duncan & Marsh, 2006).
The Rooi Rand and the Northern Limpopo dyke swarms, which outcrops as relatively dense north-south trending structures, are hosted by the Lebombo Group lavas. The lavas also host gabbroic and granophyric sills, while only one mafic igneous centre is exposed near the intersection between the Lebombo and Mwenetzi Monoclines (Klausen, 2009).

The Mashikiri Formation consists of nepheline and the formation forms a relatively thin unit of less than 170 m (Duncan & Marsh, 2006) at the base of the volcanic sequence in the northern Lebombo region.

The overlying Letaba Formation conformably overlies the Clarens Formation, Soutpansberg Group or Archaean Granites (Visser, 1989). The Letaba Formation consists of picritic (Olivine-rich) lava, forming the main mafic unit in the northern Lebombo region and thins southwards to about 25ºS (Duncan & Marsh, 2006). The Formation is overstepped by the Sabie River Formation consisting of basaltic lavas (Duncan & Marsh, 2006) similar to that of the Drakensberg Group (Visser, 1989).

The Jozini Formation overlies the Sabie River Formation consisting of dense, resistance, reddish, brownish, purplish and even greenish, rhyolitic rocks that forms the Lebombo Mountain Range (Figure 68). Individual flows form extensive sheet-like bodies between 80 and 284 m thick and is tilted 10 to 35 degrees towards the east (Saggerson & Bristow, 1983; Visser, 1989).

The Movene Formation mainly consists of greenish- to bluish grey basaltic to andesitic lavas (Visser, 1989) interbedded with rhyolitic lava (Duncan & Marsh, 2006).

Figure 68: The Lebombo Mountain Range stretching along the N2 highway just south of the Pongola Poort Dam, South Africa.

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

4.5.2.2. Lithostratigraphy of the Springbok Flats Basin

The Springbok Flats Basin is divided into two sub-basins, northern and southern, that formed from a single basin by post-Karoo folding. The basin is bounded by post-Karoo faulting (normal faults) along the north-western margin (Mtimkulu, 2009).

The Springbok Flats Basin is subdivided into the following lithostratigraphic units as follows:

- Drakensberg Group
- Clarens Formation (Bushveld Sandstones)
- Irrigasie Formation (Elliot/Molteno)
- Hammanskraal Formation (Ecca – Vryheid Form.)
- Dwyka Group (Karoo surface scree)
Dwyka Group
The Dwyka Group seldom exceeds a few metres in thickness, but in local basement depressions it can be up to 40 m thick (Mtimkulu, 2009). The Group consists of mudstone, diamictite and conglomerate with occasional coal seams (Johnson, et al., 2006).

According to De Jager (1983) the Dwyka Group of the Springbok Flats Basin can be correlated locally with the Dwyka Group of the Main Karoo Basin, where otherwise, as a pebbly, gritty mudstone that more conclusively points to being surface scree on the pre-Karoo land surface. Clasts range from pebble to boulders in size (Johnson, et al., 2006).

Hammanskraal Formation
The base of the Hammanskraal Formation consist of medium-to-coarse grained, immature sandstone, locally interbedded with shaly coal that can be up to 12 m thick. The base is overlain by a grey mudrock dominated interval that coarsens upward into micaceous, fine- to medium-grained sandstone (Johnson, et al., 2006) and according to De Jager (1983) may be the time-equivalent of the Vryheid Formation. The top of the Formation consists of a Coal zone that is up to 12 m thick comprising of alternating carbonaceous mudrock (60-70 %) and bright coal seams (30-40 %). The thickness of the Hammanskraal Formation is highly variable, with a maximum of 65 m and pinches out towards basement highs (Johnson, et al., 2006).

Irrigasie Formation
The Irrigasie Formation is situated between rocks of the Ecca Group (Hammanskraal Formation) and the Clarens Formation and attains a maximum thickness of about 200 m (Johnson, et al., 2006). The lower part of the Irrigasie Formation consists of massive dark-grey mudstone that becomes reddish to purplish upwards and weathers in a blocky fashion (De Jager, 1983; Visser, 1989). Overlying this mudstone unit is a medium- to coarse grained sandstone unit, characterised by upward-fining depositional cycles which extend over thicknesses of a few metres (Visser, 1989), but this sandstone unit also contains relatively small thicknesses of light-grey to purplish mudstone. Thin small-pebble conglomerate is often developed at or near the base of the sandstone unit (De Jager, 1983). The sandstone unit is followed by a reddish mudstone unit (in places sandy) alternating with beds of purple mudstone, and coarse-grained sandstones are also encountered in the upper parts (De Jager, 1983; Visser, 1989).

Clarens Formation
The Clarens Formation (Bushveld sandstones) attains a maximum thickness of 120 m (Johnson, et al., 2006) in the Springbok Flats Basin. As in the Main Karoo Basin it consists
of fine-grained, white to yellowish sandstone, pinkish or faintly red in the lowermost parts of the formation. Thin mudstone intercalations occur sporadically (Johnson, et al., 2006).

**Drakensberg Group**
Remnants of the Drakensberg Group, consisting of basaltic lava, overlie the sedimentary rocks of the Springbok Flats Basin.

### 4.5.2.3. Lithostratigraphy of the Ellisras Basin

The Ellisras Basin is situated in the Limpopo Province. The sediments of the Ellisras Basin are preserved in faulted blocks and a half-graben structure that parallels the ancient Limpopo Mobile Belt (Faure et al., 1996). The preserved basin strikes east to west for approximately 90 km with a width of about 35 km and is bounded in the north and south by the Zoetfontein and Eenzaamheid faults respectively.

The rocks of the Ellisras Basin are sub-horizontally deposited, where it gently dips towards the basin axis (Fourie et al., 2009). The Karoo rocks were also displaced by two major faults (Eenzaamheid & Daarby faults), with a displacement greater than 250 m (Bester & Vermeulen, 2010). The general landscape of the basin is extremely flat and is almost entirely covered by recent sands, grits and gravels.

The Ellisras Basin is subdivided into the following lithostratigraphic units as follows:

- Lebombo Group
- Clarens Formation
- Lisbon Formation
- Greenwich Formation
- Eendragtpan Formation
- Ecca Group
- Dwyka Group

**Dwyka Group**
The Dwyka Group is divided into two separate formations namely:

- Wellington Formation
- Waterkloof Formation

The basal Waterkloof Formation consists of diamictite, mudstone and conglomerate, overlying rocks of the Waterberg Group and Archaean basement rocks (Faure et al., 1996). According to Johnson et al. (2006) the diamictite and conglomerate attains thickness of over
9 m consisting of rounded and angular clasts set in a clayey or sandy matrix. The mudstones however are over the 17 m thick.

The overlying Wellington Formation consists of mudstone with angular drop-stones and sandstone intercalations. At the base of the formation there is however places where fine-to coarse-grained sandstones are more extensively developed (Faure et al., 1996; Fourie et al., 2009). The formation is generally 20 to 30 m thick, but in the southwest and southeast it reaches thicknesses of 160 m and 180 m respectively (Johnson, et al., 2006).

**Ecca Group**

The Ecca Group is divided into three formations as follows:

- Grootegeluk Formation
- Goedgedacht Formation
- Swartrant Formation

The Swartrant Formation overlies the Wellington Formation and attains a maximum thickness of 130 m (Johnson, et al., 2006) in the central part of the basin. The formation consists of a Lower, Middle and Upper zone consisting of sandstone, siltstone, carbonaceous mudstones (Faure et al., 1996), and locally developed coal seams. The Lower and Middle zones are separated by a one metre thick coal seam, where the Middle zone is capped by an alternating coal and mudstone up to six metre thick (Johnson, et al., 2006).

The Goedgedacht Formation is only present in the north and north-western part of the basin and the thickness decreases from the north towards the south where it interfingers with the Swartrant Formation. The formation consists of mudstone units (0.5 to 4 m) that is characterised by graded bedding (coarsening-upward) and locally developed medium- to coarse-grained sandstone at the top (Johnson, et al., 2006).

The Grootegeluk Formation conformably overlies the Swartrant Formation and consists of a repetitious sequence of carbonaceous shales and mudstones with interbedded bright coal seams (Faure et al., 1996). The Grootegeluk Formation is subdivided into 11 coal-bearing zones that are currently being mined at the Grootgeluk open-pit coal mine (Figure 69)
Eendragtpan Formation (Beaufort Group)
The Eendragtpan Formation overlies the coal-mudstone cycles of the Grootgeluk Formation. The formation consists of medium- to light-grey massive mudstone (Faure et al., 1996) which is used to mark the contact between the Ecca and Beaufort Groups in the Ellisras Basin. Purplish to red-coloured mudstones dominate towards the top of the formation and whole formation attains a maximum thickness of 110 m in the central part of the basin.

Greenwich Formation (Molteno Formation)
The Greenwich Formation consists largely of medium- to coarse grained purplish-red, whitish or greenish sandstone and granulestone, separated from the Eendragtpan Formation by a sharp erosive contact. The thickness of the formation varies between 7 and 33 m (Johnson, et al., 2006).

Lisbon Formation (Elliot Formation)
The Lisbon Formation consists mainly of red, massive mudstone and siltstone as well as minor medium- to coarse-grained sandstone. The thickness (100-110m) of the formation is fairly constant throughout and bioturbation is common (Johnson, et al., 2006).

Clarens Formation
In the Ellisras Basin, the Clarens Formation forms prominent hills and ridges and attains a maximum thickness of 130 m (Johnson, et al., 2006) As in the Main Karoo Basin it consists of fine-grained, white to yellowish sandstone, pinkish or faintly red in the lowermost parts of the formation, however, medium-to coarse-grained units and thin pebbly layers are locally developed.
Letaba Formation (Lebombo Group)
As already discussed the Letaba Formation consists of picritic lava. Only a small piece of the Letaba Formation is preserved within the Ellisras Basin.

4.5.2.4. Lithostratigraphy of the Tshipise and Tuli Basins
The Tshipise and Tuli Basins are both situated in the Limpopo Province. The rocks of the Tshipise Basin are preserved in fault blocks that follow the trend (ENE-WSW) of the Limpopo Mobile Belt (Johnson, et al., 2006). The Tuli Basin extends into Botswana and Zimbabwe, and only a small piece is preserved in South Africa. The rocks of the Tuli basin in South Africa were deposited in a small intercratonic graben-type structure (Durand, 2009) before the break-up of Gondwanaland.

The Tshipise and Tuli Basin is subdivided into the same lithostratigraphic units. The lithostratigraphy described in this thesis is mainly summarised from Johnson, et al. (2006) and Brandl (2002) unless otherwise referenced.

The Tshipise and Tuli Basins is subdivided into the following lithostratigraphic units as follows:

- Lebombo Group
- Clarens Formation
- Bosbokpoort Formation
- Klopperfontein Formation
- Solitude Formation
- Fripp Formation
- Mikambeni Formation
- Madzaringwe Formation
- Tshidzi Formation

Tshidzi Formation

Tshipise Basin
The Tshidzi Formation consists generally of diamictite, with angular to rounded clasts of pink quartzite, up to 2 m in diameter, which are set in an argillaceous or sandy matrix. There are places where interbedded coarse-grained sandstones do occur. The formation is approximately 5 m thick, but there are areas where it is up to 20 m thick.
**Tuli Basin**
The Tshidzi Formation in the Tuli Basin is deposited on an uneven floor of Beit Bridge gneisses. In areas of topographic elevation the basal Karoo is represented by a local development of coarse diamictite containing angular clasts of up to 80 cm in diameter. The clasts are neither sorted nor rounded and no imbrications occur. There are places where the diamictite is absent. The diamictite deposits are overlain by coarse reddish micaceous grits that pass upward into the laminated shale of the Madzaringwe Formation (Durand, 2009).

**Madzaringwe Formation**

**Tshipise Basin**
The Madzaringwe Formation is up to 200 m thick and thins (to approximately 9 m) towards the Mogalakwena River area, consisting of alternating cross-bedded sandstone, siltstone and shale containing thin coal seams. The basal shale layer, 25-35 m thick, is characterised by small white angular dropstones and thin coal seams. The main coal seam is 2 to 3 m thick and developed between 85 and 100 m above the basal shale layer. The formation is capped by massive, course-grained sandstone that is 10 to 15 m thick.

**Tuli Basin**
The Madzaringwe Formation consist primarily laminated shale with intermittent lenses of red yellowish grit in its lower sequences. Higher up in the sequence, there is a distinct coal zone that is up to 20 m thick. The overlying sequence consists of very fine-grained, purplish-red mudstone that is overlain by micaceous, course-grained sandstone, marking the top of the Madzaringwe Formation.

**Mikambeni Formation**

**Tshipise Basin**

Three units (lower, middle & upper), consisting of mudstones, shale and laminated sandstone can be recognised. The lower unit (15-20 m thick) consists of alternating black shale and grey, feldspathic sandstone. The middle unit (50 m thick) consist of black, carbonaceous shale with occasional coal seams. The upper unit (60-70 m thick) consists of dark grey mudstone with plant fragments and occasional coal seams. The whole formation attains a maximum thickness of 150 m.

**Tuli Basin**
The Mikambeni Formation consists of grey to yellowish shales and siltstones with small coal seams occurring here and there. The rocks of the formation are identical to that of the Madzaringwe Formation.
**Fripp Formation**

*Tshipise Basin*

The Fripp Formation rests unconformably on the Mikambení Formation and consists of white, medium-to coarse-grained sandstone with interbedded mudstone and siltstone. Thin pebble layers also occur within the sandstone. The formation is up to 110 m thick in the north-eastern part of the Tshipise Basin but it generally ranges between 20 and 40 m.

*Tuli Basin*

The Fripp Formation consists of a 5 to 10 m thick whitish or greyish, medium- to coarse-grained sandstone, together with gritty layers and coarse conglomerate lenses. Planar cross-bedding are fairly common.

**Solitude Formation**

*Tshipise Formation*

The Solitude Formation has a gradational contact with the underlying Fripp Formation. The formation generally consists of purplish mudstone and grey shale, but in the type area it consists of 30 m grey shale that is overlain by 80 m of alternating purple and grey mudstone with three intercalated siltstone units. The thickness of the formation is generally 120 m but in the extreme west it only reaches 60 m.

*Tuli Basin*

The Solitude Formation consists of siltstone that shows more reddish variations towards the top. Very fine-grained sandstone also occurs within the formation with subordinate grey mudstone. In the western part of the basin the formation attains a maximum thickness of approximately 25 m but attenuates to 3.5 m in the eastern part.

**Klopperfontein Formation**

*Tshipise Basin*

The Klopperfontein Formation has an unconformable relationship with the underlying Solitude Formation and is rarely exposed. The formation consists mainly of coarse-grained, feldspathic sandstone and grit. Cross-bedding is present but not well developed. It attains a maximum thickness of approximately 20 m but is generally 5 m thick, but in the extreme west it very thin or even absent.

*Tuli Basin*

The Klopperfontein is only developed or preserved in the central part of the Tuli Basin where it reaches a maximum thickness of 10 to 12 m. The formation consist of coarse-grained,
poorly sorted sandstone and grit with frequent conglomerated horizons of rounded to sub-rounded 3 cm quartz clasts. Trough cross-bedding is a characteristic feature of the formation (Durand, 2009).

**Bosbokpoort Formation**

**Tshipise Basin**
The Bosbokpoort Formation overlies the Solitude Formation where the Klopperfontein Formation is not developed. The formation is characterised by red lithologies, varying from mudstone to very fine-grained sandstone. The thickness of formation varies between 120 and 150 m but in the Mogalakwena River area it varies between 30 and 60 m. Calcareous nodules are also a characteristic feature.

**Tuli Basin**
The rocks of the Bosbokpoort Formation are rarely exposed in the Tuli Basin but are up to 60 m thick, consisting of brick-red to purplish mudstones with subordinate white siltstone layers and occasional intra-formational conglomerates. The siltstone layers are mainly developed in the upper half of the succession. The contact between the Bosbokpoort Formation and Solitude Formation is somewhat arbitrary, where the Klopperfontein Formation is absent.

**Clarens Formation**
The Clarens Formation in the both the Tshipise and Tuli Basins are subdivided into the Red Rocks and Tshipise Members. The Red Rock Member forms the base of the Clarens Formation.

**Tshipise Basin**
The Red Rocks Member consists of very fine-to fine-grained, light red sandstone with irregular parches or occasional layers of cream-coloured sandstone. Calcareous concretions are common. The thickness is relatively constant (±100 m), but there are areas where it is absent. The overlying Tshipise Member reaches a thickness of 150 m, consisting of fine-grained, well sorted, white or cream-coloured sandstone. Large-scale cross-bedding and calcareous concretions are often developed towards the base of the member.

**Tuli Basin**
The Red Rocks Member attains a thickness of approximately 30 to 40 m, consisting of very fine-to fine-grained, white or pinkish to red sandstone with characteristic mottled appearance. A concretionary zone is developed at the top of the member. The overlying
Tshipise Member consists of fine-grained, well sorted, white or cream-coloured sandstone. The thickness is variable and ranges from 5 to 140 m. The Tshipise Member covers much of the area, forming characteristic flat top hills underlain by Red Rocks lithologies.

**Letaba Formation**

*Tshipise Basin*
The Letaba Formation covers extensive areas in the Tshipise Basin, especially to the south of Alldays. Consists almost entirely of basalt and generally underlies flat country, often covered by red clayey or brown turfy soils. The thickness is difficult to estimate but it might not exceed 100 to 200 m.

*Tuli Basin*
The Letaba Formation form complex outcrop patterns, which reflect the flow of lava around and between the dunes of the Clarens Formation. Only the lowermost part of the Letaba Formation crops out in the South African part of the Tuli Basin. The weathered surfaces are dark reddish brown, and frequently pitted due to the weathering of mafic minerals.

<table>
<thead>
<tr>
<th>Main Karoo Basin</th>
<th>Springbok Flats Basin</th>
<th>Ellisras Basin</th>
<th>Tuli &amp; Tshipise Basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormberg Group</td>
<td>Clarens Formation</td>
<td>Clarens Formation</td>
<td>Tshipise Member</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red Rock Member</td>
</tr>
<tr>
<td>Elliot Formation</td>
<td>Irrigasie Formation</td>
<td>Lisbon Formation</td>
<td>Bosbokpoort Formation</td>
</tr>
<tr>
<td>Molteno Formation</td>
<td></td>
<td>Greenwich Formation</td>
<td>Klopperfontein Formation</td>
</tr>
<tr>
<td>Beaufort Group</td>
<td>Eendragtpan Formation</td>
<td></td>
<td>Solitude Formation</td>
</tr>
<tr>
<td>Eccca Group</td>
<td>Hammanskraal Formation</td>
<td>Grootgeluk Formation</td>
<td>Fripp Formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Goedgedacht Formation</td>
<td>Mikabeni Formation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Swartrant Formation</td>
<td>Madzaringwe Formation</td>
</tr>
</tbody>
</table>

4.5.2.5. Karoo Dolerite Suite

The dolerite intrusions of the Karoo Supergroup (Jurassic in age), consist of an interconnected network of dykes and sills, which best developed in the Main Karoo Basin (Figure 70) but present in most of South Africa. These dolerites intruded into the sediments of the Karoo Supergroup during a period of extensive magmatic activity that took place over
almost the entire Southern African sub-continent during one of the break-up phases of Gondwanaland (Chevallier et al., 2001). It appears that there is a lithological control on the emplacement of dykes within the Western Karoo Basin, as the bulk of the dykes are strata bound and concentrated in the Upper Ecca and Beaufort Group (Woodford & Chevallier, 2002).

Figure 70: Interconnected dykes and sills of the Main Karoo Basin, including a schematic cross section through the basin (Courtesy of Prof. Gerrit van Tonder).

According to Chevallier et al. (2001), three major structural domains, indicated by dyke distribution, have been identified in the Main Karoo Basin (Figure 71):

1) **The Western Karoo Domain** extends from Calvinia to Middelburg and is characterised by two distinctive structural features: east west trending zone of long and thick dykes associated with right lateral shear deformation and north northwest dykes.

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

3) **The Transkei-Lesotho-Northern Karoo Domain** consists of two swarms: northwest trending dykes in the Transkei Region, curving to east-west in the Free State and northeast trending dykes mainly occurring within and alongside the Lesotho basalt.

The dolerite dykes of the Karoo Supergroup are all sub-vertical (Figure 72) with a dip rarely below 70°. The attitude of the dykes often changes with depth due to vertical offsetting as a result of vertical en-échelon segmentation (Figure 73(a)) or due to interconnecting of dykes between sediment layers. Intense fracturing is commonly associated with this vertical en-échelon segmentation (Woodford & Chevallier, 2002).

The host rock of a dolerite intrusion is often fractured during and after dyke emplacement. These fractures can be either parallel to its strike or perpendicular. The fractures parallel to strike forms master joints over a distance that does not vary greatly with the thickness of the dyke (5 to 15 m), whereas, the thermal- or columnar-jointing perpendicular to the margins only extend into the host rock over a distance not exceeding 0.3 to 0.5 m from the contact (Figure 73(b)). Van Wyk (in Woodford & Chevallier, 2002) identified two types of jointing associated with dyke intrusions in a number of coalmines in the Vryheid-Dundee area, namely:

I. Three sets of pervasive-thermal, columnar joints that are approximately 120° apart.

II. Joints parallel to the contact, confined mainly to the host rock alongside the dyke.

Tectonic reactivation of dolerite dykes are sometimes observed, especially in the Loxton-Victoira West area, where reactivation is a result of Cretaceous kimberlite activity or by more recent master jointing (Figure 73). The reactivation often results in sub-vertical fissures within the country rock and/or dyke itself, which are commonly highly weathered and filled with secondary calcite/calcrete (Figure 74). Localized upwarping of the host rock is often observed adjacent to dipping dykes (Figure 73 & Figure 75).
Figure 71: Dolerite dykes of the Main Karoo Basin. Inset is a simplified structural map showing the three structural domains. Modified after Woodford & Chevallier (2002).
Figure 72: Sub-vertical dolerite dyke intrusion in the rocks of the Elliot Formation.

Figure 73: Structures and fractures related too dolerite dykes; a) En-échelon dolerite dyke; b) Dyke showing Vertical Tectonic and Horizontal Thermal Jointing; c) Fissures related to Tectonic Reactivation and Jointing related to weathering/erosional unloading. (Woodford & Chevallier, 2002).
Figure 74: Sub-vertical fissures filled with calcite due to tectonic reactivation. Inset- slickenslides on calcite indicates movement along the contact zone.

Figure 75: Upwarping of Karoo rocks adjacent to dolerite dike intrusion.
Dolerite sill and ring complexes are a prominent feature of the Karoo landscape. These structures are easily identified on satellite images (Figure 76). These structures have the same geographical distribution than the dykes and are the major tectonic style that controls the geomorphology and drainage system of the Main Karoo Basin (Chevallier et al., 2001; Woodford & Chevallier., 2002). The relationship between the dykes and sill or ring complexes is very complex. The dykes are characteristically encountered in massive arenaceous rocks, while the sills are more common in laminated argillaceous rocks of the Karoo Supergroup (Lurie, 1981).

Sills and inclined sheets range from a few metres to 200 m or more in thickness, where dykes are generally 2 to 10 m wide and 5 to 30 km long, although some can be followed for 80 km (Duncan & Marsh, 2006). In the drier parts of South Africa, dolerite sills, caps softer sedimentary strata of the Karoo Supergroup, forming characteristic table top hills, like the Platberg Mountain near Harrismith (Figure 77).

Figure 76: Satellite image (Landsat-5 TM Band 745) of dolerite ring structures in the Queenstown area (Smart, 1998).
Figure 77: Platberg Mountain near Harrismith is an outlier of Clarens Formation sandstone, capped by a Karoo dolerite sill.

Three major types of fracturing within a dolerite sill and ring complex (Figure 78) can be identified (Chevallier et al., 2001):

I. Vertical thermal columnar jointing. This is well developed within the flat-lying sill (F1). From air photo examination and satellite imagery it appears that the outer sill often displays a very dense system of columnar jointing.

II. Fractures parallel to the strike of the intrusion are dominant within the inclined sheet (F2). Air photo and satellite imagery show that the actual circular inclined-sheet is the most fractured part of the complex.

III. Well-developed, oblique or sub-horizontal open fractures develop within curved portions of the sill. In the western Karoo, these fractures are often infilled with secondary calcite (F3). Similar observations were made in the Eastern Karoo.

The most recent tectonic interpretations led to the development of two emplacement models for Karoo dolerite sills (Figure 79). According to these models, the rim of the ring-structure is the most tectonised unit within the sill/ring complex, however, the two models can vary considerably especially concerning the development of fracturing below the ring and above the centre of the inner sill (Woodford & Chevallier, 2002).
Figure 78: Different types of fractures associates with sill and ring complexes (Chevallier et al., 2001).

Figure 79: Dolerite sill/ring emplacement models; a) Ring dyke model; b) Laccolith model. (Woodford & Chevallier, 2002).
4.5.2.6. Dolerite Breccia Plugs and Volcanic Vents

Clusters of dolerite breccia plugs occur along the western and northern edges of the Karoo Basin, whereas the volcanic vents (necks or diatremes) occur along the foothills of the Drakensberg Mountains (Figure 80).

**Dolerite Breccia Plugs**

These breccia plugs are mostly restricted to the Ecca Formation (Skurkop & Muldersfontein plugs penetrate base of Beaufort Group) and the clusters are variable in size from a few hundred metres to up to 50 km in diameter, containing up to 80 plugs. The breccia plugs commonly form small, low-relief, circular hills (Figure 81), 50 to 80 m in diameter. They also occur as circular, negative-relief depressions of a similar dimension with characteristic calcrete development. (Woodford & Chevallier, 2002).

Two main facies are recognised (Woodford & Chevallier, 2002):

I. **Molten Facies** – domed, baked, molten, re-crystallised and highly contorted sediment containing xenoliths for the underlying strata. Melting is often accompanied by gas-vugs, which are commonly filled with secondary calcite, quartz and to a lesser extent grossular and vesuvianite.

II. **Breccia Facies** – a true breccia with fracture, broken, shattered, displaced and recemented blocks of sediment. This facies is often accompanied by mineralization of quartz, calcite, gypsum, chlorite, apophyllite, baryte, siderite, fluorite, pyrite, pyrrohotite, sphalerite, galena, chalcopyrite, marcassite, bornite and traces of gold.

According to Woodford and Chevallier (2002) the molten facies is more frequently encountered in the field than the breccia facies. Probably, because the molten facies, is more resistant to erosion, resulting in more easily detectable features of positive relief. Whereas the breccia facies erodes more easily, resulting in the less prominent features of negative relief. Figure 82 show geological logs of core-boreholes drilled into the Enkelde Wilgenboom and Kopoas Fontein breccia plugs.

The proposed mode of emplacement is that localised hydrothermal activity (often explosive), occurred when the early (lowermost) dolerite sills intruded into the partially indurated, "wet Karoo Supergroup sediments. Resulting in the brecciation and melting of the host sediments, as well as the mobilisation and upward transport of elements from the Whitehill and Prince Albert Formations.
Figure 80: Distribution of mapped Breccia Plugs and Volcanic Vents in the Karoo Basin (Woodford & Chevallier, 2002).
Figure 81: The positive-relief of the Jagkop Breccia Plug in the Carnarvon district (Woodford & Chevallier, 2002).

Figure 82: Geological logs of core-boreholes drilled into breccia plugs and a stratigraphic borehole (Woodford & Chevallier, 2002).
Volcanic Vents

The volcanic vents are restricted to the Clarens Formation and occasionally occur in the Drakensberg basalts, varying in shape and size from a few metres to a couple of kilometres. They represent the first volcanic outbursts that preceded the outpouring of the lava flows. These vents are described as a mixture of agglomerate and yellowish tuffs made up of shattered and pulverized sandstone from the Clarens Formation, and containing clasts of dolerite and amygdoidal basalt (Woodford & Chevallier, 2002).

These volcanic vents probably formed by phreatic-explosive activity (intruding magma encounters a groundwater body) where excessive water and steam pressures overcome that of the magma, resulting in fragmentation of the country rocks and poor participation of the magma (Woodford & Chevallier, 2002). Figure 83 show geological log of core-boreholes drilled into a volcanic vent (by SEOKOR in 1968) just north of Ladybrand, revealing a relatively deep structure of 170 m.

Figure 83: Geological log of stratigraphic borehole drilled (LA1/68) into a volcanic vent, near Ladybrand (Woodford & Chevallier, 2002).
4.5.2.7. Kimberlite and Associated Alkaline Intrusive Complexes

Kimberlites occur as clusters of linear or arcuate swarms of dykes and fissures associated with several enlargements, blows of pipes (Figure 84). The geographical extend of kimberlite dykes and associated fractures in the Karoo are indicated by Figure 85.

Kimberlite fracture swarms consist of parallel fissures and associated joints or fractures (Figure 86). Each swarm can be divided into sub-swarms of smaller size (Figure 87). Fissures of each sub-swarm are closely spaced (10 to 50 m) and 0.5 to 4 m wide and often show strong upwarping of the surrounding Karoo rocks. Blows and enlargements frequently occur along the fissures (Woodford & Chevallier, 2002).

Kimberlite diatremes are unevenly distributed and very variable in size, with diameters of 10 to 400 m in the western Karoo, and 200 to 1 000 m on the Kaapvaal Craton. They are also less common in the western Karoo. Kimberlites contain a large amount and a wide variety of mantle and crustal xenoliths as well as megacrysts. Both the fresh and weathered Kimberlite can form positive-relief hills or negative-relief, calcrete rich depressions (Woodford & Chevallier, 2002).

Figure 84: Kimberlite fissure and pipe in the vicinity of Loxton (Woodford & Chevallier, 2002).
Figure 85: Distribution of Cretaceous Kimberlites and Carbonatites in the Karoo Basin (Woodford & Chevallier, 2002).
Figure 86: Cross-section of kimberlite body near Victoria West. Note thin kimberlite, calcite and calcrete stringers parallel to the main body (Woodford & Chevallier, 2002).

Figure 87: Proposed vertical geometry of a swarm. Modified after Woodford and Chevallier (2002).

4.5.3. Geohydrology

4.5.3.1. Dwyka Group

Geohydrological Characteristics
The Dwyka Group are generally considered to be an aquitard rather than an aquifer, as the diamictite and shales have very low hydraulic conductivities and virtually no primary voids (Vivier, 1996). Even though the Dwyka Group is considered to be an aquitard, there are a few localities where there are exploitable aquifers and this is where sand and gravel were deposited on beaches or where the Dwyka Group was fractured significantly (Woodford & Chevallier, 2002). These features are only exploitable if the recharge in these areas is
significant. Thus the Dwyka Group is not ideal for the development of large-scale development for groundwater supply.

The groundwater of the Dwyka Group is generally brackish, especially along the coastal zones, (saline) with EC values often exceeding 300 mS/m. EC values tend to decrease inland. The quality of the groundwater improves in fractures or jointed zones of the Dwyka Group, where significant groundwater movement and turnovers take place, with EC values ranging between 25 and 200 mS/m (Meyer, 2001). Sodium, calcium, magnesium, chloride and sulphate may often or even maximum allowable limits (Meyer, 2001).

Borehole Yields
According to various authors the Dwyka Group is a low yielding aquifer, as it is generally considered an aquitard rather than an aquifer. Yields are generally lower than 0.5 l/s. Areas where the Dwyka Group have been fractured significantly can have yields of up to 10 l/s (King, 2002), but it is rather rare. According to Schafer (2011), fractures or joints that are present within the Dwyka Group have the tendency to be mineralised (kaolinised), and this mineralisation can actually be followed on surface. The mineralisation of this fractures or joints decreases the potential yield that can be encountered.

According to King (2002) the success rate of drilling a successful borehole in the Dwyka Group is 30 to 40 %. If one is successful in locating groundwater within the Dwyka Group, the sustainable yield is normally not that fantastic, as the aquifer normally have a complete linear response (Schapers, 2011).

4.5.3.2. Ecca Group

Geohydrological Characteristics
The Ecca Group consists mainly of shales that are generally very dense, and for this reason, overlooked as significant sources of groundwater. As illustrated in Figure 88, the porosity of the shales tend to decrease from about 0.1 in the north to less than 0.02 in the south and south-eastern parts of the Basin, while the density increases from approximately 2 000 to 2650 kg.m$^{-3}$. Vertically these shales act as an aquitard and horizontally as an aquifer, thus the term “aquitardifer” was developed to describe this behaviour.

It is expected to find high-yielding boreholes within the deltaic sandstones but it is not the case as these sandstones generally have very low permeabilities (Figure 89). According to Woodford and Chevallier (2002) the main reason for this is that these sandstones are generally poorly sorted, and that their primary porosities have been lowered considerably by diagenesis.
Figure 88: Contour map of porosities and bulk densities of the Ecca shale (Woodford & Chevallier, 2002).

Figure 89: Porosity and permeability variations in the sandstone/siltstone of the Ecca Group (Woodford & Chevallier, 2002).
Borehole Yields
Generally the Ecca Group is considered a low yielding aquifer system with yields commonly between 0.1 and 2 l/s. Yields higher than 2 l/s can, however be obtained in fold, fault and joint structures, where favourable recharge conditions exist. In the Petrusburg area, thick enough calcretes, with a high effective porosity, has a positive influence on groundwater occurrence (Figure 90), as high yielding boreholes are fairly common (Meyer, 2003).

Figure 90: High recharge in calcretes resulting in springs.

4.5.3.3. Beaufort Group

Geohydrological Characteristics
It is expected that the aquifers in the Beaufort Group will like those in the Ecca Group be anisotropic but the geometry of the aquifers are further complicated by the migration of braided and meandering streams (Vivier, 1996). Thus the sandstones and mudstones of the Beaufort Group are also characterised by significantly low (virtually absent) primary porosity and permeability. Secondary properties of these rocks, such as the degree, density, continuity and interconnection of fracturing, control the occurrence, storage and movement of groundwater (Van Wyk & Witthueser, 2011). The fact that many of the coarser sediments are lens shaped further complicates these aquifers, as the life-span of a borehole drilled into such structures may thus be limited, if not frequently recharged (Vivier, 1996).
The groundwater of the Beaufort Group are generally potable, but there are areas where this is not the case. The EC values vary between 70 and 1 200 mS/m with the majority below 300 mS/m. Sodium, chloride, fluoride and sulphate may exceed the maximum recommended limits.

**Borehole Yields**

According to Baran (2003), the lithology of the sedimentary deposits of the Beaufort Group appears to have little effect on the borehole yields. The majority of yields are generally between 0.1 and 2 l/s. Higher yields can occasionally be obtained by targeting occasional folds, faults and joint structures, where favourable recharge conditions exist.

The average water level depth varies between 10 and 20 mbgl but localities with shallower water levels are also common (mostly wide river valleys) (Baran, 2003).

### 4.5.3.4. Stormberg Group

**Geohydrological Characteristics**

The characteristics and depositional history, together with the geometry (sheet-like and more persistent than Beaufort Group) of the sedimentary rocks of the Molteno Formation is an indication that the Formation should be an “ideal” aquifer in terms of groundwater storativity (Vivier, 1996; Woodford & Chevallier, 2002). The Molteno Formation does not extend over a large area and tends to form topographical highs, thus the siting of high-yielding boreholes becomes difficult.

The Elliot Formation consists almost entirely of mudstones that are relatively impermeable but highly porous (Vivier, 1996). Thus the Formation would rather represent an aquitard than an aquifer. An approach, suggested by Vivier (1996) to exploit the groundwater potential of these rocks is to drill through the Elliot Formation into the underlying Molteno Formation restrict pumping to the latter. This would probably allow water to ‘leak’ downwards into the Molteno Formation.

The Clarens Formation is the most homogeneous formation of the Karoo Supergroup. From Table 14 it is clear that the Clarens Formation has a relatively high (average = 8.46 %) and uniform porosity, indicating that the Formation should be an ‘ideal’ aquifer. Unfortunately the Clarens Formation is poorly fractured and thus the permeability of the formation is very low (low hydraulic conductivity). The sandstones can thus store large quantities of water, but is unable to release it quickly (Vivier, 1996; Woodford & Chevallier, 2002).
Table 14: Porosity of the sandstone of the Clarens Formation (Vivier, 1996).

<table>
<thead>
<tr>
<th>Type of Sandstone</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fine Grained</td>
<td>6.19-9.82</td>
</tr>
<tr>
<td>Cross-bedded Sandstone</td>
<td>8.87-10.75</td>
</tr>
<tr>
<td>Average</td>
<td>8.46</td>
</tr>
</tbody>
</table>

The groundwater quality of the Stormberg Group is generally of good quality. EC values are generally less than 300 mS/m (Barnard, 2000; Baran, 2003; Meyer, 2003). In the drier regions of South Africa, the groundwater tends to be more brackish. Sodium, magnesium, and chloride may occasionally exceed the maximum allowable limit.

