# An approach to groundwater targeting in the Springbok region, Central Namaqualand, Northern Cape Province, South Africa

**By**

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## KEYWORDS

Namaqualand, Springbok, Stratigraphy, Tectonics, Stress, Lineament, Fracture, Borehole, Groundwater, Fractured Aquifer.

## DECLARATION

I declare that *An Approach to groundwater targeting in the Springbok region, Central Namaqualand, Northern Cape Province, South Africa* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Anthony Fielies Date: February 2003

Signed:

# ABSTRACT

Namaqualand is a semi-arid region where water is not only a necessity and basic need, but also very much a luxury. As a consequence, various studies were undertaken to find water sources, whether surface or groundwater, (by researchers such as DWAF, the University of the Western Cape and other companies such as Toens and Partners), to alleviate water scarcity.

The Springbok region in Central Namaqualand generally comprises intrusives and metasediments ranging in age from 1800 – 1100 Ma. The metasediments are the Okiep group outcropping over the Namaqua Highlands, whilst the intrusives comprise various suites such as the Koperberg Suite (youngest) and the Gladkop Suite being the oldest known intrusive. Gneisses and granites dominate the intrusive rocks. These rocks underwent various deformation phases attributed to different stresses that formed the various structures. The stress field in the area over time has mostly favoured a NW-SE direction, the only exceptions being the Gladkop Suite (NNE-SSW), and the Pan-African Nama sediments formed during the Late Proterozoic to early Phanerozoic by an ENE-WSW compressional direction. The Neotectonic stress field in the area is NW-SE. This stress field is set to be part of the Wegener Stress Anomaly. The Neotectonic stress field is important, since it formed the structures e.g. fractures and faults which act as groundwater conduits. Given that the NW-SE stress field had dominated in the past and also is the present day stress field, these fractures are not only favourable for groundwater location, but also saw a variable degree of

reactivation since they were already open. Therefore, the NW-SE fractures should be targeted in search of groundwater.

The study was dominated by lineament identification and analyses on a regional and local scale using LANDSAT TM 4 and aerial photographs respectively. Structural mapping was undertaken to identify the various fracture orientations, densities and their characteristics in the field. Both the LANDSAT TM 4 and aerial photographs highlighted the following strikes of lineaments: E-W, N-S to NNW, NNE, NE and NW. Field mapping revealed dominant fracture orientations of N-S, E-W, and ESE-WNW & ENE-WSW directions. Fieldwork also indicated that the N-S fracture set is actually a fracture system that can be further divided into the NNW-SSE and the NNE-SSW fracture sets (N10-$30^0$W) with dyke material having intruded along most of these fractures. Some of the least dominant fractures in the field are the NW-SE & NE-SW fracture sets. On a local scale, water flows from exfoliation surfaces striking N-S with these surfaces fed by other fractures. Lineament analyses using LANDSAT TM 4 revealed that large lineaments direct regional groundwater flow whilst the 1:60 000 aerial photographs showed that smaller lineaments are groundwater carriers locally.

Groundwater in Namaqualand is mostly located within the alluvium of rivers, the fractured weathered system of, and within the freshly fractured crystalline basement. The majority of boreholes though, gave significant water in the fractured weathered system; as a result nearly all boreholes were (are) drilled in it. The fractured weathered system is fairly differential but can be up to 80m thick in some boreholes.

Boreholes yielding up to 7 l/s have been drilled in this weathered fracture system. However current data suggest that large amounts of yielding boreholes are below 100m. The study area is located in the Buffelsriver catchment with groundwater normally saline and boreholes mostly drilled in structurally controlled valleys. Lower saline waters are found in the higher lying parts of the catchment.

The position of fractured aquifers may to a certain extent be reliably predicted by taking in account deformational events and its related stratigraphy, stress fields and its resulting fracture and lineament patterns, as well as topography and weathering patterns.

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# CHAPTER 1

## GENERAL INTRODUCTION

### 1.1 Introduction

Groundwater is a major source of water for local use in rural areas and includes 65% of their total water supply. Groundwater potential in South Africa is divided into four sections, i.e. major -, minor -, poor-groundwater systems and large dams. Groundwater in the Namaqualand region comprises both minor and poor groundwater systems (Figure 1) and 1-10% of people are exclusively dependent on groundwater. (http://www.dwaf.gov.za/water%20services/test/intranetapps/…).



