A BASELINE STUDY TO EVALUATE THE GROUNDWATER CONDITIONS AND PREDICT FUTURE IMPACTS OF MINING AT MATSOPA MINERALS

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DECLARATION

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

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

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Psalm 23: 6

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CHAPTER 1:
INTRODUCTION

1.1 GENERAL

Mining is the extraction of valuable mineral resources from the subsurface of the earth. Mining operations take place as opencast mines, which are shallow, and deep underground mines, which occur at great depth under the subsurface, with the deepest mine in world being Anglo Gold Ashanti's Mponeng Gold Mine south-west of Johannesburg, South Africa (Winde and Stoch, 2010). Mining is an activity that is of economic importance not only locally but globally. In South Africa the economy is strongly dependent on the mining sector. Amongst precious metals and minerals, industrial minerals such as bentonite are mined. Clay mineral deposits (including bentonite) are mined in the Free State and Western Cape Provinces (Figure 1-1). The mining operations of the current study are located in the northern Free State Province, in the Koppies area.

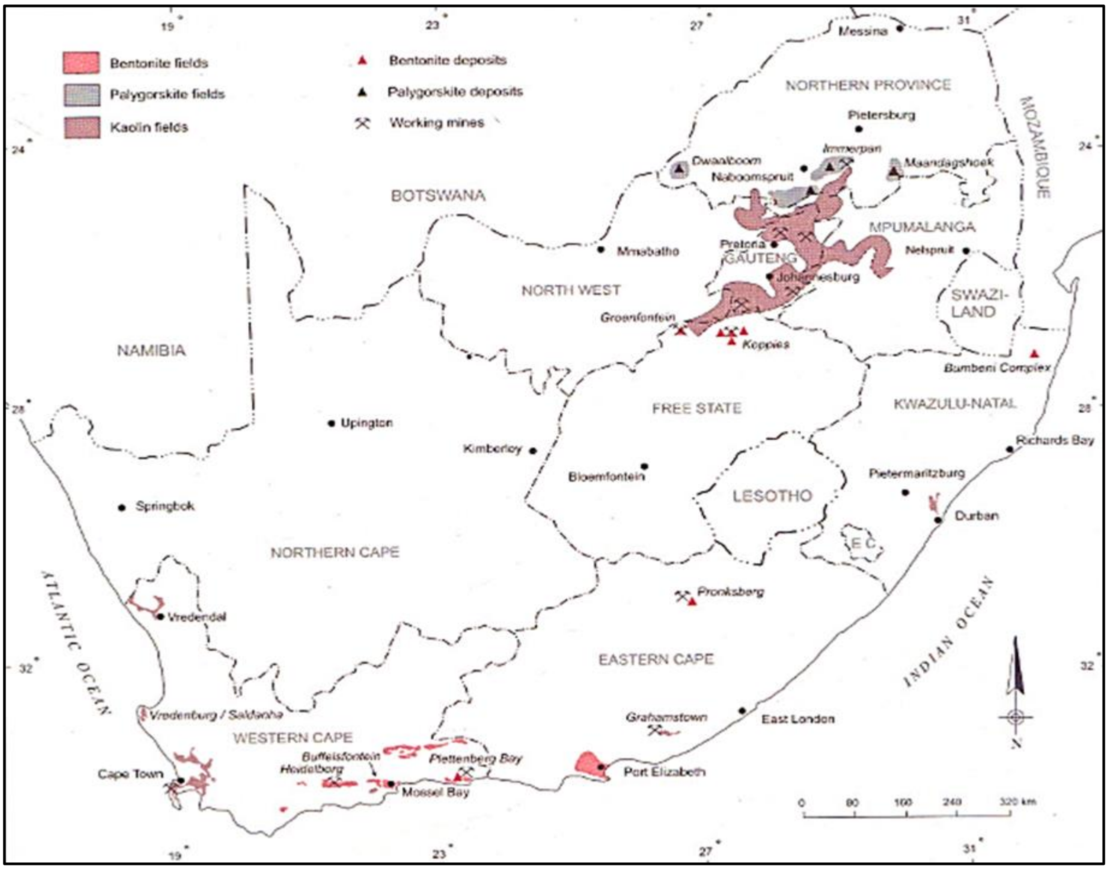


Figure 1-1: The distribution of clay mineral deposits in South Africa (source: Horn and Strydom, 1998)

The mining of bentonite at Koppies has been taking place since the 1950s and at that stage the bentonite occurred at surface (Horn and Strydom, 1998). The mine operated by Matsopa Minerals (Pty) Ltd is divided into two sections, namely: the Ocean and Blaauwboschpoort Mines. The Ocean Mine has been rehabilitated, while current mining operations take place at Blaauwboschpoort Mine. The latter mine is an opencast mine with a bench of 20 m.

The bentonite mining operations have taken place over a long period of time (60 to 70 years) and it is of great interest to conduct a study relating to the groundwater conditions of the area. A baseline study was proposed to determine the groundwater conditions and the influence of the mining on the groundwater system. However, since the mining operations at Matsopa Minerals Mine are well in the brownfields stage, the results of the current research study will not yield information on the true baseline conditions prior to mining. Rather, the study will provide information on the current conditions which can then be used as a benchmark against which the results of future investigations can be compared to evaluate the impacts of mining on the groundwater system.

Besides mining, farming is also practised in this study area. Mining operations make use of water and this can put stress on water resources as South Africa is a water-scarce country. In South Africa the mining industry is a large consumer of water resources (Tewari, 2012). Due to the scarcity of water in the country, some parts rely on groundwater as a source of water. The study area in which the mine is located is no different and suffers from water scarcity, therefore the mine and its surrounding community solely depend on groundwater as a water source. According to the DWA (2012) the utilizable groundwater exploitation potential in South Africa is estimated at 10 300 million m^3 per year (7 500 million m^3 in a drought year), allowing factors such as physical constraints on extraction, potability, and a maximum allowable drawdown. The groundwater in study area of the current investigations is of importance and should therefore be protected and monitored.

Investigating the current groundwater conditions is required to determine the groundwater quality since the water quality should be suitable for human consumption. Determination of the presence of contaminants in the groundwater of the area will give an indication of the quality of the groundwater and the risk associated with the use of the contaminated water. Most mining areas are associated with contamination of groundwater, and South Africa is faced with water quality challenges which are mainly induced by human activity. The problems arise from industries which produce chemical waste and acidic and metal-rich water from mining (Tewari, 2012). As contamination can be confused with pollution, Freeze and

Cherry (1979) defined contaminants as all solutes introduced into the hydrologic environment as a result of human activities regardless of whether or not the concentrations reach levels that cause degradation of water quality. Pollution is reserved for situations where contaminant concentrations attain levels considered to be objectionable. According to the National Water Act (Act 36 of 1998) of South Africa, pollution is defined as the direct or indirect alteration of physical, chemical or biological properties of a water resource so as to make it:

- less fit for any beneficial purpose for which it may reasonably be expected to be used; or
- harmful or potentially harmful to
  - the welfare, health or safety of human beings;
  - any aquatic or non-aquatic organisms;
  - the resource quality; or
  - property.

The National Water Act is used for the regulation and monitoring of water resources. Most contaminant releases initially affect shallow groundwater. Groundwater contamination can occur by infiltration, recharge from surface water, direct migration, and inter-aquifer exchange (Boulding and Ginn, 2004). Should there be contamination of groundwater this will pose a threat to the community at large as people and their livestock are dependent on the groundwater.

1.2 PROBLEM STATEMENT

Mining has had a great impact on the environment in South Africa, especially the water bodies in the country. The quality of water bodies (both surface and ground water) have deteriorated as result of mining, and mitigation measures are limited. Contamination of groundwater can occur at any stage of a mining project. The main reason for the research is to determine whether there is contamination of groundwater due to mining at Matsopa Minerals Mine. The project is carried out because the groundwater in the surrounding area of the mine is used by farmers for domestic and livestock use, and some groundwater contaminants can be detrimental to humans. The mine also utilises the groundwater for domestic use and therefore the groundwater has to be monitored, and its safety determined for present and future use. The hydraulic characteristics of the surrounding aquifer should also be investigated to allow insight into how the mining affects these properties.

1.3 AIMS AND OBJECTIVES

The main aim of the study is to investigate the current groundwater conditions at Matsopa Minerals and to assess the impact that mining has had on the surrounding aquifer in the area. The results of the current investigations are to be used as a benchmark against which future conditions can be compared to assess the impact of mining on the groundwater system. To address the aim of the research project the following objectives were identified:

- To determine the current groundwater quality in the vicinity of the mine as well as on the adjacent properties,
- To investigate the use of groundwater at the mine and on the adjacent properties,
- To detect and delineate geological structures that may influence groundwater migration and contaminant transport in the subsurface by using geophysical methods,
- To investigate the hydraulic properties of the aquifer system to allow insight into the expected rate of groundwater flow,
- To determine the mineralogical character of the geology of the area to predict which minerals and elements could potentially affect the groundwater quality, and,
- To assess the risks posed by mining at Matsopa Mine on the groundwater environment, and make recommendations to reduce these risks.

1.4 RESEARCH METHODOLOGY

To achieve the aims and objectives of the research project the following actions were taken:

- A literature review was done on the characteristics of the clay mineral that is being mined, its applications, the mining methods, the environmental impacts of mining and the geology of the area studied as part of the desktop study.
- A hydrocensus survey was conducted to determine the groundwater use in the area. The survey was also conducted to determine the number of boreholes in use in the area and monitoring boreholes were selected from these boreholes. The hydrocensus was conducted to delineate and select sites for geophysical surveys.

- Geophysical surveys were conducted to delineate geological structures such as fractures which may be associated with igneous intrusions. This was done because these structures may provide preferential pathways for groundwater and contaminants. The electrical resistivity tomography and magnetic techniques were used.

- Geochemical investigations were conducted to determine the mineralogical and elemental composition of the ore and gangue material. This was done to determine whether these materials are a potential source of groundwater contamination. X-ray fluorescence and X-ray diffraction techniques were employed.

- Hydraulic characteristics of the aquifer were determined by conducting a pump test to estimate the hydraulic parameters of the aquifer.

- Groundwater monitoring was conducted for a period of approximately one year. This was conducted to determine the groundwater quality in and around the mine area. Groundwater levels were also monitored. However, the number of boreholes available for monitoring was limited due to problems of access to some boreholes, and only limited data could be collected.

1.5 STRUCTURE OF DISSERTATION

The structure of the dissertation is as follows:

Chapter 1: INTRODUCTION

This chapter discusses the background of the project, its aims and objectives and how these aims and objectives are to be achieved. It also introduces the methods used and gives the outline of the dissertation.

Chapter 2: LITERATURE REVIEW

The chapter discusses the available literature relevant to the current project, including the effects of mining on the environment, and in particular, the effects of clay mineral mining.

Chapter 3: SITE DESCRIPTION

The chapter discusses the physiography of the study area, its location, topography, climate, geology and geohydrological conditions.

Chapter 4: HYDROCENSUS

This chapter discusses the results of the hydrocensus survey that was conducted within a 3 km radius from the mine.

Chapter 5: GEOPHYSICAL INVESTIGATIONS

The chapter discusses the geophysical surveys that were conducted within the study area. The results of the geophysical surveys are interpreted to investigate the presence of geological structures in the study area.

Chapter 6: GEOCHEMICAL INVESTIGATIONS

The chapter discusses the different geochemical techniques used during the study to investigate the geochemical characteristics of the rock and ore at the mine. The results obtained are interpreted to assess whether the geological material in the study area has the potential to contaminate the groundwater.

Chapter 7: GROUNDWATER MONITORING

In this chapter the results of a groundwater monitoring programme are discussed by using certified standards and hydrochemical diagrams to classify the groundwater type and quality.

Chapter 8: AQUIFER HYDRAULIC PARAMETERS

In this chapter, methods for the assessment of the aquifer hydraulic parameters are described. The results of hydraulic tests performed on the aquifer system at the mine are discussed, and the aquifer hydraulic parameters are estimated.

Chapter 9: CONCLUSIONS AND RECOMMENDATIONS

In Chapter 9, conclusions are drawn from the results of the research study, and recommendations for future actions are made.

1.6 LIMITATIONS OF THE STUDY

This research study was limited by a number of factors beyond the control of the researcher. The lack of hydrochemistry data prior to the commencement of mining at Matsopa Minerals meant that true baseline (greenfield) conditions could not be determined in the current study. Mining started in the 1950s and, until recently when G & W Base Industrial Minerals (Pty) Ltd took over the mining operations, no groundwater monitoring was done.

As part of the current study, a drilling programme was planned. However, due to financial constraints, the drilling programme did not proceed and groundwater sampling had to be done from existing boreholes. The drilling programme would have allowed the installation of boreholes at positions remote and upstream from the mine, to gain insight into the groundwater conditions unaffected by mining. Such groundwater conditions would have allowed a better insight into baseline conditions that could have existed prior to mining.

An additional limitation of the current study is the fact that limited research has been done on the assessment of clay minerals as possible groundwater pollutants. Only limited information could therefore be obtained during the literature review.

CHAPTER 2:
LITERATURE REVIEW

2.1 INTRODUCTION

The current study investigates the possible contamination of groundwater due to mining at Matsopa Minerals Mine in the Koppies area. In this chapter the literature of mining and its impact on the environment, particularly groundwater, is reviewed and forms part of the desktop study of the investigation. This undertaking will aid the field investigations to follow. For example, the geophysical investigations to be undertaken during the course of the study will be facilitated by first gaining a proper understanding of the principles and limitations of the different geophysical methods to allow selection of the most suitable and/or relevant methods for the investigations. In this chapter, a description of the mineral being mined is given; this is to gain a better understanding of the characteristics of the mineral and its possible impact on the environment. The geology of the area is also described as it forms a very important component of the study. The description of the geology allows insight into the formation and characteristics of the mineral being mined. The geology of the area also allows insight into the geohydrological conditions expected in the area.

2.2 PHILOSOPHY OF BASELINE STUDIES

A baseline study is a descriptive cross-sectional survey that mostly provides quantitative information on the current status of a particular situation (Anyaegbunam *et al.*, 2004). The baseline data that is collected is basic information gathered before a project begins. It is used to provide a clear picture of a particular situation and a comparison for assessing the net effect of the project (ASARECA, 2010).

The purpose of the baseline study is to provide an information base against which to monitor and assess an activity during implementation after the activity is completed. When baseline data is known changes can be measured and compared to the baseline data. There are two common ways to measure changes (Thomas *et al.*, 2011):

- ‘with and without’ activity – this seeks to mimic the use of an experimental control, and compares change in the activity location to change in a similar location where the activity has not been implemented, and,

- ‘before and after’ activity – this measures change over time in the activity location alone.

The study should be closely linked with the activity monitoring plan so that the data collected can be replicated if necessary during ongoing activity monitoring, for any midterm review, when the activity has not been assessed for the activity completion report and for any subsequent evaluations (Thomas *et al*., 2011). According to ASARECA (2010) the following steps should be taken in order to conduct baseline studies:

- Prepare a baseline plan;
- Conduct the baseline study according to the baseline plan;
- Analyse the collected and review the generated results;
- Formulate the baseline report and share the results.

The baseline study for the research project was to assess and monitor groundwater quality in the study area. The lack of background data made it difficult to make any comparisons of the current data with previous data from before mining commenced.

2.2.1 Risk impact assessment for a mine

Impact assessment is conducted to assess and understand the risk that a pollutant or contaminant will cause in the surrounding environment. The most basic risk assessment methodology is based on defining and understanding three basic components of the risk, i.e. the source of the risk (source term), the pathway along which the risk propagates, and finally the target that experiences the risk (receptors) (DWS, 2008).

A full mine site risk assessment may require a fully integrated assessments where various source terms, pathways and receptors are considered together (Figure 2-1). A more rational approach for the integrated risk assessment would be to undertake an initial screening level assessment and to then determine the critical receptor for a particular source term which would be severely impacted upon and to focus the assessment on determining the risk to that critical receptor (DWS, 2008).

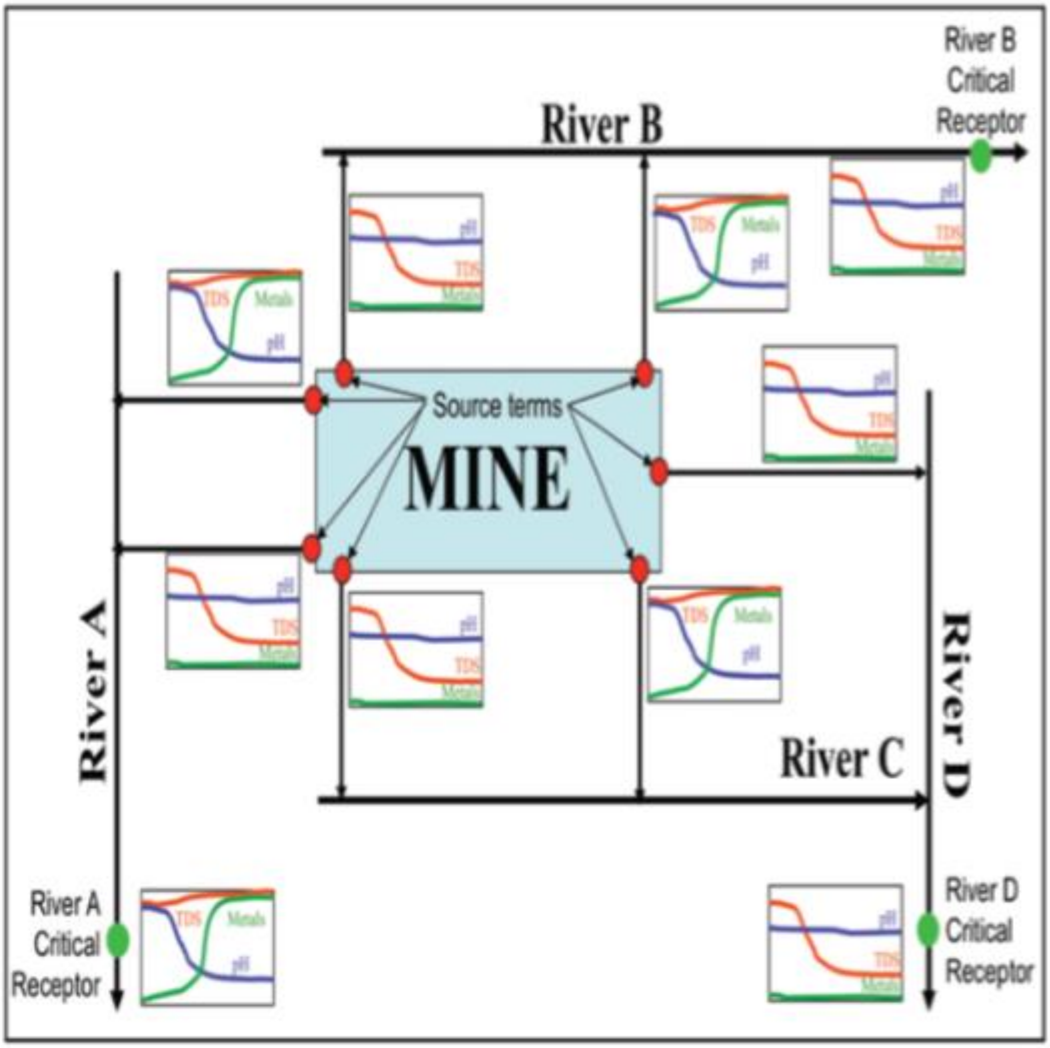


Figure 2-1: Risk assessment for multiple source terms and multiple receptors (source : DWS, 2008)

For the research project the opencast pit is a potential source term, the movement through an aquifer, fractures/voids and surface run-off are the potential pathways for contaminants. The potential receptors are the farmers down-gradient and the local streams in the surrounding area.

2.3 Clay Mineral Chemistry

Clay minerals are abundant on earth and are mainly found in the soil. There are different types of clay minerals and these minerals are classified into different groups. In the past years there have been many definitions of clay minerals and overtime the definition of clay minerals has been revised. Bailey (1980) restricted the definition of clay to fibre-grained phyllosilicates while Velde (1992) defined clay minerals as the fine-grained part of geology and less than 2 µm in diameter, beyond the limit of microscopic resolution. Guggenheim and

Martin (1995) considered clays to be all the fined-grained mineral components that give plasticity after hydration to rocks or materials which harden after drying or burning. From these definitions it can be deduced that clay minerals are fine-grained silicates with complex structures and properties. In simple terms Wenk and Bulakh (2004) have defined clay minerals as hydrous aluminous sheet silicates with variable composition and water content.

2.3.1 Clay mineral groups

The different groups in which clay minerals are classified under are based on the number of ions present in the octahedral layer (two-dioctahedral or three-trioctahedral), the numbers and kind of ions present between the basic sheet structures (interlayer ions) which are ionically bonded to the oxygen networks (Velde, 1977). The clay mineral groups are kaolinite, serpentine-chlorite, pyrophyllite, talc, illite and smectite group (Figure 2-2). The group of interest in this study is the smectite group which has saponite ($Mg_3Si_4O_{10}$ $(OH)_2.nH_2O$), beidellite ($Al_2Si_4O_{10}(OH).nH_2O$) and nontronite ($Fe_2Si_4O_{10}(OH)_2.nH_2O$) and end members, as well as montmorillonite. The montmorillonite clay mineral generally does not have an ideal formula due to the substitutions that take place between elements.

In their simplest form, clay minerals consist of an arrangement of sheets, where each sheet comprises (1) two planes of oxygen atoms arranged in tetrahedral coordination around Si_4^+ (or Al_3^+ and Fe_3^+) cations sharing the basal oxygen between adjacent tetrahedral, and (2) oxygen atoms and OH groups ordered in octahedral coordination around centrally located Al_3^+, Mg_2^+, Fe_2^+ and Fe_3^+ cations by sharing oxygen located on the octahedral edges. The smallest structural clay unit contains three octahedrons, known as a unit cell. Each clay mineral group can be identified by the very characteristic arrangement of these sheets in layers, the latter displaying very distinct spacing for a specific clay mineral (Deer *et al.*, 1962).

The smectite clay minerals have a high cation exchange capacity (CEC) and specific charge area than most clay minerals and because of these properties they can expand and accept other ions and molecules. In smectite and mica groups, large metallic cations such as Na^+ and Ca_2^+ and molecules such as H_2O occur in very close arrangement in respect to the neighbouring tetrahedral and octahedral sheets and can be exchanged for other cations or molecules (Deer *et al.*, 1962). The exchange of ions occurs in between the sheets and the space is usually called the interlayer/interlamellar surfaces as seen in Figure 2-2 where water molecules and cations occur. The interlamellar surfaces of expanding clay minerals contain cations, the hydration of which provides the driving force for expansion. Not only does the interlamellar spacing depend on the cation but also the absolute amounts of water sorbed, the shape of the sorption isotherm and the acidity function of the water molecules (Newman, 1987).

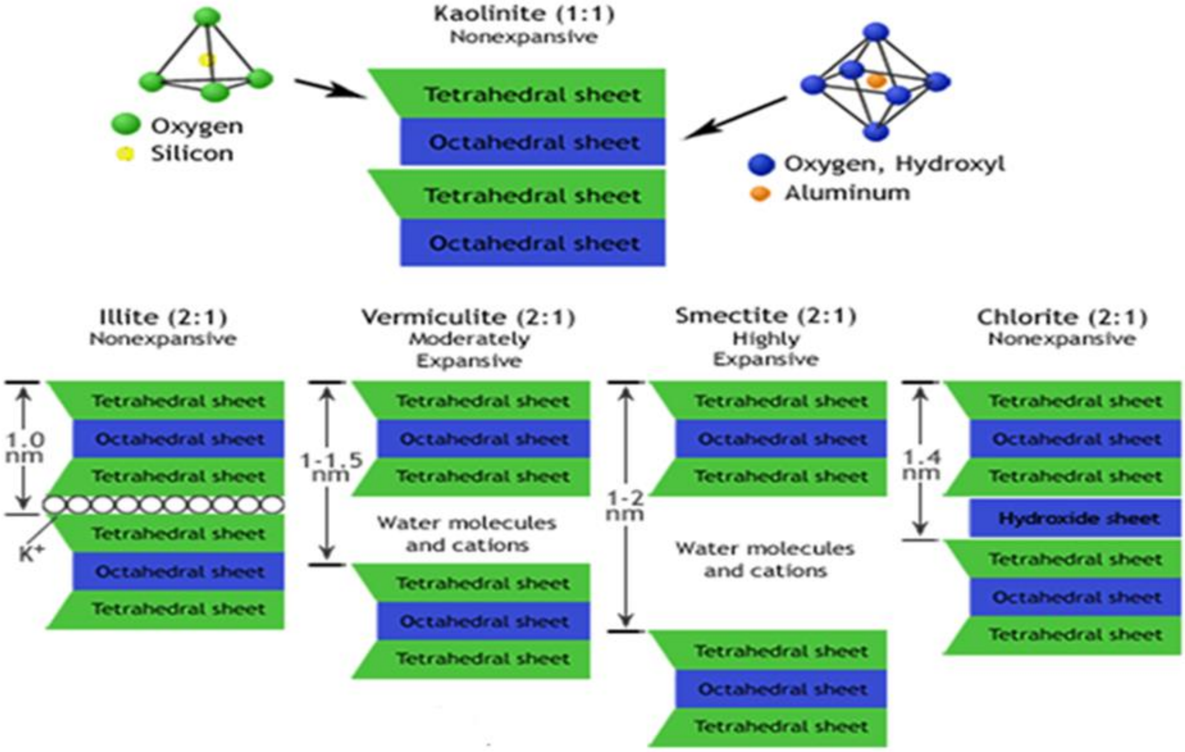


Figure 2-2: Different clay minerals and their structures (source: www.soilsurvey.org)

2.3.2 Bentonite clay mineral properties

Montmorillonite is a 2:1 layer clay mineral and according to Searle and Grimshaw (1959), the excess electrical layer charge on any of the layers in a 2:1 structure is balanced by the presence of interlayer ions which could be cations such as K^+, CaH, Na^+ or anions such as hydroxyl groups or organic molecules. Pure montmorillonite clays which exhibit pronounced absorption properties are known as bentonite (Wenk and Bulakh, 2004). There are different types of bentonite clay minerals which are dominated and named after the different cations namely: potassium (K^+), sodium (Na^+), calcium (Ca^{2+}) and aluminum (Al^{3+}) bentonites.

Bentonite has a soft, plastic, slippery consistency. Its colour ranges from white to light green and light blue, when removed from the ground upon atmospheric exposure it becomes light cream in colour then gradually changes to yellow, red or brown (Fuenkayorn and Daemen, 1996). Bentonite clays are used in different industries and this is because of their expansion properties. Due to the reason that cations in the interlayer can be exchanged by other cations or molecules in their structure, it is an important characteristic and it relates to the ease with which the clay can be chemically altered during beneficiation to yield a product used in a wide range of products.

In most montmorillonite clays and shales the Na^+ is concentrated in the finer fraction and Ca in the coarser fraction. This probably because Na^+ allows much greater interlayer expansion (McAtee, 1958). Therefore Na – bentonite can expand more than other bentonites. There are common exchange of cations in bentonite clay minerals and the three main types of bentonite are classified according to their predominant exchangeable cations. The most common type being Type *i:* (Ca-Mg) exchange types, type *ii:* (Mg-Ca) bearing bentonite deposits, and Type *iii*: Na-bearing bentonites which are rare. If it is accepted that the cations represented in the bentonite reflect the environment in which it is deposited, it can be concluded that Type *i* bentonite formed in relatively quiescent conditions in brackish water in which the Ca-concentrations exceeded that of Mg. Type *ii* and Na-rich bentonite (Type *iii*) deposits formed in open sea water and fresh water respectively (Horn and Strydom, 1998).

The bentonite that occurs in the Koppies area which is being mined by Matsopa Minerals is characterized as Type *I* bentonite and is enriched in Ca. Bentonite has a high concentration of montmorillonite and the remaining part of bentonite depends on the geochemical conditions during the formation of bentonite. Typical accessory minerals present in bentonites are other clay minerals, quartz, feldspars, gypsum, calcite, pyrite and various iron oxides/hydroxides. Most of the high montmorillonite clays (known as bentonite) produced in South Africa have Ca^{2+} as the exchangeable cation. The sorptive characteristics of the bentonite are therefore greatly enhanced if the Ca^{2+} cations which naturally occur in the interlayer spaces, are replaced by Na^+ (Horn and Strydom, 1998).

2.4 APPLICATIONS OF BENTONITE

There is a wide variety of bentonite uses and this is due to its properties, its ability to expand when in contact with water. Bentonite is used in different industries and pharmaceutical products. When bentonite is mixed with water, the water molecules bond with the clay flakes and the mixture then exhibits adhesive properties. According to Clem and Doehler (1961) the plastic properties of a clay-water system increases as the ratio of water to clay increases. The authors further state that when bentonite disaggregates in water and swelling takes place, the average clay particle size increases.

In clay-water mixtures: bentonite mixed with water is used as a bonding agent in foundry sand and iron ore pelletizing. The mixture is used as a binder for rock wool and asbestos fibre producing industrial insulation products, as well as an ingredient to create pellets of animal feed from coarse ground components (Clem and Doehler, 1961). Bentonite is used as a borehole seal as well as pet waste absorbent, and also in the preparation of muds for drilling oil wells.

In ceramic and concrete products, a small amount of bentonite is used as a plasticizing and bonding agents. The plastic state aids in shaping and moulding the raw materials. Some of the many uses of bentonite suspensions include application as drilling mud for rotary drills, as fire retardant gel, and as media for suspending materials which range from medicines that are taken internally, to lumps of coal as part of a float-sink or seperatory process (Clem and Doehler, 1961). The functions of drilling mud include removal of cuttings from the borehole, prevention of blow-outs, strengthening of the wellbore and reduction of fluid loss from the mud, prevention of weighing agents and cutting from settling down the well when circulation stops, and lubrication and cooling of the drilling bit and string (Clem and Doehler, 1961).

The large surface area and reactivity of bentonite is of advantage because some chemicals can be adsorbed. It can be used for the adsorption of insecticides and other organic compounds as well as inorganic trace metals such as Cu, Zn, U, Hg etc. other uses of this mineral due to these properties are clarifying and decolourising. According to Clem and Doehler (1961) the process of decolourising is simple and used to decolourise oils by allowing the percolation through bentonite beds in which a selective adsorption of some organic types onto the clay mineral surface takes place. The portions of the oil which are darkest in colour are moved preferentially by the clay.

Clay minerals are also used as barriers in landfills and mine tailing ponds to prevent contaminants from entering the local groundwater system. The table below (Table 2-1) gives more examples of the application of bentonite in different industries.

Table 2-1: Different applications of bentonite in different industries (source: Horn and Strydom, 1998)

Industry	Applications	Examples of applications	Most important raw and value-added clay materials
Steel	Foundary Sands	Binders: which improve the strength, plasicity and moulding properties of natural and synthetic foundary and core sands	Natural, calcic and sodic bentonite depending on application. Soda-ash activated bentonite is used when natural sodic bentonite is not available. Thermally activated palygorskite and sepiolite. Ball clays (highly plastic kaolinite are frequently used). Recycling of used sand-clay mixtures are large, limiting volume of bentonite sales. Important properties are compressive strength, green and hot strength, flowability and moulding properties, (Exchangeable cations largelydetermine binding propperties.)
	Ore pelletising	Binding agent	
Absorbants and adsorbent	Agriculture, horticulture	Binders and carriers in pelletising animal feeds, fertilisers and soil conditioners and water-catchment sealing applications	Acid (HCI) alkaline (soda ash)-activated bentonite. Thermally activated palygorskite and sepiolite
	Mineral oil and tar exploitation	Refining, claryfing of mineral oil and grease thickening (Tar explotaition not in RSA)	Organically and acid-activated bentonite. Very small volumes used by petrochemical industry in preparation of catalysts.
	Foodstuffs	Refining, claryfing/bleaching, deodorising plant and animal foods and fats. Refining and claryfing of sugar, wine fruit and malt beverages	Acid-activated bentonite not used in wines due to increase in sulphur content from the H_2SO_4 used in clay activation (AFCEM Pty Ltd, pers, commun.), Mostly thermally treated bentonite currently used by wine and fruit-juice industry
	Pet litter	Cat sands. Palygorskite has a very large share of the cat-litter market	Akaline-activated bentonite (limited volumes). Thermally treated palygorskite and sepiolite
	Desiccants	Moisture control agent used e.g the packaging of electronic equipment	Heat-treated. Ca bentonite and sepiolite
	Cleaning and detergents	Regeneration of cleaning fluids. Industrial cleaning on factory floors	Alkaline-activated bentonite. Thermally treated palygorskite and sepiolite
Chemical	Sulphur production	Bitumen extraction,sulphur extraction and decolourising during bitumen extraction (not in RSA)	Acid-activated bentonite
	Pharmaceutical	Manufacturing of stater materials for medicine, basis for creams and cosmetic products, healing earths. Both minerals used as an absorbent of pathogenic bacteria, enzymes and poisons in gastro-intestineal conditions. Palygorskite is also used as an active agent and adsorbent in anti-diarrhoeical medicines	Alkaline-activated bentonite. Palygorskite and thermally treated palygorskite and sepiolite

Table 2-1 (continued): Different applications of bentonite in different industries (source: Horn and Strydom, 1998)

Industry	Applications	Examples of applications	Most important raw and value-added clay materials
Filler extenders and thickeners	Oil exploration; (large quantities of bentonite used in drilling muds)	Thickening and thixotroping of borehole suspensions (muds) for borehole scavenging and cleeaning	Alkaline and acid-activated bentonite. Thermally activated palygorskite and sepiolite are especially suitable in highly saline environments. Most important are the rheological, thixotropic, viscosity and borehole-wall sealing properties. Muds must display high inertness to changing electrolyte concentrations. Density of the fluids is controlled by addition of weighting materials such as barytes.
	Paint, vanish, coating products, sealing cements, sealinng paints and adhesives	Thickening, thixotroping, emulsifying, stabilising and anti-settling agent	Acid-activated bentonite. Thermally activated palgorskite and sepiolite
	Tar	Thixotroping and emulsifying of tar-water emulsions, and tar asphalt coatings	Acid-activated bentonite
Construction, civil and mining engineering and environmental applications	Buildings and dam walls	Sealing of foundations against moisture	Alkaline and acid-activated bentonite. Thermally activated palygorskite and sepiolite
	Pipe jacking and shaft sinking	Anti-friction products	Alkaline and acid-activated bentonite
	Toxic waste from mining industrial and agricultural activities	Sealing off of toxic-waste disposal sites, slimes dumps and effluent from housing and idustrial sites and in soil conditioning for golf courses to allow the absorption and adsorption of agrochemicals	Alkaline and acid activated. Thermally activated palygorskite and sepiolite
	Concrete	Additive to plasters, cements and concrete to enhance placticising properties	Alkaline-activated bentonite
Ceramics		Bentonite improves plasticising, green strength and fluxing properties (not added in ceramics in RSA, however, it might be a natural constituent of the kaolinitic clay used). Palygorskite not used in South Africa for this purpose	Alkaline-activated bentonite
Paper	Carriers	Pigment and colour developer for carbonless copying paper	Alkaline and acid-activated bentonite. Thermally activated palygorskite and sepiolite
		Adsorption of impurities in white-water systems	Alkaline-activated bentonite

2.5 PRODUCTION OF BENTONITE IN SOUTH AFRICA

The production of bentonite in South Africa is shown in Figure 2-3 and Table 2-2, which shows that there are fluctuations in the demand for the mineral. South Africa is the 21st largest producer of bentonite in the world. The mineral is used in different industries for different purposes; some of the uses include drilling mud during rotary drilling, a fire retardant gel, a bonding agent in foundry moulding sand and as a groundwater barrier – as it acts as lining of a borehole.

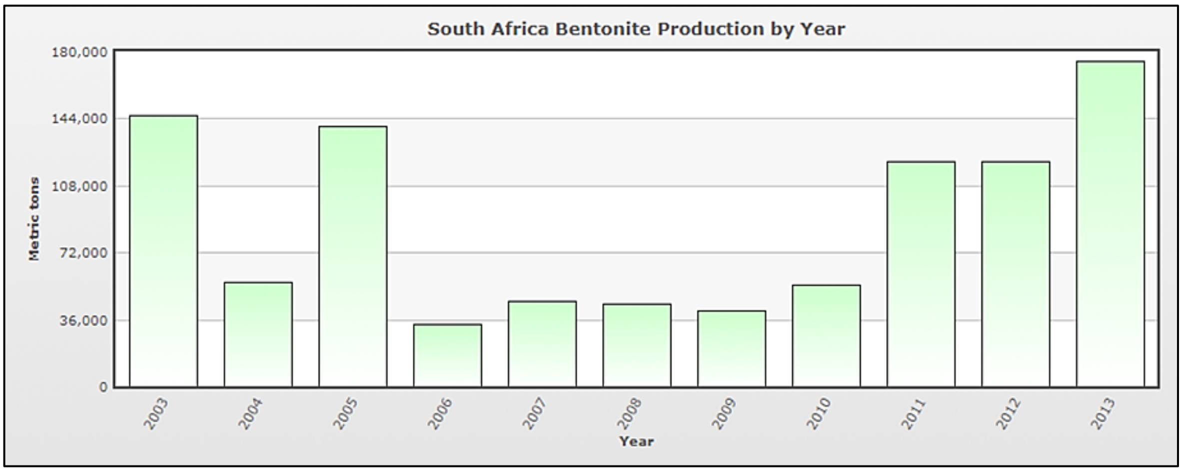


Figure 2-3: Production of bentonite in South Africa (source: www.indexmundi.com)

Table 2-2: Production of bentonite in South Africa

Year	Production	Unit of Measure	% Change
2003	145060	Metric tons	N/A
2004	55859	Metric tons	-61,49%
2005	139833	Metric tons	150,33%
2006	32878	Metric tons	-76,49%
2007	45778	Metric tons	39,24%
2008	44067	Metric tons	-3,74%
2009	40340	Metric tons	-8,46%
2010	54311	Metric tons	34,63%
2011	120417	Metric tons	121,72%
2012	120566	Metric tons	0,12%
2013	174786	Metric tons	44,97%

2.6 MINING METHODS

Mining is a form of extracting ore or industrial material (example clay mineral) from an enriched mineral deposit. Unlike farming where there's a choice of where and what to grow mining can take place only where minerals occur (Fuggle and Rabie, 1999). Before mining can commence the ore body has to be investigated to characterise the ore and with industrial mineral the most important properties are investigated. These properties are (1) its mineralogical nature, (2) its geochemical character and most importantly, (3) its physical properties.

There are two main types of mining methods that are being used in the mining industry which are surface mining (open-cast/open-pit) and underground mining. In industrial mineral mining, open-cast/open-pit method is used in most cases. Open-cast mining is used because of safer working conditions, greater mechanisation possibilities and lower exploitation costs in surface mines (Libicki, 2006). In open-cast mining the overburden is removed and the ore is exposed to the surface, the overburden is usually removed by using bulldozers and dump trucks. According to Younger *et al*, (2002) there are three principle activities involved in all surface mining:

- The striping of overburden (i.e. the excavation of non-economic deposits which overlie the ore or coal),
- Mining of the ore or coal, and,
- Restoration and/or abandonment of the mine void.

2.6.1 Mining of the ore

There are other important factors that need to be determined before open-cast mining is undertaken. Factors that include the overburden to ore ratios, dip of the ore body, nature of the overburden and host rock, ore grade or thickness variations, ore beneficiation and transport costs, these factors are important in determining the viability of a mine. In most cases in surface mining once the overburden is removed the mineral or ore is worked from stepped horizontal benches. The benches generally vary from around 18 to 45 m, and are separated by faces between nine and 30 m tall.

Open-pit mines are typically developed in situation where there is little gangue in the ore body, so that a significant shortfall of waste rock and/or tailings precludes easy restoration of the final void by back-filling (Younger *et al*, 2002). Bentonite is extracted from the subsurface by using surface mining through open-pit mines. International organisations like AMCOL and Wyoming that mine bentonite also use the method of surface mining, they use a process called *backcasting* whereby reclamation is done concurrently with mining by using the overburden and soils from subsequent pit to fill the ones before them. This process makes the reclamation of the mine to be done quickly.

At Matsopa Minerals the bentonite is mined by open-cast mining with concurrent backfilling of the overburden into the void created during the previous mining campaign. The stepped benches of the pit are at 20 to 25 m in depth.

2.7 ENVIRONMENTAL IMPACT OF MINING

Pollution and/or contamination of the environment can occur in many different ways as there are many sources of environmental pollution (Table 2-3). An anthropogenic source due to human activities which includes mining is one of the worst pollutants in the environment. Mining is the first operation in the commercial exploitation of minerals or energy resources. It is defined as the extraction of material from ground in order to recover one or more component parts of the mineral of the mined material (Lottermoster, 2010).

Most mining activities if not all have an impact on the environment which is negative and causes the degradation of the environment. The worst impact that mining has on the environment is the pollution/contamination of air, soil and water (both surface and ground water). Other impacts that mining has on the environment includes erosion, formation of sinkholes, loss of biodiversity, and the contamination of the soil. The source of pollution in mining ranges from the geology of the mining area; the overburden to the ore being mined and the waste produced during mining.

2.7.1 Geology

The geology in which the mining activity is taking place plays an important role and may have an impact on the pollution of the environment. During mining, when the overburden is removed possible pollutants can be released as rocks are composed of different minerals bonded by different elements which were formed during the geologic cycle. During recharge the water that enters the subsurface can have some reaction with the geology depending on the composition of the geology. Therefore a number of chemical and physicochemical reactions can take place. The geology of recharge areas of aquifers influences the quality of groundwater.

The number of pollutants and degree of pollution in groundwater depends on the geology and the mineralogical compositions of rocks through which the water flows (Egboka *et al.*, 1989).

Table 2-3: Sources and types of contamination (Zaporozec *et al*., 2002)

Category	Source Type	Usual Character	Normal Location
Natural sources	Inorganic substances Radionuclides Organic compounds Microorganisms	Not application	Not application
Agriculture and forestry	Fertilisers	Diffuse	Surface
	Pesticides	Diffuse	Surface
	Animal waste	Diffuse/point	Surface/unsaturated zone
	Animal feedlots	Point	Surface
	Irrigation return flow	Diffuse	Surface
	Stockpiles	Point	Surface
Urbanisation	Solid waste sites	Point	Surface/unsaturated zone
	On-site sanitation	Point	Surface/unsaturated zone
	Wastewater, effluent	Point and line	Surface/unsaturated zone
	Salvage and junk yards	Point	Surface/unsaturated zone
	Leaking underground storage tank	Point	Unsaturated zone
	Runoff, leaks, spills	Line and point	Surface
Mining/Industry	Mine tailings	Point	Surface/unsaturated zone
	Mine water	Point and line	Various
	Solid waste	Point	Surface/unsaturated zone
	Wastewater, effluent	Point and line	Surface/unsaturated zone
	Injection wells	Point	Below water table
	Spills, leaks	Point	Surface
Water mismanagement	Well-field design	Point	Below water table
	Upconing	Point	Below water table
	Seawater intrusion	Line	Below water table
	Faulty well constructio	Point	Below water table
	Abandoned wells	Point	Below water table
	Irrigation practices	Diffuse	Surface
Miscellaneous	Airborne sources	Diffuse	Surface
	Surface water	Line	Below water table
	Transport sector	Point and line	Surface/unsaturated zone
	Natural disasters	Point and line	Surface/unsaturated zone
	Cemeteries	Point	Unsaturated zone

It is important to know the geology and the mineral distribution in recharge areas of aquifers and the flow direction of water as well as the different geological structures present (joints, fractures, faults etc.) in which the pollutants can be transported. The major factor that influences contaminant release is the geology of the mined resource (Lottermoster, 2010).

Groundwater may also acquire pollutants and contaminants as it flows across different geological and mineralogical zones or units of formations. Water as a form of recharge or surface water draining through different lithological sequences can absorb some ions which will be introduced in the groundwater system. Example, surface water draining in areas of sulphide mineralisation can introduce free iron and other metallic ions in the groundwater.

2.7.1.1 Gangue and ore

Gangue are those minerals that form part of the ore body, but do not contribute to the economically extractable part of the deposit while ore is any naturally occurring material from which a mineral or aggregate of value can be extracted at a profit (Robb, 2005). The ore and associated minerals (gangue) should be assessed if they are of acid potential (AP) or neutralising potential (NP). Acid potential minerals are sulphide minerals which generate waters with a low pH when in contact with water.

Some of the minerals which are mined and the accessory minerals can be of sulphide mineralisation. These minerals are problematic because they can cause pollution of the groundwater. The sulphide minerals are pyrite, arsenopyrite, pyrrhotite or chalcopyrite and are associated with acid mine drainage (AMD). Some ore minerals and gangue can also contain sulphate which in contact with water can produce sulphuric acid. This takes place when a sulphide mineral is exposed but not oxidised by the air, but produce sulphuric acid when oxidised by ferric iron such sulphide mineral is sphalerite. AMD is usually associated with gold and coal mines in South Africa.

2.7.2 Mining method

The different types of mining methods may have an environmental impact, mining is associated with the removal of the soil and some meters of rock material. Subsurface impacts are generally associated with water ingress (flooding) into underground mine workings. The attendant threat of dewatering the source groundwater regime and in post mining phase, providing source of acid mine water for potential migration into the groundwater environment during dewatering (Heath *et al.*, 2004).

Open pit mining requires the removal of the overburden and usually the groundwater table is intercepted and the pits have to be dewatered. Surface mining however exerts an undesirable effect on the environment in general and groundwater in particular (Libicki, 2006). Mining operations conducted below the groundwater table require a drawdown of the water table. This drawdown is affected both by the mine itself and by the drainage systems. Such depression of water table is not limited to the mine area. Therefore natural geological conditions are disturbed quantitatively without affecting the quality (Libicki, 2006).

According to Zaporozec (2002) mine dewatering brings about the oxidation of rocks and minerals at deeper levels, the chemical composition of the dewatered groundwater changes and may contain more metals, phosphates, sulphates, trace elements etc. This pumped water from the mine may spread on the land surface or discharged towards a stream and may infiltrate the local groundwater of the mine polluting the groundwater. Mine dewatering changes the groundwater flow pattern which may result in water of a high salinity or otherwise poor quality from deeper parts of the groundwater system moving towards water wells (Zaporozec *et al.*, 2002).

2.7.3 Tailings and mine waste

Mine waste can be defined as solid, semi-solid, or liquid waste materials from the extraction and processing of ores and minerals. These wastes include soils, waste rock and overburden as well as tailings, slag and other processed materials (Saracino and Phipps, 2002). Tailings are products from mining and extracting resources and it is also called mine dumps. Contamination of groundwater can take place during rain fall on uncovered or unlined stockpiles/tailings. The water will come into contact with the tailing material and it can leach heavy metals, salts, organic or inorganic constituents which will seep through the unsaturated zone and reach the aquifer in the saturated zone.

The composition of the leachate is extremely diverse and depends on the minerals that are mined, source rock composition, and mining processing techniques. Leachate percolating through subsoil may threaten groundwater resources underlying the tailings and surrounding area or endanger nearby open water courses (Zaporozec *et al.*, 2002).

Tailings can undergo chemical change when in contact with water due to chemical reactions that take place between the present constituents. According to Praharaj and Frotin (2008) tailings undergo forms of diagenesis, in addition, physical and biological process occur such as compaction, cementation, recrystalisation as well as mineral dissolution and formation assisted by microorganisms. During mining mine wastewater is produced from the processing of the ore mineral and dewatering of mine workings.

2.8 ENVIRONMENTAL IMPACT OF BENTONITE

Bentonite is clay mineral of the smectite group which is mainly composed (>50%) of montmorillonite. There are many applications of this mineral (described in Table 2-1), and most of these applications are for the remediation of environmental problems. Bentonite is used in liners for waste dumps, tailings dam and wastewater dams. The most important properties of bentonite is the cation exchange capacity (CEC) and surface area which are related to the swelling and shrinkage properties of the mineral. The sodium (Na)-bentonite is characterised by its ability to absorb large amounts of water and other compounds. While calcium (Ca)-bentonite is characterised by it low water absorption and swelling capabilities and inability to stay suspended in water. Therefore Na-bentonite is more favoured than the Ca-bentonite.

Bentonite is used as a seal because when in contact with water, it swells to many times its original volume which makes it a very good seal for boreholes (Remenda and van der Kamp, 1997). Na bentonites are preferred in landfills because they have low shrinkage and hydraulic conductivity (Ozel *et al.*, 2012). The sealing properties of a specific bentonite material are strongly dependent on the mass of bentonite per volume, and several density describing variables are commonly used (Karnland, 2010). In Turkey bentonite, zeolite and expanded perlite particles were used for the removal of nitrate, ammonium-nitrogen, phosphate, chemical oxygen demand and organic matter in leachate. It was determined that the bentonite can be used to fill up spaces between of natural zeolite and expanded perlite particles. The filling rate of bentonite is low, but will serve to decrease percolation of leachate and increase the removal efficiency of pollutants (Ozel *et al.*, 2012).

In agricultural practices nitrogen (N) fertilizers are used to provide nutrients in soils, in most cases the end results of N fertilizers becomes a major source of ammonium in groundwater and surface water. The decrease of the transformation and moving of N compounds using adsorbent materials such as zeolite and bentonite is crucial to save groundwater and environmental quality in intensive agricultural production (Buragohain *et al.*, 2013). Bentonite can be used for the attenuation of heavy metals in soils and waterbodies. The use of Na-bentonite and Ca-bentonite is a promising method for reducing the extractability and possibly the bioavailability of heavy metals in sewage-sludge-contaminated soil, and therefore for remediation of the soil (Usman *et al.*, 2004).

2.8.1 Possible contaminants at Matsopa Minerals

From the above discussed contamination sources in a mine site the most likely contamination source to be associated with Matsopa Minerals will be the geology. The chemical analysis of the associated minerals and ore will be give proof of whether the geology will pose a threat or not to the environment. The geology of the mine area is mainly composed of sedimentary rocks of the Karoo Supergroup and according to Egboka *et al.*, (1989) sedimentary rocks provide the largest aquifers and water passing through such rocks acquire considerable concentrations of chemical components of these rocks.

The mineral mined (bentonite) does not have any past environmental degradation associated with it, though the chemistry of the bentonite occurring at this specific site can be investigated. This will be done determine whether the elements that make up this mineral, their mobility and geochemical properties when in contact with water could cause harm to the aquifer. The major accessory mineral associated with bentonite is quartz, this mineral does not cause environmental problems when in contact with water as its solubility is very low. Bentonite clay mineral is usually used to remediate environmental areas affected by contamination and pollution. In a study done by Sekhamane (2001) at a mining site in Lesotho the findings that were obtained showed there was no evidence to support incidences of groundwater pollution in an area of clay mining.

A study done by Digby Wells for Matsopa Minerals for an integrated water and waste management plan (IWWMP), found that the minerals being mined do not cause soluble salts to form, and the only potential of major impact is from siltation (Moeketsi, 2012). Contaminants of groundwater can be produced during the processing or beneficiation of the ore material. During the beneficiation of the bentonite little to no waste is produced as the beneficiation process involves the mixing of bentonite and soda ash to activate the bentonite by allowing the exchange of Ca^{2+} Mg^{2+} for Na^+.

Domestic waste can be a problem in the site as the sewage from domestic accommodation is disposed by means of French drain located near the change block, this drain is connected to the septic tank like a septic drain field. The tremendous increase in the use of septic tanks for home sewage disposal has contributed a great deal of dissolved solutes polluting groundwater. When present in highly drained soils with a deep water table, and is densely distributed they tend to release heavy loads of nitrate to the water table (Egboka *et al.*, 1989; Zaporozec *et al.*, 2002). When investigating groundwater contamination on a specific site, all activities taking place on the site has to be assessed. The focus should not be on one activity because there are different sources of pollution especially in the mining environment.

2.8.2 Previous work done at Matsopa Minerals

Two studies were done at Matsopa Minerals by different environmental consulting companies. The results of their investigations are summarised below:

Cabanga Concepts Consulting

The consulting firm was requested to conduct an environmental impact assessment (EIA) and develop an environmental management programme for Matsopa Minerals. The study was conducted in 2013. A hydrocensus survey was performed during which sampling points were identified (Barnes, 2013). Surface water points were sampled and the water was analysed. The results of the water quality analyses showed that it is unlikely that heavy metal concentration can occur as result of mining at Matsopa Minerals.