**Borehole Yields**

The Stormberg Group can be regarded as a low yielding aquifers system with the majority of boreholes yielding less than 2 l/s, but yield occasionally exceed 2 l/s (Barnard, 2000; Baran, 2003; Meyer, 2003). The Clarens Formation seems to be the best aquifer system within the Stormberg Group and according to a borehole analysis done by Meyer (2003) have yield generally between 0.5 and 5 l/s. The Elliot Formation is usually dry when drilled and water generally encountered at the Elliot-Molteno contact zone.

**4.5.3.5. Drakensberg and Lebombo Groups**

**Geohydrological Characteristics**

Both the Drakensberg and Lebombo Groups can be classified as intergranular and fractured aquifer systems.

A characteristic feature of the Drakensberg Group is the numerous low yielding springs (Figure 91) emerging in elevated areas, especially along the contacts between weathered and solid basalts, and the contacts between the basalts of the Drakensberg Group and the sandstones of the Clarens Formation (King, 2002; Meyer, 2003). Springs are also fairly common within the Lebombo Group, especially on the eastern slopes of the Lebombo Mountain Range south of Swaziland (King, 2003).

The volcanic rocks of the Drakensberg and Lebombo Groups are generally dense with limited transmissivities. Thus groundwater movement is confined to weathered and fractured zones within the volcanic rocks.
Quality data of the Drakensberg group is scarce. Meyer (2003) had two EC data points and only one chemical analysis available. The analysis suggests that EC values may vary between 60 and 120 mS/m. The available data is however inadequate to support this claim.

The groundwater quality of the Lebombo Group is highly variable with qualities ranging between good and poor. The variability of the quality according to King (2003) is demonstrated by a good quality borehole drilled 300 m away from bad quality borehole. The average EC values ranges between 140 and 177 mS/m. Fluoride and chloride are the main constituents influencing the quality. Fluoride is usually high, making the quality unsuitable for long-term human consumption, unless treated. Sodium, magnesium, calcium, fluoride and chloride occasionally exceed the maximum recommended limit (King, 2003; Du Toit & Lelyveld, 2006).

![Figure 91: Low yielding springs emerging from basalts of the Drakensberg Group near Barkly East.](image)

**Borehole Yields**

The basalts (Letaba Formation) of the Lebombo Group can be regarded as a low to moderate yielding aquifer system as the majority of boreholes have yields ranging between 0.5 and 2 l/s (Du Toit & Lelyveld, 2006). The rhyolite deposits (Jozini Formation) can be regarded as a very low yielding aquifer system, due to the limited transmissivity and inconsistent recharge conditions, resulting in total dewatering of boreholes (Du Toit, 1998). Borehole yields within the Lebombo Group do exceed 2 l/s with a maximum reported yield of 14 l/s.

The static groundwater levels of the Lebombo Group are highly variable, probably the result of compartmentalisation by the Rooi Rand Dolerite Swarm (King, 2003).
The Drakensberg Group can be regarded as a low yielding aquifer system as the majority of borehole yields range between 0.5 and 2 l/s including that 20% of the boreholes analysed by Meyer (2003) have yields less than 0.1 l/s. There are areas where yields greater than 2 l/s were obtained.

4.5.3.6. Karoo Dolerite Suite

Geohydrological Characteristics of Dolerite Dykes

Dolerite dykes generally represent thin, linear zones of relatively higher permeability, acting as conduits for groundwater flow within the Karoo aquifers. They may also act as semi-to impermeable barriers to the movement of groundwater.

Woodford and Chevallier (2002) summarised the geohydrological properties of the Karoo Dolerite Dykes as follows:

- On regional scale – structural domains (Figure 71) have not as yet been shown to influence the regional geohydrology of the Karoo Supergroup. Major magma feeders (east-west Victoria dyke, north northwest Middelburg dyke & dykes near East London) are accompanied by extensive fracturing due to shearing and jointing. These dykes form regional discontinuities that, although likely to have propagated laterally, extend to great depths within the earth’s crust and theoretically could form part of a fracture network wherein deeper-seated groundwater flows on a more regional scale.
- On local scale – geometry, attitude, grain size, degree of weathering and fracturing of dykes influence the geohydrological properties of individual structures. The geohydrology of a particular dyke is related to a complex interplay of these parameters and can thus vary dramatically along the strike of the structure.

Borehole Yields

Borehole yields drilled next to or in dolerite dykes are highly variable, due the variability of the aquifer parameters along the strike of dykes. Various borehole analyses was conducted in various parts of the Karoo to determine if there is a relation between borehole yields and distance from dyke contact and width of dyke. The results are as follows.

- **Distance from dyke:**
  - Enslin (in Woodford & Chevallier, 2002) concluded that highest borehole yields are obtained within 1 m of the dyke contact (Figure 92), but the dip of the dyke and if it is water-bearing should be considered.
- Borehole analysis done in the north-eastern Free State (Bethlehem, Ficksburg, Fouriesburg & Senekal) indicate that boreholes drilled into dykes have significantly higher yields than the fractured contact zone (Table 15).
- Woodford and Chevallier (in Woodford & Chevallier, 2002) only found a weak statistical correlation between borehole yield and distance drilled from the dyke contact in the western Karoo.

- **Width of Dyke:**
  - The drilling results in the north-eastern Free State illustrated a relationship between width of the dyke and borehole yield (Figure 93). It was concluded that dykes 4 to 11 m wide produce the highest yields.
  - No significant correlation between dyke width and borehole yields could be found in the western Karoo, but it was concluded that dykes less than 2 m do not deliver yields more than 4 l/s (Woodford & Chevallier, 2002).

![Figure 92: Borehole yield versus distance from dyke contact (Woodford & Chevallier, 2002).](image-url)
Table 15: Borehole yield data for the north-eastern Free State (Woodford & Chevallier, 2002).

<table>
<thead>
<tr>
<th>Borehole Position</th>
<th>Number of Boreholes</th>
<th>Percentage Successful Boreholes (&gt;0.1 l/s)</th>
<th>Average Depth (mbgl) of Successful Boreholes</th>
<th>Average Borehole Yields (l/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyke Contact (Upper)</td>
<td>417</td>
<td>19</td>
<td>28</td>
<td>0.5</td>
</tr>
<tr>
<td>Dyke Contact (Lower)</td>
<td>75</td>
<td>76</td>
<td>46</td>
<td>5.8</td>
</tr>
<tr>
<td>Dyke Only</td>
<td>144</td>
<td>99</td>
<td>54</td>
<td>15</td>
</tr>
<tr>
<td>Stormberg Sediments, away from dolerite</td>
<td>3220</td>
<td>1</td>
<td>25</td>
<td>0.95</td>
</tr>
<tr>
<td>Total</td>
<td>3856</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 93: Dyke width versus yield of boreholes drilled into dykes in the north-eastern Free State (Woodford & Chevallier, 2002).

4.5.3.7. Dolerite Breccia Plugs and Volcanic Vents

Geohydrological Characteristics

Breccia plugs and volcanic vents are highly permeable structures due to their fractured and brecciated nature. It should be kept in mind that these structures is only a highly permeable conduit for groundwater flow, similar to a dyke, and it is the rate of recharge from and
storativity of the host rock reservoir that will eventually determine sustainable yields of borehole tapping these features (Woodford & Chevallier, 2002).

According to Woodford and Chevallier (2002), groundwater struck below 100 m has elevated fluoride values (3-12 mg/l) and that the EC values of the deeper groundwater interceptions are often considerably fresher than the upper interception in the Calvina, Vanwyksvlei and Bitter Poort areas. The borehole at the golf course in Calvinia can be used as an example with an EC value of approximately 300 mS/m, while the EC of the high yielding, deeper groundwater is approximately 120 mS/m.

**Borehole Yields**

The breccia plugs can be regarded as a moderate to high yielding aquifer systems with borehole success rates of 70 % in excess of 3 l/s (Table 16). Woodford and Chevallier (2002) concluded that high yields in excess of 8 l/s are almost always encountered in the intensely brecciated sections of a plug which seems to be at about 60 to 150 mbgl.

**Table 16: Yield of boreholes drilled into breccia plugs (Woodford & Chevallier, 2002).**

<table>
<thead>
<tr>
<th>Final borehole blow-yield range (l/s)</th>
<th>Number of boreholes within range</th>
<th>Percentage boreholes within yield range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>1</td>
<td>3.8</td>
</tr>
<tr>
<td>&gt;0 &amp; ≤1</td>
<td>2</td>
<td>7.7</td>
</tr>
<tr>
<td>&gt;1 &amp; ≤3</td>
<td>5</td>
<td>19.2</td>
</tr>
<tr>
<td>&gt;3 &amp; ≤5</td>
<td>7</td>
<td>26.9</td>
</tr>
<tr>
<td>&gt;5 &amp; ≤10</td>
<td>7</td>
<td>26.9</td>
</tr>
<tr>
<td>&gt;10</td>
<td>4</td>
<td>15.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>26</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

**4.5.3.8. Kimberlite and Associated Alkaline Intrusive Complexes**

**Geohydrological Characteristics**

Kimberlite intrusions did not significantly alter the hydrological properties of the sediments it intruded; however, on a regional scale cluster of kimberlites may represent important fractured domains (Woodford & Chevallier, 2002).

On a local scale, thin kimberlite dykes, less than 3 m thick, are generally weakly jointed possess a very low permeability, especially within the highly decomposed upper section. Kimberlite blows or enlargements with a diameter of 4 to 10 m may represent more
permeable zones along the dykes, as they are always more heterogeneous in texture, more deeply weathered and marked by dense bush growth (Woodford & Chevallier, 2002).

**Borehole Yields**

Kimberlite dykes or fissures can be regarded as a low to moderate yielding aquifer system. A borehole yield analysis conducted by Woodford and Chevallier (2002) indicates that 48% of boreholes yield 1 l/s or less, but boreholes yielding more than 5 l/s are located further than 2 m from the dyke itself. They concluded that the abnormally higher yielding boreholes appear to be located away from the dyke, where the probability of intercepting yields greater than 5 l/s increases at distances in excess of 5 m away from the contact.

### 4.5.4. Locating Groundwater Resources

#### 4.5.4.1. Target Formations and Geological Features

The Karoo Supergroup, covering approximately two thirds of South Africa’s surface area, is potentially the largest and most important source of groundwater. Thus, understanding the occurrence of groundwater within these aquifers becomes fundamental.

Specific target features within the rocks of the Karoo Supergroup include the following:

I. Weathered and fractured zones associated with faulting and folding.
II. Intrusive dolerite dyke and sill/ring contact zones.
III. Breccia plugs and volcanic vents.
IV. Lithological contact zones.
V. Bedding-parallel fractures.
VI. Transition zone between weathered and hard rock.

Weathered and fractured zones associated with faulting and folding is confined to the southern Karoo, adjacent to the Cape Supergroup. The formation of shallow anticlines and synclines, due to folding, has characteristic open joints and fractures (Figure 94). According to Van Tonder (1978) and Wellman (2011) these structures are seldom dry when drilled, although quality may be problematic (generally brackish).
Dolerite dykes are a well known target within the rocks of the Karoo Supergroup, due to the fact that they are often surrounded by highly fractured zones. These dykes are generally easy to locate on aerial images, in the field (Figure 95) and with existing geophysical techniques.

Figure 95: Parallel dolerite dykes (visible on surface) just outside Smithfield, targeting the dykes for groundwater development. Red circles indicate position of wind-pumps.
According to Van Tonder (1978) the highest yields are generally obtained where the dolerite/host rock contact zone is struck at a depth below the water table. Generally at a depth greater than 20 m below the water level, these joints and fractures have the tendency to be close. This is not always the case, as Van Tonder (1978) indicates that in the vicinity of the town Kestell, these joints are still open at depths of up to 90 m below the water level and yields of up to 20 l/s are obtainable.

Kruger and Kok (in Woodford & Chavellier, 2002) produced a schematic diagram showing where boreholes should be sited in order to maximize groundwater yields, based on a detailed analysis of boreholes targeting dykes in the north-eastern Free State (Figure 96). Paver et al. (1943) states that the dip of the dyke (if impermeable) in relation to the drainage direction should be accounted for. In such case, they suggest that boreholes should be sited as follows:

- If the dyke is vertical or near vertical then a site should be chosen of the drainage side of its outcrop and close to the contact (Figure 97 A-C).
- If the dyke dips steeply downstream a site should be chosen downstream from its outcrop and at such a distance from it that the borehole will penetrate the dyke, and tap water trapped on the upstream side (Figure 97 D).
- If a dyke dips steeply upstream a site should be chosen upstream from its outcrop and such a distance from it that the borehole will reach the water level before penetrating the dyke (Figure 97 E).
- If the dyke cuts the drainage obliquely a site should be chosen in accordance with the above and towards the side of the valley where the dyke is furthest downstream (Figure 97 F).

Figure 96: Borehole site selection on dolerite dykes (Woodford & Chevallier, 2002).
Figure 97: Correct siting of boreholes alongside dykes cutting drainage features. Modified after (Paver et al., 1943).

Figure 98 illustrates a dipping dolerite sheet intrusion into layered sediments of the Karoo Supergroup. The weak yields of boreholes A and B indicates that water-bearing fractures are poorly developed in both the weathered and fresh siltstone and mudstone. The upper and lower contact zones of the dolerite sheet only yield water where fracturing has been opened by unloading and weathering.

Yield of boreholes drilled next to dolerites are highly variable, since the dykes, especially ring dykes (Vivier, 1996; Botha et al., 1998) and dykes thicker than 10 m (less weathered than dykes less than 10m), are impermeable, confining aquifers to isolated compartments. Thus restricting the area from which a borehole can withdraw its water considerably. A method, suggested by Botha et al. (1998), to increase the yield of such limited aquifer is to drill a
production borehole through the dyke dividing aquifers and tap the water of both the aquifers simultaneously, but they have proved that this method is not always successful.

Figure 98: Schematic section through dipping dolerite sheet intrusive into an alternating succession of horizontally disposed Karoo siltstone and mudstone beds (Vegter, 1995).

Upper contact zones of dolerite sills are capable of yielding water if these zones are encountered less than 15 m below the water level. The lower contact zones only yield water near the edges of the dolerite sill where the dolerite is intensely weathered (Van Tonder, 1978). The shape of these sills can be very heterogeneous as illustrated in Figure 99.

Figure 99: Heterogeneous shaped dolerite sill intrusion within the rocks of the Karoo Supergroup.
Younger dolerite dykes that cut sills are often good targets for groundwater. This is especially true in a valley-bottom situation where the sill material is highly weathered. Transgressive fractures are often well developed in the vicinity of dykes/sill contacts improving possibility of striking good yielding aquifer systems (Woodford & Chevallier, 2002).

Water-bearing open fractures within dolerite sill and ring complexes develop at specific locations within the dolerite and surrounding host rock. Figure 100 is a hydro-morphotectonic model of a dolerite sill and ring complex, indicating the areas of water-bearing fractures related to these structures. According to Woodford & Chevallier (2002) fractures associated with the junction between a feeder dyke/inclined sheet and a sill is very localise, whereas, fractures associated with the sediment above an up-stepping sill or at the base of an inner-sill can extend some distance away from the dolerite contact into the host rock.

![Figure 100: Hydro-morphotectonic model of a dolerite sill and ring complex (Chevallier et al., 2001). Detailed fracture pattern for inclined sheet indicated in (Figure 78).](image)

The size and geometry of breccia plugs and volcanic vents are good groundwater targets, due to their high permeability. The size and geometry of the breccia plugs makes it possible to easily locate and site successful boreholes, without the added cost of geophysical surveys. It is believed that the groundwater occurrence within volcanic vents is similar to that in breccia plugs and also represents easily located drilling targets for high yielding boreholes because of their shape, size and degree of brecciation (Woodford & Chevallier, 2002). According to Woodford and Chevallier (2002), volcanic vents may prove to be the
most important groundwater exploration targets in the sandstones of the Clarens Formation, which are generally poorly fractured and have a low permeability.

Farmers tend to avoid drilling into the centre of kimberlite dykes due to experience of low yields and problems with borehole collapse (Woodford & Chevallier, 2002). However, better yields seem to be located away from the dykes. Woodford and Chevallier (2002) found that only seepage occur in the weakly jointed transition zone between the weathered and fresh kimberlite, but significant amounts of groundwater can be obtained from mega-joints that accompanied the emplacement of the kimberlite.

Weathered and joined zones (bedding plane fractures) of the sedimentary rocks of the Karoo Supergroup away from dolerites and the Cape Fold Belt (CFB) can yield reasonable quantities of water. Van Tonder (1978) summarised these areas as follows:

- In the Northern Cape Province and the western parts of the Free State where the Dwyka and Ecca Groups are undeformed, poor drilling results are obtained.
- Sandstones in large parts of the Upper-Karoo are well jointed. Good drilling results away from dolerite intrusions are obtainable. Reported yields of up to 25 l/s have been obtained (Noupoort area).
- In northern Kwazulu-Natal, a large percentage of borehole drilled into the Lower-Ecca shales have been successful, whereas, the boreholes drilled into the Middel- and Upper-Ecca are usually unsuccessful (massive and less jointed).

Lithological contacts zones are also favourable zones for developing good yielding boreholes. This can be sandstone-mudrock contacts, especially at unconformable contact zones which are generally more weathered (Smart, 1998). The lithological contact between the Drakensberg basalts and the Clarens Formation are also favourable targets. The Drakensberg basalts are usually targeted in weathering basins where the weathering extend below the water level.

The preferred geophysical methods used to detect these features are:

I. Magnetics
II. Electromagnetics
III. Resistivity

Magnetics are commonly used in the Karoo Supergroup for detecting dolerite dykes and sills. Electromagnetics are sometimes used in conjunction with the magnetic method in detecting dykes and sills. The resistivity method is applied in support of the magnetic and electromagnetic methods and can detect basins of weathering and their deepest area for
optimum borehole siting (Baran, 2003). Applying the resistivity method is expensive and especially time consuming and therefore not that commonly used as the magnetic and electromagnetic methods.

4.6. The Cape Supergroup (340 – 475 Ma)

4.6.1. Location and Extend
The Cape Supergroup is situated in the Western and Eastern Cape Provinces, extending from Vanrhynsdorp to Cape Agulhas and then eastwards to Port Elizabeth. It is a linear outcrop that extends for about 900 km (Rosewarne, 2002a).

4.6.2. Geology

4.6.2.1. Lithostratigraphy
The Cape Supergroup (Figure 101) is divided into three main groups which are lithologically distinctive and show lateral continuity throughout the length of the Cape Supergroup (Thamm & Johnson, 2006). In ascending order they are:

- Witteberg Group
- Bokkeveld Group
- Table Mountain Group

Figure 101: Distribution of the Cape Supergroup. Section lines of Table Mountain Group (1-3) and Bokkeveld Group (A-E) (Thamm & Johnson, 2006).
Table Mountain Group (TMG)

The TMG can be subdivided into six lithostratigraphical units and is given in Table 17. A brief description of each of the units is discussed below (Figure 102).

The Piekenierskloof and Graafwater Formations stretches mainly from Lamberts bay, east- and southwards to Piket Mountain (Visser, 1989). In the north-eastern part, the Piekenierskloof Formation consists of course grained sandstone, conglomerate and minor mudrock where the conglomerate layer is confined to the base of the formation (Thamm & Johnson, 2006). The sandstone is dominantly whitish in colour and can be equally being called a quartzite when fresh (Du Toit, 1954).

The Graafwater Formation follows concordant on the Piekenierskloof formation and represents the area between Graafwater and Piekenierskloof but thins out toward the east and the south (Visser, 1989) and does not extend eastwards beyond 21°E (Thamm & Johnson, 2006). The base of the Graafwater Formation consists of purple shale with quartzite and clay pebble conglomerate which is then followed by reddish and white, fine-grained sandstone and quartzite with reddish siltstone, shale and clay pebble conglomerate (Visser, 1989). Trace fossils (Thamm & Johnson, 2006), wave ripple and cross bedding are common sedimentary features within the Graafwater formation (Visser, 1989).

<p>| Table 17: Lithostratigraphy of the TMG. Figures in brackets are the approximate maximum thicknesses in metres (Thamm &amp; Johnson, 2006). |</p>
<table>
<thead>
<tr>
<th>Formation</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>West of ~21°E</td>
<td>East of 21°E</td>
<td></td>
</tr>
<tr>
<td>Nardouw Subgroup</td>
<td>Rietvlei (200)</td>
<td>Baviaanskloof (200)</td>
</tr>
<tr>
<td></td>
<td>Skurweberg (300)</td>
<td>Skurweberg (400)</td>
</tr>
<tr>
<td></td>
<td>Goudini (200)</td>
<td>Goudini (300)</td>
</tr>
<tr>
<td></td>
<td>Cedarberg (120)</td>
<td>Cedarberg (50)</td>
</tr>
<tr>
<td></td>
<td>Pakhuis (80)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peninsula (2000)</td>
<td>Peninsula (2700)</td>
</tr>
<tr>
<td></td>
<td>Graafwater (430)</td>
<td>Sardinia Bay (900?)</td>
</tr>
<tr>
<td></td>
<td>Piekenierskloof (900)</td>
<td></td>
</tr>
</tbody>
</table>
The Peninsula Formation is the most magnificent formation of the Cape Supergroup with a thickness that varies from 1800-2700 m (Visser, 1989) and comprises of quartz arenite with minor shale and conglomerate (Thamm & Johnson, 2006). Cross bedding is a characteristic sedimentary feature, indicating a source region from the northwest (Visser, 1989).

The Pakhuis Formation with an average thickness of 40 m dies off in the area of the Swartbergpas (Visser, 1989). The Pakhuis Formation consists of diamictite, pebbly sandstone and mudrock with drop stones all of which host facettted, striated, and polished clasts (Thamm & Johnson, 2006). The clasts include quartz, chert, quartzite, jasper, and hornfels (Visser, 1989). The Cedarberg Formation (Figure 103) forms a persistent negative-weathering marker and consists of dark shale at its base which coarsens upward into siltstone (Thamm & Johnson, 2006). The Cedarberg Formation is also known as the Cedarberg Shale Formation. The thickness of the formation varies from 50-120 m (Thamm & Johnson, 2006).
The Nardouw Subgroup occurs along the whole of the Cape’s folded series and attains a maximum thickness of 1200 m near Citrusdal in the western part of the basin but thins rapidly northwards (Thamm & Johnson, 2006). The Nardouw Subgroup consist of quartzitic sandstones (Thamm & Johnson, 2006) which is divided into the lower Goudini Formation, the middle Skurweberg Formation (Figure 104) and the upper, laterally equivalent Rietvlei and Baviaanskloof Formation.
Bokkeveld Group
The thickness of the Bokkeveld Group in the western and eastern parts of the basin is 2200 m and 3500 m respectively, consisting of a cyclic alternation of fine-grained sandstone and mudrock units (Thamm & Johnson, 2006). The Bokkeveld Group can be subdivided into three lithostratigraphical subgroups and is given in Table 18 (Figure 105).

The Ceres Subgroup forms the base of the Bokkeveld Group. The Ceres Subgroup thickens towards the east (Visser, 1989) and becomes progressively thinner north of the basin axis, while the sandstone units also shale out in the south and becomes difficult to distinguish from the intervening mudrock units south of 34°S (Thamm & Johnson, 2006). Three upward-coarsening cycles can be recognised within the Ceres Subgroup across the entire succession of the Bokkeveld Group consisting of mudrock, siltstone and fine- to medium-grained sandstone layers (Thamm & Johnson, 2006). The Ceres Subgroup is overlain by the Bidouw and Traka Subgroups in the western and eastern parts of the basin respectively.

The top of the Bidouw Subgroup is characterised by upward-coarsening cycles consisting of shale, micaceous siltstone and quartz arenite (Thamm & Johnson, 2006). The Bidouw Subgroup is the thickest in the west and undergoes a lateral variation to the east (Visser, 1989) and consists mainly of mudrock, siltstone and fine-grained sandstone (Thamm & Johnson, 2006).

The Traka Subgroup consists of dark rhythmites and shale, which becomes silty and lenticular-beded upwards with a thickness of up to 200 m and 300 m (Visser, 1989; Thamm & Johnson, 2006). The Adolphspoort Formation which consists mainly of wavy-beded siltstone and very fine-grained sandstone tends to weather positively compared to the underlying units (Thamm & Johnson, 2006).
Table 18: Lithostratigraphy of the Bokkeveld Group. Figures in brackets are the approximate maximum thicknesses in metres (Thamm & Johnson, 2006).

<table>
<thead>
<tr>
<th></th>
<th>West of 21°E</th>
<th>East of 21°E</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bidouw Subgroup</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Karoopoort</td>
<td>(150)</td>
<td>Sandpoort (400)</td>
<td>Mudrock, siltstone, sandstone</td>
</tr>
<tr>
<td>Osberg</td>
<td>(55)</td>
<td>Adolphspoort (600)</td>
<td>Sandstone (siltstone in east)</td>
</tr>
<tr>
<td>Klipbokkop</td>
<td>(300)</td>
<td>Karies (1300)</td>
<td>Mudrock, siltstone, sandstone</td>
</tr>
<tr>
<td>Wuppertal</td>
<td>(70)</td>
<td>Sandstone, siltstone</td>
<td>Karies Formation: Mudrock, rythmite</td>
</tr>
<tr>
<td>Waboomberg</td>
<td>(200)</td>
<td>Sandstone, siltstone</td>
<td></td>
</tr>
<tr>
<td><strong>Ceres Subgroup</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boplaas</td>
<td>(70)</td>
<td>Boplaas (100)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Tra-Tra</td>
<td>(85)</td>
<td>Tra-Tra (350)</td>
<td>Mudrock, siltstone</td>
</tr>
<tr>
<td>Hex River</td>
<td>(60)</td>
<td>Hex River (60)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Voorstehoek</td>
<td>(200)</td>
<td>Voorstehoek (300)</td>
<td>Mudrock, siltstone</td>
</tr>
<tr>
<td>Gamka</td>
<td>(70)</td>
<td>Gamka (200)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Gydo</td>
<td>(150)</td>
<td>Gydo (600)</td>
<td>Mudrock, siltstone</td>
</tr>
</tbody>
</table>
Figure 105: Representative sections (A-E) of the Bokkeveld Group. See Figure 101 for location of sections (Thamm & Johnson, 2006).

Witteberg Group

The Witteberg Group follows concordant on the Bokkeveld Group (Visser, 1989) and its overall thickness decreases from 1700 m in the east to 1200 m in the south-western part of the basin, diminishing rapidly north-wards along the western margin (Thamm & Johnson, 2006). The Witteberg Group can be subdivided into three lithostratigraphical subgroups. In ascending order they are:

- Kommadagga Subgroup
- Lake Mentz Subgroup
- Weltevrede Subgroup

Thicknesses and dominant lithologies of the various formations of the Witteberg Group are given in Table 19 and Figure 106.
The Subgroups consists of mudrock, siltstone and sandstone. Most of the Witteberg Group sandstones are quartz arenites or sub-feldspathic arenites (Shone & Booth, 2005).

Table 19: Lithostratigraphy of the Witteberg Group. Figures in brackets are the approximate maximum thicknesses in metres (Thamm & Johnson, 2006).

<table>
<thead>
<tr>
<th>West of ~22°E</th>
<th>East of ~22°E</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation</td>
<td>Formation</td>
<td>Lithology</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kommadagga</td>
<td>Dirkskraal (110)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Subgroup</td>
<td>Soutkloof (165)</td>
<td>Shale, rhytmite</td>
</tr>
<tr>
<td></td>
<td>Swartwaterpoort (6)</td>
<td>Sandstone</td>
</tr>
<tr>
<td></td>
<td>Miller (95)</td>
<td>Diamictite</td>
</tr>
<tr>
<td>Lake Mentz</td>
<td>Waaipoort (250)</td>
<td>Mudrock, sandstone</td>
</tr>
<tr>
<td>Subgroup</td>
<td>Waaipoort (460)</td>
<td>Mudrock, sandstone</td>
</tr>
<tr>
<td></td>
<td>Floriskraal (120)</td>
<td>Shale, sandstone</td>
</tr>
<tr>
<td></td>
<td>Floriskraal (120)</td>
<td>Shale, sandstone</td>
</tr>
<tr>
<td></td>
<td>Kweekvlei (200)</td>
<td>Shale</td>
</tr>
<tr>
<td></td>
<td>Kweekvlei (130)</td>
<td>Shale</td>
</tr>
<tr>
<td>Weltevrede</td>
<td>Witpoort (400)</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Subgroup</td>
<td>Witpoort (850)</td>
<td>Sandstone</td>
</tr>
<tr>
<td></td>
<td>Swartruggens (300)</td>
<td>Shale, siltstone, sandstone</td>
</tr>
<tr>
<td></td>
<td>Blinkberg (100)</td>
<td>Sandstone, siltstone</td>
</tr>
<tr>
<td></td>
<td>Wagen Drift (165)</td>
<td>Shale, siltstone, sandstone</td>
</tr>
<tr>
<td></td>
<td>Weltevrede (850)</td>
<td>Shale, siltstone, sandstone</td>
</tr>
</tbody>
</table>
Figure 106: Section of the Witteberg Group at Waaipoort, northeast of Steytlerville. See Figure 101 for locality (Thamm & Johnson, 2006).
4.6.2.2. Structural Geology

The Cape Supergroup (Cape Fold Belt) is characterised by a series of northwest-to north-trending folds in the west, stretching from Stellenbosch in the south to Vanrhynsdorp in the north, and by folds striking approximately east-west in the central and eastern areas, from Swellendam in the west to the Great Fish River mouth in the east (Figure 107 & Figure 108) (Newton et al., 2006). The two fold branches meet in a syntaxial zone (domain of complex faulting & folding) characterised by a pattern of interference structures (Shone & Booth, 2005).

![Figure 107: Map of the Cape Fold Belt showing the traces of fold axes and major fault lines (Newton et al.; 2006).](image)

![Figure 108: Folded quartzites of the Cape Supergroup due to compressional forces.](image)
According to Hälbich (1983), there were four major compressional episodes (Figure 109) (Cape Orogeny) that led to the deformation of the Cape Supergroup strata, the pre-Cape basement and some of the Karoo cover rocks, during the Permian and Triassic, followed by an episode of relaxation. During subsequent breakup of Gondwana, Cape Supergroup strata were subjected to tensional stresses resulting in complex horst, graben and half-graben structures (Shone & Booth, 2005).

The western branch of the Cape Fold Belt (CFB) is characterised by gentle, fairly open folds, whereas tighter north-verging folds occur in the southernmost parts of the southern branch, where the deformation becomes less intense and the folds more open northwards (Shone & Booth, 2005). The southern branch of the of the CFB is more often characterised by sets of closely-spaced thrusts and stacked thrust sheets with thrust planes that dips most of the times southwards, with a northward direction of thrust propagation (Shone & Booth, 2005).

Figure 109: Phase of folding and thrusting in the Cape Fold Belt (Newton et al.; 2006).
4.6.3. Geohydrology

The TMG is the main aquifer targeted within the Cape Supergroup, therefore the geohydrology of the TMG will be discussed in more detail than that of the Bokkeveld and Witteberg Group Aquifers.

4.6.3.1. Table Mountain Group

Hydrogeological Units

According to the groundwater region classification of South Africa done by Vegter (2001), there are 64 regions in South Africa of which 23 are within the TMG deposit area and 16 in its outcrop area (Figure 183, Appendix A).

The hydrogeological conditions of the TMG are far more complex than the groundwater region classification of Vegter (2001). The complexity of the hydrogeological conditions is due to the Permo-Triassic Cape Orogeny that caused deformation and low-grade metamorphism of the Cape rocks (Sohnge & Halbich, 1983), resulting in various water-bearing fold/fault systems (Xu et al., 2009). It is for this reason why Xu et al. (2009) demarcated the TMG aquifer system into distinguishable hydrogeological units (Figure 110) based on features of lithology, geomorphology and faulting, which could form a regional groundwater barrier, or a recharge or discharge boundary. The boundaries in the TMG area are summarized as follows:

I. Contacts between the TMG and the Pre-Cape basement rocks such as the Malmesbury, Kango, Gamtoos, and Kaaimans Groups; these contacts generally form the hydrogeological boundaries at the bottom of the TMG.

II. Contacts between the TMG/Bokkeveld, and TMG/Witteberg forming the boundaries at the top of the TMG, whereby the TMG is mostly confined by the argillaceous rock formations.

III. Regional faults such as the Worcester fault and Kango-Baviaanskloof fault.

IV. Basement coinciding with faults.

V. Main rivers such as the Breede, and Olifants-Doring.

VI. Primary catchments.

VII. Discharge boundaries along the coastlines.

VIII. Extent boundary in the north where the TMG dies out.
Figure 110: The TMG area divided into fifteen hydrogeological units (Xu et al., 2009).
Types of Aquifers in the TMG
In general a hydrodynamic aquifer system has three elements, namely aquifer, aquitard and hydraulically impermeable boundaries, and possesses a recharge area, a flow area and a discharge area (Xu et al., 2007).

The TMG aquifers can be regarded as a combination of lithological, tectonic and climatic features (Xu et al., 2009). The TMG aquifers are classified as secondary aquifers and are categorized into four categories (Xu et al., 2007):

I. Horizontal strata aquifer system (Figure 111).
II. Fold strata aquifer system (Figure 112 & Figure 113a).
III. Fracture zone aquifer system (Figure 113b & Figure 114).
IV. Composite aquifer system (Figure 114).

Horizontal strata aquifer systems are limited to the Cape Peninsula and the far northwest of the TMG area where the gentle-dipping TMG terrain controls both the extension of the aquifer and the topographical features that influence the aquifer's recharge (Xu et al., 2009). Perched and unconfined aquifers are the two types of aquifers occurring in the horizontal strata aquifer system as illustrated by Figure 111.

![Figure 111: An example of a horizontal strata aquifer in Table Mountain, Cape Town (Xu et al., 2007).](image1)

![Figure 112: Models of syncline aquifer system (Xu et al., 2007).](image2)
Figure 113: Lithology and structural controlled aquifers; (a) Syncline, the Baths hot spring model, (b) Fault and basement bounded outcrop model, there are not yet a conceptual model that describe this fracture block aquifer system (Xu et al., 2009).

Figure 114: A model of the TMG composite fractured rock aquifer system (Xu et al., 2007).
Fold strata aquifer systems include aquifers consisting of synclines, anticlines and monoclines and is assumed to be homogeneous and the folding is used to account for the occurrence of some thermal springs in the TMG where the aquifer strata are bounded by relatively low permeable layers of the Bokkeveld and Witteberg Groups (Xu et al., 2009). Figure 112 illustrates the four typical configurations that control the occurrence of groundwater in a fold strata aquifer system:

I. Fault-fold-lithology controlled.
II. Fold –lithology controlled.
III. Leakage.
IV. Overflow.

The composite aquifer system normally occurs on a regional scale and is a combination of the independent aquifer systems. An independent aquifer system normally occurs locally rather than regionally, as regional aquifer systems are always complex and synthetically produced (Xu et al., 2007). The composite aquifer systems of the TMG are as follows:

I. The monocline -fault aquifer system (Cape Peninsula).
II. The syncline-fault aquifer system (Montagu, Witzenberg).
III. The anticline-fault aquifer system (Vermaaks River Valley).
IV. The syncline-anticline-fault (fold-fault) aquifer system (Brandvlei).

Geohydrological Characteristics
A characteristic feature of the TMG is the abundance of springs present (Meyer, 2001). Both Meyer (2001) and Kotze (2002) recognized three types of springs within the TMG which are classified as follows:

I. Type 1 – Shallow springs emanating at perched water tables.
II. Type 2 – Lithologically controlled springs, due to the presence of inter-bedded aquitards.
   a. Springs emanating from contacts with the Cedarberg Aquitard
   b. Springs emanating at the TMG/Bokkeveld contacts.
   c. Springs at unconformities
III. Type 3 – Fault Controlled Springs

Type 1 springs occur across the Peninsula and Nardouw Aquifers of the Cape Mountains and is not connected to the greater groundwater flow system of the TMG on any scale (Kotze, 2002). These are shallow circulating springs, seeping from various small fracture systems and bedding planes within the TMG aquifers, directly above localised aquitards.
(Meyer, 2001; Kotze, 2002). They are very evident during and shortly following rainy periods and are responsible for the myriad of springs in the TMG, often referred to as seeps (Kotze, 2002). They are however highly seasonal and cease to exist with the onset of the dry weather conditions (Meyer, 2001).

Type 2 springs is relatively shallow circulating springs (Meyer, 2001), and originate at the contact between an aquifer and aquitards (Kotze, 2002). Yields from these springs are less constant and seasonal yield fluctuations are a distinctive feature (Meyer, 2001).

