THE IDENTIFICATION OF POTENTIAL GROUNDWATER ZONES IN THE KAMIESBERG REGION, NORTHERN CAPE PROVINCE, SOUTH AFRICA.

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A full thesis submitted in partial fulfillment of the requirements for the degree of Magister Scientiae in the Department of Earth Sciences, University of the Western Cape

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THE IDENTIFICATION OF POTENTIAL GROUNDWATER RESOURCES IN THE KAMIESBERG REGION, NORTHERN CAPE PROVINCE, SOUTH AFRICA

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KEYWORDS

Namaqualand

Kamiesberg region

Groundwater resources

Fractured basement aquifers

Remote sensing

Lineaments

Identification

Borehole location

Sustainable yield

Stress

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ABSTRACT

THE IDENTIFICATION OF POTENTIAL GROUNDWATER RESOURCES IN THE KAMIESBERG REGION, SOUTH AFRICA.

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The aim of the study is to apply remote sensing techniques to identify potential groundwater resources for the Kamiesberg region. This region, with vast water shortages relies solely on groundwater and is characterized by a fractured crystalline basement aquifer that lacks primary porosity. Groundwater in basement rock aquifers is likely to occur along open fractures and in weathered overburden zones.

The study consisted of remote sensing analysis, aerial photography and Landsat images, and field investigations to ground truth the conceptual understanding.

Field studies included geological mapping, lineament analyses and hydrogeological investigations. The Kamiesberg region is situated in the Namaqualand Metamorphic Complex (NMC), which is known for its mineral

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and alluvial diamond deposits. The NMC primarily consists of an assemblage of low- to high-grade metasedimentary rocks, unmetamorphosed platform sediments and an array of granitic, basic and ultrabasic intrusive rocks. Three prominent deformations caused the general geological outline of the region, namely the Proterozoic deformations, Pan African orogenesis and Mesozoic breakup. The fracture and joint analyses confirmed a NNW mean trend. Secondary orientations are E-W, NW- SE and NE- SW. Fracture and joint analysis were contoured in lineament frequency/density and lineament intersection maps. The fractures and joints are zones of increased weathering and have a greater potential for groundwater storage. The maximum principle compressive stress (σ_1) or neotectonic stress is orientated in a NW direction. The present groundwater state inferred from the national groundwater database (NGDB) suggests that boreholes are predominantly dry (37%), low yielding <1 l/s (49%) and drilled in the weathered overburden at a depth of 40- 80m (90%).

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The results of the research identified potential groundwater zones for the Kamiesberg region. These zones were identified from a combination of lineament frequency/density maps, lineament intersection maps, groundwater analyses and fieldwork. The zones are situated in and around the town of Kamieskroon and Leliefontein and south of Karkams. One of the potential sites identified, Kamieskroon, has current data on the groundwater state, and provides confidence to the conceptual understanding. The town has eight

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boreholes with yields ranging from 0.6- 1.6 l/s. Four of these boreholes are located in the weathered overburden (shallow boreholes), and the others are located along the NNW trending lineaments (deep boreholes). The zones identified from the study are potential groundwater resource sites, however, confirmation with geophysical surveys is essential. The data, however, has various shortcomings varying from lack of reliable data to the proximity of the potential resource to the community. It is critical to monitor existing and future groundwater resource sites (water levels, quality) and manage the resources in a sustainable way for optimal lifetime.

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DECLARATION

I declare that *The identification of potential groundwater zones in the Kamiesberg region, SouthAfrica* is my work, that it has not been submitted before for any degree or examination in any other university, and that all sources I have used or quoted have been indicated and acknowledged by complete references.

SEAN DAVIDS FEBRUARY 2003

SIGNED: ....

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TABLE OF CONTENTS

UNIVERSITY of the WESTERN CAPE
http://etd.uwc.ac.za/

UNIVERSITY of the
WESTERN CAPE

http://etd.uwc.ac.za/

CHAPTER 5

Conclusion and Recommendations

UNIVERSITY of the
WESTERN CAPE

http://etd.uwc.ac.za/

LIST OF FIGURES

UNIVERSITY of the WESTERN CAPE

http://etd.uwc.ac.za/

UNIVERSITY of the
WESTERN CAPE

http://etd.uwc.ac.za/

LIST OF TABLES

UNIVERSITY of the
WESTERN CAPE

http://etd.uwc.ac.za/

CHAPTER 1

1.1 General introduction

Groundwater is an important asset to rural communities where surface water is scarce or non-existent. In South Africa, over 90% of the water resources are located in fractured rock aquifers, which are normally exploited by means of boreholes (Pietersen, *et al*., 1996). The variable geological terrains in South Africa pose different challenges to groundwater practitioners. The identification of potential groundwater resources is vital for the sustainability of the water resources, surface and groundwater, in South Africa. The study area, located between latitudes $17^0 45^{'}$E, $18^0 15^{'}$E, longitude 30^0S, and $30^0 30^{'}$S includes three towns, namely Kamieskroon, Leliefontein and Karkams, and various small farms (Fig. 1.1). Groundwater is the only source of drinking water for the inhabitants of this area, which is located within the Namaqua Province that forms part of the crystalline basements in the Northern Cape and southern Namibia. The Northern Cape (Namaqualand), an arid to semi arid region, has variable climate, periodic precipitation and scant vegetation. The study area covers the Kamiesberg mountain range and will be referred to as the Kamiesberg region.

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1.2 Climate

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Climatic conditions within the Namaqualand region vary sporadically. The area is located within the Cape winter rainfall region, where anticyclonic conditions off the west coast are due to the cold, northward flowing Benguela current. The determining factors that control the climate is the altitude, topography and the distance from the sea. Air movement is blocked by the mountainous region, causing fluctuation of inland temperature plus condensation of moist coastal air allowing for the survival of endemic flora. Hot, bergwind conditions are common during the winter months. According to Williamson (1990), the mid-year escarpment

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temperature before dawn is at frost level compared to the coastal plain, which might be about 6^{0}C.

1.3 Vegetation

The vegetation is characterized by the Nama Karoo biome, which is dominated by a mixture of grasses and low shrubs to the east (Low and Rebelo, 1996). The western part is characterized by the succulent Karoo biome, whilst dwarfs and succulent shrubs with deep root systems dominate the vegetation. The Kamiesberg mountain range has a sclerophyllous bush type (op. cit).

Vegetation is highly dependent on groundwater. Plant species such as *Prospis* (moderately drought tolerant, facultative phreatophytes) indicate where groundwater is available (Low and Rebelo, 1996). Acacia Karoo (riparian shrubs and trees) is found in the alluvial aquifers of the Buffels River.

1.4 Precipitation

The region is situated within an arid to semi arid area of South Africa. Maximum rainfall occurs within the higher lying areas of Kamiesberg mountain (Table 1.1) south of Springbok. The high rainfall is due to the orographic effect. Snow during winter months is common in the Kamiesberg mountains. Potential evapotranspiration can be between 12-15 times the precipitation, and in some areas this factor is as high as 22 times (Titus, *et al.*, 2002). This high evaporation to precipitation ratio means that salts will easily be formed on the subsurface.

Run-off is 0- 2,5 mm and as high as 5mm along the Kamiesberg mountains. Soil depth is shallow, with a sandy texture along the steep relief (Midgley, *et al.*, 1994).

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Table 1.1 Climatological data for the three catchments that comprise the Namaqualand region (After, Adams, *et al.*, 2002).

Catchments	Gross Area (km^2)	MAE* (mm)	MAP* (mm)	MAE/ MAP
F30	9756	2200	143	15
F40	5346	1900	140	14
F50	4869	1900	159	12

**MAE- mean annual evaporation*

**MAP- mean annual precipitation*

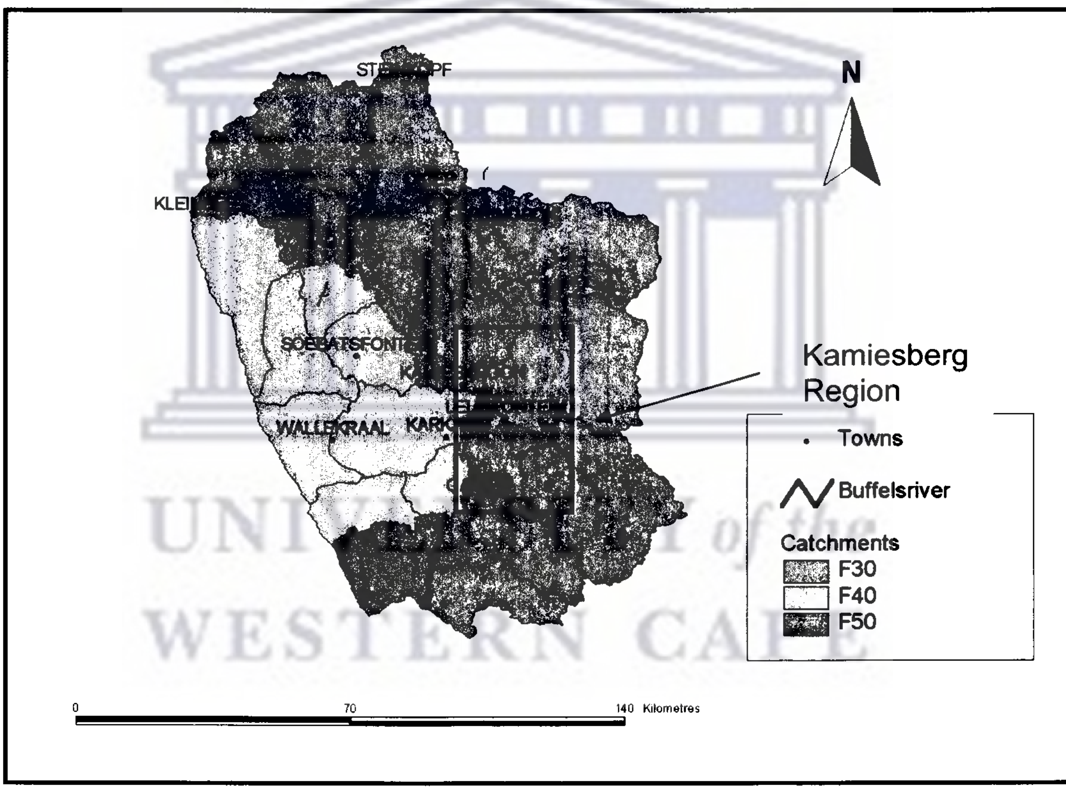

Figure 1.1. Locality map of the study area, the Kamiesberg region.

Groundwater in crystalline basement rocks or ‘hard rocks’ (Wright, 1992) occurs mainly along fractures, faults, shear zones and in the weathered overburden (Titus, *et al.*, 2002). A high degree of fracture density/ frequency results in greater weathered overburden (Edet, *et al.*, 1994).

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The weathered overburden zones are inferred to be the optimal sites for potential groundwater resources (Greenbaum, 1992). The focus of the thesis is to apply remote sensing techniques to identify potential groundwater resources in the Kamiesberg region. Remote sensing techniques aid with mineral, groundwater and petroleum exploration (Siegel and Gillespie, 1980).

1.5 Background of the study

This study forms part of a two year Water Research Commission (WRC) funded project entitled: "Sustainable management and utilization in the semi-arid Northern Cape: Geomechanical mapping as a tool for groundwater exploration of fractured rock aquifers".

The rural region of the Northern Cape experiences vast water shortages primarily due to the low rainfall and the complex nature of the geology. The large towns, Springbok, Nababeep, Okiep and Kliensee, (figure 1.1) have water supplied from the Orange River. The area has a complex geological history of fractures, faults, folds and shears. The region is characterized by a fractured crystalline basement aquifer that lacks primary porosity. Groundwater occurs mostly along fractures and no serious attempt has previously been made to identify potential groundwater resources for the area.

There is a lack of reliable data on the present groundwater state in the Northern Cape. The conceptual understanding is based on field investigation and discussions.

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1.6 Aims and Objectives

The aim of the study is to apply remote sensing techniques to identify optimal zones as potential groundwater resources in the Kamiesberg region.

The objectives are to:

- Understand the flow and storage of groundwater in a fractured crystalline basement rock environment;
- Infer the influence of palaeo-stress and neotectonic activity and their influence on fractured basement aquifers;
- Investigate the present groundwater state of the region, i.e. borehole location, yield and depth; and
- Infer the optimal zones for borehole location

1.7 Organization of the study

The first three chapters concentrate on the descriptive and observed characteristics of the area. The remaining chapters focus on the presentation of results and discussion. A case study of Kamieskroon is presented in these chapters.

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Chapter 1- General introduction.

Chapter 2- Literature review.

Chapter 3-Methodology.

Chapter 4- Results and a case study. A discussion follows the presentation of the results.

Chapter 5- Conclusions and recommendations.

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CHAPTER 2

Literature review

2.1 Introduction

The application of remote sensing techniques is a necessary preliminary tool to plan any groundwater assessment study for a region or a catchment (Hartnady and Hay, 2000). This chapter reviews remote sensing techniques, tectonic stress and its influence on the region, the geomorphology and its weathered profiles and the current groundwater state. The literature reviewed in this and subsequent chapters investigate the influence of these different variables.

2.2 Previous work

No previous work relating to this research has been attempted in the Namaqualand region to date. The Department of Water Affairs and Forestry (DWAF) and consulting companies, Toens and Partners, are responsible for existing groundwater supply to communities in the Northern Cape region. The University of the Western Cape (UWC) in partnership with the Water Research Commission (WRC) conducted numerous projects in the Northern Cape. These projects are based on the groundwater assessment and strategies for sustainable resources supply in arid zones (Titus, *et al.*, 2002), and groundwater recharge to crystalline basement aquifers (Adams, *in prep.*).

Additional research consists of:

- A hydrochemical evaluation of groundwater in parts of the Namaqualand region (Stevens, 1999),
- Quantitative estimation of groundwater recharge methods of crystalline basement rock aquifers in Namaqualand (Davids, 2000, Flanagan, 2000, Mafanya, 2000),

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- An approach to aquifer test pumping in fractured crystalline aquifers (Hassan, 2002) and,
- Measurement of intrinsic porosity and permeability of fractured crystalline basement rock aquifers (Flanagan, *in prep.*).