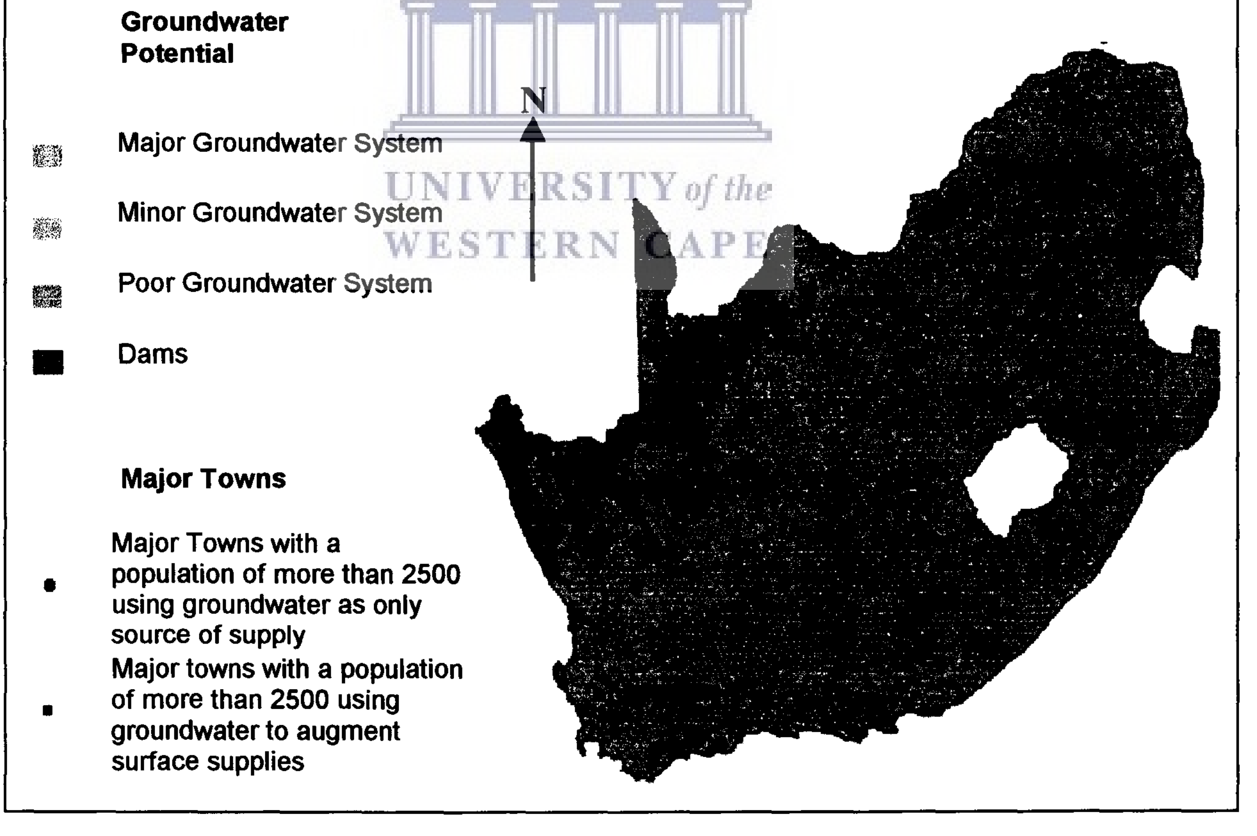



Figure 1. The groundwater systems in South Africa with specific reference to Namaqualand (not to scale) (after http://www.dwaf.gov.za/water%20services/test/intranetapps/)

In the Springbok area, most of the locals obtain their water from surface water (e.g. Buffels river) with groundwater quality in Namaqualand normally in excess of >2000 TDS (mg/l) and in some areas 1001-2000 TDS (http://www.dwaf.gov.za/water%20services/test/intranetapps/).

Groundwater in Namaqualand generally occurs within the weathered overburden, alluvium and secondary fractured aquifers of igneous and metamorphic origin, and is largely controlled by structural features such as fractures (plate 1), faults, folds and the topography (Titus *et al.*, 2002).

Plate 1. Mesklip granite south in the study area with water flowing from horizontal fractures/ exfoliation surfaces.

## 1.2 Background to the study

This study forms part of a two-year Water Research Commission (WRC) Project entitled: "Sustainable Groundwater management and utilization in the Northern Cape: Geomechanical modeling as a tool for groundwater exploration of fractured rock aquifers". It entails establishing existing water needs in the study area, current water sources and the identification of new groundwater sources, to help alleviate water shortages in this region.