Type 3 springs is generally deep circulating springs, often with large constant supply (Meyer, 2001). A characteristic feature of these springs is the elevated temperatures of groundwater, ranging from greater than 20°C to greater than 40°C, rising to the surface along fractures intercepting aquitards and aquicludes at depth (Kotze, 2002).

Rosewarne (2002) divided the TMG Aquifer into two hydrogeological domains to describe the characteristics of the TMG as each of these domains possesses its own characteristics. The domains are as follows:

I. Intermontane Domain.
II. Coastal Domain.

The Intermontane Domain covers all of the inland outcrop and sub-outcrop area. The Coastal Domain (plain) is mainly developed along the Southern Cape Coast between Cape Hangklip and Mossel Bay and from Oyster Bay to Port Elizabeth and comprises a wave-cut platform, bounded inland by foothills of coastal mountain ranges of differing geological formations.

The characteristics of the Intermontane Domain are as follows (Rosewarne, 2002a):

I. Deep groundwater circulation.
II. Enhanced groundwater potential in adjacent formations.
III. High direct recharge from both rain and snowmelt.
IV. There are visible targets for borehole siting.
V. Occurrence of hot springs.
VI. Artesian boreholes are common.
VII. Associated alluvial deposits are important for direct groundwater supply and indirect recharge.
VIII. Associated groundwater has very low electrical conductivity (EC) and is corrosive.

The characteristics of the Coastal Domain are as follows (Rosewarne, 2002a):
I. Comprises a wave-cut platform.
II. There is usually a covering of Quaternary sands and calcrete.
III. Shallower groundwater occurrence.
IV. Lack of visible targets for borehole siting.
V. Possibility of seawater intrusion.
VI. Moderate to poor groundwater quality.
VII. Indirect recharge.
VIII. Associated with cold springs.

From a groundwater quality point of view, the groundwater from TMG are generally of good quality with EC values ranging between 10 and 100 mS/m, Fe concentrations can be high (Parsons, 2011b; Meyer, 1999; Meyer, 1998). Rosewarne (2002b) states that this high Fe concentration appears to be a characteristic feature of the Nardouw Subgroup, especially when juxtaposed to shale of either the Cedarberg Formation or Bokkeveld Group. Thus once a borehole is functional, the action of Fe bacteria can set in under certain circumstances resulting in the plugging of screen pores and perforated slotting, and may even retard fracture permeability leading to a decrease in borehole productivity (Meyer, 1999; Meyer, 1998).

**Borehole Yields**
The main groundwater intersections within the TMG Aquifer are commonly at depths of greater than 100 m bgl (Rosewarne, 2002a). Borehole yields generally increase with depth (Figure 115) (Kotze, 2002; Rosewarne, 2002a), but this characteristic feature goes against conventional structural geological theory that joint/fracture openings will close-up with increasing depth due to the pressure of the overlying rock mass.

![Figure 115: Graph showing that there is an increase in borehole yield with increasing borehole depth. Grabouw-Villiersdorp area (Rosewarne, 2002a).](image-url)
4.6.3.2. Bokkeveld Group

Geohydrological Characteristics

The Bokkeveld Group is classified as a secondary aquifer system. According to Meyer (2001) the arenaceous : argillaceous ratio of the Bidouw Subgroup (Upper Bokkeveld) and that of the Ceres Subgroup (Lower Bokkeveld) plays a noticeable groundwater role both quantitatively and qualitatively.

According to Weaver (2011) the sandstone layers of the Ceres Subgroup are good aquifers but with limited yield over the long term. The more argillaceous, Bidouw Subgroup is a lower yielding aquifer with bad quality water (Parsons, 2011a). The water quality of the Bokkeveld Group deteriorates (increase in EC and TDS values) as one move away from the Nardouw Subgroup of the TMG (Weaver, 2011).

The EC values of the Ceres Subgroup varies between 30 and 400 mS/m (Meyer, 2001; Meyer, 1999) but in the Steytlerville area and the area west of Port Alfred it commonly exceed 200 mS/m (Meyer, 1998). The EC values of the Traka/Bidouw Subgroup are generally well in excess of 400 mS/m (Meyer, 2001; Meyer, 1999). Sodium, magnesium, chloride, sulphate often exceeds maximum recommended limits, and may even exceed maximum allowable limits within the Ceres Subgroup but generally exceed maximum allowable limits within the Traka/Bidouw Subgroups (Meyer, 2001; Meyer, 1999; Meyer, 1988).

The Bokkeveld aquifer is characterised by enhanced recharge, as groundwater flow along cross-cutting structures from the TMG into the Bokkeveld aquifer, originating from the high rainfall occurring in the Mountains of the TMG (Rosewarne, 2002a; Parsons, 2011b).

Borehole yields

The Bokkeveld Group are generally a low yielding aquifer with bad quality water if compared with that of the TMG (Parsons, 2011b). Yields of up to 5 l/s are not that uncommon in the Ceres Subgroup but the sustainability of these boreholes is generally less than 5 l/s (Meyer, 1998; 1999). These higher yields are only common in areas where the recharge conditions are favourable (Meyer, 2001). Yields rarely exceed 5 l/s within the Traka/Bidouw Subgroups with the majority of yields less than 1 l/s (Meyer, 1998; 1999).
4.6.3.3. Witteberg Group

Geohydrological Characteristics
The Witteberg Group can also be classified as a secondary aquifer system. Very little is known about the geohydrological characteristics of the Witteberg Group.

The shale components of the Witteberg Group is associated with bad quality groundwater with EC values that ranges between 200 and 700 mS/m, where the EC values of the groundwater within the Sandstone units generally ranges between 70 and 150 mS/m (Meyer, 1998; 1999; 2001). Sodium, chlorite and total alkalinity may occasionally exceed maximum recommended limits within the sandstone units and often exceed the maximum allowable limits within the shale components (Meyer, 1998; 1999; 2001).

Positioning of boreholes on fractures in the sandstone unites close to shale units often pose the danger of poor quality groundwater being drawn in from the shale units (Meyer, 1998; 2001).

Borehole Yields
Borehole yields within the Witteberg Group are generally less and equal to 0.5 l/s. The shale layers rarely exceed 2 l/s but the yield potential of the sandstone components are noticeably better, especially the Witpoort Formation where yields higher than 2 l/s up to 5 l/s are common (Meyer, 1998; 1999; 2001). According to Weaver (2011) the groundwater potential of the Witteberg Group is not entirely known and suggests that more research need to be done on the geohydrology of the Witteberg Group.

4.6.4. Locating Groundwater Resources

4.6.4.1. Target Formations and Geological Features
The TMG is the main drilling target for locating groundwater resources within the Cape Supergroup Region due to its large extend, strong yielding springs and boreholes, and good quality water. The Bokkeveld and Witteberg Groups are less targeted by geohydrologist and according to Parsons (2011) the Bokkeveld Group should generally be avoided, but there are exceptions. Due to the mountainous terrain of the Cape Supergroup, large areas are thus inaccessible for drilling rigs; therefore groundwater development is generally limited to the foothills of mountains (Meyer, 2001).

The target formations within the Cape Supergroup are (Rosewarne & Weaver, 2002):

I. Piekenierskloof Formation.
II. Peninsula Formation.
III. Nardouw Formation.
IV. Lower Bokkeveld Formation (Ceres Subgroup)

Specific target features within the various formations include the following (Rosewarne & Weaver, 2002; Smart, 2011; Weaver, 2011; Wellman, 2011; Parsons, 2011b):

I. Major regional fault systems.
II. More localised fractures/faults associated with folding and other local stress fields (Figure 116).
III. Bedding planes (Figure 117) or contact zones.

These structures are very heterogeneous and for this reason the fracture systems should be studied in detail. Fractures can be classified into five types according to the hydrogeological function as follows (Figure 114) (Sheng et al., 1985):

I. Tensile fracture – the permeability of this fault is larger than the hanging wall and footwall.
II. Conduit fracture – connects different aquifers.
III. Impermeable fracture – the permeability of the fault is much smaller than that of the hanging wall and footwall.
IV. Storage fracture – defined as a closed storage space in a fault zone.
V. Water-scarce fracture – a fault where no water-runs and where there is no storage space with a very low permeability.

The following features are also illustrated by Figure 114 (Xu et al., 2007):

I. Fractures are divided into open, closed and infilled fractures.
II. Fracture density is related to the thickness of the layer of lithology.
III. Conduits, storage as well as exclusion of groundwater can be present in a fracture.
IV. There are weathered and tectonic fractured rock aquifer systems.
V. Hydraulically connected aquifers occur in different aquifers by conduit fractures.
VI. In a fracture zone aquifer system, groundwater can be obtained at another side of the mountain and the opposite bank of the river as well.
VII. Cool water occurs in local flow, but thermal water can occur in regional flow, which may flow along the TMG buried by thick younger formations in basin area.

In the Tsitsikamma and Plettenberg Bay areas, the contact between the Cedarberg shale and the Peninsula formation, which is normally declined, normally results in good yielding boreholes when drilled (Wellman, 2011).
When targeting the Nardouw Subgroup, Weaver (2011) advises that one should target the high silica zone, which is situated within the central core of the Nardouw Subgroup as the outer, less silica-rich parts seems to seals up immediately where it deformed.

According to Smart (2011) it is advisable that one should target the damaged zones just away from a fault as these areas seems to result in good yielding boreholes, especially when the fault itself is impermeable.

The preferred geophysical methods used to detect these features are:

I. Electromagnetics

II. Resistivity

Aerial photographs and geological maps are the main techniques used to detect the geological structures within the rocks of the Cape Supergroup. The electromagnetic and resistivity methods are generally applied for conformation. The results of the electromagnetic method can be doubted, unless there is a definite trend. Use experienced geophysicists when applying resistivity (Parsons, 2011).

Figure 116: Fractured nature of folded quartzites of the Cape Supergroup.
4.6.4.2. Case Studies

Arabella Country Estate

Parsons (2002) started a groundwater exploration programme, to develop a sustainable groundwater supply for the Arabella Country Estate, situated 100 km of east of Cape Town and some 15 km east of the town of Kleinmond.

The Estate straddles the western fault of a typical horst and graben structure that resulted in development of the north-south trending Bot River Valley. The fault extends some 40 km north-eastwards and is the same structure targeted by Weaver (2002) in 1988. The position of the fault was readily determined by aerial photographs and resistivity profiling (Wenner & Schlumberger Arrays).

The upthrown north-western part of the fault, consisting of quartzites and sandstones of the Nardouw Subgroup (TMG), was targeted for drilling, as the downthrown south-eastern part of the fault contains poor quality groundwater of the Bokkeveld Group. In March 1997 two exploration boreholes were drilled north-west of the fault (LL-BH1 & LL-BH2) and in February 1998 two production boreholes were drilled adjacent to the fault (LL-BH3 & LL-
BH4) and in December 1999 a third production well was drilled about 600 m west of LL-BH1 (LL-BH5). The data of the boreholes drilled at the Estate are given in Table 20.

After a few years of pumping, samples taken in 2000 (late winter) indicated a dramatic increase in iron concentration accompanied by a decrease in pH, and an increase in EC and sulphate levels. Iron and sulphate concentration is highest after the winter recharge period and decreases with summer abstractions. According to Parsons (2002) it appears that oxidation of pyrite results in acid rock drainage (ARD) when oxygen is introduced into the subsurface during by lowering the piezometric surface during summer abstraction.

Parsons (2002) recommended that all abstraction rates for the production boreholes should be reduced to 6 l/s. The pumps are switched off during the winter raining season and abstraction only occurs in the summer months.

Table 20: Data from the five boreholes drilled at Arabella Country Estate (Parsons, 2002).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LL-BH1</th>
<th>LL-BH2</th>
<th>LL-BH3</th>
<th>LL-BH4</th>
<th>LL-BH5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Observation</td>
<td>Standby</td>
<td>Production</td>
<td>Production</td>
<td>Production</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>56</td>
<td>82</td>
<td>95</td>
<td>103</td>
<td>142</td>
</tr>
<tr>
<td>Blow Yield (l/s)</td>
<td>3.7</td>
<td>11</td>
<td>+25</td>
<td>+25</td>
<td>10</td>
</tr>
<tr>
<td>Static Water Level (mbc)</td>
<td>0.3</td>
<td>Artesian</td>
<td>4.13</td>
<td>Artesian</td>
<td>?</td>
</tr>
<tr>
<td>EC (mS/m)</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>Fe (mg/l)</td>
<td>8.7</td>
<td>8.9</td>
<td>10.9</td>
<td>15.5</td>
<td>12.7</td>
</tr>
<tr>
<td>pH</td>
<td>5.7</td>
<td>6.1</td>
<td>6.5</td>
<td>6</td>
<td>6.3</td>
</tr>
<tr>
<td>Recommended Rate – Individual (l/s)</td>
<td>3.8</td>
<td>7.5</td>
<td>22.5</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Recommended Rate – Simultaneous (l/s)</td>
<td></td>
<td></td>
<td>14.5</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Pumping Rate (l/s)</td>
<td>2.1</td>
<td>9</td>
<td>11</td>
<td>8.4</td>
<td></td>
</tr>
</tbody>
</table>
Botrivier Water-Supply
The well field established at Botrivier, for water-supply, by Weaver (2002) in the late 1980’s also target the same fault as that targeted by Parsons (2002). Pumping rates of the Boreholes established vary from 1.8 to 6 l/s for 24 h/d.

Weaver (2002) learned two important aspects that made the project slightly different:

I. The thick saturated overburden of sand and weathered TMG overlying the fractured quartzites of the Nardouw Subgroup, provide leaky aquifer conditions and a large storage, which is accessible to fractures. This geological setting, if present, can be classed as a prime target for drilling, so as to obtain a sustainable yield.

II. Daily and annual recharge to the wellfield. The wellfield is fed by the aquifer underlying the large area of the mountain lying to the west of Botriver consisting of Nardouw Subgroup quartzites with a large amount of water in storage, plus an annual recharge, which makes this an aquifer that will be difficult to deplete.

Hex River Valley
An area where the Bokkeveld Group is mainly targeted for groundwater abstraction is the Hex River Valley. The Hex River Valley has developed along a synclinal fold axis, developed in rocks of the TMG and Bokkeveld Group (Rosewarne, 2002b).

The valley floor is covered with a thick layer of alluvial deposits, about 60 m in thickness (Rosewarne, 2002b). The following summary of the geohydrological features of the Hex River Valley is obtained from a case study done by Rosewarne (2002b):

I. Most of the production boreholes derive groundwater from the Bokkeveld Group rocks, although the main source of recharge is rainfall on the TMG rocks of the Hex River Mountains, during the winter rainfall months.

II. Alluvium derived from the TMG is an important reservoir for groundwater storage and of the order of 5 Mm³/a of this groundwater leaks into the underlying TMG/Bokkeveld Aquifer during the pumping season.

III. There is a tong-shaped intrusion of brackish groundwater (EC>80 mS/m) originating from the Bokkeveld rocks in the east and extending as far as Orchard. Best quality water originates from the TMG Aquifer, where EC values are less than 10 mS/m.

IV. According to borehole water level records, it appears that boreholes on the northern flanks of the Valley fully recover, while those in the central and southern areas do not and show continual decline in response to below average rainfall.
4.7. The Natal Group (470 – 500 Ma)

4.7.1. Location and Extend

The Natal Group is situated in Kwazulu-Natal, where the depositional basin of the group extends from Hlabisa in the north to just north of Port Shepstone in the south (Figure 118). The western margin of the basin is approximately parallel to the Kwazulu-Natal coastline in the east. North of Durban, the Natal Group forms two sub-parallel belts that are separated by basement rocks. The general attitude of the western belt is horizontal and that of the eastern belt gently dips towards the east (Marshall, 2006).

Figure 118: Distribution of the Natal Group and areal extent of the various members (Marshall, 2006).
4.7.2. Geology

4.7.2.1. Lithostratigraphy

Extensive work on the lithostratigraphy of the Natal Group was done by Marshall (2002). Thus the lithostratigraphy discussed within this thesis is mainly from the work done by Marshall (2002) unless otherwise stated. The Natal Group is subdivided into two formations (Table 21):

- Marianhill Formation
- Durban Formation


<table>
<thead>
<tr>
<th>Formation</th>
<th>Member</th>
<th>Dominant Lithology</th>
<th>Maximum Thickness (m)</th>
<th>Mean Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marianhill</td>
<td>Westville</td>
<td>Matrix-supported conglomerate</td>
<td>30</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>Arkosic sandstone</td>
<td>&gt;368</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Tulini</td>
<td>Small-pebble conglomerate</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td>Durban</td>
<td>Dassenhoek</td>
<td>Silicified quartz arenite</td>
<td>422</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Situndu</td>
<td>Coarse arkosic sandstone</td>
<td>84</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Melmoth</td>
<td>Medium-coarse arkosic sandstone and shale</td>
<td>168</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Kranskloof</td>
<td>Silicified quartz arenite</td>
<td>51</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Eshowe</td>
<td>Arkosic sandstone and shale</td>
<td>142</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Ulundi</td>
<td>Coarse clast-supported conglomerate</td>
<td>59</td>
<td>18</td>
</tr>
</tbody>
</table>

**Durban Formation**

The Durban Formation forms the lower most unit of the Natal Group, subdivided into six members (Table 21). The upper part of the Formation consists of more resistant lithologies and is consequently more prominent than the younger Marianhill Formation.
The Ulundi Member forms the basal unit of the Durban Formation and is limited to the northern and north-western portions of the basin with minor occurrences in the southwest. The Member rests unconformably on Precambrian basement rocks and is generally overlain by rocks of the Eshowe or Melmoth Members, except in certain localities near the western margin of the basin where it is overlain by rocks of the Dwyka Group. The Ulundi Member consists of greyish-red, generally matrix poor clast supported, boulder to pebble conglomerates with minor lenticular beds of sandstone and shale.

The Eshowe and Situndu Members have very similar lithologies, making it very difficult for mapping them separately. Where these two members merge with its other in the north-eastern part of the basin it becomes the Melmoth Member. These three members consist of interbedded sub-arkosic to arkosic sandstone, quartz arenite, siltstone, shale and conglomerate. The sandstones constitute the largest part of the succession and are coarse- to very coarse-grained, immature and poorly sorted. The colour ranges from greyish red to dusky red, where the finer-grained rocks are darker in colour. A common feature of the Eshowe Member is erosion channels that are 15 to 30 cm deep and 1 to 2 m wide which have been filled with very coarse sand and rip-up clasts of shale, or with sandstone.

The Eshowe and Situndu Members are the most widely distributed units of the Natal Group and lies unconformably on Precambrian basement rocks, where the Ulundi Member is not present.

The Kranskloof Formation overlies the Eshowe Member conformably and is located just south of the Mhlatuze River. The member is fairly resistant to weathering, forming magnificent cliffs. Consist mainly of silicified greyish red to pale red sandstone (quartz arenites) with subordinate interbedded shales and siltstone and is conformably overlain by the Situndu Member. The sandstones are massive with planar stratification being the most common sedimentary structure. The thickness of this member varies extremely from 1.5 to 51 m. A fairly common characteristic of the Kranskloof Member is the presence of vertical to near-vertical clefts (large cracks; 1-5 m wide & 40-100 m long) that formed by the weathering of a fracturing or weathered dolerite dykes.

The Dassenhoek Member forms the uppermost unit of the Natal Group, resembling the Kranskloof member in colour, composition, sedimentary structures and outcrop appearance. The thickness varies from 3 to 42 m with an overall average of 11.5 m and is conformably overlain by the Tulini Member and where absent by the Newspaper Member.
Marianhill Formation

The Marianhill Formation occurs throughout the basin and is subdivided into three members (Table 21). The Tulini Member forms the basal unit of the Marianhill Formation and occurs over most of the central northern portion of the basin. In the north it overlies the Melmoth Member and southwards it progressively oversteps onto the Kranskloof, Situndu and Dassenhoek Members. The thickness of this member varies between 0.9 and 27.5 m. Two distinct facies, southern (Facies A) and northern (Facies B) can be identified (Marshall, 2006):

- **Facies A**: Consists of vein quartz, clast-supported to matrix supported small pebble conglomerate with interbedded coarse-to very coarse-grained sandstone and granule conglomerate.

- **Facies B**: Consists of matrix supported conglomerate consisting of clasts that are larger and less well rounded than those of Facies A. Clasts are from different lithologies (polymict).

The Newspaper Member that conformably overlies the Tuluni Member forms the major portion of the Marianhill Formation. This member consists of greyish red to pale cream, medium- to very coarse-grained sandstone, granule conglomerate and interbedded shale and siltstone. These rocks are not very resistant to weathering and almost completely removed and only present from Hlabisa in the north to Hibberdene in the south. The Newspaper Member is characterised by calcite concretions and south of Durban it is distinguished from the Durban Formation by the presence of soft-sediment deformation.

The Westville Member conformably overlies the Newspaper Member and is disconformably overlain by the Dwyka Group of the Karoo Supergroup and occurs very intermittently throughout the basin. The Westville Member consists of matrix supported polymict conglomerate (Marshall, 2006). Slumping structures are very common.

**4.7.3. Geohydrology**

**Geohydrological Characteristics of the Natal Group**

Groundwater in the Natal Group has been exploited on a very limited basis when compared to the drier parts of South Africa (Bell & Maud, 2000), thus resulting in limited information about the characteristics of the Natal Group sediments.

The Natal Group sediments represent a typical secondary or fractured rock aquifer with negligible primary porosity and permeability (Geomeasure Group, 2007; KV3 Engineers, 2009) however it seems to a far better aquifer system than the surrounding lithologies with
measured hydraulic conductivities ranging between 0.4 to 7.7 m/day (King 2002; 2003). The sustainability of the aquifers within the Natal Group is mainly a factor of rainfall recharge and aquifer through flow (KV3 Engineers, 2009).

The groundwater quality of the Natal Group is generally good with EC values generally less than 100 mS/m (King 2002; 2003). According to Bell and Maud (2002) the groundwater EC values of the Natal Group within the coastal zone (Durban Area) ranges between 23 and 185 mS/m where in the inland area it rarely exceeds 45 mS/m (if not polluted). The groundwater is often slightly acidic and occasionally contains high levels of iron and manganese (King 2002; 2003; KV3 Engineers, 2009).

**Borehole Yields**

The sandstones of the Natal Group are a moderate to low yielding aquifer system. Various authors (Bell & Maud, 2000; King, 2002; 2003) reported median yields ranging between 0.1 and 2 l/s, but yields of up to 10 l/s can be obtained if ideal conditions for high yielding boreholes exist and intersected during drilling (KV3 Engineers, 2009).

The probability of drilling a successful borehole within the sandstones of the Natal Group ranges between 60 to 90 % (King, 2002; 2003; Schapers, 2011).

4.7.4. Locating Groundwater Resources

4.7.4.1. Target Formations and Geological Features

The sandstones and quartzites of the Natal Group exhibits a high quartz content (King, 2003), thus it will behave in a brittle manner (brittle deformation) when deformed. Adjacent to faults and dolerite intrusions, brittle deformation of the sandstones, forms local zones of intense fracturing which enhances the recharge and permeability and offer preferential groundwater flow paths (Bell & Maud, 2000; Geomeasure Group, 2007; KV3 Engineers, 2009). These zones of intense fracturing is thus ideal zones for targeting groundwater resources as groundwater movement within the Natal Group mainly occurs within joints, fractures or bedding planes (KV3 Engineers, 2009). Thus targeting features within the Natal Group are:

I. Major fault systems
II. Dolerite dyke intrusions
III. Bedding planes or contact zones

Fault zones are important high yielding features, but care should be taken when targeting this feature as it may be silicified (King, 2003), decreasing the change of intercepting a high
yielding aquifer system. If the ideal conditions within these fracture zones adjacent to faults and dolerite intrusions exist, then yields of up to 10 l/s could be obtained.

The preferred geophysical methods used to detect these features are:

I. Magnetics
II. Electromagnetics
III. Resistivity

The magnetic and electromagnetic methods are generally used in conjunction in detecting dolerite dykes and zones of fracturing. Resistivity can also be used to detect zones of fracturing (fault zones), but is expensive and time consuming. According to Schapers (2011) the magnetic anomalies within the sandstones of the Natal Group are not very prominent, but this is not always the case.

4.8. The Malmesbury Group (650 – 770 Ma)

4.8.1. Location and Extend

The Malmesbury Group is situated in the Western Cape Province forming part of the Saldania Belt that is subdivided into three tectonostratigraphic terranes (Figure 119). The Malmesbury Group extends from Redelinghuys southwards to just south of Stellenbosch. The succession is related to the opening of oceanic basins following the break-up of a Mesoproterozoic supercontinent and subsequent Pan-African orogenesis (Gresse et al., 2006).
4.8.2. Geology

4.8.2.1. Lithostratigraphy
The Tygerberg, Swartland and Boland Terranes are separated from each other by prominent northwest-trending fault and shear zones (Figure 119), and the stratigraphic and tectonic link between them are poorly understood (Gresse et al., 2006). The Malmesbury Group is intruded by syn- to post- and anorogenic granitoids of the Cape Granite Suite (Rozendaal et al., 1999).

Tygerberg Terrane
The Tygerberg Terrane is bounded by the Colenso Fault in the north-east and the coast line in the south-west (Figure 119). The Tygerberg Formation is the only component recognised within the Tygerberg Terrane. The formation is characterised by rhythmic alternations of greywacke, phyllitic shales and siltstone, immature quartzite and conglomerate beds. These rocks display sedimentary structures such as cross-bedding, ripples, ripple cross-lamination, grading, slumping and channelling. The locally developed volcanic succession,
Bloubergstrand Member, composed of tuff, agglomerate and altered amygdaloidal, calc-alkaline andesite (Rozendaal et al., 1999).

**Swartland Terrane**

The Swartland Terrane is bounded by the Boland and Tygerberg Terranes in the north-east and south-west respectively (Figure 119). The Malmesbury Group within the Swartland Terrane is subdivided into the following subgroups and formations:

- Franchhoek Formation
- Bridgetown Formation
- Swartland Subgroup

The Swartland Subgroup is exposed in the gently plunging, northwest-elongated Swartland and Spitskop Domes (Figure 119) and is composed of the Berg River, Klipplaat and Moorreesburg Formations. These formations are tectonostratigraphic units with deformed lower and upper contacts. The Swartland Subgroup consists of chlorite and quartz schists, greywacke, with interbeds of phyllite and limestones (Rozendaal et al., 1999).

There are areas where the Franchhoek Formation unconformably overlies the Swartland Subgroup. The formation consists of feldspathic conglomerate and quartzite, grit, slate and phyllite. These rocks are intruded by quartz porphyry dykes and sills relate to the last phase of the Cape Granite Suite magmatism (Rozendaal et al., 1999).

The Bridgetown Formation is a metavolcanic succession which follows the Swartland – Boland Terrane boundary. It consists of a complex of greenstone bodies, intrusive dykes, dolomite, chert and graphitic schists (Rozendaal et al., 1999).

**Boland Terrane**

The Piketberg Formation, which is the lowermost formation of the Boland Subgroup, consists of foliated and lineated quartzites, greywackes, schist, BIF, grit, conglomerate and some impure marly limestones. These lithologies interfingers with lower limestone, chert and quartzite of the Porterville Formations, which is dominated by phyllitic shales and greywacke. There are areas where the base of the Porterville Formation consists of altered pillow lavas and volcaniclastics together with conglomerate. The Brandwacht Formation consists of greywacke and pelite with interbedded lenses of poorly sorted conglomerates and metavolcanic rocks (Rozendaal et al., 1999).
4.8.3. Geohydrology

Geohydrological Characteristics

The Malmesbury Group can be classified as a fractured aquifer system. The aquifers tend to be confined to semi-confined (Colvin & Saayman, 2007), thus the vulnerability of anthropogenic impacts are somewhat limited.

The groundwater quality of the Malmesbury Group varies considerably, which is probably due to the variable lithologies and recharges conditions. The better quality groundwater is generally associated with areas where groundwater movement takes place. According to Weaver (2011) the Malmesbury Group rocks closer to the coast have the tendency to be more saline than those further inland. EC values ranges between 10 and 1 000 mS/m where sodium, magnesium, chloride and sulphate occasionally exceed the maximum
recommended and even maximum allowable limits, especially in the argillaceous rock units (Meyer, 2001).

**Borehole Yields**
The Malmesbury Group can be regarded as a low yielding aquifer system, but high yielding boreholes are obtainable. The borehole yield analysis of Meyer (2001) indicates that the majority of boreholes have yields less than 2 l/s with 32 % yielding less than 0.5 l/s. Reported yields of up to 12 l/s have been encountered (Colvin & Saayman, 2007).

Groundwater levels are variable, but are generally in the range of 5 to 30 mbgl, with deeper levels associated with elevated topography (Parsons & Associates, 2002; Parsons, 2011b).

**4.8.4. Locating Groundwater Resources**

**4.8.4.1. Target Formations and Geological Features**
Locating groundwater resources within the Malmesbury Group can often be problematic due to its poor exposure, the largely argillaceous and thus incompetent nature of many of the lithological units and overall structural complexities (Meyer, 2001). Thus targeting the arenaceous units would probably result in better yielding aquifer system.

Specific target features within the various formations of the Malmesbury Group include the following (Meyer, 2001; Weaver 2011; Parsons 2011a):

I. Major regional fault zones and their associated fracture zones.
II. Contact zone with Cape Granite Suite intrusions (if favourable groundwater conditions exist).
III. Areas where arenaceous units are overlain by alluvium.

The TMG aquifer system is a far better aquifer system than that of the Malmesbury Group and thus less targeted by geohydrologist. According to Parsons (2011a) the Malmesbury Group is only targeted if no other more favourable aquifer is present. A general rule of thumb, suggested by Weaver (2011), is to target areas close to the recharge zone (quartzite mountains).

Groundwater recharge to the fractured arenaceous units is occurring through alluvium in the Breede River Valley near Wolseley. Within this same area the average borehole yields of the areas overlain by alluvium are considerably higher than those where the alluvium is absent (Meyer, 2001).

The preferred geophysical methods used to detect these features are:
I. Electromagnetics
II. Resistivity

These methods according to Parsons (2011) are not very reliable within the rocks of the Malmesbury Group (hit/miss affair).

4.9. The Namaqua-Natal Metamorphic Province (1 000 – 2 050 Ma)

4.9.1. Location and Extend

The Namaqua-Natal Metamorphic Province (NNMP) occurs along the southern and south western margin of the Kaapvaal Craton and is bounded in the west and south by the Gariep and Saldania Belts respectively (Figure 121). The NNMP outcrops in the Northern Cape (Namaqua Sector or Namaqua Mobile Belt) and Kwazulu-Natal (Natal Sector or Natal Metamorphic Belt) Provinces. The igneous and metamorphic rocks of the NNMP formed during the Namaqua Orogeny that occurred approximately 1200 to 1000 Ma ago (Cornell et al., 2006).

Figure 121: Geological setting of the Namaqua-Natal Metamorphic Province (Cornell et al., 2006).
4.9.2. Geology

The NNMP is subdivided into different tectonostratigraphic subprovinces and terranes, based on marked changes in lithostratigraphy across structural discontinuities (Cornell et al., 2006). The general geology of the Namaqua and Natal Sectors will be discussed separately.

4.9.2.1. Lithostratigraphy of the Namaqua Sector

The Namaqua Sector of the NNMP can be subdivided into tectonostratigraphic subprovinces and terranes. Various authors (Joubert, 1986; Thomas et al., 1994; Praekelt et al., 1997) suggested different subdivisions for the Namaqua Sector of the NNMP. These are illustrated from Figure 122 to Figure 124. For the purpose of this thesis the subdivision of Thomas et al. (1994) was used.

Figure 122: Map of tectonic subprovinces and terranes of the Namaqua Sector of the NNMP (Joubert, 1986).
Figure 123: Tectonostratigraphic terranes of the Namaqua Sector of the NNMP (Praekelt et al., 1997).

Figure 124: Tectonic subdivision of the Namaqua Sector of the NNMP (Cornell et al., 2006). 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.
**Richtersveld Subprovince**

The Richtersveld Subprovince is bounded by thrusts or sub-vertical shear zones and contains some of the oldest supracrustal rocks in the NNMP. The subprovince is made up of a volcano-sedimentary sequence known as the Orange River Group consisting of rhyolites and andesites, and an intrusive suite known as the Vioolsdrift Suite consisting of gabbro complexes or plutons (Onstott *et al.*, 1986). Deformation caused displacement along the stratigraphic contacts even before the intrusion of the Vioolsdrift Suite that on its own further disrupted the stratigraphic relationships (Cornell *et al.*, 2006). According to Onstott *et al.* (1986) the Richtersveld Subprovince was intruded by three generations of dyke swarms:

I. Aplite and pegmatite dykes of the Namaqualand **Pegmatite Swarm** which occur as irregular veins, dykes and sheets.

II. Felsic dykes of the **Richtersveld Dyke Swarm**.

III. Basic Dykes of the **Ganakouriep Dyke Swarm**.

**Bushmanland Terrane**

The Bushmanland Terrane is bounded by the Groothoek Thrust in the north and the Hartbees River Thrust in the east (Figure 124). The terrane consists of rocks of three distinct age groups, a basement complex consisting of granitic rocks, a variety of supracrustal sequences of mixed sedimentary and volcanic origin, and intrusive rocks that are granitic to charnockitic in composition (Cornell *et al.*, 2006). In the south the rocks of the Bushmanland Terrane is overlain by rocks of the Karoo Supergroup and Vanrhynsdorp Group.

The basement complex, also known as the Kheisian basement, occurs along the northern margin, adjacent to the Richtersveld Subprovince. These rocks include the Gladkop Suite (Steinkopf area) and the Achab Gneiss (Pofadder area). Both these gneisses contain xenoliths of amphibolite, calc-silicate rock and quartzite, interpreted as remnants of an older supracrustal sequence (Cornell *et al.*, 2006). The Gladkop Suite was intruded by the Brandewynsbank Gneiss, which is, in turn, intruded by the Noenoemaasberg Gneiss.

The supracrustal rocks of the Bushmanland Terrane occur in several discontinuous east-west-trending belts within the terrane, with an increasing abundance towards the south. The supracrustal belts are dominated by leucocratic and biotite-bearing quartzofeldspathic gneiss (Cornell *et al.*, 2006). The Bushmanland Terrane is subdivided into the Bushmanland Group comprising of the Aggeneys Subgroup which forms part of the Aggeneys Terrane of Colliston, Praekelt and Schoch (1989). Praekelt, Schoch and Visser (1997) provided detail descriptions of all the formations of the Aggeneys Subgroup (Figure 125).
The central and north-eastern part of the Bushmanland Terrane are characterised by voluminous concordant bodies of red-weathering quartzofeldspathic gneisses, often referred to as pink gneiss and collectively known as Hoogoor Suite (SACS, 1980).

Figure 125: Stratigraphy of the Aggeneys Subgroup (Cornell et al., 2006).
Kakamas Terrane
The Kakamas Terrane lies to the east of the Bushmanland Terrane, bounded by the Hartbees River Trusts in the west and the Boven Rugzeer Shear Zone in the east (Figure 124). The Kakamas Terrane is characterised by northwest-trending stratigraphic units and structure (Cornell et al., 2006), and is dominated by various intrusions (Figure 126) with various degrees of deformation, along with sequences of metasedimentary rocks (Pettersson, 2008). The metasediments or supracrustal rocks are composed of marbles, calc-silicates, sandstones, schists and metapelites which are folded and intruded by undeformed granites. These rocks were subdivided into various groups and suites as illustrated in Figure 126.

Areachap Terrane
The Areachap Terrane is a north northwest trending belt bounded by the Trooilapspan and Brackbosch Shear zones in the east and the Boven Rugzeer Shear Zone in the west (Figure 124). The Areachap Terrane consists of metavolcanic rocks and immature sediments which are occasionally migmatized (Pettersson, 2008). The rocks of the Areachap Terrane are

Figure 126: Simplified geology of the Kakamas and Areachap Terranes (Cornell et al., 2006).
collectively known as the Areachap Group. The Areachap Group is subdivided into four formations and illustrated Figure 127.

![Diagram of Areachap Group lithostratigraphy and distribution.](image)

**Figure 127:** Lithostratigraphy and distribution of the Areachap Group (Cornell et al., 2006).

**The Kaaien Terrane**

The Kaaien Terrane lies to the east of the Areachap Terrane, bounded by the Dabep Thrust in the east and the Brakbosch-Trooilapspan Shear Zone system (Figure 124). The Kaaien Terrane can be subdivided into four groups that are dominated by thick sequences of quartzites (Pettersson, 2008), and minor volcanic sequences (Cornell et al., 2006). The Brulpan, Vaalkoppies and Wilgenhoutsdrif Groups are highly deformed, whereas the Koras Group is relatively undeformed and unmetamorphosed (Cornell et al., 2006). Each of these Groups consist of varies formations that are illustrated in Figure 128.
The relatively undeformed and unmetamorphosed Koras Group consists of a sequence of sedimentary and volcanic rocks and unconformably overlies the Brulpan, Wilgenhoutsdrif and Vaalkoppies Groups, as well as intrusive rocks associated with the Namaqua Orogeny. All of the Groups within the Kaaien Terrane were intruded by various pre-or syntectonic intrusions.