It was determined that elevated concentrations of heavy metals in surface water points were most likely due to rock-water interactions, since the study area is underlain by igneous rocks that contain heavy metals as part of their chemical composition. Water in contact with the weathered igneous rocks can thus become contaminated.

Digby Wells Environmental

The Integrated Water and Waste Management Plan (IWWMP) develop by Digby Wells and the Integrated Water Use License Application outline the proposed management of the impacts from the mining operations on the receiving surface and groundwater environment and other recipients (Moeketsi, 2012). The report describes the current status of the environment, an assessment of impacts resulting from the activities, mitigation measures and a summary of the findings for the Public Participation Process (PPP).

The groundwater uses within the mine vicinity were identified to be for potable water and process use from two boreholes. Both surface and groundwater quality analysis were conducted. The results of the surface water showed a high Al, Fe and Mn concentrations. Faecal coliform concentrations exceeded the allowable limits at some sampling points.

Groundwater quality analyses were conducted on 11 borehole samples. The Piper diagram was used to classify the water type and the groundwater samples plotted in the left quarter indicating water of the calcium-magnesium bicarbonate type, which indicates freshly recharged water. One sample plotted in the upper quarter indicating a sulphate dominant water type. Though the analyses did not show elevated sulphate, this is due to high Ca and Cl concentrations, possibly from groundwater and saltwater interaction in a buffer reaction (Moeketsi, 2012). The chemistry of all the samples generally indicates good groundwater quality (Moeketsi, 2012).

The following potential groundwater pollution sources were identified:

- Manure storage and transport:
    - Groundwater contamination could occur when the surface water contaminated with nitrogen, organic matter or phosphates seeps into the ground entering groundwater resources.
- Waste handling:
    - Incorrect handling and storage could result in infiltration of dirty water into the groundwater environment.
- Fuel and lubricants storage:
    - Incorrect storage could cause contamination of groundwater sue to either an infrastructure failure or spillages during normal operations.

2.9 GEOLOGY

2.9.1 Introduction

The geology of an area can be complex depending on the formation and geological environments associated with the formation of the different rocks and ore bodies associated with it. According to history different geological events took place at different times to form the world as it is known today. Sometimes to better understand the present geology it is best to go back in time to unravel the historical events that took place in the past. The study area falls under the Karoo Supergroup which is part of the ancient continent called the Kaapvaal Craton. The history of the geology will be evaluated to better understand the geology of the area and further understand its implications on the geohydrology of the area.

2.9.2 Kaapvaal Craton

The Kaapvaal Craton was formed during the Archean Eon. The Kaapvaal Craton is an ancient segment of continental crust which formed in southern Africa between about 3.7 Ga to 2.7 Ga (Robb and Meyer, 1995). The craton is buried beneath younger rocks and it has remained unchanged for 3000 Ma from when it was formed (MacDonald *et al.*, 2005). The formation of the craton is by an extensive granitoid basement and amalgamation with arc-like oceanic terranes and associated igneous intrusions around its margin (de Witt *et al.,* 1992; McCarthy and Rubidge, 2005).

The craton is bordered on the north by the high-grade Limpopo mobile belt, initially formed when the Kaapvaal and Zimbabwe cratons collided at 2.6 billion years ago. On its southern and western margins, the craton is bordered by the Namaqua-Natal Proterozoic orogens, and it is overlapped on the east by the Lebombo sequence Jurassic rocks recording the breaking Gondwana. The collision between the two cratons not only saw the formation of the Limpopo belt but also the formation of the basin in which much of the Witwatersrand sequence eventually formed in (Robb and Meyer, 1995). The Kaapvaal Craton contains two basins of vast enrichment which is of economic importance in South Africa, the basins known as the Witwatersrand and the Karoo basins. The craton is composed of granitoids, granite, gneiss and greenstone.

2.9.3 Karoo Supergroup

The main Karoo Basin is formed on the ancient Kaapvaal Craton and was deposited from the late Carboniferous (~300 Ma) to Mid-Jurassic (~180Ma). It covers approximately two-thirds of the land surface of South Africa (McCarthy and Rubidge, 2005; Johnson *et al.,* 2006). The Karoo Supergroup is also known as the Karoo Basin which is a foreland basin, it is thickest at the south and thins towards the north. The Karoo Supergroup covers some 700 000 km^2 of South Africa (van Vuuren, 1983). The Karoo Supergroup is made up of the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg Groups (Figure 2-4), the supergroup is dominantly composed of a thick pile of sedimentary formations and igneous intrusions.

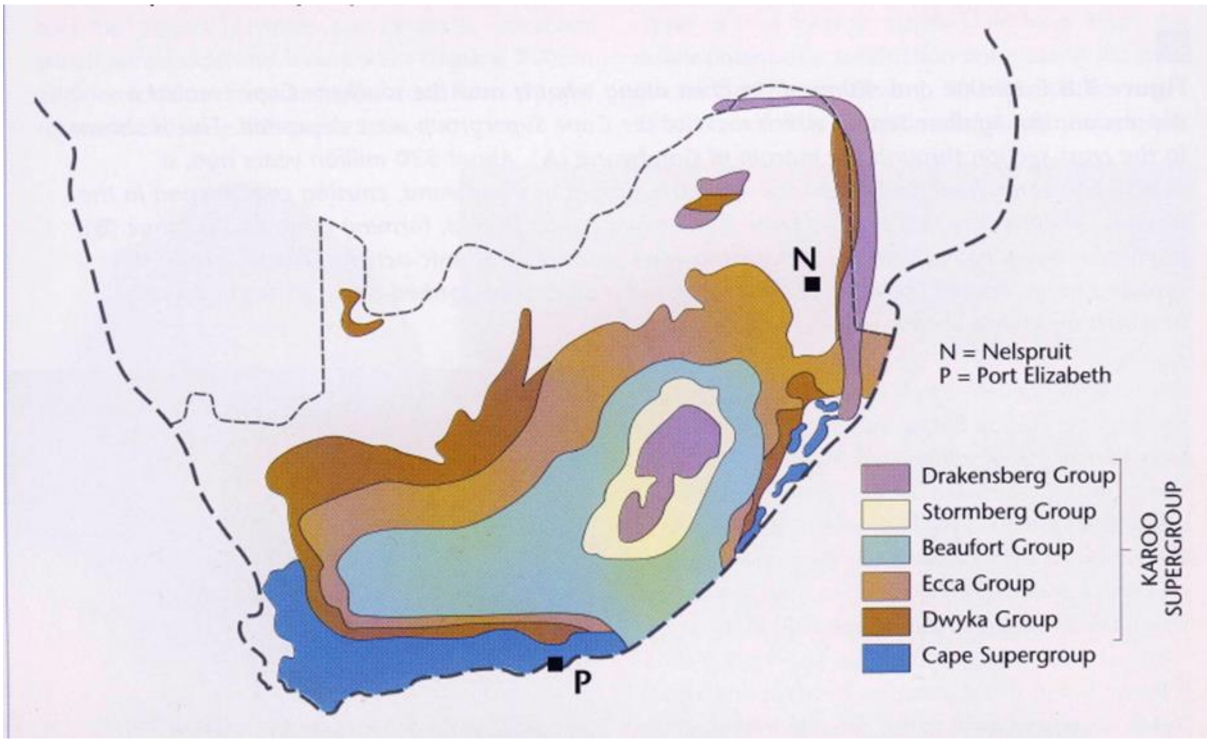


Figure 2-4: Schematic view of the Karoo Supergroup and the associated groups (source: McCarthy and Rubidge, 2005)

2.9.3.1 Dwyka Group

During the drifting of the Supercontinent Gondwana, the southern part of the Gondwana was covered in an ice-sheet. The glacial deposit were the first sediments to be deposited in the developing Karoo depression (McCarthy and Rubidge, 2005). This deposit will later be the Dwyka Group. The Dwyka Group was deposited during the Late Carboniferous to Early Permian age. It rests upon the glaciated Precambrian bedrock in the northern basin margin, in the south it overlies the Cape Supergroup conformably and paraconformably, and in the east it overlies the Natal Group and Masikaba Formation (Johnson *et al.*, 2006). The Dwyka is mainly composed of tillites with the presence of conglomerate, sandstone, rhythmite and mudrock (both with and without dropstones) (McCarthy and Rubidge, 2005).

2.9.3.2 Ecca Group

The Permian Ecca Group is underlain by the Dwyka tillite formation generally considered to be of Carboniferous to lower Permian age and is overlain by the Permian Beaufort Group (van Vuuren, 1983). The deposition of the Ecca Group took place during different cycles due to the reason that the Gondwana was still drifting northwards, and consists of 16 formations (Figure 2-5) (Johnson *et al.*, 1996). The Ecca Group was deposited when rivers began to drain as the glacial started to melt thus creating an inland sea. Sediments were deposited along the shoreline and large deltas were formed (McCarthy and Rubidge, 2005).

The geology of the southern part of the Ecca Group is different to that of the northern. These rocks were deposited under different depositional conditions and mainly consists of shales with thickness that vary from 1500 m in the south to 600 m in the north (van Vuuren, 1983; Botha *et al.*, 1998). The rocks of the Ecca Group in the southern part of the basin, nearer the rising Cape Fold Belt, are different from those in the north, and do not contain coal (McCarthy and Rubidge, 2005).

In the northern part of the Karoo basin the Ecca Group is subdivided in ascending order into the Pietermaritzburg shale formation, the predominantly sandy Vryheid formation and the Volksrust shale formation. The Pietermaritzburg Formation is the lowermost unit of the Karoo Supergroup in the northeastern part of the basin and overlies the Dwyka Group (Johnson *et al.*, 2006). In the north-eastern part of the basin, the coal bearing Vryheid Formation comprises both coarsening-upward deltaic cycles and fining-upward fluvial cycles, with the latter occurring largely in the middle part of the formation.

The regressive Vryheid formation is sandwiched between the mudrocks of the Pietermaritzburg and Volksrust Formations which represent transgressive “shelf” sediments (Johnson *et al.*, 1996). The Volksrust shale formation reveals overall transgression and regressive relationships relative to the Vryheid Formation and Beaufort Group, shales encountered in the Volksrust are thicker than those of the prodelta origin shale of the Vryheid Formation (Johnson *et al.*, 1996). The Volksrust Formation is a predominantly argillaceous unit which interfingers with the overlying Beaufort Group and underlying Vryheid Formation (Johnson *et al.*, 2006).

The Ecca is subdivided into the Prince Albert and the Whitehill Formations in the south, west and northwest of the main Karoo basin which are mainly composed of shale (van Vuuren, 1983). The deposition of the Prince Albert and the Whitehill Formation mudrock succession were deposited in deep water as result of suspension settling (Johnson *et al.*, 1996). The Prince Albert Formation thickness varies from 40 m to 150 m. Towards the northeast it thins and pinches out against the basement or merges into the Vryheid and/or Pietermaritzburg Formations (Johnson *et al.*, 2006).

The Prince Albert Formation comprises of the southern and northern facies. The northern facies is characterized by the predominance of the greyish to olive-green micaceous shale and grey silty shale with a pronounced transition to the underlying glacial deposit. While the southern facies is characterized by the predominance of dark-grey, pyrite-bearing, splintery shale and presence of dark coloured chert and phosphatic nodules and lenses (Johnson *et al.*, 2006).

The Whitehill Formation consists of black (white-weathering) carbonaceous shale, which distinguishes it from the underlying and overlying shale units in the main Karoo basin (Johnson *et al.*, 1996). The thickness of this formation varies from 10 m to 80 m thick. The predominant facies are of black, carbonaceous, pyrite-bearing shale with presence of thin tuffaceous beds and ferruginous carbonate concretions. The formation is important because of the occurrence of fossils such as the Mesosaurus reptile fossil (Johnson *et al.*, 2006).

The southern formations of the main Karoo basin consist of the Collingham, Vischkuil, Lainsburg, Ripon, Fort Brown and the Waterford Formations. Along the southern edge of the main Karoo basin (the “foredeep” part of the basin) the sandstones of the Ripon, Lainsburg and Skoorsteenberg Formations represent turbidites deposited as submarine fan complexes at the foot of advancing delta slopes (Johnson *et al.*, 1996).

The Collingham Formation is generally 30 m to 70 m thick and comprises a rhythmic alternation of thin, continuous beds of hard, dark-grey, siliceous mudrock and very thin beds of yellowish tuff (K-bentonite) (Johnson *et al.*, 2006). The Vischkuil Formation is predominantly argillaceous, with dark shales alternating with subordinate sandstones, siltstones and minor yellowish tuff layers. The Vischkuil Formation overlies the Collingham Formation in the southwestern part of the basin, and its thickness varies between 200 m and 400 m, becoming more arenaceous towards the east and grades into the Ripon Formation (Johnson *et al.*, 2006).

The Lainsburg Formation comprises of four sandstone-rich intervals separated by shale units and is approximately 400 m thick. The thick massive sandstones are fine to medium grained and remarkably parallel-sided, with sharp upper and lower contacts (Johnson *et al.*, 2006). The Ripon Formation is generally 600 – 700 m thick, but is over 1000 m in the eastern part of its outcrop area. It consists of poorly sorted, fine- to medium-grained lithofeldspathic sandstone alternating with dark-grey clastic rhythmite and mudrock (Johnson *et al.*, 2006).

The Fort Brown Formation is approximately 1000 m thick, with values ranging from 500 m to 1500 m. Outcrops are confined to the southern margin of the basin (Johnson *et al.*, 2006). The mudrocks and rhythmites of the Fort Brown Formation and the upper parts of the

Kookfontein and Tierberg Formations constitute distal deltaic deposits which grade upwards via coarsening-upward cycles into the sandstone-rich delta front Waterford Formation (Johnson *et al.*, 1996).

The Waterford Formation overlies the Fort Brown Formation and its thickness varies between 200 m and 800m. It comprises of alternating very fine-grained lithofeldspathic sandstone and mudrock or clastic rhythmite units. Ball-and-pillow and related structures characterise the Waterford Formation (Johnson *et al*., 2006).

The western and northwest formations are the Tierberg, Skoorsteenberg, Kookfontein and Waterford Formations. The Tierberg formation is a predominantly argillaceous succession with its bulk rock comprising of laminated dark shale, with the presence of yellowish tuffaceous beds. This formation is approximately 700 m thick along the western margin of the basin, and thinning to about 350 m towards the northeast. It rests with a sharp contact on the Collingham or Whitehill Formations or, where the latter is absent, into the Adelaide Subgroup (Beaufort Group) (Johnson *et al*., 2006).

The Skoorsteenberg Formation is a lens shaped, arenaceous unit located between the Tierberg and Kookfontein Formations in the south-western part of basin. This formation has a thickness of approximately 250 m and comprises up to five sandstone-rich units with shale units separating them (Johnson *et al.*, 2006). The Kookfontein Formation overlies the Skoorsteenberg Formation with a sharp contact and grades upwards into the Waterford Formation. Its thickness is approximately 350 m thick. The lower part of the formation comprises horizontally laminated dark-grey shales alternating with clastic rhythmites, with upward coarsening cycles (Johnson *et al.*, 2006).

The Waterford Formation in the western part of the basin has a thickness of 130 m, and comprises of fine- to medium-grained sandstone, siltstone, shale and rhythmite; characterising upward coarsening cycles.

2.9.3.3 Beaufort Group

The Beaufort is a group that consists of thick pile of mudstone and sandstone which was deposited under fluvial environment. The Beaufort consists of the Adelaide Subgroup and Tarkastad Subgroup. The deposited sediments were brought in by northward-flowing, meandering rivers, flanked by extensive floodplains where periodic floods deposited mud (McCarthy and Rubidge, 2005).

The Adelaide Subgroup of the Late Permian age, comprises of the Koonap, Middleton, Balfour Formations in the southeastern part of the basin, in the west it consists of the Abrahamskraal and Teefloof Formations. The Adelaide Subgroup has a maximum 5000 m in the southeast and thins to about 800 m in thickness in the centre of the basin. While Tarkastad Subgroup of the Early Triassic age, comprises of the Katberg Formation in the lower south and the Bugersdorp Formation in the upper south. In northeastern region there is the Normandien Formation. The rocks of the Beaufort Group consist of feldspathic sandstone and mudstones distinguished from the underlying Ecca Group by being more colourful and less shaly (Mountain, 1968).

The Middleton and Teekloof Formations are characterised by a greater abundance of red mudstone compared with the underlying and overlying units with boundaries of sandstone that act as marker units. The Middleton and Teekloof Formations have a thickness of 1600 m and 1000 m respectively. The Koonap Formation has a thickness of 1300 m, Balfour Formations is 2000 m thick, Abrahamskraal is 2500 m while Normandein Formation has the thickness of 320 m (Johnson *et al.*, 2006).

The southern and central part of the basin comprises of alternating bluish-grey, greenish-grey or greyish-red mudrocks and grey, very fine- to medium-grained lithofeldspathic sandstones. These parts of the basin consist of the Abrahamskraal and Teekloof Formations of the Adelaide Subgroup. In the northern part of the basin coarse to very coarse sandstones, or even granulestones, are common in the Normandein Formation (Johnson *et al.*, 2006).

The Tarkastad Subgroup has a maximum thickness of approximately 2000 m in the south, it decreases to approximately 800 m in the middle of its outcrop and thins to 150 m or less in the far north (Johnson *et al.*, 2006). Burgersdorp Formation sandstones are fine grained, greenish grey or light brownish grey and display horizontal lamination, cross-bedding and ripple lamination. Deposition environment is believed to be of meandering river or flood-basin palaeoenvironment (Johnson *et al.*, 2006).

The Katberg Formation is composed of sandstone that is fine to medium grained with scattered pebbles in the coastal outcrops, and light brownish grey or greenish grey. The deposition in the south of this formation display braided stream environment with upward fining cycles (Johnson *et al.*, 2006).

2.9.3.4 Stormberg Group

The Stormberg Group is composed of the Molteno, Elliot and the Clarens Formations. The bulk of the Beaufort Group including the Molteno, Elliot and Clarens Formations in the main basin accumulate to a thickness of up to 7000 m (Johnson *et al.*, 1996). The rocks of the Stormberg Group reflect a gradual change to increasingly more arid conditions – a change recorded in the sequence rocks that make-up the Stormberg Group (McCarthy and Rubidge, 2005). The processes in which the formations were deposited are different. The Stormberg Group is completely surrounded by the Beaufort Group (Mountain, 1968).

The Elliot consists almost entirely of fining-upward fluvial sediments. The rivers were mostly high sinuosity (meandering) types, with extensive floodplain muds predominating over lenticular channel sands (Johnson *et al.*, 1996). The sandstone-rich Molteno Formation was deposited by braided low sinuosity rivers. While the Clarens Formation was formed during arid, aeolian conditions which prevailed with massive, loess-type deposits as well as cross-bedding dunes being present.

2.9.3.5 Drakensberg Group

The Drakensberg Group of the Jurassic age was deposited at the end of sedimentation of the Karoo Supergroup and compression took place throughout the deposition of the sediments of Karoo Supergroup. The lava deposits of Drakensberg Group took place during the rupture of the crust and basaltic lava flowed out over the Clarens dessert and parts of the Gondwana continents (McCarthy and Rubidge, 2005).

The Drakensberg Group volcanics are preserved in the Drakensberg and Maluti Mountains of Lesotho forming the Great Escarpment which separates the interior of South Africa from the east coast. The Drakensberg lavas are associated with a network of dykes, sills and sheets of dolerite scattered widely in southern Africa and are composed of the same minerals. Due to their weathering resistance they are still visible and have modified the landscape (Mountain, 1968).

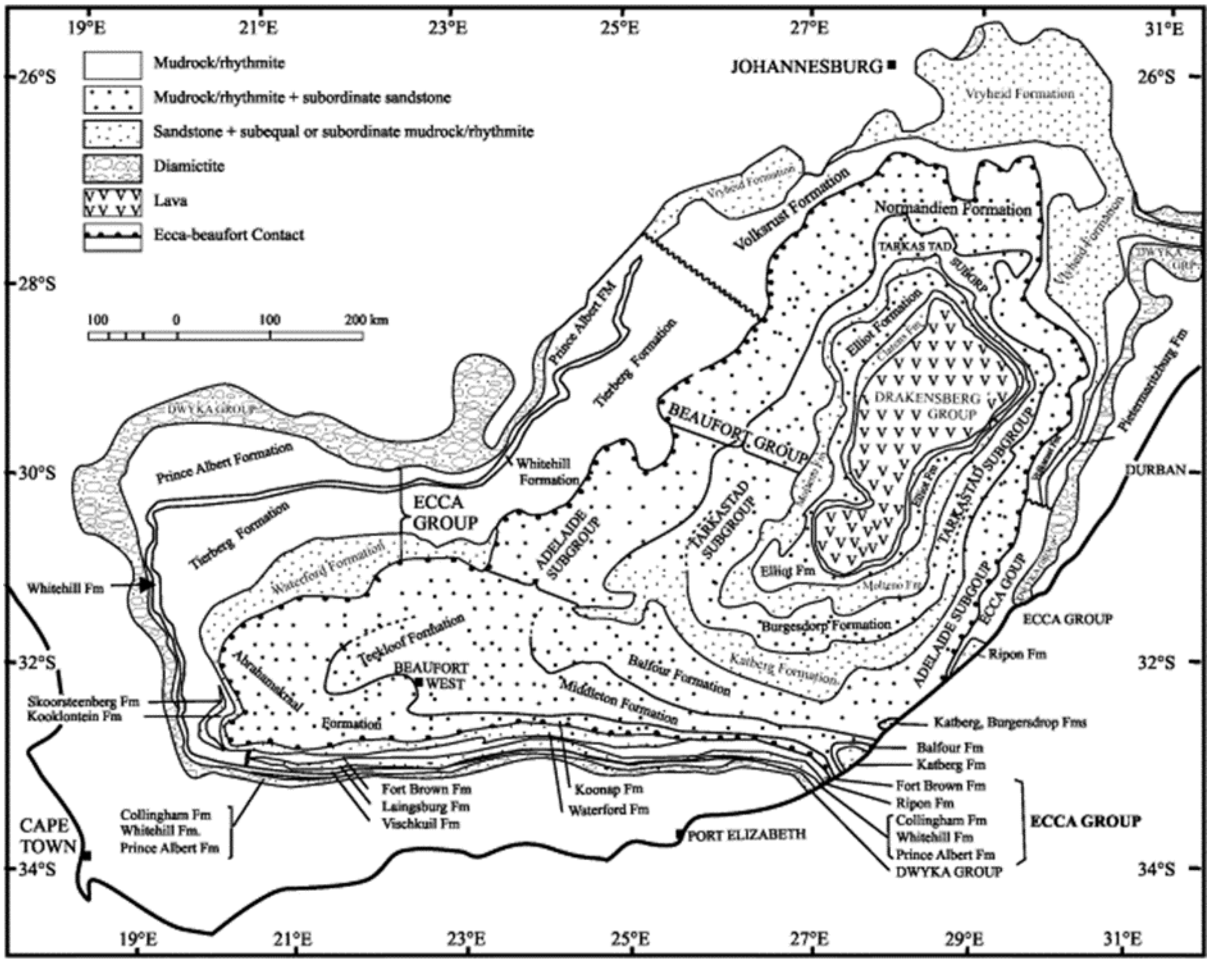


Figure 2-5: Schematic view of the Main Karoo Basin showing the geographic and stratigraphic relationships of the formations of the Ecca Group (source: Johnson *et al.*, 2006)

2.9.4 Vredefort Dome

The Vredefort dome was formed as a result of the meteorite impact that took place approximately two billion years ago, which created a dome shape feature on the surface of the earth. The upturning of rocks due to the impact took place (Figure 2-6). Exhumation and overturning of rocks in the Witwatersrand Basin and crystalline basement are attributed to isostatic recovery of an ∼300 km diameter crater following meteoritic impact (Flowers *et al.*, 2003).

The Vredefort impact structure has been subdivided into three concentric lithological zones. The sub-vertical to overturned rim is composed of a ~10 km thick section Transvaal (2.25 – 2.5 Ga), Ventersdorp (2.7 Ga), and Witwatersrand (2.8 – 2.9 Ga) metasedimentary rocks and the Dominion Group metavolcanics rocks (3.074 Ga). Regionally, the strata are of low metamorphism grade and sub-horizontal except in the vicinity of the structure. The amphibolite facies Outer Granite Gneiss and the heterogeneous granulite facies Inlandsee Leucogranofels domain comprise the inner two basement zones (Flowers *et al.*, 2003).

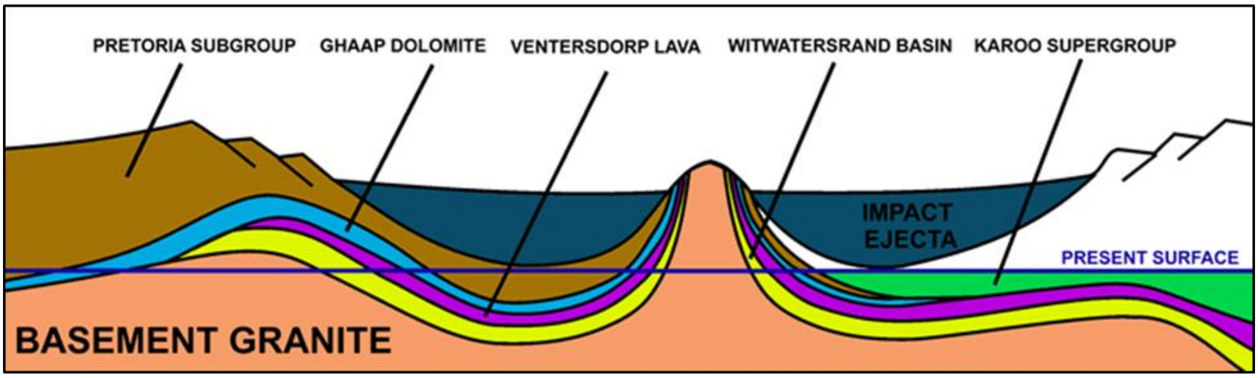


Figure 2-6: Schematic cross-section of the Vredefort Dome

The centre of the dome has rocks believed to be of Archean times, the ridges of dome which form a mountain land are quartzite layers of the Witwatersrand Supergroup with intervening softer mudstones that produce valleys (McCarthy and Rubidge, 2005). The Archean rocks which occur in the centre of the Witwatersrand Basin consist of upper amphibolite- to granulite-grade granitoid gneiss and migmatites with subsidiary mafic and metasedimentary xenoliths.

In the southern sector of the dome is a sequence of mid-greenshist facies ultramafic to mafic rocks with komatiitic, komatiitic basalt and tholeiitic basalt compositions. The southeastern metavolcanics and subordinate mafic-intermediate tuffaceous units are exposed as an inlier within Phanerozoic sediments and dolerite sills of the Karoo Supergroup (Lana *et al.*, 2003; Johnson *et al.*, 2006).

The rocks in the dome are variably affected by an impact induced thermal metamorphic overprint, which increases in grade radially inward from ~300°C in the collar rocks to >1 000°C in the centre of the dome (Lana *et al.*, 2003). In Figure 2-7 the location of Matsopa Minerals Mine is shown in relation to the Vredefort dome, and it appears to be at the "foot" of the dome.

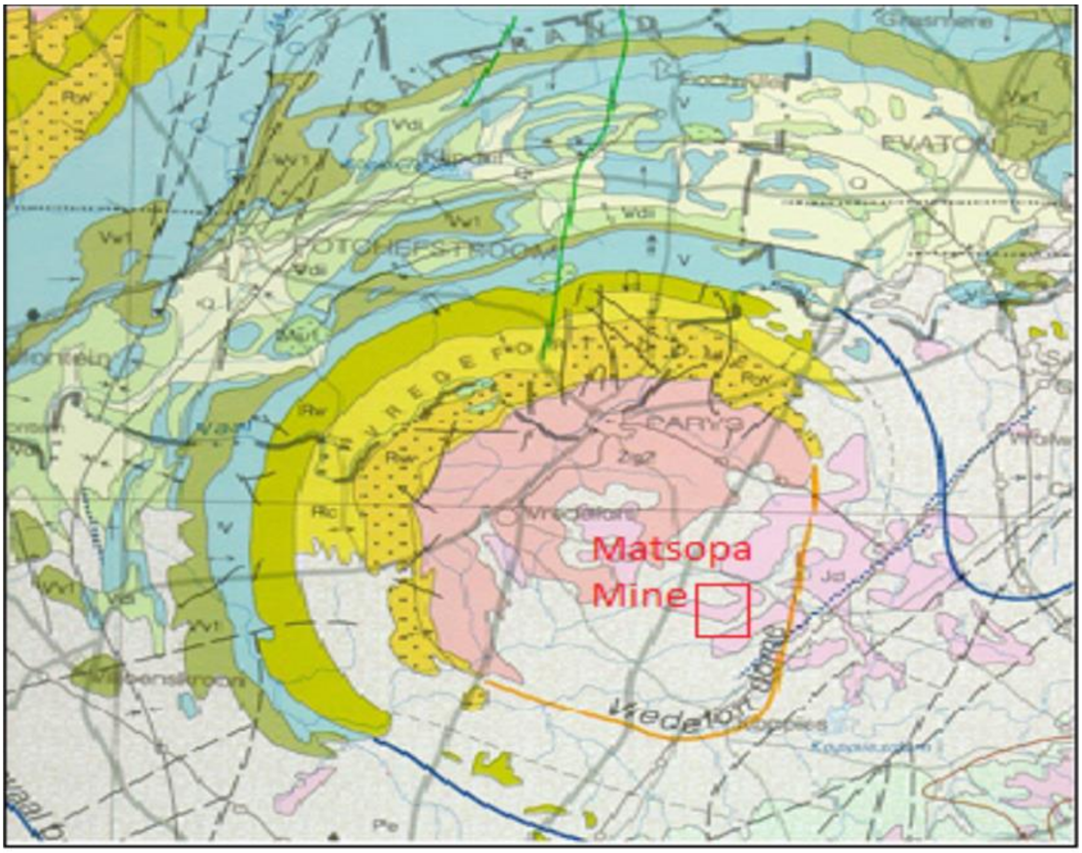


Figure 2-7: The position of the Matsopa Mine in the Vredefort Dome

2.9.5 Formation of clay minerals

Clay minerals are hydrous aluminous sheet silicates with variable composition and water content. They are components of the soil. As previously mentioned in Section 2.3.1, there are different variations and groups of clay minerals, with different cation exchange capacity ratios. The formation of clay minerals is of interest in this study because the clay mineral bentonite is being mined in the study area. It is of importance to understand as where it is derived from and its associated minerals.

Clay minerals form as a result of a number of processes, including: weathering, sedimentation, burial, diagenetic and hydrothermal alteration (Figure 2-8) (Velde, 1977). Most clay minerals are products of weathering or hydrothermal solution alteration. Different clay minerals can result from the same parent rock depending on the climate and the amount, chemistry and flow of water involved in the weathering process (Bonewitz, 2008).

Kaolinite is a product of the weathering or alteration of feldspars, muscovite and other Al-rich silicates usually in acid rocks (felsic igneous rocks). Smectite group minerals form similarly like other clay minerals but can also form by diagenetic processes in sedimentary deposits. Montmorillonite and beidellite are the main constituents of bentonite deposits and form as a result of alteration, the bentonite is derived mainly from igneous eruptive tuff and volcanic ash (Bonewitz, 2008; Deer *et al.,* 2013).

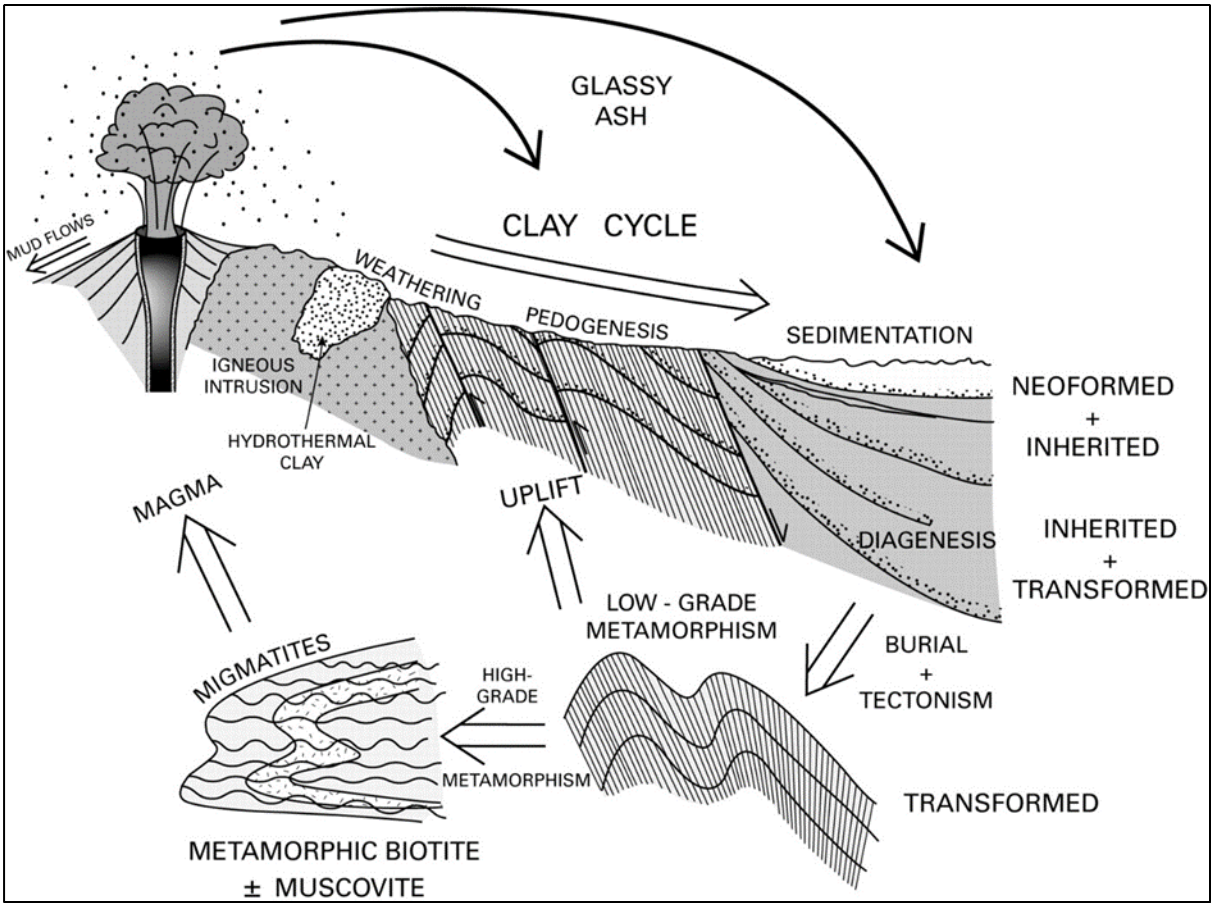


Figure 2-8: Clay cycle showing the different clay forming processes

Bentonite is commonly associated with cristobalite, zeolites, biotite, quartz, feldspar and zircon. The alteration usually occurs in situ, in aqueous (mostly marine) environments. Like zeolites; smectite (montmorillonite) minerals form under diagenetic processes one of which is the hydrologically open system. In hydrologically open systems, the terrestrial accumulations of volcanic material lavas and pyroclastic deposits are subject to alteration by meteoric water and groundwater, the meteoric water percolating through permeable pyroclastic deposits and reacting with glass shards to form smectite clays and alkali solutions (Deer *et al.,* 2013).

The material from which the bentonite could have formed from may be derived from the material that got exposed during the upturning of rocks as result of the meteorite impact of the Vredefort dome. The upturning of rocks, exposed old rocks of ages between 3600 – 2100 Ma. The rocks of these years represent the Swazian granite-greenstone basement rocks, the Witwatersrand Supergroup, Dominion, Transvaal Supergroup and the Ventersdorp

Supergroup. Clay minerals are mainly secondary minerals which are alteration products. The rocks of these geological sequences have mineralogical compositions that are feasible for the formation of clay minerals. The Transvaal Supergroup volcanics dominate the Pretoria Group, Wolkberg and Buffalo Springs Group. The Pretoria Group is divided into the three thick volcanic intervals – Hekpoort basalt, the Machaddorp and Dullstroom volcanics (Tankard *et al.*, 1982).

The greenschist of the Swazian age contains minerals like chlorite, micas and amphiboles that alter to clay minerals as result of weathering or hydrothermal solutions. The Dominion Group comprises of arenaceous units and thick sequence of volcanic rocks and is overlain by the Witwatersrand Supergroup. The strata of the Dominion Group crop out on the northern rim of the Vredefort Dome (Watchorn, 1980). The volcanic material of all these geological sequences maybe have undergone hydrothermal alteration and the material was enough to form the bentonite seam that is being mined.

2.10 GEOPHYSICS

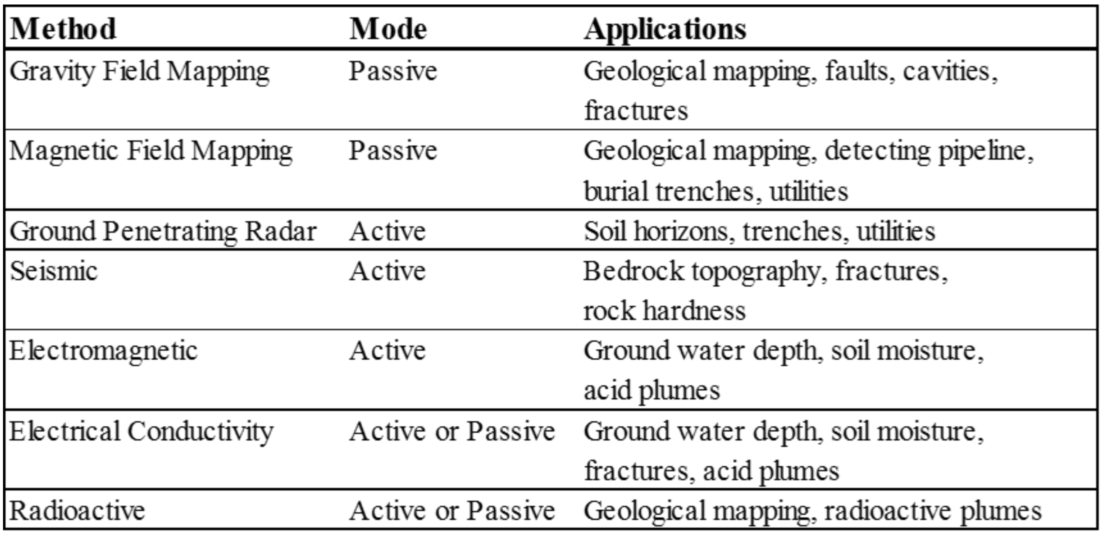
2.10.1 Introduction

Geophysics is the study of the physics of the earth, its properties and how the earth works. It is mainly used to get a better understanding of the subsurface and deeper parts of the earth. Geophysical methods are widely used in ore exploration and groundwater exploration. In a semi-arid country like South Africa whose most parts of the country has been declared dry, geophysics forms an important component in identifying areas with good groundwater prospects.

There are different methods that can be used for different types of exploration depending on what is being explore (Table 2-1). The success of any geophysical method relies on there being a measurable contrast between the physical properties of the target and surrounding medium (properties include density, elasticity, magnetic susceptibility, electrical conductivity and radioactivity), (Milsom and Eriksen, 2011).

Geophysical methods are either passive or active while some are both passive and active. Passive methods can detect variations within the natural field associated with the earth (such as the earth's magnetic field). Active methods involve generating signals in the subsurface in order to induce a measurable response associated with a target. The observer has control over the level of energy input to the ground and measures variation in energy transmissibility over distance and time (Milsom and Eriksen, 2011; Reynolds, 2011). In this research study both passive and active methods were used, namely the magnetic and resistivity methods, respectively.

Table 2-4: Passive and active geophysical methods (Won, 1990)



Method	Mode	Applications
Gravity Field Mapping	Passive	Geological mapping, faults, cavities, fractures
Magnetic Field Mapping	Passive	Geological mapping, detecting pipeline, burial trenches, utilities
Ground Penetrating Radar	Active	Soil horizons, trenches, utilities
Seismic	Active	Bedrock topography, fractures, rock hardness
Electromagnetic	Active	Ground water depth, soil moisture, acid plumes
Electrical Conductivity	Active or Passive	Ground water depth, soil moisture, fractures, acid plumes
Radioactive	Active or Passive	Geological mapping, radioactive plumes

2.10.2 The Magnetic Method

2.10.2.1 Background

The magnetic method is widely used by geophysists/geologists in mineral exploration and geohydrologists to identify intrusive rocks that cause the development of fractures, joints and fissures in sedimentary rocks. This method is an easy and inexpensive survey that can be carried out.

The geomagnetic field is produced by electric currents induced within the conductive liquid outer core as a result of slow convective movements within it (Reynolds, 2011). The earth’s large-scale magnetic field is superimposed by small-scale magnetic anomalies related to magnetized rocks. The earth’s magnetic field can be explained as a vector equivalent to a magnet bar Figure 2-9, which consists of two magnetic monopoles, one positive and the other negative, separated by some distance (Ernstson, 2006). The magnet with two monopoles is called the magnetic dipole.

Magnetic field lines are drawn to visualize the magnetic force, and to describe the direction of the magnetic force. They show the magnetic field at the surface of the earth to be vertical at the north and south magnetic poles and horizontal at the magnetic equator. Between these two extremes the direction of the field is at an angle to the earth’s surface. The direction of the field is taken as being towards the north pole and positive in this direction (Lowrie, 2007; Reynolds, 2011).

The vector magnetization may have arbitrary orientation in a rock, and that is why geometrically identical magnetic bodies can show different magnetic anomalies.

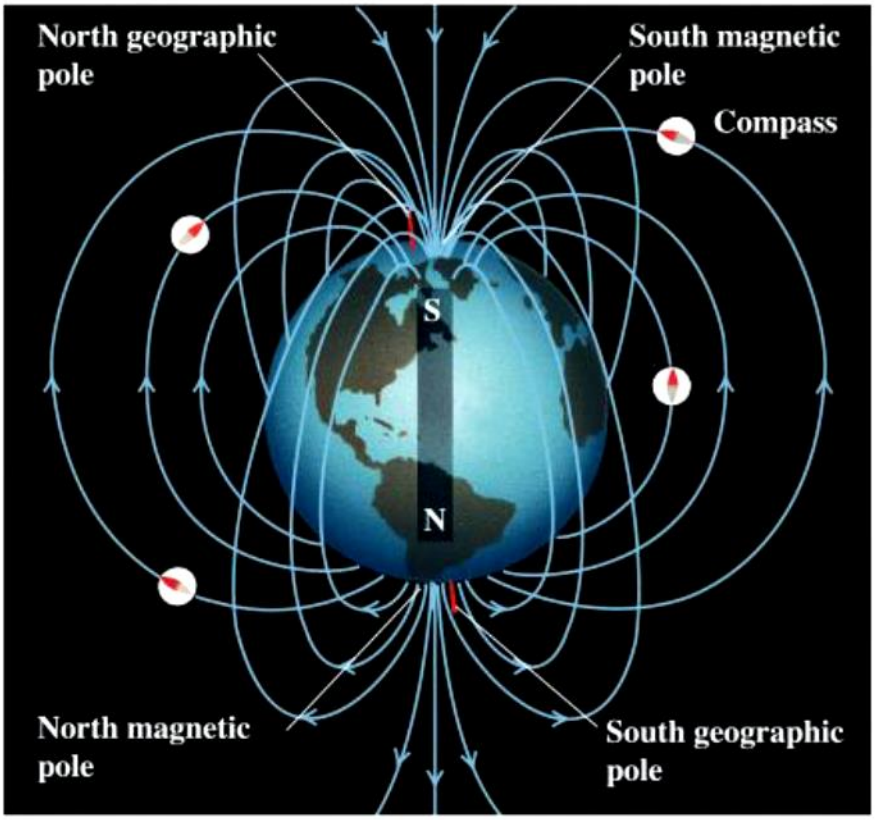


Figure 2-9: Image showing the earth's magnetic field as that of a magnetic bar (source: Becker, 2002)

2.10.2.2 Induced and remnant magnetization

There are two situations to be taken into account: (1) the location and orientation of a magnetic body in various latitude (known as induced magnetism), and (2) the remanent magnetisation. The induced magnetisation of a body is in the same direction of the present day earth’s field whereas remanent magnetisation do not need be in the same direction and could even oppose the earth’s field (Roux, 1980).

The induced intensity depends on the magnetic susceptibility and the magnetising field, while the remanent intensity depends upon the geologic history of the rock (Parasnis, 1962). With induced magnetisation the magnetic field intensifies when approaching a magnetic body and weakens the further away from the magnetic body because the magnetic field is taken away from the magnetic body. Remanent magnetisation in rocks is acquired by magnetic minerals during cooling from high temperatures by chemical and several other processes, if they are exposed to a magnetising field, normally the earth's magnetic field (Ernstson, 2006).

Magnetisation of the magnetic body can be input in a formula: $M_i = k.F$

where M_i is the induced magnetisation that is characteristic to all rocks, F is the magnetic field intensity, and k is the dimensionless magnetic susceptibility of the rock.

2.10.2.3 Magnetic declination and inclination

There are common magnetic field direction used for the projection of the magnetic field on the earth's surface namely the declination, inclination, magnetic equator and magnetic field.

Declination – The magnetic declination was first discovered by Christopher Coulomb in the year 1492 during his first voyage. In the second half of the 16th century it was well known and measured at sea or in harbours (Lanza and Meloni, 2006). The magnetic declination is the angle which the horizontal component of the earth's field makes with the true north and is the angle that a compass deviates from true north (Figure 2-10). This value is measured positive through east and varies from 0 to 360° (Roux, 1980).

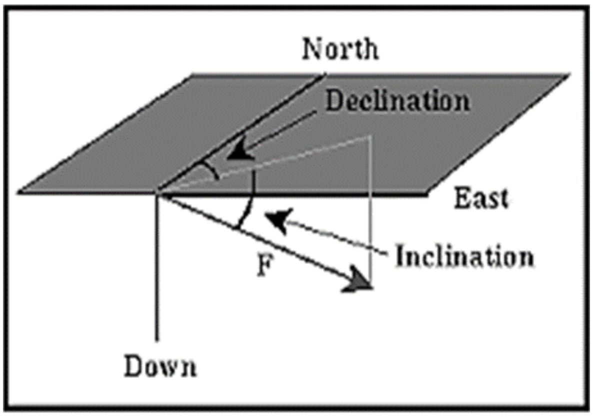


Figure 2-10: Magnetic inclination and declination to the earth

Inclination – the angle that the earth's magnetic field makes to the horizontal. In southern Africa the magnetic inclination is approximately 60°. At the magnetic equator the inclination is zero (Roux, 1980). The discovery of inclination led to the correct drawing of the magnetic field lines of force, and therefore to a more complete description of the field (Lanza and Meloni, 2006).

2.10.2.4 Temporal variations of the magnetic field

The earth's field varies with time and this causes temporal variations of the magnetic field. The variations are dependent on the occurrence and source. The variations last for periods of seconds, minutes and hours, and are direct and indirect consequence of solar winds. There are different types of temporal variations:

2.10.2.4.1 Secular variations

These are long-term variations in the main magnetic field which are regional rather than worldwide phenomenon. These variations are presumably caused by changes in convection currents in the core, in the mantle coupling and in the rotational speed of the earth. These variations occur slowly with respect to the time of completion of a magnetic survey, and will not complicate data reduction efforts (Telford *et al.*, 1976).

2.10.2.4.2 Diurnal variations

These variations occur during local daylight hours and are related to variations in the earth's external magnetic field. Diurnal variations are not predictable and can have variations of 10 to 30 nT per day but can be corrected for by adopting a suitable procedure in the field (Lowrie, 2007).

2.10.2.4.3 Magnetic storms

Magnetic storms are violent form of diurnal variation that occurs when the magnetic activity in the ionosphere increases abruptly. These storms correlate with enhanced sunspot activity. The observed magnetic field is highly irregular and unpredictable the magnetic storm can last up to a day or several days. When a magnetic storm occurs the magnetic survey should not be conducted as the magnetic readings cannot be corrected for (Lowrie, 2007).

2.10.2.5 Magnetic properties of minerals and rocks

The susceptibility of rocks depends on the mineral composition of the rocks as some minerals are magnetic and some are not (Figure 2-11). Some minerals are diamagnetic like quarts and calcite, and have a negative susceptibility in the order of 10^{-5}. Minerals like feldspars and micas are paramagnetic and have high (positive) susceptibility (10^{-4} – 10^{-2}). The positive susceptibility of ferromagnetic minerals like magnetic (k~1-10) and titanomagnetites is even larger by some orders of magnitude and in general most important for the magnetization of rocks (Ernstson, 2006).

Usually igneous plutonic rocks like dolerite are susceptible as opposed to the country rock it intrudes because it contains magnetic minerals. According to rocks Ernstson (2006), the susceptibility of rocks in ascending order may be addressed as follows: (k~0.0001) sedimentary rocks-metamorphic rocks (0.0001) acid volcanic and plutonic rocks (0.01) basic volcanic rocks (0.1).

Water is diamagnetic ($k=-9.05\times10^{-6}$) and has no importance for the actual magnetization of the rock. However, water plays an important role in the alteration of rocks and is sometimes the carrier of iron bearing and chemically active solutions. Water can change the magnetisation of rocks during geologic times. Magnetisation changes of rocks by contaminated groundwater may be addressed in environmental geophysical survey.

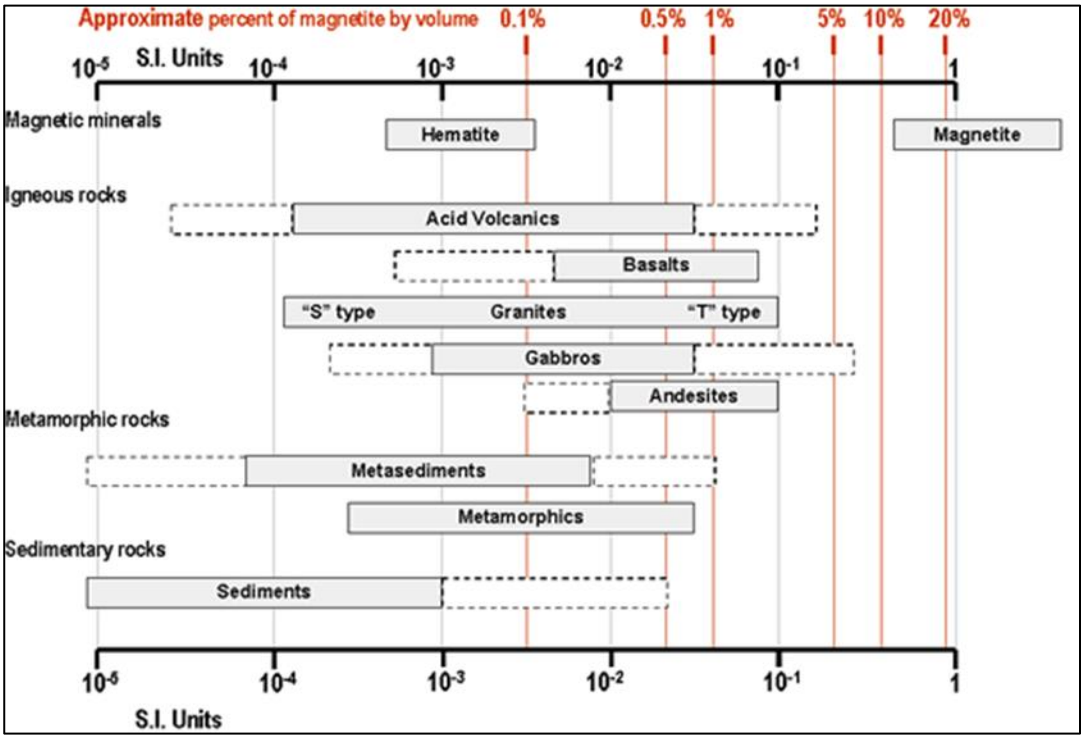


Figure 2-11: Magnetic susceptibility of rocks (source: Clark and Emerson, 1991)

2.10.2.6 Instruments

Magnetic instruments are one of the oldest instruments in existence as the force of magnetisation was discovered centuries ago, when Charles Coulomb discovered the force of repulsion or attraction. Some instruments are as simple as a compass that can provide measurement of the declination of the magnetic field, and a dip-needle instrument used to measure the inclination of the magnetic field. The most common instruments that are used in magnetic geophysical surveys are magnetometers.