The need for Geomechanical modeling (groundwater flow prediction) came about due to inadequate research done when siting boreholes, which resulted in dry boreholes, and in a wasting of time and money. Not only is it important to identify these groundwater sources, which are situated in the alluvium, weathered overburden and fractured aquifers in the area, but also to ensure optimal utilization of these newly founded aquifers in a sustainable manner.

## 1.3 Objectives of the study



The main objectives set out in the initial WRC project were:

- Prediction of fractured rock aquifers by geomechanical modeling
- Validation of geomechanical model through hydrogeological data.
- Providing information to assist in the establishment of a groundwater-monitoring network.
- Contributing to quantification of groundwater in the Northern Cape community water supply.
- Provision of adequate supply of water for domestic and/or agricultural purposes.

The objectives as part of this project in aiding the WRC objectives are:

- The prediction of fractured rock aquifers using structural geological analyses and remote sensing.
- Identifying possible drilling sites for domestic and/or agricultural purposes.

## 1.4 Organisation of the study

The first three chapters deal with general information and data necessary for a groundwater study in the area, with the remaining chapters dealing with the presentation and interpretation of data and subsequent results obtained during the study.

Chapter 2 highlights some of the literature reviewed as a whole and deals with specific aspects essential for a hydrogeological investigation in fractured aquifers with specific reference to the study area.

The methodology used during fieldwork as well as the data and results obtained as part of it are outlined in Chapter 3. Chapter 4 summarizes some of the findings given in the thesis as well as probable recommendations.

# CHAPTER 2

## LITERATURE REVIEW OF THE STUDY AREA

### 2.1 Introduction

This chapter entails basic information for compiling and executing a groundwater study, including Geographical setting, Climate and Vegetation, Geology, Geohydrology as well as Tectonics and its particular reference to the area.

### 2.2 Geographical setting

#### 2.2.1 Location of the study area

The study area (Figure 2) is situated in the Northern Cape Province of South Africa, and is generally known as the Namaqualand region. It is found between longitudes 29°10'S - 29° 45'S and latitudes 17°30'E - 18°E and covers an approximate area of 62km in length and 24 km in width and stretches from the Buffelsriver in the south, to just past Bulletrap north of the town of Springbok. The western margin is set in the Spektakel Pass before the Spektakel mine and the town of Nababeep. The towns of Carolusberg and Concordia define the eastern boundary. It includes major towns like Springbok, Okiep, Nababeep as well as some of the surrounding farms (Figure 2).