Figure 128: Distribution of the lithostratigraphic units of the Kaaien Terrane and adjoining Kheis Province (Cornell et al., 2006).
4.9.2.2. Lithostratigraphy of the Natal Sector

The Natal sector of the NNMP can be subdivided into three tectonostratigraphic terranes (Figure 129). The lithostratigraphy comprises of supracrustal gneisses, granitoid gneisses and younger intrusive rocks (McCourt et al., 2006) and geochemical data of these lithologies suggest an island arc tectonic setting and thus the terranes was interpreted as island arcs that accreted onto the southern margin of the Kaapvaal Craton (Grantham et al., 2012).

![Simplified geology map of the Natal Sector of the Namaqua-Natal Metamorphic Province (Cornell et al., 2006). Red box indicates location of detailed map of the Tugela Terrane (Figure 130).](image-url)
Margate Terrane
The Margate Terrane is bounded in the north by the Melville Thrust and stretches towards the south where it disappears beneath younger Phanerozoic cover sediments (Figure 129). The lithostratigraphy of the Margate Terrane is dominated by granitoid gneisses and subordinate basic gneisses with minor carbonate and pelitic supracrystalline gneisses (McCourt et al., 2006). The carbonate and pelitic supracrystaline gneisses are known as the Mzimkulu Group subdivided by the SACS (1980) into three formations:

- Mucklebraes Formation
- Marble Delta Formation
- Leisure Bay Formation

The Mzimkulu Group is intruded by calc-alkaline and tholeiitic, mafic to intermediate suites and a number of granitic sheets and plutons (Mendonidis et al., 2009; Grantham et al., 2012).

Mzumbe Terrane
The Mzumbe Terrane is bounded in the North by the Lilani-Matigulu Shear Zone and stretches southwards for approximately 150 km, where it is bounded by the Melville Thrust (Figure 129). The Mzumbe Terrane consists of layered gneisses and migmatites and fine-grained felsic gneisses, interpreted as representing a calc-alkaline sequence of volcanic/volcaniclastic rocks and their sedimentary derivatives, formed in a major island-arc complex which developed as a result of subduction of the Tugela Ocean (Jacobs et al., 1997). These rocks are collectively known as the Mapululo Group and subdivided into two formations by the SACS (1980):

- Quha Formation
- Ndonyane Formation

The rocks of the Mapululo Group were then intruded by pre-, syn- and late tectonic tonalitic gneisses and younger granite suites (McCourt, 2006). The Quha and Ndonyane Formations occur as relatively thin belts (<1 km in width), elongated parallel to the regional strike or as discontinuous septa between younger granitoid intrusions (Cornel et al., 2006; McCourt et al., 2006).

The Quha Formation consists of a series of grey gneiss and migmatites of broadly intermediate composition, with interbedded layered amphibolite, whereas the Ndonyane Formation consists of strongly foliated and streaky felsic gneisses and migmatites that seem
to be heterogeneous in appearance but uniform in mineralogy (Cornel et al., 2006; McCourt et al., 2006).

**Tugela Terrane**

The Tugela Terrane is situated between the Lilani-Matigulu Shear Zone in the south and the Tugela Front in the north (Figure 129). The terrane can be grouped into the Natal Thrust Belt and the Natal Nappe Complex (McCourt, 2006). The Natal Thrust Belt forms a narrow, 2 to 5 km wide, southerly dipping imbricate zone, subdivided into the Ntingwe and Mfongosi Groups, whereas the Natal Nappe Complex consists of four west-plunging thrust sheets (Figure 130). These thrust sheets are:

- Tugela Nappe
- Mandleni Nappe
- Madidima Nappe
- Nkomo Nappe

The Tugela Nappe is dominated by the Manyane amphibolite, comprising amphibolite, amphibole gneiss and tremolite-chlorite schist, whereas the lower part of the sequence includes felsic gneiss, and rare layers of magnetite quartzite and dolomite interfoliated with the amphibolites (Bisnath et al., 2008). The rocks of the Tugela Nappe were intruded by varies plutonic bodies which include the Kotongweni meta-tonalite, Mkondene meta-diorite, Tugela Rand Complex and the Dimane granite (Figure 130).

The Mandleni Nappe lies structurally below the Tugela Nappe (Bisnath, et al., 2008), dominated by the Dondwana gneiss unit which has both a felsic and mafic component, where the mafic component is referred to as the Wosi amphibolite (McCourt et al., 2006; Bisnath et al., 2008). The Mandleni Nappe also contains two igneous complexes which include the Sitholo (ultramafic) and Mambula (layered gabbroic) complexes (Figure 130).

The Madidima Nappe consists of a thick succession of biotite gneiss known as the Dulumbe paragneiss which then grades downwards into a heterogeneous succession of meta-sedimentary rocks known as the Gazeni meta-sedimentary sequence (Bisnath et al., 2008). These rocks were intruded by Mtungweni granitiods which are a series of sheets and dykes which commonly occur as concordant, 5-10 cm thick sills that are parallel to the foliation in the enclosing wall rocks (McCourt et al., 2006).
Figure 130: Simplified geological map of the Tugela Terrane illustrating the distribution of the thrust sheets and their associated intrusions. Modified after McCourt et al. (2006). See Figure 129 for location.

The Nkomo Nappe is the structurally the lowest unit of the Tugela Terrane, dominated by the Halambu granitoid gneiss and Khomo amphibolite units (Bisnath et al., 2008). Xenoliths of foliated amphibolite are common throughout the outcrop of the Halambu granitoid gneiss implying it has an intrusive relationship with the Khomo amphibolite (McCourt et al., 2006). The Nkomo Amphibolite is folded with feldspathic gneiss and apalitic dykes (Bisnath et al., 2008).

4.9.2.3. Structural Geology

Structural Evolution of the Namaqua Sector

According to Pettersson (2008), the structural evolution of the eastern terranes seems to be similar, with four fold phases, related to four deformation events (D1-D4). The first event (D1) is partly overprinted by the main deformational phase D2, which caused isoclinal local to regional scale north northwest trending folds. It was followed by generally northeast trending, large-scale, upright and open folds of the D3-event along with wrench-faulting near major shear zones. The last deformational event, D4, is mainly related to compression from
the southwest and affected by the geometry of the wedge-shaped Kaapvaal Craton around Prieska.

The western terranes, the Richtersveld Subprovince and the Bushmanland Terrane, display three to four major deformation phases. The first folding event is seen as isolated fold closures in the Bushmanland, whereas the second event (D2) is dominated by regional recumbent east northeast trending folds. The third deformational phase occurs as east northeast striking open folds along those of D2.

**Structural Evolution of the Natal Sector**

McCourt *et al.* (2006) interpreted the assembly of the Natal orogen to be a two accretionary event (Figure 131). The first accretionary event involved collision between the Tugela arc and the Mandleni oceanic island with the margin of the Kaapvaal Craton (Figure 131 B). Syn-to post-accretion uplift resulted in deformation of the accreted terrane by northeast-striking folds and thrusts and emplacement onto the continental margin of the Kaapvaal Craton. The emplacement of the Tugela Terrane onto the edge of the Kaapvaal Craton isolated the terrane from the magmatic events related to the second accretionary event, explaining why the granitoids of the Oribi Gorge Suite are not present in this part of the orogen.

The main fabric-forming event in the Mzumbe-Margate arc occurred during the second accretionary event (Figure 131 C) which involved juxtaposition of the Mzumbe-Margate components of the arc system with the Tugela-Kaapvaal margin; intrusion of the Equeefa Suite magmas and the Glenmore granite; crustal thickening to produce the regional deformation fabrics and metamorphic mineral assemblages in gneisses of the Mzumbe-Margate terrane; uplift and intrusion of late- to post-kinematic S-type granitoids.
4.9.3. Geohydrology

Geohydrological Characteristics of the Namaqua Sector

Groundwater within the Namaqua Sector of the NNMP occurs within three different aquifer systems (Friese et al., 2006; Pietersen et al., 2009):

- Fractured bedrock
- Weathered zone (regolith)
- Sandy or alluvial aquifers

The geometry of these aquifer systems are controlled and influenced by the underlying geology of igneous and metamorphic rocks and its deformation history of metamorphic
evolution, and the geomorphic development of the Namaqua Belt, including weathering (Pietersen et al., 2009). Despite the great variety of these metamorphic and igneous rocks, they are homogenous in two respects (Vegter, 2006):

I. Virtually no primary porosity (except alluvial aquifers).
II. Secondary porosity due to fracturing and weathering.

According the Pietersen et al. (2009) the fractured bedrock and regolith systems are generally linear systems associated with the structurally controlled valleys (Figure 132) and may be laterally extensive depending on the nature of the faults systems. Weathering processes; mechanical disintegration, chemical solution and deposition modifies the porosity/permeability of the fractures systems, implying either an increase or decrease in porosity and or permeability (Vegter, 2006). As a result of these structurally controlled valleys (Figure 132 & Figure 133), localised, shallow circulation groundwater flow systems are dominant in the near surface environment (Friese et al., 2006).

Groundwater flow within the Namaqua sector is complex as it is a function of complex topographic and hydrogeological environments with multiple flow systems (Friese et al., 2006). The natural groundwater flow can be subdivided into local, intermediate and regional flow regimes:

- *Local flow* paths are characteristic short.
- *Intermediate flow* paths are longer and deeper than local flow and can underlie several local flow regimes.
- *Regional flow regimes* theoretically extend from regional recharge areas to distant discharge areas, such as rivers or may be presented by higher salinity structurally controlled artesian springs.
Figure 132: Proposed aquifer geometry and local to intermediate flow regimes for a typical structurally controlled valley (Friese et al., 2006).

Figure 133: Structurally controlled valley in the rocks of the Namaqua sector of the NNMP. Windpump indicates that the valley have been targeted for groundwater.
According to Vegter (2006), in contrast to areas with thick sandy cover, recharge is favoured by shallow sandy soil, calcrite and exposures of fractured rocks. The reasons are twofold:

I. A thick sand-cover retains and prevents rain water from entering the underlying formations and thus allows its complete dissipation through evapotranspiration. On the other hand, once rain water has passed through a shallow cover and has entered the underlying fractured rocks, evapotranspiration loss is minimized.

II. Runoff is promoted by shallow sandy soil, calcrite and rock exposure and accumulates in low lying areas and rivers. Here the concentrated volume favours recharge provided infiltration is not inhibited by the presence of clayey soil.

Geohydrological Characteristics of the Natal Sector

Groundwater in the Natal Sector of the NNMP has been exploited on a very limited basis when compared to the drier parts of South Africa, thus resulting in limited information about the characteristics of the igneous and metamorphic rocks of the Natal Belt.

The igneous and metamorphic rocks of the Natal Belt represent an intergranular (weathered zone) and fractured rock (bedrock) aquifer system. The intergranular aquifer system consists of weathering material that has a high porosity and a low hydraulic conductivity due to their clayey nature. The thickness of this weathered zone is generally less than 25 m and is in hydraulic connectivity with the underlying fractured or solid bedrock. These aquifers are generally less yielding than the surrounding sedimentary rocks of the Natal Group and Karoo Supergroup.

The groundwater quality of the Natal Sector of the NNMP is generally good. Fluoride occasionally exceeds the maximum allowable limits within argillaceous metamorphic rock aquifers.

Borehole Yields of the Natal Sector

The Natal Sector of the NNMP is a low yielding aquifer system, with yields typically ranging between 0.1-0.4 l/s for the weathered zones, whereas the underlying fractures have yields of up to 0.5 l/s. The probability of drilling a successful borehole within the rocks of the Natal Sector is approximately 70 %.
4.9.4. Locating Groundwater Resource

4.9.4.1. Target Formations and Geological Features

Namaqua Sector

Groundwater plays a fundamental role within the Namaqua Sector of the NNMP as surface water resources are very limited. The quartzites of the Namaqua Belt are probably the best rock type to be targeted for groundwater resources quality wise (Esterhuyse, 2011), otherwise there are no specific rock formation targeted. The following geological features within the igneous and metamorphic rocks are targeted:

- Regional Fault Systems
- Weathered zones
- Ephemeral rivers and palaeo-channels
- Igneous dyke intrusions
- Contact zones between intrusions and its host rocks

According to Pietersen et al., (2009) the following analysis should be done in order to locate groundwater resources:

I. Stress field analysis
   - The understanding of the structures is important to locate best sites for drilling – usually places where fractures in the rock are open and can transmit groundwater.
   - Generally the most recent tectonic events have the most significant influence on the nature of the existing fracture network and subsequently on the regional flow characteristics.

II. Geomorphic analysis
   - The more transmissive and especially larger fault zones have been weathered and eroded more intensely to form open valley profiles.

III. Regolith analysis
   - The depth and extend of the weathered zone is important for groundwater yields in fractured hard rock aquifers.
   - The Namaqua Belt rocks are characterized by relatively thin saturated regolith, which is generally present just above the deeper groundwater levels.
   - This scenario in arid regions necessitates the drilling of deep boreholes to intercept structural features and contact zones within the unweathered bedrock.
Fault or fracture zones striking north northeast and north northwest generally represent zones where the fractures are open, especially where these structures intersect older fault systems (Pietersen et al., 2009; Potgieter, 2011), thus resulting in good yielding boreholes (not always the case). According to Potgieter (2011), it is advisable to target the eastern side of these fault zones, approximately 20 to 30 m away from the main fault (rather to far than to close).

The preferred geophysical methods used to detect these features are:

I. Resistivity
II. Magnetics

Geophysical methods plays a minor role in locating the geological structures of the Namaqua sector of the NNMP, due to the fact that these structures are generally visible on surface. If geophysics needs to be applied, resistivity is the best method in locating weathered basins and highly fractured fault zones, whereas, the magnetic method is used for detecting intrusive dykes, if they are not visible (Potgieter, 2011).

Figure 134: Typical fracture systems of the Namaqua Sector of the NNMP, Namaqualand, South Africa.
### Natal Sector

The occurrence of groundwater within the igneous and metamorphic rocks of the Natal Sector is associated with fracturing and near surface weathering processes. Thus the targeting features within the Natal Sector of the NNMP are:

- Major fault systems
- Dolerite dyke intrusions
- Weathered zone

Thrust and strike-slip faulting are the dominant faults systems within the Natal Sector, thus care should be taken when targeting these features as the associated fractures are generally closed rather than open (compressional forces dominating) (Schapers, 2011).

### 4.10. Waterberg and Soutpansberg Groups (1 700 – 2 050 Ma)

#### 4.10.1. Location and Extend

The Waterberg Group occurs in the Limpopo (Waterberg & Nylstroom Basins), Gauteng and Mpumalanga Provinces (Middelburg Basin), whereas the Soutpansberg Group only occurs within the Limpopo Province (Soutpansberg Basin) (Figure 135) and is a mountainous, wedge-shape terrain which is partially buried beneath Karoo Supergroup rocks. The Waterberg Group covers an area of approximately 20 000 km².

![Figure 135: Regional setting of the Waterberg and Soutpansberg Groups (Barker et al., 2006).](image)
4.10.2. Geology

4.10.2.1. Lithostratigraphy of the Waterberg Group

The Waterberg Group can be subdivided into three different basins (Figure 135) as follows:

- Waterberg Basin (Main Basin)
- Nylstroom Basin
- Middelburg Basin

The lithostratigraphy of the Waterberg and Nylstroom Basins is illustrated in Figure 136, Figure 138 and Table 22. From Table 22 it is clear that the same subgroups of the Waterberg Group occur within the Waterberg and Nylstroom Basins.

Figure 136: Distribution of the lithostratigraphy of the Waterberg Group in the Waterberg and Nylstroom Basins (Barker et al., 2006).

Nylstroom Subgroup

The Swaershoek Formation forms the basal unit of the Nylstroom Subgroup. It consists of reddish to brown or purple, coarse-grained sandstone with locally interbedded shale, siltstone, pebble and boulder conglomerate, and trachytic lavas (Jansen, 1982). The rocks of the Swaershoek Formation are overlain by rocks of the Alma Formation.
The middle portion of the Alma Formation consists of siltstone and mudstone (Jansen, 1982) where the rest of the succession consists of medium- to coarse-grained feldspathic sandstones. The Formation dips towards the north and is up to 3000 m thick (Visser, 1989).

Table 22: Stratigraphic subdivision of the Waterberg Group in the Waterberg and Nylstroom Basins (Barker et al., 2006).

<table>
<thead>
<tr>
<th>Subgroups</th>
<th>Main Basin (south/southwest &amp; central area)</th>
<th>Main Basin (north/northeast &amp; central area)</th>
<th>Nylstroom Basin</th>
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</thead>
<tbody>
<tr>
<td><strong>Waterberg Group</strong></td>
<td></td>
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<tr>
<td>Kransberg</td>
<td>Vaalwater (≤475 m)</td>
<td>Vaalwater (≤475 m)</td>
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<tr>
<td></td>
<td>Cleremont (~125 m)</td>
<td>Cleremont (~125 m)</td>
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<tr>
<td></td>
<td>Sandriviersberg (1250 m)</td>
<td>Mogalakwena (≤1500 m)</td>
<td></td>
</tr>
<tr>
<td>Matlabas</td>
<td>Aasvoëlkop (≤600 m)</td>
<td>Makgabeng (≤1200 m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Skilpadkop (≤600 m)</td>
<td>Setlaole (≤450 m)</td>
<td></td>
</tr>
<tr>
<td>Nylstroom</td>
<td>Alma (≤3000 m)</td>
<td></td>
<td>Alma (1200-1800 m)</td>
</tr>
<tr>
<td></td>
<td>Swaershoek (≤1000 m)</td>
<td></td>
<td>Swaershoek</td>
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<tr>
<td></td>
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<td>(≤2500 m)</td>
</tr>
</tbody>
</table>

**Matlabas Subgroup**

The Matlabas Subgroup is subdivided into four formations. The Skilpadkop Formation consists of gritstone, sandstone and conglomerate (Visser, 1989) and the absence of fine-grained feldspathic sediments, distinguish it from the underlying Alma Formation (Jansen, 1982). The sandstone is coarse-grained, thick bedded to massive and reddish-purple to purplish brown in colour (Jansen, 1982) and becomes white to yellowish towards the top (Visser, 1989).

The Setlaole Formation that is present in the eastern part of the Waterberg Basin consists of gritstone, sandstone and conglomerate and at the base of the formation it is interbedded with tuff, mudstone and clay-pebble conglomerate (Visser, 1989). According to Jansen (1982) the sandstones are slightly feldspathic and locally micaceous. The Setlaole
Formation attains a thickness of 450 m in the Sterkrivier Valley and increases to 600 m in the west (Visser, 1989).

The lower part of the Aasvoëlkop Formation consists of siltstone, mudstone and shale with interbedded sandstone which is followed by fine-grained conglomeritic sandstone, whereas the top of the succession consists of fine-grained sandstone (Visser, 1989). In the western portion of the Basin, the thickness of the formation varies between 500 and 600 m and decreases towards the east to approximately 300 m (Jansen, 1982).

The Makgabeng Formation that occurs in the north-eastern portion of the Waterberg Basin consists of light-yellowish to light-red to brown sandstone that are characterised by large scale cross-bedding (Visser, 1989). The thickness varies from 300 to 600 m in the south and the west and increases to 1000 m in the northeast (Jansen, 1982).

![Reddish weathered sandstones and subordinate conglomerates (inset) of the Waterberg Group in a road cutting between Lephalale (Ellisras) and Marken. Bedding planes and associated fractures are clearly illustrated.](image)

**Figure 137:** Reddish weathered sandstones and subordinate conglomerates (inset) of the Waterberg Group in a road cutting between Lephalale (Ellisras) and Marken. Bedding planes and associated fractures are clearly illustrated.

**Kransberg Subgroup**

The Kransberg Subgroup is subdivided into four formations. The Sandriviersberg Formation forms the base of the Kransberg Subgroup and consists entirely of coarse-grained, yellowish (Visser, 1989) sandstone (Jansen, 1982). The formation coarsens towards the northeast where it grades into the Mogalakwena Formation (Barker et al., 2006) that is represented by
beds of coarse-grained sandstone, grit, conglomerate and shale (Jansen, 1982). According to Visser (1989) the Mogalakwena Formation is well developed in the Marken area with a thickness of 1200 to 1500 m.

The overlying Cleremont Formation consists of white, coarse-grained sandstone with purple, fine-grained sandstone locally developed at the base (Visser, 1989). The Formation is approximately 125 m thick and stays relatively consistent throughout the basin (Jansen, 1982; Visser, 1989).

![Figure 138: Stratigraphy of the Waterberg Group, simplified after (Barker et al., 2006). A: southern, western and central part of the basin; B: northern, eastern and central parts of the basin; C: south-western part of the Alma Trough (Gatkop block-fault zone).](image-url)
The Vaalwater Formation consists of greyish to red arenites (Barker et al., 2006) that are fine-to medium-grained. Micaceous siltstone also occurs within the formation (Visser, 1989). According to Jansen (1982) the Vaalwater Formation attains a maximum thickness of approximately 475 m.

**Wilge River Formation**

The Wilge River Formation only occurs within the Middelburg Basin of the Waterberg Group and is also the only unit present. The Formation unconformably overlies the Loskop Formation along its northern, eastern and south-eastern margins and along its southern margin it overlies the Pretoria Group (Barker et al., 2006). The Formation consists of red, medium- to coarse-grained sandstone with interbedded conglomerate and shale (Visser, 1989). The thickness of the Formation varies between 400-800 m (west) and 2 000-2 500 m (east) (Visser, 1989; Barker et al., 2006). There are areas where the Wilge River Formation is unconformably overlain by rocks of the Karoo Supergroup (Visser, 1989).

### 4.10.2.2. Lithostratigraphy of the Soutpansberg Group

The Soutpansberg Group consists of volcanic and sedimentary rocks and rests unconformably on Archaean granulite-grade gneisses, as well as on the Blouberg Formation. The Soutpansberg Group is subdivided into the following six formations according to SACS (1980):

- Nzhelele Formation
- Musekwa Formation
- Wyllie’s Poort Formation
- Fundudzi Formation
- Sibasa Formation
- Tshifhefhe Formation

Figure 139 illustrates the distribution and extensive faulting of the formations of the Soutpansberg Group where the stratigraphic section is illustrated by Figure 140.

**Tshifhefhe Formation**

The Tshifhefhe Formation is only locally developed in the eastern part of the Soutpansberg Basin and only a few metres thick (Bumby et al., 2002) comprising of epidotised clastic sediments, including shale, greywacke and conglomerate (Barker et al., 2006).
Figure 139: Distribution of the formations in the Soutpansberg Group as well as the Blouberg Formation (Barker et al., 2006).

**Sibasa Formation**
The Sibasa Formation is dominated by massive volcanic rocks, that are basaltic in composition, with intercalated pyroclastic and sandstone lenses (Bumby et al., 2002). The basalt is dark green in colour and it is estimated that it could reach a thickness of approximately 3 000 m (Barker et al., 2006). Basalt is speckled white in frequently developed amygdaloidal zones.

**Fundudzi Formation**
The Fundudzi Formation is only developed in the eastern half of the Soutpansberg Basin (Figure 139). The formation consists generally of sandstone with a few thin pyroclastic beds (Bumby et al., 2002) with intercalated basaltic lava at the top of the succession (Barker et al., 2006).

**Wyllie’s Poort Formation**
The Wyllie’s Poort Formation is dominated by red-pink quartzite with minor pebble washes and the base of the Formation is marked by a prominent agate pebble conglomerate (Bumby et al., 2002). The Formation reaches a maximum thickness of approximately 1 500m (Barker et al., 2006).

**Musekwa Formation**
The Musekwa Formation consists entirely of volcanic rocks (Figure 140). According to Barker et al. (2006) the basaltic lavas of the Musekwa Formation are similar to that of the
Sibasa Formation but locally it exhibits a very coarse gabbroic texture. The formation is approximately 400 m thick.

**Nzhelele Formation**

The Nzhelele Formation forms the upper unit of the Soutpansberg Group. The Formation reaches a maximum thickness of approximately 600 m and consists of red argillaceous and arenaceous sediments with several thin, consistent layers of pyroclastic rocks (Barker *et al.*, 2006).

![Figure 140: Stratigraphy of the Soutpansberg Group in the western, central and eastern Soutpansberg areas, as well as the Blouberg area (Barker *et al.*, 2006).](image)
4.10.3. Geohydrology

4.10.3.1. Waterberg Group

Geohydrological Characteristics

The rocks of the Waterberg Group possess no primary porosity and the permeability and storage capacity is generally very low (Owen & Madari, 2009; Du Toit & Sonnekus, 2010). Groundwater occurrences are controlled by fault and fracture zones, as well as bedding planes. Thus the Waterberg Group can be classified as secondary fractured aquifer system. Recharge is also very limited (Crosby, 2011).

The groundwater quality of the Waterberg Group varies throughout the unit. According to Du Toit and Sonnekus (2010), the EC values for the Cleremont Formation in the eastern parts of the Waterberg Group range between 2 and 50 mS/m, whereas in the central areas (between Vaalwater, Marken and Ellisras) it ranges between 10 and 400 mS/m and increases towards the Botswana border in the west, where values of up to 1 100 mS/m have been reported.

Borehole Yields

Borehole yields within the Waterberg Group are generally very limited with the majority of yields less than 0.5 l/s (Barnard, 2000; Du Toit & Sonnekus, 2010). Thus the rocks of Waterberg Group are low yielding aquifer systems. According to Du Toit and Sonnekus (2010) 35 % of the successful boreholes drilled within the Waterberg Group have yields ranging between 0.5 and 2 l/s. Yields greater than 3 l/s can be obtained, when targeting fault and fracture zones (Levin, 2011). The average groundwater level depth ranges between 10 and 40 mbgl (Barnard, 2002; Owen & Madari, 2009).

4.10.3.2. Soutpansberg Group

Geohydrological Characteristics

The water bearing characteristics of the Soutpansberg Group is very similar to that of the Waterberg Group. The Soutpansberg Group can be classified as a fractured (quartzites and sandstone) and intergranular aquifer system. Groundwater occurrences within the group are generally controlled by faults and shear zones and diorite dykes and sills (Du Toit, 1998; Du Toit & Sonnekus, 2010; 2011). The geohydrological characteristics of the formations within the Soutpansberg Group are as follows (Du Toit, 1998; Du Toit & Sonnekus, 2010; 2011):

- **Sibasa Formation**: Is an intergranular and fractured rock aquifer system. The formation has a poor to moderate aquifer potential. The majority of water strikes are within the first 30 mbgl with no strikes greater than 50 mbgl, indicating that the weathered/fractured zone is approximately 50 m thick. Chemical weathering (high
rainfall) results in clay material produced, reducing the permeability and subsequently the yielding potential of the formation.

- **Stayt Formation:** Is an intergranular and fractured rock aquifer system. The formation has a low to moderate aquifer potential.
- **Fundudzi Formation:** Is a fractured rock aquifer system. The formation has a low to very low aquifer potential. Studies done in the Kruger National Park indicated that the transmissivity in the Fundudzi Formation decreases with depth. The formation is considered a double porous medium. The sedimentary rocks have low to very low primary permeability with low storage potential. The majority of water strikes range between 30 and 50 mbgl with no strikes greater than 60 mbgl, indicating that the weathered/fracture zone is approximately 60 m thick.
- **Wyllie’s Poort Formation:** Is a fractured rock aquifer system. The formation has a low aquifer potential. The primary porosity is almost zero. The majority of water strikes are within the first 50 mbgl with no strikes greater than 100 mbgl, indicating that the weathered/fractured zone is approximately 100 m thick.
- **Nzhelele Formation:** Is a fractured rock aquifer system. The Formation has a moderate aquifer potential.

The groundwater quality of the Soutpansberg Group is generally of good quality. According to Du Toit and Sonnekus (2011), the EC values of the Nzhelele Formation ranges between 10 and 555 mS/m with only 4 % of the tested samples exceeding the maximum allowable limit. The EC values of the Wyllie’s Poort Formation ranges between 3 and 912 mS/m where the harmonic mean of the tested samples is 18 mS/m, whereas, the Fundudzi Formation generally have EC values less than 150 mS/m. Flouride, sodium, magnesium, nitrate and chloride may occasionally exceed the maximum allowable limit. The areas with poorer quality water are located near villages, indicating that poor sanitation practices combined with shallow sandy overburden and open fracture system might contribute to the higher values (Du Toit & Sonnekus, 2010; 2011).

**Borehole yields**
The Soutpansberg Group is generally a low to moderate yielding aquifer system. Yields of successfully drilled boreholes generally range between 0.5 and 2 l/s, but yields greater than 5 l/s are obtainable (Du Toit & Sonnekus, 2011). Studies done within the Kruger National Park concluded that there is no linear relationship between yields and depth of boreholes. High yielding boreholes (up to 22 l/s) was drilled in the Punda Maria Camp within the Kruger National Park (Du Toit, 1998). These high yielding boreholes is associated with east-west
striking faults, but they are situated on a groundwater divide which may result in decreasing yields over time and even the depletion of groundwater within the boreholes (drying up).

4.10.4. Locating Groundwater Resources

3.9.4.1 Target Formations and Geological Features

The permeability and storage capacity of the Waterberg and Soutpansberg Groups is generally low and for this reason, locating sustainable groundwater resources seems to be a difficult task. Groundwater occurrences are mainly associated with secondary geological structures as boreholes drilled into these rocks tend to be dry if these structures are not intersected. The specific target features within the various formations include the following (Du Toit, 1998; Du Toit & Sonnekus, 2010; 2011; Weideman, 2011):

I. Regional fault/fracture systems.
II. Contact zone between sediments and intrusive dykes/sills.
III. Fractures related to anticlines and bedding planes (Figure 137).

These structures are very heterogeneous and for this reason these fracture systems should be studied in detail.

The east-west striking Tshipise Fault system, that bounds the Soutpansberg Group in the north, is a main target for locating groundwater resources within the Soutpansberg Group (Weidemann, 2011). According to Du Toit (1998) these east-west trending faults give rise to high yielding boreholes as the ones drilled at the Punda Maria Camp in the Kruger National Park. Good yielding fractures occur at depths of up to 250 mbgl that results in good yielding groundwater resources (Du Toit & Sonnekus, 2010), but to determine the position of these features is extensively difficult or may even be impossible.

There are areas where diabase and dolerite dykes/sills are more extensively weathered than the surrounding sedimentary rocks, forming depressions. Where these sills are weathered and fractured to extended depths below the groundwater table, good groundwater resources can be abstracted (Owen & Madari, 2009).

When faults and the contact zones between sediments and intrusive dykes are targeted, do not drill directly on to these structures but rather further away from them to intersect them at depths below the groundwater table (Crosby, 2011; Weidemann, 2011). Faults and dykes oblique to strike within the Wyllie’s Poort Formation of the Soutpansberg Group, forms narrow valleys that are preferred target areas for groundwater resources (Du Toit & Sonnekus, 2011).
The preferred geophysical methods used to detect these features are:

I. Electromagnetics
II. Resistivity
III. Magnetics

Aerial photographs and geological maps are the main techniques used to detect the geological structures within the rocks of the Waterberg and Soutpansberg Groups. The magnetic method can be used to detect intrusive dykes and sill, but generally not very effective, especially within the rocks of the Waterberg Group. Due to high iron content, both magnetic and electromagnet values tend to be very erratic (Crosby, 2011).

4.11. The Bushveld Igneous Complex (2 050 – 2 070 Ma)

4.11.1. Location and Extend
The Bushveld Igneous Complex (BIC), that is situated north and northeast of Pretoria, is the world’s largest layered igneous intrusion and covers an area of approximately 65 000 km² (Visser, 1989). The BIC stretches across the Limpopo, North West, Mpumalanga and Gauteng Provinces (Figure 184, Appendix A). The BIC intruded into the Transvaal Supergroup.

4.11.2. Geology

4.11.2.1. Lithostratigraphy
The BIC is grouped into mafic and Felsic rocks. The BIC is subdivided into the following three suites and one group:

- Rashoop Granophyre Suite (Felsic)
- Lebowa Granite Suite (Felsic)
- Rustenburg Layered Suite (Mafic)
- Rooiberg Group

The Rooiberg Group is stratigraphically associated with the Transvaal Supergroup and petrogenetically linked with the BIC (Lenhardt & Eriksson, 2011), and for this reason it will be included with the BIC. Figure 141 illustrates the distribution of the lithostratigraphic subdivisions of the BIC.
Rustenburg Layered Suite

The Rustenburg Layered Suite (RLS) is characterised by magmatic layering, comprising rock types ranging from dunite and pyroxenite through norite, gabbro and anorthosite to magnetite-and apatite-rich diorite (Cawthorn et al., 2006). The RLS is divided into five compartments known as the northern, Potgietersrus, eastern, western and far western limbs (Figure 141). SACS (1980) used different names for the magmatic sequences (Table 23) in each limb, but due to the similarities of the sequences (Cawthorn et al., 2006), the zonal stratigraphy method is better suited for description purposes (Figure 142, Table 23).

The zonal stratigraphy is as follows:

- Marginal Zone – noritic
- Lower Zone – ultramafic
- Critical Zone – ultramafic to mafic with prominent layering
- Main Zone – gabbro-noritic
- Upper Zone – ferrogabbroic
Figure 142: Simplified stratigraphic column through the western and eastern limbs of the Rustenburg Layered Suite. Maximum thicknesses are indicated. Numbers 1-7, 8-14 and 17-21 refer to clustered magnetite layers. Modified after (Cawthorn et al., 2006).

The RLS is also characterized by the occurrence of marker reefs such as the Merensky Reef at the top of the Critical Zone, the Thornhill pyroxenite layers in the Main Zone and the Main Magnetite layer near the base of the Upper Zone (Eriksson et al., 1995).
Table 23: Formal lithostratigraphic classification of the Rustenburg Layered Suite adopted by SACS (1980), as subsequently modified, compared with the standard zonal nomenclature (Cawthorn et al., 2006).

<table>
<thead>
<tr>
<th>Rustenburg Layered Suite</th>
<th>Standard zonal subdivision</th>
<th>Nomenclature recommended by SACS (1980), including subsequent additions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All Areas</td>
<td>Eastern limb</td>
</tr>
<tr>
<td>Upper Zone</td>
<td>Subzone C</td>
<td>Luipershoek Olivine Diorite</td>
</tr>
<tr>
<td></td>
<td>Subzone B</td>
<td>Ironstone Magnetite Gabbro</td>
</tr>
<tr>
<td></td>
<td>Subzone A</td>
<td>Magnet Heights Gabbro-norite</td>
</tr>
<tr>
<td>Main Zone</td>
<td>Upper Subzone</td>
<td>Mapoch Gabbro-norite</td>
</tr>
<tr>
<td></td>
<td>Dsjate Subsuite</td>
<td>Leolo Mountain Gabbro-norite</td>
</tr>
<tr>
<td></td>
<td>Lower Subzone</td>
<td>Winnaarschoek Norite-Anorthosite</td>
</tr>
<tr>
<td>Critical Zone</td>
<td>Upper Subzone</td>
<td>Winterveld Norite-Anorthosite</td>
</tr>
<tr>
<td></td>
<td>Dwars River Subsuite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Subzone</td>
<td>Mooihoek Pyroxenite</td>
</tr>
<tr>
<td></td>
<td>Upper Pyroxenite Subzone</td>
<td>Serokolo Bronzitite</td>
</tr>
<tr>
<td></td>
<td>Croydon Subsuite</td>
<td>Jagdstub Harzburgite</td>
</tr>
<tr>
<td></td>
<td>Lower Pyroxenite Subzone</td>
<td>Rostock Bronzitite</td>
</tr>
<tr>
<td>Lower Zone</td>
<td></td>
<td>Clapham Bronzitite</td>
</tr>
<tr>
<td>Marginal Zone</td>
<td></td>
<td>Shelter Norite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Lebowa Granite Suite together with the Rashoop Granophyre Suite occurs as two semicircular lobes within the BIC. The SACS (1980) subdivided the Lebowa Granite Suite into different types of granite on the basis of field relationships, radiometric dating, and petrological and geochemical studies. They are as follows:

- Nebo Granite
- Verena Granite
- Klipkloof Granite
- Bobbejaankop Granite
- Lease Granite
- Balmoral Granite
- Makhutso Granite

The Nebo Granite (Figure 143) forms the bulk of the felsic (acid) phase of the BIC, forming 2 to 3 km thick sheets overlying the mafic layered rocks (RLS) in most parts of the complex (Cawthorn et al., 2006). The Nebo Granite is also known as the Bushveld Granite. The Granite is coarse-grained, pink to grey in colour.