Magnetometers are highly accurate instruments that measure magnetic fields to a high degree of precision. There are different types of magnetometers used in magnetic surveys; borehole magnetometers, ground magnetometers and airborne magnetometers. Discussed below are the most common ground magnetometers used in magnetic geophysical survey.

Magnetic balance magnetometer – makes use of a small bar magnet which is suspended about its centre point by a horizontal quartz fibre. An external magnetic field will tilt the magnet in one or other direction. The amount of deflection will be related to the strength of the field and the direction relates to an increase or decrease of the field (Roux, 1980). This type of magnetometer is the oldest form of magnetometers, it works no different than a compass used by early mariners (Zhdanov, 2009).

Fluxgate Magnetometer – originally the magnetometer was developed to detect submarines during the World War II, thereafter several designs for recording diurnal variation for airborne geomagnetics and as portable ground magnetometers (Reynolds, 2011). The detector consists of cores of magnetic material, such as mu-metal or ferrite, which are wound coils through which alternating current can be passed. Variations in the electrical properties of the circuits with magnetisation of the cores can be converted into voltages proportional to the external magnetic field along the core axes. Magnetic measurements are in the direction in which the sensor is pointed (Telford *et al.,* 1990; Milsom, 2003).

Portable magnetometers used for ground surveys consists of: a coil sensitive to magnetic field, an electronic oscillator and amplifier, a meter, a device for compensating the earth’s field (Roux, 1980). Fluxgate do not measure absolute fields and therefore require calibration (Milsom, 2003)

Proton magnetometer – this type of magnetometer depends on the measurement of the free-precession frequency of protons that have been polarised in a direction approximately normal to the direction of the earth’s fields (Telford *et al.,* 1990).

The sensor of the proton magnetometer consists of a container of proton-rich fluid, usually kerosene around which is surrounded by a coil of a wire. The protons act as small dipoles and normally align parallel to the ambient geomagnetic filed. A current is passed through the coil to generate a magnetic field 50-100 times larger than the geomagnetic field, in a different direction, causing protons to realign in this new direction.

When the polarizing field is suddenly removed, the protons return to their original alignment by spiralling or precessing, in phase around the direction (Roux, 1980; Telford *et al.,* 1990;

Kearey *et al.,* 2002). Proton magnetometers measure the total intensity of the earth magnetic field vector at a resolution of 0.1-1 nT (Ernston, 2006).

2.10.2.7 Properties of magnetic anomalies

The data obtained through measuring the magnetic permeability of rocks can be used to get an anomaly and magnetic contours. An anomaly is created when the earth’s magnetic field is disturbed by an object that can be magnetised. The shape, wavelength and amplitude of the anomaly can give an indication of the orientation and size of the magnetic body (Figure 2-12). Compact bodies give rise to one shape anomaly, while long thin bodies or flat sheet-like bodies give rise to others. The shape of the anomaly is determined by the geometry of the magnetic body with respect to the direction of the earth’s magnetic field.

The amplitude of the anomaly is controlled by a combination of the susceptibility, permanent magnetisation and the distance from the body that you are observing. An object with a high magnetisation will have a long and narrow peak. While the deeper the object, the weaker and broader the peak on the profile will be.

2.10.2.8 Applications

Magnetic methods can be applied for different investigations and these are:

- Finding buried steel tanks and waste drums
- Locating unmarked mineshafts
- Accurately mapping archaeological features
- Mapping basic igneous intrusive and faults
- Evaluating the size and shape of ore bodies
- Map old waste sites and landfills boundaries
- In groundwater studies is used to map the depth to the magnetic basement rock

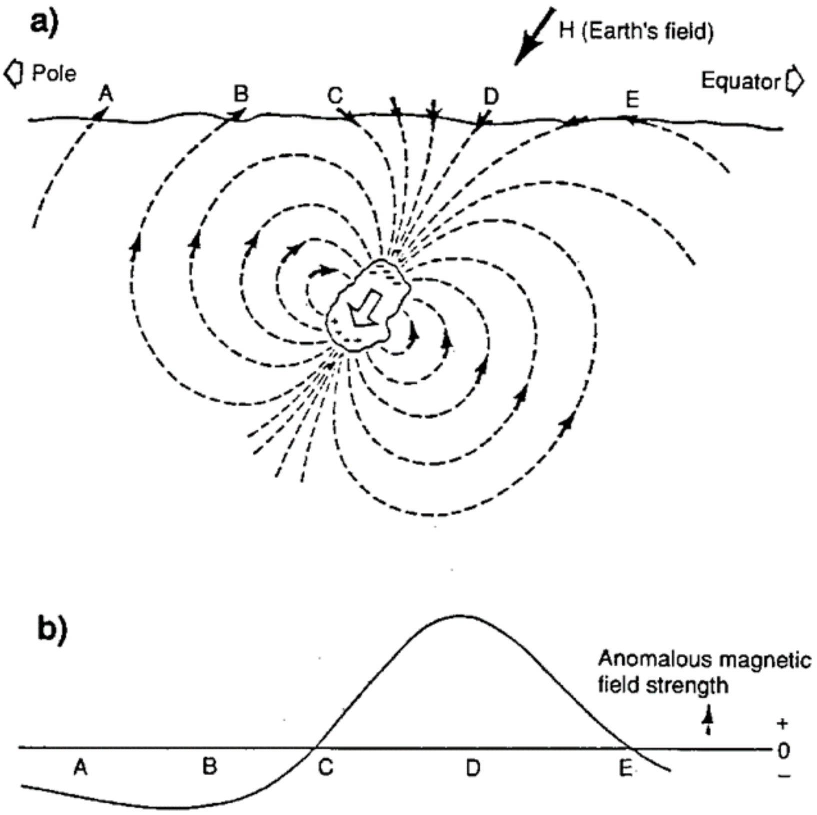


Figure 2-12:An example of a magnetic anomaly (a) showing the magnetic body in the subsurface and (b) showing the anomaly in a form of a magnetic profile

2.10.3 The Resistivity Method

2.10.3.1 Background

Electrical prospecting involves the detection of surface effects produced by electric current flow in the ground. Using electrical methods, potentials, currents and electro-magnetic fields can be measured (Telford *et al.*, 1976). Resistivity of the ground is measured by injected currents and the resulting potential differences at the surface. The current that flows in a material can be calculated using Ohm's law:

$$V = IR \qquad (1)$$

where R is resistance of a unit measured in ohm, I is the current measured in ampere and V the voltage measured in volt.

Resistivity is measured using a second pair of electrodes of high-impedance voltmeter; this is because using a single pair of electrodes to pass currents in the ground and measuring its voltage does not work as the contact resistance depends on factors like ground moisture and contact area (Milsom, 2003). Two pairs of electrode are required: electrodes A and B are used for current injections, while electrodes M and N are for potential difference measurements Figure 2-13. For homogenous ground and an arbitrary electrode arrangement the resistivity ρ (unit: Ohm*meter, Ωm) as the relevant petrophysical parameter can be calculated from the current I and the potential difference ΔV by $\rho = K \cdot \frac{\Delta V}{I}$. For heterogeneous ground *apparent resistivity* is introduced and measured by:

$$\rho_A = K \cdot \frac{\Delta V}{I} \tag{2}$$

where *K* is the geometric factor, calculated from:

$$K = \frac{1}{2\pi} \cdot \left[\left(\frac{1}{AM} - \frac{1}{BN} \right) - \left(\frac{1}{AN} - \frac{1}{BN} \right) \right]^{-1} \tag{3}$$

where *AM* is the distance between electrodes A and M, and so forth. The apparent resistivity ρ_A depends also on the location of the electrodes with respect to the geological units. Resistivity soundings are done by selecting an apparent electrode configuration, by systematically changing and/or moving its configuration, and by sampling the related apparent resistivities ρ_A (Telford *et al.*, 1976). Resistivity surveys can be affected by background noise levels. Geometric factors are not affected by interchanging current and voltage electrodes but voltage electrode spacing are normally kept small to minimise the effects of natural potentials (Milsom, 2003).

In groundwater studies, the resistivity method can furnish information on subsurface geology which might be unattainable by other geophysical methods. A thick clay layer separating two aquifers usually can be detected easily on a sounding curve (Zohdy *et al.*, 1974).

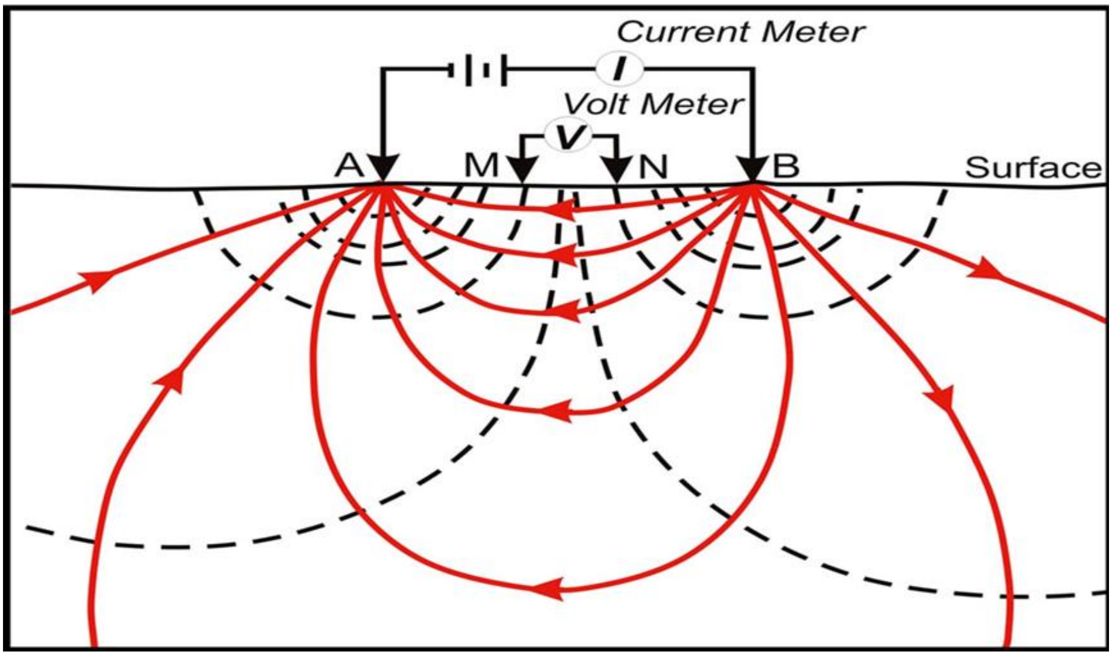


Figure 2-13: Example of current flow in the subsurface. The red lines shows current flow and the black dashed lines show electrical potential (Clark and Page, 2011)

2.10.3.2 Resistivity of rocks and minerals

Of all the physical properties of rocks and minerals, electrical resistivity shows the greatest variation. In looser classification, rocks and minerals are considered to be good, intermediate and poor conductors (Telford *et al*., 1976). Rocks that contain water, oxides and ores are considered to be intermediate conductors while common rock-forming minerals such as silicates, carbonates and sulphates are poor conductors. Resistivity of rocks varies as it is dependent of the minerals the rock is composed of.

Igneous rocks have the highest resistivity, sedimentary rocks has the lowest while metamorphic rocks are intermediate (Figure 2-14). The resistivity of particular rock types vary directly with age and lithology, since the porosity of the rock and salinity of the contained water are affected by both (Telford *et al*., 1976). The resistivity of rocks is strongly influenced by the presence of groundwater, which acts as an electrolyte (Lowrie, 2007).

Isotropic materials have the same resistivity in all directions. Most rocks are reasonably isotropic but strongly laminated slates and shales are more resistive across the laminations than parallel to them, and these rock results in having anisotropic electrical resistivity and thus having a low resistivity (Milsom, 2003; Kirsch, 2006). Clay material is present in abundance as well in the study area and clays are characterised by low electrical resistivity in the range of 5-60 Ωm and often a target in electrical or electromagnetic surveys (Kirsch, 2006). The low resistivity in clay minerals is caused by surface conductivity because clay minerals are flat and have a large surface area as they allow the exchange between ions and also accommodate water molecules. Since the electrical resistivity of most minerals is high (exception: clay, metal ores and graphite), the electrical current flows mainly through the pore water (Kirsch, 2006).

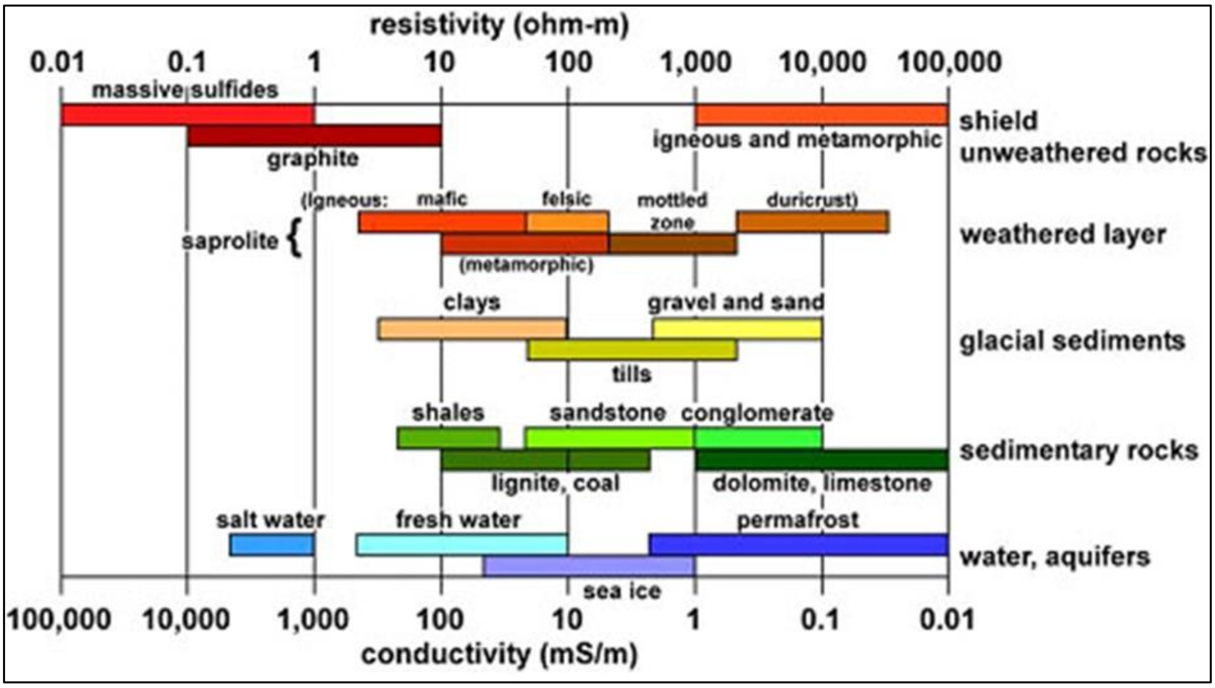


Figure 2-14: The resistivity measures of different rock types

2.10.3.3 Electrode configurations

Various electrode configurations (geometries, arrays) can be used during resistivity surveys. Some of the more commonly used arrays are described in this section.

2.10.3.3.1 The Wenner array

The Wenner array is the simpler configuration in that current and potential electrodes are maintained at an equal spacing a (Kearey *et al.*, 2002). Four electrodes A, M, N and B are placed at the surface of the ground along a straight line so that: $AM = MN = NB = a$

The apparent resistivity is given by:

$$\rho_a = 2\pi a \frac{\Delta V}{I} \qquad (4)$$

The apparent resistivity ρ_a is a function of the single distance variable a (Zohdy *et al.*, 1974). For lateral exploration or mapping, the spacing remains constant and all four electrodes are moved along the line from station to station.

2.10.3.3.2 The Schlumberger array

The four electrodes are placed along a straight line in the same order AMNB as in the Wenner array, but with $AB \geq 5MN$ (Zohdy *et al.*, 1974). The potential electrodes (M and N) are closely spaced and fixed to the centre of the array and the current A, B move outwards. The apparent resistivity can be given by:

$$\rho_a = \pi \frac{(AB/2)^2 - (MN/2)^2}{MN} \frac{\Delta V}{I} \tag{5}$$

If $MN \rightarrow 0$, then the equation can be written as: $\rho_a = \pi (AB/2)^2 \, \frac{E}{I}$. The resistivity is then defined in terms of the electric field E rather than potential difference ΔV, and the apparent resistivity ρ_a becomes a function of a single distance-variable $(AB/2)$ (Zohdy *et al.*, 1974). In constant separation traversing surveys with Schlumberger configuration several lateral movements of the potential electrodes may be accommodated without having to move the current electrodes (Kearey *et al.*, 2002).

2.10.3.3.3 The dipole-dipole array

Electrodes A, B and M and N are in each case closely spaced to form a current electrodes and the distance between the potential electrodes is smaller than the distance *r*, between the centres of the two dipoles. The apparent resistivity is a function of a single distance variable:

$$\rho_a = \left(\sqrt{\left(AB/2^2\right) + r^2} \right) \frac{\Delta V}{I} \tag{6}$$

In principle, the dipoles may have arbitrary azimuthal orientation, but the radial and equatorial arrays are most common (Zohdy *et al.*, 1974). In the dipole arrays the current electrodes remain fixed, a depth penetration is achieved by increasing separation, and the potential dipole will increasingly be influenced by equipotential lines of larger depth extent (Ernstson and Kirsch, 2006). The dipole-dipole configuration is popular in induced polarisation (IP) work because the complete separation of current and voltage circuits reduces the vulnerability to inductive noise (Milsom, 2003).

2.10.3.3.4 Depth penetration

The depth of current penetration depends on the configuration that has been chosen to be used during a survey. The configuration chosen will depend on the layering and separation of current electrodes to reach the target penetration. The investigation depth of commonly used arrays is in the range of L/6 to L/4, where L is the spacing between the outer active electrodes (Janik and Krummel, 2006). The voltage electrode positions determine which part of the current field will be sampled (Milsom, 2003).

To obtain qualitative resistivity contrast at great depth the spacing between the outer electrodes needs to be expanded. For any array, there is an expansion at which the effect of a thin horizontal layer of different resistivity in homogeneous ground is a maximum.

The dipole-dipole is the most and the Wenner the least penetrative array (Milsom, 2003).the Wenner array has a better vertical resolution power, therefore it locates flat lying structures more accurately than Schlumberger. Dipole-dipole is more suited for mapping lateral changes, and has the best resolution in detecting single objects and is the best choice for low multi-electrode measurements. The Wenner and Schlumberger are best suited at regions with high electrical noise, to increase signal strength (Milsom, 2003; Janik and Krummel, 2006).

2.10.3.4 Field investigations

2.10.3.4.1 Electric sounding

Vertical electric sounding (VES), is used to obtain information on the variation in the subsurface conditions with depth. This type of survey makes use of arrays which the distances between some or all of the electrodes are increased systematically. In homogeneous ground and isotropic layers, electrical sounding data represent only the variation of resistivity with depth. In heterogeneous ground, electrical sounding data are influenced by both the vertical and horizontal (Zohdy *et al.*, 1974).

The field procedure for this type of survey is to increase the electrode spacing from one reading to the next while the centre of the electrode spread remains in one spot (Acker, 1974). Apparent resistivities are plotted against expansion on log-log paper and matched against type curves, the electrode expansion is determined by $a, \frac{AB}{2}$ or r and the curve of the sounding curve is determined by $\rho_\alpha = f\left(a, \frac{AB}{2}, or\ r\right)$ (Zohdy *et al.*, 1974; Milsom, 2003).

The Wenner and Schlumberger are the common arrays that used for VES. Schlumberger is used because only two electrodes are moved therefore it is easy to carry out the survey unlike using the Wenner array where all four electrodes are moved. To avoid topographic effects affecting the sounding curve, the direction of the electrode spread should be chosen to enable a more or less horizontal electrode line. For dipping layers, the direction of the electrode spread should be expanded parallel to the strike direction to minimise disturbing effects (Ernston and Kirsch, 2006; Milsom, 2003).

Sounding is valuable in the following applications: estimation of variation of resistivity with depth; the sequence of high and low resistivity zones; estimation of depth to sand gravel, to bedrock, to a water-bearing layer; and indication of thickness of a layer (Acker, 1974).

2.10.3.4.2 Electric profiling

Electric profiling method detects lateral variation, the resistivity anomalies are caused by fracture zones, cavities or waste deposits (Zohdy *et al.,* 1974; Milsom, 2003; Ernstson and Kirsch, 2006). Any common array can be used for mapping purposes, once the array has been chosen array parameters are kept constant and the depth penetration varies only with changes in subsurface layering.

The field procedure for this type of survey is to choose a suitable electrode spacing and maintain this spacing as the whole electrode array is moved along a profile after each measurement is taken (Ernston and Kirsch, 2006). Maximum apparent resistivity anomalies are obtained by orientating profiles at right angles to the strike of the geologic structure (Zohdy *et al.,* 1974).

Depth information can be obtained from a profile if only two layers, of known and constant resistivity, are involved since each value of apparent resistivity can be converted into a depth using a two-layer type-curve (Milsom, 2003). In horizontal profiles at least two different electrode spacing can be used, in order to distinguish the effects of deeper ones (Zohdy *et al.,* 1974). The results are presented as apparent resistivity maps or apparent resistivity profiles.

Electrical profiling is suited for outlining sand and gravel deposits, locating faults or fault zones or locating steeply dipping contacts between different rock types, buried stream channels, veins and dikes (Acker, 1974; Zohdy *et al.,* 1974).

2.10.3.4.3 2D electrical imaging

2D measurements are a combination of sounding and profiling to obtain 2D resistivity imaging, especially used to investigate complicated geological structures with lateral resistivity changes. The combination of sounding and profiling survey gives information for both lateral and vertical image along a profile. In 2D imaging it is assumed that resistivity does not change in the direction that is perpendicular to the survey line (Loke, 1999).

2D measurements

The measurements are taken in such a way that all the electrodes that are used are measured. An example is using the Wenner array (Figure 2-15), the spacing between electrodes are the same “a”. The sequence of measurements will start with spacing of “1a”. The first measurements electrodes number one, two, three and four are used. Electrode one is used as the first current electrode C_1, electrode two is the first potential electrode P_1, electrode three is the second potential electrode P_2, and electrode four is second current electrode C_2. For the second measurement electrodes number two, three, four and five are used for C_1, P_1, P_2 and C_2 respectively (Loke, 1999). This is repeated down line until the last electrodes are measured for the “1a” spacing measurements. After the “1a” measurements are completed then the sequence is carried out for the “2a” electrode spacing measurement. The first measurements will be one, three, five and seven for the “2a” electrode spacing.

The process is carried out for line spacing “3a”, “4a” etc. until the whole sequence is completed for the survey. An increase in electrode spacing will result in measurement decrease. The number of measurements that can be obtained for each electrode spacing, for a given number of electrodes along the survey line, depends on the type of array used (Loke, 1999).

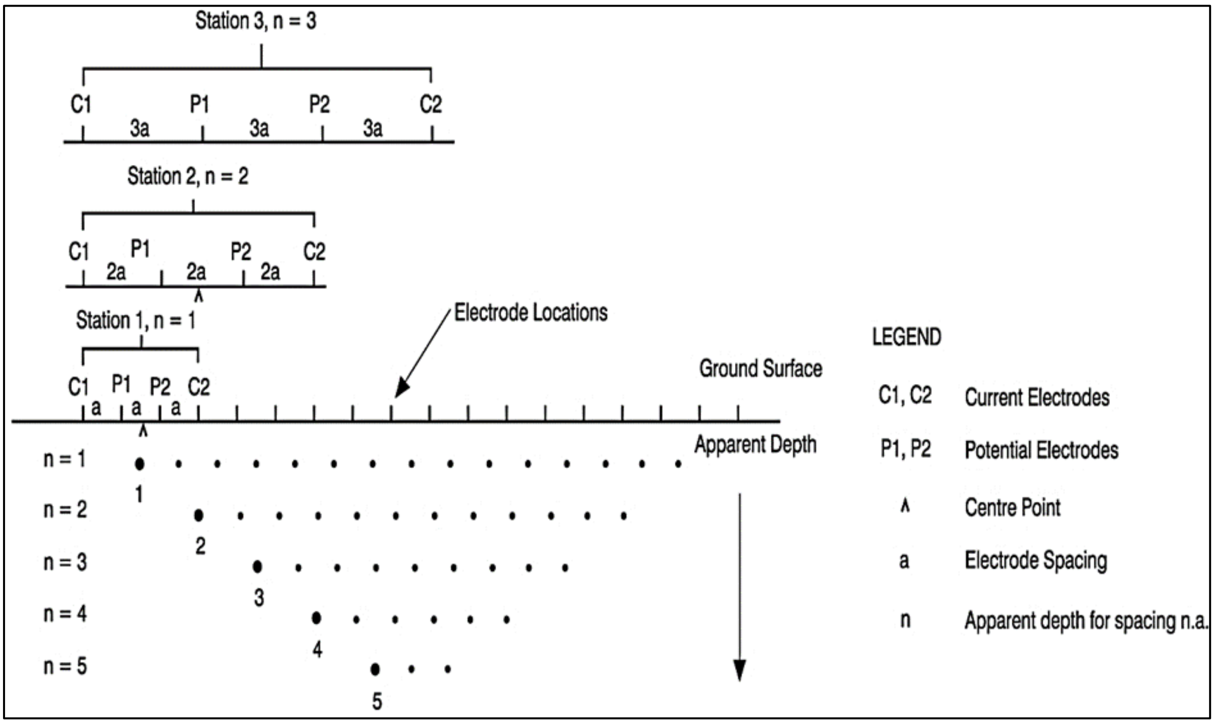


Figure 2-15: Schematic view of the layout and data capture of ERT

Field equipment

ERT equipment has undergone changes over the years and has become more user friendly. The equipment is more efficient for survey procedures, the quality of the data has improved and there is an increase of the depth of the investigation. In VES survey rectangular DC pulses or even low-frequency AC are used. The field equipment is completed by a cable wheels and electrodes for current injection and voltage record.

For highly accurate DC or DC pulse measurements, unpolarisable electrodes as used in self-potential surveys are strongly recommended (Ernston and Kirsch, 2006). The equipment used in resistivity survey consists of cable wheels, steel electrodes for current injection and a receiver where measurements are taken. Most resistivity meters employ low-frequency alternating current rather than direct current (Kearey *et al.,* 2002).

2.10.3.5 Electrical resistivity applications

There are different types of applications of electrical resistivity tomography (ERT) in which the method is employed. Some are listed below together with the advantages and disadvantages of ERT method.

- Performing geologic and stratigraphic mapping

- Mapping leachate leaking from evaporation ponds
- Estimating volumes of tailing piles and tar pits
- Optimising the placements of water supply wells and groundwater monitoring wells
- Conducting validity exams of sand and gravel deposits
- Location of sinkholes and cavities
- Archaeological sites
- Exploration of groundwater
    - Groundwater depth
    - Lithology favourable for groundwater
    - Contamination of groundwater
    - Depth of freshwater-saltwater interface

Advantages

- The equipment is light, portable and inexpensive
- Qualitative interpretation of the data is rapid and straightforward
- Field expenses are minimal
- It is flexible and can be used for various purposes and depths of investigation
- Shallow investigations are rapid

Disadvantages

- Deep investigations require long cables and consume field time
- Interpretation of complex geologic structures is difficult and ambiguous
- Presence of metal pipes, cables, fences and electrical grounds can complicate interpretation
- Accuracy of depth determination is lower than with seismic techniques

CHAPTER 3:
SITE DESCRIPTION

3.1 REGIONAL SETTING

Koppies whose name means hills, is a small town in the northern Free State in Fezile Dabi district. The small town is situated about 63 km north-east of Kroonstad, 48 km west of Heilbron and 42 km south of south-east of Parys. The town is also situated near the Renoster River. The river feeds the Koppies Dam which supplies the town with water. The area consists of residential settlement, local farms and the mining areas. The mining area which is the study site, is located 10 km north of Koppies. The site is surrounded by local farms that are characterized by summer and winter crop production as well as cattle farming. The study area consists of two bentonite mine pits namely the Ocean and Blaauwboschpoort pit, Figure 3-1. The mining initially started on the Ocean farm in the 1950s (Horn and Strydom, 1998).

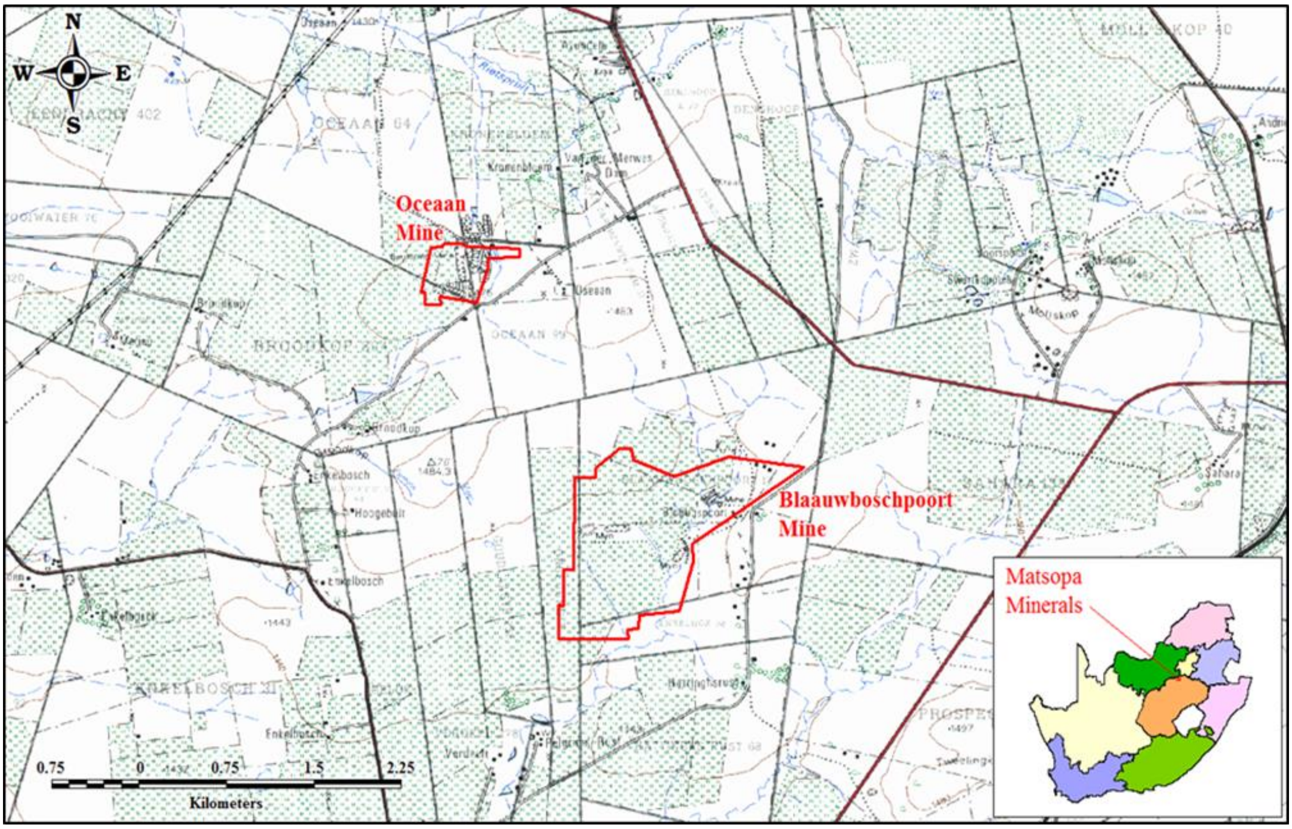


Figure 3-1: Topographic map showing the two bentonite mine pits

3.2 GEOLOGICAL SETTING

3.2.1 Regional geology

The Ecca Group falls under the sedimentary Karoo Supergroup, composed mainly of shale, sandstone, mudstone, coal and igneous intrusive rocks. The Ecca is overlain by the Permian – lower Triassic Beaufort and underlain by the Carboniferous – lower Permian Dwyka, while it occupies most of the Permian time (McCarthy and Rubidge, 2005; Catuneanu *et al.*, 2006). According to Jordaan, (1981), lithologically the upper part of Ecca Group consists of a basal unit comprising dark shales and rhythmic alternations of dark mudstones and sandstones which become a arenaceous unit. Fine to very fine-grained sediments were deposited on prodeltas, as silt and clay. This explains the sediments in the Ecca Group tend to coarsen upwards (Botha *et al.*, 1998).

The igneous intrusive rocks in the area are of the Swazian Quaternary, rocks of this age are believed to be ancient rocks which form part of the Kaapvaal craton. The Swazian is of pre-310 Ma granite-greenstone basement where the deposition of the Witwatersrand Triad occurred with the outpouring of the Dominion volcanics, during a period of extensional tectonism (Robb and Meyer, 1995).

3.2.2 Geology of the study area

The study area falls under the Volksrust Formation of the upper part of the Ecca Group. The area is dominantly composed of shale with other sedimentary rocks such as mudstone. There are igneous intrusive rocks such as the basement granite gneiss as well as the occurrence of the Swazian-aged greenstone rocks of the Blaauwboschpoort Formation (Figure 3-2).

The shale sandwich the bentonite ore body which consists of montmorillonite, some illite and quartz. The ore bodies are tabular and lenticular (Horn and Strydom, 1998). The formation of the bentonite clay mineral could have resulted in a number of processes. The geological environments in which clay minerals form can be divided into five types: weathering, sedimentation, burial, diagenetic and hydrothermal alteration (Velde, 1977).

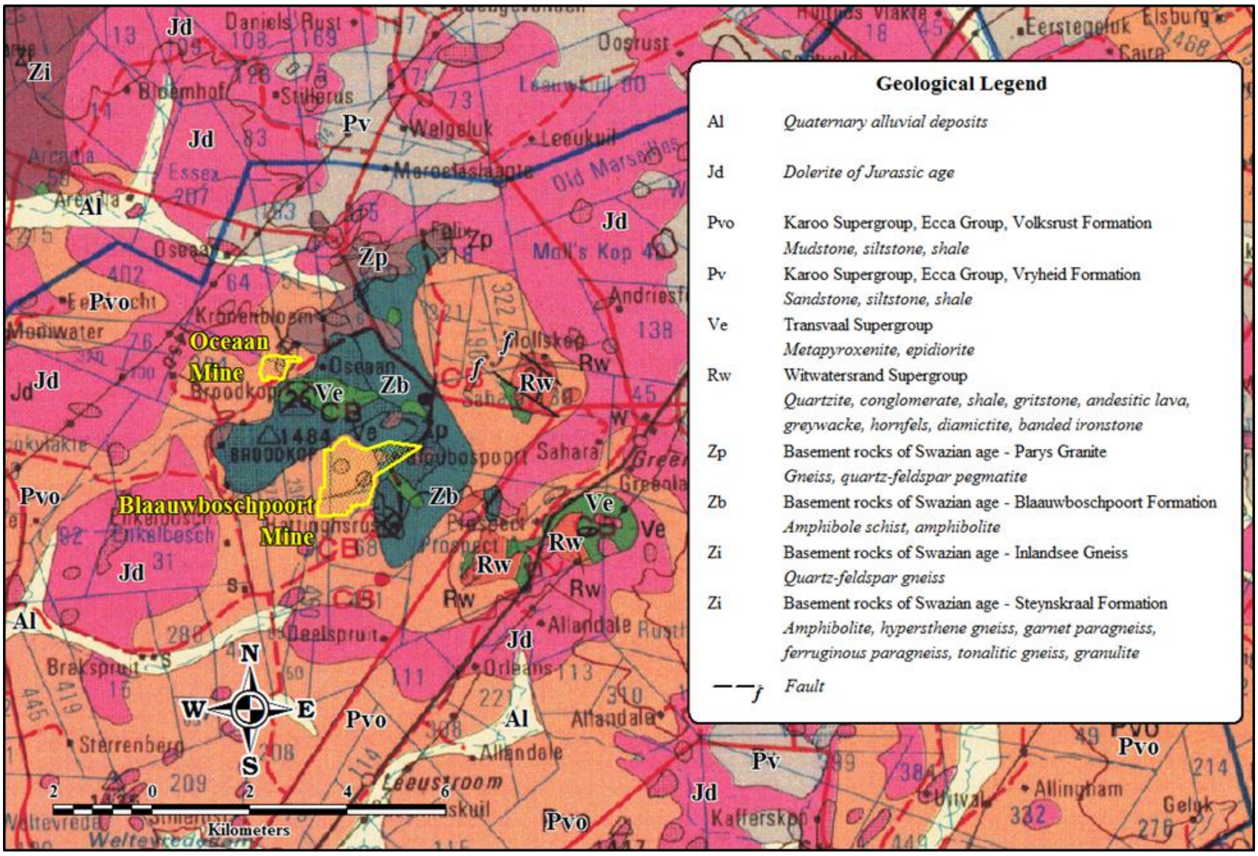


Figure 3-2: Geological setting of the Matsopa Mine area

3.2.3 Geohydrology of the area

Geology has an impact on the geohydrology of an area because groundwater is found in geological formations called aquifers. An aquifer is a geological formation that can store water and there are different types of aquifers – confined, unconfined and semi-confined aquifers. Some properties of the rock will determine whether the aquifer will be a high yielding or low yielding aquifer before drilling boreholes. The two main properties are permeability and porosity which are dependent on the rock type.

The study area is mainly composed of Karoo sedimentary rocks particularly shale (Figure 3-3). Botha *et al.* (1998) indicate that the majority of the Karoo formations have very low yields (<3.6 $m^3.h^{-1}$). Shale is a sedimentary rock that has high porosity but low permeability. The Ecca rocks' porosities tend to decrease from 0.1 north to <0.02 in the southern and south-eastern parts, while their bulk densities increase from 2 000 to >2 650 $kg.m^{-3}$ (Botha *et al.*, 1998).

Shales have low permeability therefore the transmission of water will be low which will result in low storage of water in the aquifer. It can be expected with high yielding boreholes in the area the water will be derived from fractures; bedding plane fractures or fractures created during the intrusion of igneous intrusive rocks. The conceptual model in Figure 3-3 depicts the presence of intrusive rock in the area. Therefore there is a presence of fractures in which water can be derived from. Botha *et al*. (1998) suggests that fractures develop in all formations of the Karoo Supergroup and in all three directions, most likely in the inelastic sandstone rather than the elastic shale layers. The difference in elasticity of various formations may also have favoured the development of fractures along their bedding planes during uplift.

The presence of intrusions in the Karoo rocks creates pathways for the migration of water and thus regarded as a major source of groundwater in the Karoo rocks. During the intrusion fissures, fractures, cracks and joints are formed as well as the baking of the host rock takes place. The mechanical deformation of the host rock due to the intrusion has also influenced the geohydrological properties of the rocks. The presence of dolerite dykes in the area represent thin, linear zones of relatively higher permeability which act as conduits for groundwater flow within the aquifer. These fractures usually have an aperture width of millimeters or up to centimeters in range.

Fractures have always been, and still are the preferred drilling targets for groundwater in the Karoo away from the big valleys (Chevallier *et al.,* 2001). The water in the borehole can be received from both the fracture and the matrix, and this termed is double porosity. The presence of fractures not only produce preferential pathways for groundwater but also for contaminants. The flow of the contaminants and groundwater is at a higher velocity in a fracture compared to the matrix. Therefore the migration of contaminants will be higher in a fracture than in the matrix.

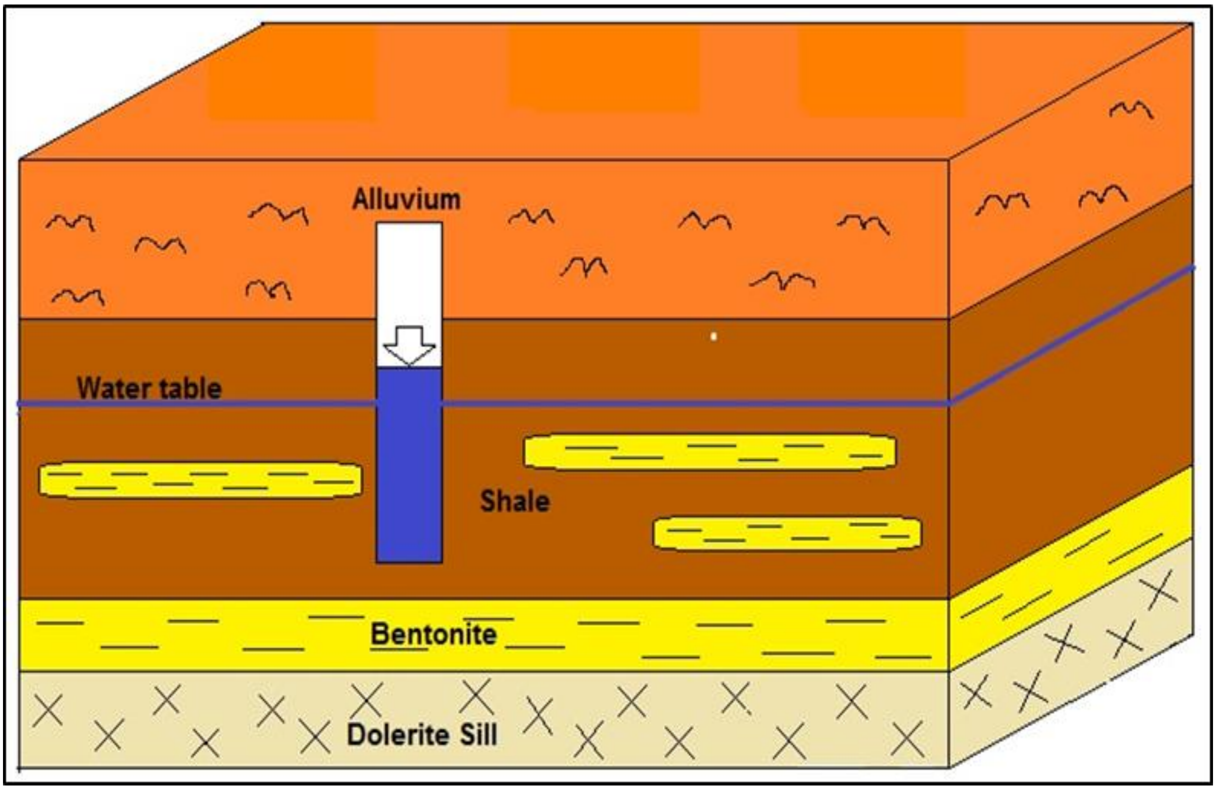


Figure 3-3: Conceptual hydrogeological model with the different lithologies

3.3 REGIONAL MAGNETIC SETTING

The study site is within the area of the Vredefort meteorite impact dome that is associated with magnetism. Figure 3-4 below shows the regional magnetism of the dome as well as the position of mine within the dome. Therefore it would be expected that magnetic anomalies will be intersected in this area. The Vredefort Impact Structure includes a highly magnetic zone in the gneissic basement core, which covers some 8 km beneath the West Rand Group in the crust-on-edge model for the structure (Corner, 2015).

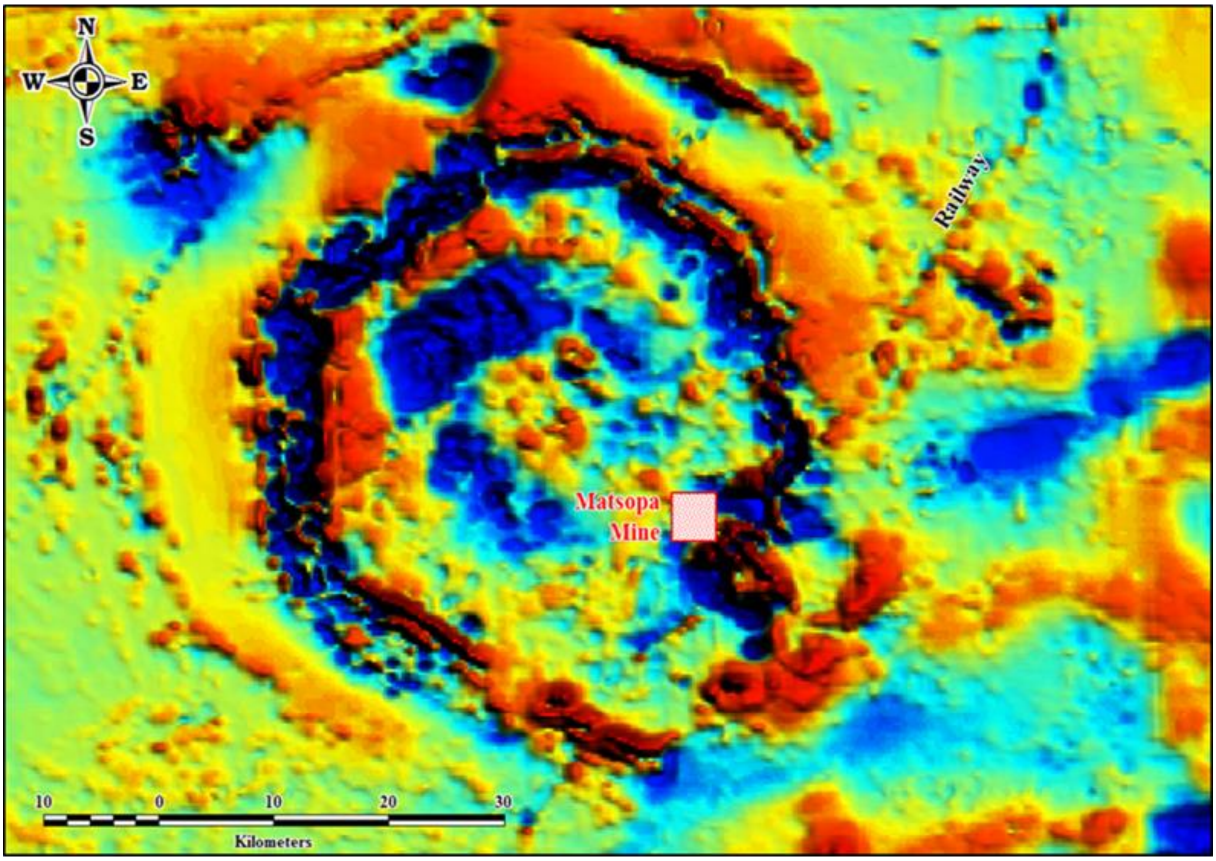


Figure 3-4: Regional magnetism of the Vredefort Dome and the position of Matsopa Mine within the dome

3.4 TOPOGRAPHY AND DRAINAGE

The topography of the Karoo is mainly low-lying with hills. The Koppies area is no exception to that and the name of the area attests to exactly that. The mean surface elevations of the study area vary between 1420 – 1490 m above sea level. The Rietspruit flows at the upper parts of the Ocean Mine and in the surrounding farms close to the Blaauwboschpoort Mine flows the Brakspruit. These streams are tributaries of the Renoster River which in turn a drains into the Vaal River. The Vaal River follows a meandering path between the sharp hills formed by the Vredefort Impact Crater (Figure 3-6).

There are dams namely Weltevrede Dam and Koppies Dam which are the major source of water in the Koppies area as it supplies the town with water as well as small reservoirs in the area. The study area is located in Secondary drainage region C1A and C70F (Figure 3-5) quaternary sub-catchment of the Middle Vaal Water Management Area (WMA).

Table 3-1: Summary of town with notes on its water resources (source: DWS, 2004)

Name of town	Quaternary catchment	Key notes
Renoster: Key Area 1		
Koppies/Kwakwatsi	C70F	Receives water from Koppies Dam Historic yields analysis indicated no shortage in supply

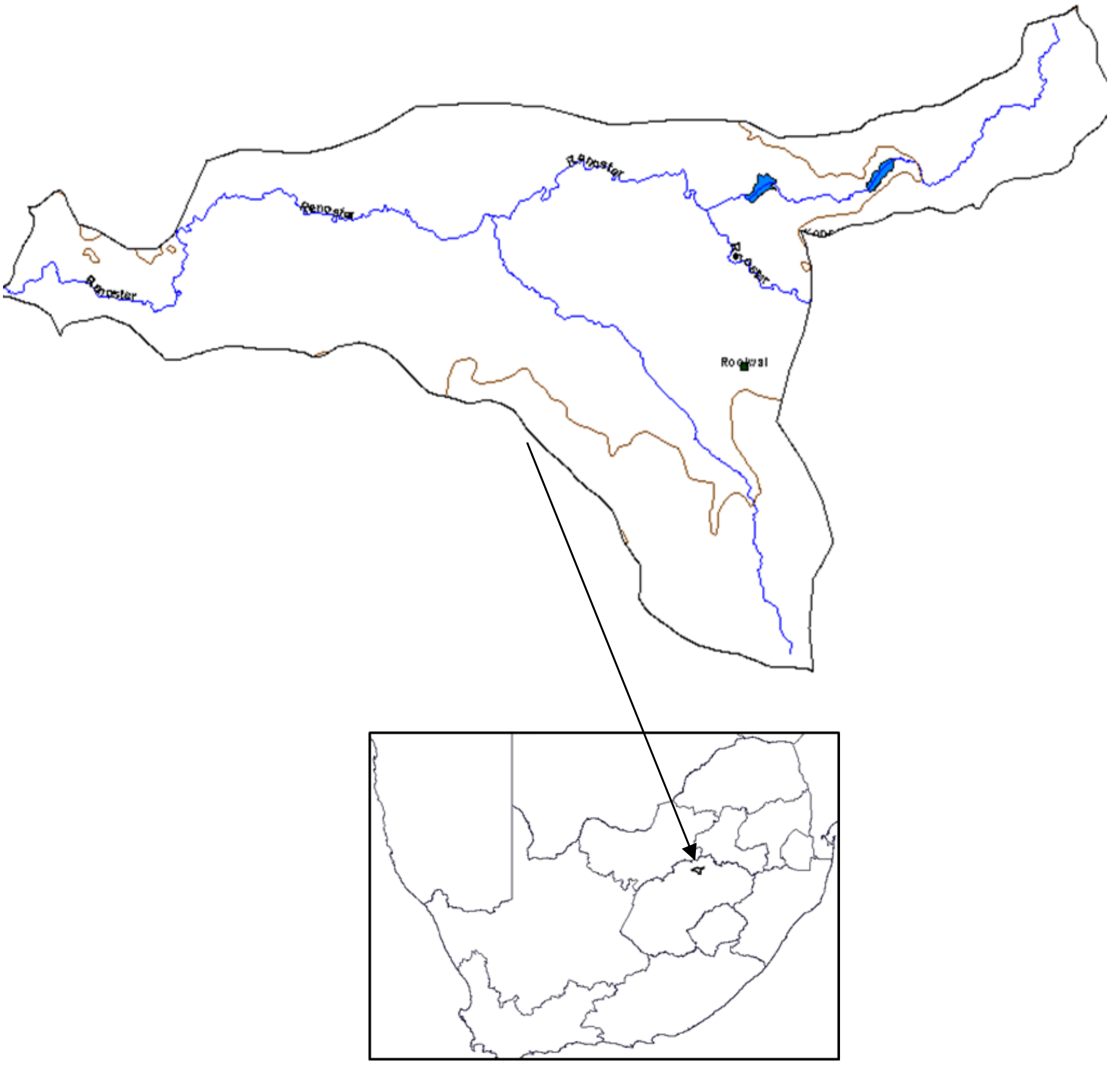


Figure 3-5: The drainage of the area in its quaternary sub-catchment

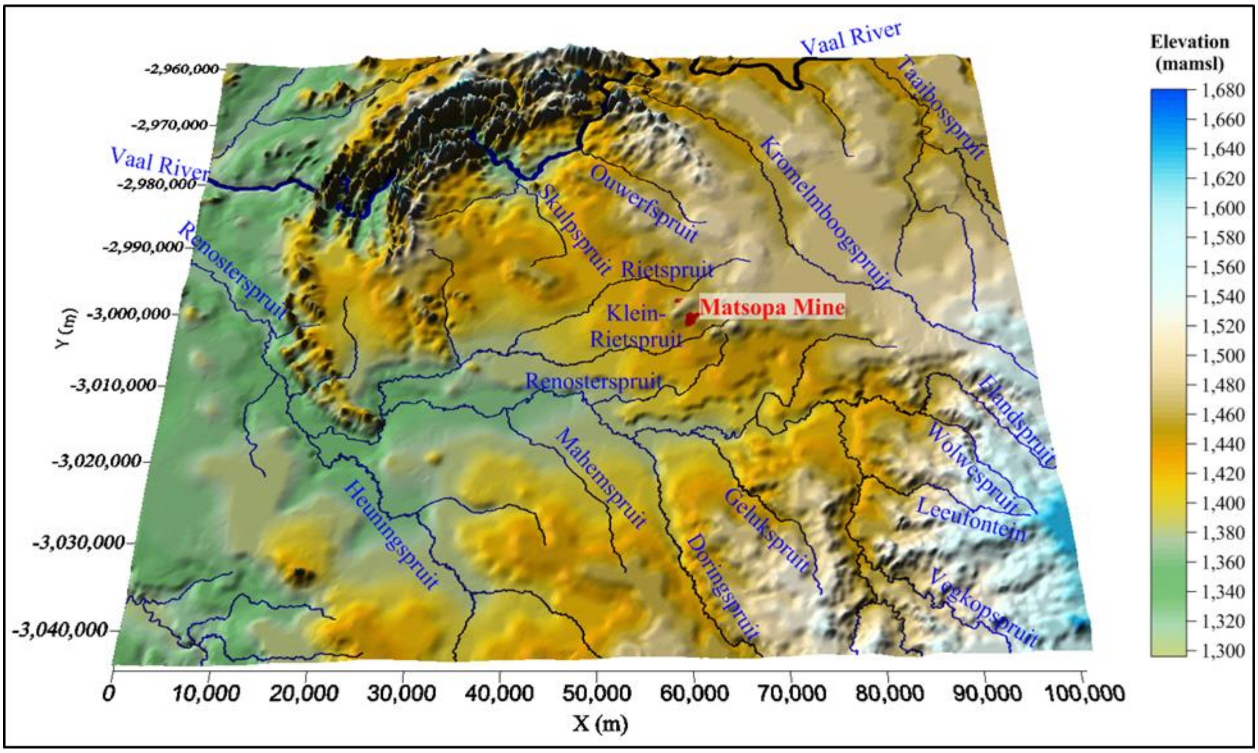


Figure 3-6: Topography and drainage in the vicinity of the mine

The flow direction of groundwater is expected to follow the topography. In Figure 3-7 the topographic gradient in the vicinity of Matsopa Minerals is shown as arrows indicating the direction and magnitude (length of arrow) of the gradient. This figure suggests that the groundwater flow in the vicinity of Ocean Mine is predominantly to the north-west, while groundwater flow in the Blaauwboschpoort Mine is expected to take place to the south-west.