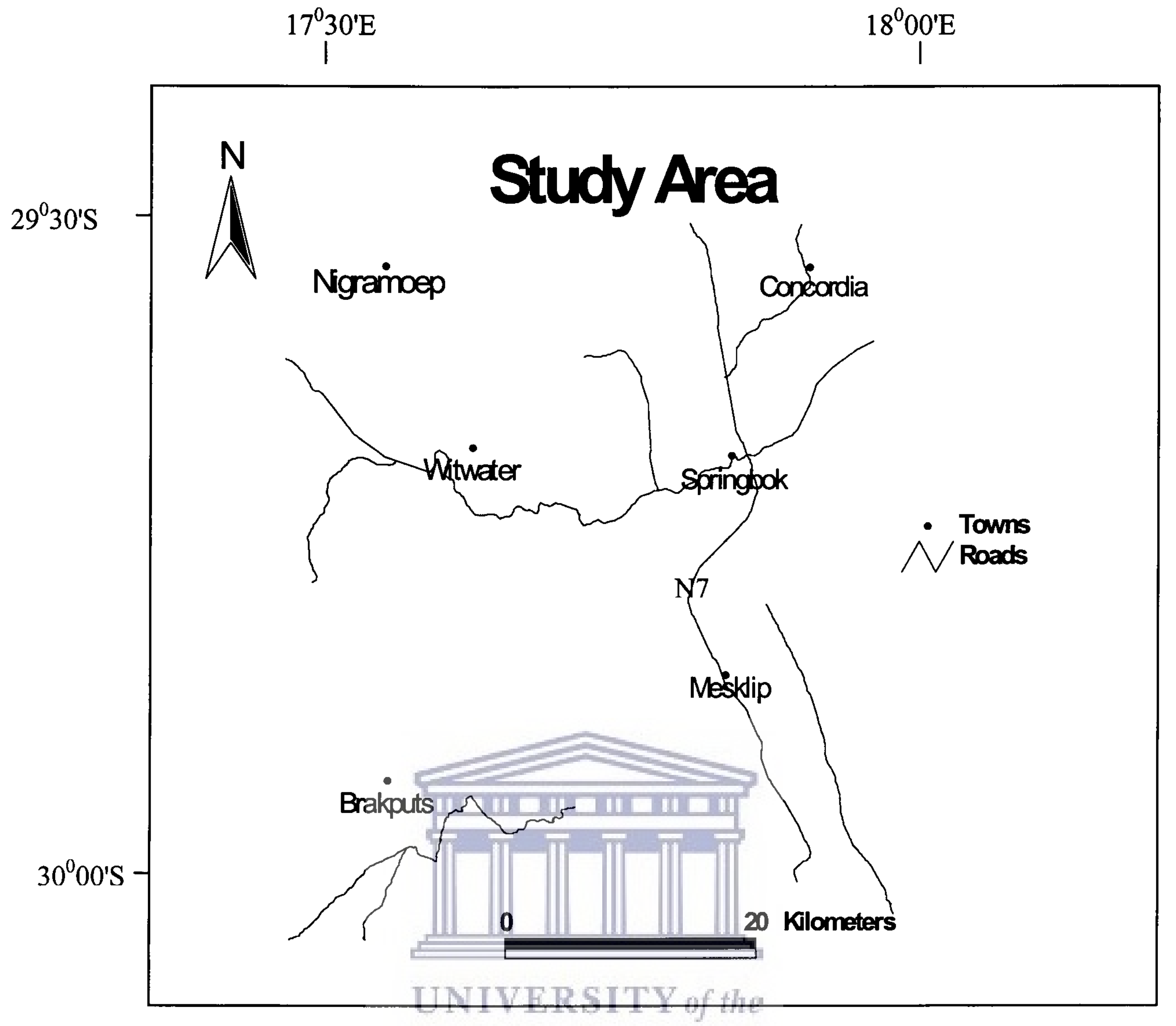



Figure 2. The location of the Study Area.



## 2.2.2 Physiography of the study area

### *2.2.2.1 Soils & Vegetation*

In Namaqualand the soils are mainly lithosols with the soils northeast of the study area moderately deep, sandy and undulating in relief. In the central part of the area shallow, sandy, loam soils prevail. The vegetation in the area is mostly Karoo and Karroid with some patches of false Karoo (Midgley *et al.*, 1994).

## 2.3 Climate

### *2.3.1 Climate*

Namaqualand has a semi-arid climate mainly as a result of low rainfall of less than 200mm and in some parts less than 100mm per annum. At the coast morning sea fog readily develops, and disappears at about noon. During summer the temperatures at the coast are generally mild and increase inland, with temperatures often exceeding $40^0$C in some parts. In winter the temperatures range between 25°C and $30^0$C during the day, and freezing temperatures at night. Consequently night frosts are not unusual (http://www.southafrica-travel.net/climate/eklima8.htm).

### *2.3.2 Precipitation*

Midgley et.al (1994) estimates a MAP (mean annual precipitation) in the study area (Figure 2) between 100-200 mm. This is partly due to the cold Benguela current that does not absorb huge amounts of humidity and as a result rain clouds seldom form. Sporadically, showers can occur in the winter months, as large enough clouds build up over Botswana and northern Namibia (adjoining countries to the north) and then extends down into Namaqualand (http://www.southafrica-travel.net/climate/eklima8.htm).



### *2.3.3 Evaporation*

The evaporation increases from 1300mm along the Orange River to 1600mm at the Namaqualand coast. Mean Annual Evaporation in the study area ranges from about 2000mm-2600mm (Figure 2) (Midgley *et al.*, 1994).

### *2.3.4 Runoff*

The mean annual runoff in the study area is 0-2.5mm (Midgley *et al.*, 1994).

## 2.4 Stratigraphy

The study area (Figure 2) encompasses the Namaqualand Metamorphic Complex, which consists of metasedimentary -, metavolcanic- as well as intrusive rocks, which are mainly gneissic in character (Figure 3). The lithostratigraphic subdivision of this complex is given in Table 1 (SACS, 1980).