2.3 Remote sensing

The application of remote sensing techniques has aided with various mineral, petroleum and groundwater exploration. Kneppe, *et al.*, (1994) used remote sensing (aerial photographs) and air borne geophysics for the detection and mapping of potential aggregate sources. Rowan, (1998) used it for the location of mineral resources in the eastern United States whilst Tavaglia (1998), applied the technique for the exploration of groundwater in the Syrian Arab Republic. In South Africa, remote sensing techniques are used widely in all aspects of earth and environmental science. Hartnady and Hay (2000), applied it to the groundwater exploration in the Table Mountain Group aquifer and Sami, et al., (2002) applied it to groundwater exploration in geological complex terrains in South Africa.

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Kearey (1996), defines remote sensing as the recording of images of parts of the Earth's surface using electromagnetic radiation, normally from an aircraft or satellite at sufficient height for a broad area to be covered. Siegel and Gillespie (1980), define it as the science of gathering information in areas that are inaccessible (i.e. rugged, political turmoil, hazardous location). Modern techniques analyze multispectral images that record the way solar energy is reflected or emitted by the materials exposed at the Earth's surface (Rowan, 1998). Remote sensing systems collect digital measurements that are processed, analyzed and interpreted using computer techniques, and are easily incorporated into geographical information system (GIS) databases (Kneppe, *et al.*, 1994). The technique includes passive aerial photography and Landsat satellites using multispectral scanner and thematic mapper, and the SPOT-1 satellite, and

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active techniques, such as radar, which show the topographic texture in the presence of cloud cover.

The uses of remote sensing techniques to groundwater practitioners are:

- To identify rock types, fracture zones, fault zones, drainage patterns and various types of unconsolidated deposits or different vegetation patterns that possibly act as groundwater indicators;
- To identify features in hard rock areas with limited regolith cover;
- To infer potential fracture or fault systems or magnetic structures like dykes and sills that can show up as linear features, commonly referred to as lineaments;
- To find possible targets, which can be corroborated by field visits and geophysical surveys.
- To use as a necessary preliminary tool for the planning of any regional catchment management study;
- To facilitate planning for the collection of data for modeling.

The electromagnetic spectrum is divided into wavelength bands of various lengths and frequencies. The short wavelengths (high frequencies) are the ultraviolet bands (UV), whilst microwave and radio bands have long wavelengths (low frequencies). The resolution of Landsat thermal mapper bands is 30m (Rowan, 1998), except for band 6, which is 120m. Table 2.1 gives a list of the seven spectral bands used by Landsat TM and their application to geological features (Sami, *et al.*, 2002).

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Table 2.1. Spectral divisions used by Landsat TM and their application to geological features (after Sami, *et al.*, 2002).

Visible region (0.4- 0.7 µm)	Band 1 (0.45- 0.52 µm)	Designed for water body penetration-useful for coastal water mapping Differentiation of soil from vegetation and deciduous from coniferous flora
	Band 2 (0.52- 0.6 µm)	Designed to measure green reflectance peak of vegetation for vigor assessment
	Band 3 (0.63- 0.69 µm)	A chlorophyll absorption band important for vegetation discrimination
Reflected Infrared (0.7- 3 µm)	Band 4 (0.76- 0.9 µm)	Determining biomass content Delineation of water bodies Tectonic analysis
	Band 5 (1.55- 1.75 µm)	Vegetation moisture Soil moisture content Differentiation of snow from clouds
	Band 7 (2.08- 2.35 µm)	Discrimination of rock types Hydrothermal mapping
Thermal Infrared (3- 5 µm and 8- 14 µm)	Band 6 (10.40- 12.50 µm)	Useful in vegetation stress analysis Soil moisture discrimination Thermal mapping

Several different enhancing techniques can be employed to highlight groundwater-controlling features. Those considered of relevance to groundwater investigations are listed in Table 2.2 (Sami, *et al.*, 2002).

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Table 2.2. Purpose of different digital techniques (after, Sami, *et al.*, 2002)

Digital technique	Purpose
Linear stretching	Normalization of raw data
False colour composite	Extraction of geology, Hydrogeomorphic features
Band combination	Extraction of vegetation distribution within valley zones and lineaments
Principle component analysis	Extraction of hydrogeomorphic features
Filtering	Extraction of linear features like fractures, faults, dykes, joints using algorithms

2.4 Tectonic stress

The Kamiesberg region is characterized by a crystalline basement aquifer that lacks primary porosity. The groundwater is mainly found along fracture conduits and faults resulting from brittle deformation and active seismic zones.

The Kamiesberg region displays relatively low intensity (<5M) stress release recorded from the Vaalputs nuclear waste depository site (Andreoli, *et al.*, 2001, Figure 2.1). There is a distinct diffuse distribution of seismicity with scattered occurrences of localized zones of concentrated seismicity in South Africa (Meus and Chevallier, 2000). These epicenters are responsible for variable intensity earthquakes in the region. More energetic earthquakes are at present recorded near Leliefontein close to the intersection between the Griqualand- Transvaal and the Kamiesberg axis (Andreoli, *et al.*, 1996). The Kamiesberg region is affected by two important uplift axes activated between Miocene and Pliocene-Pleistocene times (Brandt, 1998).

The Kamiesberg region is situated along energetic seismic zones, which, because of the influence on the fractures and faults, has a positive effect on the groundwater state of the region (Andreoli, *pers. comm.*, 2002).

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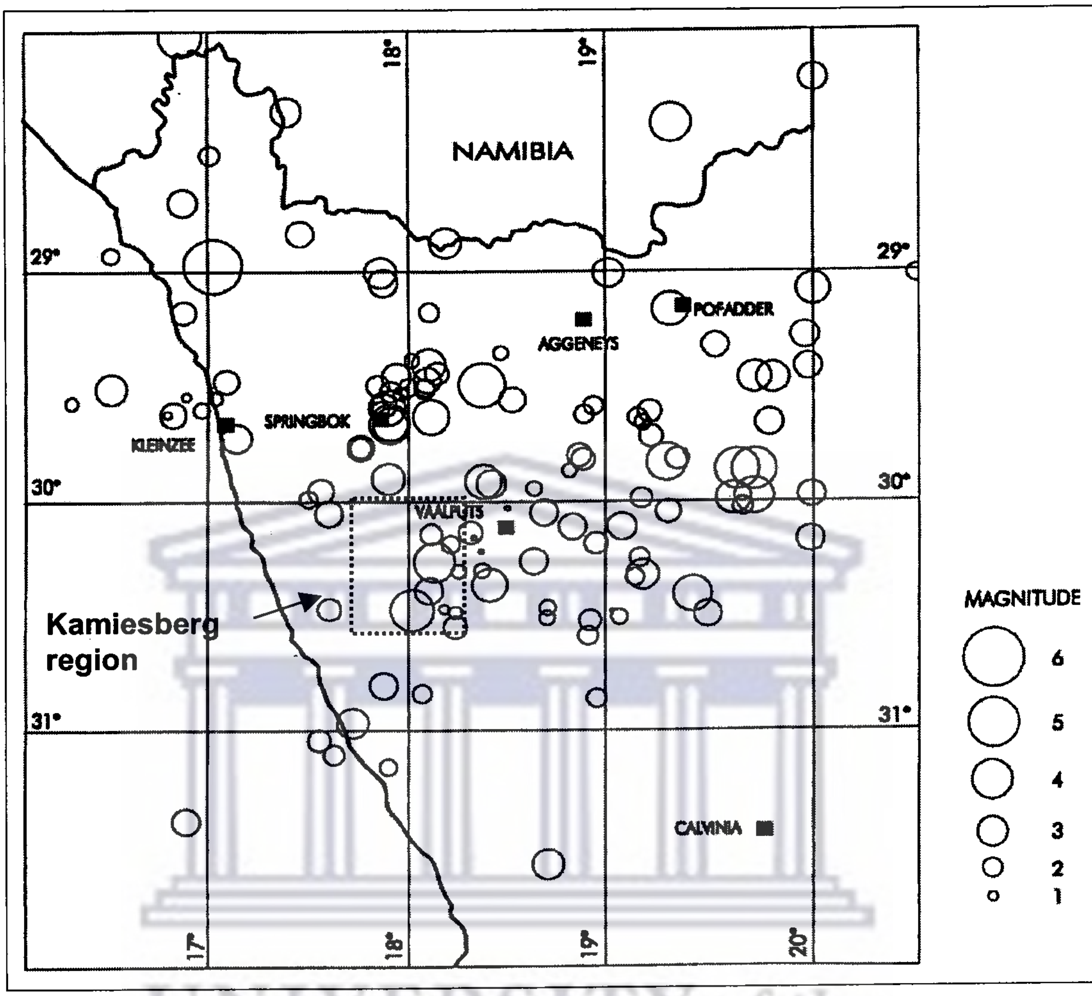

Figure 2.1. Epicenters of seismic events recorded by the A.E.C. in the northwestern Cape (after Brandt, 1998).

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2.5 General geology

The area under investigation forms part of the Namaqualand Metamorphic Complex (NMC) that has been intensely studied and mapped. The Bushmanland Subprovince is not only the largest part of the NMC, but is also the most important as far as mineral deposits are concerned. This area includes the unique noritoid ore bodies of Okiep, the stratiform deposits of Aggeneys and Gamsberg, a number of other small base metal deposits, the bulk of the pegmatite's yielding minerals of economic value, (Joubert, 1986), and the alluvial diamond deposits along the coast and the

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Buffels River. Previous authors in the NMC have all concentrated on specific aspects of geology. The region referred to as the NMC includes the western part of the Namaqua- Natal mobile belt.

The Proterozoic Namaqualand Metamorphic Complex (NMC) encompasses a large region. Van der Merwe (1995) defines it as that domain which was subjected to the 1000- 1200 Ma Namaqua orogeny, and it also includes rocks of the 1700- 2000 Ma Richtersveld Province (Blignault *et al.*, 1983). Joubert, (1971, 1974b; 1986,1986a) completed a detailed study of the lithology, structure, deformation and metamorphism in the NMC. His work concluded that the NMC is a polyphase deformed and metamorphosed gneissic terrain consisting of paragneisses derived from various sedimentary and volcanic rocks, intruded by a great variety of igneous rocks. Gibson *et al.*, (1996) relates the complex deformational and intrusive history to two main orogenic events, at ~1200- 1250 Ma and ~1030 Ma.

Tankard, *et al.*, (1982) referred to a 'missing basement' whilst Joubert (1986), proposed a model of Proterozoic accretion as the origin of the basement of the area. Waters, (1986), van Aswegen, *et al.*, (1987), and Moore (1989), investigated the metamorphic effects and concluded that high-grade metamorphism of upper amphibolite facies occurred throughout the NMC. The metamorphic peak postdates tight and recumbent folding and metamorphic fabrics imprint upon granitic augen gneisses, which are believed to represent early, or syntectonic intrusions (Joubert, 1974b; Waters, 1986). Van der Merwe (1995) discussed the tectonic development of the Namaqua mobile belt with specific reference to thrusting, vertical shearing and folding in the three tectonic domains recognized by Blignault, *et al.*, (1983). Joubert, (1971, 1974b, 1986a) and Gibson, *et al.*, (1996) recognized four phases of deformation D_1- D_4, with a main (D_2) event. However, Marais, *et al.*, (2001), recognized six phases, the first four are represented by folding and the last two by faulting and

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shearing events. The geology of the NMC is inherently complex and was investigated by various authors through different times.

According to Joubert, (1971,1974b, 1986a), Blignault, *et al.*, (1983), Gibson, *et al.*, (1996), Moore, (1989) and van der Merwe, (1995), the four deformation phases recognized in Namaqualand are:

D_1: The early deformational episode (D_1) is seen in the metavolcanics of the Orange River Group. It involves isoclinal folding with planar and linear fabrics (Blignault, *et al.*, 1983). Evidence for the D_1 deformation phase is not apparent and is poorly defined.

D_2: evidence of the D_2 deformation event is recorded in the supracrustal gneisses of the NMC. According to Blignault, *et al.*, (1983), the D_2 event is responsible for the subhorizontal, east west structural trends in the Bushmanland Subprovince. The D_2 deformational event resulted in the highest intensity of structural modification, (Moore, 1989), and created major isoclinal folds, thrust planes and large-scale re-orientation of primary fabric features (van der Merwe, 1995). A prominently developed mineral lineation occurs as a *b*- fabric in the minor folds belonging to the D_2 generation (Blignault, *et al.*, 1983). Pegmatites and emplaced basic bodies are seen as part of the D_2 deformation (Joubert, 1971). Within the Okiep District (Gibson, *et al.*, 1996), the most characteristic D_2 feature is a heterogeneously- developed, generally pervasive, subhorizontal S_2 gneissose foliation. The S_2 foliation is associated with a regional, subhorizontal, east-north-easterly- trending mineral lineation, L_2, which is defined by flattened feldspar augen, quartz aggregates, and mafic aggregates. According to Gibson, *et al.*, (1996), the D_2 commenced shortly before the intrusion of the Spektakel Suite. The L_2 lineation is recognized throughout the area and is expressed by alignment of the high- grade metamorphic minerals (Joubert, 1986).

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D_3: Joubert, (1971), recognized folds deforming the earlier structures and resulted in the formation of large periclinal structures due to the interference with F_2 folds. The deformation occurred throughout the area and is responsible for the east- west lithological banding over large parts of the area. The D_3 structures are generally asymmetric, with steep northerly dipping axial planes. They trend east- west and has a shallow plunge of variable intensities ranging from large open structures to tight, nearly isoclinal structures (Moore, 1989).

D_4: The D_4 deformation event is marked by structures with variable intensity, style and trend. According to Blignault, *et al.*, (1983), minor folds deforming D_3 structures have axial planes striking northeasterly with steep northwesterly dips and are referred to as D4 folds. The deformation is concentrated on the open D3 structures.