The Verena Granite is coarse-grained, porphyritic granite (SACS, 1980) with mantled alkali feldspar phenocrysts (Cawthorn et al., 2006). It occupies an area of 400 km² east-northeast of Pretoria.

The Klipkloof Granite is a medium-to fine-grained, pink to grey, generally porphyritic granite that occurs as irregular sills and dykes within the Nebo and Bobbejaankop Granites (SACS, 1980; Cawthorn et al., 2006). The granite is characterised by an extremely low content of mafic minerals and there are areas where it contains tourmaline-rich spheres or irregular clasts (10-20 cm) (Cawthorn et al., 2006).

The Bobbejaankop Granite is a coarse-grained, red coloured granite (SACS, 1980). Biotite is usually altered to chlorite (Cawthorn et al., 2006). The granite appears to be developed in the higher levels of the Lebowa Granite intrusion.

The Lease Granite that is generally developed along the margin of the Nebo Granite, it is fine-grained, apalitic granite characterised by coarse pegmatitic patches (SACS, 1980).

The Balmoral Granite is a light-coloured, porphyritic granite that intruded into the rocks of the Pretoria Group (Witwatersrand Supergroup) and is overlain by rocks of the Waterberg Group (SACS, 1980).
The Makhutso Granite is a medium-grained, grey, biotite-rich granite (Cawthorn et al., 2006) that can only be observed in the central and eastern parts of the BIC. It forms small dykes, stocks and gently dipping sills within the Nebo Granite (SACS, 1980).

**Rashoop Granophyre Suite**

SACS (1980) subdivided the Rashoop Granophyre Suite into three formal units (Table 24) on the basis of textural variations, whereas Cawthorn *et al.* (2006) subdivided the suite into four units (Table 24) and can be classified as magmatic or metamorphic.
Table 24: The subdivision of the Rashoop Granophyre Suite according to SACS (1980) and Cawthorn et al. (2006).

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stavoren Granophyre</td>
<td>Stavoren Granophyre (Magmatic)</td>
</tr>
<tr>
<td>Rooikop Granophyre</td>
<td>Rooikop Porphyritic Granite</td>
</tr>
<tr>
<td>Zwartbank Pseudogranophyre</td>
<td>Zwartbank Pseudogranophyre (Metamorphic)</td>
</tr>
<tr>
<td>Diepkloof Granophyre</td>
<td>Diepkloof Granophyre (Metamorphic)</td>
</tr>
</tbody>
</table>

The Stavoren Granophyre occurs as sheet-like bodies (Cawthorn et al., 2006) and is characterised by relatively coarse-grained intergrowths of quartz and K-feldspar (SACS, 1980). The Stavoren Granophyre is generally located between Nebo Granite and overlying Rooiberg Group, but there are areas (Brits) where it separates the Nebo Granite and RLS form each other.

The Zwartbank Pseudogranophyre that is found in the western BIC between the Nebo Granite and RLS are characterised by irregular quartz-feldspar intergrowths (SACS, 1980).

The Diepkloof Granophyre is found in the eastern BIC and is situated between rocks of the RLS and Rooiberg Group in areas where the Nebo Granite is absent (Cawthorn et al., 2006). The texture resembles that of the Stavoren Granophyre but differs geochemically.

The Rooikop Porphyritic Granite or Granophyre Porphyry occurs as sill-like intrusions that occur within the Rooiberg Group (Cawthorn et al., 2006). It consists of K-feldspar and quartz phenocrysts, set in a fine-grained granophyric groundmass (SACS, 1980).

**Rooiberg Group**

The Rooiberg Group is a major felsic volcanic succession that covers an area of approximately 50 000 km², which unconformably overlie rocks of the RLS and Transvaal Supergroup. The Rooiberg Group is subdivided into four formations (Figure 144):

- Schrikkloof Formation
- Kwaggasnek Formation
- Damwal Formation
- Dullstroom Formation
Figure 144: Simplified stratigraphic column of the Rooiberg Group. RLS=Rustenburg Layered Suite; RGS=Rashoop Granophyre Suite (Buchanan, 2006).
The Dullstroom Formation, that forms the basal unit of the Rooiberg Group, consists of volcanic flows that are up to 400 m thick, ranging in composition from basalts to dacite (Buchanan et al., 2004). These volcanic flows are interbedded with thin, laterally extensive sedimentary rocks (Eriksson et al., 1994) consisting of poorly sorted sandstone with smaller proportions of mudrock and chert, where the sandstone recrystallized to quartz (Buchanan & Reimold, 1998). These quartzites display upward-fining cycles, ripple marks, mudcracks, planar and trough cross-bedding and channel fill structures.

The Dullstroom Formation is overlain by a thick sequence of increasingly siliceous extrusive rocks of the Damwal, Kwaggasnek (Figure 145) and Schrikkloof Formations that are a continuation of the same magmatic activity (Buchanan et al., 2004). These volcanic units of the Rooiberg Group are generally composed of a fine-grained groundmass with variable proportions of phenocrysts, porphyroblasts and amygdales (Buchanan, 2006). These units are characterised by manganese and iron hydroxides stains along fractures (Figure 145).

![Figure 145: Rhyolite of the Kwaggasnek Formation (Rooiberg Group) in a road cutting along the N1 south of Mookgopong (Naboomspruit). Inset indicating manganese (black) and iron (red) staining along fractures.](image)

The characteristic iron hydroxide and manganese staining are a result of groundwater, somewhat acidified by carbon dioxide in the air, dissolving iron and manganese from the rocks as it passes through the fractures. Eventually the fluids lose their dissolving
capabilities and evaporate, leaving the new minerals, manganese and iron hydroxides, behind.

4.11.3. Geohydrology

Geohydrological Characteristics

The BIC can be classified as a fractured (crystalline rocks) and intergranular aquifer system. The intergranular aquifer system is confined to the weathered (chemical) zone that ranges in thickness from 12 to 50 m. The geometry of the shallow intergranular weathered aquifer is controlled by the degree or intensity of chemical weathering of the crystalline rocks. The matrix of the underlying crystalline rock has a very low hydraulic conductivity and its effective hydraulic conductivity is determined by fractures and mine voids (Titus et al., 2009).

The weathered zone of the BIC is characterised by low to moderate transmissivity but high storativity. Pumping tests conducted by Titus et al. (2009) yielded reasonable and comparable transmissivities of 3 to 8 m²/d and that storativity values can vary by several orders of magnitude (E-04 to E-03) due to semi-confined conditions in areas overlain by confining layers. They have reported transmissivities of up to 500 m²/d and storativities of 0.15 for highly transmissive zones.

The fractured aquifer system (crystalline rocks) is generally characterised by very low porosities and high hydraulic conductivities if fractures are intersected. Groundwater is generally stored and transmitted in fractures within a relatively impermeable matrix. A characteristic feature of crystalline rocks is that their hydraulic properties are very heterogenic as hydraulic conductivity values can vary, within the same rock mass, by orders of magnitude, even over short distances (Titus et al., 2009). Recharge of the fractured aquifer system can be reduced by the weathered zone as mafic rocks weathers to a clay-rich soil with a low permeability (Barnard, 2000).

The groundwater quality of the BIC is generally of good quality but there are cases where it is not suitable for domestic use. Du Toit & Lelyveld (2006) found that groundwater from the RLS are not suitable for domestic use due high nitrate values, whereas the groundwater quality analysis done by Barnard (2000) yielded an average EC value of 105 mS/m for the RLS. The average EC values for the rest of the suites of the BIC ranges between 31 to 60 mS/m. Chloride, fluoride, nitrate and sulphate may occasionally exceed the maximum allowable limits, where elevated fluoride is especially associated with the granites of the Lebowa Granite Suite (Barnard, 2000).
Borehole Yields
The BIC can be regarded as a low to moderate yielding aquifer system as the majority of boreholes yields less than 2 l/s, but there are areas where yields greater than 5 l/s have been obtained. The groundwater level within the BIC generally ranges between 5 and 40 mbgl (Barnard, 2000; Du Toit & Lelyveld, 2006; Du Toit & Sonnekus, 2010).

The Rooiberg Group, Rashoop Granophyre and Lebowa Granite Suites have borehole yields generally less than 2 l/s, whereas the RLS seems to be a better aquifer with a moderate to high yielding aquifer potential (Barnard, 2000; Du Toit & Lelyveld, 2006). The yields of the RLS generally range between 0.5 to 5 l/s with yields up to 25 l/s. The granites of the Lebowa Suite occasionally have yields greater than 3 l/s but the probability of drilling a successful borehole is approximately 20 % (1 out of 5) (Du Toit & Lelyveld, 2006).

4.11.4. Locating Groundwater Resources

4.11.4.1. Target Formations and Geological Features
The specific target features within the various suites of the BIC include the following:

I. Transition zone between weathered zone and solid rock.
II. Contact zone between intrusive dykes and host rock.
III. Faults and their associated shear and fracture zones.
IV. Intrusive carbonatite complexes.

Groundwater occurrence within the suites of the BIC is generally associated with the transition zone between weathered and solid rock. These weathered aquifers are the result of local deep weathering of major structures (Botha & Van Rooy, 2001). The norites of the RLS seems to weather more intensely than other rocks within the BIC and this characteristic, in association with north-south striking dykes cutting through the norites, have formed groundwater compartments that resulted in basins than have the potential to be extremely good aquifers (Du Toit & Lelyveld, 2006; Du Toit & Sonnekus, 2010).

According to Mouton (2012), dykes perpendicular to the strike of the host rocks are good targets for groundwater resources. During a groundwater supply project (near Potgietersrus) these features were targeted and 14 boreholes were drilled, producing a total of approximately 18.5 l/s. Magnetite gabbro can be confused for large dolerite dykes during a magnetic survey, as they have a positive anomaly response (Mouton, 2012).

The Spitskop Carbonatite Complex within the Nebo Granites was targeted by Botha & Van Rooy (2001) when exploring for groundwater resources during a community water supply project. They identified four possible target zones associated with the carbonatite complex.
that resulted in good yielding boreholes (blow yields ranging from 5 to 23 l/s). These targets are as follows:

I. Contact between the carbonate and Nebo granites (magnetic low anomaly).

II. Contact between the dolomite and the igneous rock.

III. Tectonic structures in the carbonatite.

IV. Radial geological features.

Botha & Van Rooy (2001) proved that irrespective of the amount of sophisticated data obtained from geophysics and other remote sensing techniques, the geology must be fully understood to interpret such data. Thus it is very important to carefully select the probable groundwater targets in these crystalline rocks of the BIC, to determine the aquifer parameters as accurately as possible and to choose the most sustainable exploitation options.

The preferred geophysical methods used to detect these features are:

I. Electromagnetics

II. Magnetics

III. Resistivity

The magnetic and electromagnetic methods are used in conjunction to delineate the position of intrusive dyke, but one should be cautious when applying the magnetic method. The resistivity and electromagnetic method work well when used in conjunction in detecting basins of weathering and their deepest area for optimum borehole siting (Crosby; Weidemann, 2011).

4.12. Transvaal Supergroup (2 070 – 2 650 Ma)

4.12.1. Location and Extend

Rocks of the Transvaal Supergroup are preserved within two structural basins in South Africa, the Griqualand West and Transvaal Basins, and a third basin (Kanye Basin) in Botswana (Figure 146). The Griqualand West Basin is situated in the Northern Cape and North West Provinces and stretches from Prieska in the south to Vryburg in the North. The Transvaal Basin stretches over the North West, Gauteng, Mpumalanga and Limpopo Provinces and was intruded by the Bushveld Igneous Complex.
4.12.2. Geology

4.12.2.1. Lithostratigraphy

The correlation between the preserved rocks in the Transvaal Griqualand and West Basin of the Transvaal Supergroup (Table 36, Appendix B) varies from good for the basal clastic and chemical sedimentary units, to poor for the upper volcanic and clastic formations (Eriksson et al., 1995).

Black Reef and Vryburg Formations

The Black Reef Formation unconformably overlies the underlying rocks where the Wolkberg Group is not present and conformable where it is and predominantly consists of quartzite with lenses of grit and conglomerate (SACS, 1980). The conglomerate is generally confined to the base of the formation and become finer upwards where the rest of the cycle coarsens upwards (Figure 149). The thickness of the Black Reef Formation varies from approximately 20 m to 200 m (Figure 149). The Black Reef Formation of the Transvaal Basin is correlated with the Vryburg Formation of the Griqualand West Basin.
Figure 147: Simplified geology of the Transvaal Basin of the Transvaal Supergroup (Eriksson et al., 2006).

Figure 148: Simplified geology of the Griqualand West Basin of the Transvaal Supergroup (Eriksson et al., 2006).
The Vryburg Formation (Vryburg Siltstone Formation) consists predominantly of siltstone, with subordinate shale, quartzite and lava that unconformably overlies rocks of the Ventersdorp Supergroup (SACS, 1980). A basal, transgressive conglomerate occurs locally. The thickness of the Formation is generally 100 m thick in outcrop, but may be up to 340 m thick (Eriksson et al., 2006).

Figure 149: Typical vertical sections through the Black Reef Formation. Inset – isopach map of the Black Reef Formation thicknesses in metre (Eriksson et al., 2006).

Chuniespoort and Ghaap Groups

The Ghaap Group in the Griqualand West Basin conformably overlies the Vryburg Formation (SACS, 1980) and in the Shishen area it is up to 3 000 m thick (Eriksson et al., 1995). The Chuniespoort Group in the Transvaal Basin overlies the Black Reef Formation and is separated from the overlying Pretoria Group by an unconformity (Table 36, Appendix B).

The Ghaap Group is subdivided into four subgroups (Table 36, Appendix B) where the Koegas Subgroup is only preserved in the southern part of the Griqualand West Basin and along the south-western rim of the Maremane Dome (Figure 148) (Eriksson et al., 2006).
The Chuniespoort Group is subdivided into three units and in the central, western and south-eastern areas of the Basin, the upper portions of the succession are missing (SACS, 1980).

The basal Schmitzdrif Subgroup of the Ghaap Group is up to 275 m thick, consisting of dolomites and limestones of the Boomplaas Formation followed by shale and a quartzite marker horizon of the Clearwater Formation (Eriksson et al., 1995).

The Campbell Rand Subgroup and its correlate in the Transvaal Basin, the Malmani Subgroup, both consists of varies formations, generally consisting of dolomites (Figure 150) and subordinate limestone, which is separated from each other on the basis of stromatolite facies, interbedded cherts, shales and even low angle unconformities (Eriksson et al., 1995; 2006).

The Asbestos Hills Subgroup that follows conformably (SACS, 1980) on the Campbell Rand Subgroup is subdivided into two formations (lower Kuruman & upper Griquatown Formations) which correlate with the Penge Formation (Eriksson et al., 1995) of the Chuniespoort Group in the Transvaal Basin. These formations consist of banded iron formation (BIF) (Figure 151 & Figure 152), brown jaspilite, amphibolite and subordinate
shale (SACS, 1980). Rocks of the Penge Formation are partly, thermally metamorphosed due to the intrusion of the BIC (Eriksson et al., 2006).

The Penge Formation is unconformably overlain by the Duitschland Formation that consists of carbonaceous mudrocks, limestones and dolomites, with subordinate conglomerates, diamictites and lavas (Eriksson et al., 1995). Whereas, the Koegas Subgroup in the Griqualand Basin (only preserved within the southern part of the basin) conformably overlies the BIF’s of the Asbestos Hills Subgroup and consist of shales, siltstone and quartzites with subordinate stromatolitic carbonates and a thin layer of BIF (Eriksson et al., 2006).

![Figure 151: BIF of the Asbestos Hills Subgroup in a road cutting just outside Griquatown. Note the dip of the layers and folding (inset).](image)

**Postmasburg and Pretoria Groups**

The Postmasburg Group in the Griqualand West Basin reaches a thickness of 1 500 m and can be correlated with the lower part of the Pretoria Group in the Transvaal Basin. The Pretoria Group is approximately 6 to 7 km thick (Eriksson et al., 2006). The Postmasburg Group is subdivided into two formations and one subgroup, where the Pretoria Group is subdivided into ten formations (Table 36, Appendix B).
The lowermost formation of the Postmasburg Group, the Makganyene Formation, consists predominantly of massive, poorly sorted diamictite (Moore et al., 2001) and to a lesser degree BIF, shales, sandstones, and dolomite (SACS, 1980; Moore et al., 2001). According to Moore et al. (2001), there is no major unconformity between the Ghaap and Postmasburg Groups as the Makganyene Formation is conformably inter-banded with the Koegas Subgroup in the west and transgressive across the Asbestos Hills Subgroup in the east.

The Makganyene Formation is unconformably overlain by the Ongeluk Formation. The Ongeluk Formation consists of andesitic pillow lavas (Figure 153), hyaloclastites (Figure 153, Figure 154) and massive lava flows (Eriksson et al., 2006). Pipe amygdales and lenses of red jasper are also present (SACS, 1980).

The Voëlwater Subgroup that is only preserved in the northern part of the Griqualand West Basin is subdivided into a lower Hotazel Formation and an upper Mooi德拉ai Formation (Table 36, Appendix B). The Hotazel Formation conformably overlies the lavas of the Ongeluk Formation and consists of BIF that is characterised by alterations of chert-rich and magnetite-rich bands (Polteau et al., 2006). A gradational contact separates the Hotazel
and MooiDraai Formations, where the latter consists of limestone, dolomite and subordinate chert (Polteau et al., 2006).

Figure 153: Hyaloclastite and pillow lava of the Ongeluk Formation. Hyaloclastite overlain by pillow lava. Also see Figure 154.

Figure 154: Close-up photo of the hyaloclastite of the Ongeluk Formation.
The Pretoria Group in the Transvaal Basin overlies the Chuniespoort Group with an angular unconformity, which is believed to represent a weathered palaeo-karst surface (Eriksson et al., 1995). The formations of the Pretoria Group will not be discussed in detail, as Figure 155 provides a good summary of the lithostratigraphy of the Pretoria Group. The Pretoria Group consists predominantly of an alteration of mudrock and quartzite units with subordinate conglomerates and diamictites and carbonate beds (Figure 156). There are three interbedded volcanic units, the Bushy Bend lavas of the lower Timeball Hill Formation, the Hekpoort Formation (correlates with the Ongeluk Formation) and the Machadodorp Member of the Silverton Formation.
<table>
<thead>
<tr>
<th>FORMATIONS</th>
<th>WESTERN AREA</th>
<th>CENTRAL AREA</th>
<th>EASTERN AREA</th>
<th>SOUTHERN AREA</th>
<th>Inferred palaeoenvironments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houtenbek</td>
<td>Mudrock (tuffaceous in places), sandstone, limestone</td>
<td>Rayton/Woodlands Formation in far west (mudrock, sandstone) ≤200 m</td>
<td>150–200 m</td>
<td>Absent</td>
<td>Fan, fan-delta, delta, shallow lacustrine</td>
</tr>
<tr>
<td>Steenkampsberg</td>
<td>Sandstone</td>
<td>Rayton Formation (mudrock, sandstone, minor andesite and dolomite) ≥1200 m</td>
<td>450–600 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nederhorst</td>
<td>Sandstone (arkosic in places)</td>
<td></td>
<td>200–800 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lakenvalei</td>
<td>Sandstone</td>
<td></td>
<td>200–350 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vermont</td>
<td>Mudrock (tuffaceous in places)</td>
<td></td>
<td>500–700 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magaliesberg</td>
<td>Sandstone with mudrock lenses and interbeds</td>
<td>150–430 m, significant mudrock, sandstones thickens westwards and eastwards</td>
<td>290–340 m, subordinate mudrocks thicken westwards</td>
<td>≤225–550 m, subordinate mudrock</td>
<td>≤340 m, mostly eroded</td>
</tr>
<tr>
<td></td>
<td>Carbonate rocks</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lydenburg Shale Member (commonly tuffaceous)</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Machadodorp Volcanic Member (pyroclastic rocks, basalt)</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boven Shale Member</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td>Silverton</td>
<td></td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td>Daspoort</td>
<td>Sandstone, mudrock</td>
<td>≤65–120 m, sandstone pebbly in far west</td>
<td>~40–110 m, pebbly sandstone common</td>
<td>~10–120 m, sandstone pebbly, thicker in north, ironstones in northeast</td>
<td>~45–80 m, sandstone pebbly</td>
</tr>
<tr>
<td>Strubenkop</td>
<td>Mudrock, subordinate sandstone</td>
<td>~50–360 m, minor sandstone</td>
<td>~100–150 m, sandstone, minor tuff</td>
<td>~30–145 m, thickens to north and south</td>
<td>~80–185 m, thicken southwards</td>
</tr>
<tr>
<td>Dwaalheuwel</td>
<td>Sandstone, conglomerate, subordinate mudrock</td>
<td>~15–70 m, basal conglomerate in north</td>
<td>≤3–4 m, lenticular, absent in places</td>
<td>~40–110 m, minor conglomerates in north</td>
<td>Absent</td>
</tr>
<tr>
<td>Hekpoort</td>
<td>Basaltic andesite, pyroclastic rocks</td>
<td>≤190–890 m, thins northwards</td>
<td>≤340–630 m, air-fall and reworked pyroclastics relatively common</td>
<td>~90–500 m, thins northwards, pyroclastics relatively common</td>
<td>~430–1140, significant tuffs (200–300 m thick), thicken southwards</td>
</tr>
<tr>
<td>Boshoek</td>
<td>Sandstone, conglomerate, diamicite</td>
<td>≤35–70 m, significant conglomerates</td>
<td>≤2 m, mostly absent</td>
<td>~20–80 m, large channels</td>
<td>~30–60 m, localised diamicite</td>
</tr>
<tr>
<td></td>
<td>Upper mudrock unit</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diamictite/conglomerate/arkose lens</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td>Timeball Hill</td>
<td>Klapperkop Quartzite Member</td>
<td>Quartzite ~30–620 m, thicks westwards</td>
<td>Quartzite ~40</td>
<td>Quartzite ~70–230 m, thins southwards</td>
<td>Quartzite ~40–100 m, thins southwards</td>
</tr>
<tr>
<td></td>
<td>Lower mudrock unit</td>
<td>Mudrock ~160–460 m, thins westwards</td>
<td>Mudrock ~220–350 m</td>
<td>Mudrock ~300–580 m, thins to south, thin tuff bed</td>
<td>Mudrock ~80–540 m, thicks southwards</td>
</tr>
<tr>
<td></td>
<td>Bushy Bond Lava Member</td>
<td>Minor basalt lavas</td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
<tr>
<td>Rooihougle</td>
<td>Polo Ground Quartzite Member</td>
<td>~17–232 m, basal conglomerate thick in north, shale thick in south</td>
<td>~10–50 m, breccia and conglomerate lenticular, Polo Ground Member thin</td>
<td>≤2–140 m, thickest in Dennesite and Marble Hill fragments</td>
<td>~14–150 m, thick breccia</td>
</tr>
<tr>
<td></td>
<td>Bevets Conglomerate/Breccia Member</td>
<td></td>
<td></td>
<td>Absent</td>
<td></td>
</tr>
</tbody>
</table>

Figure 155: Schematic lithostratigraphic summary of the Pretoria Group across the Transvaal Basin (Eriksson et al., 2006).
4.12.3. Geohydrology

4.12.3.1. Black Reef and Vryburg Formations

Geohydrological Characteristics
The Black Reef and Vryburg Formations are both classified as fractured aquifer systems. The low transmissivity of the quartzites of the Black Reef Formation, results that the formation regionally acts as a barrier for groundwater flow from adjacent lithologies. This feature produces generally shallow groundwater levels. Areas where the movement of groundwater is from the Black Reef Formation towards the dolomite, the groundwater...
gradient is generally much steeper through the quartzitic rocks than in the dolomitic formations (Barnard, 2000; Van Dyk & Kisten, 2006). This characteristic has been demonstrated by Hobbs (1988) in the area southwest of Pretoria, where the Black Reef Formation separates the Basement Complex granite of the Halfway House Granite dome from the dolomite of the Chuniespoort Group. Thus it seems if the groundwater depths within the formation are generally controlled by the direction of groundwater movement between this lithology and the adjoining dolomites of the Chuniespoort Group.

The groundwater quality of the Black Reef and Vryburg Formations are generally of good quality and suitable for most purposes. The average EC value determined by Barnard (2000) for the Black Reef Formation is 34.3 mS/m with a maximum of 139 mS/m. Sulphate occasionally exceeds the maximum allowable limit and is related to mining activities (Barnard, 2000).

**Borehole Yields**

The Black Reef and Vryburg Formations are both regarded as low to moderate yielding aquifer systems as the majority of boreholes yields less than 2 l/s (Barnard, 2000; Van Dyk & Kisten, 2006), but there are areas where yields greater than 5 l/s have been obtained.

### 4.12.3.2. Chuniespoort and Ghaap Groups

The carbonate rocks of the Chuniespoort and Ghaap Groups represents the most important aquifer system in South Africa, due to their high yielding capabilities. The water from these dolomitic aquifers is mainly used for irrigation purposes (Bredenkamp, 1995).

**Hydrogeological Units/Compartments**

Vertical or sub-vertical intrusive dykes of different composition occur throughout both the Chuniespoort and Ghaap Group dolomites, whereas sills appear to be lacking in the Ghaap Group and one or more are found in the Chuniespoort Group (Vegter, 1984). These intrusions, generally impermeable, acts as barriers for groundwater flow through the dolomite, resulting in the formation of compartments. The various compartments or hydrogeological units are illustrated in Figure 185 (Appendix B). These units can also be subdivided into subunits.

Characteristic features within these compartments are the generally low groundwater level gradient and a marked discontinuity or step in groundwater level that occurs at the dykes (Figure 157). The low groundwater level gradients are typical of areas with high transmissivities (Kafri et al., 1986). Outflow of groundwater from these compartments and its subunits generally occurs as (Bredenkamp et al., 1986):
• Discharge into surface drainage system.
• Flow from springs which are located at the lowest surface elevation of a compartment in proximity to a dyke.
• Underground flow through deeply weathered of fractured dykes or leakage over (near-surface flow) impermeable dykes to adjacent compartments.

Figure 157: Groundwater compartments of the far west rand, illustrating the low groundwater level gradient and steps occurring at dykes. Modified after Vegter (1984).

Geohydrological Characteristics

The carbonate rocks of both these groups possess no primary porosity, but due to karstification they have a very high storage capacity and often highly permeable characteristics. Only the karstified superficial zone of these units, acts as an aquifer, therefore, classified as a karst aquifer system (Figure 158).

Karstification is a process whereby infiltrating rainwater, containing weak carbonic acid, percolates through the dolomite along faults, fractures and joints associated with deformation, dissolves the dolomite, resulting in the formation of open cavities and caves. Karstification is controlled by several geological factors (Kafri et al., 1986):

• Lithology:
  - Carbonate rocks are more susceptible to karstic weathering along fractures, joints, and other heterogeneities. Calcitic rocks are more susceptible to dissolution than dolomitic rocks.
• Stratigraphy:
  - There are several ancient phases of exposure to erosion (unconformities). These palaeo-karst horizons may be found today buried at depth.
- Chert-rich formations can be expected to be more susceptible to dissolution than the chert poor dolomites, being more calcitic, lithological heterogeneous and significantly more fractured and jointed.

- Structural elements:
  - Large scale tensional features, faults and joints are all features likely to allow easier movement of groundwater and consequently the development of karst.

![Diagram of karst aquifer](image)

**Figure 158**: Schematic cross section through a typical dolomite (karst) aquifer (DWA, 2006).

Four types of karst morphology on the Malmani Subgroup dolomites (Figure 159) have been recognised (Vegter, 1984):

- **Plateau type** – developed more or less on the continental watershed between Krugersdorp and the Botswana border.
- **Escarpmnt type** – rugged topography, characteristic of Mpumalanga escarpment, but also present between Pretoria and Krugersdorp.
- **Bushveld type** – between Thabazimbi and the Botswana border where caves are uncommon.
- **Vaal River type** – between Johannesburg and Klerksdorp where the Plateau type has been weakly incised.
From a groundwater point of view, the Plateau and Vaal River types are the most important.

The dolomites of both the Chuniespoort and Ghaap Groups are characterised by an abundance of springs. Flows from these springs vary from less than 1 l/s to as much as 2 000 l/s, whereas the major springs have flows ranging from 50 l/s to 2 000 l/s (Vegter, 1984). The majority of these springs occur on or near the contacts of dykes (Figure 157 & Figure 158), some near the contact of the underlying quartzites of the Black Reef Formation and other near to or on the contact of the overlying clastic sediments of the Pretoria Group (Vegter, 1984).

The storativity and transmissivity of the dolomites are very heterogeneous, due to the heterogeneity of the karstification of these rocks. Storativity values ranges from as low as 0.00005 to 0.1 in accordance with the degree of karstification and the hydraulic conditions, which vary from unconfined to semi-confined. The dolomites can be nearly impervious to highly transmissive with values ranging from 10 to 29 000 m²/d (Vegter, 1984). In the Carletonville area, Enslin and Kriel (1967) indicated that the storativity of dolomites in this vicinity decreases with depth below surface. A decline from an estimated 9.1 % at a depth of 61 mbgl to 1.3 % at a depth of 146 mbgl is reported.

These aquifer properties are mainly controlled by (Kafri et al., 1986):
- **Stratigraphy:**
  - The chert rich formations (Monte Christo & Eccles Formations) showed higher transmissivities than the chert poor formations (Oaktree & Lyttelton Formations). Storativity values can be expected to reflect this trend.

- **Structural lineaments:**
  - High transmissivities are likely to occur in this environment regardless of the dolomitic type and especially where these features are associated with karstification.

- **Palaeo-karstic erosion levels:**
  - Depressions in the pre-Karoo Supergroup palaeo-karstic surface are usually areas of high transmissivity.
  - Palaeo-karstic erosion levels also exist at depth and have high transmissivities.

The recharge percentage of these dolomite aquifers have been summarised by Vegter (1984) from values represented by various authors and is given in Table 25 below.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Mean Rainfall (mm/a)</th>
<th>Mean Recharge (mm/a)</th>
<th>Recharge %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuruman &amp; other eyes Northern Cape Province</td>
<td>346</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Grootfontein Compartment</td>
<td>560</td>
<td>31-43</td>
<td>5.4-7.7</td>
</tr>
<tr>
<td>Wondergat Compartment</td>
<td>560</td>
<td>46</td>
<td>8.3</td>
</tr>
<tr>
<td>Steenkoppies Compartment</td>
<td>670</td>
<td>63-80</td>
<td>9.6-11.8</td>
</tr>
<tr>
<td>Gemsbokfontein Compartment</td>
<td>675</td>
<td>86</td>
<td>12.8</td>
</tr>
<tr>
<td>Venterspost Compartment</td>
<td>680</td>
<td>103-109</td>
<td>15.1-16</td>
</tr>
<tr>
<td>Bank Compartment</td>
<td>680</td>
<td>51</td>
<td>7.4</td>
</tr>
<tr>
<td>Zuurbekom Compartment</td>
<td>686</td>
<td>90</td>
<td>13.1</td>
</tr>
<tr>
<td>Blyde River Catchment</td>
<td>1156</td>
<td>229</td>
<td>19.8</td>
</tr>
</tbody>
</table>

The groundwater quality of these karst aquifers are generally of good quality. The average EC value for the Plateau and Vaal River Type dolomites determined by Barnard (2000) is 63 mS/m with a maximum value of 397 mS/m. Du Toit and Lelyveld (2006) determined an average EC value for the Escarpment type dolomite of 55 mS/m and a maximum of 166 mS/m, whereas DuToit and Sonnekus (2010) determined an average value of 68 mS/m and
a maximum value of 374 mS/m for the Escarpment type near Polokwane and Bushveld type dolomites. Chloride, sulphate and nitrate occasionally exceed the maximum allowable limit. These constituents indicate contamination in some of the groundwaters, thus caution should be exercised when considering dolomitic groundwater for human consumption. The sources of these contaminations are generally due to mining activities, surface agriculture practices and pit latrines or cattle kraals in the vicinity of villages (Barnard, 2000; Du Toit & Lelyveld, 2006; Van Dyk & Kisten, 2006; Du Toit & Sonnekus, 2010).

**Borehole Yields**

The dolomite of the Ghaap Group is regarded as a moderate yielding aquifer system as the majority of borehole yields ranges between 0.5 to 2 l/s, but more than 10 % of the boreholes analysed by Van Dyk and Kisten (2006) have yields greater than 5 l/s.

The dolomites of the Chuniespoort Group are regarded as moderate to very high yielding aquifer systems with borehole yields commonly greater than 5 l/s and have yields of up to 126 l/s (Barnard, 2000). High yielding boreholes are generally associated with the chert rich dolomite formations (Eccles & Monte Christo Formations). High yielding boreholes are obtainable within the chert poor dolomite, but only in areas where they are associated with structural lineaments or Karoo Supergroup outliers (Kafri et al., 1986).

4.12.3.3. Pretoria and Postmasburg Groups

**Geohydrological Characteristics**

The Pretoria Group is classified as an intergranular and fractured aquifer system, whereas the Postmasburg Group is classified as a fractured aquifer system. Only a small unit of the Pretoria Group, south of Thabazimbi, is classified as a fractured aquifer system (Du Toit & Lelyveld, 2006).

The groundwater quality of the Pretoria Group is generally of good to moderate quality with EC values ranging from as low as 1.6 mS/m to a maximum of 1089 mS/m. The majority of EC values are generally less than 300 mS/m. Chloride, fluoride, nitrate, sodium and sulphate occasionally exceeds the maximum allowable limit near villages (Barnard, 2000; Du Toit & Lelyveld, 2006; Du Toit & Sonnekus, 2010).

**Borehole Yields**

The Pretoria Group is regarded as a low to moderate yielding aquifer system, with borehole yields ranging from less than 2 l/s to yields exceeding 5 l/s. The majority of yields seem to
be less than 2 l/s. Yields of up to 20 l/s have been reported by Du Toit and Lelyveld, (2006) for the Pretoria Group southwest of Phalaborwa.

4.12.4. Locating Groundwater Resources

4.12.4.1. Target Formations and Geological Features

The dolomitic rocks of the Transvaal Supergroup, the Ghaap Group and Malmani Subgroup, is the main drilling targets for locating groundwater resources due to its capability to yield large quantities of good quality water for human consumption and irrigation schemes.

The most important target formations within the Transvaal Supergroup are:

I. Schmidtsdrif and Campbell Rand Subgroups (Ghaap Group).
II. Malmani Subgroup (Chuniespoort Group).

Specific target features within the above mentioned subgroups are:

I. Karstification zones.
II. Dolerite/diabase intrusive dykes.
III. Major regional fault systems.

The dolomites of the Ghaap Plateau (Ghaap Group) has no well developed karstification zones, except along the BIF/dolomite contact zone, confined to the western parts of the plateau. In the central parts of the plateau the dolomites are more massive and homogenous (lack of karstification), although high yielding boreholes are still obtainable they are generally not sustainable (Esterhuyse, 2011; Van Wyk, 2011). Karstification zones are more common in the dolomites of the Chuniespoort Group (Transvaal Basin).

When targeting dolerite dykes 30 to 50 m in width, drilling should be done 30 to 50 m away from the dyke and for dykes less than 30 m in width, 5 to 10 m away. According to Esterhuyse these zones are highly fractured, promoting the formation of cavities. Large dykes and lineaments, generally strikes north northwest, north northeast and east-west (Van Wyk, 2011).

It should be noted that the karstification zones are generally filled with rubble. Drilling within this rubble is a difficult task; therefore an experienced driller should be used that know his way around dolomitic karstification zones (Van Wyk, 2011).

The preferred geophysical methods used to detect these structures are as follows:

I. Gravity
II. Electromagnetics
III. Magnetics

The gravity and electromagnetic methods is generally used to detect the zones of karstification, whereas the magnetic method is used to delineate the position of dolerite dykes. Areas where the karstification zones are filled with BIF-rubble, the magnetic method can be applied as magnetic readings react very erratic (Van Wyk, 2011).

4.13. Ventersdorp Supergroup (2 650 – 2 750 Ma)

4.13.1. Location and Extend

The Ventersdorp Supergroup is situated in the Gauteng, North West and Northern Cape Provinces. It extends from Johannesburg in the northeast to southwest of Kimberley (Figure 160). The basin occupies an elliptical area of about 300 000 km$^2$ and the region around Bothaville, between the Welkom and Klerksdorp Goldfields, represents an area best developed. The Ventersdorp Supergroup provides a unique volcano-sedimentary supracrustal record and contains the largest and most widespread sequence of volcanic rocks on the Kaapvaal Craton (Van der Westhuizen et al., 2006).