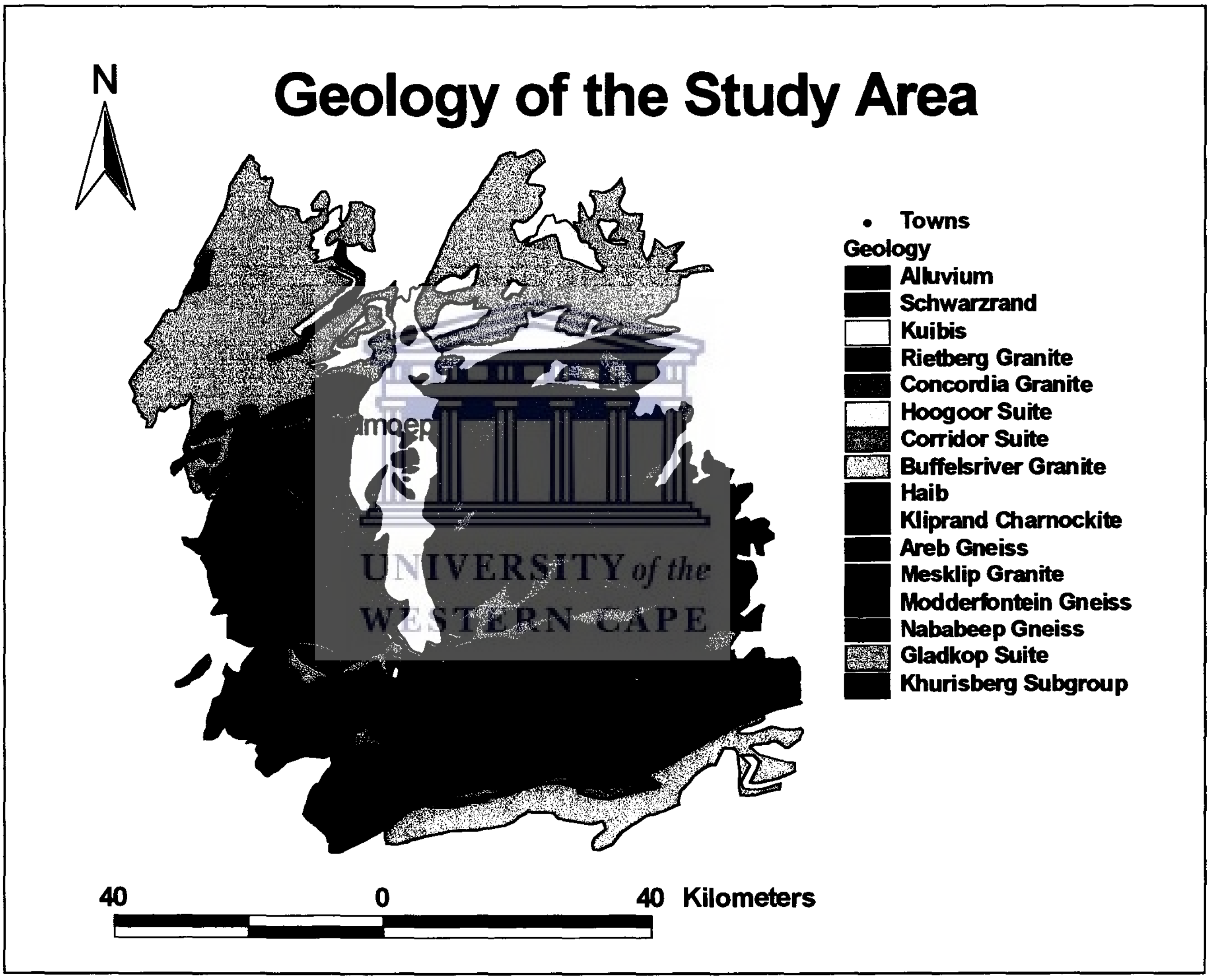



Figure 3. The Geology of the study area.

The geology is expressed by dominating gneisses and granites (section 3.5.1), metasediments, and volcanics in the form of the Khurisberg Subgroup (section 3.5.1).