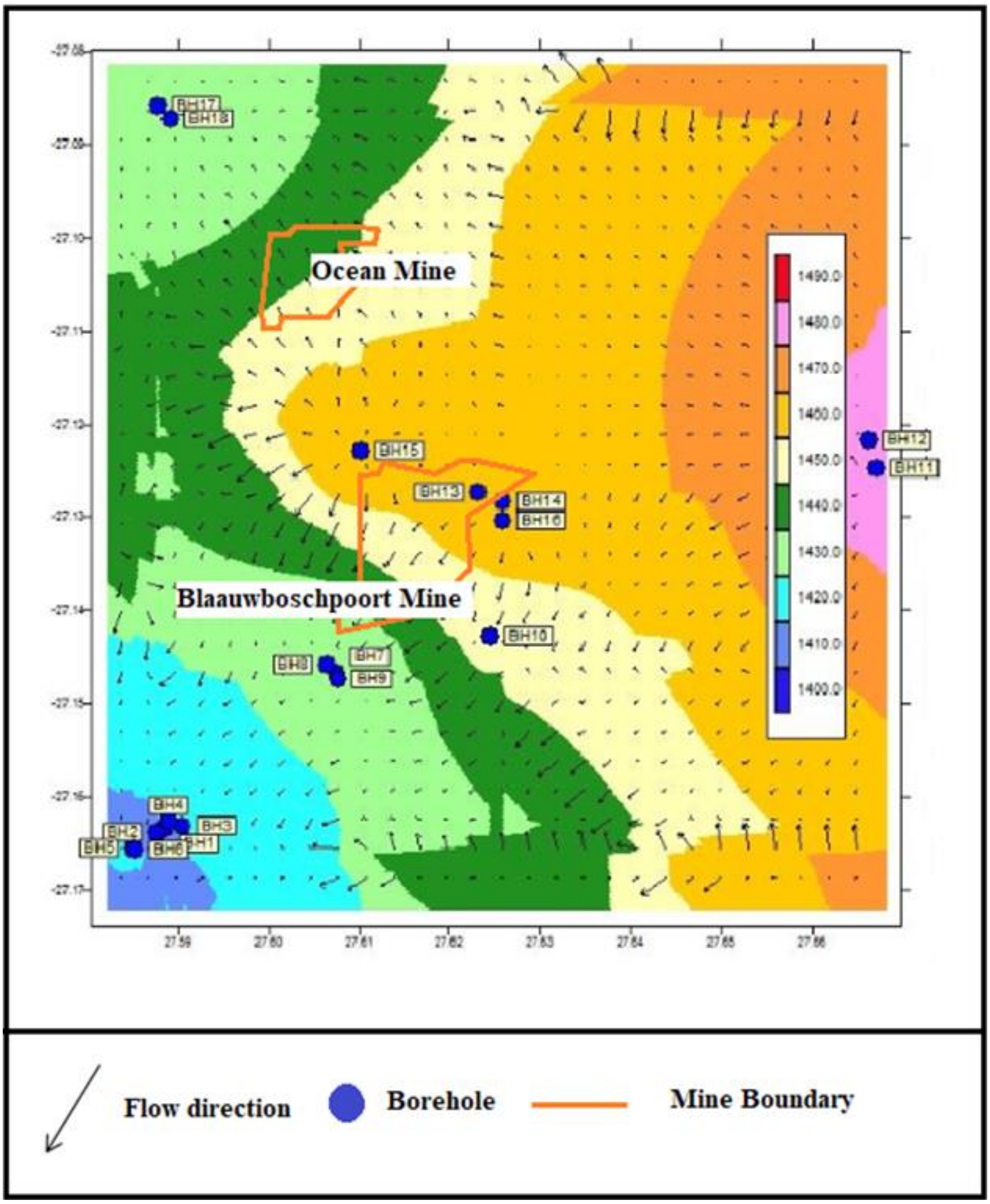


Figure 3-7: Predicted flow direction of the groundwater

3.5 CLIMATE

3.5.1 Precipitation

South Africa is a semi-arid to arid country whose mean rainfall decreases from the eastern to the western part of the country. The Free State has the characteristics of a semi-arid region, some areas receive high rainfall while other parts of the province are characterized with low rainfall. The study area is also characterized by seasonal rainfall which is experienced during the summer months. In recent months South Africa has been experiencing water scarcity and most parts of the country being declared to be experiencing drought. The Free State being one of those provinces, some parts of the province received little or no rainfall. Figure 3-8 shows that the Koppies area had a decline in rainfall during the year 2014 and 2015.

The study area experienced rainfall during the summer months but some rainfall was received during the autumn months (March and April) in 2016 which brought relieve from the drought. Therefore groundwater recharge was not only experienced during summer season but also in autumn.

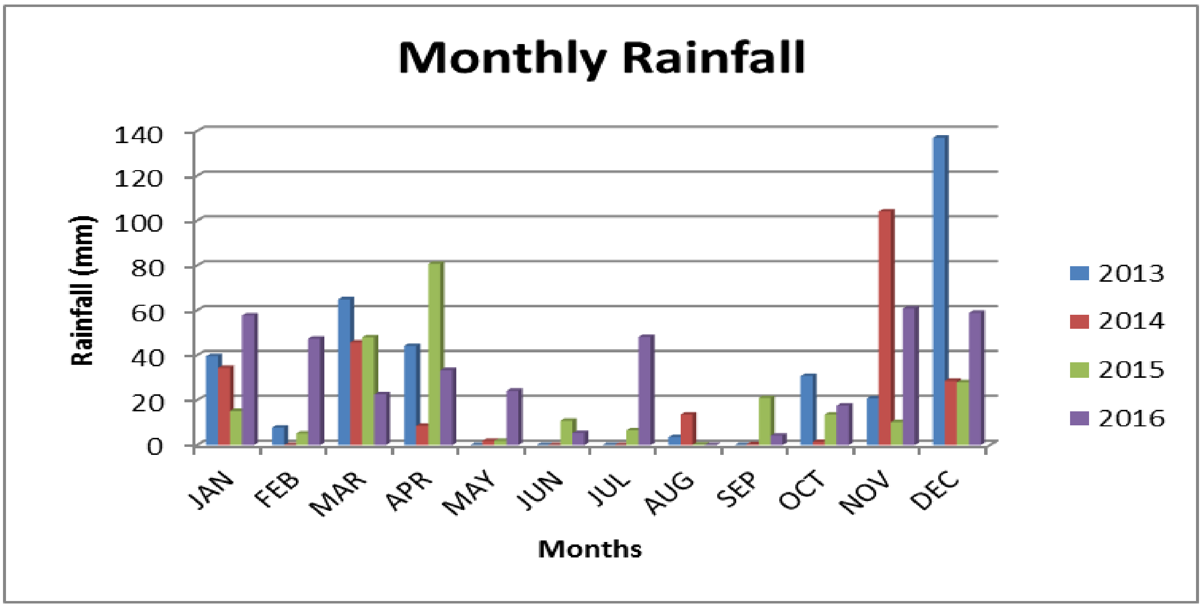


Figure 3-8: Average monthly rainfall for Koppies (Source: Weather SA station 03653988 – Kroonstad, 2015)

3.5.2 Temperatures

Temperatures in most parts of the Free State experience very hot summer months and very cold winter months (Figure 3-9 and Figure 3-10). The temperature can drop to below freezing point in winter and exceed 30 degree Celsius (°C) in summer. Drought accompanied by very hot temperatures promotes high rates of evaporation, depending on the moisture available, severity and duration of the drought.

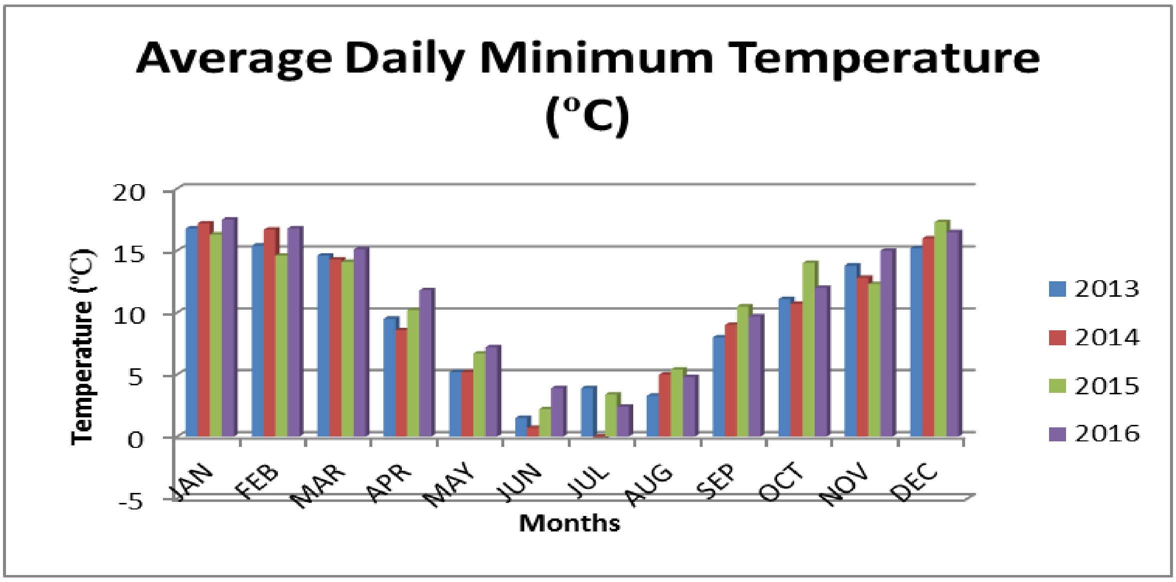


Figure 3-9: Average daily minimum temperatures

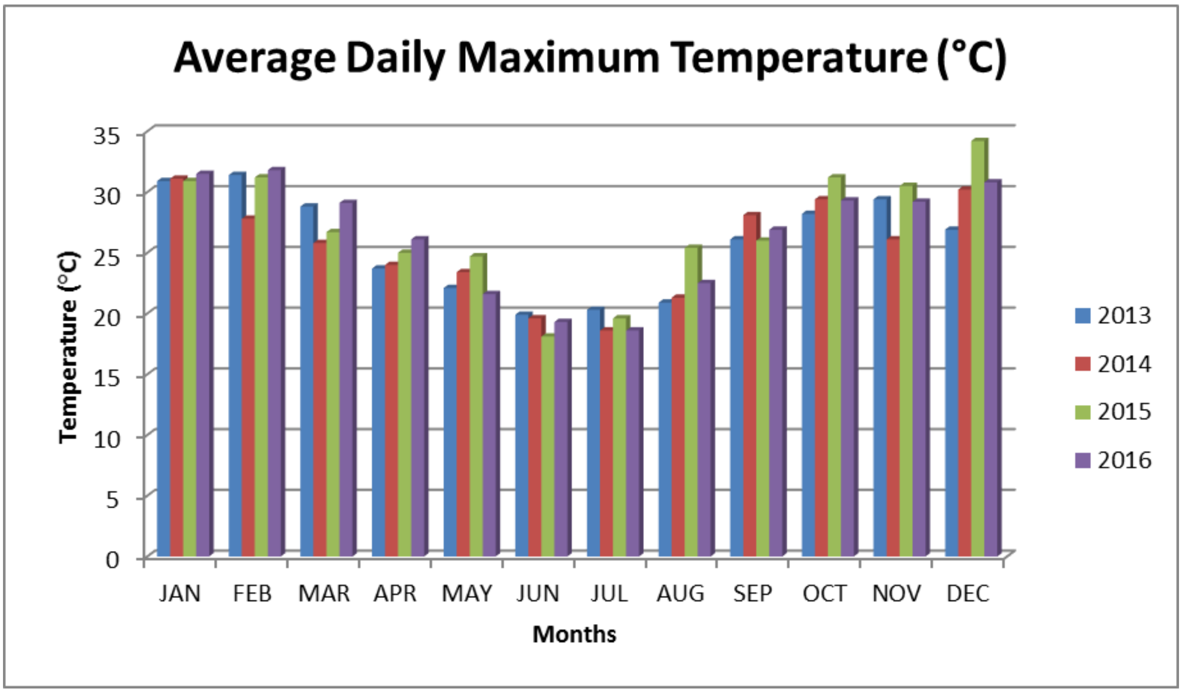


Figure 3-10: Average daily maximum temperatures

3.6 WATER RESOURCE AND USE

The study area comprises of both groundwater and surface water resources. A major source of water in the town is from the Koppies dam. The water supply in the vicinity of the study area is mainly from groundwater, the groundwater is used by the mine as well as local farmers in the area. The farmers including the mine pump groundwater from boreholes and store the water in small dams and tanks. The groundwater is mainly used for domestic use as well as irrigation purposes for crops and cattle farming.

CHAPTER 4:
HYDROCENSUS

4.1 INTRODUCTION

The hydrocensus was conducted for reconnaissance survey to get a better understanding of the study area in terms of activities taking place in the area and the impact of the mining in the area. The hydrocensus survey was conducted in September 2015, while a previous hydrocensus was conducted by Cabanga Concepts in 2013. The previous hydrocensus aided in identifying sampling points of interest of the current hydrocensus. The radius of the previous survey was about 500 m while current was increased to 3 km to include the sampling points that are upstream from the mine. A total number of 19 boreholes were identified during the hydrocensus and out of the total number only 11 boreholes are in use, see Appendix A. The following data was collected:

- GPS co-ordinates of all boreholes;
- Presence of surface water bodies;
- Water sources;
- Water use;
- Land owner;
- Existing equipment;
- Reported yield;
- Reported and measured depth;
- Static water level.

4.2 OBJECTIVES OF THE HYDROCENSUS

The main objectives of the hydrocensus were to:

- Identify possible groundwater monitoring boreholes;
- Aid in the planning of field tests (hydrogeological investigation), possible drilling sites, monitoring points;

- Develop a map that could be used to determine groundwater flow direction;
- Measure groundwater levels in accessible boreholes to have water level monitoring data;
- Determine the use of the groundwater in the area.

4.3 RESULTS

The hydrocensus aided in identifying boreholes that will be used as monitoring points for both water quality and water level monitoring. It also helped in assessing the flow direction of the groundwater which will later aid in determining the flow direction of contaminants if present. There are wetlands present in the vicinity of the mining area, one at the Blaauwboschpoort and another at the Ocean mines respectively (Figure 4-1). During the hydrocensus electrical conductivity (EC) logging was conducted this was done to determine whether the boreholes are of fractured or porous aquifer system. Figure 4-2, shows the boreholes and Figure 4-3 shows the surface points identified during the hydrocensus.

Figure 4-1 Wetlands in the vicinity of the mining area (source: Moeketsi, 2012)

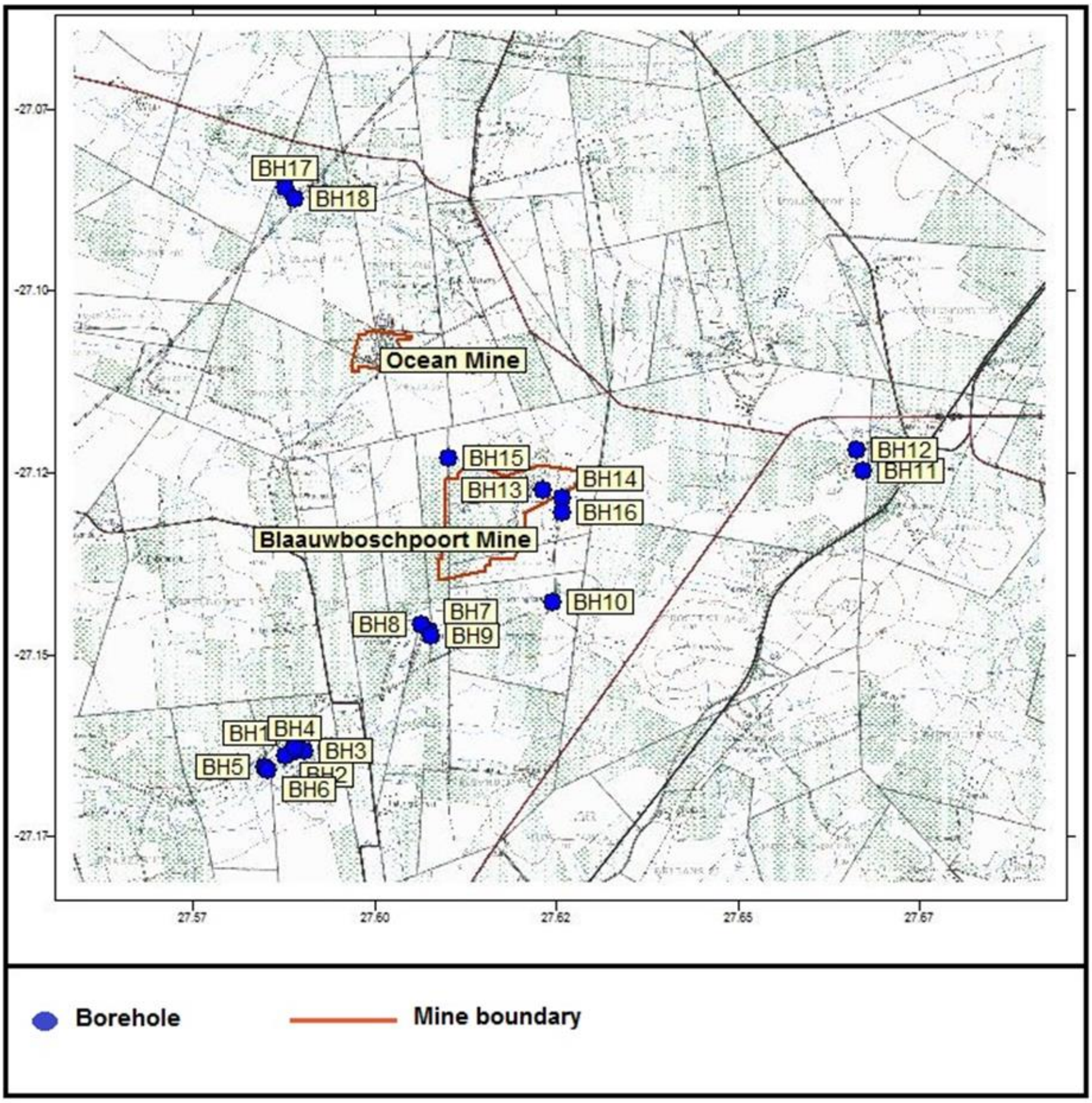


Figure 4-2: Boreholes identified during the Hydrocensus survey

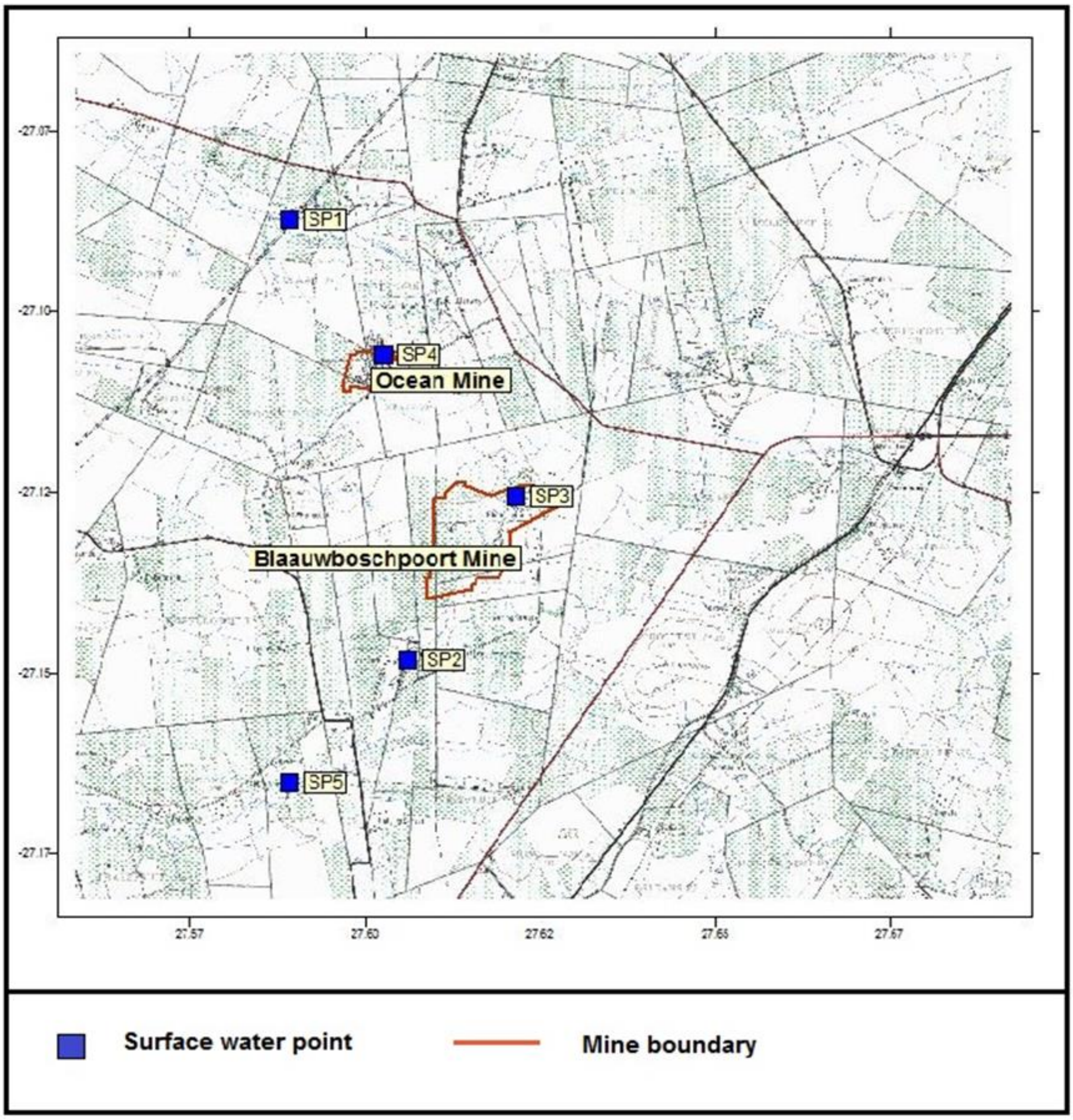


Figure 4-3: Surface waterbodies identified during the Hydrocensus survey

The electrical conductivity (EC) logging was conducted on two boreholes, both being shallow boreholes, BH1 and BH5 at a depth of 14 m and 27 m respectively. EC is used to measure the change of conductivity in water, it is indicative of the amount of salt present in the water. EC can be used as a tool to identify preferential flow paths for contaminants associated with high electrical conductivity. Hence it is used to identify water bearing fractures zones (Gomo, 2009).

On the EC plot of BH5 the EC aided identifying water bearing fracture zone around 14.5 m (Figure 4-4). The EC for BH5 increases with depth therefore the groundwater at greater depth is more saline compared to the shallow water, while BH1 the EC decreases with depth (Figure 4-5).

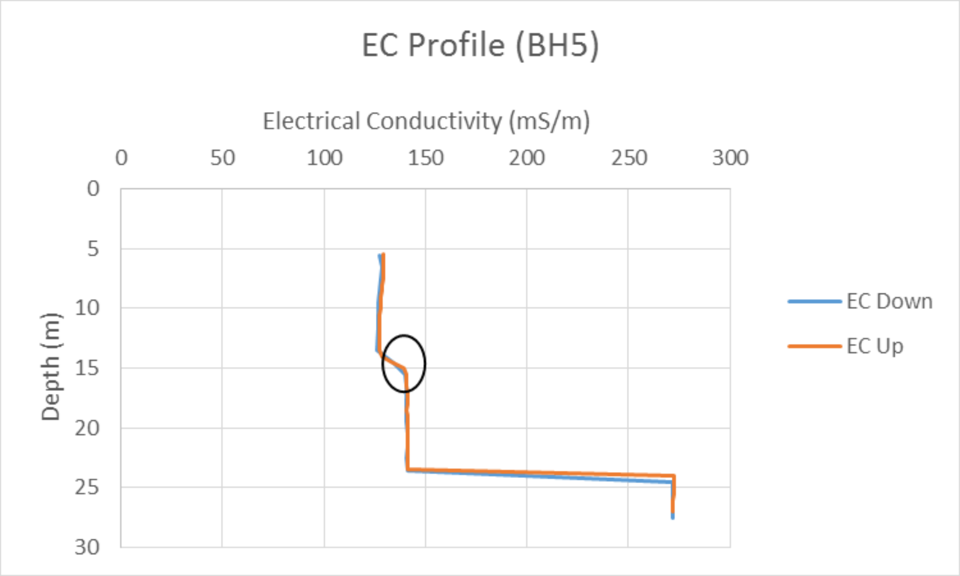


Figure 4-4: EC Profile of BH5

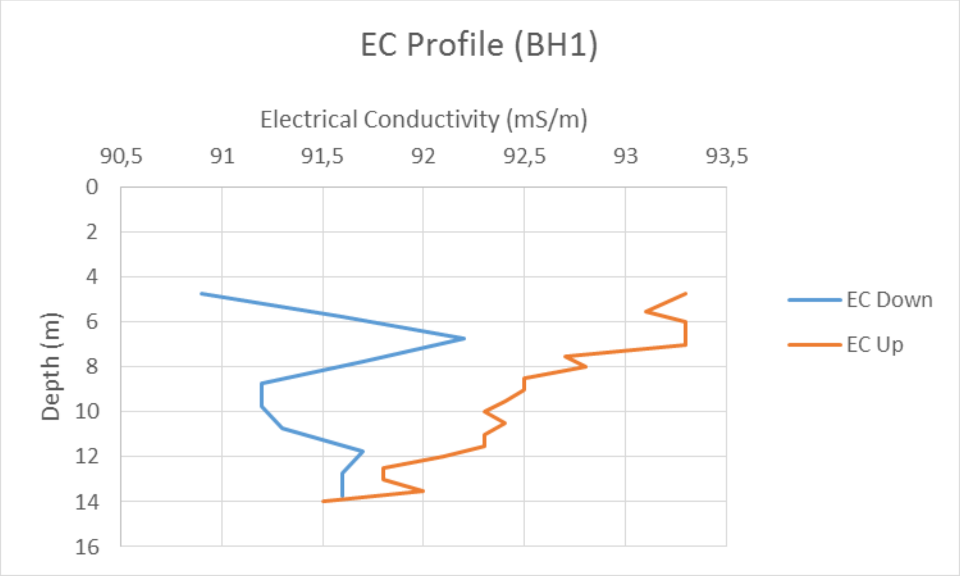


Figure 4-5: EC Profile of BH1

One of the most important aspects of conducting a hydrocensus survey was to determine the use of groundwater in the area. As seen on the pie graph below (Figure 4-6) the population in the area is highly dependent on the groundwater for domestic and farming use. Some of the farmers use groundwater for irrigation.

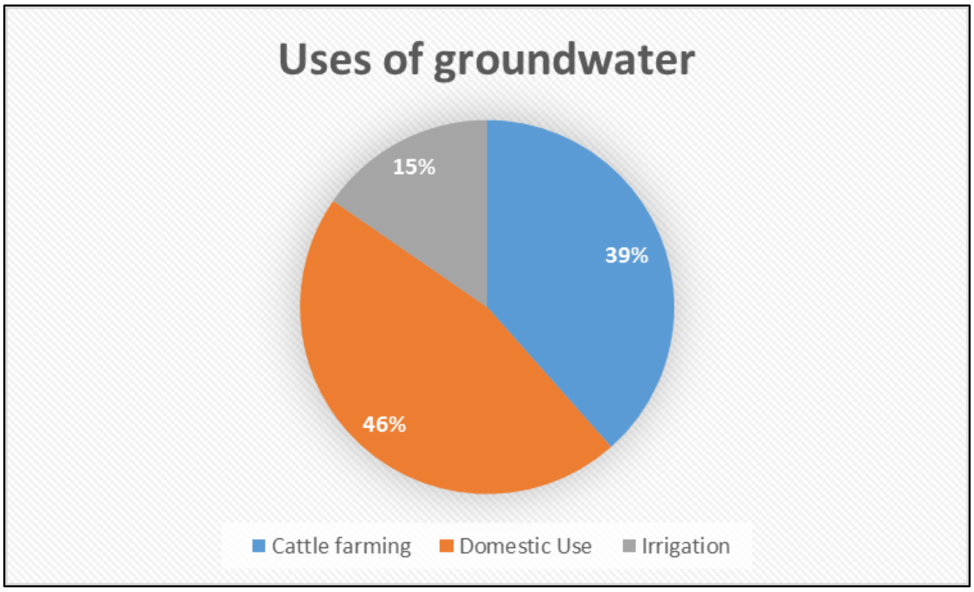


Figure 4-6 Groundwater use activities in and around Matsopa Minerals Mine

Figure 4-7: BH13 at Matsopa Mine (top) and BH1 at a farm (bottom)

Figure 4-8: Borehole BH8 (top) and BH9 (bottom) at Herbst farm

Figure 4-9: BH11 that is in use (top) and borehole that is no longer in use (bottom) at Ludwig farm

CHAPTER 5:
GEOPHYSICAL INVESTIGATIONS

5.1 INTRODUCTION

A geophysical investigation was carried out to identify the type of geology in the area and associated structures. The geophysical investigation also formed part of the mine's reconnaissance study to determine possible presence of reserve of the ore in the vicinity of the mine. By identifying the different rocks and their associated structures, the type of aquifer(s) can be determined. Knowing the structures associated with certain rock types possible groundwater pathways can be characterised. Example a dolerite rock intrusion will form structures such as cracks, joints and fractures on the host rock upon intrusion. The geological structures can act as conduits and transmit groundwater only if they are not filled by minerals such as quarts, calcite, clay minerals or many others.

Should there be contaminants in the area, the fractures will form preferential pathways for both the water and contaminants especially in impermeable rocks. Intrusive rocks can also act as barriers or groundwater boundaries. Therefore the geophysical investigations are conducted to detect and delineate geological structures. Electrical resistivity tomography (ERT) and magnetic methods were used during the geophysical investigation. It is useful to use more than one geophysical methods in a study area to help to constrain the interpretations (Reynolds, 2011).

5.2 GEOPHYSICAL TECHNIQUES EMPLOYED

5.2.1 Introduction

The geophysical techniques used are electrical resistivity tomography (ERT) and magnetic method. The ERT method was employed because it illustrates good contrast between the country rock and intrusive rocks. Due to the reason that 2D resistivity models can be depicted, different layers of geological units and their depth can be depicted.

The magnetic method was conducted to obtain contrast between the country rock and the intrusives as well. The intrusive rocks have a higher susceptibility than the surrounding sedimentary rock therefore a contact between the two geological units can be delineated.

Intrusions of igneous rocks into the Karoo sediments causes deformation of the country rock thus creating fractures, joints and fissures which are preferential pathways for groundwater.

5.2.2 Electricity resistivity tomography (ERT) investigations

The ERT method was employed to measure the electrical resistivity of rocks, which will aid in identifying different rock types. This method can also aid in giving the distribution of the rocks in the subsurface. The results are displayed in a form of an inverse resistivity model. The survey was conducted at both the Ocean and Blaauwboschpoort mine. The ERT method is useful because both the lateral and vertical imaging of the subsurface are modelled. The different rocks are identified by their electrical conductivity, the resistivities of the different rocks are described in (Chapter 2).

Both ERT traverses were conducted in a W-E direction and at a length of 1 400 m for the Blaauwboschpoort mine and 1 000 m for Ocean mine. Cables with a standard electrode spacing of 5 m were used. In a standard resistivity method, the resolution and maximum depth of investigation depend on the separation and geometry of the electrodes (Lowrie, 2007). The Wenner electrode array was used during the survey (Chapter 2 discusses the different arrays extensively), this array is sensitive to vertical changes in the subsurface resistivity allowing horizontal boundaries to imaged.

A *leap-frog* method was used to obtain measurements because the traverses were longer than the electrode layout. The measurements recorded during the ERT survey will yield pseudo-sections which are processed using the inversion software package Res2DInv to obtain the two-dimensional (2D) models of the subsurface resistivity distribution. The resistivity model clearly delineates the contacts between the different rock layers.

5.2.3 Magnetic investigations

The magnetic geophysical method was used to determine the presence of igneous intrusive rocks. This method is applicable because of their susceptibility to magnetism. The method aids in identifying possible fracture zones along the contact zones between the host rock and the intrusive rock. Along the contact zone there is the baking of the host rock and joints, fractures, cracks are formed. The magnetic survey was conducted around the pit.

This was done to determine any immediate possible fracture zones that will transmit groundwater and/or contaminants from the pit boundaries to the surrounding aquifer.

Ground magnetic data of four traverses on three sides of the pit (12 traverses in total) were recorded. The direction of the traverses were E-W and N-S. The station spacing was at 5 m interval to define the anomaly because should the spacing be large the target might be missed.

Measurements of the magnetic field intensities were taken using a proton magnetometer. The magnetic intensity measurements were then filtered to remove background noise by using a method called the *running averages* method. The filtered data is then used to plot magnetic profiles which illustrate magnetic anomalies. Magnetic data can be displayed in a form of magnetic contour maps or magnetic intensity profiles that can be used for interpretation.

Another magnetic survey was conducted on the outer boundaries of the mine on the surrounding farms. The aim of this survey was to delineate the presence of intrusive rocks. Also to determine whether there is a possible link or network of interconnected aquifer system. Should there be a network of aquifers than the aquifer surrounding the pit of the mine will be connected to the aquifer system on the surrounding farms. This can mean that possible contaminants can be transmitted from the mine to the surrounding farms.

A GEM GSM19 overhauser magnetometer was used to conduct the survey. Walkmag mode was used therefore the station spacing was neglected. Figure 5-1 below shows the position and orientation of the ground geophysical traverses that were surveyed.

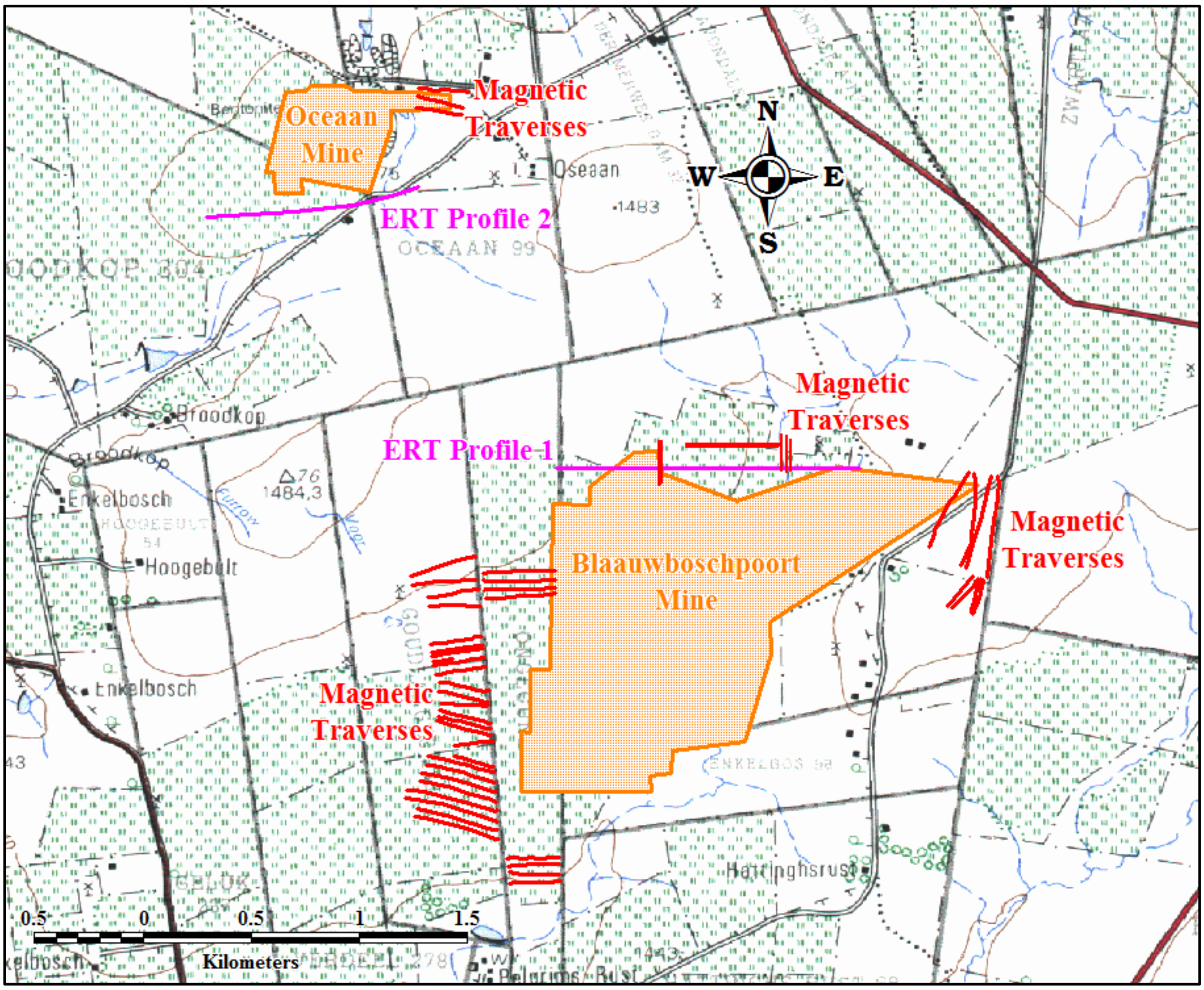


Figure 5-1: Positions and orientations of the geophysical traverses

5.3 INTERPRETATION OF RESULTS

5.3.1 ERT survey

Rocks were identified according to their electrical resistivities. The rocks identified were shale, dolerite intrusion, bentonite clay bed and unconsolidated top soil from the modelled resistivity contour levels, Figure 5-2. The section in Figure 5-2 displays a contrast of the low resistivity and high resistivity zones. The layers of the different rocks types are clearly defined.

The top layer is defined by high resistivity which represent the weathered top soil. The layer with low resistivity represent the bentonite and shale layer. The similarity in electrical resistivity between bentonite and shale makes it difficult to differentiate between the two layers. The contact between the topsoil and the bentonite layer is well defined, at a depth of approximately 4 m. The bottom layer with very high resistivity is represented by a red zone. This zone may be a representation of an igneous intrusive rock particularly dolerite.

The zone extends from 300 m to the eastern end of the model, therefore this indicates that the zone may be a dolerite sill. On the western part of the model there is a presence of a near-vertical zone with very high electrical resistivity also characterised by the red colour. The zone may be a representation of an igneous intrusion in a form of a dyke, this zone is clearly depicted in the top profile. The contact zone between the low and high resistivity marks clearly the boundary between the high resistivity layer of the topsoil and the low resistivity bentonite and shale layer. As well as the boundary between the low bentonite/shale boundary resistivity layer and the high dolerite sill layer. The dolerite dyke may be a younger intrusion compared to the dolerite sill.

In terms of the aquifer types determined using ERT, there are two types of aquifers namely the shallower porous aquifer and the fractured aquifer. The porous aquifer can be described as an unconfined aquifer and the latter as the confined aquifer due to the presence of confining clay layer. The conductivity of the rock is proportional to the conductivity of the groundwater, which is variable because it depends on the concentration and type of dissolved minerals and salts it contains (Lowrie, 2007).

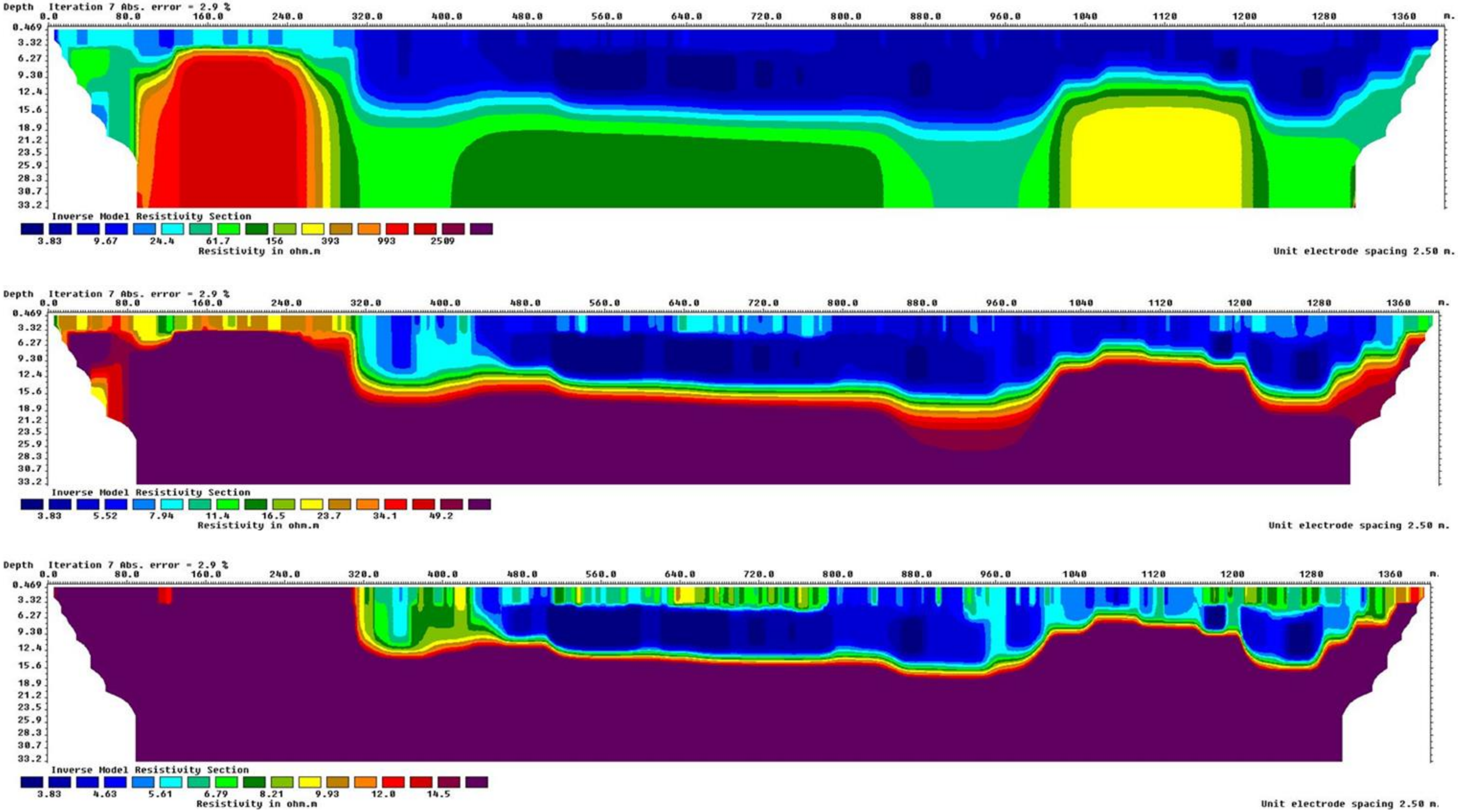


Figure 5-2: Modelled resistivity section

A model with topographic features was also imaged. According to Milsom and Eriksen (2011) it is important to measure the relative heights of electrodes in the field and model the topographic effects, as topography can mask some features in the apparent resistivity data. Even when the topography does not significantly affect the resistivity values, it is important that it be recovered, because it provides some additional information about the site being investigated.

In relation to the topography the low resistivity clay which is at the pit forms at near valley slope at higher elevations and shallow depth, top model of Figure 5-4. The bottom profile of the modelled section in Figure 5-4 show the different boreholes that were drilled along the ERT line. The orange lines represent the depth at which these boreholes were drilled. The core log of the drilled boreholes depicts the image of the subsurface similar to that of the ERT model. Therefore the ERT model gives a clear picture of the subsurface

5.3.2 Magnetic survey

The magnetic contour maps shows the magnetic intensity of the study area, Figure 5-3. On the map (Figure 5-3) there is contrast in the magnetic intensities, this contrast can be seen clearly on the western and eastern boundary of the mine. On the western boundary of the mine low magnetic intensities are exhibited in the south, and towards the north there is a presence of rocks with high magnetic intensities. The high magnetic rocks exhibit the characteristics of intrusive structure in a form sills rather than dykes.

The profiles of the western boundary of the mine (Figure 5-6) show anomalies associated with a sill. The wavelengths of the anomalies are short and narrow. Meaning that the magnetic body is at shallow depth and the thickness of the magnetic body is relatively thin. The intensities of the dolerite intrusion display the intrusion to have a more concentric shape. The contact between the sill and the country rock appears to have a south-west/north-east strike.

The eastern boundary of the study area also exhibits the presence of dolerite intrusives. There is a clear distinction from the low magnetic intensities that represent the country rock to the high magnetic intensities that represent the dolerite intrusion. The dolerite intrusion structure is also in a form of a sill. The eastern boundary is largely composed of greenschist rocks (these are metamorphosed rocks whereby metamorphism took place under low temperatures and pressures), which tends to be slightly magnetically susceptible. The greenschist rocks simulate structures that forms as greenschist dyke outcrops shown in Figure 5-5.

A magnetic survey that was conducted along the northern boundary of the pit. These traverses were surveyed parallel to the electrical resistivity tomography survey line. The profiles of the traverses in Figure 5-7 illustrates anomalies and there this indicates a presence of a magnetic body. The wavelengths of the anomalies are short relating to shallow near-surface magnetic body.

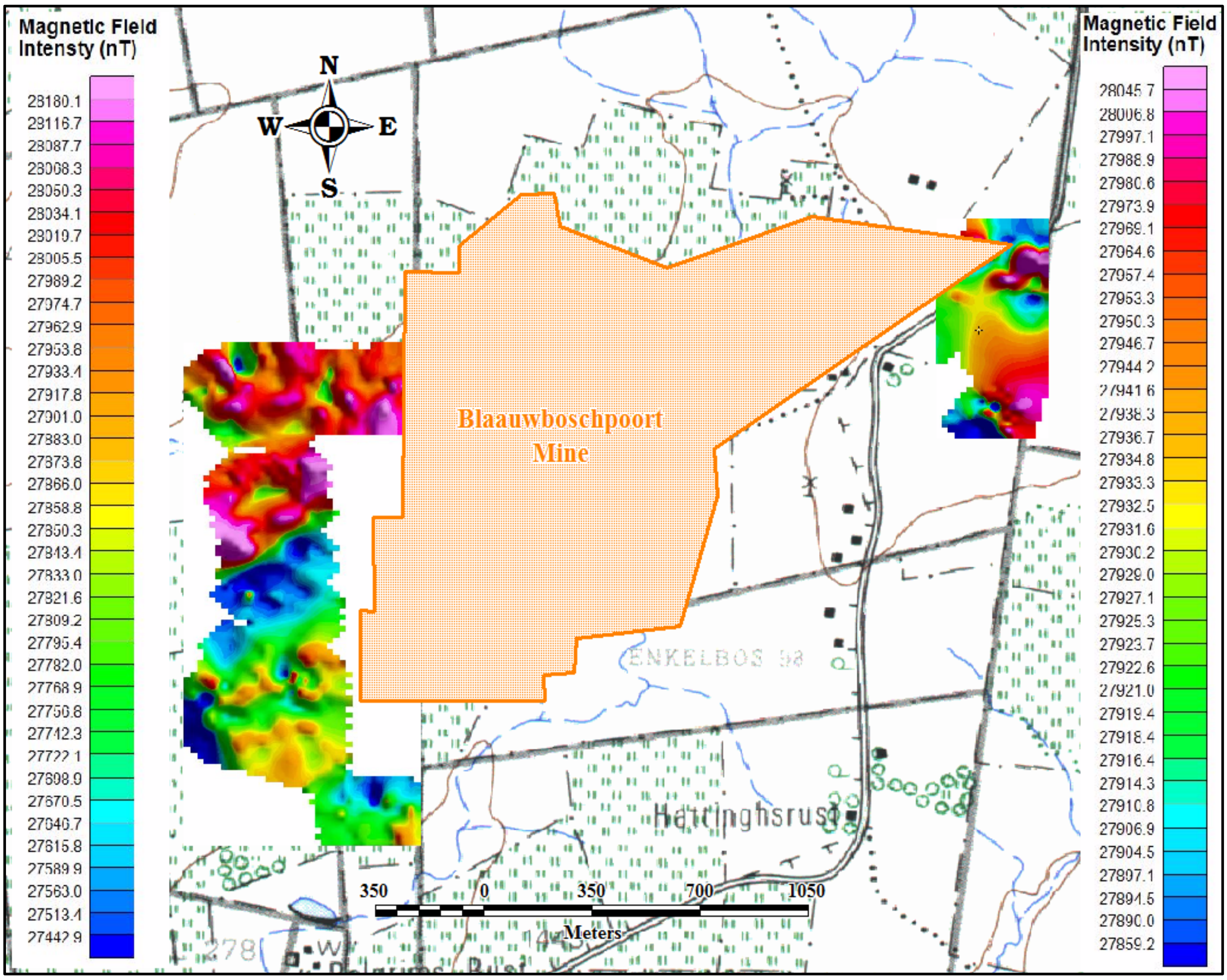


Figure 5-3: Contour map of the magnetic intensities at the Blaauwboschpoort mine

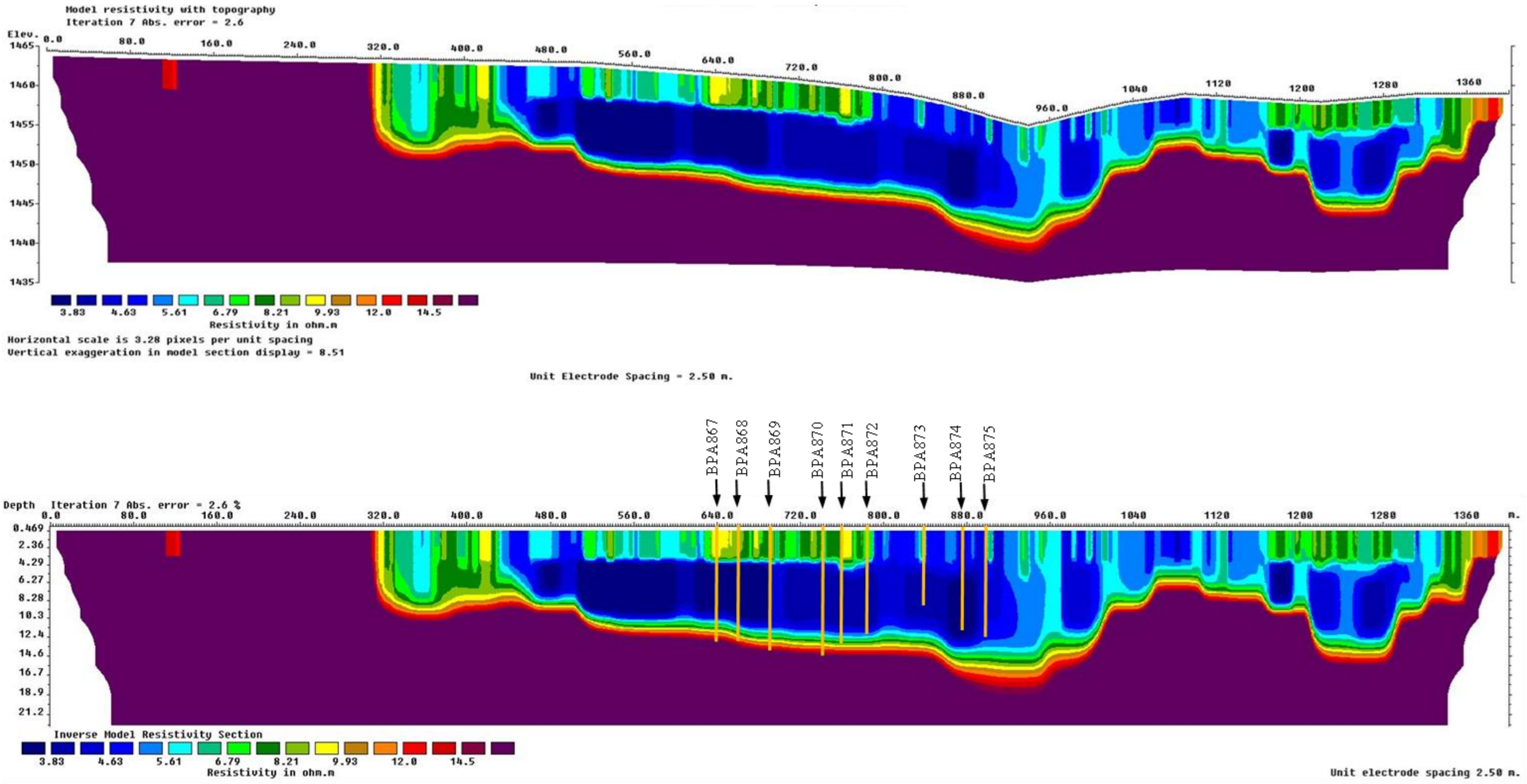


Figure 5-4: Modelled resistivity section with surface topography (top profile) and drilled boreholes along the resistivity test line (bottom profile

Figure 5-5: Greenschist outcrop in the form of a dyke

5.3.3 Correlation between the results of the geophysical investigations

As mentioned previously the importance of using more than one geophysical method in the same area is to obtain better conclusive results. Hence the use of both electrical resistivity tomography (ERT) and magnetic techniques. Magnetic traverses were recorded north of the pit, parallel to the ERT survey line. In order to get a correlation of results between the magnetic data and the ERT data. The ERT line was part of the excavated pit at the time the magnetic survey was conducted. Therefore the magnetic field recordings could not be recorded exactly along the ERT line.