2.6 Lithostratigraphy

An extensive lithostratigraphic breakdown of the Namaqualand Metamorphic Complex (NMC) is given in SACS, (1980), whilst subsequent authors, Visser (1989) and Marais, *et al.*, (2001) provide a crisp summary. The area is characterized by an assemblage of low- to high-grade metasedimentary rocks, unmetamorphosed platform sediments and an array of granitic, basic and ultrabasic intrusive rocks varying in age from early Mokolian (Kheisian) to Namibian (Marias, *et al.*, 2001). Extensive Cenozoic deposits characterize the coastal area. However, a lithostratigraphic investigation is treated with caution within this multi-deformational region, mostly because all the authors working in the area assign different names to the units making correlations virtually impossible.

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Council of Geosciences, (1997), 1: 1 000 000 map of South Africa provides a crisp interpretation of all the basic lithostratigraphic units that are located in the Kamiesberg region (Table 2.3).

Table 2.3. The lithological units identified in the Kamiesberg region.
(* Not yet accepted by SACS but incorporated into the latest 1: 1 000 000 geological map of South Africa, Council of Geosciences, 1997)

INTRUSIVES		METASEDIMENTS		
Suite/Group	Formation	Subgroup	Group	
	*Buffels River Granite			AGE (~1200 Ma) ↓
	*Kamieskroon Gneiss	Bitterfontein		
*Stalhoek Complex	Nababeep Gneiss		Bushmanland	

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2.6.1. Metasediments

The Bitterfontein Subgroup of the Bushmanland Group is the only metasedimentary group that occurs throughout the Kamiesberg region. The rocks of this Subgroup are exposed to the south of Garies, near and around the town of Bitterfontein (figure 2.2). Near Bitterfontein, where several rock types belonging to this Subgroup occur repeatedly, it is suspected that they were folded isoclinally (Visser, 1989).

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The most common succession found is:

(3) white metaquartzite, locally feldspathic and arkosic, and quartz-sericite schist

(2) cordiorite sillimanite- garnet gneiss and schist, together with thin intercalations of quartzite, amphibolite, biotite schist and gneiss, with the latter graphitic in places

(1) a thin layer of quartz feldspathic gneiss that occurs sporadically at the base, and is locally separated from the overlying rocks by amphibolite (SACS, 1980; Visser, 1989).

2.6.2 Syntectonic intrusives

The syntectonic intrusives cover a large percentage (70%) of the study area. The syntectonic Suites and Formations that will be investigated include the Nababeep gneiss, the *Buffels River Granite, the *Stalhoek Complex and the *Kamieskroon Gneiss.

2.6.2.1 The Nababeep Gneiss

The Nababeep Gneiss is the oldest intrusion and underlies a large portion of the core area of the Springbok antiform (Marais, *et al.*, 2001).

The gneiss is composed of well-foliated quartz-feldspar-biotite gneiss, with the augen composed of aggregates of quartz and feldspar, surrounded by biotite. According to Joubert, (1971) and Blignault, *et al.*, (1983), the D_2 penetrative foliation and regional lineation are prominent in the Nababeep gneiss around Springbok. South and southeast of Springbok, the foliation disappears and the coarseness increases. The augen become undeformed and consist of aggregates of quartz and microcline. However, according to SACS, (1980) and Visser, (1989) the augen becomes angular and are found within the undeformed granitic gneiss.

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2.6.2.2 The Stalhoek Complex

The Stalhoek Complex consists of leucocratic biotite gneiss with variations of quartz feldspar gneiss (Council of Geosciences, 1997). The minerals cordiorite, aluminium-rich garnet, and sillimanite are visible in certain areas (Visser, 1989).

2.6.2.3 The Kamieskroon Gneiss

According to the Council of Geosciences, (1997), the Kamieskroon gneiss consists of a leucocratic gneiss (feldspar, quartz, biotite, hornblende). The lithology consists of red- brown weathering, homogeneous, foliated biotite-augen gneiss containing garnet in places; 'augen' consists of aggregates of quartz and K- feldspar surrounded by biotite- streaks.

2.6.2.4 The Buffels River Granite

The Buffels River Granite, a biotite granite, is located at the intersection of the N7 national road with the Buffels River. The Buffels River granite is emplaced syntectonically during the early stages of the major D2 structural event (Moore, 1989).

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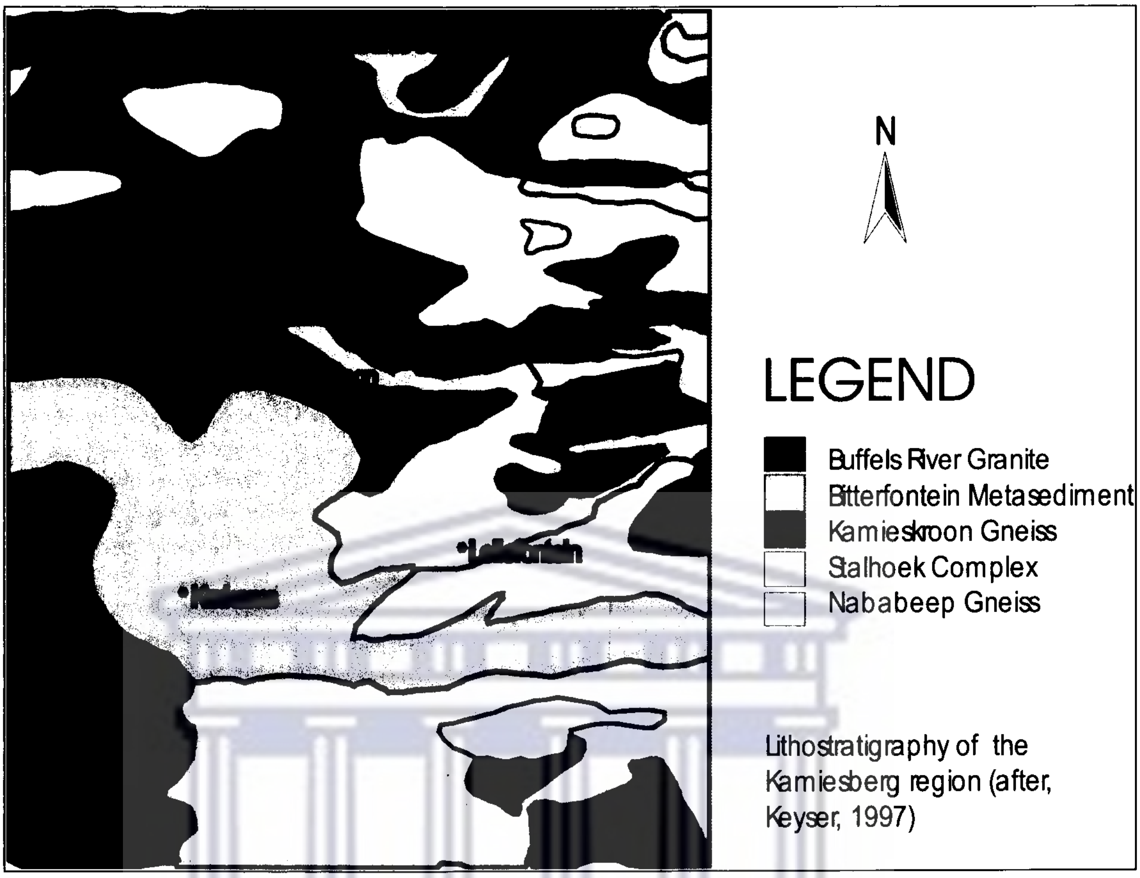

Figure 2.2. Lithostratigraphy of the Kamiesberg region (after Council of Geosciences, 1997)

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2.7 Geomorphology

Moon and Dardis, (1980), Partridge and Maud, (1987, 2000), Gilchrist, *et al.*, (1994) and Partridge, (1998) meticulously discuss the geomorphic evolution of Southern Africa. However, on the local scale, there have been no geomorphic investigations in the Kamiesberg region. Ellis (1988) interpreted the soils of the Karoo including the Namaqualand region, with Bense, *et al.*, (1998) conducting morphotectonic and hydrogeomorphic investigations along the Buffels River catchment. The geomorphic history of South Africa, post Gondwanaland, is divided into various stages, namely the African erosional phase, the Post African I erosional phase and the Post African II erosional phase, with the latter being the youngest in age. A gentle pediplain (African surface) extends across most of South

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Africa at an elevation of 500- 600m prior to Miocene rifting (Partridge and Maud, 1987).

The break up of Gondwanaland during the Miocene caused the general outline of South Africa (Moon and Dardis, 1980). There are a number of problems associated with the application of denudation chronology in landscape interpretation. The problems arise from the manner in which surfaces develop and the relationship between surfaces, base levels and tectonic events (King, 1942, Moon and Dardis, 1980).

The African erosional phase is the oldest and the most prominent erosional event in South Africa. It is rarely in pristine condition and is partly planed. The long duration allowed for the transgression of geological structures by plantation, deep weathering and the formation of duricrust (Partridge and Maud, 1987). Miocene uplift initiated the Post African I erosional phase that lasted until the Late Pliocene. The African erosional phase was terminated by a major landscape uplift of the subcontinent during the Miocene. Vertical movement varied from 300m (south Swaziland) to 200m (Umtata) and 150m inland, from the west coast (op cit.). The Post African surfaces (I and II) are less varied. Below the Great Escarpment, the Post African I erosional surface is present in pristine condition but it occurs usually as dissected tablelands. The short duration of the Post African I erosional phase (terminated Pliocene) resulted in imperfect planation in most areas to levels of no more than 100- 300m below the African erosional surface (Partridge and Maud, 1987). Miocene uplift induced the incision of structurally controlled African I landscapes. The Post African II erosional surface is expressed by recent incisions (Moon and Dardis, 1980). Partridge and Maud (1987), suggest that the African surface is the highest and oldest erosion surface, although dissected highlands exist at greater altitudes.

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2.7.1 Weathering profiles

McFarlane, (1987), McFarlane, *et al.*, (1992), Wright, (1992), Greenbaum, (1992), Gustafson and Krásný, (1994), Chilton and Forster, (1999) discuss the effect that weathering has on basement rock aquifers. The weathered zones are inferred to be the optimal zones for siting of boreholes in these environments (Greenbaum, 1992). Aggressive weathering and differential leaching has, through the downward movement of infiltrating water, resulted in deep regolith profiles (figure 2.3). The residual soil is generally characterized by kaolinite, quartz and oxidized iron (Fe) minerals. The soils have relatively high infiltration capacity as well as pathways for preferential flow in low permeable soils (Chilton and Forster, 1999). This zone has different formational characteristics. The weathering and erosional episodes are responsible for the formation of regolith, a zone of alteration products, normally more than 10m thick and overlain by residual soil (Gustafson and Krásný, 1994, Chilton and Forster, 1999). The residual soil is generally characterized by red, silty quartz-sand with basal lateritic concentrations. A zone of saprolite extending down to 20m consists of massive accumulations of mainly secondary clay (especially kaolinite), with subordinate silty sand and occasional weathered rock fragments. The lower reaches of the saprolite have a higher proportion of primary minerals, rock fragments and basal breccia. The saprock consists of deeply weathered and partially decomposed rock with some fractures filled by secondary clays; the fresh, intact rock is largely unweathered and contains some staining (Chilton and Forster, 1999). The hydrogeologic properties of the regolith, including the rate and depth of weathering, are influenced by bedrock type, the presence of Fe- Mg minerals and the density of structural features such as fracture zones and dykes (Titus, *et al.*, 2002). The weathering and leaching processes tend to increase the porosity, permeability and specific yield (positive groundwater effects), whilst the deposition of clay minerals (as products of weathering processes) can cause a reduction in these hydrogeological properties (Chilton and Forster, 1999).

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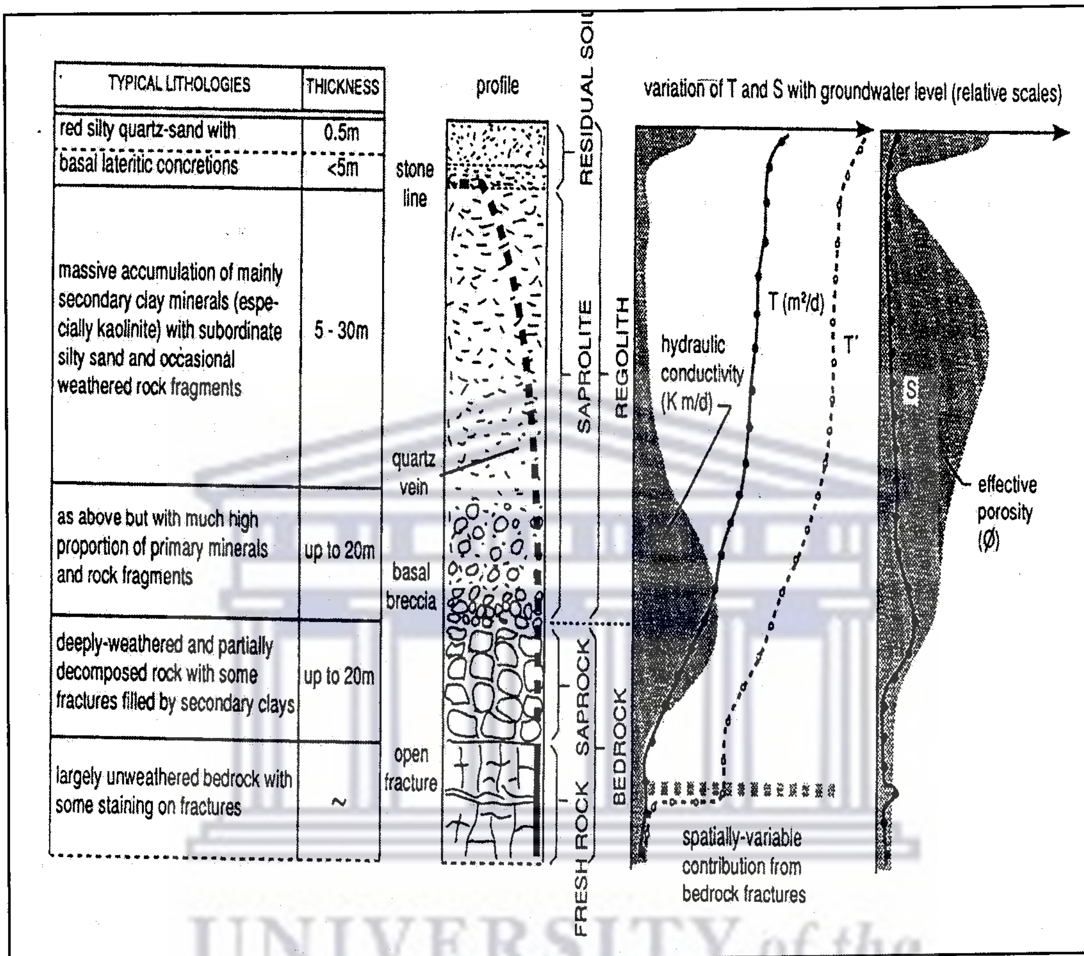

Figure 2.3. Typical weathered profile for Precambrian basement rocks (after Chilton and Foster, 1999).