Table 1. The Lithostratigraphic subdivision of the Namaqualand Metamorphic Complex (after SACS, 1980).

| | Rock Types | Age (Ma) |
|---|---|---|
| **Koperberg Suite** | | 1100 |
| **Spektakel Suite** | | 1000-1200 |
| Keimoes Suite | | |
| Hoogoor Suite | **Syntectonic intrusive rock units** | |
| **Little Namaqualand Suite** | | 1200 |
| **Gladkop Suite** | | 1800 |
| Vioolsdrif Suite | | |
| | | |
| Orange River Group | | 2000 |
| **Okiep Group** | | |
| Bushmanland Group | **Pretectonic metasedimentary and metavolcanic rock units** | |
| Korannaland Sequence | | |
| Marydale and Kaaien Groups | | 3000 |

The study area (Figure 2) incorporates the Okiep group as part of the metasedimentary and metavolcanic rock units (supracrustals) and all the syntectonic rock units except the Vioolsdrif suite as outlined in Table 1 (SACS, 1980).

### 2.4.1 Okiep Group

This group is exposed over the Namaqua highlands (Visser D.J.L, 1989) and occurs as large continuous bands to small xenoliths in various gneissic granites of batholitic proportions (SACS, 1980). This group is consistent over large areas in Namaqualand (SACS, 1980). In the area between Springbok and Bitterfontein the Garies subgroup (of the Okiep group) is exposed. In the other regions the rest of the subgroups (described below) occur sporadically because of the intrusion of the various syntectonic granites belonging to the Hoogoor, Gladkop, Spektakel and Little Namaqualand suites (Visser D.J.L, 1989).

The Okiep group is divided into five subgroups:

i) Khurisberg subgroup
ii) Aardvark subgroup
iii) Bitterfontein subgroup
iv) Eenriet subgroup
v) Garies subgroup (SACS, 1980)



Some of these subgroups are lithologically similar e.g. in the above i-iv are metaquartzites and schists whilst the Garies subgroup consists of undifferentiated gneisses (SACS, 1980).

### 2.4.2 Syntectonic Intrusives

#### *2.4.2.1 Gladkop Suite*

This suite is found between the Eenriet and Khurisberg subgroups of the Okiep group and continues underneath the Nama sediments on the Neint Nababeep plateau (Visser D.J.L, 1989) . The Gladkop Suite consists of grey granulite and gneiss. Three members can be differentiated based on texture, viz the Steinkopf Gneiss, Brandewynsbank Gneiss and Noenoemaasberg Gneiss.

#### *2.4.2.2 Little Namaqualand Suite*

Includes all the coarse-grained, intrusive augen gneisses of Little Namaqualand (Visser D.J.L, 1989) and underlies huge areas of the metamorphic belt (SACS, 1980). It is composed of a series of quartz-feldspar-biotite orthogneisses intrusive into one another and into the country rocks (Visser et.al, 1989). Eight members can be distinguished:



i) Modderfontein Gneiss
ii) Leeupoort Gneiss
iii) Nababeep Gneiss
iv) Areb Gneiss
v) Brandberg Gneiss
vi) Konkyp Gneiss
*vii)* Aroams Gneiss
viii) Eendoorn Granite

#### *2.4.2.3 Spektakel Suite*

Comprises an assemblage of distinctly leucocratic granites, with three units, viz the Kweekfontein granite, Rietberg granite and Concordia granite (SACS, 1980).

#### *2.4.2.4 Koperberg Suite*

This suite, the youngest of the syntectonic intrusives in the study area, is a mixed assemblage of small basic bodies, varying in composition from hypersthenite to norite to diorite and anorthosite (SACS, 1980). It is found as pipes, dyke-like bodies or irregular bodies of these minerals (Visser D.J.L, 1989) .

## 2.5 Tectonics/ Neotectonics

### 2.5.1 Tectonics

#### *2.5.1.1 Namaqua Mobile Belt*



This mobile belt is thought to be that domain which has been affected by structural, metamorphic, igneous and/or thermal processes of the 1000-1200 Ma tectogenesis (Blignault *et al.*, 1983). It forms part of the Kibaran system of mobile belts, including rocks belonging to the Eburnian (2000 Ma) and Kibaran (1000 Ma) age groups. The dominant effects of the Namaqua tectogenesis found SW of the Namaqua front (major NW striking linear zone NE of the Namaqua Mobile belt) is defined as the Namaqua Province (op cit).

Southern Africa has many early Precambrian to Cambrian structural provinces covered by relatively undeformed sequences whose ages range from late Archaean to

Cenozoic. These structural provinces are shown in Figure 4 with the Namaqua tectonic province forming the basis of the study (Tankard *et al.,* 1982).