However, because the geology in the area is the same, the magnetic traverses were projected parallel to the ERT survey line. The results of the magnetic survey correlated with those of the ERT survey. The data obtained displayed similarities in the subsurface geology. The near vertical magnetic body that was detected during the ERT survey was detected during the magnetic survey. The resistivity model showed the presence of dolerite intrusion in forms of dykes and sills. The use of magnetic methods detected and delineated dolerite intrusions not only around the mine pit but also along the borders of the mine.

A number of 14 boreholes were drilled along the ERT survey line. The core log of the boreholes were logged and the log revealed or depicted the same image as that of the resistivity model. The core log showed the dolerite intrusion as a form of a sill. The depth at which the different geological layers occurs correlates to the core log depth. In the core log the bentonite and shale layer can be distinguished from each other, unlike in the resistivity model. The depth at which the different geological layers occur, depicted on the inverse resistivity model, can aid in delineating the depth of the aquifer.

5.4 CONCLUSION

The geophysical investigations yielded the results that displayed the presence of igneous intrusive rocks. It was important to detect and delineate the rocks and their lithology. The investigations were done to determine possible risk factors associated with the different rock types. The presence of intrusive rocks brings up possible risk factors, in a form of secondary structures such as fractures. Fractures which create possible pathways for contaminants that may pose a threat to the groundwater quality.

Fractures formed during the intrusion of dykes and sills allow the passage/transmission of groundwater through them. Dolerite dykes represent thin, linear zones of relatively higher permeability which act as conduits for groundwater flow within the aquifer. They have always been, and still are preferred drilling targets for groundwater in the Karoo away from big valleys (Chevallier *et al.*, 2001).

Fractures do not only transmit groundwater but also contaminants should there be any present in the aquifer. Fractures transmits groundwater at a higher rate due to their high permeability. Should contaminants be present in the area as a result of mining, the fractures will aid in transmitting the contaminants from the mine to the surrounding groundwater system. If the aquifer is a network system due to a network of fractures the contaminants will spread throughout the surrounding area of the mine.

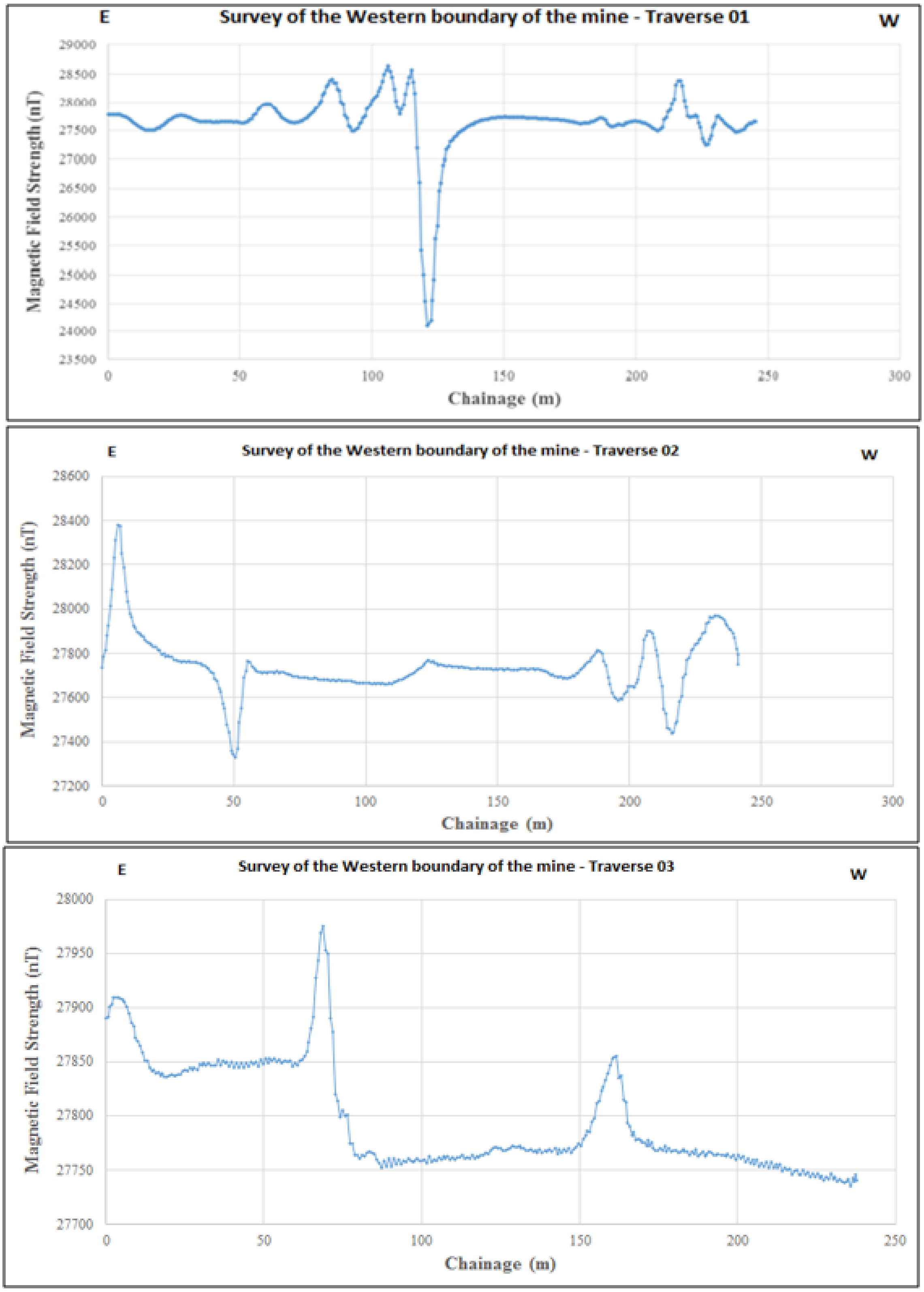


Figure 5-6: Total magnetic intensity recorded along the western boundary of the Matsopa Minerals Mine

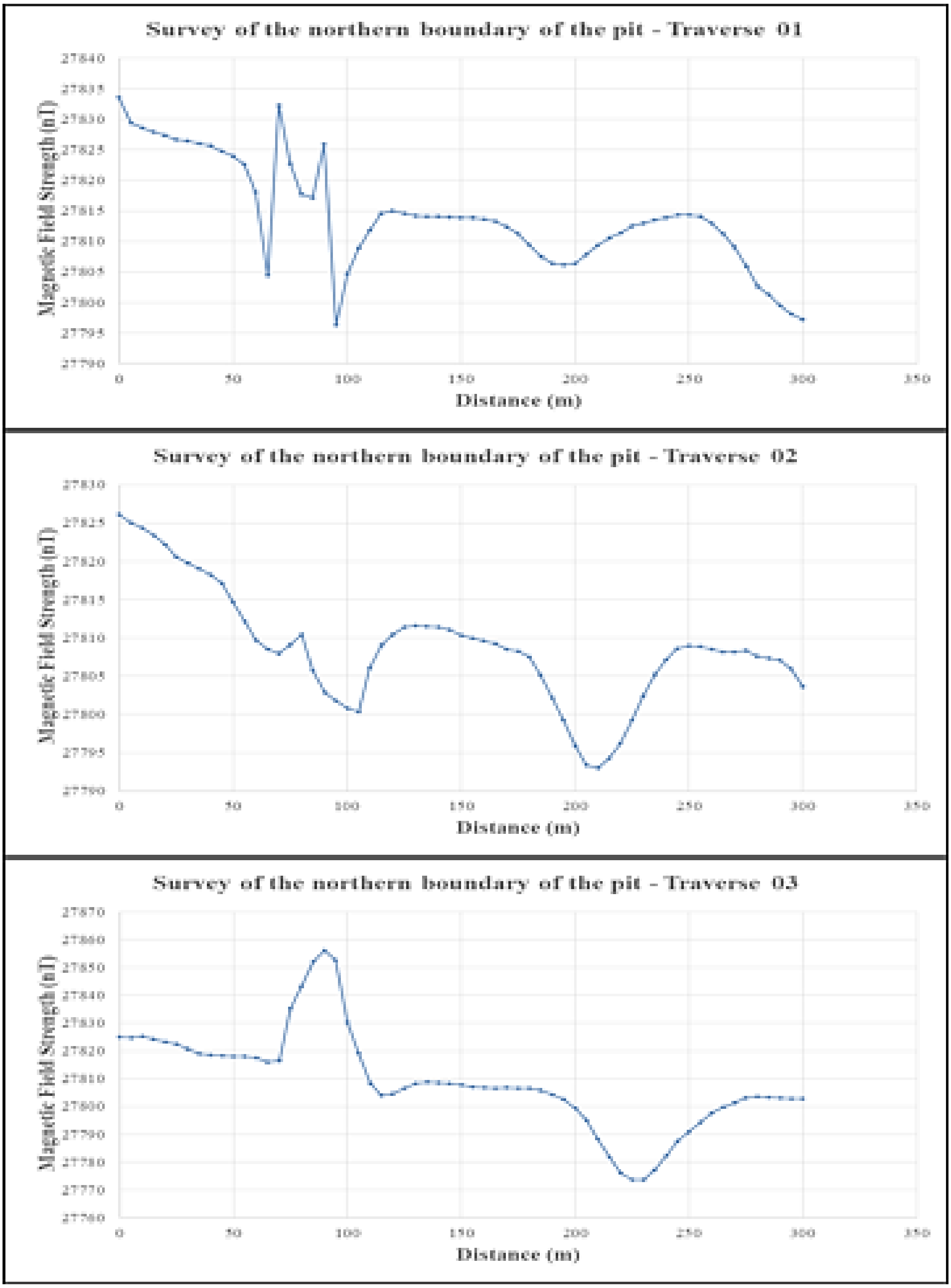


Figure 5-7: Total magnetic intensity recorded along the northern boundary of the Matsopa Minerals Mine

CHAPTER 6:
GEOCHEMICAL INVESTIGATIONS

6.1 INTRODUCTION

Geochemical investigations were undertaken because of the important role that geology plays in groundwater. Groundwater is stored in a geological unit known as an aquifer. Some rocks constitute minerals and elements that tend to pose a threat to the environment especially when they are disturbed. Some harmful elements occur naturally in the environment and usually at low concentrations. Since there is a disturbance of the environment due to mining in the study area. The environment may be polluted or contaminated in different forms as a result.

The most common problematic form of contamination as a result of mining is acid mine drainage. Acid mine drainage during and after mining activities can cause severe environmental pollution due to the release of contaminants (including transition; -heavy and semi-metals) to the soil and waters (Carbone *et al.*, 2013). Geochemical investigations using X-ray fluorescence and X-ray diffraction techniques were conducted. To determine whether the mineralogical and elemental composition of the rocks and minerals in the study area have a potential to threaten the environment, especially the groundwater environment.

6.2 GEOCHEMICAL ANALYSES

X-rays were discovered in 1895 by Röntger then soon after, work by von Laue and Bragg and his son followed. X-rays behave like visible light. They can be refracted and diffracted, and they show interference. Their velocity is that of light (Volborth, 1969).

X-rays originate outside the atomic nucleus, they must be excited. Energy must be supplied so that atoms (or ions) can emit them. X-rays are therefore generated when an atom receives energy and the electron of the inner shell (K-shell) closest to the nucleus is removed from the influence of the nucleus. The atom is said to be in an excited state and will return to ground state when an electron from the outer shell (L-shell) falls into the vacancy, Figure 6-1.

The excitation of x-rays is a quantum phenomenon. The excitation produces the emission of primary x-rays with lines of wavelengths typical of the target. Heat and continuum or “white” radiation are also produced (Volborth, 1969; Energlyn and Brealey, 1971; Liebhafsky and Pfeiffer, 1971).

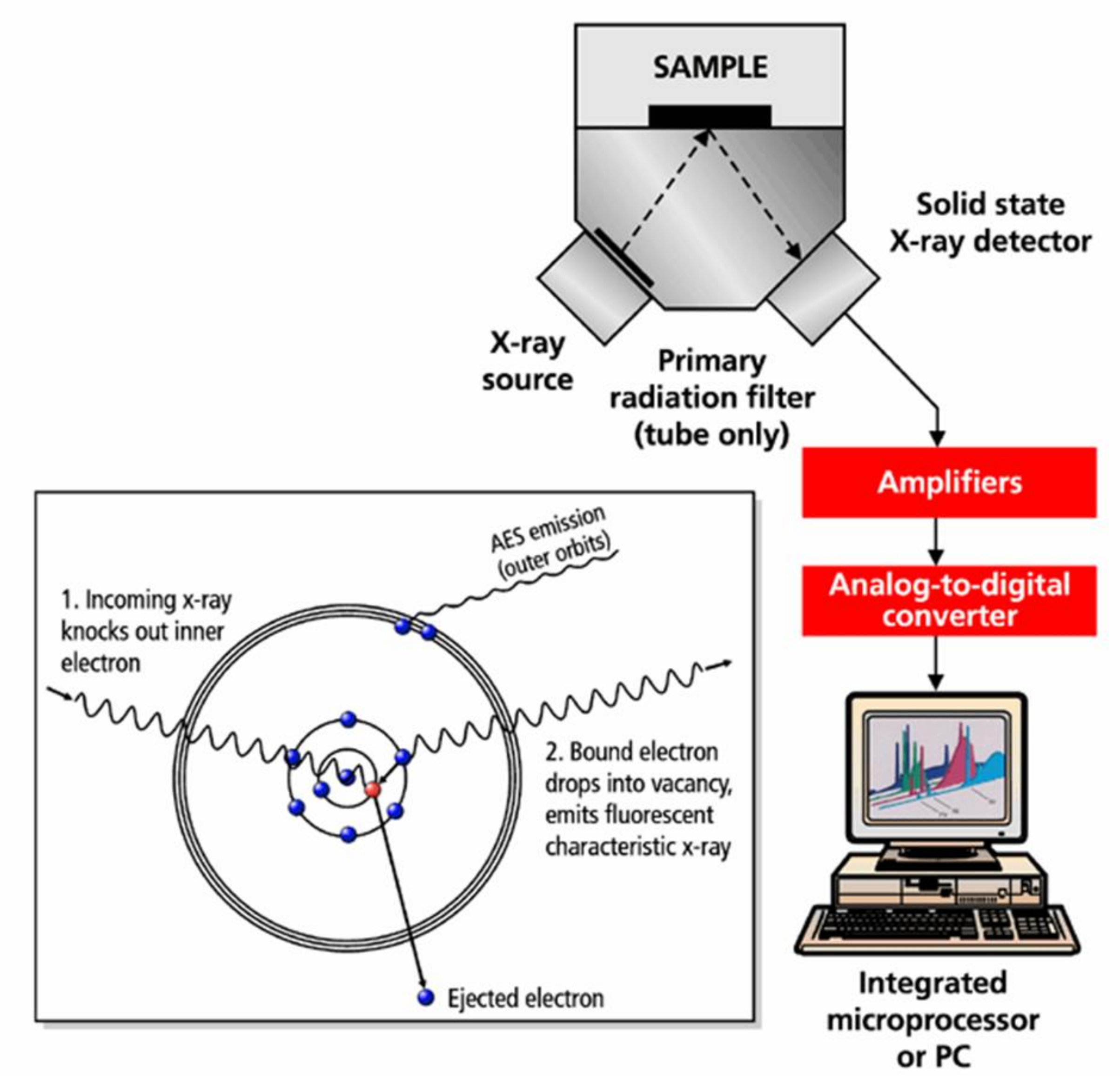


Figure 6-1: A simple schematic view of an X-ray machine and an example of the excitation of electrons

The primary X-rays produce secondary X-rays termed fluorescent radiation. The technique used with secondary x-ray is called *X-ray fluorescent* (XRF). Bragg's law is used to explain another X-ray spectrometry technique by making use of reflected Bragg waves which results in a diffraction pattern. This technique is called *X-ray diffraction* (XRD).

Both X-ray techniques were used during the analysis of rock samples collected at the mine. The main aim for the use of these techniques was to determine the mineral and elemental composition of the material (samples). This will lead to the determination of whether the rock material within the vicinity of the mine poses a threat to the environment or not.

6.2.1 X-ray fluorescence

Secondary X-rays are produced when an atom is bombarded by X-rays with high energy and intensity that the primary X-ray beam excites the secondary X-rays and fluorescence occurs (Figure 6-1). Fluorescent X-rays have the same properties as the primary X-rays (Volborth, 1969). The secondary X-rays are emitted at particular wavelengths and intensities. The characteristic radiation of the element to be determined is isolated from the X-rays on the basis of its wavelength or energy, and it intensity measured (Volborth, 1969; Fletcher, 1981). XRF is useful in the determination of major and trace elements of rock samples.

6.2.2 X-ray diffraction

The diffractive nature of rays can be best explained by using Bragg's law which is fundamental in X-ray diffraction. According to Bragg's law when X-rays of a certain wavelength, λ, pass through a crystal with the distance, d, between two planes of atoms, interference or reinforcement will occur at a certain angle of incidence, θ.

$$n\lambda = 2d\sin\theta$$

n is some integer indicating that various orders of reflection occur only at specific θ values. The reflection of X-rays is a process of diffraction, Figure 6-2.

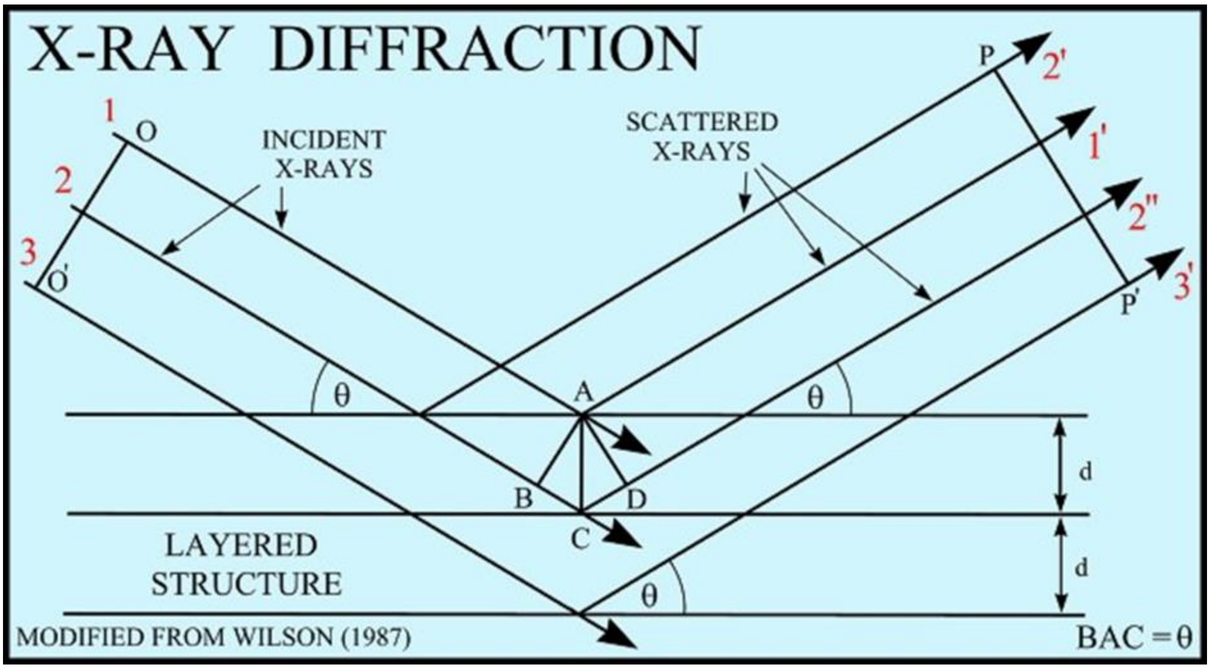


Figure 6-2: The image of the principle of X-ray diffraction, illustrating the Bragg's Law (source: www.engineersdaily.com)

X-ray diffraction takes place when a monochromatic, unidirectional X-ray beam is incident to a number geometrically similar planes in a crystal at an angel such as that the reflected beams from each layer reinforce each other and an intense diffracted beam results (Energlyn and Brealey, 1971). XRD is a good method for the determination of crystal structure and also mineralogical composition of rock samples.

6.2.2.1 Measurement of line intensity

Once the monochromatic radiation is emitted from the sample in a form of photons the energy of each photon which is a function of wavelength. The intensity of the line is the rate of the photon emission. The amount of each element present is then determined by measuring the intensity of the analytical line (Energlyn and Brealey, 1971; Liebhafsky and Pfeiffer, 1971).

6.2.3 Sampling method

Before the analysis of material can commence samples are collected first. There are different sampling methods that can be used. A sampling method is dependent on the type of sample that is being collected and analysis. The sample should be collected in such a way that its representative of the bulk mass of the material that it is collected from.

In this project material of the undisturbed and stockpiled material were sampled, as well as the ore. A trench was dug using a spade in order to get a sample at depth that has not being exposed to atmospheric processes. The sample was then taken from the side of the wedge using a geological harmer. Once the sample is retrieved it is placed in a plastic bag, sealed and labelled.

6.2.4 Sample preparation

Depending on the bulk size of the sample, it is firstly crushed to a small size and then milled. This is done to a point where the particles of the sample are in a form of powder. The powder is then pressed against hard flat chrome-plated steel to produce a pellet with plastic frame and backing. Pelletizing has the advantage of giving somewhat greater intensities, more reproducible results and enabling exactly the same sample to be re-analysed (Fletcher, 1981). Fusion discs are prepared by taking the small amount of powder, mix it with a binder and rolling this mixture between two microscopic slide glasses. The pellet and fusion disc are used for XRF and XRD techniques respectively.

6.3 RESULTS AND INTERPRETATION

6.3.1 X-ray diffraction results

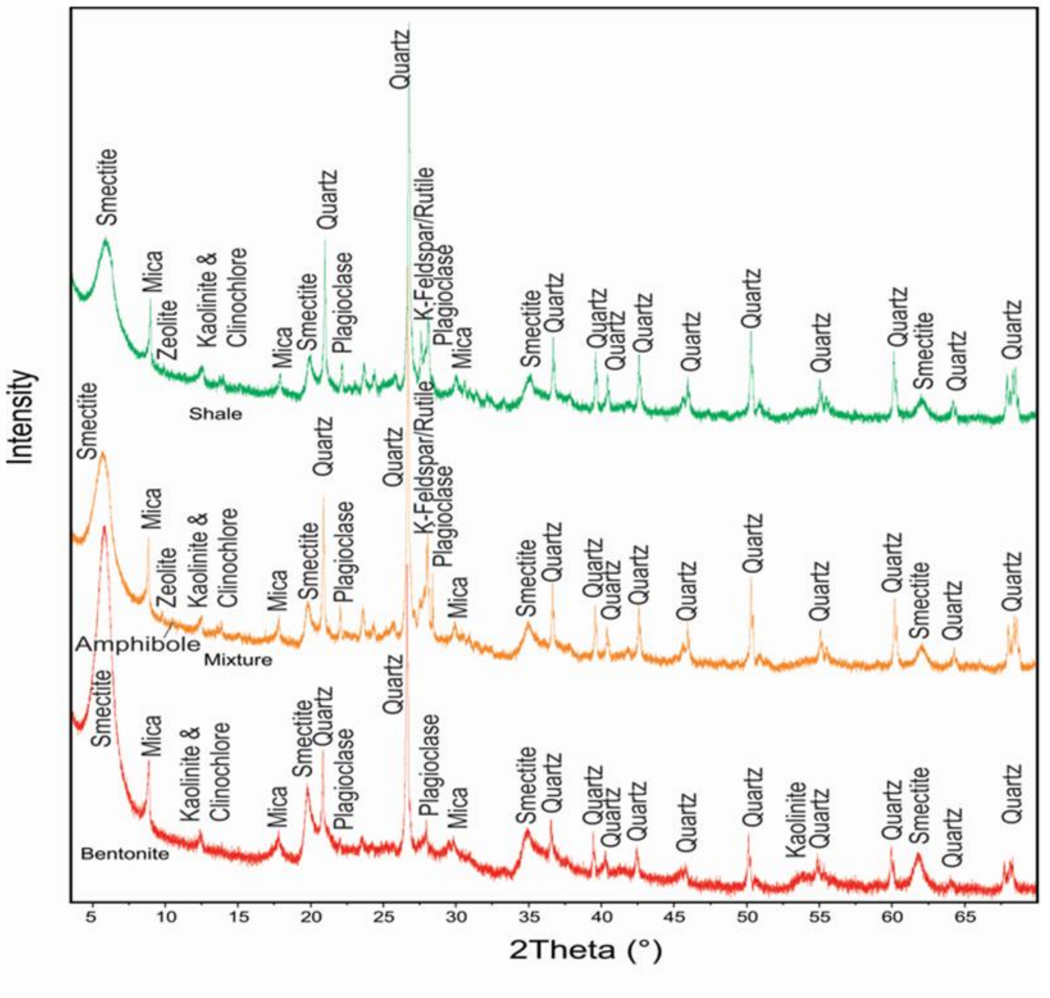
The X-ray diffraction results show the mineral composition of the ore and the overburden material. In Figure 6-3, the minerals present in the ore and overburden are mainly different types of silicate minerals. The bulk of common rocks in the earth's crust are siliceous. Silicate minerals dominate in most igneous, metamorphic and sedimentary rocks (Volborth, 1969). Minerals found in the samples are characteristic of the Karoo Supergroup which is mainly composed of sedimentary rocks.

The ore is dominated by montmorillonite with accessory minerals such as quartz, plagioclase, mica, chlorite and other clay minerals. The minerals found in the ore and shale are similar to the mixture overburden. Thus gives an indication that the mixture is a combination of the shale and the bentonite ore. The mixture contains more bentonite compared to the shale material. Some of the minerals found represent different formation environments and this is indicative that some minerals are not of sedimentary origin. The minerals are of igneous and metamorphic origin.

6.3.2 X-ray fluorescence results

The XRF results show a high concentration of silica (SiO_2) in the major ions of the samples. Most minerals are silicate minerals therefore the major ions will be dominated by silica. Aluminum oxide is the second highest concentration and this is due to the secondary and accessory minerals associated with the primary minerals in the geology of the area. The same applies to the other major ions, for example, the iron oxide is the third-most abundant major ion. This is attributed by the presence of mica in the area. From the XRD results it is evident that mica is abundant in the geology of the area.

Trace elements that pose a threat to the environment, these are transition metals, and they are at low concentrations, except for barium. The stockpiled material has been exposed to atmospheric processes and therefore will have undergone chemical changes. When compared to the undisturbed material there is a difference in the concentration of both the major ions and trace elements (Figure 6-4 and Figure 6-5). For the undisturbed overburden the major ions concentrations are lower than those of the stockpiled material. Therefore there is enrichment of ions and possible precipitation of minerals. The trace elements concentrations have lowered in the stockpile material as compared to the undisturbed material therefore there is a depletion of these elements.



	Quartz	Plag	K-feld	Mica	Zeolite	Kaolinite	Clinochlore	Smectite	Amphibole
Shale	26	7	6	15	6	7	6	27	
Mixture	23	7	3	16	6	6	6	33	5
Bentonite	15	4		13		7	7	54	

Figure 6-3: XRD results of the ore and the overburden (gangue)

6.3.3 Mineralogy and associated mineral forming environments

As previously mentioned the minerals found in the study area are different types of silicate minerals, of different environments. Below is a brief description of the mineralogy, formation environments and risks associated with the minerals.

Quartz

Quartz is silica mineral that is the most abundant mineral on earth. Quartz is a framework silicate mineral and is composed of silicon dioxide (SiO_2). It is a member of the SiO_2

polymorph. The other members include; tridymite, cristobalite, coesite and stishovite. The polymorphs are coordinated by four oxygen atoms at the corners and the silicon atom at the centre of the SiO_4^{4-} tetrahedron (Wenk and Bulakh, 2004). The atoms of quartz are bonded together by ionic-covalent bond.

Quartz is common in many sedimentary, igneous and metamorphic rocks as well as in hydrothermal veins. It also occurs as a secondary mineral, often as a cementing material in sediments. Quartz is chemically incompatible with feldspathoids and as a result it is absent in undersaturated igneous rocks (Deer *et al.,* 2013). Quartz is resistant to weathering and as a result it becomes concentrated during sedimentary processes to give rise to sands and sandstones (Deer *et al.*, 2013).

While quartz is not harmful to the environment. The exposure of silica dust can be detrimental to the health of people. The exposure of silica dust can lead the development of *silicosis* through inhalation. Silicosis is a progressive lung disease characterised by the development of scar tissue, the fibrotic nodules develop in the region of small airways (Wenk and Bulakh, 2004).

Amphibole Group

The structure of amphiboles is similar to that of pyroxene but occur as a double chain (consists of two interconnected chains of silica tetrahedra) instead of a single chain, they are also known as inosilicates.

Amphibole minerals are common in igneous and metamorphic rocks, and occur at a wide range of pressure (P) and temperature (T) environments. In metamorphic rocks they commonly found in *amphibolite, greenschist* and *lower granulite facies*. These facies are characteristic to regional metamorphism. Amphiboles occur less in contact metamorphism (Deer *et al.*, 2013).

Pyroxenes and amphiboles occur in similar types of rocks: igneous rocks, skarns, gneisses and schists. Amphiboles crystalize at shallower depth and replace pyroxene during retrograde metamorphic processes at decreasing P-T with increasing chemical activity (Wenk and Bulakh, 2004).

Amphiboles especially the asbestos amphiboles have can be harmful to humans. An increased period of exposure to the mineral in form of dust can lead to significant asbestos-related diseases such as *mesothelioma* (Gunter *et al*., 2007).

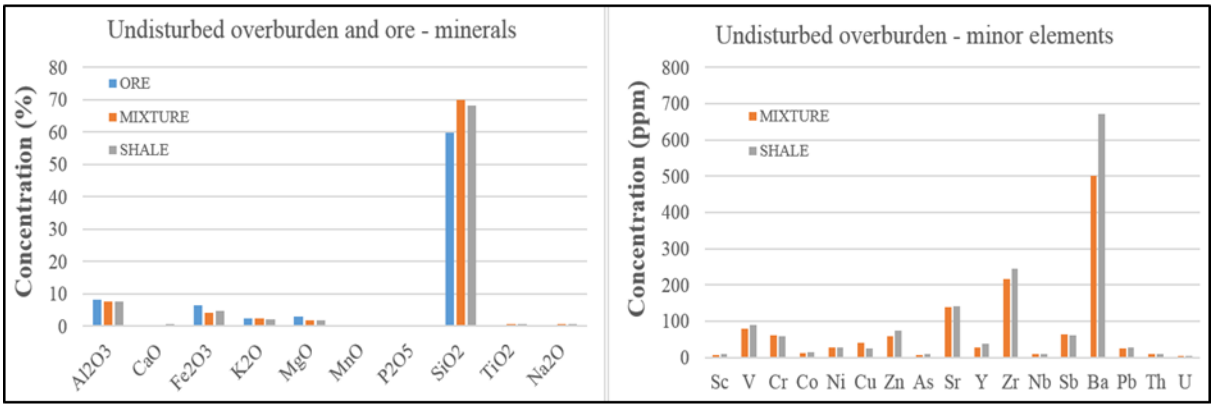


Figure 6-4: XRF results of the undisturbed overburden and ore samples at Matsopa Mine, showing the major ions (left) and trace element concentrations (right)

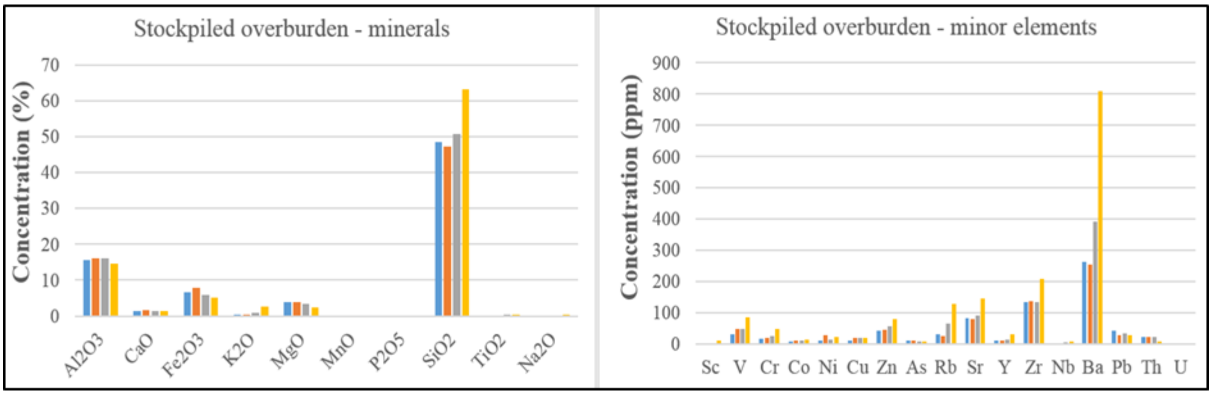


Figure 6-5: XRF results of stockpiled overburden at Matsopa Mine, showing the major ions (left) and trace element concentrations (right)

Mica Group

Micas are layered silicates, some minerals are trioctahedral and others are dioctahedral. Part of the tetrahedral Si^{4+} is replaced by Al^{3+}. To maintain charge balance, large cations (Na^+, K^+, Ca^{2+}) are introduced between the sheets (Wenk and Bulakh, 2004). Most micas are enriched with iron like the biotite group but muscovite contains very little iron and is almost a pure aluminous mica.

Biotites occur in a wide range of geological environments than most micas. In metamorphic rocks they crystallise in wide range of T-P conditions, and occur abundantly in contact and regionally metamorphosed sediments (Deer *et al.*, 2013). Muscovites are found in granites and pegmatites as large crystals and also in gneisses and schists.

Pure solid and dust form of mica contains free silica. Exposure of mica together with quartz and other silicates in a form of dust may cause silicosis. The exposure of mica powder to mine workers may cause irritation of the respiratory tract, and, after several years nodular *fibrotic pneumoconiosis* can occur (Osinsky and Stellman, 1998).

Zeolites

Zeolites are tectosilicates and chemically are aluminosilicates. Zeolites have large cavities and open channels that contain variable amounts of H_2O molecules. They have extra-framework cations that are easily exchangeable, the water is reversibly lost upon heating (Wenk and Bulakh, 2004; Deer *et al.,* 2013). Zeolites have been classified according to their exchange properties. Every zeolite has its own ion exchange capacity (Wenk and Bulakh, 2004).

Zeolites are low-T minerals that form under hydrothermal conditions. Zeolites also occur in sedimentary or tuffaceous-sedimentary rocks at a late-diagenetic early metamorphic stage. They form as a product of the alteration of feldspars and volcanic glass, or as an authigenic mineral in the matrix (Wenk and Bulakh, 2004). Zeolites form in hydrologically open systems, hydrologically closed systems, soils and surface deposits, and marine sediments from arc-source terranes environments (Deer *et al*., 2013).

Zeolites are used to remove toxic material in the environment. Zeolites together with perlite and bentonite are used as landfill liners to remove chemical and biological constituents by filtration and adsorptive action (Ozel *et al.,* 2012). The use of these minerals as landfill liners is to protect the groundwater from being contaminated. Natural zeolites are used for the removal of radio-nuclei from low- and medium-level nuclear waste due to their ion exchange properties (Townsend and Coker, 2001).

Chlorite

The chlorite group is a group of layered silicate minerals known as phyllosilicates. The crystal structure of chlorites are similar to that of micas but chlorites have a 2:1 ratio of the octahedral layer sandwiched between two tetrahedral layers. The brucite layer replaces the large cations in micas. Chlorites occur in different varieties which include magnesium, iron, and aluminium-rich chlorites. All these cations compete for the octahedral position (Wenk and Bulakh, 2004). The most common chlorite members are clinochlore and chamsite.

Chlorites occur in low-grade regionally metamorphosed rocks, as hydrothermal alteration products of ferromagnesium minerals in igneous rocks. Together with clay minerals zeolites occur in argillaceous sedimentary rocks. Chlorites are typically alteration products of olivine, pyroxenes and hornblendes (Wenk and Bulakh, 2004; Deer *et al.,* 2013).

The major exposure of chlorite to the environment is through drinking water. Chlorite reacts quickly with water and moist body tissues. In taking food and water with high amounts chlorite may result in irritation in the mouth, esophagus or stomach. Severe damage caused by chlorite may result in shortness of breath and other respiratory problems (Taylor *et al.*, 2004).

Feldspars

Feldspars are abundant minerals in the earth's crust and are rock forming minerals. The structure of feldspars is related to the silica minerals but in some feldspars the Si^{4+} is replaced by Al^{3+}. The pure end members of feldspars are: anorthite (Ca-feldspar); albite (Na-feldspar); and K-feldspar (sanidine, orthoclase and microcline). Commonly feldspars are called alkali-feldspar; K-feldspar or plagioclase. The K-feldspars are stable products of both high-grade thermal and regional metamorphism.

K-feldspars are common in schists and gneisses in the vicinity of igneous rocks. Plagioclases are found in igneous rocks such as felsic intermediate, mafic and alkali igneous rocks, as well as gneisses and amphibolites. The variety of plagioclase is dependent on the rock in which it formed in. Felsic rocks are enriched in calcium and aluminium-rich varieties and mafic rocks in pure albite (Wenk and Bulakh, 2004). The alteration products of plagioclase are montmorillonite, scapolite, prehnite and various zeolites when altered by hydrothermal solutions.

Feldspars like most silicate minerals may be harmful to humans upon long period exposure. Chronic inhalation of feldspars may cause *silicosis* due to the presence of substantial amounts of free silica to mine workers (Osinsky and Stellman, 1998).

6.3.4 Element Mobility

Element mobility describes the changes which takes place in rock after its formation, usually through interaction with fluid. Element mobility will take place under different processes namely; weathering, diagenesis and metamorphism or through interaction with hydrothermal fluid. The mobility of major elements is controlled by three factors – the stability and composition of the minerals in the alteration product and the composition, temperature and volume of the fluid phase (Rollinson, 1993). Chemical processes/conditions such as hydrolysis, oxidation and reduction also plays a role in the mobility of ions.

Free ions which are mobile under certain chemical conditions can be mobile. Example, free Fe^{2+} under oxidizing conditions will be oxidized to Fe^{3+}, in water the Fe^{3+} can be problematic with the production of acidic waters which will lead to contamination of the water. Should there be other metals in this type of water with sufficient oxygen acid mine drainage can occur. The water will contain significant amounts of metals as some metals stay in solution in acidic waters.

The minerals associated with the ore and gangue like amphiboles and micas may contain elements such as iron which can be mobile under oxidising chemical conditions. Due to the stability of the compounds in which the elements are integrated in, there is little to no mobility of this elements. Most groundwater do not contain significant amounts of oxygen, oxidation of sulphide minerals is generally confined to the surface weathering environment (Nelson Eby, 2004).

The low concentration of large-ion lithophile (LIL) metals which are more mobile than the high field strength (HFS) metals, which are further reduced upon exposure to the atmosphere once stockpiled (Figure 6-5). This reduces the possibility of contamination. The one element contrary to this is barium (Ba) which increased in the stockpile material.

Barium is a stable element but its solubility depends on the compound in which it formed. In the acetate, nitrate and halide forms, barium compounds are soluble in water, but the carbonate, chromate, fluoride, oxalate, phosphate and sulphate forms are quite insoluble (WHO, 2004). The groundwater monitoring will aid in determining whether the ion is mobile or immobile. Also whether it reached the groundwater system, thus increasing the concentration of barium in the system resulting in the contamination of the groundwater.

6.3.5 Acid potential minerals

Commonly acid producing minerals are sulphide minerals such as; pyrite, pyrrhotite, chalcopyrite. These minerals are usually associated with the formation of acid mine drainage. One of the reasons for the XRD analysis of the sample material was to define the different minerals in the area. To determine the presence of acid potential minerals. In most cases the acid producing minerals contain sulphur and are metals that may pose a threat to the environment. The production of acid drainage is mainly the result of fluid-rock interaction. As previously mentioned, Eby (2004) stated that the oxidation of sulphide minerals is confined to the surface weathering environment as groundwater does not contain significant amounts of oxygen. Therefore it would be expected that acid drainage in groundwater is a result of leaching from the surface into the groundwater environment.

The results of the geochemical analysis show that the study area is mainly composed of silicate minerals. Silicate minerals are considered as buffers rather than acid producing minerals. Therefore these minerals counter acidity in soils and waterbodies. In sediments free of carbonate minerals, silicate weathering is the most important buffer mechanism against acidification of soil and groundwater (Appelo and Postma, 1994). Should there be an elevated concentration of metals and acidity in the groundwater system the mineralogy in which the aquifer is composed with will counter the effect to reach an equilibrium and buffer the system.

6.4 CONCLUSIONS

The XRD and XRF analysis used aided in the identification of the mineralogy, major and trace ions respectively. The minerals of the ore and gangue associated with it, are mainly silicate minerals which formed under different P-T conditions. Minerals associated with metamorphism may be as a result of the meteorite impact that took place at Vredefort. The investigation on the mineralogy was to determine whether the minerals associated with the ore can be source of groundwater environment.

The results show silicates as previously mentioned and these minerals are buffer products therefore they are neutralizing material and combat acidification of the soil and groundwater. It can then be concluded that mining and stockpiling of material at Matsopa Minerals will not cause pose a threat to the groundwater environment, particularly the groundwater environment.

CHAPTER 7:
GROUNDWATER MONITORING

7.1 INTRODUCTION

Monitoring of the groundwater is important because any change in the groundwater quality can be identified. The monitoring programme was conducted from March 2016 to April 2017. The groundwater quality and groundwater level were monitored. The monitoring of groundwater quality was conducted to determine any changes in the water quality of the as result of contamination due to mining.

The monitoring of the water levels was conducted to determine whether there are fluctuations in the groundwater level. To determine whether the fluctuations are a result of seasonal changes or effects of hydraulic changes due to impact of mining. The groundwater quality is of outmost importance because the community of the area is solely dependent on the groundwater for drinking water, domestic use and livestock watering.

7.2 HYDROCHEMISTRY

The groundwater quality is prone to change due to natural and anthropogenic activities that may cause contamination to the groundwater. The composition of soil water and groundwater will depend on the rock type which the water flows (Appelo and Postma, 1994). In South Africa, agricultural practices and industrialisation (especially mining) are the main sources of anthropogenic contamination of groundwater. The monitoring points were identified during the hydrocensus for both surface and ground water, Figure 7-1.

7.2.1 Sampling

Samples were collected on bimestrial basis during the duration of the monitoring programme. For surface water; samples were collected directly from streams and taps for the groundwater samples. Boreholes were highly equipped, and thus bailers could not be used for the collection of samples. Figure 7-2, shows the sampling the groundwater and surface water.

For water chemistry samples 500 ml plastic bottles were used, the bottle is rinsed three times before the water sample is taken. Bacterial water samples were taken and glass bottles were used to contain the sample.

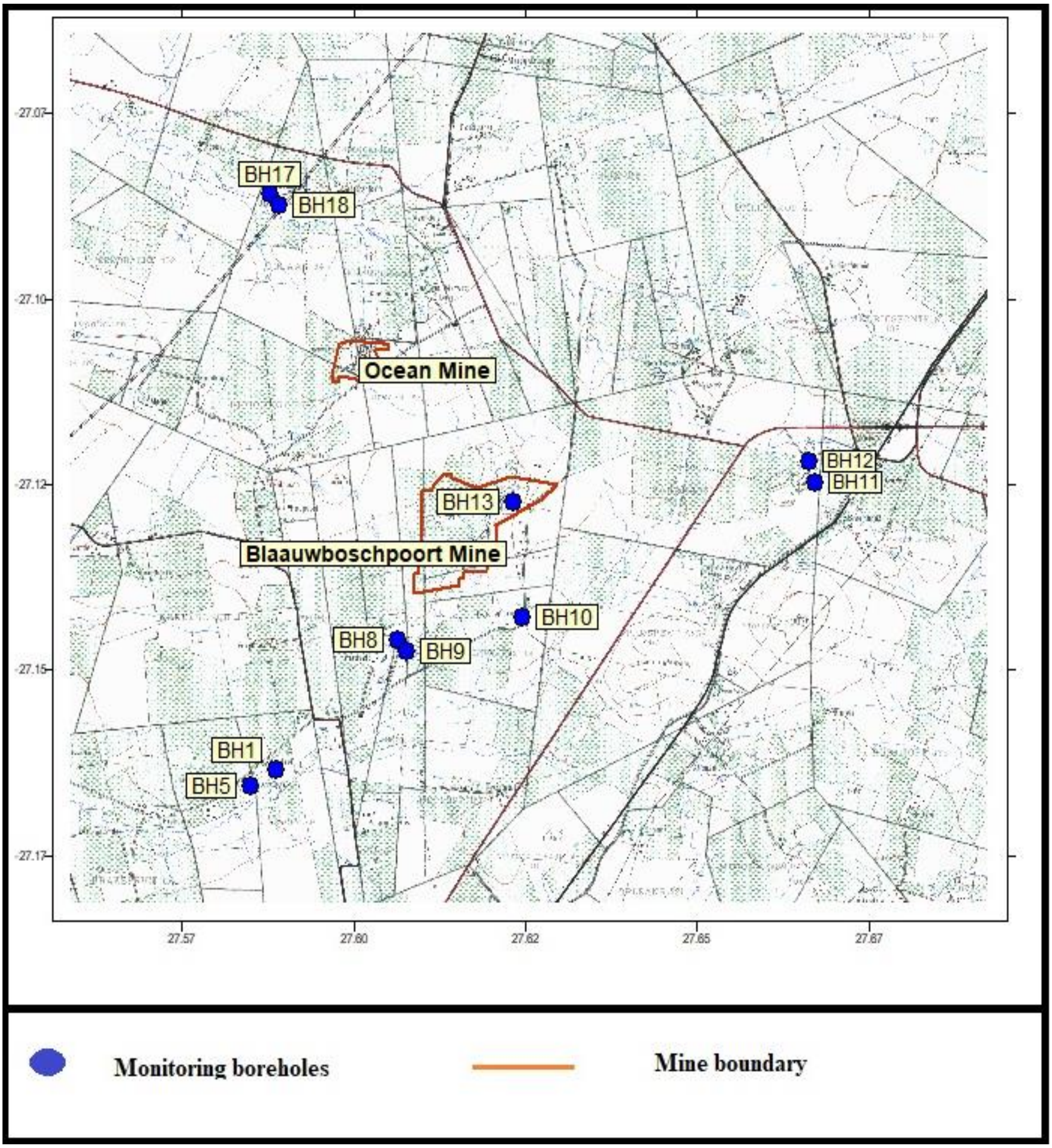


Figure 7-1: Selected monitoring boreholes

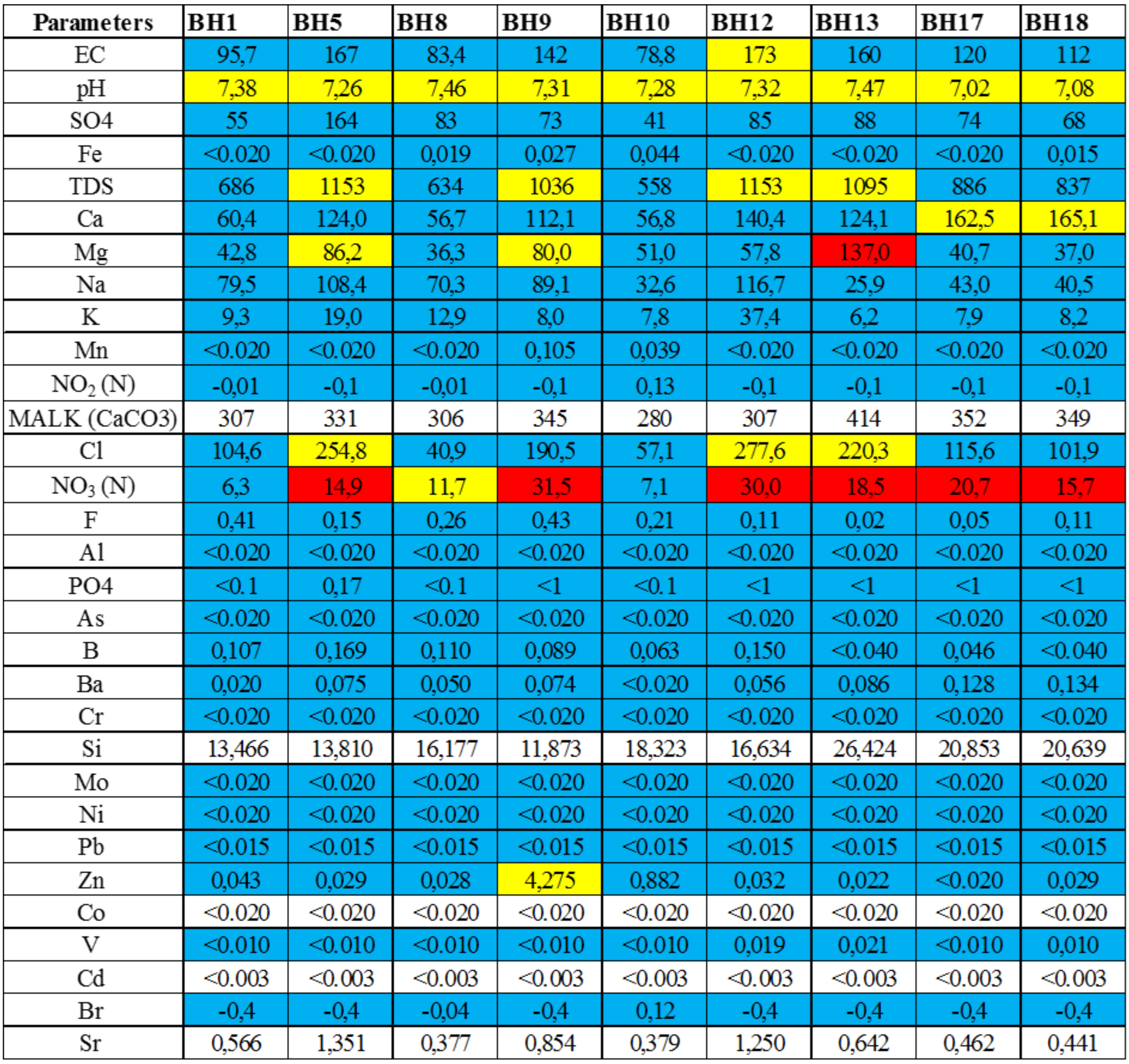
Figure 7-2: Sampling for ground and surface water samples

7.2.2 Hydrochemistry analysis results

Groundwater and surface samples were submitted to the Institute for Groundwater Studies Laboratory for analysis. The number of samples varied depending on whether access was gained at some farms, and on whether streams and boreholes had dried out or not. The SANS241: 2006 & 2015 standard was used for drinking water.