2.8 Hydrogeology

The water supplied to the communities in the Kamiesberg region is solely from boreholes. The Department of Water Affairs and Forestry (DWAF) and consulting company, Toens and Partners, are responsible for the groundwater assessment and supply to the Namaqualand region. The groundwater characteristic is of marginal quality and quantity (Piet Roux, Kamiesberg municipality, *pers. comm.*, 2001). Delineating groundwater flow in central Namaqualand is difficult due to paucity and irregular

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distribution of the boreholes. Most boreholes in the region are located within the structurally controlled valleys (Titus, *et al.*, 2000).

Within boreholes observed in the Namaqualand region, there are spatial as well as vertical variations in the groundwater chemistry. This seems to be dependent on the position of the sampling point within either shallow, fast (i.e. active) or deeper, slower circulating flow systems (Titus, *et al.*, 2000). The deeper circulating, higher salinity groundwater probably experiences insignificant recharge under present climatic conditions (Adams, *et al.*, 2002). It is also affected by the different flow systems, i.e. the varying flow-path length (residence time) and water rock interaction.

According to Pietersen, *et al.*; (1996), the electrical conductivity (EC) values of the Leliefontein rural area vary between <300mS/m to more than 1000mS/m with values as low as 74mS/m and as high as 2918 mS/m. It is expected that groundwater with high Cl and Na values are generally associated with high EC values (op cit.). The groundwater found in the Leliefontein region has Na and Cl values that conform to the recommended SABS levels for drinking water. The fluoride concentration varies between 1.2 mg/l and 5.6 mg/l. The best quality water occurs in granites (EC ± 400 mS/m), with pink feldspathic granite yielding the best quality water (EC ± 151 mS/m). Schists, leptite and gneisses yield progressively less quality water. These differences in EC and fluoride values are ascribed to variations in rather unfavorable evaporation/ rainfall ratios, annual precipitation controlled by elevation and local geology (op cit.).

The groundwater quality on a regional scale depends on various factors namely, rainfall, evapotranspiration, topography and geology (Titus, *et al.*, 2002).

Other important factors influencing the chemical composition on a less extensive or even local scale include:

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1. Surface water bodies and their chemical composition,
2. Micro-climate, and precipitation quality (which often depends on the proximity to the sea),
3. Anomalies in rock composition (e.g. mineral deposits, soluble minerals such as gypsum and salts) and
4. Zones of discharge of deep-seated groundwater (Gustafson and Krásný, 1994).

The Northern Cape region offer groundwater challenges regarding the chemistry, borehole yield and potential resources. However, no real attempt has been made to identify potential groundwater resources in this fractured crystalline basement environment. The present research tries to resolve that problem by supplying information to a data-lacking environment.

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CHAPTER 3

3.1 Introduction

The study integrated two processes, namely a desktop analysis and field studies. The field study commenced after the initial desktop analysis and was used to ground truth the initial understanding of the region.

3.2 Methodology

3.2.1 Remote sensing analysis

Aerial photographs, topographic maps, published geological maps and satellite images were part of the remote sensing analysis. The aerial photographs were used to identify major structural trends and basic geomorphic features.

The aerial photographs were viewed under a stereoscope for three-dimensional viewing. The photographs were viewed along a north south flight plan (60% overlap) and the linear features identified on different tracing sheets. A reference point was used to mosaic the 75 traced sheets along their borders. All the sheets of the different flight plans were traced onto a single sheet that covered the Kamiesberg region. This single sheet was transferred onto a digitizing board and traced with MapInfo computer drawing program. The aerial photographs were scanned at 600 dpi resolution and resampled to 300 dpi in order to achieve file size reduction without the loss of image resolution. The scanned images were georeferenced, projected and subsequently mosaiced into a single image.

Four topographic 1:50 000 sheets (3017BB; 3018AA; 3017BD; 3018AC) were scanned at 600 dpi and resampled to 300 dpi in order to achieve file size reduction without the loss of image resolution. The sheets were georeferenced and included as a data layer.

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Landsat TM scenes 176/80 and 176/81 were georeferenced and projected to the specified projection parameters. A band combination of 741 was selected for highlighting structural features and differences between lithological units most effectively in a semi-arid terrain such as the Namaqualand region of the Northern Cape Province. Additional contrast enhancement was achieved by performing a principal component analysis (PCA) for all bands of both Landsat TM scenes, with the exception of the thermal band 6. Having selected only the first principal component (PC1) of both Landsat TM scenes, a high boost filter was applied to the PC1s.

The observed lineaments from both the aerial photographs and Landsat images were merged and in ERDAS, grid files were created. The grid files were subsequently contoured in Surfer to create lineament frequency and lineament intersection maps. The data layers were viewed in a geographical information system (GIS) database Arc View 3.1.

3.2.2 Field methods

A comprehensive structural analysis of joint and fracture planes and borehole investigations was conducted in the Kamiesberg region.
The dip, strike and dip direction readings of the various fractures and joints were recorded with the aid of a Freiberger compass. The Freiberger compass is essentially used to verify dip direction, dip and strike of the planar features; and the plunge and trend of linear features. The resultant data were interpreted in geological programs, Stereo and Rose, similar to the stereographic projection technique. The program records dip and direction measurements and can be used to infer stress orientations and pervasive fracture, joint and lineation orientations.

3.2.3 Hydrogeological study

The hydrogeological study commenced with the investigation of the national groundwater database (NGDB). The NGDB provides the location, yield, discharge, depth, water level, chemistry and the date that the

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boreholes were measured. The field investigations and the current groundwater reports were used for the verification of the dataset. The current groundwater state of the town Kamieskroon was investigated as part of enquiries into the local water supply. Borehole depth and the pumping yield were recorded from the existing work of consulting companies.

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CHAPTER 4

Results and Discussion

4.1 Introduction

This chapter presents all the results from the study conducted in the Kamiesberg region. The remote sensing analysis, fieldwork and additional work are recorded in various data layers. The structural trends, lineament analyses (frequency, intersections), fracture trends and groundwater state are used to validate the interpretation. Potential groundwater zones have been identified for the Kamiesberg region.

4.2 Structural trends

The Kamiesberg region displays varied structural trends. The trends are inferred from field investigations and the relevant literature. The region experienced multi-deformational activity from the Early Proterozoic to the Late Phanerozoic. This is quite evident along the Buffels River (southern border of Kamiesberg region) where ductile deformation (shearing) and later brittle deformation (fracturing and faulting) is evident. Pegmatites and basic dykes of variable age, size and composition are common throughout the Kamiesberg region. Their dominant strike is east west (E-W) with orientations of north-northeast (NNE) and north-northwest (NNW) also present.

Blignault, *et al.*, (1983) described the Buffels River shear zone as part of a regionally widespread, east- to southeast trending system of shears, the Nous shear system. This shear system has been interpreted as a dextral, north side down oblique- slip shear system. Brittle deformation along the Buffels River shear zone is seen in the NNE trending fracture systems (figure 4.1).

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Figure 4.1. NNE striking fractures along the Buffels River shear zone.

The generally pervasive, subhorizontal, east west trending S_2 foliation, (D_2 deformation) is cut by the NNE trending fractures. The fractures are filled by dyke material, which Joubert, (1986a), related to the Gannakouriep dyke swarm (550Ma- 920Ma) of the Pan African orogenesis. This fracture system also displaces the pegmatitic intrusives. The intrusive Buffels River granite, (Council of Geosciences, 1997), is cut by easterly trending pegmatitic and quartzitic veins. Joubert, (1986a) relates the pegmatites to the fourth phase of deformation in the NMC (900- 1000Ma). The NNE trending fractures of the Pan African orogenesis displaced the pegmatites, creating graben structures with a downthrow of 4cm to the south (figure 4.2). The latter is insignificant when compared to the regional deformational events; however, it can be used as a time marker on the local scale for brittle deformation.

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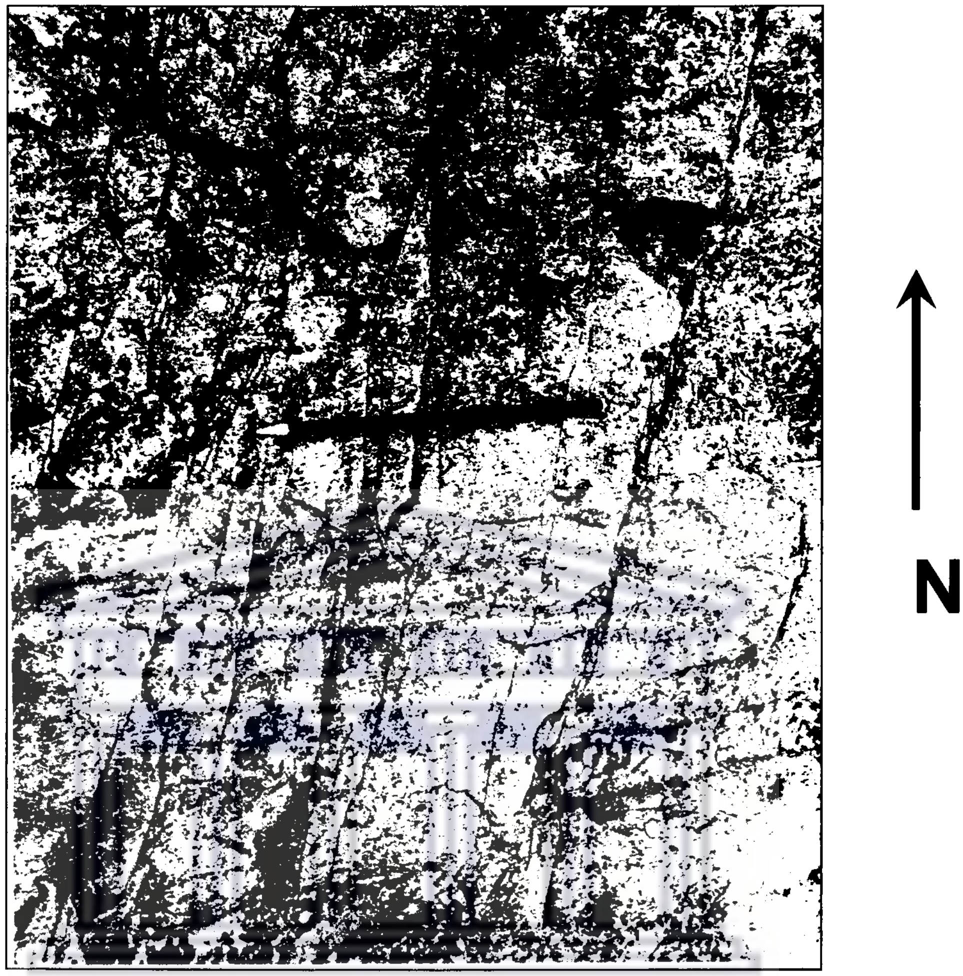

Figure 4.2. Plan view of east west trending pegmatite veins being faulted by NNE trending fractures.

The Kamiesberg region is the southern extent of the Okiep copper district where high-grade metamorphism of upper amphibolite to granulite facies occurs (Gibson, *et al.*, 1996). Various fold styles are visible in the region. In figure 4.3 an isoclinal fold with round hinge zone is visible in the gneissic banding of the Kamieskroon gneiss. Joubert, (1986a) ascribes these folds to the main deformational event (D_2, deformation).

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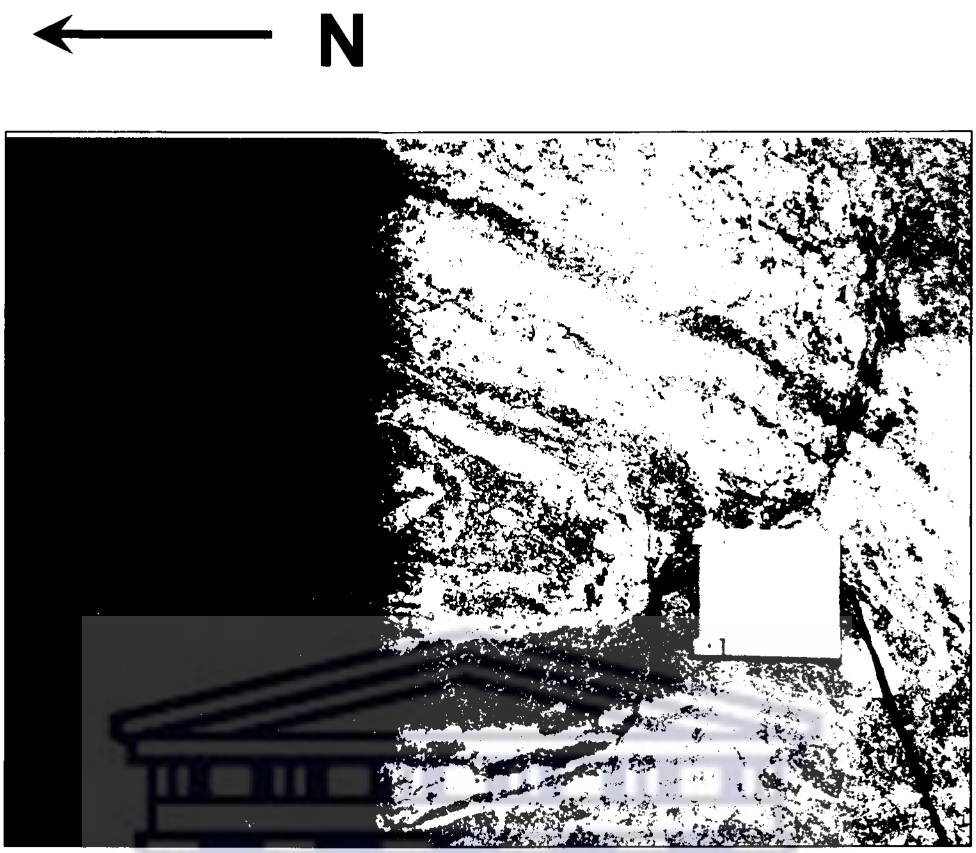

Figure. 4.3. Tight D_2 folding of the Kamieskroon Gneiss near Kamieskroon. (Section View, 3017BB)

Folding of pegmatite veins is seen in the Bitterfontein metasediments. Folds are gentle to open, with axial planes dipping to the north-northeast (figure 4.4). Gibson, *et al.*, (1996) correlate these folds with the D_3 deformational phase that deformed the S_2 foliation and L_2 lineation seen in the Bushmanland Subprovince.