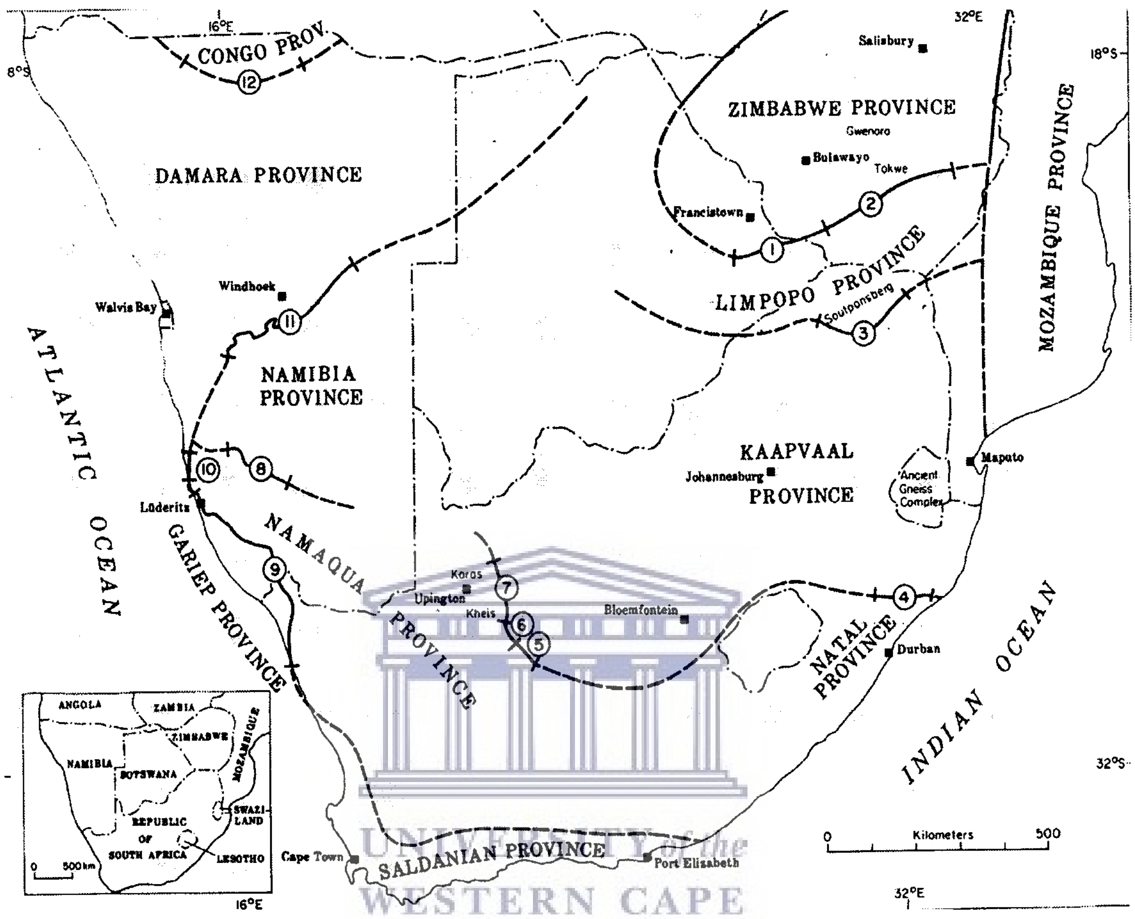




Figure 4. The structural provinces of Southern Africa with specific reference to the Namaqua subprovince (After Tankard *et a*l 1982).

### *2.5.1.2 Namaqua Province*

This province formed during Middle Proterozoic times and was subjected to high-grade metamorphism (Hartnady *et al.,* 1985). It comprises the largest crystalline basement of South Western Africa (Tankard *et al.*, 1982) and is part of the Namaqua-Natal Province, a 200-400 km wide, E-SE trending belt of polydeformed metamorphosed Palaeo-Meso Proterozoic rocks (Gibson *et al.*, 1996). Tankard *et al.*,

(1982) divide the Namaqua Province into the Western-, Central- and Eastern marginal Zones (Figure 5a). Hartnady *et al.*, (1985), re-named these zones; the Gordonia,-Bushmanland-and Richtersveld tectonic subprovinces respectively. The largest part of the Namaqua Province is known as the Central Zone, a deformed heterogeneous group of gneisses and intrusions metamorphosed to medium and high grades, collectively termed the Namaqua Metamorphic Complex (Tankard *et al.*, 1982).