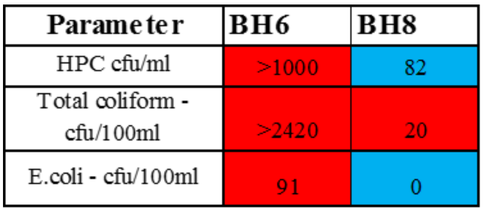
Table 7-1 shows part of the results; the uncoloured cells indicate that there are no standards assigned to the specific parameter. Table 7-1 shows the results of the major and trace elements found in the water samples taken during the month of April 2017. The results of the parameters are given in mg/l, for the EC is micro-Siemens per meter (mS/m) and the pH is given in units. Table 7-2 gives the results of the bacterial analysis of BH 6 and 8. The rest of the hydrochemistry results are attached on Appendix C.

Table 7-1: Results of hydro-chemical analysis of April 2017



Parameters	BH1	BH5	BH8	BH9	BH10	BH12	BH13	BH17	BH18
EC	95,7	167	83,4	142	78,8	173	160	120	112
pH	7,38	7,26	7,46	7,31	7,28	7,32	7,47	7,02	7,08
SO4	55	164	83	73	41	85	88	74	68
Fe	<0.020	<0.020	0,019	0,027	0,044	<0.020	<0.020	<0.020	0,015
TDS	686	1153	634	1036	558	1153	1095	886	837
Ca	60,4	124,0	56,7	112,1	56,8	140,4	124,1	162,5	165,1
Mg	42,8	86,2	36,3	80,0	51,0	57,8	137,0	40,7	37,0
Na	79,5	108,4	70,3	89,1	32,6	116,7	25,9	43,0	40,5
K	9,3	19,0	12,9	8,0	7,8	37,4	6,2	7,9	8,2
Mn	<0.020	<0.020	<0.020	0,105	0,039	<0.020	<0.020	<0.020	<0.020
NO_2 (N)	-0,01	-0,1	-0,01	-0,1	0,13	-0,1	-0,1	-0,1	-0,1
MALK (CaCO3)	307	331	306	345	280	307	414	352	349
Cl	104,6	254,8	40,9	190,5	57,1	277,6	220,3	115,6	101,9
NO_3 (N)	6,3	14,9	11,7	31,5	7,1	30,0	18,5	20,7	15,7
F	0,41	0,15	0,26	0,43	0,21	0,11	0,02	0,05	0,11
Al	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
PO4	<0.1	0,17	<0.1	<1	<0.1	<1	<1	<1	<1
As	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
B	0,107	0,169	0,110	0,089	0,063	0,150	<0.040	0,046	<0.040
Ba	0,020	0,075	0,050	0,074	<0.020	0,056	0,086	0,128	0,134
Cr	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Si	13,466	13,810	16,177	11,873	18,323	16,634	26,424	20,853	20,639
Mo	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Ni	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Pb	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015
Zn	0,043	0,029	0,028	4,275	0,882	0,032	0,022	<0.020	0,029
Co	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
V	<0.010	<0.010	<0.010	<0.010	<0.010	0,019	0,021	<0.010	0,010
Cd	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Br	-0,4	-0,4	-0,04	-0,4	0,12	-0,4	-0,4	-0,4	-0,4
Sr	0,566	1,351	0,377	0,854	0,379	1,250	0,642	0,462	0,441

Table 7-2: Results of bacterial analysis



Parameter	BH6	BH8
HPC cfu/ml	>1000	82
Total coliform - cfu/100ml	>2420	20
E.coli - cfu/100ml	91	0

🟦 Target water quality
🟨 Acceptable water quality
🟥 Unacceptable water quality

7.2.2.1 Ions with elevated concentrations

A brief description of the ions that occur at high concentrations in the groundwater is given. Here the possible sources of these ions, health effects on humans and animals and possible mitigation methods are described.

Nitrate (NO_3^-)

Nitrate is an inorganic compound (are compounds that do not contain both hydrogen and oxygen) which is composed of nitrogen and oxygen atoms. It can be found naturally in nature and in several foods. The standard for nitrate is ≤11 mg/l according to the SANS 241: 2006 & 2015 standard. The nitrate concentrations for some boreholes were elevated over certain period of time during the monitoring of the groundwater quality. Figure 7-3 below shows the trend of nitrate overtime.

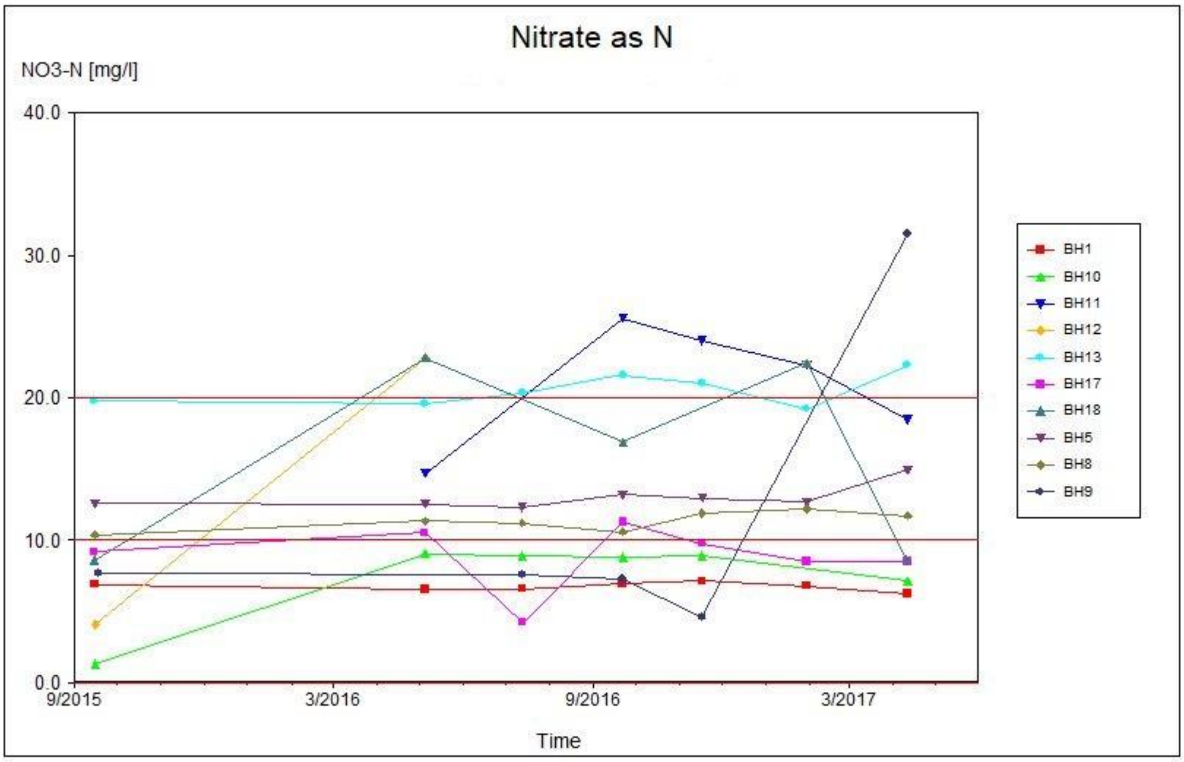


Figure 7-3: Trend of Nitrate during the monitoring of groundwater quality

- Sources of nitrate

Nitrate in groundwater originates primarily from fertilizers, septic systems, and manure storage or spreading operations. Nitrogen from fertilizers that is not taken up by plants, volatilized, or carried away by surface runoff; leaches into the groundwater in a form of nitrate. This not only makes the nitrogen unavailable to crops, but also elevate the concentration of nitrate in groundwater above acceptable drinking water standards.

Nitrate can come from wastewater treatment plants, landfill sites and from oxidation of nitrogenous waste products in human and animal excreta.

- Health effects of nitrate

Nitrate is one of the most common groundwater contaminants in rural areas. The toxicity of nitrate to humans is mainly attributable to its reduction to nitrite. It is regulated in drinking water primarily because excess levels can cause methemoglobinemia, or "blue baby" disease. Upon absorption, nitrite combines with the oxygen-carrying red blood pigment, haemoglobin, to form methaemoglobin, which is incapable of carrying oxygen

Nitrate in drinking water starts affecting the health of the general populace at levels in the range of 100 to 200 mg/l nitrate-N. Its effect on any given person depends on many factors, including other sources of nitrate and nitrite in their diet. Consuming water with nitrate levels close to the unacceptable level of drinking water standard does not normally increase the methaemoglobin level of humans beyond infancy. Some individuals, however, may have increased harm to methemoglobinemia due to exposure to antioxidant medications and chemicals (DWS, 1996).

- Mitigation methods

There are no simple ways to remove nitrate from water in the home, as it doesn’t evaporate when boiling or freezing. The boiling water for more than 10 minutes can make the nitrate more concentrated. Home water-treatment units are generally a limited option. A properly operating distillation system will remove nitrate, but is quite expensive to install and operate and must be adjusted properly. Reverse-osmosis units are another option, but are also expensive to install and operate. According to the South African Water Quality Guidelines nitrate can be removed from water by ion-exchange methods as well as reverse osmosis treatment. As well as having a diet with adequate Vitamin C, as this partially protects against the adverse effects of nitrate/nitrite.

Bacterial analysis

Bacterial test are done to determine the possible presence of pathogens in water and possible bacterial growth in boreholes. The reason for bacterial tests was to determine the safety of water for human consumption and livestock watering. Indicator organisms that were tested for microbiological analysis were:

- Total coliform bacteria: used as an indicator of the general hygienic quality of water, and is used in routine monitoring of drinking water supplies;
- Escherichia coli (E-coli): highly specific indicator of faecal pollution which originates from humans and warm blooded animals (DWS, 1996);
- Heterotrophic plate count (HPC): HPC measures colony formation on culture media of heterotrophic bacteria in drinking water. HPC can be used to measure the overall bacteriological quality of drinking water (Gandham, 2017).

The results in Table 7-2, shows high counts of HPC, total coliforms and E-coli for borehole BH6. While BH8 had low counts of HPC and zero counts of the E-coli. The results indicate that there are waterborne pathogens in sample BH6. Both samples were taken from the same farm but the boreholes which they were taken are located far from each other. This is indicative that there are different activities taking place on the farm.

- Sources of bacteria

Commonly used indicators are excreted or released consistently by virtually all humans because they are members of the normal microbial flora of humans. Some of the indicators are also consistently excreted by warm-blooded animals. Faecal indicators are, therefore, always present in sewage-polluted water and their numbers are in relatively close correlation with levels of faecal pollution and the time since pollution has taken place.

- Health effects of bacteria

These micro-organisms cause diseases such as gastroenteritis, giardiasis, hepatitis, typhoid fever, cholera, salmonellosis, dysentery and eye, ear, nose and skin infections, which have worldwide been associated with polluted water.

- Mitigation methods

Several conventional water purification processes, including sedimentation, absorption, coagulation and flocculation will all result in the partial removal of micro-organisms in water. These processes, however, do not necessarily inactivate the micro-organisms and additional disinfection processes need to be applied. Chlorine disinfection is often practised. Disinfection, however, requires careful process control of the disinfection species, dosage and contact time (DWS, 1996).

In situations where no conventional treatment is practised, micro-organisms can be destroyed by boiling the water before use.

7.2.3 Graphical presentation of water chemistry

The graphical presentation of hydrochemistry is done using diagrams which show the abundance of major ions which occur in water. The most common diagrams which are used are; Stiff and the Piper diagram. The concentration of ions in water chemistry diagrams are expressed in milli-equivalents per litre (meq.L^{-1}). In this study the Stiff, Piper, Durov and SAR diagrams are used to graphically represent the water chemistry results. The graphical and numerical interpretation of chemical analysis of water are based on the relationship of ions, or group of ions, forming a chemical type of water (Zaporozec, 1972).

7.2.3.1 Stiff diagram

A Stiff diagram uses parallel horizontal axes extending on each side of a vertical zero axis. Four cations are plotted on the left and the anions on the right of the vertical axis. The resulting points are connected and usually give a polygon showing the major ions. This diagram is useful in showing the water composition and is also used to determine the source-rock of the water.

The results of the groundwater sample shown in the Stiff diagram are of the overall average of the samples analysed during the monitoring programme. The dominating water types are that of calcium-bicarbonate and magnesium-bicarbonate (Figure 7-4).

7.2.3.2 Piper diagram

Piper diagrams are trilinear representation of cations, anions, and combined cation and anion proportions (Nelson Eby, 2004). The cations and anions are plotted in triangles on the left and right respectively. These points are then projected on the diamond shape between the triangles. The Piper diagram is used to classify water types. It can also be used to determine whether the water represent recently recharged groundwater, mixing of two types and polluted water types. The water types that are classified are: calcium/magnesium bicarbonate; sodium bicarbonate/chloride; sodium chloride and calcium/magnesium sulphate/chloride waters.

The Piper diagram in Figure 7-5, represent the results of the water samples of the monitoring programme. The water of the boreholes using the Piper diagram can be classified as calcium/magnesium bicarbonate water type which is dominant then, followed by the calcium/magnesium sulphate/chloride water type. The calcium/magnesium bicarbonate water type is associated with recently recharged waters. During the monitoring of the groundwater one of the samples from BH17 resulted in a different water type, during the month of July. The results of this borehole showed a high concentration of sodium and chloride (see Appendix C). The water resulted in sodium chloride water type. The chloride enrichment could be the result of leachate from domestic waste.

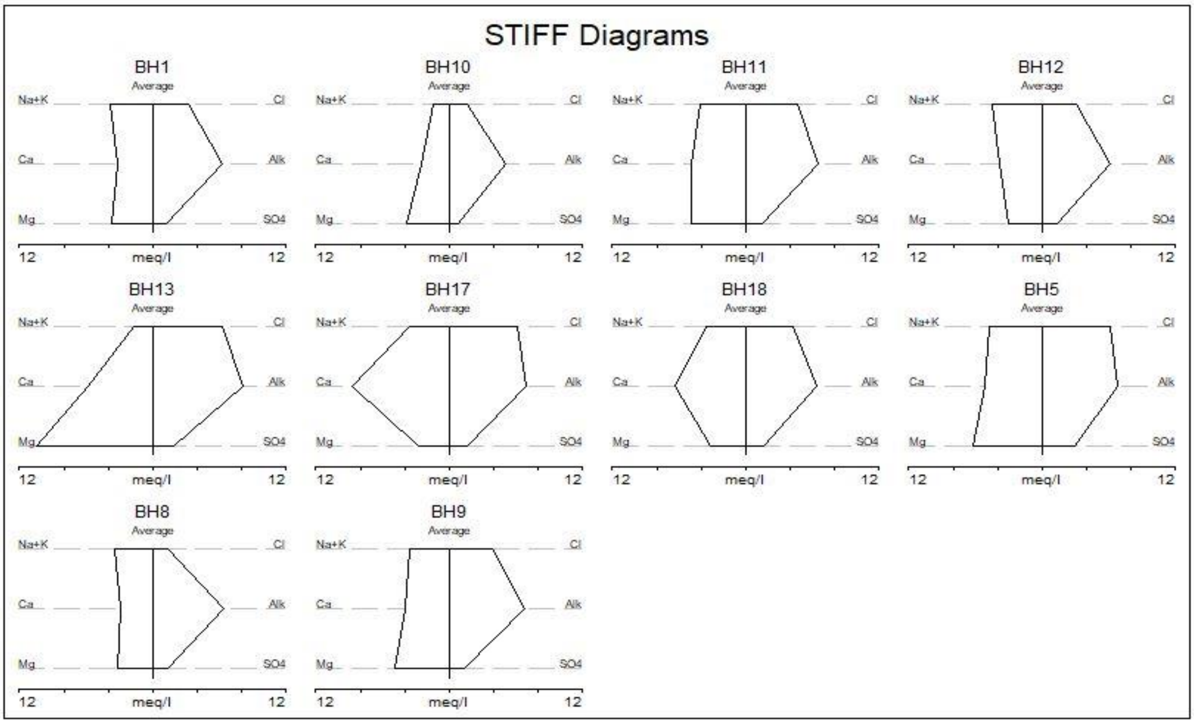


Figure 7-4: Stiff diagram of the groundwater samples

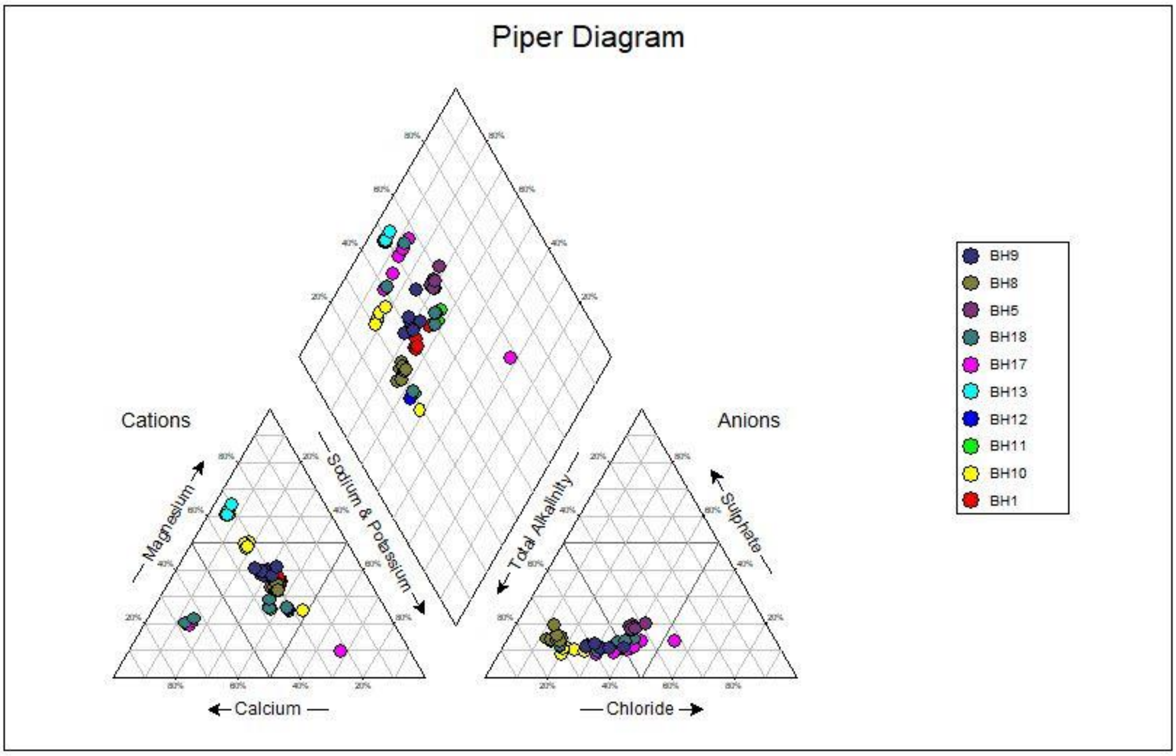


Figure 7-5: Piper diagram of the monitoring of groundwater quality

7.2.3.3 Durov diagrams

The Durov and expanded Durov diagrams are similar to that of the Piper diagram. Unlike the Piper diagram the Durov takes into account the pH and EC of the water samples. In the expanded Durov; the square plot is divided into nine areas which gives the water types associated with the water samples. The Durov diagram (Figure 7-6) shows the water quality to be similar during the course of the monitoring, except for the sample of BH17 during the month of July. The position in which the sample plotted may be due to the high concentration of sodium and chloride.

The expanded Durov diagram describes the water type. The water results in Figure 7-7 plots mostly in the unpolluted square. Therefore during the monitoring of the groundwater quality, the water in the boreholes was unpolluted as a result of mining activities. During some months some boreholes, BH5; BH13; BH17 and BH18, had enrichment in sulphate. This is indicative of water found in a mining environment. One sample of BH17 plots on the bottom right square as result of the high chloride concentration. The chloride enrichment in the water sample is indicative of leachate from domestic waste.

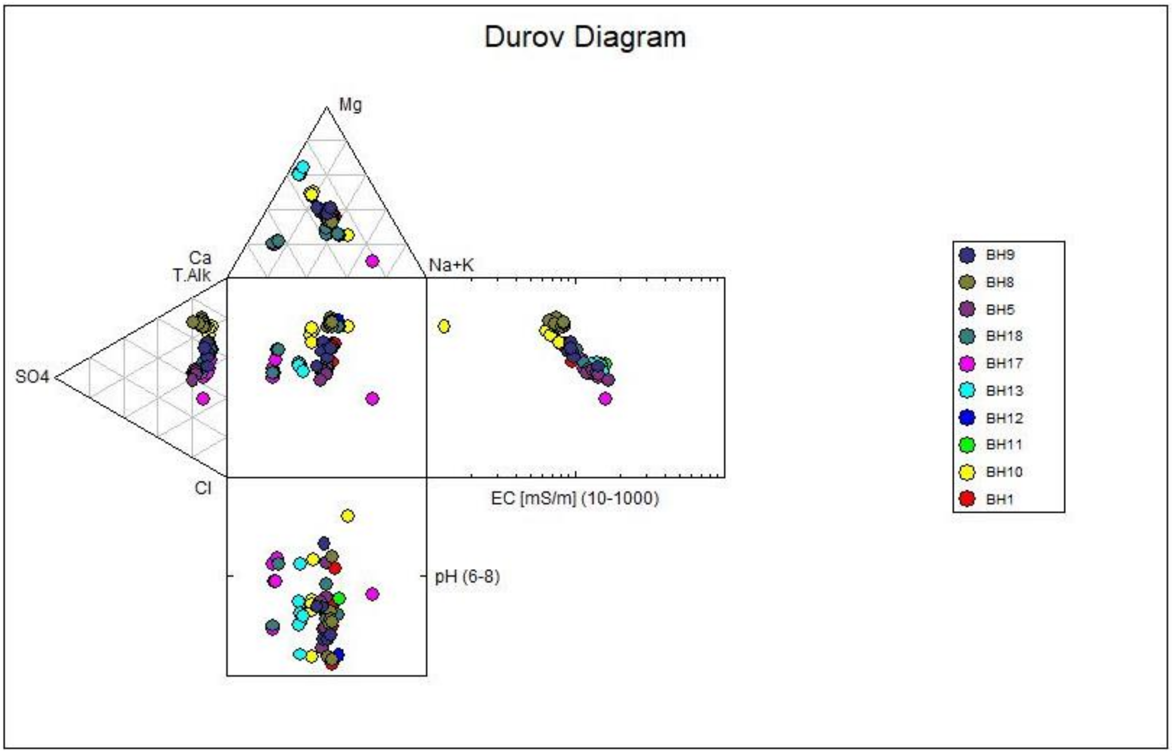


Figure 7-6: Durov diagram of the monitoring of the groundwater quality

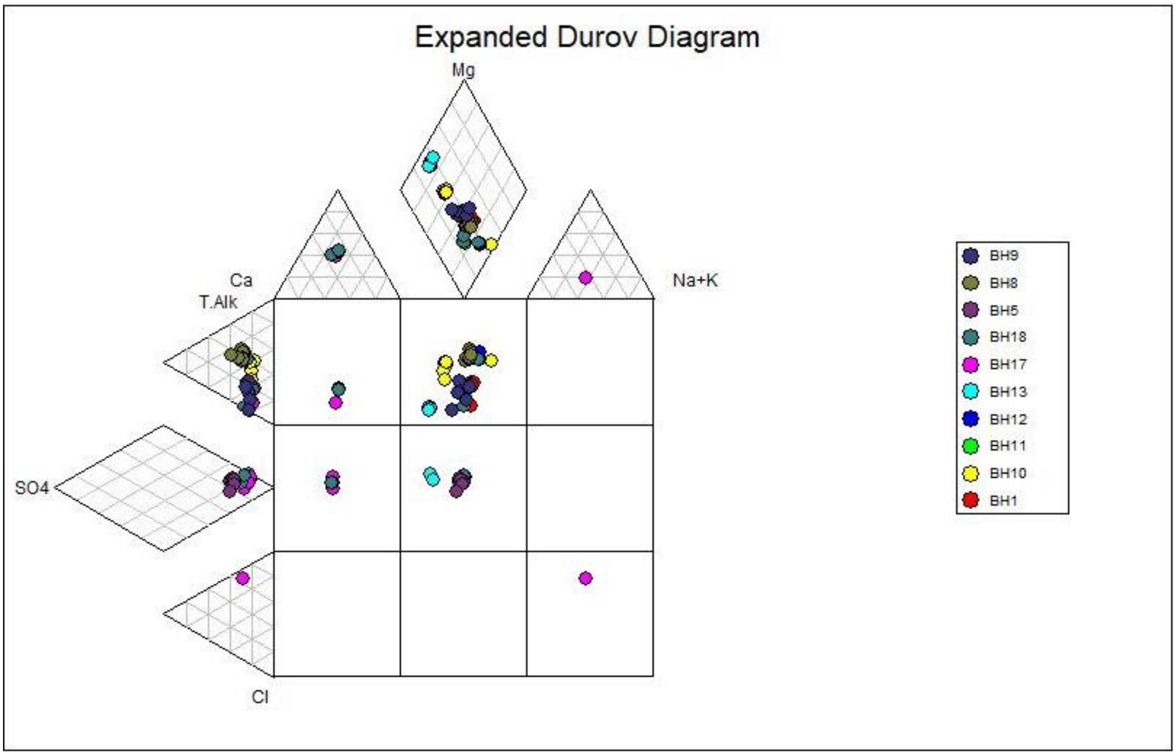


Figure 7-7: Expanded Durov diagram of the monitoring of the groundwater quality

7.2.3.4 Sodium absorption ratio (S.A.R) diagram

The SAR diagram gives a graphical representation of the electrical conductivity (EC) in terms of salinity and the dissolved salts in water. The SAR is used to determine whether the water is suitable for agricultural use. The most important characteristics of irrigation water in determining its quality are: (i) Total concentration of soluble salts; ii) Relative proportion of sodium to other principal cations; (iii) Concentration of boron or other element that may be toxic, and (iv) Under some condition, bicarbonate concentration as related to the concentration of calcium plus magnesium (Sadashivaiah *et al*.,2008).

The results of the water samples overtime show that the water has a low sodium content which is good but the EC is high and therefore the water is highly saline (Figure 7-8). When the water with high salt concentration is used for irrigation and little or no leaching takes place, the salt will accumulate in the soil and saline soil will form. The saline soil will affect the yield of crops and should the salinity be severe it impacts the growth of the crops (DWS, 1996).

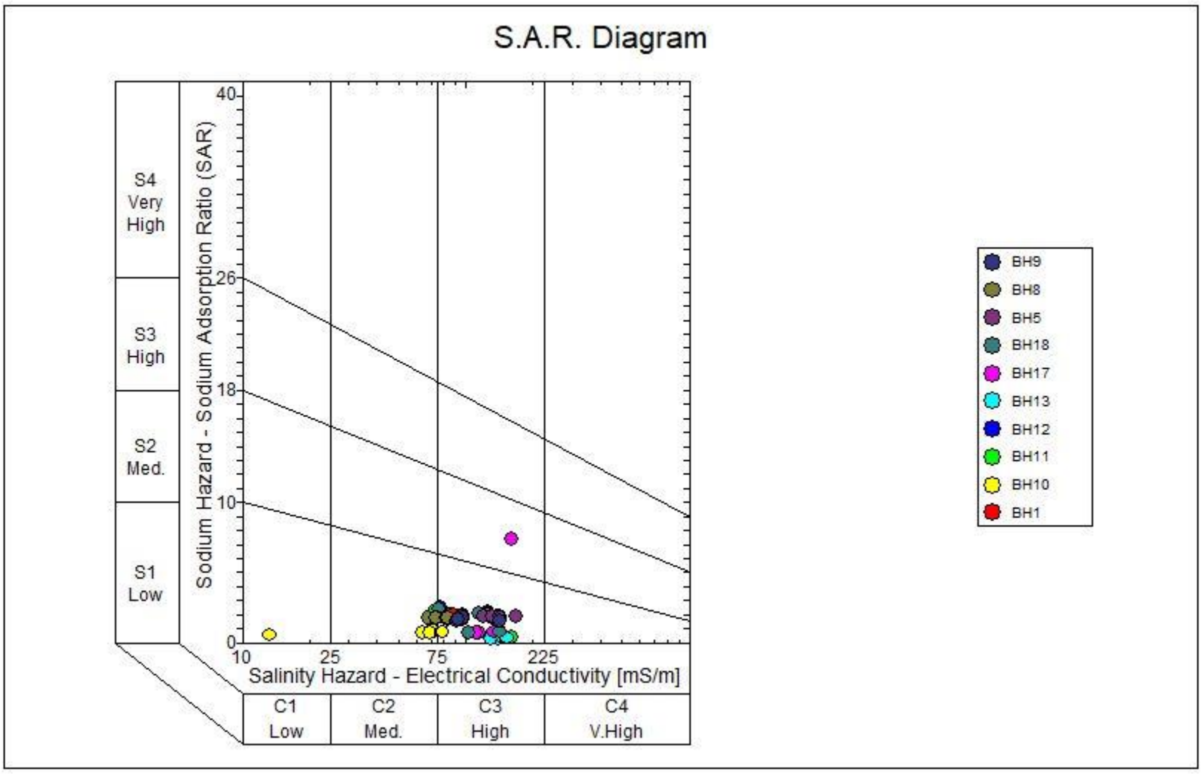


Figure 7-8: SAR diagram of the monitoring of the groundwater quality

7.3 GROUNDWATER LEVELS

The water level monitoring was conducted to determine whether the abstraction of water and the creation of the pit have impacted the water table of the surrounding aquifer. As well as the hydraulic characteristics of the surrounding aquifer this will be discussed in the next chapter. Most boreholes were highly equipped and the monitoring of the water levels was only conducted on three boreholes. Boreholes BH1, BH5 and BH8 were used with BH8 being closest to the mine compared to the other boreholes. Monitoring of the water levels aided in determining whether the variation in water levels were seasonal or not.

The water level overall has a steady increasing trend and there are no fluctuations in the water level to show any influences on the water levels. There is a significant increase between the months of November 2016 to April 2017 (Figure 7-9). Prior to these months the water levels were low due to little rainfall experienced in area. The area was affected by the drought though it was not as detrimental as other parts of the country. Only a few boreholes ran dry during the dry months.

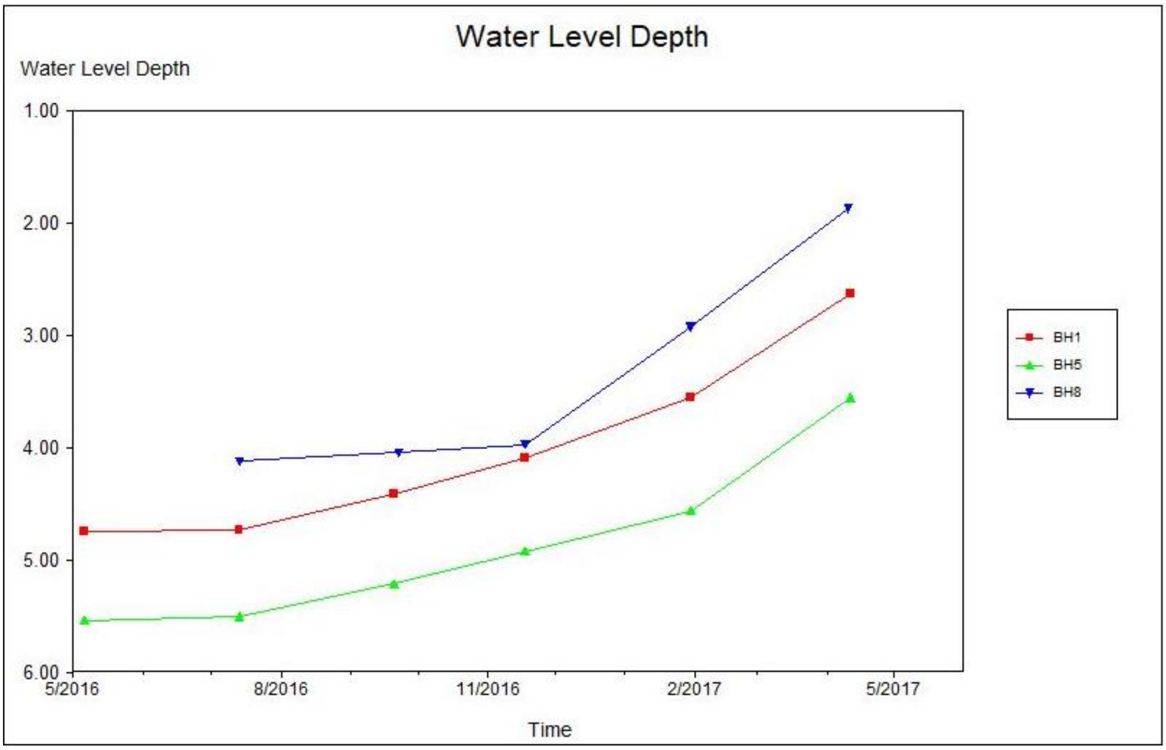


Figure 7-9: Water level of three boreholes during the course of the monitoring programme

7.3.1 Influence of drought

Drought conditions are a result of low rainfall and very high temperatures, resulting in less runoff, low storage levels and loss of soil moisture (DWS, 2012). During the period of the research project the country was experiencing drought with some parts being more affected than others and are still being affected presently.

The region of the study area was also affected by the drought. The water levels of groundwater, dams and flows in rivers are affected by drought. The groundwater in the area was not detrimentally affected by the drought unlike the surface water bodies, streams had dried out during the hot dry months. Late last year the area started experiencing some rainfall and there was an increase in the groundwater levels, and the groundwater was recharged. Figure 7-10, illustrates the impact of drought on the surface water bodies in the study site. Drought conditions are putting pressure on South Africa and are a threat on livestock farming as it diminishes food and water supply (DWA, 2012).

7.3.2 Influence of dewatering

Dewatering can be defined as a process of lowering the water table level at and around a particular contract site. It also refers to the removal of groundwater usually by pumping or evaporation (McKay, 2010). The presence of water in a mine’s pit hinders mining operations. The mining operation at Matsopa Minerals takes place during the dry winter months, this is ideal because the mining can take place effectively.

Since the mine is mining a clay mineral when there is an inflow of water in the pit, the extraction of this mineral is virtually impossible. During the winter months small amounts of rainfall was received and water levels in the pit increased, the mining operations were hindered. Therefore for mining operations to commence dewatering of the water in the pit had to be conducted. There are different methods of dewatering for both open-pit and underground mining that can be used at Matsopa Minerals. The dewatering method used was the simplest type which is the sump pumping (Figure 7-11).

Figure 7-10: The above image shows the dry stream during the months of drought and the image below shows the stream following the drought when the area received rainfall

Figure 7-11: Dewatering of the pit at Matsopa Mine

7.4 CONCLUSIONS

The results of the groundwater quality of the monitoring programme shows that the groundwater in the area is not affected by contamination as a result of mining. Instead high concentrations of nitrate in the groundwater is a result of agricultural activities. The high concentrations of barium that were detected in the geochemical analysis (using XRF techniques) are at below detection limit in the groundwater samples. Therefore the ion is immobile in the surrounding geology. The trend of groundwater levels in the surrounding aquifer is influenced by the seasonal changes. Though the trend shows a steady increase, showing possible recharge this is occurring at a small scale.

CHAPTER 8:
AQUIFER HYDRAULIC PARAMETERS

8.1 INTRODUCTION

Hydraulic characterisation of aquifers are determined by using hydraulic tests. The tests range from slug test to step test and pumping test. A slug test is conducted by submerging a slug of given volume into the borehole and the water in the borehole will be displaced. The slug is then removed and the rate of recovery for the water to return to its original level is measured. From these measurements the aquifer's transmissivity (T) and hydraulic conductivity (k) can be measured. The step test is conducted by increasing the discharge at least twice before the discharge rate is kept constant. The constant pump test is conducted by pumping the borehole at a constant discharge rate and the test should allow for sufficient drawdown. Pumping tests are important tools that provide information on the hydraulic behaviour of a borehole, the reservoir and the reservoir boundaries. In general the objectives of a pumping test are (van Tonder *et al.*, 2001):

- To obtain an understanding of the aquifer,
- To quantify the aquifer's hydraulic and physical properties and,
- To determine the sustainable yield and efficiency of a borehole.

8.2 PUMP TESTING

The pump test was conducted to assess the hydraulic characteristics of the aquifer system. The drawdown against time were measured and the recovery measurements were also measured. The pump test was conducted on a single borehole BH13 and there were no observation boreholes within the vicinity of the mine. The other two boreholes on the property of the mine are not operational and are abandoned. The borehole in which the test was conducted at is generally a shallow borehole with a depth of 22 m. The borehole log data for the specific borehole is not available but the conceptualised understanding of the geology in the mine area is that, the borehole penetrates the different shale layers (mainly micaceous and calcareous shale). The bentonite clay layer which is approximately 13 m which is followed by the dolerite layer that is at a depth of approximately 15 m and this layer is followed by the shale country rock.

8.2.1 Pump test design

The duration of the pumping depends on the type of aquifer and the degree of accuracy desired in establishing its hydraulic characteristics (Kruseman and de Ridder, 2000). A slug test was not conducted in order to determine the suitable abstraction rate because the borehole was highly equipped and a slug could not be submerged into the borehole. Although this is the abstraction rate was kept at constant throughout the test. The equipment used during the test was the Gold level logger to effectively measure the water level during pumping and recovery of the borehole. The level logger was set to take measurements at one minute intervals. The discharge was measured using the Elester discharge rate metering, measurements are given in m^3/hr. The abstraction rate was kept at 9.592 m^3/hr which is equivalent to 2.66 *l/s*.

8.3 RESULTS AND INTERPRETATION

The FC-method (flow characteristic) software was used to interpret the data. The software makes use of different methods such as the Cooper-Jacob which is widely used and the Theis method to determine transmissivity (T) and storativity (S). The measured drawdown in the borehole displays a steady increase of drawdown after 50 min of pumping, Figure 8-1. The temperature also decreases with pumping and reaches a constant state.

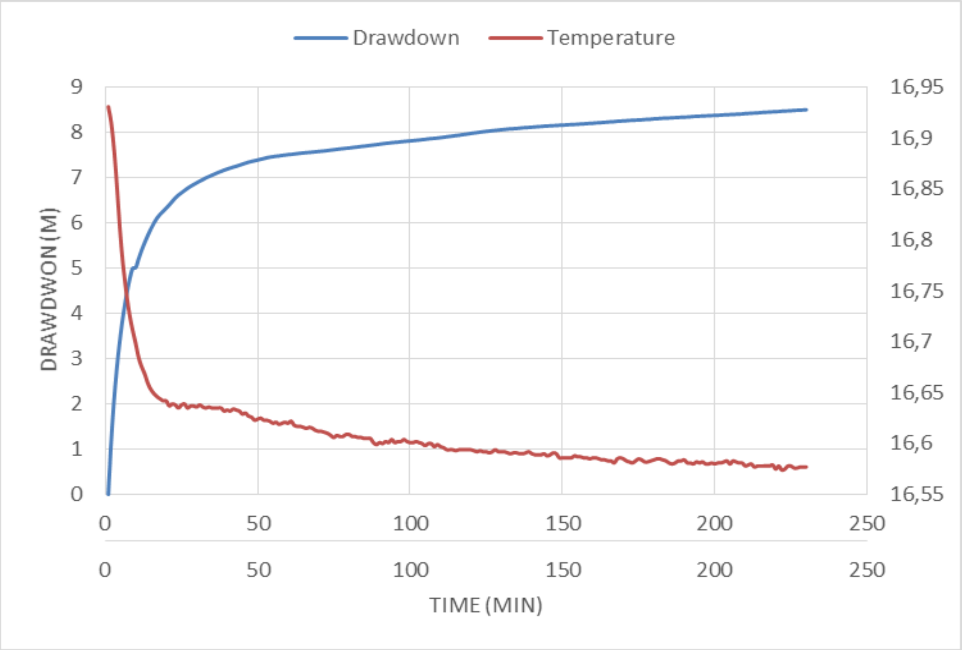


Figure 8-1: Drawdown plot against for pumping well BH13

During pumping a cone of depression will form and the depression will form rapidly as because the water is derived from aquifer storage immediately around the well (Kruseman and de Ridder, 2000). The plot of the drawdown for the duration that the borehole was pumped does not show any recharge source affecting the drawdown. As pumping continues the cone of depression will expand and deepen but at a slower rate. This is because with each additional meter of horizontal expansion larger volume of stored water becomes available (Kruseman and de Ridder, 2000).

8.3.1 Diagnostic plots and derivative flow characterisation

Drawdowns in confined and unconfined aquifers have been analysed by many practitioners using the Cooper-Jacob method, regardless of differences between field conditions and theory (Halford *et al.*, 2006). Diagnostic plots makes use of the semi-log and log-lo plots which can be used for the Cooper-Jacob and Theis methods respectively. The interpretation of diagnostic plots is best suited when the data is separated into different phases; the phases can be the early data which allow for the identification of the presence of wellbore-storage. The intermediate time data are analysed to identify the type of aquifer model that should be used and the late time is used for the identification of the boundaries that are present.

The late time that used shows the characteristic of acting radial flow. Acting radial flow because the data is limited but from the semi-log plot it gives they type of flow that could be encountered. The straight line in the semi-log plot is given between segment B and C at time 70 to 240 min (Figure 8-2). This part of the plot shows acting radial flow.

- Radial flow – appears when the cone of depression is approximately circular. The start of the radial flow indicates the time at which the fractured reservoir behaves as homogeneous (van Tonder *et al.*, 2001).

The log-log plot (Fig 8-3) follows the Theis curve, using this plot to categories the type of aquifer will results in the aquifer being confined aquifer. Relating this to the geology of the area in which the borehole is located it is fitting for the aquifer to be confined because the confining layer that is present is the bentonite clay layer. The drawdown derivative plot aids with the identification of some components that are not visible on the semi-log plots.

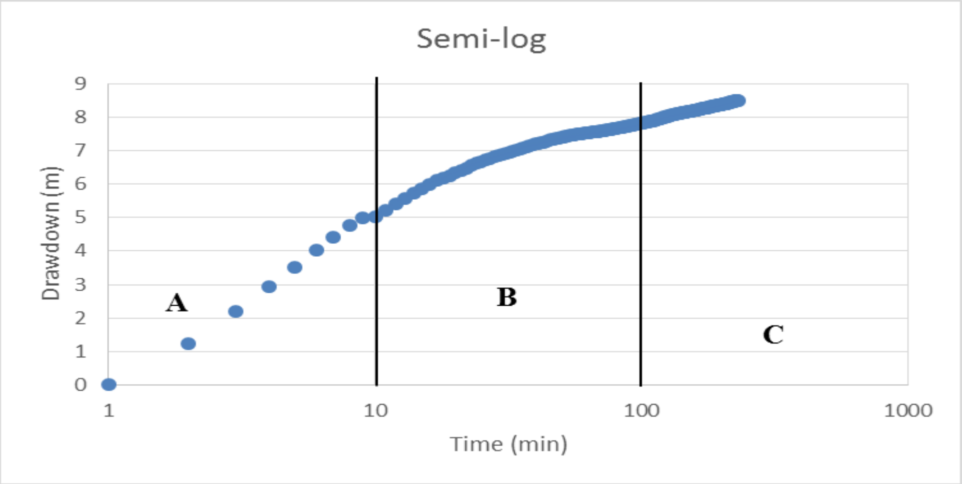


Figure 8-2: Semi-log plot of drawdown data with different segments

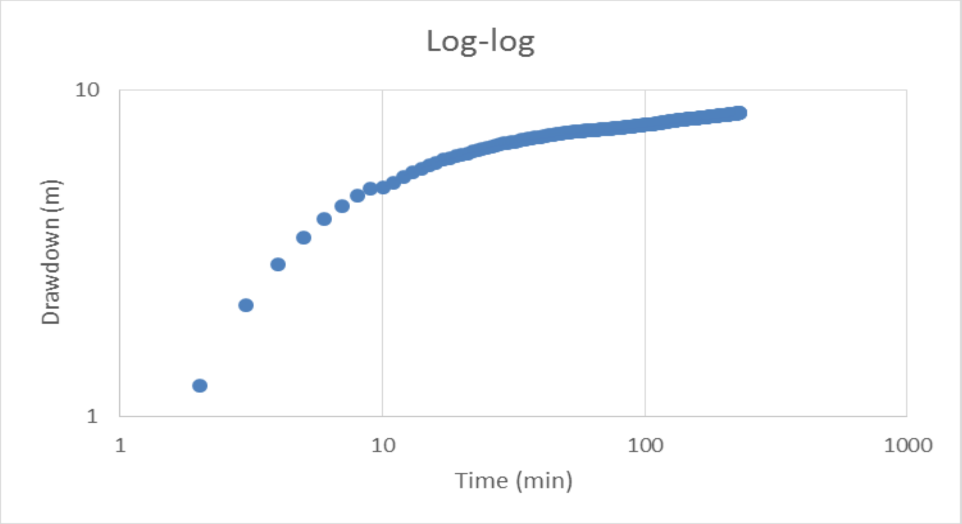


Figure 8-3: Log-log plot of the drawdown data

The derivative plot (Figure 8-4), shows that there is no wellbore storage as seen from the first segment (line represented by A) of the plot. The depression in the first segment between the 8 – 11 min can be indicative of the double porosity. On the second segment, the line represented by C (60 – 90 min) there is flattening of horizontal line of the drawdown, this can be indicative of acting radial flow.

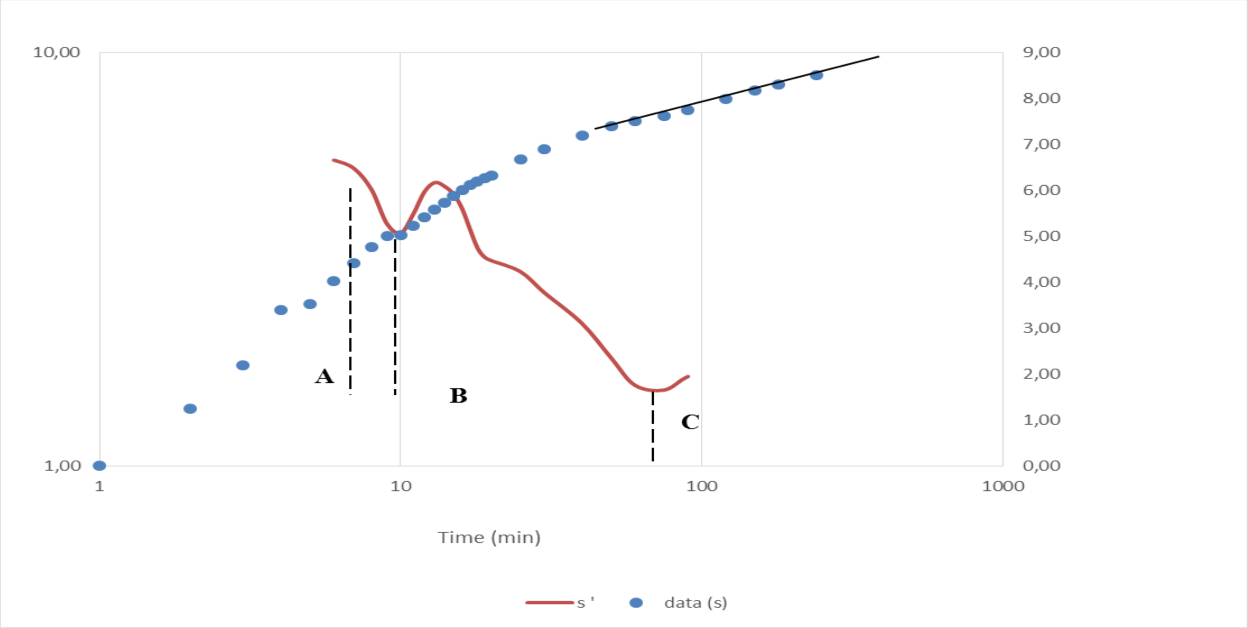


Figure 8-4: Semi-log plot of drawdown with the derivative plot

8.3.2 Recovery

The quality of the recovery data is better than that of the drawdown, as they are not influenced by fluctuations in the pumping rate (van Tonder *et al.*, 2001). The recovery of the borehole took place at a longer duration compared to pumping and the borehole reached full recovery. The advantages of a recovery test stem from its simplicity: (1) a recovery test follows naturally from a pumping test, because it only requires the recording of heads after pumping has ceased; (2) it can be used even when pumping rates are difficult to control; (3) it is fairly inexpensive and no equipment or additional observation wells are required apart from a water-level measuring device; and (4) results are usually not sensitive to well losses. The interpretation of a recovery test is performed by plotting residual drawdown against equivalent time on a semi-logarithmic plot (Willmann *et al.*, 2007). The late time of the recovery residual drawdown is the valid time to be used (Figure 8-5).

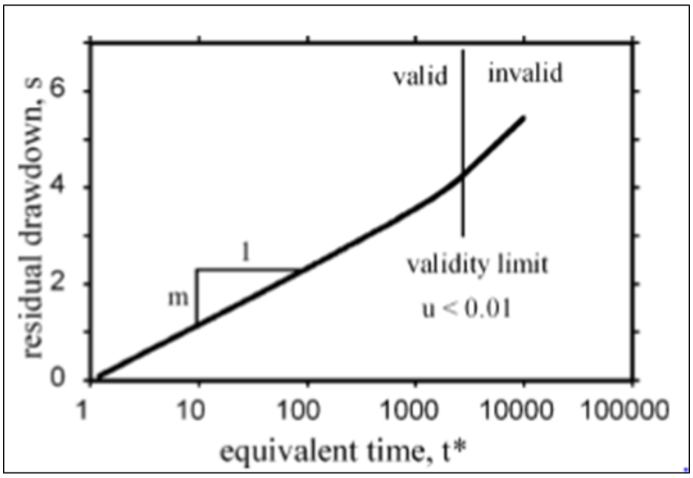


Figure 8-5: Ideal Theis recovery plot showing the valid time to be the late time (source: Willmann *et al*., 2007)

The recovery plot obtained from plotting the data follows the trend of the ideal Theis recovery plot, the red line drawn on the plot of Figure 8-6, represents the late time.

The plot of the recovery residual drawdown data will have a straight line when the aquifer is homogeneous (Samani *et al.*, 2006). From the plot (Figure 8-6) the first segment of the plot deviates from this statement. This is the case because the aquifer is heterogeneous rather than homogeneous. The recovery plot shows radial flow when the late time phase is fitted into the Cooper-Jacob method.