Figure 160: Distribution of the Ventersdorp Supergroup in South Africa (Van Der Westhuizen et al., 2006).
4.13.2. Geology

4.13.2.1. Lithostratigraphy

The Ventersdorp Supergroup provides a unique volcano-sedimentary supracrustal record (Figure 161) and contains the largest and most widespread sequence of volcanic rocks on the Kaapvaal Craton and unconformably overlies the Witwatersrand Supergroup and is best exposed at/in the North West, Northern Cape and the Gauteng Province (Van Der Westhuizen et al., 2006). The Ventersdorp Supergroup is subdivided into two lower groups and two upper formations which are as follows:

- Allanridge Formation
- Bothaville Formation
- Platberg Group
- Klipriviersberg Group

![Lithostratigraphy of the Ventersdorp Supergroup (Van Der Westhuizen et al., 2006).](image)
Klipriviersberg Group
The Klipriviersberg Group is approximately 1.5 to 2 km thick (Altermann & Lenhardt, 2012) and is subdivided into seven formations (Figure 161). The basal Venterspost Formation consists of conglomerate containing subangular to rounded pebbles of varies sizes (Van Der Westhuizen et al., 2006). According to SACS (1980), the Venterspost Formation is basically a residual sedimentary accumulation.

The sediments of the Venterspost Formation are conformably overlain by the tuffs and lavas of the Westonaria Formation (SACS, 1980). The Venterspost and Westonaria Formations are only developed within the deepest parts of the basin margins. The other formations of the Klipriviersberg Group onlap towards the basin margins so that the progressively younger formations forms the base (Van Der Westhuizen et al., 2006), for example, the Alberton Formation forms the base at its type locality (Langgeleven near Bothaville) and the Orkney Formation in the Welkom area (SACS, 1980).

The lavas of the Westonaria Formation are komatiitic in composition, whereas, the rest of the Klipriviersberg Group lavas are more mafic (Figure 161). It was deduced that the volcanism of the Klipriviersberg Group started in the east with eruption of komatiitic lavas, becoming less voluminous, before resurging with the depocentre shifting to the west and becoming more magnesium-rich (Van der Westhuizen & Bruiyn, 2000).

Platberg Group
The Platberg Group, that unconformably overlies the Klipriviersberg Group (Van der Westhuizen & Bruiyn, 2000), is subdivided into four formations (Figure 161) and consists of clastic and chemical sediments to mafic and felsic volcanic rocks (Van Der Westhuizen et al., 2006). The lowermost Kameeldoorns Formation consists of a basal conglomerate, greywacke, agglomerate, tuffs and shales (Visser, 1989) and represents a clastic wedge deposit that developed during a period of extension (Van der Westhuizen & Bruiyn, 2000). The Edenville Formation of the Klipriviersberg Group locally interfingers with the Kameeldoorns Formation.

The Kameeldoorns Formation is conformably overlain by the volcanic rocks of the Goedgenoeg Formation (Van Der Westhuizen et al., 2006) which is conformably followed by Makwassie Formation (Van der Westhuizen & Bruiyn, 2000). The Goedgenoeg Formation is an intermediate volcanic succession consisting of feldspar porphyries and less prominent non-porphyritic mafic lavas, whereas the overlying Makwassie Formation is a felsic volcanic lava consisting of quartz-feldspar porphyries interbedded with thin tuffaceous rock units (Van Der Westhuizen et al., 2006). Both these formations are the result of both high temperature ash-flow deposits and lava flows (Van der Westhuizen & Bruiyn, 2000).
The Rietgat Formation forms the upper unit of the Platberg Group. The Formation consists of alternating mafic volcanic rocks, tuffs as well as tuffaceous siltstone and stromatolitic cherty limestone that developed after the subsidence stage after the volcanic emanations (Van der Westhuizen & Bruiyn, 2000).

**Bothaville Formation**
There are regions, in depth, where the Bothaville Formation probably conformably overlies large expanses of the Rietgat Formation but generally it laps across older Ventersdorp Group formations and east of De Bron Fault, on to rocks of the Witwatersrand Supergroup (SACS, 1980). Also overlies Archaean Granites. The Bothaville Formation consists of quartzite and basal conglomerates that comprises of well rounded pebbles and boulders of vein quartz, quartzite, granite, BIF, chert tuff, lava and quartz porphyry (Van der Westhuizen et al., 2006).

**Allanridge Formation**
The Bothaville Formation is conformably overlain by the Allanridge Formation (SACS, 1980). The Allanridge Formation consist of lava that are basaltic andesites in composition and is characterised by red chalcedony amygdales in the upper part of the formation and less in the lower units (Van der Westhuizen et al., 2006).

### 4.13.3. Geohydrology

**Geohydrological Characteristics**
The Ventersdorp Supergroup can be classified as an intergranular and fractured aquifer system. The volcanic and sedimentary rocks of the Ventersdorp Supergroup is generally characterised by very low porosities and hydraulic conductivities (Van Dyk, 2011).

According to a report of De Villiers (1961), the volcanic rocks, in the vicinity of Klerksdorp, weathers to a clay material with low permeability. In between the impermeable highly weathered zone and underlying solid rock, there is highly permeable transition zone of fractured and jointed volcanic rock (confined aquifer) that has the capability to produce significant quantities of groundwater. However, there are instances where these rocks, in depth, does not appear permeable, even when weathered or extensively fractured (Burger, 2010), acting as an aquiclude rather than an aquifer, restricting downward groundwater movement from shallower or overlying aquifers.

In the instances where the sedimentary rocks and volcanic rocks occur simultaneously, the former seems to be a better aquifer for the development of groundwater resources due to the fact that the volcanic rocks did not weather deep enough (De Villiers, 1961). Weathering
of the sedimentary rocks produces sandy soil full of pebbles (normally that of Bothaville Formation) (Barnard, 2000). These conditions are generally conducive to rainwater and represents favourable recharge conditions. No recharge studies were ever conducted on these rocks, but Barnard (2000) did a comparison between the flow rate of a spring within the Bothaville Formation and its catchment areas which suggest that the percentage of rainfall recharge is relatively high.

The groundwater quality of the Ventersdorp Supergroup is generally of good quality. The average EC value for the Klipriviersberg Formation determined by Barnard (2002) is 60 mS/m with a maximum of 264 mS/m. Sulphate occasionally exceeds the maximum allowable limit with a maximum reported value of 1 038 mg/l.

The elevated sulphate values within the Kameeldoorns Formation are associated with gypsum. An extrapolation of groundwater quality done by Baran (2003), suggest that the entire Platberg Group should be avoided.

**Borehole Yields**

The volcanic rocks of the Ventersdorp Supergroup are regarded as low yielding aquifer systems with the majority of borehole yields less than 2 l/s. Whereas, the sedimentary rocks the Ventersdorp Supergroup is regarded as low to moderate yielding aquifer systems with the majority of yields ranging between 0.5 to 2 l/s as well as greater than 2l/s. However, there are areas where boreholes with in the Ventersdorp Group have yields of up to 20 l/s (Barnard, 2000; Baran, 2003; Van Wyk G., 2011).

The water level depth within the Ventersdorp Supergroup is relatively shallow and ranges between 5 and 40 mbgl (Barnard, 2000; Baran, 2003; Van Wyk G., 2011). According to De Villiers (1961) the felsic volcanic units of the Ventersdrop Supergroup have the lowest success rate (44 %) of drilling a successful borehole, whereas the mafic volcanic units and sedimentary rocks have drilling success rates of 56 % and 59 % respectively.

**4.13.4. Locating Groundwater Resources**

There is no specific target formation within the Ventersdorp Supergroup, but where both the volcanic and sedimentary rocks occur simultaneously the latter seems to be a better target for groundwater resources. The specific target features with the various formations of the Ventersdorp Supergroup include the following:

I. Deep weathered basins (circular/elliptical structures).

II. Transition zone between weathered zone and solid rock.

III. Regional faults and their associated shear and fracture zones (Sugar Bush Fault).
IV. Dolerite and diabase dykes.

According to De Villiers (1961) the best target for groundwater resources within the Ventersdorp Supergroup is the deepest part of a weathered basin. The angle or slope of the weathering plane within these weathered basins plays a fundamental role in the yielding potential of the aquifer. The angles associated with higher yielding boreholes ranges between 5º and 20º. The areas where the transition zone between the weathered zone and solid rock is basically absent, boreholes tend to have negligible yields (De Villiers, 1961).

Fractures and fault planes associated with regional fault systems are also good groundwater targets (Van Wyk, 2011). One such an example is the Sugar Bush Fault south of Heidelberg, where numerous good yielding boreholes were intercepted (Bamard, 2000).

There are areas where the diabase dykes are more intensely (deeper) weathered than the surrounding rock, so that the first 15 to 20 m of the weathered dyke consists of a thick clay and the transitions zone poorly developed resulting in low yielding boreholes. Unfortunately in some areas these dykes are the only targets for groundwater development. The soil above these dykes are clayey and brackish and for this reasons it can be easily be traced on surface (De Villiers, 1961).

The preferred geophysical methods used to detect these features are:

I. Magnetics
II. Electromagnetics
III. Resistivity

The electromagnetic and resistivity methods are used to detect the deep weathered basins and the faults zone, whereas the magnetic method is used to delineate dolerite/diabase dykes.

4.14. Witwatersrand Supergroup (2 750 – 2 970 Ma)

4.14.1. Location and Extend

The Witwatersrand Supergroup is mostly covered by younger rocks (Figure 162) with outcrops occurring within the Gauteng, North-West and Free State Provinces. The Witwatersrand Supergroup is the largest gold province in the world, with over 120 years of exploitation in the goldfields (Figure 162) (Dankert & Hein, 2010).
4.14.2. Geology

4.14.2.1. Lithostratigraphy

Only a portion of the rocks of the Witwatersrand Supergroup outcrops on surface, most being covered by younger rocks (Figure 162). The Witwatersrand Supergroup overlies sedimentary and volcanic rocks of the Dominion Group, either conformably or unconformably and unconformably overlies Archaean basement rocks where the Dominion Group is absent (Dankert & Hein, 2010). The Witwatersrand Supergroup is subdivided into two groups

- Central Rand Group
- West Rand Group
West Rand Group

The West Rand Group is subdivided into three subgroups (Figure 186, Appendix C) each with its own formations. The Group consists predominantly of quartzites and shales, with a quartzite shale ratio of about one and is also characterised by the presence of several diamicite units (McCarthy, 2006).

The Hospital Hill Subgroup consists of a thin basal quartzite unit termed the Orange Groove Formation (SACS, 2006) which is overlain by an argillaceous Parktown Formation consisting of ripple-marked quartzite and magnetic shales (McCarthy, 2006). The Parktown Formation is overlain by the Brixton Formation consisting of interbedded quartzite and shale (SACS, 2006). The Bonanza Formation which follows on the Brixton Formation consists of matured and thin conglomerate units (McCarthy, 2006).

The lithology of the Government Subgroup is more diverse than that of the underlying and overlying Hospital Hill and Jeppestown Subgroups respectively. The basal Promise Formation unconformably overlies the rocks of the Bonanza Formation of the Hospital Hill Subgroup (McCarthy, 2006). The Government Subgroup consists of diamicites, fluvial conglomerates, shales and quartzite (SACS, 2006).

The overlying Jeppestown Subgroup includes a variety of rock types. Base is defined by the quartzites of the Koedoeslaagte Formation, which lies on a major unconformity (SACS, 2006) and contains the Buffelsdoorn Reef at its Base in the Klerksdorp area. The Jeppestown Subgroup consists of shales, quartzites and andesitic lavas of the Crown Formation.

Central Rand Group

The Central Rand Group differs fundamentally from the West Rand Group and is subdivided into two subgroups (Figure 186, Appendix C). The Group consist predominantly of quartzite and conglomerates (McCarthy, 2006) and a quartzite shale ratio of 12.6 (SACS, 2006).

The Johannesburg Subgroup consists predominantly of quartzite which is characterised by a yellowish colour (Visser, 1989). The Main Formation that consists mainly of quartzite contains the economically important Main Reef, Carbon Leader and the Main Reef Leader ore units and also consists of prominent, shale filled erosion channels (SACS, 2006). The overlying Randfontein Formation consist of alternating quartzite and conglomerate and is economically important along the northern edge of the basin. The Luipaardsvlei Formation is marked at the top by a widespread unconformity and consists of pebbly quartzite and locally developed conglomerates. The overlying Krugersdorp and Boysens Formations
upwards to siltstone or shale and marks the top of the Johannesburg Subgroup (SACS, 2006).

The Turffontein Subgroup consists predominantly of quartzites and conglomerates, whereas the conglomerates become increasingly more abundant upwards until it is dominated by conglomerates. Shale filled erosion channels are also present (SACS, 2006).

4.14.3. Geohydrology

Geohydrological Characteristics

The Witwatersrand Supergroup is classified as a fractured aquifer system. Thus groundwater within the Witwatersrand Supergroup is associated with secondary fracture systems. These fractures are associated with weathered areas, shear zones and intrusive rock formations.

The rocks of the Witwatersrand Supergroup weather to sandy soil that may locally promote recharge. Groundwater generally discharges by means of springs/seeps that occur along the floors and slopes of the principle valleys.

The groundwater quality of the Witwatersrand Supergroup is generally of good quality with average EC values of 37 mS/m and 29 mS/m for the West Rand and Central Rand Groups respectively with a maximum value of 256 mS/m. Chloride and sulphate occasionally exceed the maximum recommended level which suggests the influence of contamination from mining activities (Barnard, 2000).

Borehole Yields

The Witwatersrand Supergroup is regarded as a low to moderate yielding aquifer system with the majority of boreholes yielding less than 2 l/s but yields greater than 5 l/s are obtainable. Barnard (2000) reports a maximum yield of 30 l/s. Fault zones within the deep gold mines (±2 000 mbgl) of South Africa play an important role, as these structures results in large volumes of groundwater inflow into the mines.

The water level depth of the within the Witwatersrand Supergroup is generally shallow and ranges between 10 and 25 mbgl. Deeper water levels are generally associated with the hills (Barnard, 2000).
4.14.4. Locating Groundwater Resources

4.14.4.1. Target Formations and Geological Features
The specific target features with the various formations of the Witwatersrand Supergroup include the following (De Villiers, 1961; Barnard, 2000):

I. Contact zone between sediments and intrusive sills.
II. Deeply weathered shale formations.
III. Weathered lithological contacts and bedding planes.
IV. Regional faults and their associated shear and fracture zones.

The upper and lower contact zones of the diabase, dolerite and gabbro sills with that of the sedimentary rocks results in good yielding boreholes when intersected. When these intrusive sills are weathered deeply enough they can also have relatively good yields (De Villiers, 1961).

The shales of the Witwatersrand Supergroup weather more intensely than the other rock formations within, thus resulting in a better aquifer system (De Villiers, 1961). The low lying areas are more favourable due to the fact that lithological contacts and bedding planes are more intensely weathered within these zones (Barnard, 2000).

4.15. Pongola Supergroup (2 890 – 3 020 Ma)

4.15.1. Location and Extend
The Pongola Supergroup is situated on the south-eastern part of the Kaapvaal Craton in Mpumalanga, and KwaZulu-Natal Provinces and Swaziland. It covers an area of approximately 27 500 km² (275 km × 100 km) (Figure 163). A large area of its original volume has been removed by erosion, destroyed by granitic intrusions and buried under younger rock formations (Burke et al., 1985).
Figure 163: Simplified geology map of the Pongola Supergroup, indicating its distribution in South Africa (Gold, 2006).

4.15.2. Geology

4.15.2.1. Lithostratigraphy

The Pongola Supergroup unconformably overlies Archaean granites of the Kaapvaal Craton and attains a maximum thickness of approximately 12 000 m with significant lateral variations (Strik et al., 2007). The Pongola Supergroup is subdivided into two groups (Table 26 & Figure 164):

- Mozaan Group
- Nsuze Group (formerly Insuzi Group as defined by SACS, 1980)
The Nsuze Group has been interpreted to present a rapid phase of rifting which was then followed by the deposition of the Mozaan Group that presents shallow marine shelf deposits during thermal subsidence of the Pongola Basin (Burke et al., 1985; Strik et al., 2007).

The entire Supergroup has been affected by greenschist-facies metamorphism and experienced moderate deformation except for the extreme south that experienced more intense deformation due to the overprinting of the Natal-Namaqua Orogeny (Strik et al., 2007).

**Nsuze Group**

The Nsuze Group is subdivided into the six formations (Table 26 & Figure 164) and is best developed in the north along the Pongola River (Burke et al., 1985) and attains a maximum thickness of approximately 4 600 m in the Hartland area and thins towards the south to a thickness of 1 070 m in the White Mfolozi Inlier (Gold, 2006). The Nsuze Group predominantly consists of interfingering basalts and rhyolites, basaltic andesites and dacites (Burke et al., 1985), along with minor sedimentary sequences (Table 26).

The base of the Nsuze Group is marked by the Mantonga Formation which attains a maximum thickness of approximately 800 m, consisting of medium-to very coarse-grained sandstones (quartz wackes), shale and pyroclastic rocks. The sandstone is locally interbedded with well developed, matrix-supported conglomerates (Gold, 2006).

The Mantonga Formation is overlain by rocks of the Bivane Subgroup. The two volcanic sequences, the Nhlebela and Agatha Formations, are separated by the White Mfolozi Formation (Table 26) which represents the Mantonga Formation but contains a 20 m thick calcareous unit consisting of quartzitic dolomite, dolomitic sandstone, carbonate bearing siltstones, with well developed stromatolites (Gold, 2006). Both the Agatha and Nhlebela Formations consist of basalt, basaltic andesites and andesite, whereas the Agatha Formation also includes dacites and rhyolites. Individual rhyolitic flows are generally less than 10 m in thickness (Burke et al., 1985).

The overlying Ozwana Subgroup (sharp contact) is only developed in the Hartland and Magudu areas (Gold, 2006) and is subdivided into two formations (Table 26). The lower Langfontein Formation consist of sandstone, clast-supported conglomerate (lahars/volcanic breccias) and subordinate siltstone, where the overlying Mkuzane Formation consist of banded siltstone, metamorphosed to andalusite schists within the contact aureoles of post-Pongola granites (Gold, 2006). The thickness of the Ozwana Subgroup is highly variable (200 m to 2 800 m) and according to Gold (2006) it may be of a transgressive tectonic brake at this level.
Table 26: Lithostratigraphy of the Pongola Supergroup. Modified after (Strik et al., 2007).

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>Formation</th>
<th>Dominant lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mozaan Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nkoneni</td>
<td>Ntanyana</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gabela</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bongaspoort</td>
<td></td>
</tr>
<tr>
<td>Odwaleni</td>
<td>Khiphunyawa</td>
<td>Sediments, BIF, minor volcanics</td>
</tr>
<tr>
<td></td>
<td>Tobolsk</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Delfkom</td>
<td></td>
</tr>
<tr>
<td>Dwalahoek</td>
<td>Hlashana</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thalu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ntome</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sinqeni</td>
<td></td>
</tr>
<tr>
<td><strong>Nsuze Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ozwana</td>
<td>Mkuzane</td>
<td>Mafic volcanic, minor sediment</td>
</tr>
<tr>
<td></td>
<td>Langfontein</td>
<td></td>
</tr>
<tr>
<td>Bivane</td>
<td>Agatha</td>
<td></td>
</tr>
<tr>
<td></td>
<td>White Mfolozi</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nhlebela</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mantonga</td>
<td></td>
</tr>
</tbody>
</table>
Figure 164: Lithostratigraphic columns of the Pongola Supergroup (Gold, 2006).
Mozaan Group

The Mozaan Group is subdivided into ten formations (Table 26 & Figure 164) and is best exposed in the Hartland area. It attains a maximum thickness of 4 800 m (Gold, 2006) in the northern outcrop areas and only 700 m are preserved towards the south, as most of the southern sections have been removed by erosion (Burke et al., 1985). The Mozaan Group consists predominantly of alternating shales, sandstones, conglomerates and minor BIF and volcanic rocks (Burke et al., 1985).

The lower most unit of the Mozaan Group, the Singeni Formation, consist of 2 major sandstone units that is separated by a 80 m thick layer of BIF (Gold, 2006). Pyritic conglomerates lenses are developed near the base of the lower sandstone unit (Burke et al., 1985). The overlying Dwaalhoek Subgroup is an upward-coarsening succession consisting of mudstone, siltstone and sandstone, where the base of the Thalu Formation (upper unit) is characterised by a distinctive BIF layer (Gold, 2006).

The Odwaleni Subgroup is a heterogeneous unit as it consist of various sedimentary and volcanic rocks. The lower and upper units, the Delfkom and Khiphunyawa Formations, both consist of sandstones and mudstones, whereas the Tobolsk Formation consists of highly amygdaloidal basaltic lavas containing thin tuffaceous beds at the top and bottom (Gold, 2006). The Delfkom Formations also consist of two diamicite units that display an exceptional diversity in clast size and composition.

A sharp contact separates the sandstones of the Bongaspoort Formation of the Nkoneni Subgroup from the underlying Khiphunyawa Formation. The overlying Gabela Formation consists of andesitic-to dacitic tuffs containing minor amygdaloidal lavas with interlaminated sandstone and shales, separated from very finely laminated shale of the Ntanyana Formation by a sharp contact, and followed by red-weathering sandstone which is overlain by white coloured orthoquartzite (Gold, 2006).

4.15.3. Geohydrology

Geohydrological Characteristics

The Pongola Supergroup is classified as an intergranular and fractured aquifer system. Good quality hydrogeological data for the aquifers of the supergroup is very limited, thus it is recommended that further hydrogeological exploration be conducted (King, 2003).
Borehole Yields
King (2003) analysed 60 boreholes of which the majority of boreholes (83%) yielding less than 2 l/s, thus the Pongola Supergroup can be regarded as a low to moderate yielding aquifer system.

4.15.4. Locating Groundwater Resources
The weathered zone and the underlying fractures are often targeted for groundwater development.

4.16. Archaean Granites and Gneisses (2 500- 3500Ma)

4.16.1. Location and Extend
The Archaean granitoid intrusions of South Africa are situated on the Kaapvaal Craton (Figure 165). These intrusives, outcrop at various localities, with the most prominent outcrop situated in the north-eastern parts of South Africa, stretching from the northern parts of the Limpopo Province southward towards the Mpumalanga-Swaziland border (Figure 166). The Archaean granites of the Limpopo and Mpumalanga Provinces will be discussed as two separate regions, known as the Polokwane/Pietersburg Plateau and the Lowveld regions (Figure 165).

Figure 165: Distribution of the various Archaean Granites on the Kaapvaal Craton, South Africa. Redboxes indicate location of detailed maps in Figure 166. Modified after Lana et al. (2003).
4.16.2. Geology

4.16.2.1. Lithostratigraphy

Polokwane/Pietersburg Plateau

The geology of the Polokwane/Pietersburg Plateau forms part of the Southern Marginal Zone of the Limpopo Belt. See section 4.18.2.1 for discussion. The lithostratigraphy is summarised in Table 27.


<table>
<thead>
<tr>
<th>Eraethem</th>
<th>Lithostratigraphic Unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mashashane Suite</td>
<td>Lunsklip Granite Ademellite to granodioritic.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uitloop Granite Adamellite.</td>
</tr>
<tr>
<td></td>
<td>Hugomond Granite</td>
<td>Coarse-grained biotitic granite.</td>
</tr>
<tr>
<td></td>
<td>Matok Porphyroblastic Granite</td>
<td>Ademellite to granodioritic granite. Older mafic enderbitic-charno-enderbitic phase.</td>
</tr>
<tr>
<td></td>
<td>Matlala Granite</td>
<td>Biotitic-granodiorite composition.</td>
</tr>
<tr>
<td></td>
<td>Utrecht Granite</td>
<td>Fine-grained pink biotite granite.</td>
</tr>
<tr>
<td></td>
<td>Meinhardtskraal Granite</td>
<td>Pink and red granite with pegmatite and granophyre.</td>
</tr>
<tr>
<td></td>
<td>Moletsi Granite</td>
<td>Biotite granite.</td>
</tr>
<tr>
<td></td>
<td>Smitskraal Granite</td>
<td>Biotite granite.</td>
</tr>
<tr>
<td></td>
<td>Turfloop Granite</td>
<td>Biotitic, adamellite to granodioritic.</td>
</tr>
<tr>
<td></td>
<td>Goudplaats-Hout River Gneiss</td>
<td>Grey, medium-textured tonalitic to trondhjemitic banded migmatites gneiss.</td>
</tr>
<tr>
<td>Swazian</td>
<td>Bandelierskop Complex</td>
<td>Pelitic Member Purplish brown, medium-grained gneiss. Lenses of biotite, quartzite and mafic materials occur sporadically.</td>
</tr>
<tr>
<td></td>
<td>Mafic Member</td>
<td>Dark grey to black, fine-textured rock. Serpentinite pyroxenite and peridotite bodies, usually associated with Goudplaats-Hout River Gneiss.</td>
</tr>
<tr>
<td></td>
<td>Ultramafic Member</td>
<td></td>
</tr>
</tbody>
</table>
Figure 166: Maps showing the main location of Archaean granites and gneiss intrusions in the north and north-eastern, and east and south-eastern parts of the Kaapvaal Craton. (Robb et al., 2006).
Lowveld Region

The lithostratigraphy of the Archaean granites and gneisses (Figure 167) is summarised in Table 28. Only the lithologies of the more important lithostratigraphic units will be discussed in geographical order from north to south (Figure 166):


<table>
<thead>
<tr>
<th>Erathem</th>
<th>Lithostratigraphic Unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vaalian</td>
<td>Schiel Complex</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Palmietfontein Granite</td>
<td>Small granodiorite dykes and plutons.</td>
</tr>
<tr>
<td></td>
<td>Eliland Suite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mashishimale Suite Granites</td>
<td>Perluminous granite with monzo-granitic composition.</td>
</tr>
<tr>
<td></td>
<td>Vorster Suite Granite</td>
<td>Porphyritic granite</td>
</tr>
<tr>
<td></td>
<td>Jerome Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Maranda Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Shamiriri Granite</td>
<td>Grey, medium-grained granite that varies in composition from syeno-granite to monzo-granite</td>
</tr>
<tr>
<td>Randian</td>
<td>Shirindi Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Macetce Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Meriri Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Turfloop Granite</td>
<td>Biotite, adamellitic to granodioritic</td>
</tr>
<tr>
<td></td>
<td>Mpageni Granite</td>
<td>Granite</td>
</tr>
<tr>
<td></td>
<td>Cunning Moore Tonalite</td>
<td>Homogeneous tonalite.</td>
</tr>
<tr>
<td></td>
<td>Harmony Granite</td>
<td>Trondhjemite gneiss.</td>
</tr>
<tr>
<td></td>
<td>Rooiwater Complex</td>
<td>Gabbroic and diorite rocks.</td>
</tr>
<tr>
<td>Swazian</td>
<td>Groot-Letaba Gneiss</td>
<td>Intermingled gneisses, including fine-to medium-grained tonalite, coarse-grained trondhjemite and finer banded and linear gneisses.</td>
</tr>
<tr>
<td></td>
<td>Goudplaats-Hout River Gneiss</td>
<td>Grey, medium-textured tonalitic to trondhjemitic banded migmatites gneiss.</td>
</tr>
<tr>
<td></td>
<td>Klaserie Gneiss</td>
<td>Well foliated gneiss.</td>
</tr>
<tr>
<td></td>
<td>Makhutswi Gneiss</td>
<td>Trondhjemite and tonalite gneiss.</td>
</tr>
<tr>
<td></td>
<td>Hebron Granodiorite</td>
<td>Granodiorite</td>
</tr>
<tr>
<td></td>
<td>Nelspruit Suite</td>
<td>Biotite granite, porphyritic granite, potassic gneiss and migmatite.</td>
</tr>
<tr>
<td></td>
<td>Bandelierkop Complex</td>
<td>Purplish brown, medium-grained gneiss. Lenses of BIF, quartzite and mafic materials occur sporadically.</td>
</tr>
</tbody>
</table>
Goudplaats-Hout River and Groot-Letaba Gneisses:

The Goudplaats-Hout River Gneiss form part of the Southern Marginal Zone of the Limpopo Belt, consisting of a wide variety of granitoid gneisses of various types and compositions. These gneisses range from homogeneous to strongly layered, from leucocratic to dark-grey, and from fine-grained to pegmatoidal varieties. Typically forms flat ground with poor exposure (Robb et al., 2006).

The granitoid gneisses of the Goudplaats-Hout River Gneiss occurring between the Murchison and the Pietersburg-Giyani Greenstone Belts have been grouped together under the term Groot-Letaba Gneiss (previously thought to form part of the widespread Goudplaats Gneiss). It is overlain by Karoo rocks and consists of a wide variety of intermingled gneisses, including fine-to medium-grained tonalite, coarse-grained trondhjemite and finer banded and linear gneisses (Robb et al., 2006).
**Bandelierkop Complex**

The Bandelierkop Complex is restricted to the Southern Marginal Zone of the Limpopo Belt. See section 4.18.2.1 for discussion.

**Rooiwater Complex:**

The Rooiwater Complex consists of two suites known as the Novengilla and Beesplaas Suites. These suites consist of gabbroic and diorite rocks, respectively (Vegter, 2003).

**Makhutswi and Klaserie Gneiss**

The Makhutswi Gneiss is similar to the gneiss of the Goudplaats-Hout River Gneiss and consists of medium-to fine-grained grey biotite bearing rocks of tonalitic composition (Vegter, 2003) intruded by dykes or stock-like unmigmatite biotite gneiss. It is complexly folded, containing abundant remnants of amphibolite, ultramafic, meta-quartzite and calc-silicate rocks (Robb, *et al.*, 2006).

The Klaserie Gneiss is coarse-grained well foliated gneiss that is mineralogy similar to the gneiss of the Makhutswi Gneiss, but not migmatized (Robb *et al.*, 2006).

**Cunning Moore Tonalite**

The Cunning Moore Tonalite is poorly exposed, consisting predominantly of grey, medium-grained, massive homogeneous tonalite. It intrudes into the gneisses and migmatites of the Nelspruit Suite (Robb *et al.*, 2006).

**Nelspruit Suite**

The Nelspruit Suite consists of medium-to coarse-grained biotite granite, porphyritic granite, potassic gneiss and migmatite (Figure 168). There are many places a coarse-grained pegmatite present. The Hebron Granodiorite occurs as isolated bodies within the Nelspruit Suite (Vegter, 2003).
4.16.3. Geohydrology

Geohydrological Characteristics
The Archaean Granites and Gneisses can be classified as an intergranular and fractured aquifer system. These aquifers are generally semi-confined to confined in nature (Du Toit, 2001) and predominantly structurally controlled. (Du Toit et al., 2012). These aquifers have double porosities and fractures are characterized by high permeability and low storage, and the rock matrix by low permeability and large storativity (Du Toit, 2001). This is a typical feature of hard rock aquifer systems. A conceptual model, developed by Holland (2011), of the Archaean granites and gneisses is demonstrated in Figure 169.

The weathered zone in the Limpopo Plateau generally ranges between 15 to 50 mbgl, whereas, the weathered zone in the Lowveld region rarely exceeds 30 mbgl (Holland, 2011). The fracture zone beneath the Archaean granites and gneisses in the Limpopo Plateau may extend to depths greater than 120 mbgl (Holland, 2011). This phenomenon is especially true for the Dendron and Mogwadi regions, which is known for its high yielding boreholes, which by far exceed the typical expectations of crystalline aquifer potentials (Botha; Holland, 2011).
Gneiss or granite that forms topographical highs weathers to low permeable soil. Also commonly found within these areas are ferricrete layers, forming impermeable subsurface layers within the top and middle area of these topographical highs which further reduces the recharge from the unstaturated zone to aquifers (Du Toit et al., 2001).

According to analysis done by Holland (2012), the average transmissivity values of the Archaean gneisses of the Limpopo Plateau are higher than those of the Lowveld region and also the adjacent lithologies. The major drainage channels are associated with linear structures and granite-gneiss contacts zones with well developed fracturing and jointing. The sand overlying these high-density joints and fractures are well-sorted and highly permeable, creating favourable recharge conditions if no permeable clay layers are present (Holland, 2011; Du Toit et al., 2012).

Bush (1989) found that intersecting dolerite and diabase dykes do not possess favourable geohydrological properties but according to statistical analysis done by Holland (2012) dolerite dykes have higher transmissivities than diabase dykes (Table 29). Bush (1989) noted that dyke contact zones had lower yields than those drilled away from dykes, whereas Holland (2012) found no significant relationship between transmissivity and distance to dykes (Table 29).

Table 29: Transmissivity of boreholes intercepting dykes and transmissivity according to distance to inferred dykes (Holland, 2012).

<table>
<thead>
<tr>
<th>Limpopo Plateau</th>
<th>Dyke Type</th>
<th>Diabase</th>
<th>Dolerite</th>
<th>No dyke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmissivity of boreholes intercepting dykes (m²/d).</td>
<td>No of Boreholes</td>
<td>56</td>
<td>11</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>13.4</td>
<td>83.1</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>Geo-Mean</td>
<td>4.3</td>
<td>47.3</td>
<td>10.8</td>
</tr>
<tr>
<td>Limpopo Plateau</td>
<td>Distance to inferred dyke</td>
<td>&lt; 50 m</td>
<td>50-150 m</td>
<td>&gt;150 m</td>
</tr>
<tr>
<td>Transmissivity according to distance to inferred dykes (m²/d).</td>
<td>No of Boreholes</td>
<td>30</td>
<td>52</td>
<td>645</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>45.7</td>
<td>53.0</td>
<td>43.2</td>
</tr>
<tr>
<td></td>
<td>Geo-Mean</td>
<td>12.7</td>
<td>16.6</td>
<td>13.7</td>
</tr>
<tr>
<td>Lowveld</td>
<td>Distance to inferred dyke</td>
<td>&lt; 50 m</td>
<td>50-150 m</td>
<td>&gt;150 m</td>
</tr>
<tr>
<td>Transmissivity of boreholes intercepting dykes (m²/d).</td>
<td>No of Boreholes</td>
<td>140</td>
<td>28</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>14.5</td>
<td>23.6</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Geo-Mean</td>
<td>3.2</td>
<td>12.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Lowveld</td>
<td>Distance to inferred dyke</td>
<td>&lt; 50 m</td>
<td>50-150 m</td>
<td>&gt;150 m</td>
</tr>
<tr>
<td>Transmissivity according to distance to inferred dykes (m²/d).</td>
<td>No of Boreholes</td>
<td>228</td>
<td>372</td>
<td>1 110</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>20.6</td>
<td>18.9</td>
<td>26.9</td>
</tr>
<tr>
<td></td>
<td>Geo-Mean</td>
<td>5.8</td>
<td>5.6</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Figure 169: Conceptual model of aquifers systems found in the Archaean granites and gneisses of the Polokwane Plateau and Lowveld region. Transmissivity values obtained from various borehole locations are included (Holland, 2011).
The groundwater quality of the Archaean granites and gneisses of the Lowveld is generally of good quality with average EC values ranging between 49 and 146 mS/m. There are areas where the EC values exceed the maximum recommended limits. The higher rainfall regions generally have better quality water than the lower rainfall areas. Nitrate, magnesium, fluoride and chloride occasionally exceed the maximum recommended limits (Du Toit & Lelyveld, 2006).

The groundwater analysis done by Vegter (2003a) suggest that the groundwater quality of the Archaean granites and gneisses of the Polokwane Plateau is generally of good quality with only 20% of the 975 samples analysed exceeding the maximum recommended limits. Nitrate and fluoride are the two constituents that are generally responsible for the bad quality water encountered (85%). EC values generally ranges between 43 and 214 mS/m (TDS 300-1 500 mg/l).

Borehole Yields
The Goudplaats-Hout River Gneiss of the Polokwane Plateau can be regarded as moderate to high yielding aquifer system. Borehole yields generally range between 2 and 5 l/s and higher (Du Toit & Sonnekus, 2010). The Dendron area is characterised by high yielding boreholes (Du Toit & Sonnekus, 2010; Botha, 2011) where large-scale groundwater irrigation schemes are in use (yields of up to 40 l/s). The younger granite intrusions can be regarded as low yielding aquifer systems, with yields generally less than 2 l/s (Du Toit & Sonnekus, 2010).

The Archaean granites and gneisses of the Lowveld region can be regarded as low to moderate yielding aquifer systems with the majority of yields ranging between 0.1 and 2 l/s (Du Toit & Lelyveld, 2006). The Goudplaats-Hout River and Makhutswi gneiss are an exception and can be regarded as moderate to high yielding aquifer systems with yields typically ranging between 0.5 and 5 l/s (Du Toit & Lelyveld, 2006). Du Toit and Lelyveld (2006) reports yield in access of 40 l/s. An analysis conducted by Vegter (2003) revealed that the Nelspruit Granite Suite is the least favourable of the granitic units.