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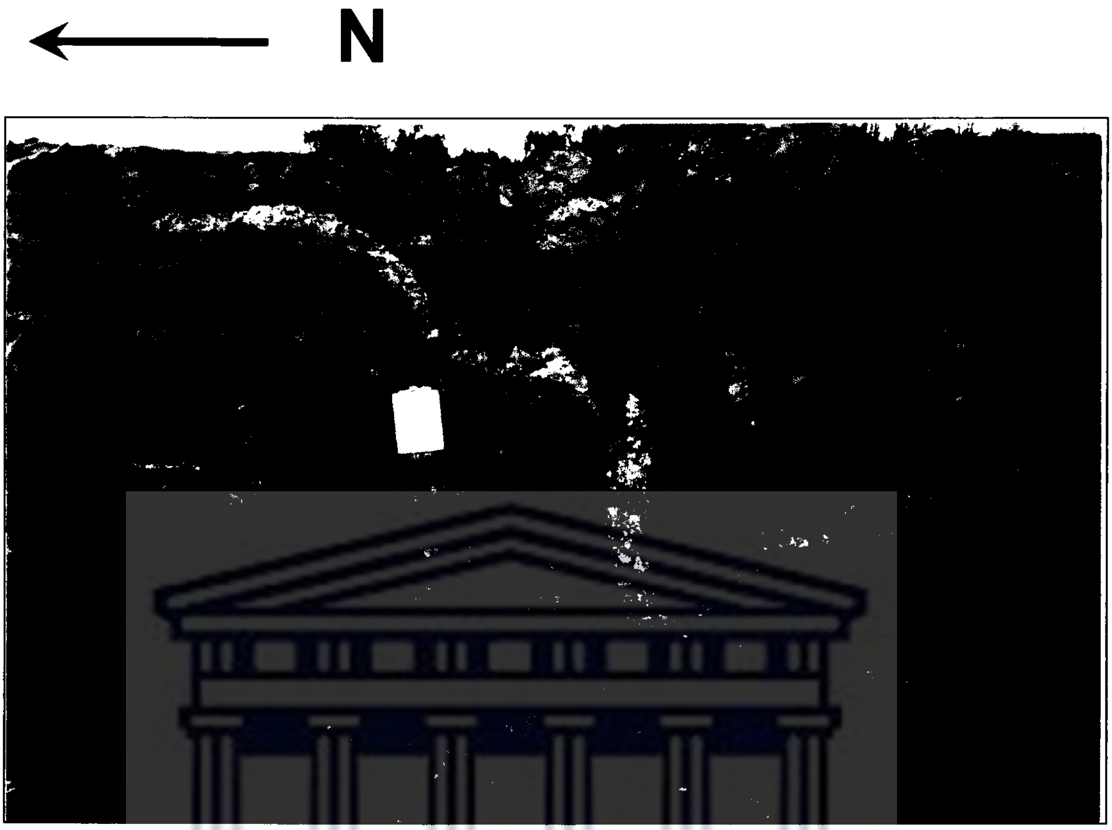

Figure 4.4. Folding of the pegmatite veins in the Bitterfontein metasediment (Council of Geosciences, 1997).

Structural deformation during the Proterozoic ductile- and semi-brittle deformational episodes, and the Pan African orogenesis, is well documented (Joubert, 1971, 1974b; 1986,1986a; Blignault *et al.*, 1983). However, the effect of Mesozoic rifting and its influence in the Northern Cape is not fully interpreted. The African continent experienced variable stress since Gondwanaland breakup. According to Friese (*pers. comm.*, Principle scientist, SRK Consulting, 2001) the north south (N-S) trending fractures and lineaments seen in the Namaqualand region are caused by the opening of the Atlantic during Mesozoic rifting (140 –110 Ma). A northeast southwest (NE- SW) ridge-push force dominated between 110-65 Ma, with the African plate moving towards the east. The northeast-southwest (NE- SW) maximum compressive stress (σ_1) dominated until ~30 Ma with the stabilization of the African plate. The maximum stress

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direction (σ_1) changed from northeast- southwest (NE- SW) to a northwest southeast (NW- SE) direction during the past 30 Ma. This change in stress is primarily due to the effect of the African Plume. According to Brandt, (1998) a northwest- southeast (NW- SE) maximum compressive stress (σ_1) is recorded in the Vaalputs region.

4.3 Lineament analysis

A total of 75 aerial photographs (1: 60 000) and Landsat images (1: 250 000) were used to trace the lineaments in the Kamiesberg region. Landsat images provided a regional scale view, whilst the aerial photographs, which increased the resolution tenfold, allowed for more detailed mapping of the lineaments. The lineaments displayed in figure 4.5 are a combination of structurally controlled valleys, ridges and prominent vertical fracturing along the sheet joints seen on the granite domes in the Kamiesberg region. The sheet joints are primarily sub parallel to the surface and possibly originated from the cooling of the granite domes. The horizontal fracturing not visible on remote sensing images has significant influences for the groundwater flow characterization in a fractured crystalline basement or 'hard rock' environment (Titus, *pers. comm*. 2002). The lineament analysis map of the Kamiesberg region does not display horizontal fracturing. The lineaments are of various ages, from Early Proterozoic to neotectonic origin. Their exact ages are difficult to establish from the geological character and multi-deformational history of the rocks. In certain areas in the Kamiesberg region, structural indicators such as foliations, lineations and crosscutting relationships are not sufficient to determine the ages of the lineaments. The intrusive history in the Kamiesberg region allows some clarity regarding the ages of the lithological units, faults and fractures, but is insufficient to determine the lineament history.

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The Kamiesberg region displays different trends and lineament orientations (figure 4.5). These trends are a result of various tectonic activities experienced in the region. A dominant northwest to southeast lineament orientation is prevalent (figure 4.5). The lineament length varies from several meters to kilometers.

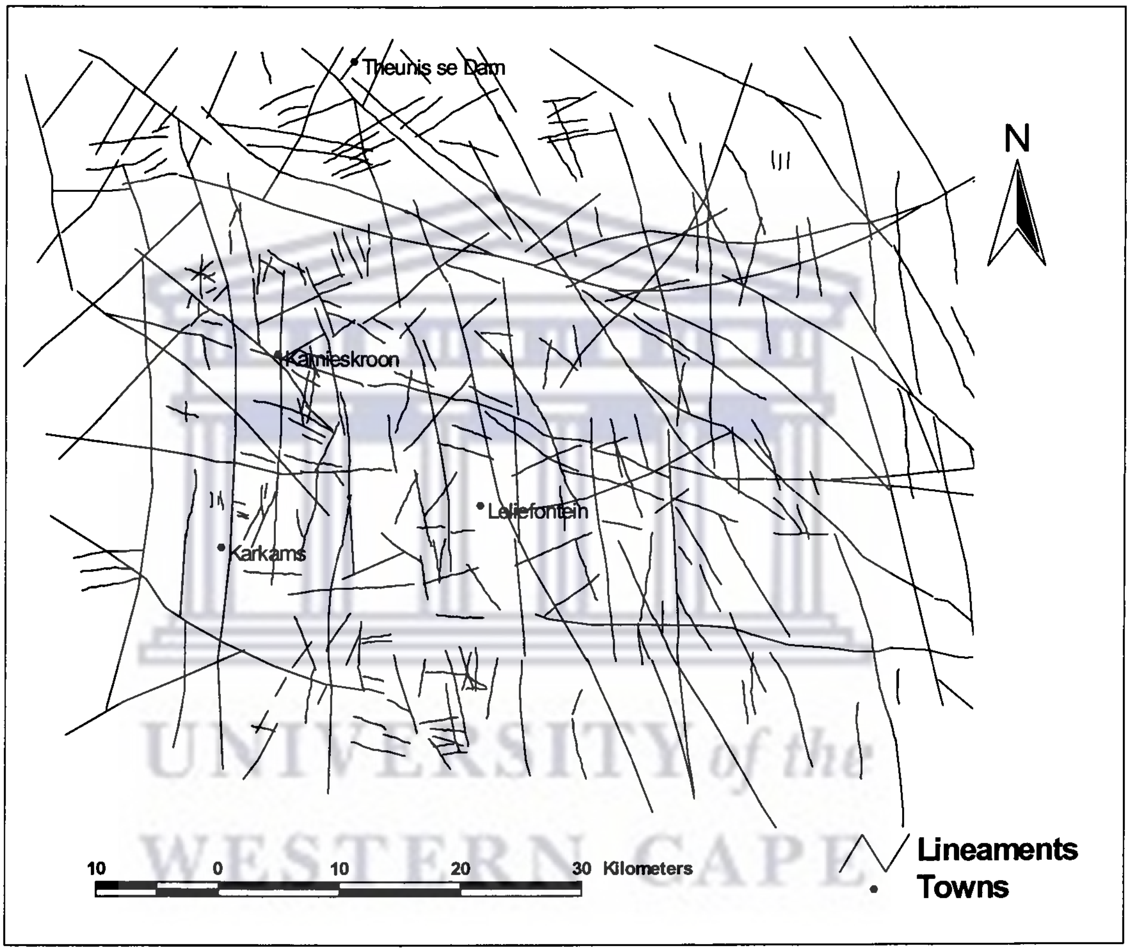

Figure 4.5. Lineament analysis map of the Kamiesberg region.

The lineament frequency (figure 4.6) and lineament intersection maps (figure 4.7) are based on the lineament analysis map recorded from the aerial photographs and Landsat interpretation. The lineament maps are manipulated in ERDAS where grid files were created and contoured in Surfer software and the lineament frequency and lineament intersection maps were created from these grid files. The maps identify areas of high

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fracture frequency and areas of high fracture intersections respectively. High lineament frequency/density is responsible for thicker weathered overburden in basement rocks (Edet, *et al.*, 1994). These areas display increased storativity and are used to assist with delineating groundwater resources (Greenbaum, 1992).

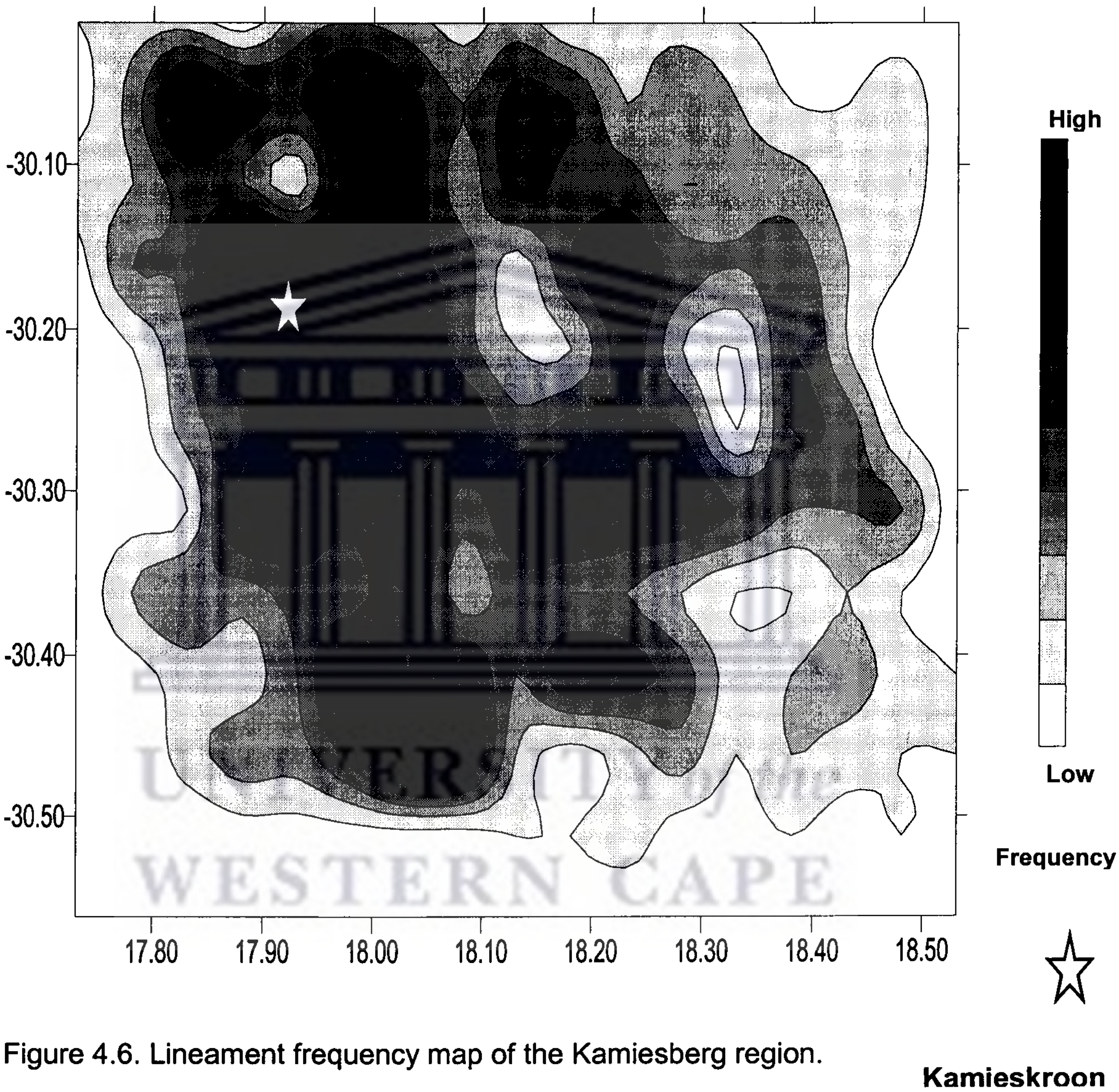

Figure 4.6. Lineament frequency map of the Kamiesberg region.