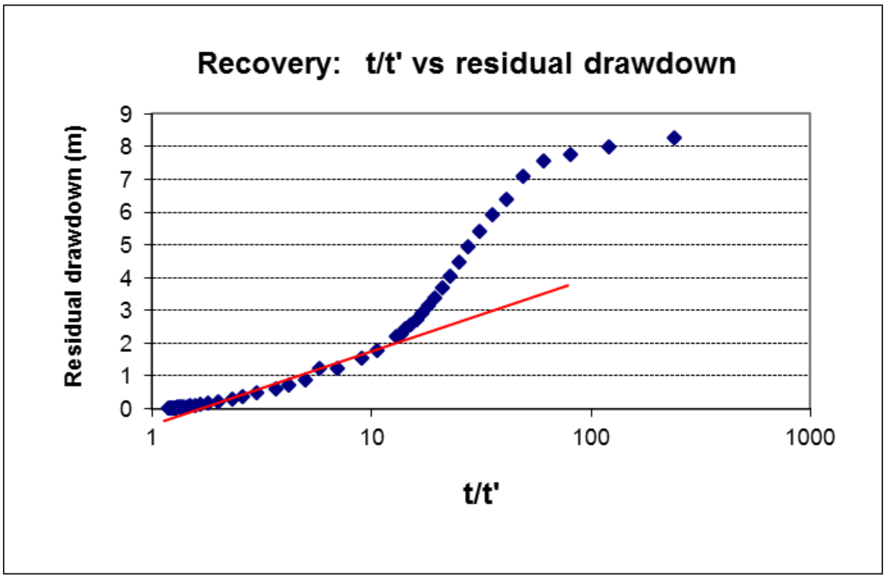


Figure 8-6: Recovery plot of the residual drawdown of BH13

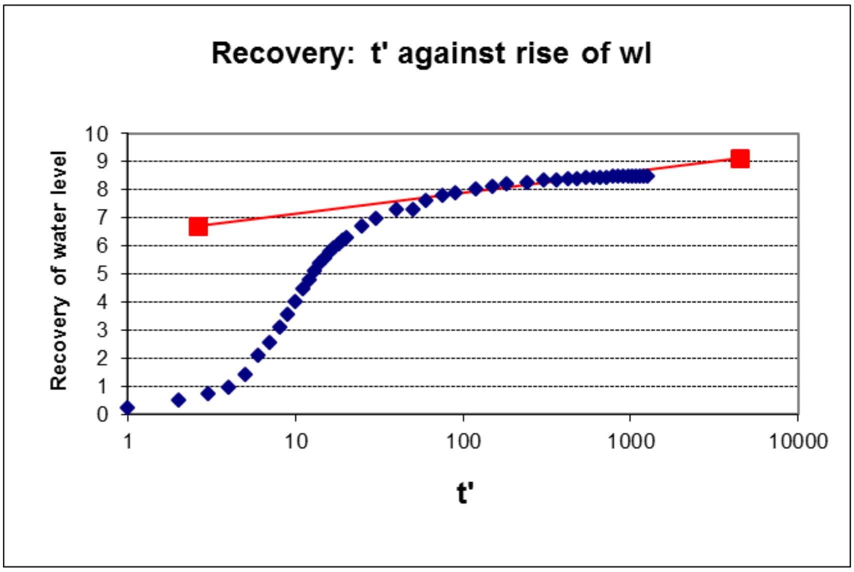


Figure 8-7: Recovery plot of BH13 with straight line fit at late time

8.3.2.1 Aquifer parameters

Aquifer parameters are usually determined using data from a pumping borehole and observation boreholes. Single pumping borehole can be used and the data can be used to determine the transmissivity (*T*). Single-well aquifer tests frequently are analysed with the Cooper-Jacob (1946) method because of its simplicity (Halford *et al*.,2006). The Cooper-Jacob method was used for the transmissivity determination by fitting a straight line on the drawdown of the semi-log plot (Figure 8-4 and Figure 8-7). The transmissivity is calculated by using the formula:

$$T = \frac{2.3Q}{4\pi\Delta s} \tag{7}$$

where Δs is the gradient of the straight line fit on the semi-log plot on the late time phase; *Q* is the constant well discharge (m^3/d); *T* is the aquifer transmissivity (m^2/d); *r* is the distance of the piezometer from the pumped well (m) and *S* is the dimensionless storativity.

$$S = \frac{2.25\,Tt_o}{r^2} \tag{8}$$

The transmissivity can be calculated using a single pumped borehole, the application of the Cooper-Jacob or Theis method to the radial acting flow phase of the recovery data, gives the *T*-value of the formation (van Tonder *et al.*, 2001). Whereas the storativity cannot be calculated by using a single well, observation wells are needed to get storativity that is representative the aquifer. The drawdown *T*-value for BH13 was estimated to be 24.7 m^2/d;

while the recovery *T*-value was 56.8 m^2/d. The storativity of the aquifer can be estimated by using the storativity values for different aquifer types that were estimated in Table 8-1.

Table 8-1: Storativity values for different aquifer types (source: van der Voort, 2001)

Aquifer type	**S value**
Fractured hard rock	1×10^{-3}
Karoo fracture rock	3×10^{-3}
Table Mountain Group	8×10^{-3}
Dolomite	1×10^{-2}
Porous	1×10^{-1}

8.4 CONCLUSION

The drawdown data was useful and correlated with the recovery data, as far as the type of flow encountered in the aquifer. Which resulted in acting radial flow. The recovery data is more reliable because it is the natural recovery without any influence or disturbance from pumping. Therefore the transmissivity value of the recovery is more representative to the aquifer. The *T*-value indicates that the aquifer is a good transmissible aquifer. In relation to the geological unit the aquifer is composed of, there is a possibility that the aquifer is a fractured aquifer for the *T*-value to be at that value.

CHAPTER 9:
CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

The main aim of the study is to investigate the impact of mining at Matsopa Minerals on the surrounding aquifer in the area. To determine the current groundwater conditions especially the quality, for its suitability for present and future use. To address the aim of the research project the following objectives were identified:

- To determine the current groundwater quality in the vicinity of the mine as well as on the adjacent properties,
- To investigate the use of groundwater at the mine and on the adjacent properties,
- To detect and delineate geological structures that may influence groundwater migration and contaminant transport in the subsurface by using geophysical methods,
- To investigate the hydraulic properties of the aquifer system to allow insight into the expected rate of groundwater flow, and,
- To determine the mineralogical character of the geology of the area to predict which minerals and elements could potentially affect the groundwater quality,
- To assess the risks posed by mining at Matsopa Minerals on the groundwater environment, and to make recommendations to reduce these risks.

In order to know whether there was any alteration to the quality of groundwater, determining the background water quality would be very useful. Defining the background water quality requires a collection of water samples from undisturbed streams or groundwater where there is no human activity like mining taking place. Drilling of boreholes in and around the mine area where mining has not taken place did not happen due to financial constraints therefore the background water quality was not determined. The groundwater risk assessment plan was the approach of the research project. The different objectives were treated by having deliverables to address each objective set out.

9.1.1 Hydrocensus

The hydrocensus survey was conducted and from the results the following was concluded:

- The identification of sites for geophysical investigations to be carried out;
- Possible sources of contamination during site walks were identified and some of the data collected aided in selecting monitoring boreholes;
- Creating groundwater flow maps to indicate the flow direction of contaminants;
- The use of groundwater is for domestic use, irrigation and livestock watering.

9.1.2 Geophysical investigations

The geophysical investigations aided with the following conclusions:

- The methods employed provided a good contrast between the sedimentary country rock and the igneous intrusive rock;
- The intrusive rock was identified as dolerite sill along the boundaries of the mine and along the boundaries of the active pit dolerite dykes were identified;
- The ERT and magnetic methods aided in the identification of possible pathways for groundwater through fractures; fissure; cracks and joints that formed during intrusion;
- The pathways not only allow for the transmission of groundwater but also for contaminants;
- The velocity in which contaminants or groundwater flows in fractures is higher than when the flow is from the pore spaces in a primary aquifer.

9.1.3 Geochemical investigations

The analysis of the geochemistry of the geological material aided with the following conclusions:

- The analysis of different geological materials were undertaken, XRF and XRD techniques were employed;
- The mineralogical, major and trace ions compositions of the material were identified;
- The purpose of the investigation and determination of the composition of the material was to determine whether the ore and gangue material were potential sources of contamination;

- The bentonite ore material was determined to not contain any material that have the potential to contaminate the groundwater;
- Barium concentrations in the overburden and stockpiled material from the XRF results occurred at high concentrations;
- Once the material is in the stockpile and is exposed to atmospheric conditions the barium concentrations increased further. The ion may pose a threat to the groundwater should it be leached out into the groundwater system.

9.1.4 Groundwater monitoring

Groundwater monitoring was conducted, from the results the following was concluded:

- The environment and the people who live in and around the study area, are potential receptors of contaminated water;
- Therefore monitoring of groundwater quality was conducted to assess the changes in groundwater quality, and whether the groundwater quality meets the required drinking water standards;
- The groundwater is dominated by Ca^{2+}-Mg^{2+}-HCO_3^- water which represents recently recharged water and some boreholes are dominated by Ca^{2+}-Mg^{2+}-$SO4^2$-Cl and this is result of domestic waste;
- As result of high concentration of barium in the geology, concerns for high concentrations of barium in the groundwater were raised. The monitoring of the groundwater aided in determining that the barium in the groundwater is within the required drinking water standards;
- Nitrate concentrations were found to be high in some borehole and was persistent in some of these boreholes;
- The source of high concentrations of nitrate is a result of agricultural activities taking place in the area. The use of fertilizers on farms has a great impact on the nitrate concentration;
- The mine’s borehole has also been contaminated with nitrate as well. This phenomenon is a result of the flow of the contaminated groundwater from the surrounding farm that has had persisting nigh nitrate concentrations. The farm is at a higher elevation to the

mine, therefore the contaminated water should it follow the topography will flow from farm (with BH11 and 12) to the mine (BH13). Figure 3-7 shows the flow of the groundwater to be from the farm of BH11 and BH12 towards the mine.

9.1.5 Hydraulic characterisation

Hydraulic test was conducted and the following conclusions were deduced from the available data:

- The drawdown data was not conclusive due to the limited duration of pumping. The recovery data was more reliable and more of a true representation of the aquifer;
- Though the drawdown data was limited some characteristics of the aquifer like the flow characteristic of the aquifer could be identified. The deductions made from the drawdown data coincided with that made from the recovery data with regards to the flow regime of the aquifer;
- The transmissivity of the recovery is a true representation of the aquifer. The T value is high and in the order of 10^1;
- The value of the T is high in a confined aquifer of low permeability (shale being the host rock) and this is the result that the aquifer is a typical fractured aquifer of the Karoo Supergroup.

Following the risk assessment of potential contamination of the groundwater, it can be deduced that there are pathways for contaminants, receptors of the contaminated groundwater. From the results obtained there is no contamination of groundwater as result of mining activities taking place in the study area. Agricultural activities on the other hand has had a negative impact on the groundwater. The groundwater has been contaminated with high concentrations of nitrate.

The current groundwater conditions at Matsopa Minerals and surrounding area are permissible especially for cattle watering and irrigation. For domestic use, especially drinking water the current conditions in some parts of the study area the water is permissible. While other farms and the mine itself have persisting elevated concentrations of nitrate, which might be harmful to infants and some individuals might have increased exposure to methemoglobinemia. The groundwater can be used presently and in future but monitoring and treatment of the nitrate should be conducted. The treatment is necessary to secure the quality of the water for human consumption.

9.2 RECOMMENDATIONS

Overall recommendations were reached from the body of work that was done and following the conclusions that were deduced. These recommendations are as follows:

- Monitoring of groundwater should be continued not only by the mine but by the surrounding farmers as they too makes use of the groundwater as portable water for domestic use and livestock watering;
- It would be recommended that monitoring should also be continued post closure of the mine. Reason being the presence of high barium in the geology of the area might be pose a threat in future should the conditions permit for the leaching of barium into the groundwater system;
- The nitrate in the groundwater can be removed by the following methods:
    - Ion exchange or desalination (removal of all salts from the water by use of reverse osmosis)
    - Biological denitrification (reducing nitrate to nitrogen gas)
- A model can be developed to estimate the extent in which the nitrate contaminated groundwater will spread in the groundwater system (especially in a fractured system) should contamination continue to persist. The model will aid in determining the duration it will take for the contamination to spread in the groundwater system of the entire area;
- It is recommended that further hydraulic tests should be conducted with the availability of observation boreholes to further understand the nature of the aquifer system extensively. Therefore more boreholes should be drilled as there is one borehole used without any observation boreholes on site.

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ABSTRACT

This dissertation investigates the possible contamination of the groundwater environment as result of the mining of a bentonite body at Matsopa Minerals. The study is crucial because the community in the area solely depends on groundwater for domestic use as well as livestock watering. A number of investigations were carried out, namely: 1) a hydrocensus to investigate the water use, groundwater flow direction, number of boreholes in use and surface water points, 2) geophysical investigations to investigate the presence of geological structures that act as groundwater conduits, 3) geochemical investigations of the ore and host rock to determine the character potential contaminant impacts, 4) groundwater monitoring to determine whether mining has impacted on the groundwater quality, and 5) aquifer hydraulic testing to determine the hydraulic parameters of the aquifer system.

The results obtained from the hydrocensus show that the groundwater is used for domestic use, livestock watering and irrigation, on a number of farms surrounding the mine. From the electrical conductivity (EC) profiling done on two boreholes, one borehole was determined to be sited on a fractured aquifer system.

The geophysical investigations were conducted using two methods, namely: the magnetic and electrical resistivity tomography (ERT) methods. Both methods revealed the presence of dolerite structures adjacent to and in the vicinity of the mine and the opencast pit. These structures are likely to be associated with fractures, joints, cracks and fissures which form preferential pathways for groundwater transmission.

Geochemical investigations were carried out by using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The methods showed that both the ore and host are dominated by SiO_2. The trace elements that could pose a threat to the environment or human health occur at low concentrations.

Groundwater monitoring was conducted on a bimestrial basis. The groundwater was found to be with little or no evidence of contaminant impacts from mining. Elevated nitrate concentrations were found in the hydrochemistry analysis from the surrounding farms as result of agricultural activities. During the monitoring events groundwater levels were recorded in the boreholes of the surrounding farms, there was increasing levels in the groundwater. This showed that recharge of the groundwater system was taking place as result of higher rainfall experienced as compared to the preceding years.

A hydraulic test was conducted on the aquifer system by performing a pump test to obtain aquifer parameters and flow characteristics. Transmissivity (*T*) measurements were obtained from recovery data and the flow regime determined was the acting radial flow regime. The storativity could not be calculated because the pump test was conducted on single well with no observation boreholes. The *T*-value obtained showed that the aquifer is a good groundwater transmissive aquifer.

The results of the studies have indicated there has not been significant detrimental impact on the groundwater environment as result of the bentonite mining at Matsopa Minerals. The groundwater contamination found in the area is the result of agricultural activities with high nitrate concentrations above the regulated standard limits. The nitrate can be treated by using any of these processes: reverse osmosis and biological denitrification.

APPENDIX A

HYDROCENSUS TABLE

BH No.	Coordinates	SWL (mbgl)	Collar (magl)	Water level (mbgl)	Depth (mbgl)	Owner	Farm	Water Use	Reported Yield (l/day)	Sample Taken	Pump Type
BH1	S 27.16344˚ E 27.58862˚	3.3	0.11	3.19	13	PW Loggenburg	Geluk 237 Ptn RE	Domestic		Yes	Submersible
BH2	S 27.16400˚ E 27.58770˚	Equipped/ no access				PW Loggenburg	Geluk 237 Ptn RE	Not in use	N/A	No	Windmill
BH3	S 27.16326˚ E 27.59047˚	Equipped/no access				PW Loggenburg	Geluk 237 Ptn RE	Not in use	N/A	No	Windmill
BH4	S 27.16279˚ E 27.58905	Equipped/no access				PW Loggenburg	Geluk 237 Ptn RE	Not in use	N/A	No	Submersible
BH5	S 27.16558˚ E 27.58503˚	4.58	0.21	4.37	24	Hannes Loggenburg	Verdeel 278 Ptn RE	Domestic		Yes	Submersible
BH6	S 27.16584˚ E 27.58534˚	Equipped/no access				Hannes Loggenburg	Verdeel 278 Ptn RE	Not in use	N/A	No	Windmill
BH7	S 27.14671˚ E 27.60759˚	Equipped/no access				Dawie Herbst	Vrede 450 Ptn RE	Domestic		Yes	Windmill
BH8	S 27.14588˚ E 27.60645˚	Equipped/no access				Dawie Herbst	Vrede 450 Ptn RE	Domestic		Yes	Submersible
BH9	S 27.14750˚ E 27.60776˚	Equipped/no access				Dawie Herbst	Vrede 450 Ptn RE	Livestock, garden irrigation		Yes	Motor pump
BH10	S 27.14288˚ E 27.62446˚	Equipped/no access				Hannes van Rooy	Huttinghs Rust 68 Ptn RE	Domestic & livestock	N/A	Yes	Submersible
BH11	S 27.12481˚ E 27.66716˚	Damaged/no access				Leeb Ludwig	Sahara 139 Ptn RE	Not in use	N/A	No	Open hole
BH12	S 27.12182˚ E 27.66635˚	Equipped/no access				Leeb Ludwig	Sahara 139 Ptn RE	Domestic	N/A	Yes	Submersible
BH13	S 27.12739˚ E 27.62319˚	Equipped/no access				Matsopa Minerals	Blaawbospoort 13 Ptn RE	Domestic	N/A	Yes	Submersible
BH14	S 27.12843˚ E 27.62589˚	Damaged/no access				Matsopa Minerals	Blaawbospoort 13 Ptn RE	Not in use	N/A	No	Open hole
BH15	S 27.12304˚ E 27.61025˚	Damaged/no access				Matsopa Minerals	Blaawbospoort 13 Ptn RE	Not in use	N/A	No	Windmill

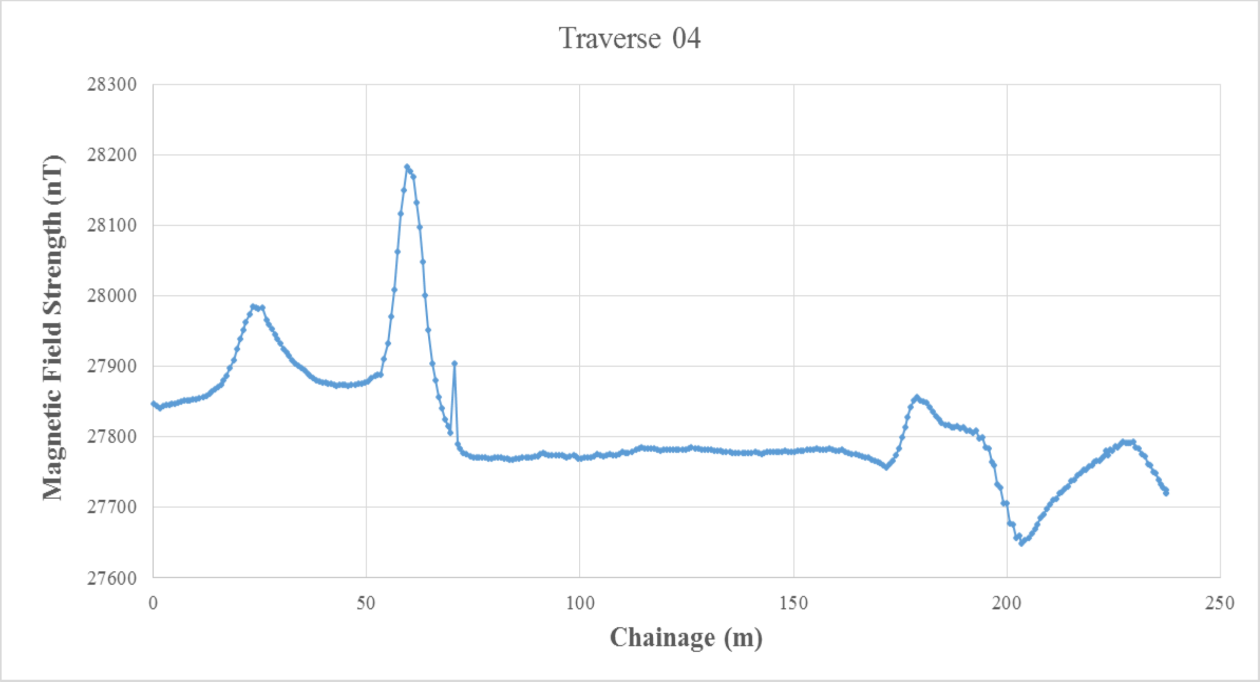
BH16	S 27.13051˚ E 27.62589˚	Equipped/no access	Matsopa Minerals	Blaawbospoort 13 Ptn RE	Not in use	N/A	No	Borehole
BH17	S 27.08594˚ E 27.58775	Equipped/no access	Leon Loggenburg	Oceaan 64 Ptn RE	Domestic	N/A	Yes	Submersible
BH18	S 27.08732˚ E 27.58920˚	Equipped/no access	Leon Loggenburg	Oceaan 64 Ptn RE	Domestic, livestock	N/A	Yes	Submersible

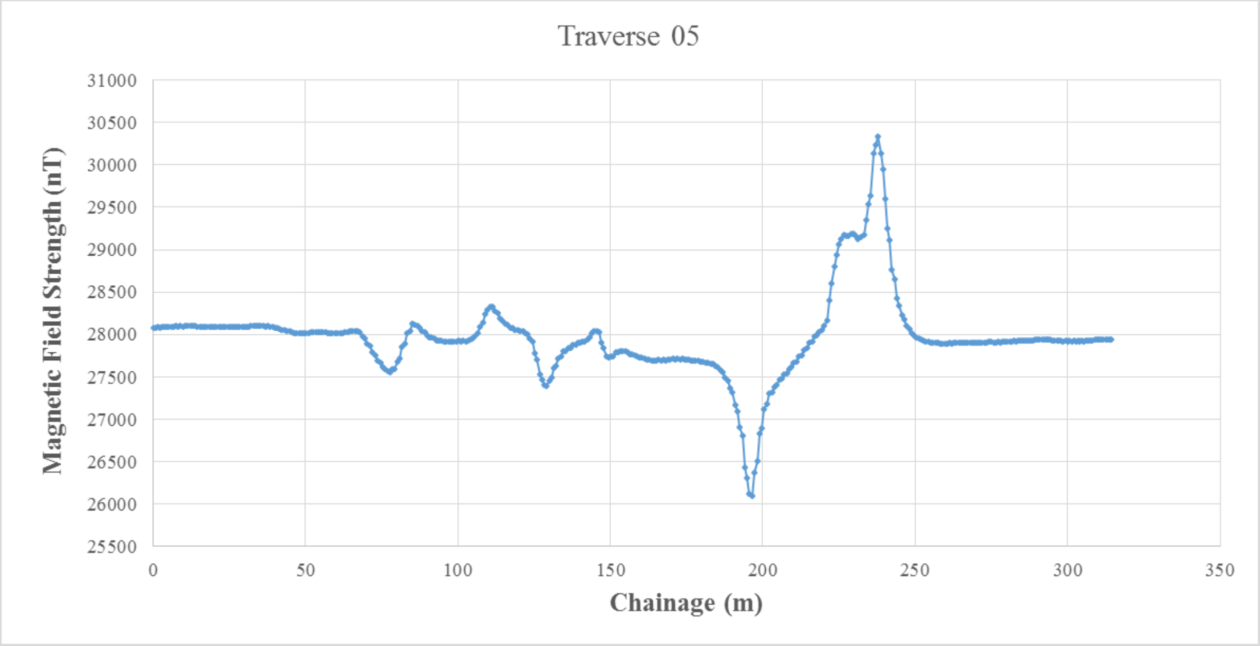
SP No	Coordinates	Ec (mS/m)	pH	ORP	Temperature (˚C)	Sample Taken	Type of SP
SP1	S 27.08748˚ E 27.58923˚	510	8,06	64	30,9	Yes	Stream
SP2	S 27.14829˚ E 27.60622˚	1230	7,92	137	31,4	Yes	Stream
SP3	S 27.12569˚ E 27.62163˚	380	8,62	56	22,8	Yes	Dam
SP4	S 27.10609˚ E 27.60283˚	650	8,2	108	31,8	Yes	Wetland
SP5	S 27.16529˚ E 27.5894˚	1240	6,68	185	24,3	Yes	Stream

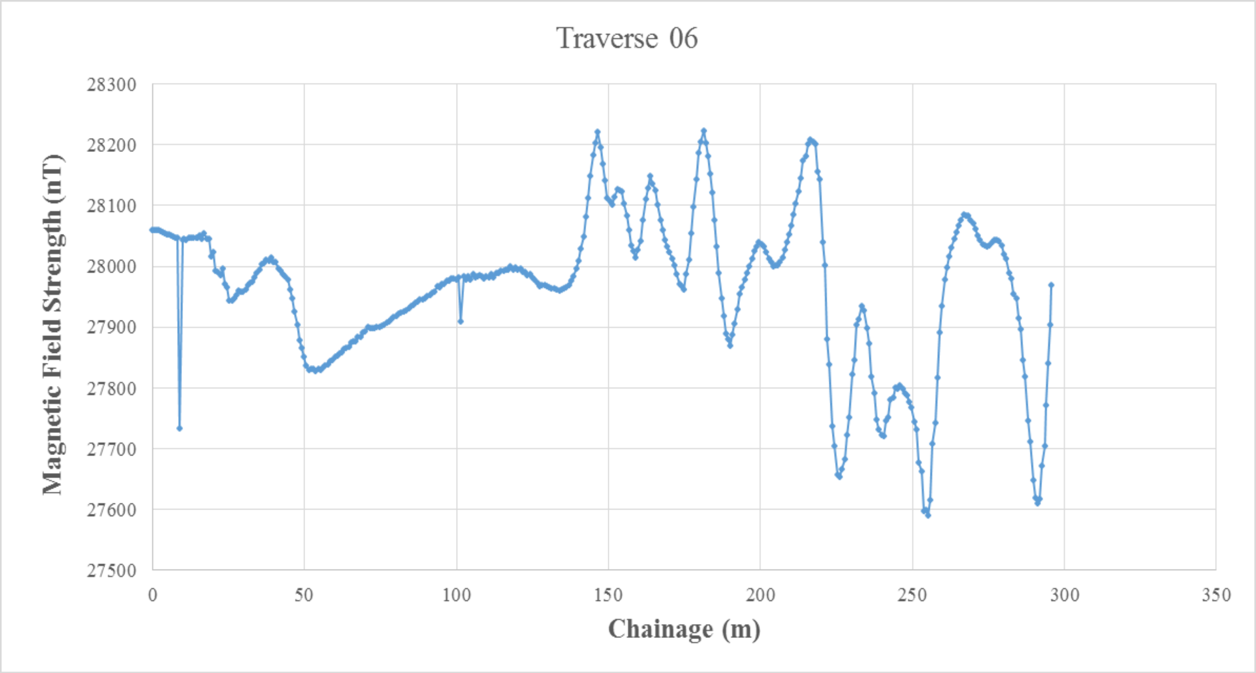
APPENDIX B

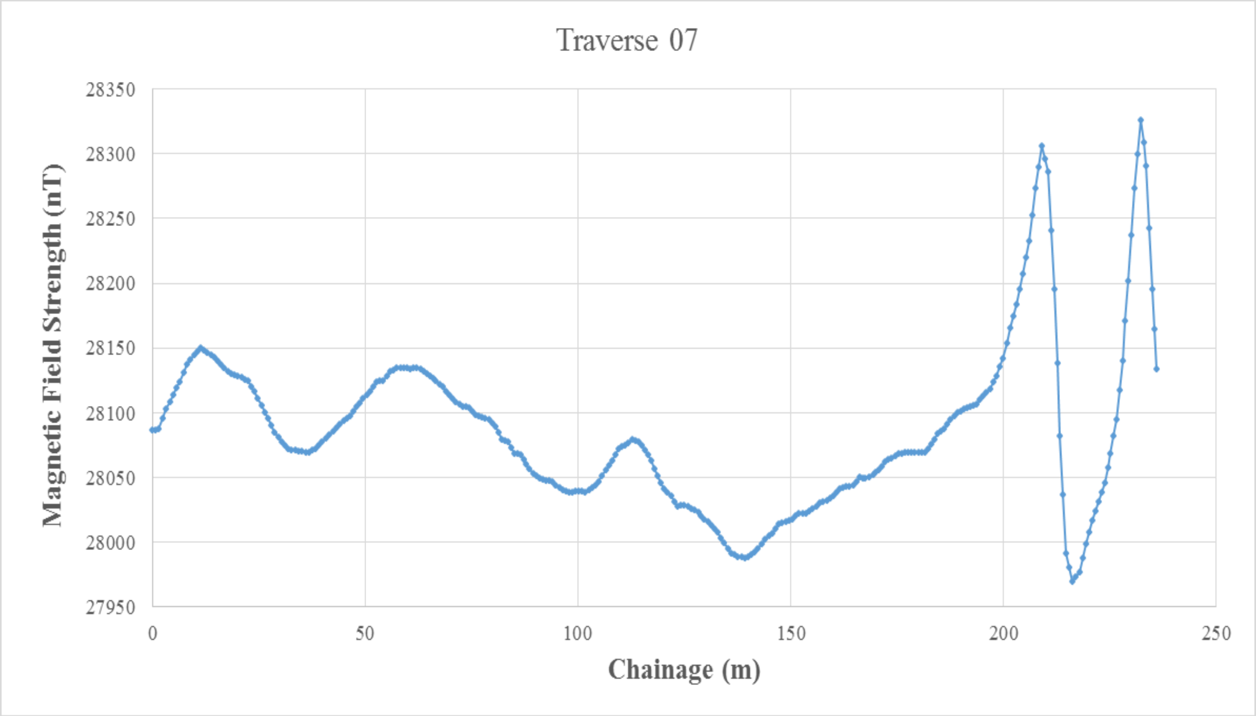
MAGNETIC SURVEY PROFILES

PROFILES OF WESTERN BOUNDARY






Traverse 06
Magnetic Field Strength (nT)
28300
28200
28100
28000
27900
27800
27700
27600
27500
0
50
100
150
200
250
300
350
Chainage (m)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Magnetic Field Strength (nT)
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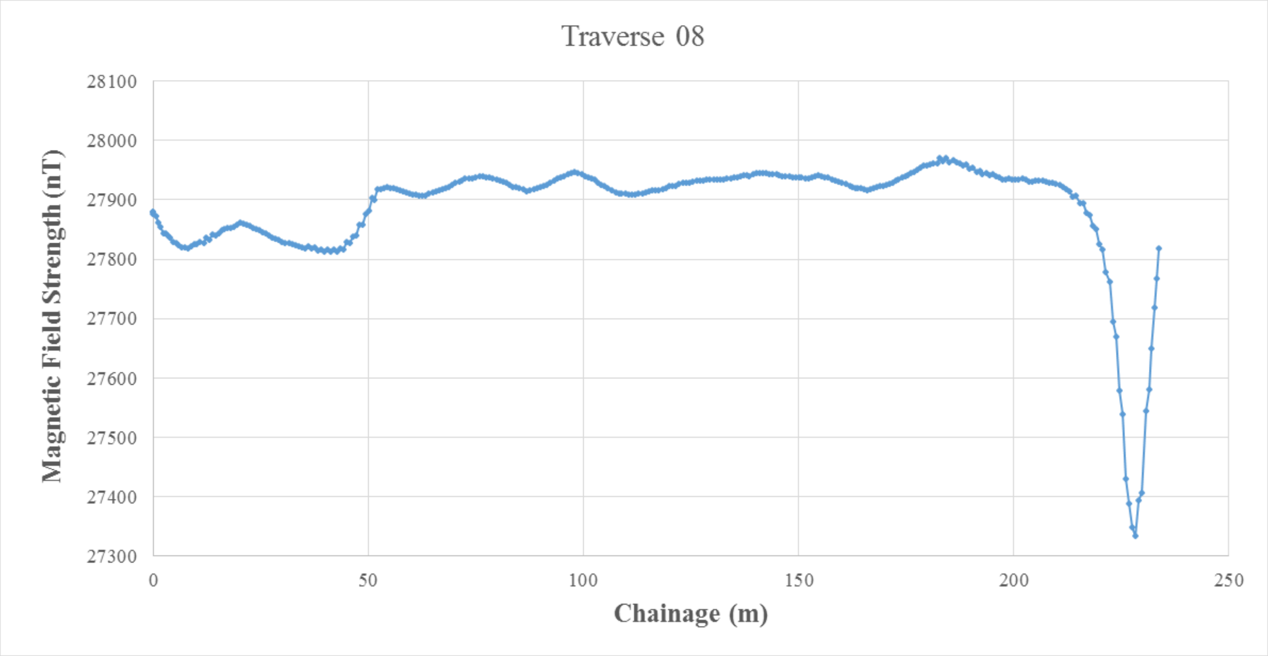
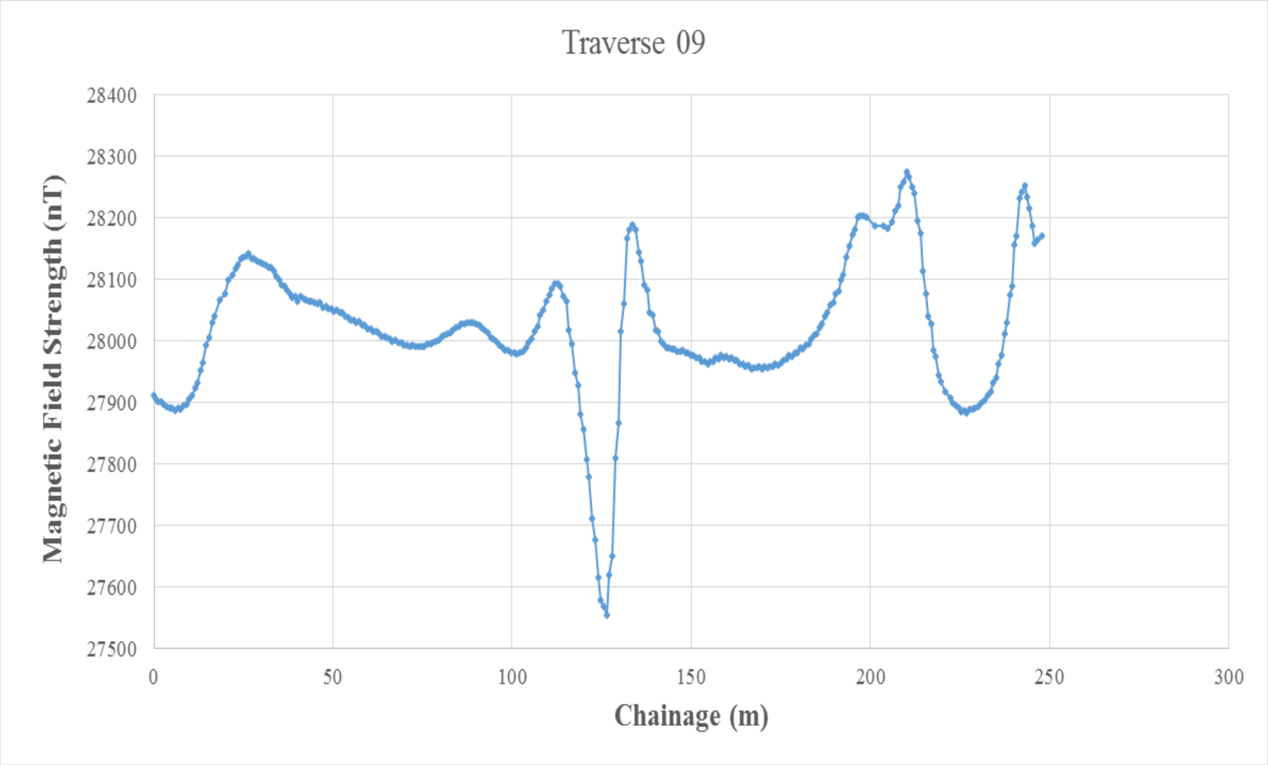
28300
28250
28200
28150
28100
28050
28000
27950
0
50
100
150
200
250
Chainage (m)


Traverse 08
Magnetic Field Strength (nT)
28100
28000
27900
27800
27700
27600
27500
27400
27300
0
50
100
150
200
250
Chainage (m)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Magnetic Field Strength (nT)
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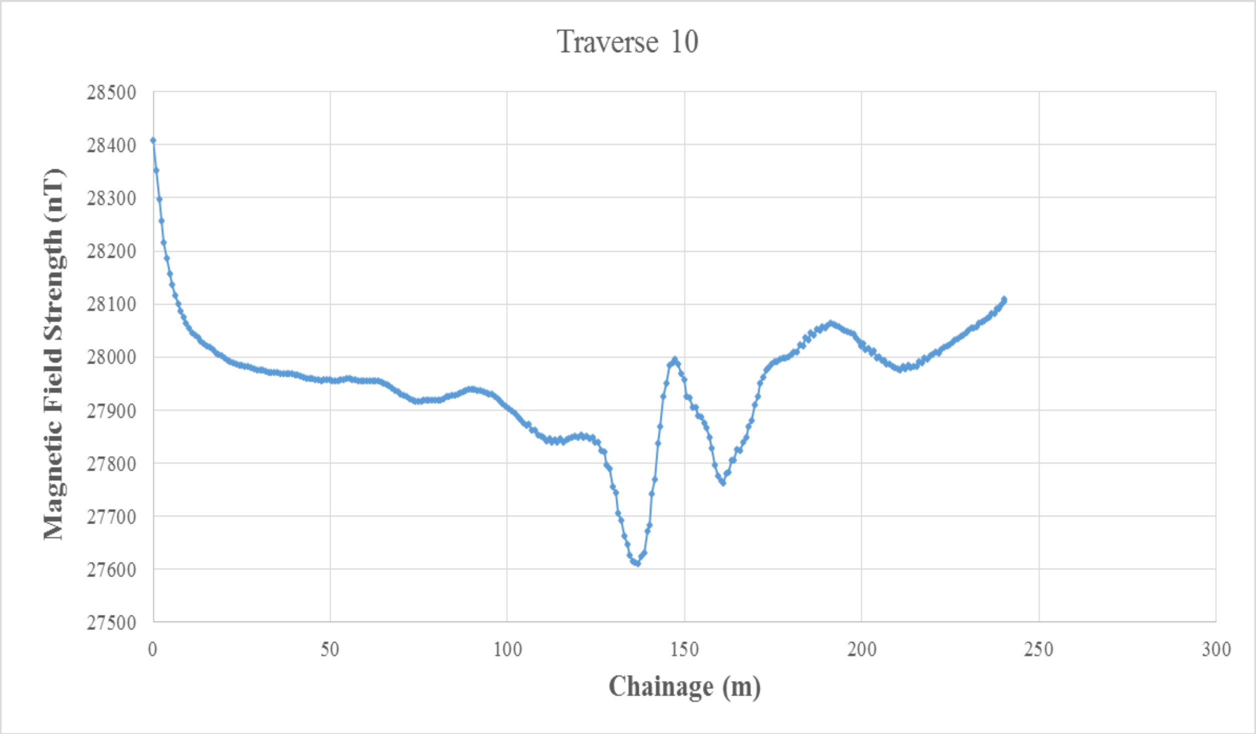
28300
28200
28100
28000
27900
27800
27700
27600
27500
0
50
100
150
200
250
300
Chainage (m)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Magnetic Field Strength (nT)
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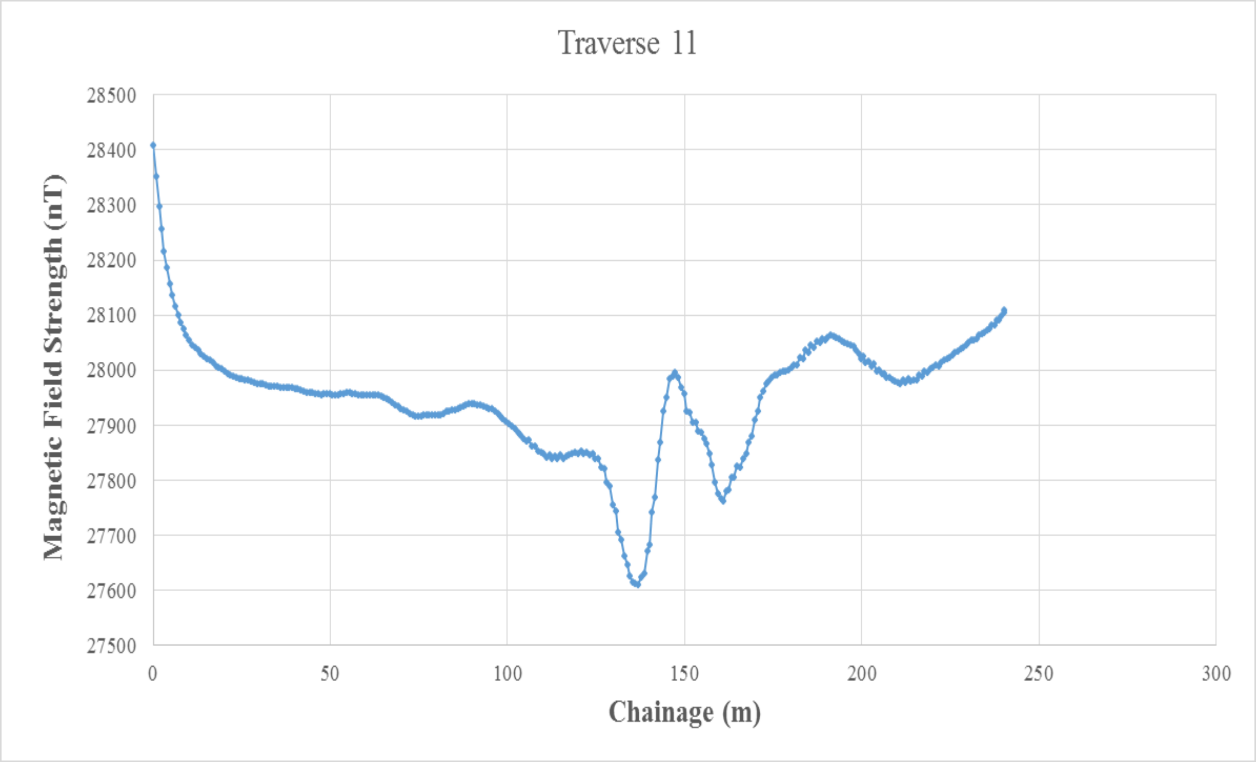
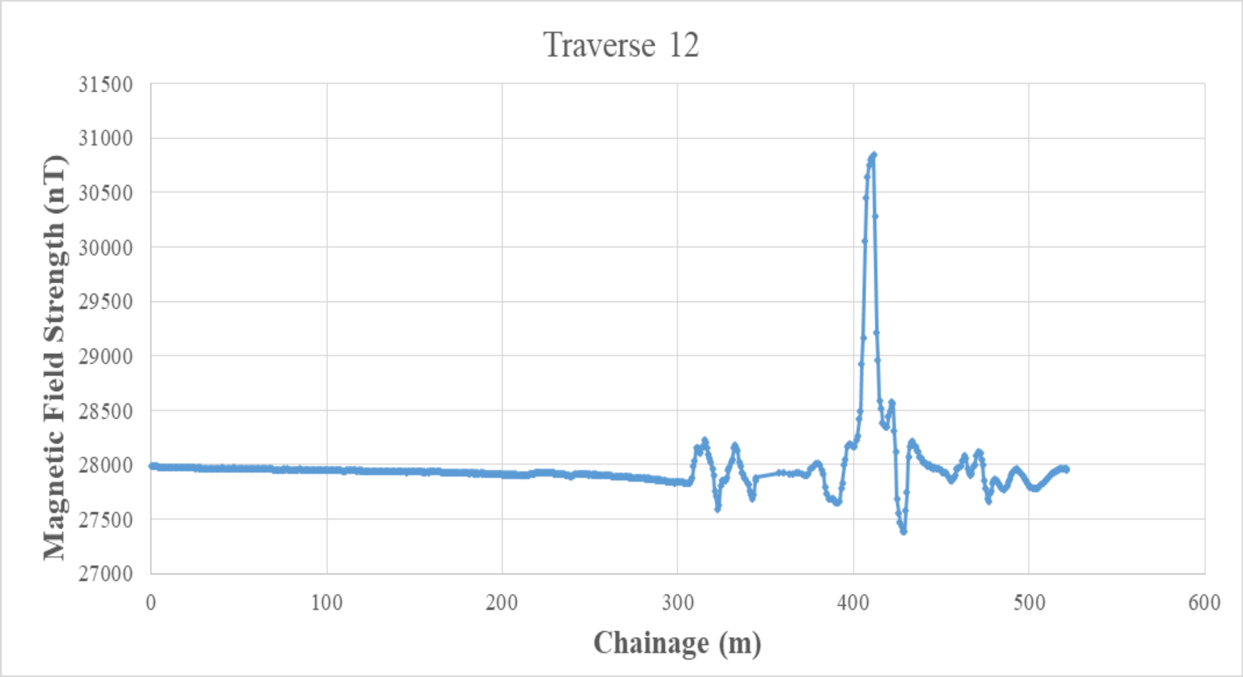
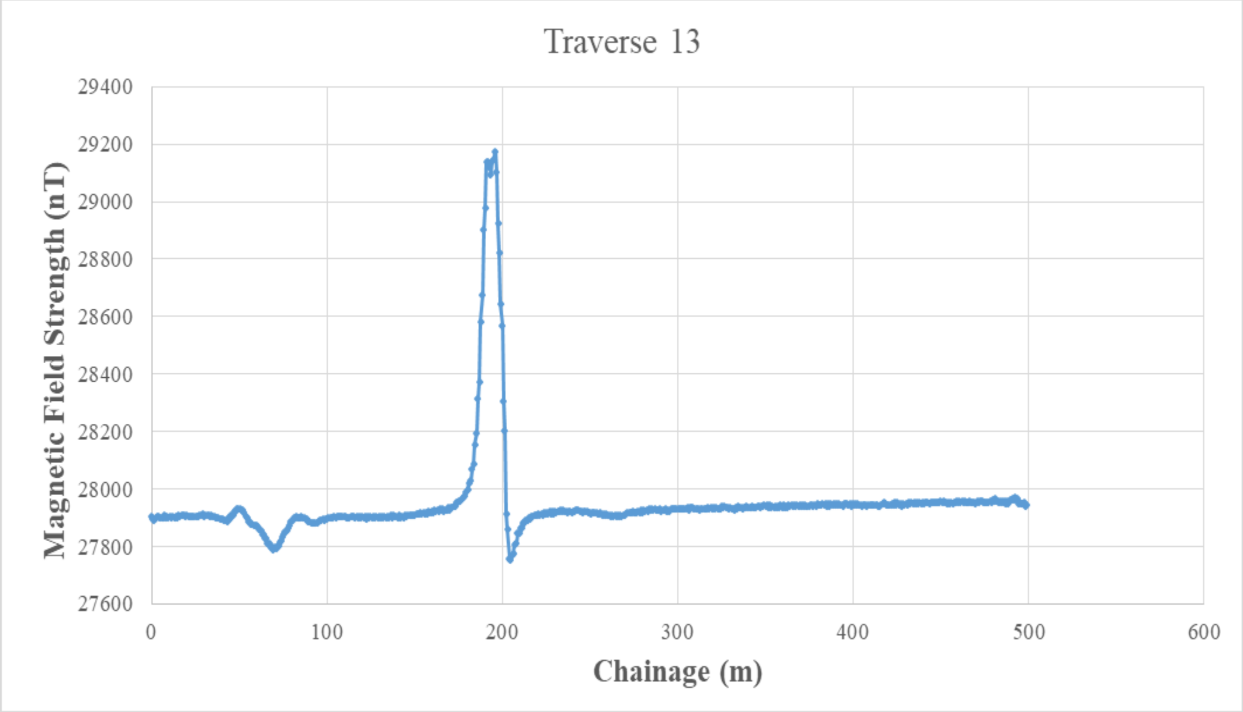
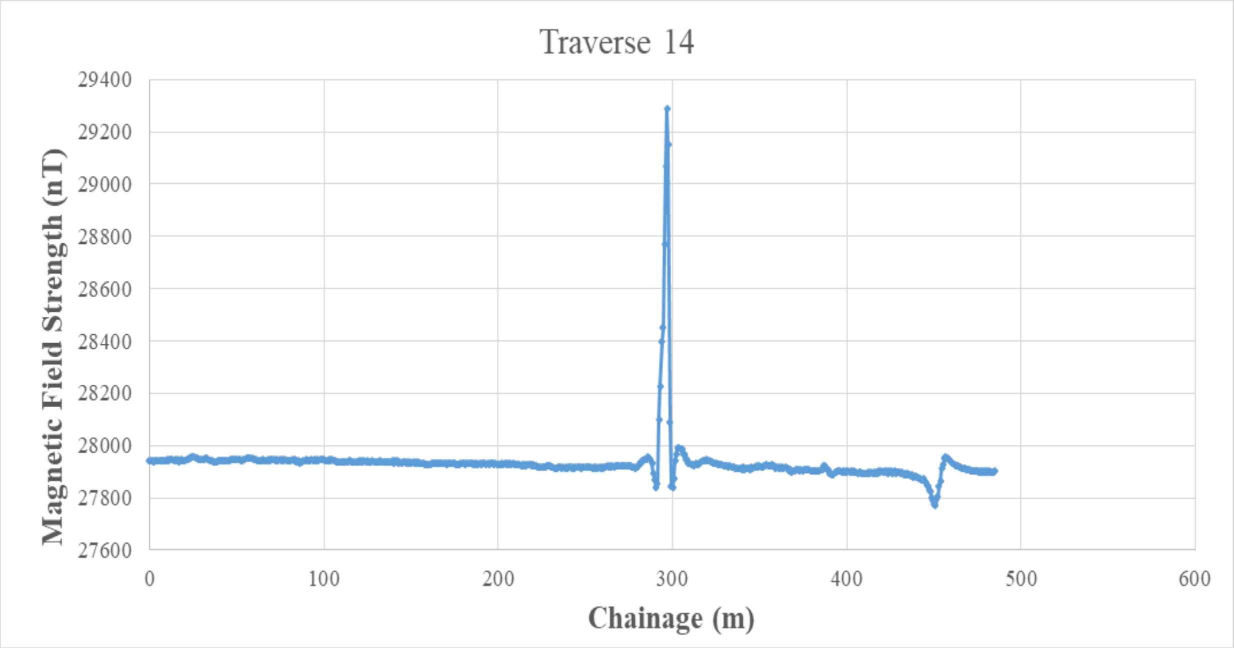
28400
28300
28200
28100
28000
27900
27800
27700
27600
27500
0
50
100
150
200
250
300
Chainage (m)


Traverse 11
Magnetic Field Strength (nT)
28500
28400
28300
28200
28100
28000
27900
27800
27700
27600
27500
0
50
100
150
200
250
300
Chainage (m)

PROFILES OF EASTERN BOUNDARY



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Magnetic Field Strength (nT)
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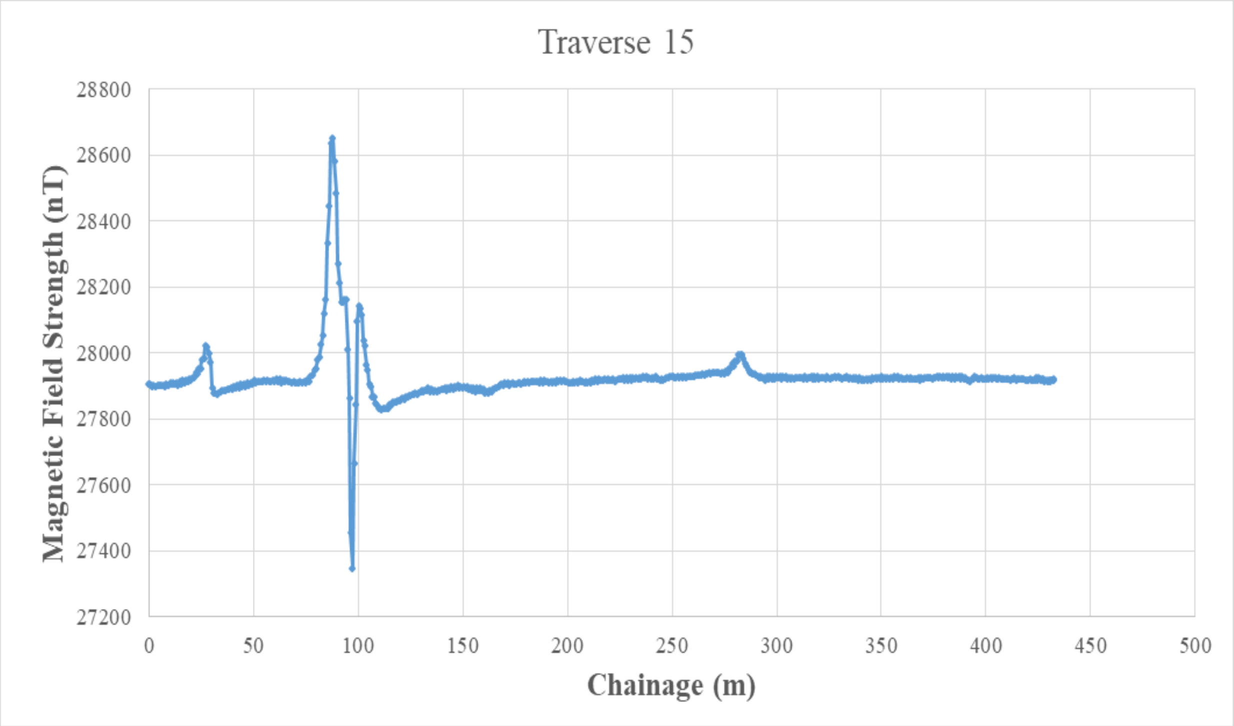
29200
29000
28800
28600
28400
28200
28000
27800
27600
0
100
200
300
400
500
600
Chainage (m)