4.16.4. Locating Groundwater Resources

4.16.4.1. Target Formations and Geological Features
Groundwater plays a fundamental role, especially within Limpopo Province, as surface water resources are limited. Both Urban and rural communities are dependent on groundwater resources.
The most favourable lithologies targeted for groundwater resources are the gneisses of the Goudplaats-Hout River and Makhutswi gneisses. The specific target feature within the Archaean granites and gneisses are as follows: (Du Toit, 2001; Du Toit & Lelyveld, 2006; Du Toit & Sonnekus, 2010; Botha, 2011; Crosby, 2011; Roos, 2011).

I. Pegmatite intrusions zones.
II. Major regional faults systems and their related structures.
III. Deep weathered basins and transition zone between weathered and solid crystalline rock.
IV. Contact aureole of large granite batholith intrusions.
V. Dolerite/Diabase intrusive dykes and sills.

According to Botha (2011) pegmatite intrusion zones have the ability to yield large quantities of water when they are penetrated beneath the weathered zone of their host rock. This is the case within the Dendron area where high yielding boreholes are fairly common, supporting large groundwater irrigation schemes (yields up to 40 l/s).

Holland (2011) found that lineaments (dykes & faults) perpendicular to the current stress regime are more favourable targets; this is the east-north-east to east and west-north-west to west striking features. Large drainage channel are generally associated with these highly fractured linear features (intensively weathered). The overlying, well sorted, highly permeable sands of the river beds creates ideal recharge conditions (Du Toit et al., 2001) resulting in high yielding boreholes when targeted.

DWA investigated the occurrence of groundwater in the aureole of large granite batholiths located west and northwest of Polokwane (Du Toit et al., 2001). They have found that the remnants of the originally gneissic roof are extensively fractured and weathered and borehole yields of up to 40 l/s are possible when targeted. The granite/host gneiss contact is regarded an insignificant target for groundwater development, but small amounts of water can occasionally be obtained in this contact where it is locally fractured. The formation of fractures associated with these granite batholiths are illustrated in Figure 170.

According to Holland (2012), boreholes that encountered diabase dykes have generally lower yields than those encountering dolerite dykes. Good yielding boreholes can be obtained when drilling commences directly into highly fractured and weathered dolerite dykes (Du Toit, 2001). When targeting dolerite dykes that are less fractured and weathered than the host rock, Botha (2011) advices, that drilling should commence a few metres away from the dolerite, generally on the eastern side, rather than directly next to it. In the
Nelspruit area dolerite dykes are unsuccessful targets as no groundwater is associated with these structures (Roos, 2011).

Figure 170: Hypothetic model for the formation of fractures in the overlying roof during batholiths emplacement (Du Toit, 2001).
The preferred geophysical methods used to detect these features are:

I. Magnetics
II. Electromagnetics
III. Resistivity

The electromagnetic and resistivity methods are generally used to detect deep weathered basins and highly fractured zones associated with faults and batholiths intrusions, whereas the magnetic method is used to delineate dolerite/diabase dykes.

4.17. Archaean Greenstone Belts (2 700 – 3 500 Ma)

4.17.1. Location and Extend

The Archaean Greenstone Belts constitutes the oldest preserved material on the earth’s surface (Brandl et al., 2006). These Greenstone Belts are linear to irregularly shaped features situated on the Kaapvaal Craton of South Africa (Figure 171). There are several greenstone belts or their remnants still preserved of which the Barberton, Pietersburg, Murchison, Giyani and Kraaipan greenstone belts are of importance.

The Barberton Greenstone Belt is situated in the eastern part of the Mpumalanga Province just north of Swaziland. The Pietersburg, Murchison and Giyani belts is situated in the central to eastern parts of the Limpopo Province. The Kraaipan belt stretches from the southern parts of the North West Province northwards to the Botswana-North West border.

4.17.2. Geology

4.17.2.1. Lithostratigraphy

**Barberton Greenstone Belt (Barberton Supergroup)**

The volcanic and sedimentary sequences of the Barberton Supergroup were originally horizontal but have been folded on itself in the form of a trough and the layers now stand on edge (Figure 172). The Supergroup is subdivided into three main groups:

- Moodies Group
- Fig Tree Group
- Onverwacht Group
The Onverwacht Group forms the base of the Barberton Supergroup that consists predominantly of volcanic rocks. It attains a maximum thickness of approximately 15 km (Anhaeusser, 2008) and is subdivided into the Tjakastad and Geluk Subgroups which are separated by a sedimentary unit named the Middle Marker (McCarthy & Rubidge, 2005). The basal Tjakastad Subgroup consists predominantly of mafic and ultramafic rocks namely komatiites, komatiitic basalts, magnesium-rich basalts and tholeiitic basalts (Anhaeusser, 2008) and is subdivided into three formations (Table 30). The Middle Marker is one to five metres thick (Brandl et al., 2006) and consists of chert layers together with layers of calcite (McCarthy & Rubidge, 2005). The Geluk Subgroup consists of repeated cycles of volcanic, volcanioclastic and sedimentary rocks (Anhaeusser, 2008) which consists of interbedded
layers of mafic and felsic lavas, pyroclastic rocks, banded chert and carbonaceous rocks with felsic lava and interbedded chert at the top (Visser, 1989).

The Fig Tree Group follows conformably on the Onverwacht Group and attains a thickness of approximately 2 000 m (Visser, 1989). The Fig Tree Group consists predominantly of sedimentary rocks ranging from sandstone siltstones, BIF and mudstone which are often black in colour due to the presence of abundant carbon (McCarthy & Rubidge, 2005). The Group also consists of volcaniclastic rocks, altered komatiitic lava and black chert layers (Brandl et al., 2006).

The Moodies Group occurs in a series of structurally isolated blocks and erosional remnants and each of the three formations represents an upward-fining cycle consisting of a coarse basal unit of conglomeratic sandstone, followed by a thick section of finer-grained
sandstone, siltstone and shale (Brandl et al., 2006). The Moodies Group attains a thickness of approximately 3 025 m (Visser, 1989).

Table 30: Lithostratigraphy of the Barberton Greenstone Belt after SACS (1980).

<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Lithology</th>
<th>Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moodies</td>
<td>Baviaanskop</td>
<td>Sandstone, grits, conglomerates. Shales, sub-greywackes, quartzite, phyllites.</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td>Joe’s Luck</td>
<td>Shales, sub-greywackes, sandstones, quartzites, phyllites, jaspilites, ferruginous shales, basaltic lava.</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>Clutha</td>
<td>Shales, quartzites, conglomerates, jaspilites.</td>
<td>1 600</td>
</tr>
<tr>
<td>Fig Tree</td>
<td>?</td>
<td>Trachytic tufts, agglomerates, lavas, tuffaceous graywackes, and greywacke conglomerates.</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>Belvue Road</td>
<td>Siltstone, shales and subordinate graywackes with banded ferruginous cherts and a trachytic tuff.</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Sheba</td>
<td>Greywackes with some shales and interlayers of chert.</td>
<td>1 000</td>
</tr>
<tr>
<td>Onverwacht</td>
<td>Zwaartkoppie</td>
<td>Felsic volcanic and interlayered chert.</td>
<td>1 815</td>
</tr>
<tr>
<td></td>
<td>Kromberg</td>
<td>Mafic and felsic lavas, pyroclastics and agglomerates. Banded cherts and carbonate rocks, mainly metamorphosed.</td>
<td>3 820</td>
</tr>
<tr>
<td></td>
<td>Hoogenoeg (Middle Marker)</td>
<td>Mafic and felsites and pyroclastics. Banded cherts. Mainly metamorphosed.</td>
<td>4 850</td>
</tr>
<tr>
<td></td>
<td>Komati</td>
<td>Mafic and ultramafic lavas (komatiites), chert, metamorphosed.</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Theespruit</td>
<td>Mafic and subordinate ultramafic lavas and felsic tufts, schists, carbonaceous cherts, mainly metamorphosed.</td>
<td>3 790</td>
</tr>
<tr>
<td></td>
<td>Sandspruit</td>
<td>Ultramafic and subordinate mafic lavas, mainly metamorphosed.</td>
<td>4 230</td>
</tr>
</tbody>
</table>

Pietersburg Greenstone Belt (Pietersburg Group)

The Pietersburg Greenstone Belt is composed of two major tectonostratigraphic rocks sequences, of which the older sequence constitutes volcanic rocks (greenstones) and the younger sequence of clastic sediments, separated by a well defined unconformity (De Wit et al., 1992). SACS (1980) subdivided the Pietersburg Group into six formations (Table 31) but according to Brandl et al. (2006) this lithostratigraphic subdivision is only applicable to the south-western part of the greenstone belt.
Table 31: Lithostratigraphic subdivision of the Pietersburg Group (SACS, 1980).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lithology</th>
<th>Max. Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uitkyk</td>
<td>Quartzites, Conglomerates, Shale, Quartz-mica, BIF</td>
<td>1500</td>
</tr>
<tr>
<td>Vrischgewaagd</td>
<td>Chloritic and quartzitic schists</td>
<td>500-1000</td>
</tr>
<tr>
<td>Zandrivierspoort</td>
<td>Mafic metalava with interlayered magnetite quartzite</td>
<td>500</td>
</tr>
<tr>
<td>Eersteling</td>
<td>Mafic metalava with subordinate ultramafics, quartz-feldspar porphyry and salic lavas.</td>
<td>10 000</td>
</tr>
<tr>
<td>Ysterberg</td>
<td>Salic lavas and tuff, shale, interbedded quartzitic schist, banded chert/ironstone quartzite</td>
<td>1400</td>
</tr>
<tr>
<td>Mothiba</td>
<td>Ultramafics with minor amphibolites, quartzitic schist, quartz-feldspar porphyry, BIF.</td>
<td>7500</td>
</tr>
</tbody>
</table>

The Mothiba Formation is the most widely developed unit of the Pietersburg Greenstone Belt and occupies a narrow but virtually continuous belt that stretches from Mokopane (Potgietersrus) to Duiwelskloof (Figure 173). The Mothiba Formations is characterised by an abundance of ultra-mafic metavolcanics (SACS, 1980) together with serpentinite, talc-schist and minor amphibolite (Visser, 1989). The thickness of the formation varies between 5 000 and 7 500 m (SACS, 1980).

It appears that the Ysterberg Formations rest conformably on the Mothiba Formation (SACS, 1980) but its distribution is limited. The Ysterberg Formation consists predominantly of salic lavas, which varies from dacitic to thyodacitic in composition (Grobler, 1972), with minor layers of pyroclastic salic material. Interbedded with the lavas are thick beds of quartzitic and ferruginous schist, and carbonaceous shale. Near the base and at the top of the Ysterberg Formation, thick layers of banded chert and ironstone are developed (SACS, 1980).

The only contact between the Eersteling Formation and underlying Ysterberg Formation was observed just west of Ysterberg (SACS, 1980). The Eersteling Formation consists predominantly of fine-grained amphibolite with intercalations of serpentinite, quartz-feldspar porphyry and quartz-amphibolite schists (Visser, 1989).

The Zandrivierspoort Formation outcrops northeast of Polokwane (Pietersburg) (Figure 173) and is nowhere observed to be in contact with the other units (SACS, 1980) of the...
Pietersburg Greenstone Belt. The Zandrivierspoort Formation consists of fine-grained amphibolite with intercalated magnetite-quartzite that is intensively folded, together with meta-quartzite (Visser, 1989). Schists are developed at the top of the formation (SACS, 1980).

The Vrischgewaagd Formation appears to conformably overlie the Eersteling Formation (SACS, 1980) but have a very limited distribution. According to SACS (1980) and Visser (1989), the Vrischgewaagd Formation probably constitutes the core of a synclinal structure and is characterised by the abundance of chloritic and quartzitic schists.

The Uitkyk Formation occurs only in the south-western area of the Pietersburg Greenstone Belt (Figure 173). The Formation rests unconformably on the underlying units and consists of a variety of sandstones, siltstones, grits, conglomerates and breccias, in variable states of deformation (De Wit et al., 1992).
Figure 173: Simplified geology map of the Pietersburg Greenstone Belt (SACS, 1980).
Murchison Greenstone Belt (Gravelotte Group)

The Murchison Greenstone Belt (Figure 174) can be divided into five domains based on their lithological association, metamorphic history and structural style (Vearncombe et al., 1992; Brandl et al., 2006). The domains are described from north to south with no necessary stratigraphic significance. They are as follows:

I. Silwana Amphibolite
II. Rooiwater Complex
III. Rubbervale Formation
IV. Murchison ultramafic, mafic, carbonated and meta-sedimentary schists
V. La France Formation

The lithostratigraphic sequence according to SACS (1980) placed these units in the Gravelotte Group and is given in Table 32. According to Vearncombe et al. (1992) this is not an acceptable classification as SACS (1980) developed it without an appreciation for the complexity of deformation in the belt. Thus the above scheme has been developed for the Murchison Belt.

Silwana Amphibolite
The Silwana Amphibolite forms a 300 m thick succession (Brandl et al., 2006) and consists of hornblende schists, amphibolite gneiss and biotite schist, the latter occurring along the contact with lower metamorphic-grade Murchison schists (Vearncombe et al., 1992).

Rooiwater Complex
In the west the Rooiwater Complex is unconformably overlain by rocks of the Transvaal Supergroup where it attains a maximum thickness of approximately 7 500 m and progressively thins towards the east into a region of a vertical shear zone (Vearncombe et al., 1992). The Complex is subdivided into a lower Novengilla Gabbro Suite, central Quagga Quartz Amphibolite, an upper Free State Diorite Suite and Berlyn Dykes (Vearncombe et al., 1992).

The Novengilla Gabbro Suite consists of metamorphosed gabbro with subordinate anorthosite and pyroxenite (Brandl et al., 2006). Sulphide-bearing horizons and a magnetite layer that are up to seven metres thick do also occur. The Quagga Quartz Amphibolite is situated the central portion of the Rooiwater Complex. It shows a mineral layering interpreted as metamorphosed igneous layering with a composition that is transitional between gabbro-anorthosite and hornblende granite (Vearncombe et al., 1992).
Figure 174: Simplified geological map of the Murchison Greenstone Belt showing the five domains, the surrounding granitoids and the overlying Transvaal Supergroup (Vearncombe et al., 1992).
Table 32: Lithostratigraphy of the Gravelotte Group according to SACS (1980).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lithology</th>
<th>Approx. Thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubbervale</td>
<td>Felsic porphyritic tuffs, mafic porphyritic tuffs and subordinate mafic lavas and sills</td>
<td>3500</td>
</tr>
<tr>
<td>Mac Kop</td>
<td>Quartzites, grits, with intercalated chlorite schists, minor sericite schists and conglomerates</td>
<td>1500</td>
</tr>
<tr>
<td>Weigel</td>
<td>Quartz-chlorite schists, quartzite “bar”, quartz-muscovite schists, variety of carbonate rocks</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mafic lavas including Mg- and Fe-rich varieties and alkali tholeiites</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td>Talc-chlorite schists (altered ultramafic lavas)</td>
<td></td>
</tr>
<tr>
<td>La France</td>
<td>Conglomerates, grits, quartzites, chlorite schists</td>
<td>2000</td>
</tr>
<tr>
<td>Leydsorp</td>
<td>Mafic lavas with interlayered BIF, quartz-chlorite schist and quartz porphyry; variously carbonatised</td>
<td>3000</td>
</tr>
<tr>
<td>Mulati</td>
<td>Mafic lavas (Basaltic komatiites, Mg metatholeiitic) lesser ultramafic lavas (peridotitic komatiites) and felsic tuffs</td>
<td></td>
</tr>
</tbody>
</table>

The Free State Diorite Suite is characterised by a leucocratic hornblende-bearing granite with a maximum thickness of 2 000 m (Anhaeusser, 2006). The Berlyn Dykes are east-west trending fine-grained granite dykes that intrude into the Novengilla Suite near the southern margin of the Rooiwater Complex (Vearncombe et al., 1992).
Rubbervale Formation

The Rubbervale Formation consists of both a northern and southern unit which are separated by a prominent, though unexposed, tectonically modified break. The units comprises of schists derived from felsic lava and tuffs, and quartz-porphyroclastic schists derived from quartz-feldspar porphyries (Vearncombe et al., 1992).

Murchison ultramafic, mafic, carbonated and metasedimentary schists

According to Brandl et al. (2006), this lithological domain can be grouped into five main rock associations:

I. **Ultramafic rocks**, which occur along the southern flank of the belt. They include serpentinite, chlorite schists, and talc-chlorite schists.

II. **Mafic rocks**, include mainly albite-chlorite-actinolite schists and quartz-chlorite schists. Pillow structures are preserved in less tectonised areas.

III. **Carbonated rocks**, Occur preferentially in the vicinity of the so-called Antimony line (Figure 174). The rocks present either as massive or schistose varieties and contain quartz, dolomite, magnesite and chlorite.

IV. **Iron-formation**, commonly interlayered with mafic lavas or associated with clastic sediments.

V. **Quartz-mica schists**, range from rare massive quartzites to highly schistose varieties. Locally thin conglomerate horizons occur intercalated with the schists.

La France Formation

The La France Formation comprises of two principal rock types, fuchsitic quartzite and quartz-mica schists (Vearncombe et al., 1992). The fuchsitic quartzite is pervasively and intensely deformed, with no primary sedimentary structures being preserved (Brandl et al., 2006). The formation differs from the other units by the presence of biotite and the development of early recumbent structures (Vearncombe et al., 1992; Brandl et al., 2006).

Giyani Greenstone Belt

The Giyani Greenstone Belt was previously known as the Sutherland Belt. In the south-western region, the belt splits into the Khavagari (north) and Lwaji (south) belts and the rocks are classified according to SACS (1980) as the Giyani Group (Figure 175).

In the central part of the belt the succession comprises ultramafic schists composed of tremolite, talc chlorite or hornblende, and thin beds of mafic volcanic rocks and iron-formation are intercalated with the schists. The ultramafic schists are followed by a thin unit made up mainly of felsic volcanic and sedimentary rocks, including quartz-sericite schist, rhyolite, ferruginous quartzite and iron-formation. The felsic volcanic and sedimentary rocks are followed by repeated cycles of ultramafic and mafic rocks (pillow structures) capped by iron-formation which grades into a ferruginous dolomite at the top (Brandl et al., 2006). The Giyani Belt is also characterised by the juxtaposition of relatively undeformed low-grade
rocks with strongly foliated amphibolites and kyanite-staurolite, and garnet-staurolite-bearing schists (De Wit et al., 1992a).

Figure 175: Simplified geology of the Giyani Greenstone Belt (McCourt & Van Reenen, 1992).

Kraaipan Greenstone Terrain (Kraaipan Group)

The Kraaipan Greenstone Terrain comprises of the following series of greenstone belts (Figure 176):

- Madibe Belt
- Kraaipan Belt
- Stella Belt
- Amalia Belt
The greenstone belts forms the Kraaipan Group which is subdivided into three main formations (Figure 176). The rocks of the basal Gold Ridge Formation are tightly folded, in places isoclinally sheared, and locally brecciated and are strongly metamorphosed (SACS, 1980). It consists of mafic metavolcanic (amphibolite) rocks and associated iron-formation with minor phyllitic, chlorite and calcareous schists and clastic sediments. The Ferndale Formation consists of laminated ferruginous chert and jaspillitic chert which is intensely folded and often show local zones of brecciation, with some interlayered felsic volcanic rocks (rhyolite). The Khunwana Formation is very similar to the Gold Ridge Formation but the
mafic metavolcanic rocks are in places strongly amygdaloidal and display pillow structures (Brandl et al., 2006).

![Lithostratigraphy of the Kraaipan Group](image)

**Figure 177**: Lithostratigraphy of the Kraaipan Group. Modified after SACS (1980).

### 4.17.3. Geohydrology

The Archaean Greenstone Belts of South Africa can all be classified as intergranular and fractured aquifer systems except for the Kraaipan Greenstone Terrain that is classified as a fractured aquifer system.

The geohydrological characteristics of the greenstone belts are discussed below.

#### 4.17.3.1. Barberton Greenstone Belt

**Geohydrological Characteristics**

The rocks of the Barberton Greenstone belt are generally impermeable. Permeability is enhanced by fractures related to faults and intrusive dykes. According to Sami et al. (2002) the meta-basalts prove to be a better aquifer than that of the granites when fractured.

Shallow groundwater strikes indicate the presence of a widespread shallow weathered zone aquifer (intergranular). The deeper fracture systems are of low permeability since yields are low despite high confining heads (Sami et al., 2002).
Borehole Yields
Sami et al. (2002) conducted a yield analysis 64 borehole located within the Barberton Greenstone Belt of which 50 % were dry and the majority of successful boreholes have yields ranging between 0.1 and 0.5 l/s. Thus the Barberton Greenstone Belt can be regarded as a low yielding aquifer system. The average yield calculated is 1.3 l/s with a median yield of 0.4 l/s. Borehole yields greater than 2 l/s are obtainable, with a maximum reported yield of 10 l/s.

Sami et al. (2002) found that there is a distinct relationship between borehole yield and distance to lineaments (Figure 178). From Figure 178 it is clear that the further the borehole is drilled form a lineament, the lower the median yield and a similar relationship exist between success rates and distance to lineaments, with an increasing percentage of dry boreholes being encountered with increasing distances to lineaments.

![Figure 178: Borehole yield and success rate in relation to the distance to mapped lineaments (Sami et al., 2002)](image)

Sami et al. (2002) did a comparison between yield and depth of water strike. The results suggest that the highest yields are associated with shallow water strikes where approximately 50% are above 25 mbgl and about 25% below 60 mbgl.

Water level ranges from 1 to 65 mbgl with a median of 11 mbgl and average of 13 mbgl (Sami et al., 2002).

4.17.3.2. Pietersburg Greenstone Belt

Geohydrological Characteristics
The Mothiba, Eersteling and Zandrivierspoort Formations are the most important units in terms of groundwater. The Mothiba Formation contains isolated basins or zones of weathering that ranges in thickness between 18 and 48 m (Orpen, 1986; Du Toit &
Sonnekus, 2010). The weathered material of these zones is porous to semi-porous and can be saturated with groundwater to within varying depths below ground level (Orpen, 1986).

The permeability of the formations decreases with an increase in the degree of weathering, where amphibolitic rocks tend to produce less clay when weathered than that of granite-gneisses (Orpen, 1986), thus the amphibolitic rocks will have higher permeabilities. The storage capacity of the Pietersburg Greenstone Belts is somewhat limited (Du Toit & Sonnekus, 2010).

The groundwater quality of the Pietersburg Greenstone Belt is generally of good quality with EC values ranging between 27 and 127 mS/m with a harmonic mean of 67 mS/m. Fluoride occasionally exceeds the maximum allowable limit (Du Toit & Sonnekus, 2010).

**Borehole Yields**

The Pietersburg Greenstone Belt can be regarded as a moderate to high yielding aquifer system with 63% of boreholes analysed by Du Toit and Sonnekus (2010) with yields in excess of 2 l/s. 42% of these boreholes have yields greater than 5 l/s. Due to the low storage capacity, over-exploitation may lead to borehole failure (Du Toit & Sonnekus, 2010).

4.17.3.3. **Murchison and Giyani Greenstone Belts**

**Geohydrological Characteristics**

The geohydrological characteristics of the Murchison and Giyani Greenstone Belts are similar to that of the Pietersburg Greenstone Belt.

The groundwater quality of the Murchison Greenstone Belt is not potable due to elevated nitrate values that exceed the maximum recommended limit. The majority of boreholes analysed by Du Toit & Lelyveld (2006) have EC values ranging between 70 and 300 mS/m. Chloride, magnesium and fluoride values occasionally exceed the maximum recommended limits (Du Toit & Lelyveld, 2006).

The groundwater quality of the Giyani Greenstone Belt is generally of good quality. The majority of boreholes analysed by Du Toit & Lelyveld (2006) have EC values less than 70 mS/m with an average of 58 mS/m. Elevated nitrate and magnesium are encountered but is believed to be of local contamination.

**Borehole Yields**

The Murchison Greenstone Belt can be regarded as a low to moderate yielding aquifer system with the majority of borehole yields ranging between 0.5 and 2 l/s of which 20% of
the boreholes analysed was dry. Higher yields are obtainable with a maximum reported yield of 8 l/s (Du Toit & Lelyveld, 2006).

The Giyani Greenstone Belt can be regarded as a moderate to high yielding aquifer system with the majority of borehole yields ranging between 0.5 and 5 l/s with yields of up to 21 l/s (Du Toit & Lelyveld, 2006).

4.17.3.4. Kraaipan Greenstone Terrain

Borehole Yields
The Kraaipan Greenstone Belt is regarded as a low yielding aquifer system. 257 Boreholes was analysed by Van Dyk (2006) of which 233 boreholes were dry. However, high yielding boreholes are obtainable, especially on the contact with granitic rocks (Van Dyk, 2006; 2011).

4.17.4. Locating Groundwater Resources

4.17.4.1. Target Formations and Geological Features
Locating groundwater resources within the greenstone belts terrain can be a difficult task due to the structural complexity of these terrains. Sami et al. (2002) proved that the drilling success rate can be improved dramatically when an evaluation of the structural geology and the hydrogeological conditions of the area together with a suitable geophysical method is applied.

According to Sami et al. (2002) the meta-basalts of the Barberton Greenstone Belt are a far better groundwater target than the granitic plutons when extensively fractured. Fractures in the granites have been intruded by extensive quartz veining, resulting in impermeable conditions and therefore poor groundwater targets.

The specific target features within the rocks of the Barberton Greenstone Belt are as follows (Sami et al., 2002):

I. Steep dipping faults and joint structures.
II. Regional strike-slip faults if no associated shear zone exists.
III. Intrusive dykes and sills (low yielding target).

Sami et al. (2002) made the following conclusions on the specific target features within the Barberton Greenstone Belt:

- Steep dipping fault and joint structures that seem to be open and good targets for groundwater exploration are:
• North to northeast trending conjugate sets with a greater possibility on the northeast trending structures.
• East-west trending structures, that are a result of the north-south wrenching of the crust, linked to the now aborted spreading ridge in the Northern Natal Valley.

East-west striking strike-slip faults are also water-bearing and are associated with the formation of deep open cavities that enhance the permeability of the greenstones. This is only the case if no shear zone is associated with these strike-slip faults as these shear zones produces a clay material that fills the fractures.

Intrusive dykes and sills are not important targets as low yielding boreholes are associated with these structures.

The target formations within the Pietersburg Greenstone Belt are (Du Toit & Sonnekus, 2010):

I. Mothiba Formation.
II. Eersteling Formation.
III. Zandrivierspoort Formation.

The Mothiba Formation seems to be a far better aquifer system than both the Eersteling and Zandrivierspoort Formations. Specific target features within the various formations include the following (Orpen, 1986; Du Toit & Sonnekus, 2010):

I. Regional faults and associated shear zones.
II. Fractures and joints associated with intrusive dykes.
III. Lithological contacts.

The groundwater potential of the Eersteling and Zandrivierspoort Formations are in general low, but strong yielding boreholes, associated with the fractures of the Zandrivierspoort and Eersteling Formations contact zone, have been reported (Du Toit & Sonnekus, 2010).

The specific target features within the Murchison and Giyani Greenstone Belts are very similar to that of the Pietersburg Greenstone Belt. Intrusive dykes of the Giyani Greenstone Belt are also good targets for the developing of successful boreholes (Du Toit & Lelyveld, 2006). It is advisable not to target the Murchison Greenstone Belt for domestic groundwater supply due to the elevated nitrate associated with the groundwater of this greenstone belt.

The specific target feature of the rocks of the Kraaipan Greenstone Terrain is as follows (Van Dyk & Kisten, 2006; Van Dyk, 2011):
I. Contact zone with between rocks of the Kraaipan Greenstone Terrain and granitic rocks.

II. Chert-rich fractured contact zones (±50 mbgl).

Generally, drilling a successful borehole within the rocks the Kraaipan Greenstone Terrain is a difficult task. Therefore it is advisable not to target these rocks unless there is no other option.

4.18. The Limpopo Belt (3 000 – 3 500 Ma)

4.18.1. Location and Extend

The Limpopo Belt is situated in the northern part of the Limpopo Province extending towards Botswana and Zimbabwe (Figure 179). The strike length of the Limpopo Belt is approximately 700 km, with a width of about 200 km. The term Limpopo Orogenic Belt is also used for the whole gneiss province as a whole (Kramers et al., 2006).

4.18.2. Geology

4.18.2.1. Lithostratigraphy

The Limpopo Belt separates the Archaean Zimbabwe Craton from the Kaapvaal Craton in South Africa (Figure 179). The belt can be described in terms of three domains, according to lithological and structural characters, and they are as follows:

- Southern Marginal Zone
- Central Zone
- Northern Marginal Zone

All of these domains are characterised by high-grade metamorphism and the boundaries between these domains, as well as the borders with the Zimbabwe and Kaapvaal Cratons, are prominent shear zones (Kramers et al., 2006). The Northern Marginal Zone will not be discussed, as this thesis focuses on the geology and geohydrology of South Africa.
Southern Marginal Zone

The rocks of this zone are broadly subdivided onto two categories, the grey migmatized tonalitic to trondhjemitic gneisses (Goudplaats-Hout River Gneiss) and the Bandelierkop Complex (Figure 180) comprising metavolcanic and metasedimentary supracrustal rocks occurring as a series of discontinuous infolded keels surrounded by migmatized Goudplaats-Hout River Gneiss (Chinoda et al., 2009). These packages were then intruded by granitoid and syenite intrusions (Kramers et al., 2006). The lithostratigraphy is summarised in Table 33.
Table 33: Simplified lithostratigraphy of the Southern Marginal Zone. Modified after Chinoda et al. (2009).

<table>
<thead>
<tr>
<th>Lithostratigraphic Unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiel Complex</td>
<td>Massive (quartz) syenite in a hornblende granite envelope.</td>
</tr>
<tr>
<td>Palmietfontein Granite</td>
<td>Several plutons of massive fine-to medium grained granite.</td>
</tr>
<tr>
<td>Matok Pluton</td>
<td>Early enderbitic and charnoenderbitic phases followed by porphyritic, uneven-grained granite.</td>
</tr>
<tr>
<td>Onlust Gneiss Pluton</td>
<td>Tonalitic to trondhjemitic granite gneiss with xenoliths of Bandelierkop Complex.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bandelierkop Complex</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelitic Member</td>
<td>Purplish brown, medium-grained gneiss. Lenses of BIF, quartzite and mafic materials occur sporadically.</td>
</tr>
<tr>
<td>Mafic Member</td>
<td>Dark grey to black, fine-textured rock. Serpentinised pyroxenite and Peridotite bodies, usually associated with Goudplaats-Hout River Gneiss.</td>
</tr>
<tr>
<td>Ultramafic Member</td>
<td></td>
</tr>
<tr>
<td>Goudplaats-Hout River Gneiss</td>
<td>Grey, medium-textured tonalitic to trondhjemitic banded migmatites gneiss.</td>
</tr>
</tbody>
</table>

Central Zone

The Central Zone is separated from the Southern Marginal Zone by the Palala-Sunnyside Shear Zone (Figure 179) which is a major east northeast trending, inward dipping, strike-slip shear zone (Basson et al.; Rigby et al., 2011). The Central Zone consists of a wide range of metamorphosed platform sediments, known as the Beit Bridge Complex, quartzo-feldspathic gneisses, tonalitic grey gneisses of the Sand River and Alldays Gneisses and other intrusive rocks with variable composition and age (Holzer et al., 1998).

Due to the great structural complexity and the widely prevailing high-grade metamorphism, stratigraphy and even intrusive relationships between the rock types can, in most places not be readily defined, and for this reason varies age determination studies have been conducted on the rocks of the Limpopo Belt. The lithostratigraphy of the Central Zone is summarised in Table 34 (does not reflect the correct and latest age relationships).
Table 34: Simplified lithostratigraphy of the Central Zone of the Limpopo Belt (SACS, 1980).

<table>
<thead>
<tr>
<th>Lithostratigraphic Unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulai Gneiss</td>
<td>Grey porphyroblastic biotite gneiss of tonalitic composition.</td>
</tr>
<tr>
<td>Messina Suite</td>
<td>Anorthosite and leuco-gabbro with gabbro, chromitite and titaniferous magnetite; sepiolite, metapyroxenite, hornblende.</td>
</tr>
<tr>
<td>Gumbu Group</td>
<td>Calc-silicate rocks and marble with leuco-gneisses, pink hornblende granitoid gneiss, metaquartzite, amphibolite – garnets common.</td>
</tr>
<tr>
<td>Malala Drift Group (Suite)</td>
<td>Leuco-gneiss with metaquartzite, pink hornblende granitoid gneiss, amphibolite, metapelites, calc-silicate rocks.</td>
</tr>
<tr>
<td>Mount Dowe Group</td>
<td>Metaquartzite with leuco-gneiss, magnetite quartzite, pink biotite-hornblende granitoid gneiss</td>
</tr>
<tr>
<td>Sand River Gneiss</td>
<td>Migmatitic grey and leucocratic gneisses – hypersthenes-bearing, of granodiorite composition.</td>
</tr>
</tbody>
</table>

4.18.2.2. Structural Geology

The Central and Southern Marginal Zones of the Limpopo Belt is characterised by east northeast trending fault and shear zones. Structural evidence shows that the Limpopo Belt experienced complex folding and refolding on all scales. The folds of the Central Zone is cylindrical folds that have steep dips and are generally sub-vertical to vertical in attitude. The magnetite quartzite in the north-western part of the area is characterised by tight, isoclinal rootless folds (Chinoda et al., 2009).

The folds of the Southern Marginal Zone are divided into the Zwartrandjes and Sand River Folds. The Zwartrandjes folds lie within the bounds of the granulite grade of regional metamorphism, consisting of two hook folds composed of rocks of the mafic and pelitic members of the Bandelierkop Complex. These folds are associated with vertical foliations trending at 060° and 080° respectively, and contain lineations plunging moderately to the southwest. A third fold occurs further to the south in association with a 105° trending vertical foliation, and containing a strong lineation plunging moderately to steeply to the southwest (Chinoda et al., 2009).

The Southern Marginal Zone is dominated by large crustal blocks of lower strain bounded by kilometre-wide zones of most intense shearing. The southern system of mainly steep, north-dipping, reverse-sense shear zones is collectively referred to as the Hout River Shear Zone.
system and includes the Hout River, Petronella and Matok Shear Zones (Figure 181) that are linked by near vertical, northeast-trending, strike-slip structures (Kramers et al., 2006).

Movement along the fault and shear zones of the Central Zone have been reactivated from Archaean to post-Karoo times. The Palala Shear Zone is probably the most notable. North of the Soutpansberg the east northeast trending faults delineate horst and graben structures that are occupied by Karoo Supergroup strata. The Main faults of this type have been named the Boskokpoort, Tshipise and Klein Tshipise (Vegter, 2001a).

Figure 181: Map of the Southern Marginal Zone showing structural blocks, major shear zones, and the subdivision into a granulite subzone and a zone of rehydration (Kramer et al., 2006).

4.18.3. Geohydrology

Geohydrological Characteristics

The Limpopo Belt can be classified as an intergranular and fractured aquifer system. The aquifers are predominantly structurally controlled as significant groundwater movement is restricted to major fracture and fault zones, primarily related to post-Karoo structures (Sami et al., 2002), even though high residual stress results in open faults and joints to close with depth. The aquifers of the Limpopo Belt is characterised by highly variable secondary aquifer characteristics (Bush, 1989).

The intergranular aquifer system is confined to the weathered zone. These zones of weathering have limited groundwater potential due to its high clay content which reduces its permeability resulting in a poor aquifer, but these saturated weathered zones contributes recharge to local fracture systems (Bush, 1989). Borehole recovery tests done by Sami et al. (2002) on the transition zone between solid rock and the weathered zone suggest that
these aquifers are extensive in nature and flow is radial. According to Sami et al. (2002) groundwater leakage from the overlying saturated weathered zone appears to be restricted to zones where an overlying alluvial aquifer exists. Thus the exploitation potential of these aquifers will therefore be generally be controlled by recharge.

Both Bush (1989) and Sami et al. (2002) depicts that there are no evidence of any aquifer at the lithological contacts of the units of the Limpopo Belt as these contacts have been deformed and metamorphosed in a ductile manner. However, the lithological contacts between the rocks of the Limpopo Belt and that of Karoo or Waterberg/Soutpansberg Supergroups have been subjected to extensive post deposition brittle deformation, associated with a dense fracture network on a macro scale (Sami et al., 2002), thus more favourable aquifer conditions exist.

The occurrence of thermal springs at various places within the Limpopo Belt suggests that there are deeper and longer groundwater flow paths.