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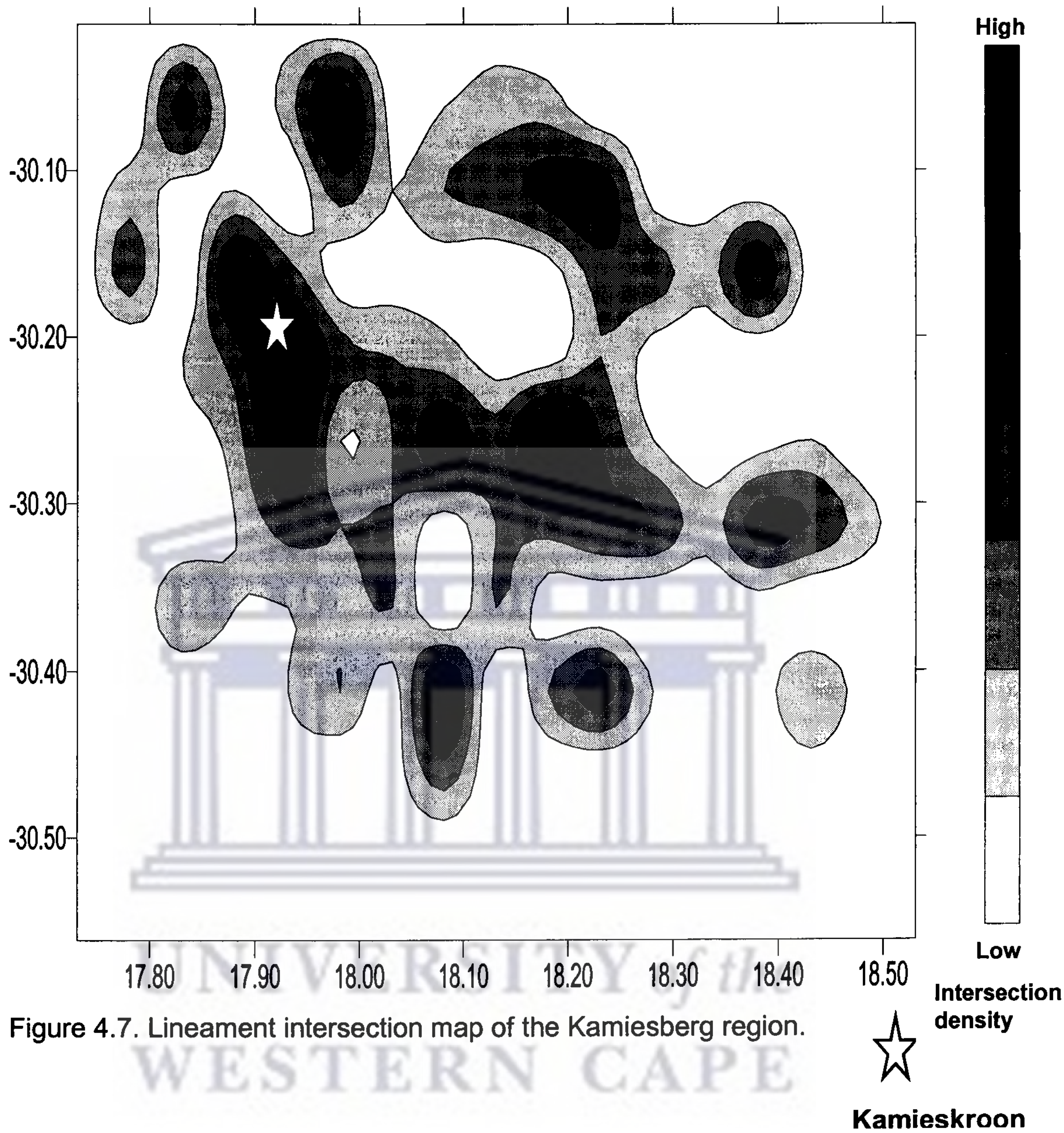

Figure 4.7. Lineament intersection map of the Kamiesberg region.

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4.4 Fracture trends

The fracture trend mapping took place as part of the field studies. The Kamiesberg region is divided into sub areas primarily due to lack of outcrops in certain areas and to recognize the variation of fold, fault and structural trends in the region (figure 4.8). The region displays a range of dominant fracture orientations (figure 4.5 & 4.8).

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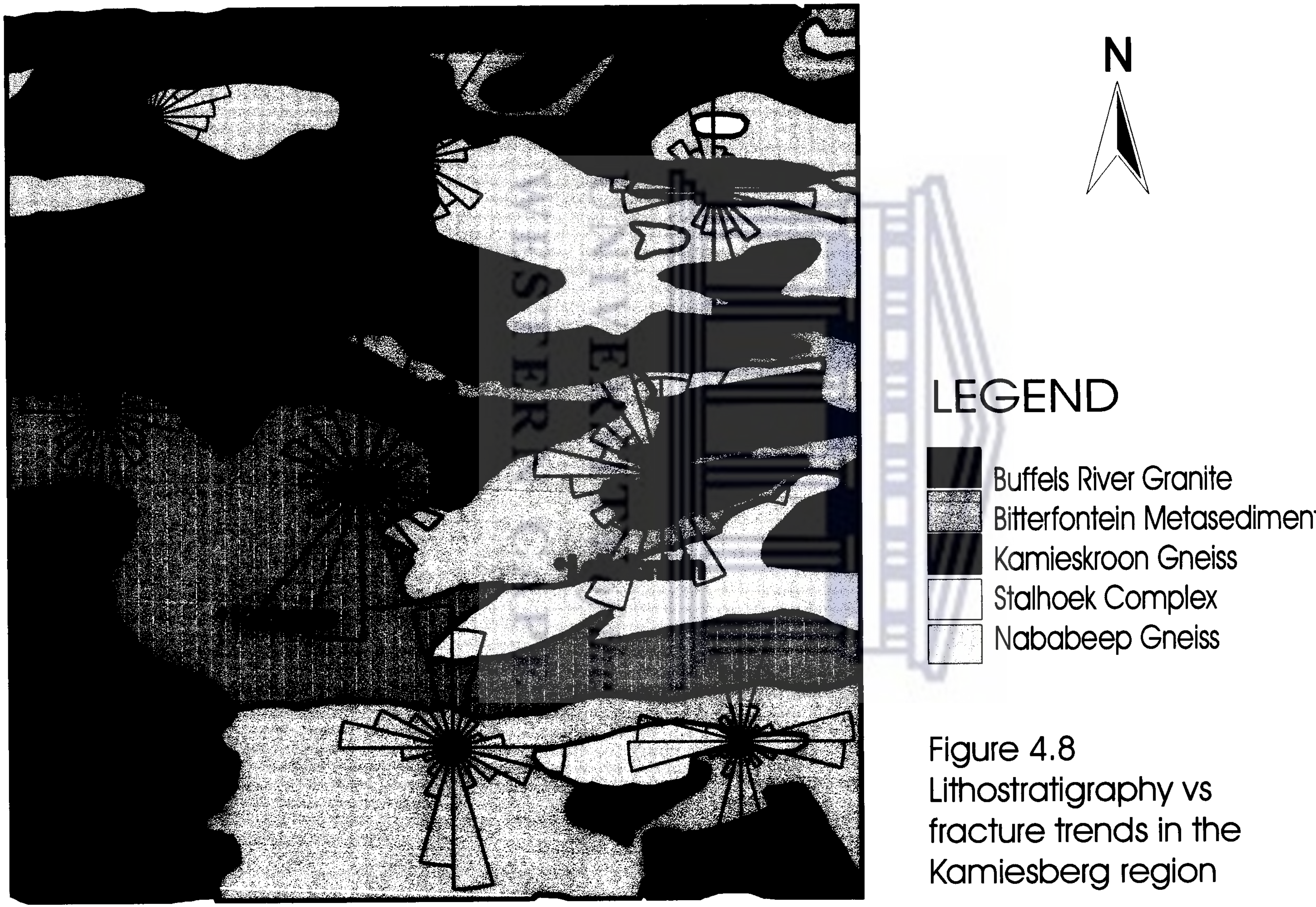

Figure 4.8
Lithostratigraphy vs fracture trends in the Kamiesberg region

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In the southern section of the Kamiesberg region, a north-northwest (NNW) and east-southeast trend (ESE) is prominent. The central and northern regions are dominated by north-northeast (NNE) fractures for the former and NNW trending fractures for the latter. When combined and contoured, the fracture data displays a mean NNW- SSE fracture trend (figure 4.9). Secondary trends are seen in N-S and WNW- ESE directions. The NNW mean fracture trends can be correlated with the extensional fault bounded sedimentary basins seen in Vaalputs, east of the Kamiesberg region (Andreoli, *et al.*, 1996). These trends compare well to the lineament analysis map (figure. 4.5).

According to Brandt, (1998) the data allows for the examination of principle stress directions (σ_1, $\sigma 2$, $\sigma 3$) from the classical interpretation (figure. 4.9). The classical interpretation states that conjugate joints sets intersect in the axis of intermediate stress (σ_2), with the axis of greatest stress (σ_1) splitting the acute angle between the conjugate fractures, whilst the axis of least stress (σ_3) bisects the obtuse angle (op cit.). Sami, *et al.*, (2002) inferred the orientation of maximum principle stress from a combination of fractures (dip-slip, thrust-slip and strike-slip faults) and the slip directions on them. This methodology is conducive in areas where fault and slickenslide orientations are consistent and abundant.

The general direction of principle stress can be obtained from the rose diagram trends (figure 4.9) according to the classical interpretation. The bisectrix of the acute angle (σ_1) is in a northwestern direction, whilst that of the obtuse angle is orientated in a northeastern direction (σ_3). The intermediate principle stress (σ_2) is vertical implying a strike slip environment (Twiss and Moores, 1992). The planes are, however, not all vertical as the data suggests, sub-vertical and horizontal planes are also present. The NW- SE maximum principle stress (figure 4.10) is consistent with the neotectonic stress direction determined by Brandt, (1998) for the Vaalputs radioactive depository site to the east of the Kamiesberg region.

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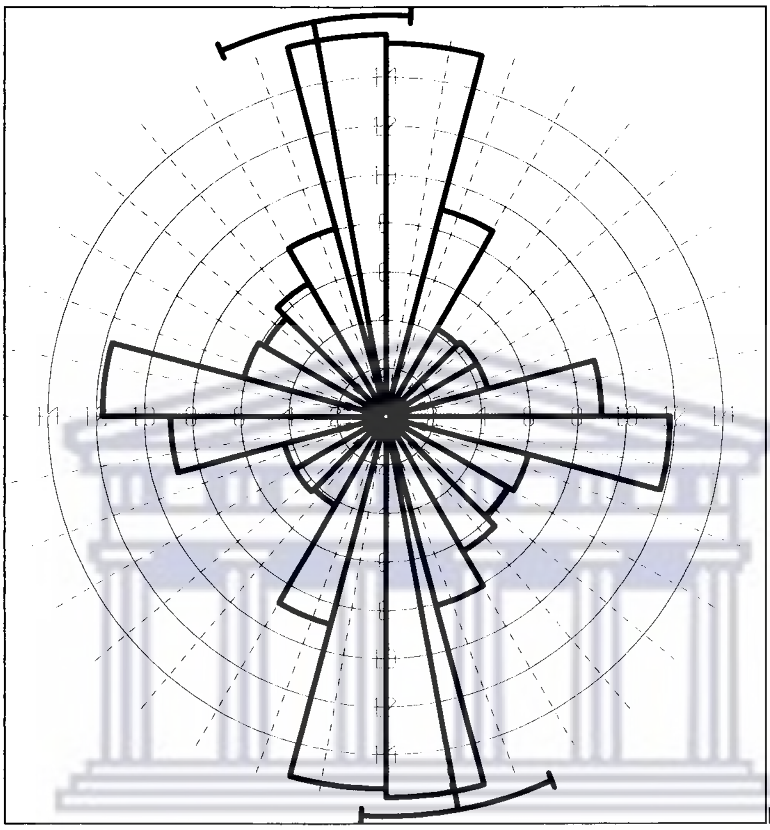
Andreoli, *et al*., (1996), Meus and Chavellier, (2000) concur with a NW- SE σ_1 stress direction for the region.



n= 1377

Figure 4.9.Rose diagram depicting the various fracture trends that are visible in the Kamiesberg region.

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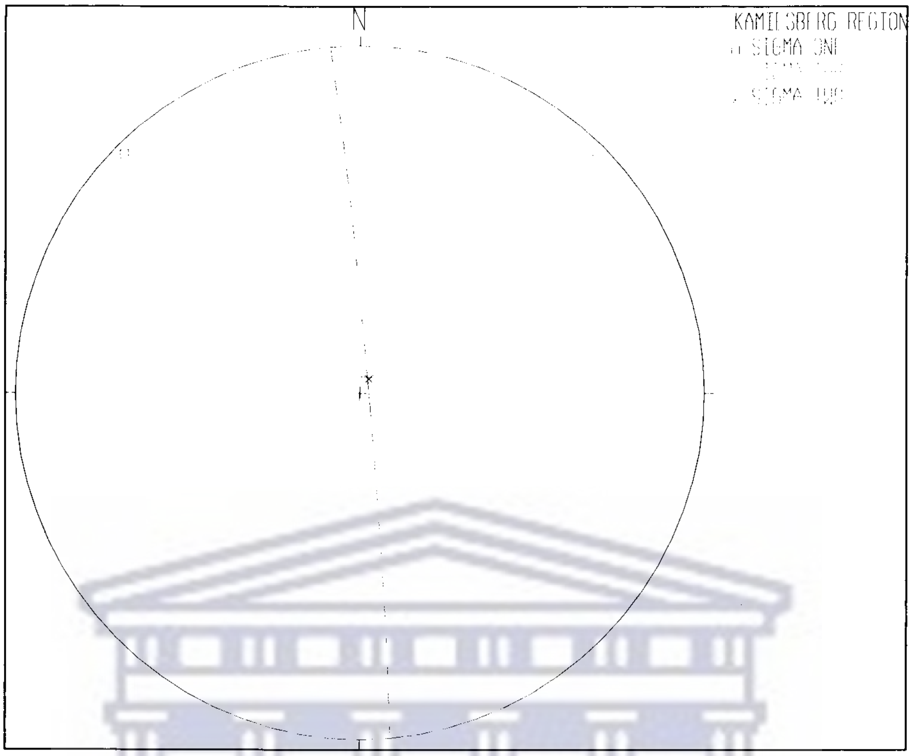

Figure 4.10. The stress direction recorded in the Kamiesberg region.