Traverse 15
Magnetic Field Strength (nT)
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28400
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28000
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27400
27200
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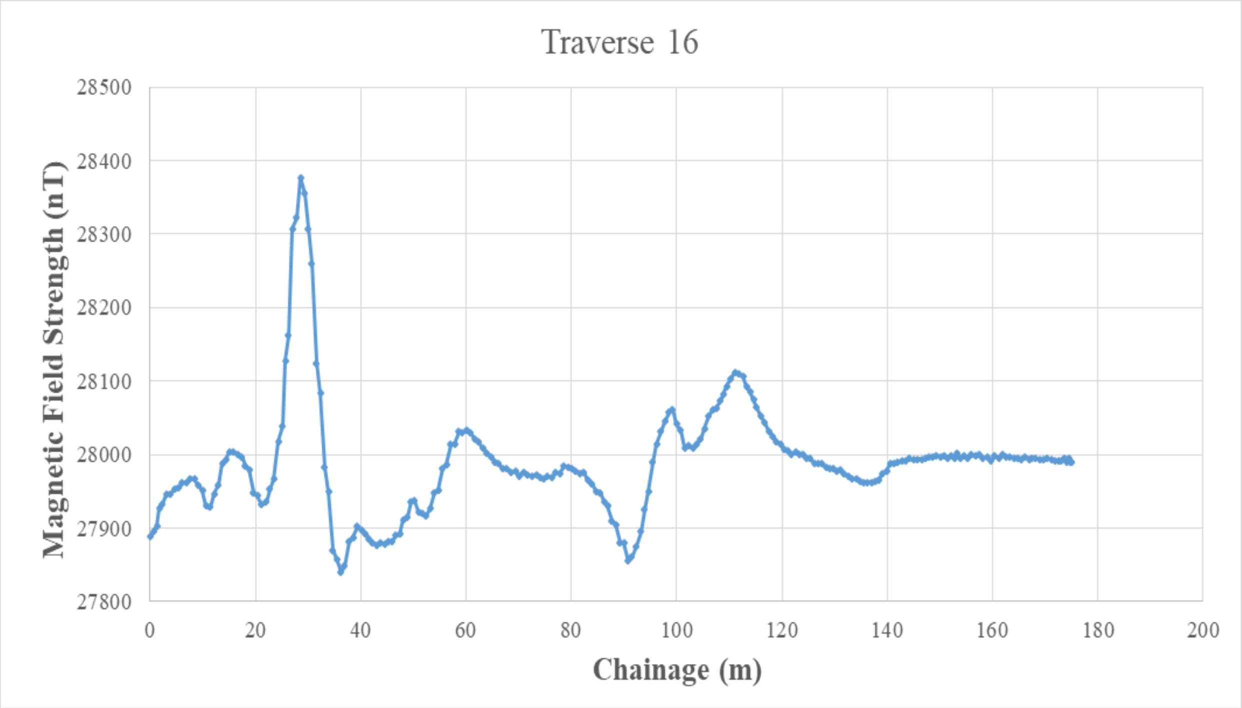
50
100
150
200
250
300
350
400
450
500
Chainage (m)


Traverse 16
Magnetic Field Strength (nT)
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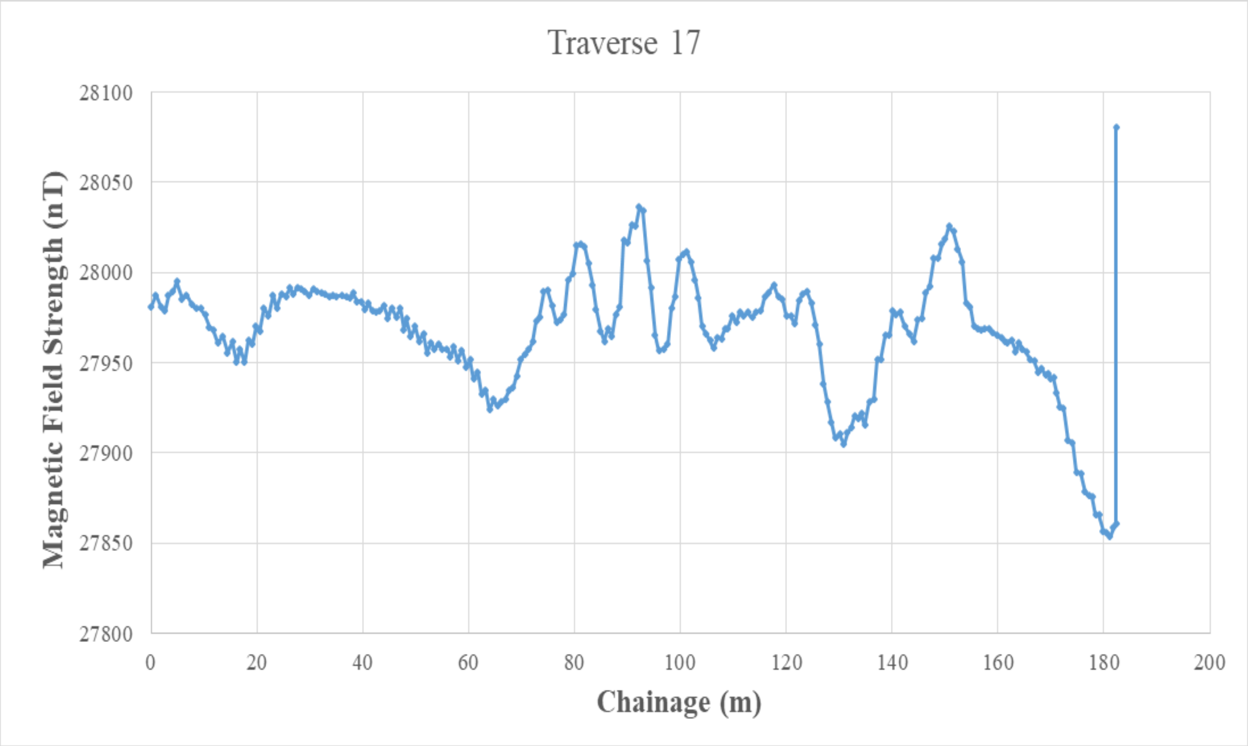
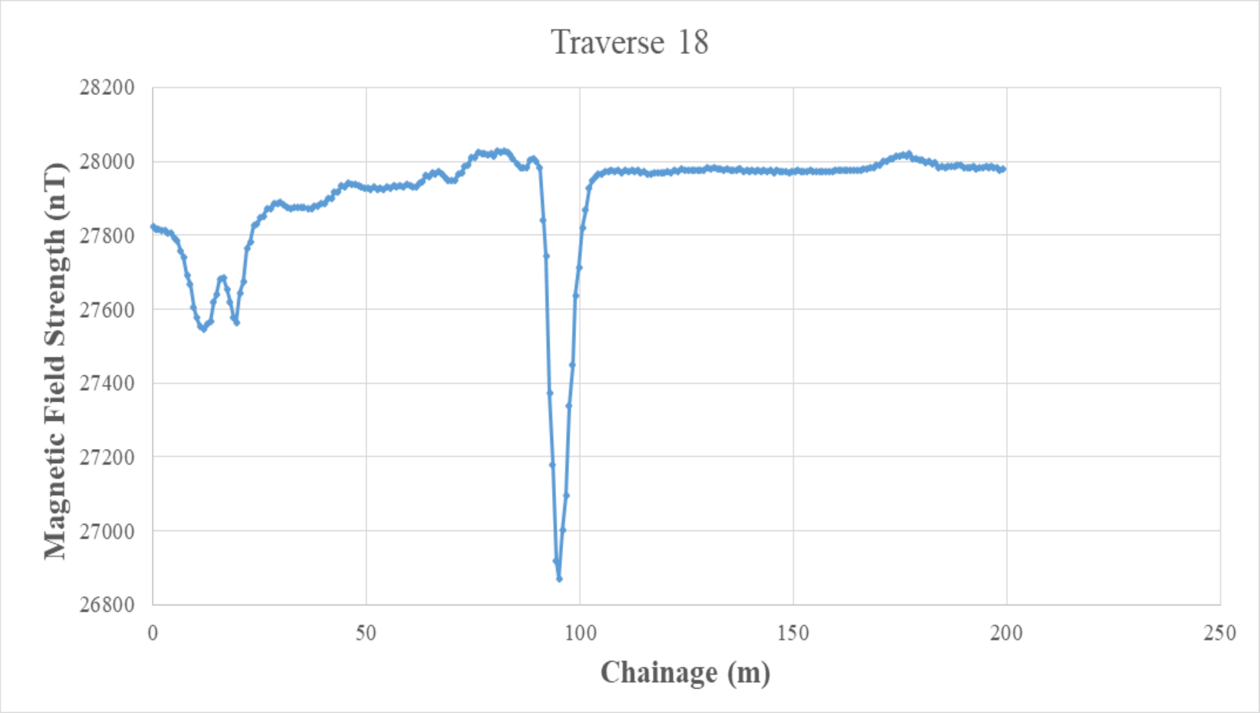
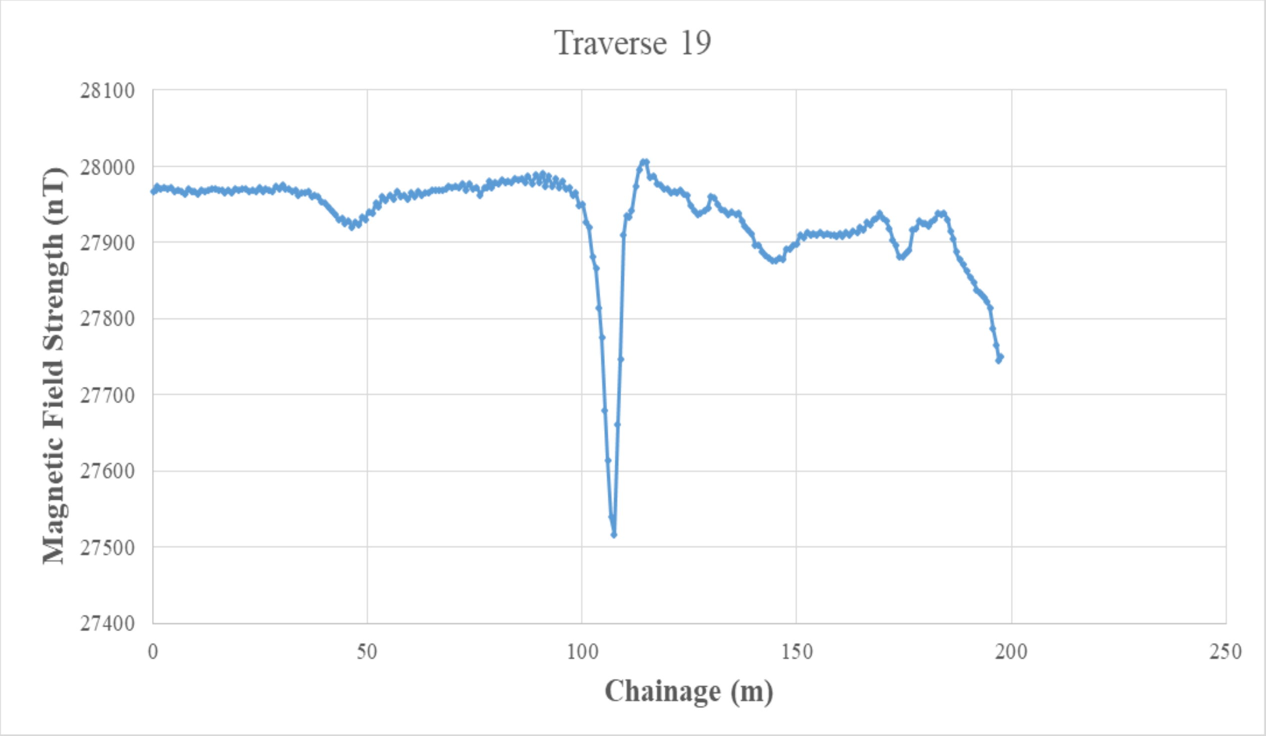
28400
28300
28200
28100
28000
27900
27800
0
20
40
60
80
100
120
140
160
180
200
Chainage (m)


Traverse 17
Magnetic Field Strength (nT)
28100
28050
28000
27950
27900
27850
27800
0
20
40
60
80
100
120
140
160
180
200
Chainage (m)


Traverse 18
Magnetic Field Strength (nT)
28200
28000
27800
27600
27400
27200
27000
26800
0
50
100
150
200
250
Chainage (m)


Traverse 19
Magnetic Field Strength (nT)
28100
28000
27900
27800
27700
27600
27500
27400
0
50
100
150
200
250
Chainage (m)

APPENDIX C

GROUNDWATER AND SURFACE WATER CHEMISTRY

Appendix C.1 September 2015

Site Name	EC (mS/m)	pH (pH Units)	SO4 (mg/ℓ)	Fe (mg/ℓ)	TDS (mg/ℓ)	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/ℓ N)	MALK (mg/ℓ CaCO3)	Cl (mg/ℓ)	NO3 (mg/ℓ N)	F (mg/ℓ)
BH1	85	7,89	60	0,016	729	68	46	88	9,74	<0,010	-0,01	324	102	6,9	0,24
BH5	138	7,72	153,2	0,016	1084	110	80	105	11,36	<0,010	0,34	348	218	12,6	-0,1
BH7	142	7,61	113,7	0,051	1154	165	75	91	11,33	0,144	-0,1	374	209	25,8	0,26
BH8	83,3	7,81	70,4	0,018	724	70	43	77	10,79	<0,010	-0,01	343	63	10,4	0,21
BH9	93,9	7,64	61,8	0,12	772	78	55	77	6,84	0,012	-0,01	350	108	7,7	0,31
BH10	70,3	7,81	43,6	0,01	558	61	53	34	8,67	<0,010	-0,01	291	60	1,3	0,11
BH11	77,3	7,8	54,5	0,012	622	61	30	94	7,15	<0,010	0,04	311	45	4,1	0,2
BH13	149	7,79	94,6	0,019	1179	135	150	26	6,96	<0,010	-0,1	446	233	19,8	-0,1
BH17	142	7,53	111,4	0,013	1139	244	44	50	10,69	<0,010	-0,1	371	267	9,2	-0,1
BH18	141	7,5	112,7	0,015	1110	245	45	49	10,62	<0,010	-0,1	370	238	8,6	0,39
SP1	239	7,93	348,6	0,024	1761	180	159	160	9	1,006	-0,1	230	671	-0,5	1,12
SP2a	117	7,92	161,1	0,08	837	71	47	153	9,89	0,02	-0,1	187	213	-0,5	0,36
SP2b	121	7,72	149,3	0,098	889	74	51	157	9,9	0,026	-0,1	208	243	-0,5	0,15
SP3	33,2	7,98	13,9	0,172	278	38	18	20	9,89	0,015	-0,01	151	28	-0,1	0,51
SP4	59,2	8	2,2	0,626	548	35	17	113	11,42	<0,010	-0,01	338	29	0,2	0,2
SP5	114	7,85	148,4	0,094	813	65	41	142	9,38	0,137	-0,1	190	220	-0,5	0,11
Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	<0,1	<10	Not Provided	≤300	<10	<1,0
Acceptable	170-370	5,5-9,7	400-600	0,2-2	1000-2400	150-300	70-100	200-400	50-100	0,1-1	10,0-20	Not Provided		10,0-20	1,0-1,5
Unacceptable	>370	>9,7	>600	>2	>2400	>300	>100	>400	>100	>1	>20	Not Provided	>300	>20	>1,5

Site Name	Al (mg/ℓ)	PO4 (mg/ℓ)	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Mn (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Si (mg/ℓ)	V (mg/ℓ)	Sr (mg/ℓ)	Br (mg/ℓ)
BH1	<0.010	-0,10	<0.010	0,075	0,033	<0.010	<0.010	<0.010	<0.010	<0.010	0,228	13,188	<0.010	0,802	0,81
BH5	<0.010	-1,00	<0.010	0,133	0,072	<0.010	0,029	<0.010	<0.010	<0.010	0,073	13,672	<0.010	1,527	1,34
BH7	<0.010	-1,00	<0.010	0,067	0,136	<0.010	0,04	0,144	<0.010	<0.010	0,038	14,153	<0.010	1,192	2,26
BH8	<0.010	-0,10	<0.010	0,070	0,081	<0.010	<0.010	<0.010	<0.010	<0.010	0,056	15,459	<0.010	0,585	1,26
BH9	<0.010	-0,10	<0.010	0,052	0,064	<0.010	<0.010	0,012	<0.010	<0.010	0,137	14,863	<0.010	0,791	0,79
BH10	<0.010	-0,10	<0.010	<0.040	0,027	<0.010	<0.010	<0.010	<0.010	<0.010	0,026	19,146	<0.010	0,494	0,67
BH11	<0.010	-0,10	<0.010	0,114	0,079	<0.010	0,012	<0.010	<0.010	<0.010	0,021	17,884	0,031	0,727	0,62
BH13	<0.010	-1,00	<0.010	<0.040	0,109	<0.010	<0.010	<0.010	0,012	<0.010	0,016	25,742	0,025	0,922	1,65
BH17	<0.010	-1,00	<0.010	0,015	0,222	<0.010	0,014	<0.010	<0.010	<0.010	0,020	19,598	0,010	0,770	2,55
BH18	<0.010	-1,00	<0.010	0,016	0,231	<0.010	<0.010	<0.010	<0.010	<0.010	0,015	19,465	<0.010	0,776	2,86
SP1	<0.010	-1,00	<0.010	<0.040	0,241	<0.010	0,018	1,006	0,015	<0.010	0,017	1,181	<0.010	0,318	4,61
SP2a	0,039	-1,00	<0.010	0,087	0,122	<0.010	<0.010	0,020	<0.010	<0.010	<0.010	5,740	<0.010	0,746	-0,40
SP2b	0,012	-1,00	<0.010	0,091	0,137	<0.010	<0.010	0,026	<0.010	<0.010	0,012	4,445	<0.010	0,799	1,02
SP3	0,118	-0,10	<0.010	<0.040	0,190	<0.010	<0.010	0,015	<0.010	<0.010	<0.010	5,544	<0.010	0,216	-0,04
SP4	0,175	-0,10	<0.010	0,080	0,091	<0.010	<0.010	<0.010	<0.010	<0.010	0,011	5,576	<0.010	0,727	-0,04
SP5	0,061	-1,00	<0.010	0,083	0,150	<0.010	<0.010	0,137	<0.010	<0.010	<0.010	6,173	<0.010	1,496	0,89
Target	<0,3	≤15,33	<0,01	≤2,400	≤ 0,700	<0,1	<1,0	<0,1	<0,15	<0,010	<5,0	Not Provided	<0,2	Not Provided	3,00
Acceptable	0,3-0,5		0,01-0,05			0,1-0,5	1,0-2,0	0,1-1,0	0,15-0,35	0,01-0,05	5,0-10	Not Provided	0,2-0,5	Not Provided	
Unacceptable	>0,5		>0,5			>0,5	>2,0	>1,0	>0,35	>0,05	>10	Not Provided	>0,5	Not Provided	

Appendix C.2 may 2016

Site Name	EC (mS/m)	pH (pH U	SO4 (mg/ℓ)	Fe (mg/ℓ)	TDS (mg/ℓ)	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/ℓ N)	MALK (mg/ℓ CaCO3)	Cl (mg/ℓ)	NO3 (mg/ℓ N)	F (mg/ℓ)
BH1	86	7,3	55,9	0,03	602	58,95	41,994	76,907	8,475	<0.010	<0.01	316	101,1	6,5859	0,4262
BH5	131	7,26	139,2483	0,026	917	97,023	69,027	92,513	15,296	<0.010	<0.1	336	214,7763	12,5466	0,4467
BH7	No Sample - borehole is dry														
BH8	74,8	7,36	58,9	0,027	523,6	54,426	33,935	65,393	11,384	<0.010	<0.01	313	39,4805	11,36	0,3084
BH9	75,9	7,34	47,8	0,024	531	58,4	28,0	92,4	5,69	<0.010	<0.01	288	53,8	14,7	0,61
BH10	71,9	7,24	42,4913	0,027	503,3	61,866	55,189	34,274	8,735	<0.010	<0.01	285	60,6	9,07	0,2555
BH11	114	7,09	78,3792	0,06	798	95,655	40,244	94,336	29,321	<0.010	<0.1	314	159,5044	22,8234	0,242
BH12	73,7	7,23	47,5525	0,026	515,9	52,909	25,458	82,785	5,114	<0.010	<0.01	287	53,6288	14,71	0,5469
BH13	139	7,26	93,4668	0,025	973	119,013	130,927	21,444	5,337	<0.010	<0.1	424	217,2249	19,5984	0,1798
BH17	115	6,88	68,3	0,028	805	183,2	33,1	37,4	9,45	<0.010	<0.1	340	197,2	10,5	0,57
BH18	115	6,97	68,5	0,028	805	184,5	33,5	38,3	9,54	<0.010	<0.1	338	197,9	11,1	0,25
Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	<0,1	<10	Not Provided	≤300	<10	<1,0
Acceptable	170-370	5,5-9,7	400-600	0,2-2	1000-2400	150-300	70-100	200-400	50-100	0,1-1	10,0-20	Not Provided		10,0-20	1,0-1,5
Unacceptable	>370	>9,7	>600	>2	>2400	>300	>100	>400	>100	>1	>20	Not Provided	>300	>20	>1,5

Site Name	Al (mg/ℓ)	PO4 (mg/ℓ	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Cd (mg/ℓ)	Co (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Si (mg/ℓ)	V (mg/ℓ)	Sr (mg/ℓ)	Br (mg/ℓ)
BH1	0,01	<0.1	<0.010	0,123	0,017	<0.010	0,013	<0.003	<0.010	<0.010	0,082	13,029	<0.010		0,8508
BH5	0,011	<1	<0.010	0,177	0,058	<0.010	0,018	<0.003	<0.010	<0.010	0,042	13,213	<0.010		1,1878
BH7	No Sample - borehole is dry														
BH8	0,013	<0.1	<0.010	0,106	0,045	<0.010	0,014	<0.003	<0.010	<0.010	0,058	14,464	<0.010		0,5587
BH9	0,015	<0.1	<0.010	0,270	0,072	<0.010	0,015	<0.003	<0.010	<0.010	0,025	18,253	0,031		0,6745
BH10	0,015	<0.1	<0.010	0,073	0,016	<0.010	0,013	<0.003	<0.010	<0.010	0,042	13,213	<0.010		0,2916
BH11	<0.010	<1	<0.010	0,172	0,039	<0.010	0,019	<0.003	<0.010	<0.010	0,109	14,828	0,011		0,9818
BH12	0,015	<0.1	<0.010	0,252	0,066	<0.010	0,012	<0.003	<0.010	<0.010	0,023	16,639	0,028		0,7159
BH13	0,01	<1	<0.010	0,043	0,078	<0.010	0,015	<0.003	<0.010	<0.010	0,027	24,421	0,025		1,1325
BH17	<0.010	<1	<0.010	0,059	0,141	<0.010	0,017	<0.003	<0.010	<0.010	0,026	18,92	0,01		2,2121
BH18	0,011	<1	<0.010	0,058	0,139	<0.010	0,015	<0.003	<0.010	<0.010	0,028	19,08	<0.010		1,8548
Target	<0,3	≤15,33	<0,01	≤2,400	≤ 0,700	<0,1	<1,0	≤ 0.003	≤ 0.500	<0,010	<5,0	Not Provided	<0,2	Not Provided	3,00
Acceptable	0,3-0,5		0,01-0,05			0,1-0,5	1,0-2,0			0,01-0,05	5,0-10	Not Provided	0,2-0,5	Not Provided	
Unacceptable	>0,5		>0,5			>0,5	>2,0			>0,05	>10	Not Provided	>0,5	Not Provided	

Appendix C.3 July 2016

	Site Name	EC (mS/m	pH (pH U	SO4 (mg/ℓ	Fe (mg/ℓ)	TDS (mg/	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/	MALK (mg/ℓ Ca	Cl (mg/ℓ)	NO3 (mg/ℓ N	F (mg/ℓ)
Groundwater	BH1	79,9	6,93	57	<0.010	694	56,7	43,6	78,6	9,22	<0.010	<0.01	317	102	6,60	0,42
	BH5	120	6,87	132	<0.010	1007	90,9	69,3	95,8	16,75	<0.010	<0.1	335	212	12,33	0,38
	BH7	No sample - borehole dry														
	BH8	67,6	6,81	60	0,004	638	54,2	34,6	67,7	12,14	<0.010	<0.01	314	45	11,22	0,39
	BH9	90,5	6,67	65	0,027	774	70,3	53,9	71,6	6,20	<0.010	<0.01	342	130	7,60	0,40
	BH10	64,5	6,83	42	<0.010	572	52,4	50,7	30,7	7,77	<0.010	<0.01	285	63	8,91	0,35
	BH11	No samples - no access to farm														
	BH12	No samples - no access to farm														
	BH13	129	6,88	91	0,015	1083	107,8	128,4	20,4	5,42	<0.010	<0.1	420	220	20,38	<0.10
	BH17	161	7,19	133	0,014	1287	85,2	22,3	297,0	6,52	<0.010	<0.1	327	394	4,23	1,18
	BH18	190	6,68	200	0,007	1652	218,0	94,7	141,4	6,89	<0.010	<0.1	388	401	45,00	0,68
Surface Water	SP3	37,56	7,58	20	0,013	151	29,8	18,7	30,2	10,13	<0.010	<0.01	157	51	<0.05	0,88
SANS 241: 2006& 2015 Guideline	Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	<0,1	<10	Not Provided	≤300	<10	<1,0
	Good	170-370	5,5-9,7	400-600	0,2-2	1000-2400	150-300	70-100	200-400	50-100	0,1-1	10,0-20	Not Provided		10,0-20	1,0-1,5
	Unacceptable	>370	>9,7	>600	>2	>2400	>300	>100	>400	>100	>1	>20	Not Provided	>300	>20	>1,5

	Site Name	Al (mg/ℓ)	PO4 (mg/ℓ	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Mo (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Co (mg/ℓ)	V (mg/ℓ)	Cd (mg/ℓ)	Br (mg/ℓ)
Groundwater	BH1	0,015	<0.1	<0.010	0,083	0,007	<0.010	<0.010	<0.010	<0.010	<0.010	0,040	<0.010	<0.010	<0.003	0,80
	BH5	0,017	<1	<0.010	0,131	0,026	<0.010	<0.010	<0.010	<0.010	<0.010	0,020	<0.010	<0.010	<0.003	1,66
	BH7	No sample - borehole dry														
	BH8	0,014	<0.1	<0.010	0,077	0,022	<0.010	<0.010	<0.010	0,011	<0.010	0,022	<0.010	<0.010	<0.003	0,61
	BH9	0,014	<0.1	<0.010	0,062	0,024	<0.010	<0.010	<0.010	0,014	<0.010	0,199	<0.010	<0.010	<0.003	0,97
	BH10	0,013	<0.1	<0.010	0,04	0,005	<0.010	<0.010	<0.010	0,013	<0.010	0,026	<0.010	<0.010	<0.003	0,35
	BH11	No samples - no access to farm														
	BH12	No samples - no access to farm														
	BH13	0,015	<1	<0.010	0,021	0,033	<0.010	<0.010	<0.010	0,018	<0.010	0,020	<0.010	0,013	<0.003	1,39
	BH17	0,017	<1	<0.010	0,417	0,039	<0.010	<0.010	0,011	<0.010	<0.010	<0.010	<0.010	<0.010	<0.003	3,11
	BH18	0,016	<1	<0.010	0,157	0,066	<0.010	0,01	<0.010	0,017	<0.010	0,011	<0.010	<0.010	<0.003	3,83
Surface water	SP3	0,030	<0.1	<0.010	0,058	0,074	<0.010	<0.010	<0.010	<0.010	<0.010	0,015	<0.010	<0.010	<0.003	0,26
SANS 241: 2006& 2015 Guideline	Target	<0,3	≤15,33	<0,01	≤2,400	≤ 0,700	<0,1	<1,0	<0,1	<0,15	<0,010	<5,0	≤ 0,500	<0,2	≤ 0,003	3,00
	Good	0,3-0,5		0,01-0,05			0,1-0,5	1,0-2,0	0,1-1,0	0,15-0,35	0,01-0,05	5,0-10		0,2-0,5		
	Unacceptable	>0,5	≥15,33	>0,5	≥2,400	≥0,700	>0,5	>2,0	>1,0	>0,35	>0,05	>10	≥0,500	>0,5	≥0,300	>3,00

Appendix C.4 September 2016

	Site Name	EC (mS/m	pH (pH U	SO4 (mg/	Fe (mg/ℓ)	TDS (mg/	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/	MALK (mg/ℓ	Cl (mg/ℓ)	NO3 (mg/ℓ N)	F (mg/ℓ)
Groundwater	BH1	88.9	7.51	59.5	0.031	753	68.4	51.0	90.3	9,22	<0.010	<0.01	330	111.8	7.0	0.45
	BH5	132	7.54	138.8	0.046	1069	113.8	84.2	107.3	19.4	<0.010	<0.1	343	204.1	13.2	0.19
	BH7	No sample - borehole dry														
	BH8	73.6	7.48	60.8	0.019	682	66.6	42.7	75.0	14.5	<0.010	<0.01	322	53.6	10.6	0.24
	BH9	96.4	7.31	64.0	0.073	827	88.2	65.2	83.0	7.43	<0.010	<0.01	349	137.0	7.3	0.36
	BH10	69	7.34	43.1	0.019	617	64.2	58.4	34.2	8.81	<0.010	<0.01	294	74.8	8.8	0.26
	BH11	76	7.39	48.3	0.017	662	60.2	29.9	91.2	6.47	<0.010	<0.01	295	54.7	16.9	0.56
	BH12	125	7.39	82.8	0.020	1033	117.6	50.9	112.7	37.1	<0.010	<0.1	315	203.4	25.6	0.30
	BH13	146	7.38	92.2	0.016	1165	131.0	150.3	24.0	6.61	<0.010	<0.1	427	238.1	21.6	<0.10
	BH17	133	7.05	84.3	0.017	1062	228.6	42.2	47.0	11.8	<0.010	<0.1	363	233.6	11.3	0.29
	BH18	No sample - borehole dry														
Surface water	SW1	31.7	7.76	4.5	0.940	280	30.0	17.6	17.7	20.5	0.297	<0.01	168	16.8	<0.05	0.42
	SW2	34.1	8.06	27.9	0.122	273	36.7	15.8	21.9	10.1	0.060	<0.01	128	32.6	<0.05	0.31
SANS 241: 2006& 2015 Guideline	Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	≤0,1	≤0,9	Not Provided	≤300	≤11	<1,0
	Acceptable	170	5,5-9,7	400-500	0,2-2	1000-1200	150-300	70-100		50-100			Not Provided			1,0-1,5
	Unacceptable	>170	>9,7	>500	>2	>1200	>300	>100	>200	>100	>0,100	>0,9	Not Provided	>300	>11	>1,5

	Site Name	Al (mg/ℓ)	PO4 (mg/ℓ	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Mo (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Co (mg/ℓ)	V (mg/ℓ)	Cd (mg/ℓ)	Br (mg/ℓ)
Groundwater	BH1	<0.010	<0.1	N/A	0.108	0.030	<0.010	0.010	<0.010	<0.010	<0.010	0.138	N/A	<0.010	N/A	0.85
	BH5	<0.010	<1	N/A	0.169	0.083	<0.010	0.018	<0.010	<0.010	<0.010	0.077	N/A	<0.010	N/A	1.35
	BH7	No sample - borehole dry														
	BH8	<0.010	<0.1	N/A	0.102	0.070	<0.010	0.015	<0.010	<0.010	<0.010	0.047	N/A	0.011	N/A	0.56
	BH9	<0.010	<0.1	N/A	0.076	0.076	<0.010	0.015	<0.010	<0.010	<0.010	0.377	N/A	<0.010	N/A	0.86
	BH10	<0.010	<0.1	N/A	0.051	0.030	<0.010	0.013	<0.010	<0.010	<0.010	0.067	N/A	0.013	N/A	0.33
	BH11	<0.010	<0.1	N/A	0.219	0.084	<0.010	0.010	<0.010	<0.010	<0.010	0.015	N/A	0.032	N/A	0.61
	BH12	<0.010	<1	N/A	0.141	0.058	<0.010	0.012	<0.010	<0.010	<0.010	0.041	N/A	0.031	N/A	1.01
	BH13	<0.010	<1	N/A	0.016	0.102	<0.010	0.012	<0.010	0.011	<0.010	0.029	N/A	0.029	N/A	1.20
	BH17	<0.010	<1	N/A	0.040	0.196	<0.010	0.013	<0.010	<0.010	<0.010	0.020	N/A	0.012	N/A	2.13
	BH18	No sample - borehole dry														
Surface water	SW1	0.761	4.2956	<0.010	0.065	0.062	<0.010	0.023	<0.010	0.017	<0.010	0.024	N/A	0.015	N/A	0.21
	SW2	0.134	<0.1	<0.010	<0.030	0.095	<0.010	0.027	<0.010	0.014	<0.010	0.020	N/A	0.020	N/A	0.11
SANS 241: 2006& 2015 Guideline	Target	<0,3	<15,33	<0,01	≤2,400	≤ 0,700	≤0,05	<1,0	<0,1	≤0,07	<0,010	<5,0	≤ 0.500	<0,2	≤ 0,003	3,00
	Acceptable			0,01-0,05				1,0-2,0	0,1-2,0							
	Unacceptable	>0,3	>15,33	>0,5			>0,05	>2,0	>2,0	>0,07	>0,010	>5		>0,2	≥0,300	

Appendix C.5 November 2016

	Site Name	EC (mS/m)	pH (pH Un	SO4 (mg/ℓ)	Fe (mg/ℓ)	TDS (mg/	Ca (mg/ℓ)	Mg (mg/ℓ	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ	NO2 (mg/	MALK (m	Cl (mg/ℓ)	NO3 (mg/	F (mg/ℓ)
Groundwater	BH1	96,3	7,45	57,4	0,022	746	65,72	44,36	84,78	9,44	<0.010	<0.01	301	150,7	7,15	0,45
	BH5	141	7,52	126,6	0,016	998	97,96	68,85	96,33	16,07	<0.010	<0.1	332	202,7	12,95	0,49
	BH7	No sample - borehole dry														
	BH8	81,6	7,84	58,1	0,027	651	57,90	36,60	70,31	12,79	<0.010	<0.01	307	55,3	11,88	0,23
	BH9	97,5	7,64	61,0	0,085	757	66,86	50,70	77,76	7,26	0,063	<0.01	325	146,9	4,61	0,22
	BH10	77,6	7,34	42,7	0,022	609	58,74	52,05	33,15	8,73	<0.010	<0.01	286	88,0	8,94	0,20
	BH11	No sample														
	BH12	126	7,47	72,0	0,035	939	99,49	41,60	100,85	31,01	<0.010	<0.1	309	179,1	24,01	0,24
	BH13	150	7,49	86,9	0,027	1119	124,15	136,58	24,11	5,96	<0.010	<0.01	420	227,4	21,03	0,13
	BH17	112	7,06	55,5	0,017	849	168,47	30,01	38,13	9,38	<0.010	<0.1	340	163,1	9,79	0,14
	BH18	113	7,08	57,4	0,018	856	172,54	30,90	39,73	9,55	<0.010	<0.1	346	157,3	9,75	0,12
Surface water	SP1	14,6	6,92	9,5	0,329	117	11,26	5,39	10,92	5,58	0,038	<0.01	65	9,1	0,00	0,25
	SP2	9,68	6,91	2,5	0,243	83	6,20	3,05	6,83	9,97	0,041	<0.01	46,8	6,3	-0,05	0,21
	SP4	21,7	7,3	9,7	0,151	161	17,97	8,44	10,97	7,51	<0.010	<0.01	87,4	18,2	0,16	0,39
SANS 241: 2006& 2015 Guideline	Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	≤0,1	≤0,9	Not Provide	≤300	≤11	<1,0
	Acceptable	170	5,5-9,7	400-500	0,2-2	1000-1200	150-300	70-100		50-100			Not Provided			1,0-1,5
	Unacceptable	>170	>9,7	>500	>2	>1200	>300	>100	>200	>100	>0,100	>0,9	Not Provide	>300	>11	>1,5

	Site Name	Al (mg/ℓ)	PO4 (mg/ℓ)	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Mo (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Co (mg/ℓ)	V (mg/ℓ)	Cd (mg/ℓ)	Br (mg/ℓ)
Groundwater	BH1	<0.010	<0.1	<0.010	0,065	0,019	0,011	<0.010	<0.010	<0.010	<0.010	0,029	N/A	N/A	N/A	0,71
	BH5	<0.010	<1	<0.010	0,120	0,056	0,009	<0.010	<0.010	<0.010	<0.010	0,027	N/A	N/A	N/A	1,15
	BH7	No sample - borehole dry														
	BH8	<0.010	<0.1	<0.010	0,062	0,048	0,01	<0.010	<0.010	<0.010	<0.010	0,028	N/A	N/A	N/A	0,50
	BH9	<0.010	<0.1	<0.010	0,044	0,038	0,011	0,024	<0.010	<0.010	<0.010	2,151	N/A	N/A	N/A	0,72
	BH10	<0.010	<0.1	0,016	<0.030	0,014	0,01	<0.010	<0.010	<0.010	<0.010	0,209	N/A	N/A	N/A	0,28
	BH11	No sample														
	BH12	<0.010	<1	<0.010	0,102	0,037	0,011	<0.010	<0.010	<0.010	<0.010	0,032	N/A	N/A	N/A	0,68
	BH13	<0.010	<1	<0.010	<0.030	0,081	0,012	<0.010	<0.010	<0.010	<0.010	0,026	N/A	N/A	N/A	1,81
	BH17	<0.010	<1	0,013	<0.030	0,132	0,01	<0.010	<0.010	<0.010	<0.010	0,017	N/A	N/A	N/A	2,07
	BH18	<0.010	<1	<0.010	<0.030	0,133	0,011	<0.010	<0.010	<0.010	<0.010	0,016	N/A	N/A	N/A	0,69
Surface water	SP1	0,432	<0.1	<0.010	<0.030	0,032	0,012	0,012	<0.010	<0.010	<0.010	0,014	N/A	N/A	N/A	0,08
	SP2	0,372	1,4164	<0.010	<0.030	0,025	0,011	0,011	<0.010	<0.010	<0.010	0,012	N/A	N/A	N/A	0,07
	SP4	0,158	<0.1	<0.010	<0.030	0,072	0,011	0,013	<0.010	<0.010	<0.010	0,018	N/A	N/A	N/A	0,05
SANS 241: 2006& 2015 Guideline	Target	<0,3	<15,33	<0,01	≤2,400	≤ 0,700	≤0,05	<1,0	<0,1	≤0,07	<0,010	<5,0	≤ 0,500	<0,2	≤ 0,003	3,00
	Acceptable			0,01-0,05				1,0-2,0	0,1-2,0							
	Unacceptable	>0,3	>15,33	>0,5			>0,05	>2,0	>2,0	>0,07	>0,010	>5		>0,2		

Appendix C.6 January 2017

	Site Name	EC (mS/m	pH (pH U	SO4 (mg/	Fe (mg/ℓ)	TDS (mg/	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/	MALK (m	Cl (mg/ℓ)	NO3 (mg/	F (mg/ℓ)
	BH1	97.5	7.26	56.9	<0.020	705	61.8	49.1	80.6	9.9	<0.020	<0.01	307	108.6	6.80	0.40
	BH5	143	7.21	133.7	0.05	1008	91.6	73.7	94.9	14.2	<0.020	<0.1	327	216.1	12.69	0.37
	BH7	No sample - borehole dry														
	BH8	83.7	7.43	67.7	0.028	653	55.9	39.1	67.6	12.3	<0.020	<0.01	307	48.8	12.22	0.23
Groundwater	BH9	93	7.60	63.7	0.083	671	56.3	51.8	71.7	7.7	<0.020	<0.01	310	109.2	<0.05	0.30
	BH10	13.3	6.4	4.1	0.268	71	5.3	3.0	6.3	8.2	<0.020	<0.01	36.2	7.4	<0.05	0.23
	BH11	126	7.44	78.9	0.021	894	91.4	45.2	94.8	19.4	<0.020	<0.1	297	168.7	22.46	0.31
	BH12	125	7.36	76.2	0.022	900	93.3	45.4	96.7	19.5	<0.020	<0.1	296	173.8	22.30	0.28
	BH13	154	7.40	88.2	<0.020	1122	112.2	146.9	22.8	6.1	<0.020	<0.1	408	253.3	19.22	0.15
	BH17	103	6.82	44.8	<0.020	774	155.1	31.3	36.4	9.6	<0.020	<0.1	335	125.3	8.50	<0.1
	BH18	103	6.88	52.1	0.036	775	147.9	31.0	35.2	9.2	<0.020	<0.1	334	127.5	8.67	0.16
Surface water	SP1	13.3	6.4	4.1	0.268	71	5.3	3.0	6.3	8.2	<0.020	<0.1	36.2	7.4	<0.050	0.23
	Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	≤0,1	≤0,9	Not Provide	≤300	≤11	<1,0
SANS 241: 2006&	Acceptable	170	5,5-9,7	400-500	0,2-2	1000-1200	150-300	70-100		50-100		Not Provided				1,0-1,5
2015 Guideline	Unacceptable	>170	>9,7	>500	>2	>1200	>300	>100	>200	>100	>0,100	>0,9	Not Provide	>300	>11	>1,5

	Site Name	Al (mg/ℓ)	PO4 (mg/ℓ	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Cu (mg/ℓ)	Mo (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Co (mg/ℓ)	V (mg/ℓ)	Cd (mg/ℓ)	Br (mg/ℓ)
	BH1	<0.020	<0.1	<0.020	0.094	<0.050	<0.020	0.008	N/A	N/A	<0.015	0.021	<0.020	<0.010	<0.003	0.63
	BH5	<0.020	<1	<0.020	0.156	0.057	<0.020	0.012	N/A	N/A	<0.015	0.132	<0.020	<0.010	<0.003	1.32
	BH7	No sample - borehole dry														
	BH8	<0.020	<0.1	<0.020	0.092	0.05	<0.020	0.006	N/A	N/A	<0.015	0.027	<0.020	<0.010	<0.003	0.52
Groundwater	BH9	<0.020	<0.1	<0.020	0.073	<0.050	<0.020	0.011	N/A	N/A	<0.015	0.811	<0.020	<0.010	<0.003	0.55
	BH10	0.241	0.33	<0.020	0.039	<0.050	<0.020	0.015	N/A	N/A	<0.015	0.0110	<0.020	<0.010	<0.003	0.12
	BH11	<0.020	<1	<0.020	0.129	<0.050	<0.020	0.01	N/A	N/A	<0.015	0.024	<0.020	0.027	<0.003	0.64
	BH12	<0.020	<1	<0.020	0.124	<0.050	<0.020	0.011	N/A	N/A	<0.015	0.025	<0.020	0.027	<0.003	1.11
	BH13	<0.020	<1	<0.020	0.021	0.08	<0.020	0.006	N/A	N/A	<0.015	0.022	<0.020	0.025	<0.003	1.31
	BH17	<0.020	<1	<0.020	0.038	0.136	<0.020	0.008	N/A	N/A	<0.015	0.017	<0.020	<0.010	<0.003	0.86
	BH18	<0.020	<1	<0.020	0.045	0.131	<0.020	0.008	N/A	N/A	<0.015	0.018	<0.020	<0.010	<0.003	0.83
Surface water	SP1	0.241	0.33	<0.020	0.039	<0.050	<0.020	0.015	N/A	N/A	<0.015	0.0110	<0.020	<0.010	<0.003	0.12
	Target	<0,3	<15,33	<0,01	≤2,400	≤ 0,700	≤0,05	<1,0	<0,1	≤0,07	<0,010	<5,0	≤ 0,500	<0,2	≤ 0.003	3,00
SANS 241: 2006&	Acceptable			0,01-0,05				1,0-2,0	0,1-2,0							
2015 Guideline	Unacceptable	>0,3	>15,33	>0,5			>0,05	>2,0	>2,0	>0,07	>0,010	>5		>0,2		

Appendix C.7 April 2017

	Site Name	EC (mS/m	pH (pH U	SO4 (mg/ℓ	Fe (mg/ℓ)	TDS (mg/	Ca (mg/ℓ)	Mg (mg/ℓ)	Na (mg/ℓ)	K (mg/ℓ)	Mn (mg/ℓ)	NO2 (mg/	MALK (m	Cl (mg/ℓ)	NO3 (mg/	F (mg/ℓ)
Groundwater	BH1	95,7	7,38	55	<0.020	686	60,4	42,8	79,5	9,3	<0.020	-0,01	307	104,6	6,3	0,41
	BH5	167	7,26	164	<0.020	1153	124,0	86,2	108,4	19,0	<0.020	-0,1	331	254,8	14,9	0,15
	BH7	No sample - borehole dry														
	BH8	83,4	7,46	83	0,019	634	56,7	36,3	70,3	12,9	<0.020	-0,01	306	40,9	11,7	0,26
	BH9	142	7,31	73	0,027	1036	112,1	80,0	89,1	8,0	0,105	-0,1	345	190,5	31,5	0,43
	BH10	78,8	7,28	41	0,044	558	56,8	51,0	32,6	7,8	0,039	0,13	280	57,1	7,1	0,21
	BH11	No sample/No access														
	BH12	173	7,32	85	<0.020	1153	140,4	57,8	116,7	37,4	<0.020	-0,1	307	277,6	30,0	0,11
	BH13	160	7,47	88	<0.020	1095	124,1	137,0	25,9	6,2	<0.020	-0,1	414	220,3	18,5	0,02
	BH17	120	7,02	74	<0.020	886	162,5	40,7	43,0	7,9	<0.020	-0,1	352	115,6	20,7	0,05
	BH18	112	7,08	68	0,015	837	165,1	37,0	40,5	8,2	<0.020	-0,1	349	101,9	15,7	0,11
Surface water	SP2	30,5	7,44	9,65	0,111	205	18	10	23	10,61	0,182	-0,01	102	31,01	0,09	0,31
	Target	≤ 170	≤5,5	<400	<0,2	<1000	150	<70	≤200	<50	≤0,1	≤0,9	Not Provide	≤300	≤11	<1,0
SANS 241: 2006&	Acceptable	170	5,5-9,7	400-500	0,2-2	1000-1200	150-300	70-100		50-100			Not Provided			1,0-1,5
2015 Guideline	Unacceptable	>170	>9,7	>500	>2	>1200	>300	>100	>200	>100	>0,100	>0,9	Not Provide	>300	>11	>1,5

	Site Name	Al (mg/ℓ)	PO4 (mg/ℓ	As (mg/ℓ)	B (mg/ℓ)	Ba (mg/ℓ)	Cr (mg/ℓ)	Si (mg/ℓ)	Mo (mg/ℓ)	Ni (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	Co (mg/ℓ)	V (mg/ℓ)	Cd (mg/ℓ)	Br (mg/ℓ)	Sr (mg/ℓ)
Groundwater	BH1	<0.020	<0.1	<0.020	0,107	0,020	<0.020	13,466	<0.020	<0.020	<0.015	0,043	<0.020	<0.010	<0.003	-0,4	0,566
	BH5	<0.020	0,17	<0.020	0,169	0,075	<0.020	13,810	<0.020	<0.020	<0.015	0,029	<0.020	<0.010	<0.003	-0,4	1,351
	BH7	No sample - borehole dry															
	BH8	<0.020	<0.1	<0.020	0,110	0,050	<0.020	16,177	<0.020	<0.020	<0.015	0,028	<0.020	<0.010	<0.003	-0,04	0,377
	BH9	<0.020	<1	<0.020	0,089	0,074	<0.020	11,873	<0.020	<0.020	<0.015	4,275	<0.020	<0.010	<0.003	-0,4	0,854
	BH10	<0.020	<0.1	<0.020	0,063	<0.020	<0.020	18,323	<0.020	<0.020	<0.015	0,882	<0.020	<0.010	<0.003	0,12	
	BH11	No sample/No access															
	BH12	<0.020	<1	<0.020	0,150	0,056	<0.020	16,634	<0.020	<0.020	<0.015	0,032	<0.020	0,019	<0.003	-0,4	1,250
	BH13	<0.020	<1	<0.020	<0.040	0,086	<0.020	26,424	<0.020	<0.020	<0.015	0,022	<0.020	0,021	<0.003	-0,4	0,642
	BH17	<0.020	<1	<0.020	0,046	0,128	<0.020	20,853	<0.020	<0.020	<0.015	<0.020	<0.020	<0.010	<0.003	-0,4	0,462
	BH18	<0.020	<1	<0.020	<0.040	0,134	<0.020	20,639	<0.020	<0.020	<0.015	0,029	<0.020	0,010	<0.003	-0,4	0,441
Surface water	SP2	0,151	0,60	<0.020	0,052	0,055	<0.020	13,057	<0.020	<0.020	<0.015	0,019	<0.020	<0.010	<0.003	-0,04	0,125
	Target	<0,3	<15,33	<0,01	≤2,400	≤ 0,700	≤0,05	Not Provide	<0,1	≤0,07	<0,010	<5,0	≤ 0,500	<0,2	≤ 0.003	3,00	
SANS 241: 2006&	Acceptable			0,01-0,05				Not Provide	0,1-2,0								
2015 Guideline	Unacceptable	>0,3	>15,33	>0,5			>0,05	Not Provide	>2,0	>0,07	>0,010	>5		>0,2			

APPENDIX D

HYDRAULIC TEST RESULTS

Drawdown data

Time (min)	Head (m)	s (m)
1	16,232	0
2	14,9903	1,2417
3	14,0425	2,1895
4	13,3016	3,4
5	12,7026	3,5294
6	12,2129	4,0191
7	11,8087	4,4233
8	11,469	4,763
9	11,2326	4,9994
10	11,2155	5,0165
11	11,0109	5,2211
12	10,8202	5,4118
13	10,654	5,578
14	10,4974	5,7346
15	10,3563	5,8757
16	10,2279	6,0041
17	10,1196	6,1124
18	10,0379	6,1941
19	9,9711	6,2609
20	9,9021	6,3299
25	9,5623	6,6697
30	9,3416	6,8904
40	9,0381	7,1939
50	8,8386	7,3934
60	8,7183	7,5137
75	8,6101	7,6219
90	8,4877	7,7443
120	8,249	7,983
150	8,0675	8,1645
180	7,9278	8,3042
240	7,7268	8,5052

Recovery data

Time t' (min)	Head (m)	s' (m)
1	7,9691	8,2629
2	8,227	8,005
3	8,4777	7,7543
4	8,6792	7,5528
5	9,1454	7,0866
6	9,82	6,412
7	10,2981	5,9339
8	10,8157	5,4163
9	11,2708	4,9612
10	11,7701	4,4619
11	12,1898	4,0422
12	12,5426	3,6894
13	12,8413	3,3907
14	13,0963	3,1357
15	13,3141	2,9179
16	13,5009	2,7311
17	13,6646	2,5674
18	13,805	2,427
19	13,9295	2,3025
20	14,0398	2,1922
25	14,4374	1,7946
30	14,6908	1,5412
40	15,0046	1,2274
50	15,2027	1,2274
60	15,3471	0,8849
75	15,5029	0,7291
90	15,6147	0,6173
120	15,7595	0,4725
150	15,8522	0,3798
180	15,92	0,312
240	16,0008	0,2312
300	16,0541	0,1779
360	16,0899	0,1421
420	16,1163	0,1157
480	16,1352	0,0968
540	16,154	0,078
600	16,1642	0,0678
660	16,1748	0,0572
720	16,1828	0,0492
780	16,1911	0,0409
840	16,1978	0,0342
900	16,2066	0,0254
960	16,2133	0,0187
1020	16,2207	0,0113
1080	16,223	0,009
1140	16,2262	0,0058
1200	16,2273	0,0047
1260	16,2296	0,0024