According to Bush (1989), recharge to the aquifers of the Limpopo Belt is limited by low rainfall, high evaporative losses, a dense drainage network (Swartwater area) deep weathering and dense vegetation cover (Beauty area).

The groundwater quality of the Limpopo Belt is generally of poor quality. More than 50 % of the 750 water samples analysed by Vegter (2001a) were not potable (Figure 182). Nitrate and fluoride are the two constituents that most commonly exceed the maximum allowable limit.

Figure 182: Distribution of the 750 samples analysed by Vegter (2001a) and their potability status within the Central Zone of the Limpopo Belt.
Borehole Yields

The Limpopo Belt is regarded as a low yielding aquifer system with the majority of boreholes yielding less than 2 l/s, together with a drilling success rate of less or equal to 40% (Vegter, 2001a; Du Toit & Sonnekus, 2011). There are areas where the borehole yields are greater than 5 l/s with maximum reported yields of up to 25 l/s.

Vegter (2001a) statistically analysed boreholes drilled into the rocks of the Limpopo belt in terms of water level frequency, water strike frequency below surface and below water level, cumulative borehole depths, water level and water strike frequencies and yield – strike depth relationship. He found that depending on location the maximum optimal strike depth ranges between 50-85 mbgl and between 15-25 m below water level and concluded that there are no correlation between higher yields and greater strike depth below water level.

West of the Lephalala River excluding the ambience of the Mokolo, Lephalala and Limpopo Rivers, water levels range between 30 and 70 mbgl. This is considerably deeper than elsewhere. From Swartwater eastwards, water levels range between 5 and 45 mbgl. The piezometric configuration of the Beauty area also differs radically from that of the rest of the region, instead of following the topography, the piezometric surface drops below river level as one proceeds away from the Mokolo, Lephalala and Limpopo Rivers (Vegter, 2001a).

4.18.4. Locating Groundwater Resources

4.18.4.1. Target Formations and Geological Features

Groundwater plays a fundamental role within the Limpopo Belt as surface water resources are limited. Both urban and rural communities are dependent on groundwater resources. Larger rivers within the area are also used for water supply, but these rivers do not necessarily have year round flows (Vegter, 2001a). Locating groundwater resources within these rocks can be a difficult task due to the variety of rocks (Haupt, 2012) and their associated groundwater quality.

According to Owen and Madiri (2009) the metaquartzites seems to be the most favourable rock type to target due to its brittle deformational behaviour. The amphibolites should be avoided as these rocks have the tendency to be dry when drilled (Haupt; Mouton, 2012).

The specific target features within the rocks of the Limpopo Belt are as follows:

I. Major regional fault systems (east northeast striking)
II. Transition zone between weathered zone and solid rock.
III. “Blokkies” dolerite dykes that are one to two metres thick.
IV. Lithological contacts between the rocks of the Limpopo Belt and that of Karoo Supergroup or Waterberg/Soutpansberg Groups.

V. Quartz-schist layer between amphibolite and big dolerite dykes (common in Venda area).

It is of upmost importance to conduct the following analysis to locate groundwater resources:

I. Stress field analysis
II. Geomorphic analysis
III. Regolith analysis

See section 3.9.4.1 for a more detail discussion of the above analysis.

The highest yielding boreholes are drilled into east-north-east to east striking faults, the orientation considered as extensional, thus fractures are more open and capable of transmitting groundwater. They are perpendicular to the current stress regime (Holland, 2012). However, the scale of the linear faults shows a strong influence on the yield of the boreholes, with regional scale faults having a far better groundwater potential than local scale structures (Sami et al., 2002).

Hydrogeological and geophysical siting of boreholes done by Vegter (2001a), shown that the probability of striking groundwater within the weathered zone is greatest:

- Where weathering extends to below the piezometric level.
- Where depth of weathering and of the piezometric surface does not exceed 40 m.
- In the first 10 m below the piezometric surface.

The “blokkies” dolerite is a local name for cube like fragments of dolerite due to closely spaced joints. These small dolerites dykes represent a white line on aerial photographs (Google Earth Images) and visible on surface. These structures can be confused with dirt roads as they look very similar on aerial photographs (Haupt; Mouton, 2012). These “blokkies” dolerite have the potential to be good yielding.

Sami et al. (2002) concluded that the lithological contact between overlying Karoo sandstones and that of the Limpopo Belt appears to be dry, unless encountered at an east-north-east tectonic contact.

A common feature within the Venda area is a quartz-schist layer that is situated between the contact of big dolerite dyke intrusion and amphibolite. Mouton (2012) experienced that these structures are reliable target for groundwater resources, with reported yields of up to 15 l/s.
The preferred geophysical methods used to detect these features are:

I. Magnetics
II. Electromagnetics
III. Resistivity

Aerial photographs and geological maps are the main techniques used to detect the geological structures within the rocks of the Limpopo Belt. The geological structures are generally visible on surface and geophysics only applied if it is not visible. The magnetic method is applied to delineate dolerite dykes, whereas the electromagnetic and resistivity methods are used to detect highly fractured zones associated with faults and weathered zones.
CHAPTER 5: CONCLUSION & DISCUSSION

Over 90% of South Africa’s aquifers are classified as secondary aquifer systems (intergranular & fractured). Thus groundwater occurrence within the rocks of South Africa is mainly controlled by secondary fractures systems. Therefore, understanding the geology and geological processes (faulting, folding, intrusive dyke/sills, weathering) responsible for the development of these fracture systems and how they relate the geohydrology becomes an important tool in locating groundwater resources.

The Karoo Supergroup is potentially the largest and most important source of groundwater within South Africa due to its large extend. Other units of importance are the TMG aquifer of the Cape Supergroup and the dolomitic (karst) aquifers of the Transvaal Supergroup that can provide large quantities of groundwater due to its high yielding abilities.

The primary aquifers of South Africa (Coastal Cenozoic Deposits) should not be neglected. These aquifers can produce significant amounts of groundwater, such as the aquifer units of the Sandveld Group, Western Cape Province.

Drilling success rates and possibility of striking higher yielding boreholes can be improved dramatically when an evaluation of the structural geology and the hydrogeological conditions of an area together with a suitable geophysical method is applied.

Table 35 provides a tabular summary to give a short description of the geological units of South Africa, considering the location and extend the general geology and geohydrology, and locating groundwater resources.
Table 35: Summary of the relation between South African geology and geohydrology.

<table>
<thead>
<tr>
<th>Geological Units of South Africa</th>
<th>Location and Extend</th>
<th>General Geology</th>
<th>General Geohydrology</th>
<th>Locating Groundwater Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Cenozoic Deposits</td>
<td>Developed along the coastal plain of South Africa.</td>
<td>Divided into seven groups, predominantly consisting of recent windblown dune sands, cycles of semi-to well consolidated calcareous sandstones, pebbly coquina, gravels and conglomerates. Limestone, mudstone,ignite, organic rich palaeosols and calcrite lenses are also present. Fossils fairly common.</td>
<td>Primary aquifer systems that is unconfined to semi-confined. Shallow groundwater levels (2-5 mbgl). Potentially able to yield large &amp; reliable quantities of water. Groundwater quality generally potable but vulnerable to pollution, especially in densely populated areas such as the Cape Flats. Sodium and chloride occasionally exceeds the maximum recommended limits.</td>
<td>Specific target features include – Coarse grained sands, conglomerate deposits &amp; palaeo-channels. Good saturation thickness acquired to obtain good yielding quantities of water. Geophysics used – Electromagnetics and resistivity.</td>
</tr>
<tr>
<td>Kalahari Group</td>
<td>Situated in the Northern Cape Province adjacent to the Botswana and Namibia Borders.</td>
<td>Six formations displaying a considerable lateral variation. Consisting of a clayey basal poorly-to moderately sorted gravel. Best develop in deeper palaeo-valleys. Overlain by red &amp; brown calcareous clays interbedded with gravel, poorly consolidated sandstones (locally thin pebble beds), calcrite with pebble layers &amp; red aeolian sands. Eroded Dwyka pebble and boulder clasts also present.</td>
<td>Complex, primary aquifer system with groundwater levels varying between 40 &amp; 50 mbgl with reported levels exceeding 120 mbgl. Recharge limited &amp; occur when rainfall is higher than normal or during flooding of river systems present. Yields generally vary between 0.2 &amp; 1 l/s; yields tend to increase with depth but the salinity usually increases as well. Groundwater quality complex; vary both vertically and horizontally – EC values can increase two or more fold within a metre in depth and in profile.</td>
<td>Groundwater generally intercepted in the lowest most formations (Wessel's, Budin &amp; Eden Formations). Specific target features include – Palaeo-valleys/channels, regional fault systems &amp; current river channels on the boundaries of the Kalahari Group, but where the thickness is no more than 180m. Best approach in locating groundwater is to map the palaeo-floor (Karoo landscape) using available borehole logs in locating the target features.</td>
</tr>
<tr>
<td>Zululand Group</td>
<td>Outcrops as a narrow north-south trending belt from just north of Ndumo southwards to Mtubatuba.</td>
<td>Three formations unconformably overlying rocks of the Lebombo Group, consisting of a basal conglomerate followed by glauconitic siltstone with interbedded sandstone.</td>
<td>Extremely poor aquifer &amp; regarded an aquiclude. Groundwater highly saline with EC values exceeding 800 mS/m.</td>
<td>Advisable not to target for groundwater resources.</td>
</tr>
<tr>
<td>Uitenhage Group</td>
<td>Occurs in half-graben-type basins developed along the southern margin of South Africa from Port Elizabeth to Worcester</td>
<td>Three formations, all recognised in Algoa Basin &amp; one/two in the other basins. Overlies rocks of the Cape Supergroup. Basal unit of alluvial piedmont fans consisting of conglomerate with metre-thick lenses silty sandstone. Overlain by two thick cycles of dark shales siltstone and minor sandstone.</td>
<td>Fractured aquifer system. Overlying mudstones acts as aquitard resulting in artesian &amp; sub-artesian condition within the lowermost formations. Recharge of basal sandstones occurs by lateral &amp; vertical pressure leakage from bounding TMG quartzite units. Low yielding aquifer; yields rarely exceed 1 l/s. Poor quality groundwater: EC commonly in excess of 300 mS/m. Sodium, magnesium, chloride, total alkalinity, sulphate &amp; fluoride regularly exceed maximum recommended limits.</td>
<td>Advisable not to target for groundwater resources, but in the case of the Uitenhage Basin, rather to target the underlying TMG aquifer.</td>
</tr>
<tr>
<td>Geological Units of South Africa</td>
<td>Location and Extend</td>
<td>General Geology</td>
<td>General Geohydrology</td>
<td>Locating Groundwater Resources</td>
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<tr>
<td>Karoo Supergroup</td>
<td>Covers approximately two thirds of South Africa’s surface, preserved in four different basins and a narrow strip along the Mozambique-South Africa border. Main Karoo Basin covers the largest area.</td>
<td>Six main groups consisting of a basal diamictite unit with minor conglomerate, pebbly sandstone &amp; mudrock. The overlying units consist of cycles of sandstone &amp; subordinate mudrock/rhythmite or shale, mudrock/rhythmite with subordinate sandstone. The top unit consist of basaltic lava. The rocks have been intruded by dolerite dykes &amp; sills, breccia plugs, volcanic vents, kimberlite &amp; associated alkaline intrusive complexes.</td>
<td>Dwyka Group: Fracture aquifer system considered an aquitard rather than aquifer. Low yielding aquifer; yields below 0.5 l/s. Drilling success rate of 30 to 40 %. Good to moderate groundwater quality – EC worst (±300 mS/m) along coastal zone &amp; improves inland. Other Sedimentary Units: Intergranular &amp; fractured aquifer systems with a complex geometry. Shale units vertically act as aquitard &amp; horizontally as aquifer – “aquitardifer”. Mudstones of Elliot Formation acts as aquitard (dry when drilled). Porosity decrease from north to south (0.1 to &lt;0.02). Low yielding aquifers; yields range between 0.1 &amp; 2 l/s, but higher yields obtainable. Good to moderate quality groundwater – EC generally less than 300 mS/m, more saline in drier regions. Sodium, magnesium &amp; chloride occasionally exceed maximum allowable limits. Dwyka Group: Fracture aquifer system considered an aquitard rather than aquifer. Low yielding aquifer; yields below 0.5 l/s. Drilling success rate of 30 to 40 %. Good to moderate groundwater quality – EC worst (±300 mS/m) along coastal zone &amp; improves inland. Other Sedimentary Units: Intergranular &amp; fractured aquifer systems with a complex geometry. Shale units vertically act as aquitard &amp; horizontally as aquifer – “aquitardifer”. Mudstones of Elliot Formation acts as aquitard (dry when drilled). Porosity decrease from north to south (0.1 to &lt;0.02). Low yielding aquifers; yields range between 0.1 &amp; 2 l/s, but higher yields obtainable. Good to moderate quality groundwater – EC generally less than 300 mS/m, more saline in drier regions. Sodium, magnesium &amp; chloride occasionally exceed maximum allowable limits.</td>
<td>Specific target features – Weathered &amp; fractured zones associated with faulting &amp; folding, intrusive dolerite dyke &amp; sill/ing contact zones, breccia plugs &amp; volcanic vents, lithological contact zones, bedding-parallel fractures &amp; transition zone between weathered and hard rock. Geophysics used – Magnetics, electromagnetics &amp; resistivity.</td>
</tr>
<tr>
<td>Dwyka Group</td>
<td></td>
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<tr>
<td>Karoo Dolerite Suite</td>
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<tr>
<td>Drakensberg &amp; Lebombo Groups</td>
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<td>Dolerite Breccia Plugs &amp; Volcanic Vents</td>
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<td>Kimberlite &amp; Associated Alkaline Intrusive Complexes</td>
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<td>Geological Units of South Africa</td>
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<td>Cape Supergroup</td>
<td>Three groups characterised by a series of northwest-to-north-trending folds in the west, stretching from Stellenbosch northwards to Vanrhynsdorp, and by folds striking approximately east-west in the central and eastern areas, from Swellendam eastwards to the Great Fish River mouth in the east. Consists mainly of sandstone/quartzites with minor mudstone, siltstone, shale &amp; conglomerate.</td>
<td>Fractured aquifer system.</td>
<td><strong>Table Mountain Group:</strong> Deep groundwater circulation; thermal springs are common. High direct recharge form both rain &amp; snowmelt. High yielding aquifer; yields increase with increasing depth – main groundwater intersections greater than 100 mbgl. Good quality groundwater – EC range between 10 &amp; 100 mS/m. Iron occasionally exceed maximum allowable limit. <strong>Bokkeveld Group:</strong> Enhanced recharge along cross-cutting structures from TMG. Low yielding aquifer; yields less than 1 l/s, but yields greater than 5 l/s obtainable if recharge conditions are favourable. Good to bad quality groundwater – EC range between 30 &amp; 400 mS/m; Steytlerville area &amp; west of Port Alfred EC commonly greater than 200 mS/m. Sodium, magnesium, chloride &amp; sulphate occasionally exceed maximum allowable limits. <strong>Witteberg Group:</strong> Low yielding aquifer; yields rarely exceed 2 l/s – more research need to be done. Good to bad quality groundwater – EC of shale units 200 to 700 mS/m; EC of sandstone units 70 – 150 mS/m. Sodium, chloride &amp; total alkalinity occasionally exceed maximum allowable limits.</td>
<td>TMG main drilling target. Target formations – Peninsula, Nardouw, Piekierskloof &amp; Lower Bokkeveld formations. Specific target features – Major regional fault systems, localised fractures/faults associated with folding &amp; other local stress fields, &amp; bedding plane/contact zones. Aerial photographs &amp; geological maps main techniques used to detect these structures. Geophysics used – Electromagnetics &amp; resistivity.</td>
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<td>Natal Group</td>
<td>Depositional basin extends from Hlabisa southwards to Port Shepstone, approximately parallel to the Kwazulu-Natal coastline. Outcrops as two sub-parallel belts, separated by basement rocks.</td>
<td>Two formations where the lower unit consist of clast-supported conglomerate followed by arkosic sandstone. Whereas the upper unit consists of small pebble conglomerate followed by arkosic sandstone and matrix supported conglomerate. Upper part of lower unit more resistant; more prominent than upper unit.</td>
<td>Fractured aquifer system with negligible primary porosity &amp; permeability. Seems to be better aquifer than surrounding lithologies (hydraulic conductivity 0.4 to 7.7 m/day). Exploited on limited basis, compared to drier parts in South Africa. Good quality water; interior area better than coastal area - EC generally below 100 mS/m. Moderate to low yielding aquifer; median yield 0.1 to 2 l/s, but up to 10 l/s can be obtained. Drilling success rate 60 to 90 %.</td>
<td>Specific target features include – major regional fault systems, dolerite dyke intrusions &amp; bedding planes/contact zones. Faults may be silicified, decreasing changes of intercepting high yielding aquifer. Geophysics used – magnetic, electromagnetic &amp; resistivity.</td>
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<td>Malmesbury Group</td>
<td>Situated in the Western Cape Province, extending southwards from Redelinghuys to just south of Stellenbosch.</td>
<td>Three tectonostratigraphic terranes separated by northwest-trending fault/shear zones and intruded by granitoids of the Cape Granite Suite. Tygerberg Terrane characterised by rhythmical alterations of greywacke, shales, siltstone, immature quartzites &amp; conglomerate beds. Volcanic succession locally developed. Swartland &amp; Boland Terrane consists of schist &amp; greywacke, with interbedded phyllite &amp; limestone, followed by conglomerate and quartzite. Metavolcanic sequences also present. Intruded by porphyry dykes &amp; sills.</td>
<td>Fractured aquifer system that tends to be confined to semi-confined. Groundwater level variable; ranges between 5 &amp; 30 mbgl. Low yielding aquifer; yields generally below 2 l/s, but yields up to 12 l/s have been encountered. Variable groundwater quality with better qualities where groundwater movement takes place; closer to coast tendency to be more saline than further inland – EC ranges between 10 &amp; 1 000 mS/m. Sodium, magnesium, chloride &amp; sulphate occasionally exceed maximum recommended limits.</td>
<td>Advisable to only target when no other more favourable aquifer exists. Arenaceous units more reliable targets. Specific target features include – Major regional fault zones and their associated fracture zones, contact zone with Cape Granite Suite &amp; areas where arenaceous units are overlain by alluvium. Geophysics used – Electromagnetics &amp; resistivity.</td>
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<td>Geological Units of South Africa</td>
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<td><strong>Namaqua-Natal Metamorphic Province</strong></td>
<td>Occurs along the southern and south western margin of the Kaapvaal Craton, bounded in the west by and south by the Gariep and Saldania Belts respectively. Outcrops in the Northern Cape (Namaqua Sector) and KwaZulu-Natal (Natal Sector).</td>
<td>Highly deformed tectonostratigraphic subprovinces &amp; terranes based on marked changes in lithostratigraphy across structural discontinuities. Namaqua Sector – consists of granitic basement complexes, supracrustal sequences, intrusive gabbro, granitic to charnockitic complexes/plutons, &amp; dyke swarms. Immature, occasionally migmatized sediments do occur. Natal Sector – consists of supracrustal gneisses, granitoid gneisses &amp; intrusive rocks of various compositions.</td>
<td>Intergranular &amp; fractured aquifer systems. <strong>Namaqua Sector:</strong> Recharge favoured by shallow sandy soil, calcrite, &amp; exposures of fractured rocks. Complex groundwater flow of local, intermediate &amp; regional flow regimes. <strong>Natal Sector:</strong> Weathered zone have high porosity with low hydraulic conductivity (high clay content). Weathered zone in hydraulic connectivity with underlying fractured bedrock. Low yielding aquifer; yield range 0.1 to 0.5 l/s. Drilling success rate of 70%. Good quality groundwater – Fluoride occasionally exceeds maximum allowable limits.</td>
<td><strong>Namaqua Sector:</strong> Specific target features – Regional fault systems, weathered zones, ephemeral rivers &amp; palaeo-channels, igneous dyke intrusions &amp; contact zones between intrusions &amp; host rock. Important to conduct stress field, geomorphic &amp; regolith analysis. Geophysics plays minor role; structures usually visible on surface. Geophysics used – Resistivity &amp; magnetics. <strong>Natal Sector:</strong> Specific target features – Major fault systems, dolerite dyke intrusions &amp; weathered zone.</td>
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<td><strong>Waterberg Group</strong></td>
<td>Occurs within the Limpopo, Gauteng and Mpumalanga Provinces, covering an area of approximately 20 000km². Three depositional basins, consisting predominantly of massive quartzite &amp; sandstone units with alternating units of conglomerate, girt and mudstone/siltstone. Intrusive volcanic rocks and tuff occurs occasionally.</td>
<td>Fractured aquifer system with a very low storage capacity. Average groundwater level ranges between 10 &amp; 40 mbgl. Low yielding aquifer; yields range between 0.5 &amp; 2 l/s – yields greater than 3 l/s obtainable in fault and fracture zones. Drilling success rate very low. Variable groundwater quality – EC ranges in eastern parts 2 to 50 mS/m, central parts 10 to 400 mS/m &amp; towards Betswana border up to 1 100 mS/m.</td>
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<td><strong>Specifc target features</strong> – Regional fault/fracture systems, contact zone between sediments and intrusive dykes/sills &amp; fractures related to anticlines &amp; bedding planes. Aerial photographs &amp; geological maps main techniques used to detect these structures. Geophysics used – Electromagnetics, resistivity &amp; magnetics.</td>
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<td><strong>Soutpansberg Group</strong></td>
<td>Occurs within the Limpopo Province as a mountainous wedge-shape terrain, partially buried beneath Karoo Supergroup rocks. Six formations, extensively faulted, unconformably overlying Archaean granite gneisses, as well as rocks of the Blouberg Formation. Base dominated by massive basicall lavas with intercalated pyroclastic &amp; sandstone lenses. Followed by thick succession of quartzite &amp; sandstone with thin pyroclastic and conglomerate beds, and intercalated basaltic lava.</td>
<td>Intergranular &amp; fractured aquifer system. Water strikes ranges between 30 &amp; 60 mbgl. Low to moderate yielding aquifer; yields range between 0.5 &amp; 2 l/s – yields greater than 5 l/s obtainable with reported yields of 22 l/s. Variable groundwater quality – EC ranges between 3 &amp; 912 mS/m; poorer water near rural villages, indicating poor sanitation practices. Fluoride, sodium, magnesium, nitrate &amp; chloride occasionally exceed maximum allowable limits.</td>
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<td>Geophysics plays a minor role; structures usually visible on surface. Geophysics used – Resistivity &amp; magnetics.</td>
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<td><strong>Bushveld Igneous Complex</strong></td>
<td>Situated north and northeast of Pretoria stretching across the Limpopo North West, Mpumalanga and Gauteng Provinces. Covers an area of approximately 65 000km². Intruded into the Transvaal Supergroup, characterised by magmatic layering with rock types ranging from dunite &amp; pyroxenite through norite gabbro &amp; anorthosite to diorite. Intruded by various granite &amp; granophyre suites, followed by a major felsic volcanic succession of andesites, dacites &amp; rhyolites, interbedded with interbedded sedimentary rocks.</td>
<td>Intergranular &amp; fractured aquifer system. Groundwater level ranges between 5 &amp; 40 mbgl. Weathered zone low to moderate transmissivity with high storativity. Recharge to fractured aquifer by weathered zone – mafic rocks weatherings to clay-rich soil with low permeability. Low to moderate yielding aquifer; yields generally below 2 l/s – yields greater than 5 l/s are obtainable. Drilling success rate in Lebowa Granite Suite 20 %. Good groundwater quality; sometimes not suitable for domestic use – Average EC ranges 31 to 105 mS/m. Chloride, fluoride, nitrate &amp; sulphate occasionally exceed maximum allowable limits.</td>
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<td>Specific target features – Transition zone between weathered zone &amp; solid rock, contact zone between intrusive dykes &amp; host rock, faults &amp; their associated shear &amp; fracture zones &amp; intrusive carbonate complexes. Geophysics used – Electromagnetics, magnetics &amp; resistivity. Geology must be fully understood to interpret geophysical data.</td>
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<td>Geological Units of Africa</td>
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<td><strong>Witwatersrand Supergroup</strong></td>
<td>Griqualand West Basin – situated in the Northern Cape and North West Provinces, extending from Prieska southwards to south of Vryburg. Transvaal Basin – stretches over the North West, Gauteng, Mpumalanga and Limpopo Provinces, intruded by the Bushveld Igneous Complex.</td>
<td>Two depositional basins consisting of a basal unit comprising predominantly of quartzite &amp; siltstone, with lenses of grit &amp; conglomerate. Following by a thick series of dolomites &amp; limestones with interbedded chert &amp; shales followed by BIF with minor jaspilite amphibolite &amp; subordinate shale. Top unit consist of an alteration of mudrock &amp; quartzite with subordinate conglomerates, diamictite &amp; limestone with minor BIF &amp; shale. Interbedded volcanic units also present.</td>
<td>Intergranular, fractured &amp; karst (most important) aquifer system. Good to moderate groundwater quality – average EC ranges between 34 &amp; 68 mS/m, maximum values ranges between 139 &amp; 397 mS/m; EC of 1089 mS/m have been reported in Pretoria Group. Chloride, fluoride, nitrate, sodium &amp; sulphate occasionally exceed maximum allowable limits – due to mining, agricultural, pit latrines/cattle kraals. <strong>Black Reef &amp; Vryburg Formations:</strong> Regionally acts as groundwater flow barrier, producing shallow groundwater levels. Low to moderate yielding aquifers; yields below 2 l/s, but yields greater than 5 l/s are obtainable. <strong>Chuniespoort &amp; Ghaap Groups:</strong> Compartimentalised by intrusive dykes – compartments characterised by low groundwater level gradients &amp; marked discontinuity at dykes. Abundance of springs (2 to 2 000 l/s). Recharge percentage ranges from 2 to 20. Moderate to very high yielding aquifers; yields commonly greater than 2 l/s with reported yields of up to 128 l/s. Vulnerable to pollution. <strong>Pretoria &amp; Postmasburg Groups:</strong> Low to moderate yielding aquifers; yields ranging from below 2 l/s &amp; exceeding 5 l/s, with reported yields of 20 l/s.</td>
<td>Dolomite rocks of Ghaap &amp; Malmani Subgroups are the main drilling targets. Most important target formations – Schmidsdrif &amp; Campbell Rand Subgroups (Ghaap), &amp; Malmani Subgroup (Chuniespoort). Specific target features – Karstification zones, Dolerite/diabase intrusive dykes, &amp; major regional fault systems. Geophysical methods used – Gravity, electromagnetics &amp; magnetics.</td>
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<td><strong>Ventersdorp Supergroup</strong></td>
<td>Outcrops within the Gauteng, North West and Northern Cape Provinces, extending from Johannesburg to southwest of Kimberley.</td>
<td>Two lower groups overain by two upper formations unconformably overlying rocks of the Witwatersrand Super group. Consists of a basal conglomerate conformably overlain by komatiitic lava followed by mafic lava. Unconformably overlain by conglomerate, quartzite, shale, limestone &amp; mafic to felsic volcanic rocks.</td>
<td>Intergranular &amp; fractured aquifer system characterised with very low porosities &amp; hydraulic conductivities. Shallow groundwater levels; ranging between 5 &amp; 40 mbgl. Low yielding aquifer; yields below 2 l/s, but yields greater than 2 l/s can be obtained with reported yields up to 20 l/s. Drilling success rate of 40 to 60 %. Good quality groundwater – EC average of 60 mS/m with maximum of 264 mS/m. Sulphate occasionally exceeds maximum allowable limit (max 1 038 mg/l).</td>
<td>Specific target features – Deep weathered basins, transition zone between weathered zone &amp; solid rock, regional faults &amp; their associated shear &amp; fracture zones, &amp; dolerite/diabase intrusive dykes. Best target is deepest part of a weathered basin. Soils above dykes are clayey &amp; brackish, thus easily traced on surface. Geophysics used – Magnetics, electromagnetics &amp; resistivity.</td>
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<td><strong>Two groups conformably &amp; unconformably overlying rocks of the Dominion Group &amp; Archaean basement rocks. Predominantly consists of quartzite &amp; shales with minor conglomerate, diamictite &amp; volcanic rocks.</strong></td>
<td>Fractured aquifer system. Shallow groundwater levels (10 – 25 mbgl). Recharge promoted by weathered sandy soil. Discharge generally through springs/seeps along floors &amp; slopes of principle valleys. Low to moderate yielding aquifer; yields greater than 5 l/s obtainable, maximum reported yield of 30 l/s. Large volumes of groundwater flow into deep gold mines along fault zones. Good quality groundwater – EC average of 39 mS/m with maximum of 256 mS/m. Chloride &amp; sulphate occasionally exceed maximum recommended level – influence of mining activities.</td>
<td>Specific target features – Contact zone between sediments &amp; intrusive sills, deeply weathered shale formations, weathered lithological contacts &amp; bedding planes, &amp; regional faults &amp; their associated shear and fracture zones.</td>
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| **Transvaal Supergroup** | Mostly covered by younger rocks, outcrops occurring within the Gauteng, North-West and Free State Provinces. Largest gold deposit in the world. | Two groups conformally & unconformably overlying rocks of the Dominion Group & Archaean basement rocks. | Fractured aquifer system. Shallow groundwater levels (10 – 25 mbgl). Recharge promoted by weathered sandy soil. Discharge generally through springs/seeps along floors & slopes of principle valleys. Low to moderate yielding aquifer; yields greater than 5 l/s obtainable, maximum reported yield of 30 l/s. Large volumes of groundwater flow into deep gold mines along fault zones. Good quality groundwater – EC average of 39 mS/m with maximum of 256 mS/m. Chloride & sulphate occasionally exceed maximum recommended level – influence of mining activities. | Specific target features – Contact zone between sediments & intrusive sills, deeply weathered shale formations, weathered lithological contacts & bedding planes, & regional faults & their associated shear and fracture zones. |
### Geological Units of South Africa

<table>
<thead>
<tr>
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<th>Locating Groundwater Resources</th>
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<td><strong>Pongola Supergroup</strong></td>
<td>Situated along the south-eastern part of the Kaapvaal Craton in Mpumalanga and KwaZulu-Natal Provinces covering an area of approximately 27,500 km². Large area removed by erosion, destroyed by granitic intrusions and buried beneath younger rocks.</td>
<td>Two groups unconformably overlying Archaean granites. Lower group predominately consists of interfingering basalts &amp; pyroclastics, basaltic anidesites and dacites, &amp; minor sequences of sandstone, mudstone &amp; conglomerate. Upper unit consists predominantly of alternating shales sandstone conglomerate &amp; minor BIF &amp; volcanic rocks.</td>
<td>Intergranular &amp; fractured aquifer system. Low to moderate yielding aquifer. Geohydrological data very limited—further research need to be conducted.</td>
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<td><strong>Archaean Granites and Gneisses</strong></td>
<td>Outcrop at various localities, with most prominent outcrop situated in the north-eastern parts of South Africa, stretching from the northern parts of Limpopo southwards towards the Mpumalanga-Swatiland border.</td>
<td>Consists of wide variety of granitoid gneisses &amp; granite suites of various types &amp; compositions. Intruded by stock-like biotite gneiss &amp; completely folded in areas.</td>
<td>Intergranular &amp; fractured aquifer system, semi-confined to confined. Average transmissivity values of Limpopo Plateau higher than Lowveld Region. Polokwane Plateau moderate to high yielding aquifer (younger granites low yielding); yields range 2 to 5 l/s – Dendron area characterised by high yields. Lowveld Region low to moderate yielding aquifer; yields range 0.1 to 2 l/s. Good quality groundwater – EC average of 43 to 214 mS/m. Nitrate, magnesium, fluoride, &amp; chloride occasionally exceed maximum recommended limits.</td>
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<td><strong>Archaean Greenstone Belts</strong></td>
<td>Linear to irregularly shaped features situated on the Kaapvaal Craton of South Africa. Barberton Greenstone Belt occurs in the eastern part of Mpumalanga just north of Swaziland. Pietersburg, Murchison and Giyani belts is situated in the central to eastern parts of the Limpopo Province. Kraaipan belt stretches from the southern parts of the North West Province northwards to the Botswana-North West border.</td>
<td>High deformed &amp; metamorphosed rocks consisting of mafic, ultramafic to felsic volcanic rocks &amp; sedimentary rocks. Sedimentary rocks ranges from conglomerate, sandstone siltstone BIF, mudstone &amp; carbonaceous rocks. Pyroclastics, amphibolite, breccias &amp; gneisses are also present.</td>
<td>Intergranular &amp; fractured aquifer systems except Kraaipan Greenstone Terrain which is a fractured aquifer system. Groundwater quality generally good, except for Murchison Greenstone Belt that is not potable. Chloride, magnesium, fluoride &amp; nitrate occasionally exceed maximum recommend limits. Specific target features – Steep dipping faults &amp; joint structures, regional strike-slip faults if no associated shear zone exists &amp; intrusive dykes &amp; silts.</td>
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<td>Geological Units of South Africa</td>
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<td>Limpopo Belts</td>
<td>Situated in the northern part of the Limpopo Province extending towards Botswana and Zimbabwe. Strike length of approximately 700 km, with a width of about 200 km.</td>
<td>Central &amp; Southern Marginal Zones separated by Palala-Sunnyside Shear Zone. Characterised by high-grade metamorphism &amp; east northeast trending fault &amp; shear zones. Complex folding. Consists of migmatized tonalitic to trondhjemitic gneisses, metavolcanic &amp; metasedimentary supracrustal rocks, &amp; intrusives of variable composition.</td>
<td>Intergranular &amp; fractured aquifer system, predominantly structurally controlled. High clay content of weathered zone limits the groundwater potential, but contributes recharge to local fracture systems. Deep groundwater circulation – thermal springs Low yielding aquifer; yields generally below 2 l/s, but yields greater than 5 l/s obtainable with maximum reported yield of 25 l/s. Poor quality groundwater. Nitrate &amp; fluoride commonly exceed maximum allowable limits.</td>
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CHAPTER 6: REFERENCES


Parsons, R., 2011a. *Geohydrology of the Western Cape Province* [Interview] (23 March 2011a).


Weaver, J. M. C., 2011. *Geohydrology of the Western Cape* [Interview] (24 March 2011).


APPENDIX A

Groundwater Regions and Simplified Geology of South Africa
Figure 183: Groundwater Regions of South Africa (Vegter, 2001).
Figure 184: Simplified geology map of South Africa (Council for Geosciences).
APPENDIX B

Correlation of the Transvaal Supergroup in the Griqualand West and Transvaal Basin and Dolomitic Compartments of the Transvaal Supergroup
Table 36: Correlation of the Transvaal Supergroup in the Griqualand West and Transvaal Basin. Modified after (Eriksson et al., 2006).

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<th>GRIQUALAND WEST BASIN</th>
<th>TRANSVAAL BASIN</th>
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<td>Clastic sediments and volcanic rocks</td>
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<td></td>
<td>Postmasburg Group</td>
<td>Pretoria Group</td>
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<td>Voëlwater Subgroup</td>
<td>Rayton Formation (sandstone, shale, volcanic rocks)</td>
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<td>Moordraai Formation (dolomites)</td>
<td>Magaliesberg Formation (sandstone)</td>
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<td>Hotazel Formation (manganeseiferous ironstone)</td>
<td>Silverton Formation (shale, lava)</td>
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<td>Ongeluk Formation (andesite)</td>
<td>Daspooi Formation (sandstone)</td>
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<td>Makganyene Formation (diamictite)</td>
<td>Strubenkop Formation (shale)</td>
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<td>Dwaalheuwel Formation (sandstone)</td>
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<td>Regional Unconformity</td>
<td>Hekpoort Formation (andesite)</td>
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<td>Boschok Formation (conglomerate, sandstone)</td>
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<td>Rooihoopte Formation (conglomerate, sandstone)</td>
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<td>Chemical sediments</td>
<td>Ghaap Group</td>
<td>Deutschland Formation (carbonate &amp; clastic rocks)</td>
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<td>Koegas Subgroup/Asbestos Hill Subgroup</td>
<td>Penge Formation (iron-formation)</td>
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<td>Campbell Rand Subgroup</td>
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<td>Various Formations (dolomite)</td>
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<td>Schmidtbril Subgroup</td>
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<td>Clearwater (shale) &amp; Boomploaas (dolomite) Formations</td>
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<td>Vryburg Formation (mixed)</td>
<td>Black Reef Formation (quartzite)</td>
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<td>Pre-Black Reef units – Wolkberg Group &amp; correlates</td>
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Figure 185: Hydrogeological units/compartments of the Chuniespoort and Ghaap Groups (Courtesy of Martin Holland)
Figure 186: Lithostratigraphy of the Witwatersrand Supergroup (McCarthy, 2006).