4.5 Groundwater state

The groundwater state of the Kamiesberg region is rife with challenges. The lack of sufficient data on boreholes (depth, water strike, water levels, yields), rugged terrain and economics plays a vital role in delineating a confident groundwater character. The groundwater state is derived from field investigations and data off the national groundwater data base (NGDB). A series of analyses consisting of borehole yield and borehole depth has been investigated.

4.5.1 Borehole yield

Table 4.1. Borehole yield analysis of the Kamiesberg region. (n= 1237)

	Dry	**< 1 l/s**	**> 1 l/s**
No. of boreholes	457	608	172
Percentages	37%	49%	14%

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Borehole yield analyses in the Kamiesberg region reveal that 457 (37%) of the borehole yields are dry, 608 (49%) of the boreholes yield <1 l/s and 172 (14%) of the boreholes yield >1 l/s (Table 4.1). The yields of the boreholes are obtained from the NGDB (M= 0.46, S.D= 1.01). The map in figure 4.11 displays the variation of borehole yields in the region. Higher yielding boreholes (> 1l/s) are scattered, whilst most of the boreholes are dry.

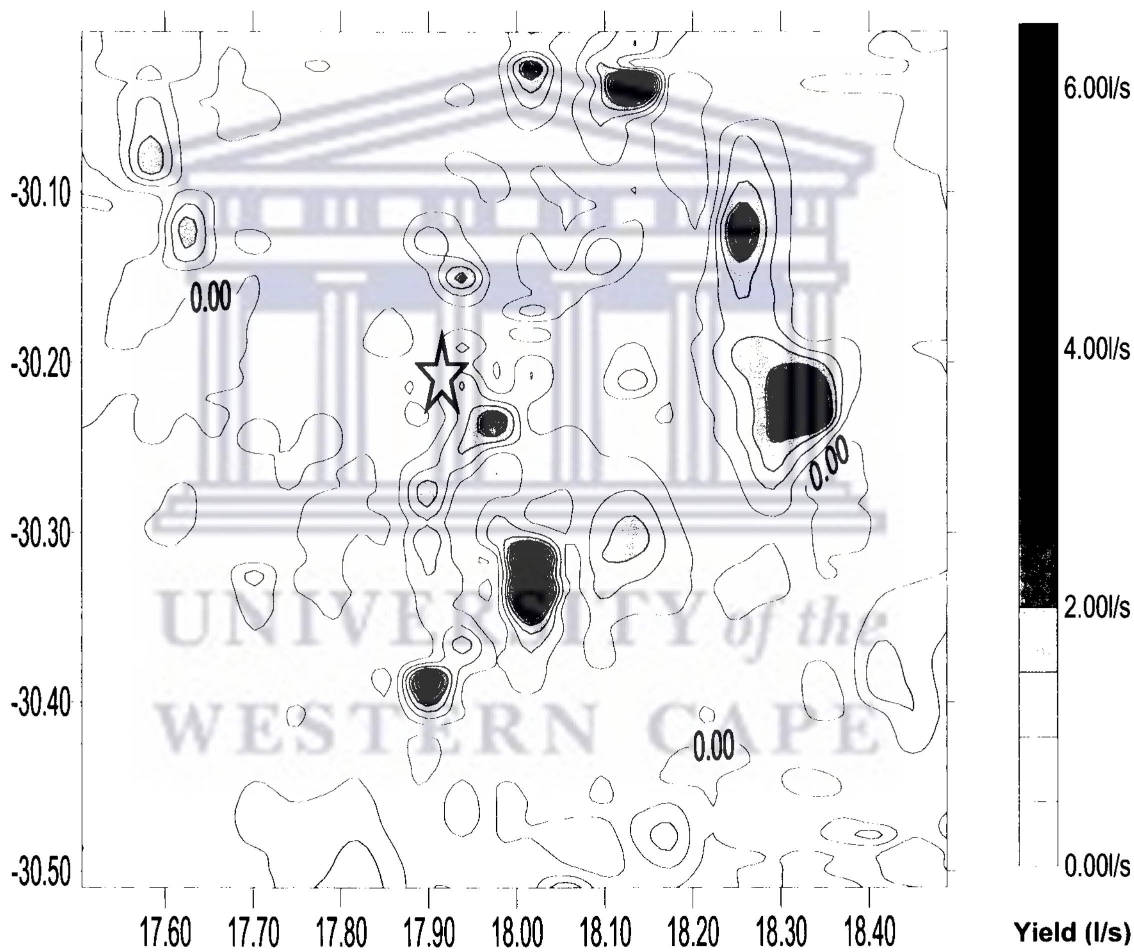

Figure 4.11. The borehole yield data for the Kamiesberg region.

Kamieskroon

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4.5.2 Borehole depth

Table 4.2. Borehole depth in the Kamiesberg region. (n= 1237)

	0- 50m	**50- 100m**	**>100m**
No. of boreholes	679	435	123
Percentages	55%	35%	10%

The boreholes in the Kamiesberg region have a mean depth of 51m (S.D. 31.8). Borehole depths in Namaqualand are severely hampered by economics, access and capacity of the drill rigs (Titus, *et al*., 2000). In the Kamiesberg region, 679 (55%) of the boreholes are drilled between 0-50m, 435 (35%) are between 50- 100m and 123 (10%) are drilled deeper than 100m (Table 4.2). The boreholes are primarily drilled in the weathered horizon and inferred 'open' fractures (Titus, *et al*., 2002). The location of boreholes in weathered horizons is observed in southeastern Zimbabwe (Greenbaum, 1992) and in Malawi (McFarlane, *et al.,* 1992) where it is the main target for borehole siting.

4.6 Identification of potential groundwater zones

The study resulted in the identification of potential groundwater zones for the Kamiesberg region. The potential zones were identified based on the relevant position of the lineament intersection map (figure 4.7) and the lineament intersection map versus the groundwater yield in the region (figure 4.12 and table 4.3). The three potential groundwater zones that were identified are in and around the towns of Kamieskroon, Karkams and Leliefontein. These areas occur in the highest fracture frequency/ density and intersection zones. The data from the NGDB is inconclusive to render a confident interpretation on the groundwater state. Additional research in the local water supply of one of the potential groundwater zones, Kamieskroon, was incorporated in the research. This was done to add confidence to the research.

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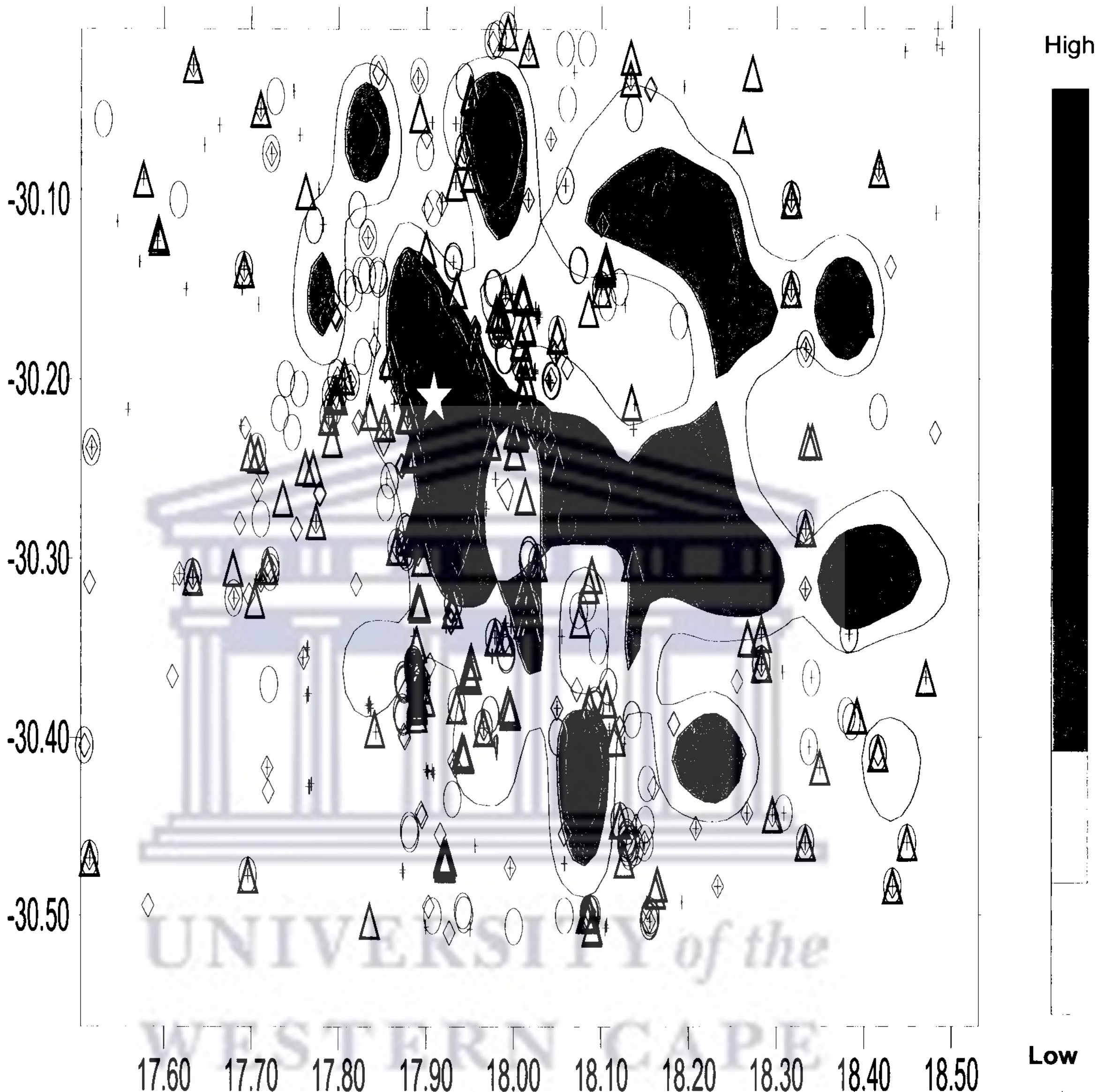

Figure 4.12. Lineament intersection vs. borehole yield map for the Kamiesberg region.

Table 4.3. Groundwater yield analyses inferred from the NGDB (n= 1237).

Yield class (l/s)	Percentage (%)	Number	Symbol
0 - 0.1	49.6	614	+
0.1 - 1	36.4	450	◇
1 - 5	12.9	159	O
5 - 11	1.1	14	Δ

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The town of Kamieskroon is situated 60km south of Springbok, in the heart of the Kamiesberg mountain range. This region is known for the flowering of its diverse annuals during spring. The town consists of a population of approximately 1000 people. There is one primary school, one hotel and several guesthouses.

The town relies solely on groundwater. There are eight (8) fully functional boreholes in the area. The boreholes, drilled between 1997 and 1999, were sited randomly with no scientific study to verify their location (pers. comm. Piet Roux, Kamiesberg Municipality, 2001). There are 3 shallow (~30m) and 5 deep boreholes (2 at 126m; 2 at 149m and 1 at 170m). The shallow boreholes yield 1.6 l/s whilst the yields of the deep boreholes vary between 1.6 - 0.6 l/s. The shallow boreholes are used periodically during the dry, summer months to extend their lifetime whilst the deep boreholes run continuously. There are marked differences in the chemistry of the water from the two boreholes (i.e. shallow vs. depth). Water from the deep boreholes has a distinct brackish taste, and the water from the shallow boreholes is reasonably 'fresh' (op cit.). The shallow, higher yielding boreholes are extracting water from the weathered overburden and the deeper holes are located on the north-northwest trending lineaments (figure 4.13) The yields of the deep boreholes in Kamieskroon (M= 1.28 l/s) are above the mean yield (M= 0.46 l/s) of the Kamiesberg region.

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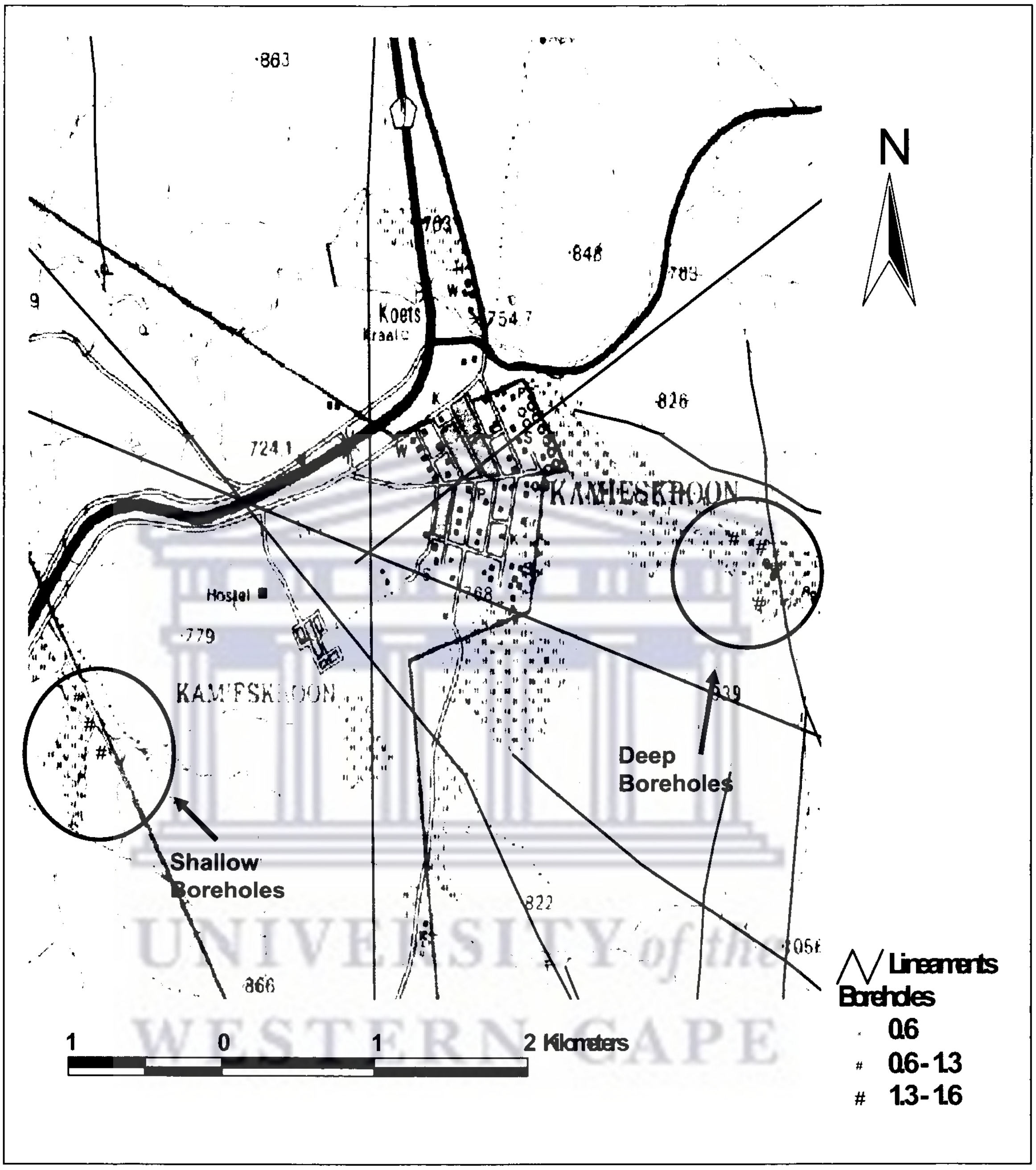

Figure 4.13. A map of the town Kamieskroon. The data layers are the borehole yield data and the lineament trend map.

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4.7 Discussion

The identification of potential groundwater resources in the Kamiesberg region is rife with challenges. The nature of basement rocks, lack of reliable data, rugged terrain and the low rainfall in the region adds to the complexity. Groundwater in basement rock aquifers is primarily found in weathered zones (Chilton and Forster, 1999, Greenbaum, 1992) and interconnected fracture systems (Titus, *et al.*, 2002). Notwithstanding these difficulties, potential groundwater zones have been located in the region.

The application of remote sensing techniques, aerial photographs and Landsat images allows an identification and understanding of the fracture systems. The fractures systems are the result of structural (ductile and brittle) deformation. Fractures and their associated weathering zones are the principle cause of permeability in basement rocks (Greenbaum, 1992).

The groundwater state recorded from the NGDB reveals that 86% of the boreholes in the Kamiesberg region are low yielding (< 1l/s) or dry and 90% of the boreholes are drilled in the weathered overburden (40- 80m). There is no direct link between the borehole yield data from the NGDB (figure 4.11), fracture frequency/density maps and fracture intersection maps for the region. The higher yielding borehole zones located in the structurally controlled valleys are found in the south-central and western parts whilst the high fracture frequencies and intersections occur in the northeastern and southern parts of the region. There is a lack of reliable data to determine a confident groundwater state of the Kamiesberg region.

The large discrepancies that were found in the NGDB data set are that;

- Most of the borehole entries are windmills,
- They are nonexistent and not functioning.
- The data is dated as far back as the early 19th century,
- The yield was recorded from blow yields,

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- The borehole depths are inconclusive and
- The coordinate system is incorrect.

The data from the study, i.e. lineament mapping, fracture frequency, fracture intersection, neotectonic study and groundwater state, provides useful information to identify potential groundwater resources in the Kamiesberg region. The remote sensing data provided the basis to identify potential groundwater resources for the region. In crystalline basement rock aquifers groundwater is primarily transmitted along connected fracture systems and stored in weathered zones. The remote sensing data identified pervasive fracture systems, high fracture frequency/ density zones and high fracture intersections zones. Theses zones are inferred to be optimal groundwater indicators based on the nature of the aquifer systems. The potential groundwater resource areas that have been identified are the areas in and around the towns of Kamieskroon, Karkams and Leliefontein. These areas are located in zones of highest fracture frequency and fracture intersection (figure 4.6 & 4.7). The town of Kamieskroon was selected for additional research primarily because of its data availability and to add confidence to the conceptual model inferred. The town has eight functioning boreholes, three shallow and five deep boreholes. The shallow boreholes are aimed at the weathered zones and the water is reasonably fresh (*pers. comm.* P Roux). The deep boreholes are drilled along the north-northwest trending lineament/ fracture system and the water has a 'brackish' taste. The shallow boreholes are used periodically due to the limited storativity of the weathered overburden, whilst the deep boreholes are pumped continuously (op cit). The shallow boreholes have a mean yield of 1.6 l/s while the deep boreholes have a mean yield of 1.28 l/s. These areas, both weathered overburden zones and NNW- SSE lineament/ fracture systems, have been identified to be the optimal zones for potential groundwater resources in the Kamiesberg region. According to Andreoli, (*pers. comm.* 2002), the NNW fracture/lineament systems are the high yielding water bearers in the

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Vaalputs region. The weathered overburden is considered to have low to moderate transmissivity but high storativity, and the fractured bedrock is characterized by high transmissivity and low storativity (Rebouças, 1993).

The Kamiesberg region experienced significant deformation, both ductile and brittle, during the Proterozoic deformation, Pan African orogenesis and Mesozoic fragmentation. The brittle deformation during these tectonic events is visible on the remote sensing data as lineaments and has a positive effect on groundwater. The mapping shows variable lineament orientation (figure 4.5), and high lineament frequency and lineament intersection zones occurring in the western and southern section of the region (figure 4.6 & 4.7). The mean fracture orientation is north-northwest (NNW) with variations occurring throughout the region (figure 4.8). The fractures, lineaments and joints are a result of tectonic processes and are thus not confined to specific formations. The fracture mapping, from joints and faults, agree with the variation of lineament orientations in the region. Edet, *et al*., (1994) conclude that high lineament density/ frequency can be related to thicker weathered overburden. The basal part of the regolith has, according to Rebouças, (1993) and Chilton and Forster, (1999), sufficient permeability to support successful boreholes for small-scale village water supply schemes. The average yield from a production borehole in a weathered basement aquifer is normally less than 1 l/s (Chilton and Forster, 1999).

A neotectonic study, recorded from the fractures, shows a northwest to southeast (NW-SE) orientated maximum principle stress (σ_1) for the region. This implies that the northwest-orientated fractures would be regarded as the 'open' fractures. The pegmatite intrusions fill the east west (E-W) fractures and the dykes fill the north-northeast to south-southwest (NNE-SSW) fractures. Andreoli, *et al*., (1996) recorded a NW-SE maximum stress direction (neotectonic) for South Africa, whilst Brandt, (1998) working in the Vaalputs region, interpreted both a northeast-

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southwest (NE- SW) and a NW-SE maximum compressive stress. Brandt, (1998) concluded the NE-SW maximum compressional stress operated in the past 60 Ma, whilst a NW- SE compressional stress was active throughout most of the Cenozoic.

Neotectonic joint systems are the most recent joint systems to form within a region subjected to uplift and erosion. The geometry of the neotectonic joint systems are characterized by simplicity, irrespective of whether they cut previously intact or already fractured rocks (Hancock and Engelder, 1989). It is very difficult to establish the exact time of formation of specific joints or joint sets. Joints are also surfaces of negligible discernable movement that may have been activated and reactivated in numerous deformational events. As joints can form in so many ways, it is impossible to determine their exact origin (Brandt, 1998). Analysis of a confident neotectonic study in the Kamiesberg region is hampered by the lack of recent geological deposits (Quaternary). The west coast consists of Quaternary alluvial deposits and to the east, in Vaalputs; Brandt (1998) recognized Cretaceous and Cenozoic deposits. The lithology of the Kamiesberg region consists primarily of Proterozoic metasedimentary rocks and syntectonic intrusives (figure2.2).

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CHAPTER 5

Conclusion and Recommendations

5.1 Introduction

The chapter discusses the conclusions and recommendations made in the research. The conclusions are discussed in terms of the objectives. All of the objectives outlined in chapter 1 have been met.

5.2 Conclusion

The Kamiesberg region, known for its flowering plants in spring and majestic mountain ranges, has vast water shortages. The application of remote sensing techniques for the identification of potential groundwater resources in the Kamiesberg region has been applied with success. The technique helps with the extraction of features that can possibly act as groundwater indicators, surface water flow assessment and hydrological modeling. The remote sensing data layers that were produced are the lineament map, lineament frequency/ density map, and the lineament intersection map. The field studies included fracture analyses and hydrological studies. A groundwater assessment is essential for the inhabitants of the Kamiesberg region.

The remote sensing maps were used in conjunction with the field studies and the hydrological datasets. The lineament frequency/ density maps and lineament intersection maps identified three zones that can be used as potential groundwater resources. These zones are in and around the towns of Kamieskroon, Karkams and Leliefontein. They are located in zones of maximum lineament frequency/ density and maximum lineament intersection.

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The hydrological dataset confirmed this with some uncertainty. The hydrological dataset used (NGDB) is unreliable and;

- Most of the borehole entries are windmills,
- They are nonexistent and not functioning.
- The data is dated as far back as the early 19th century,
- The yield was recorded from blow yields,
- The borehole depths are inconclusive and
- The coordinate system is incorrect.

The NGDB allowed a preliminary assessment of the groundwater state but current consulting reports and field investigations added confidence to the research. The local supply of water to the inhabitants of Kamieskroon provided sufficient data. The eight boreholes are located in the optimal zones inferred for the town of Kamieskroon, the four shallow boreholes are located in the weathered overburden and the deep boreholes are located along the NNW trending lineaments. The shallow boreholes ('fresh' water) have a mean yield of 1.6 l/s; the groundwater is inferred from the local flow paths and has a short residence time. On the other hand, the deep boreholes ('brackish' water), have a mean yield of 1.28 l/s and are part of the regional flow path of groundwater in Namaqualand. The boreholes in the town of Kamieskroon have a higher mean yield than that of the Kamiesberg region (M= 0.46 l/s, S.D= 1.01).

A fractured crystalline basement rock aquifer characterizes the Kamiesberg region. The nature and mode of formation of basement rock aquifers does not allow significant primary or intergranular porosity, however secondary porosity is produced by brittle deformation (fractures and faults) and the formation of weathering zones. The 'open' fractures and faults act as the conduits (high transmissivity) to the deeper flowing groundwater reservoirs, whilst the weathered overburden stores the water (high storativity). The interconnected fractures and associated weathering zones are the principle causes of permeability in basement rock aquifers.

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The Kamiesberg region, located in the Namaqualand Metamorphic Complex, (NMC) displays various tectonic activity and subsequent structural deformation. The NMC displays multi deformational events from the Proterozoic Eon to the Phanerozoic Eon. The brittle deformation is responsible for brittle fracturing and faulting. The multi-deformational structural history induced different folding, faulting and intrusive episodes. The Proterozoic syntectonic granites, Nababeep gneiss, Kamieskroon gneiss, and Stalhoek complex are the most visible rocks in the Kamiesberg region. The local intrusive episodes that affected the flow and storage of groundwater along the structurally controlled valleys are the dykes and pegmatite intrusions. The pegmatite intrusives have a predominantly east west strike, and the dykes in the Kamiesberg region strike NNW- SSE. These intrusions readily seal the fractures and form impermeable barriers for groundwater to flow. The flow of groundwater from soil (i.e. weathered overburden) to fractured crystalline bedrock occurs with a combination of suitable geological and hydrological variables. The infiltration of water from soil to rock is strongly heterogeneous and requires permeable soils, or permeable horizons (known as infiltration routes), as well as 'open' and interconnected fracture systems in the bedrock.

The reactivation of preexisting fractures or 'neotectonic' reactivation is applied for the identification of potential groundwater resources and groundwater resource assessment in South Africa. The neotectonic stress direction inferred from the field studies indicates a NW- SE maximum principal stress, σ_1. This orientation of σ_1 is generally conformable with the current work conducted in South Africa. The NW oriented fractures would be regarded as the open fractures and potential water bearers in the Kamiesberg region.

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Shortcomings of the data:

- The data does not consider the potential scale problem that exists. The data gives potential groundwater zones and does not provide a site to locate a borehole/s.
- The remote sensing data provides little information on the nature of the lineaments.
- The data also does not consider the location of the optimal frequency/density and intersection zones and should be used in conjunction with the topographic maps.
- Attention should be given to the fracture or lineament orientations in the optimal zones.
- The borehole siting should ideally be located along the 'open' fractures systems.
- The study does not consider the borehole position relative to the community. Potential zones might be too far from the communities, it might be expensive to build a pipeline, or exist in inaccessible valleys and peaks.

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5.3 Recommendations

The monitoring of existing and future groundwater resources is imperative to the communities in the Kamiesberg region. The following recommendations are made:

- Verify the optimal zones with geophysical surveys including shallow seismics, magnetics and gravimetrics.
- Implement a borehole-monitoring network with the continuous monitoring of water level, borehole yield assessment, water quality assessments and pollution control on a monthly basis.
- Complete detailed borehole information, i.e. depth, weathering profiles, water strikes, yields, position, and water levels. This will assist with delineating groundwater flow paths; infer chemical character of the water and assist with the understanding of the aquifer dynamics.
- Manage the existing groundwater resource in a sustainable way. A detailed aquifer test pumping program must be implemented to prevent aquifer mining and,
- Reassess the existing groundwater database of the region; verify the borehole location, yield, use and depth. This will aid the current understanding of the aquifer and assist present consultants, managers and policy makers.

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