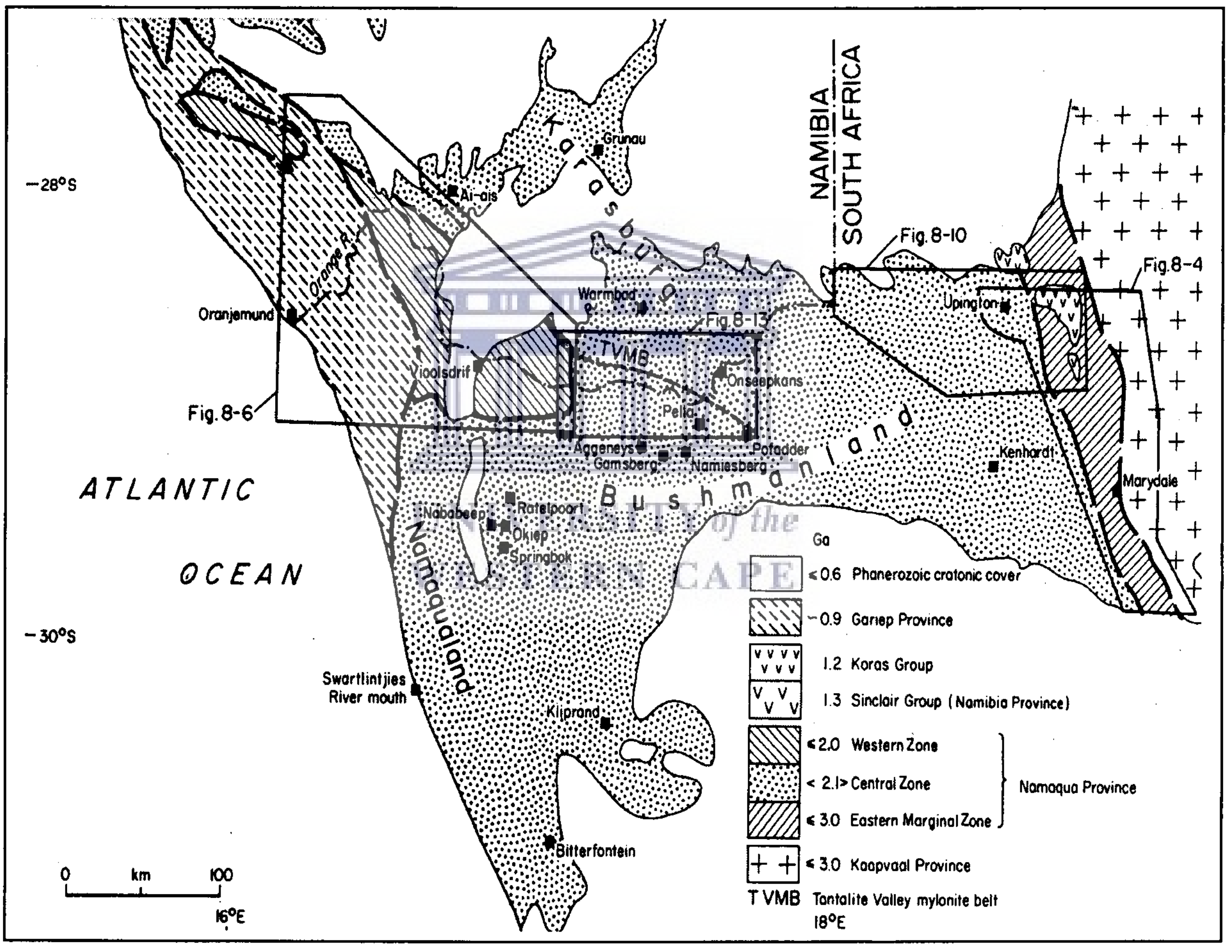



Figure 5a. The tectonic subdivision of the zones in the Namaqua Province (After Tankard *et al.*, 1982).

Visser DJL, (1998), on the other hand divided the Namaqua Metamorphic Province (Complex) into the following subprovinces (Figure 5b):

a. Kheis subprovince
b. Richtersveld subprovince
c. Bushmanland subprovince
d. Gordonia subprovince

The study area is incorporated in the Bushmanland subprovince (Figure 5b), and specifically in the Okiep Terrane as mentioned by Visser DJL, (1998) or the Okiep Copper District as described by authors like Van der Merwe (1995) and Gibson *et al.*, (1996). For descriptive purposes the latter terminology will be used.

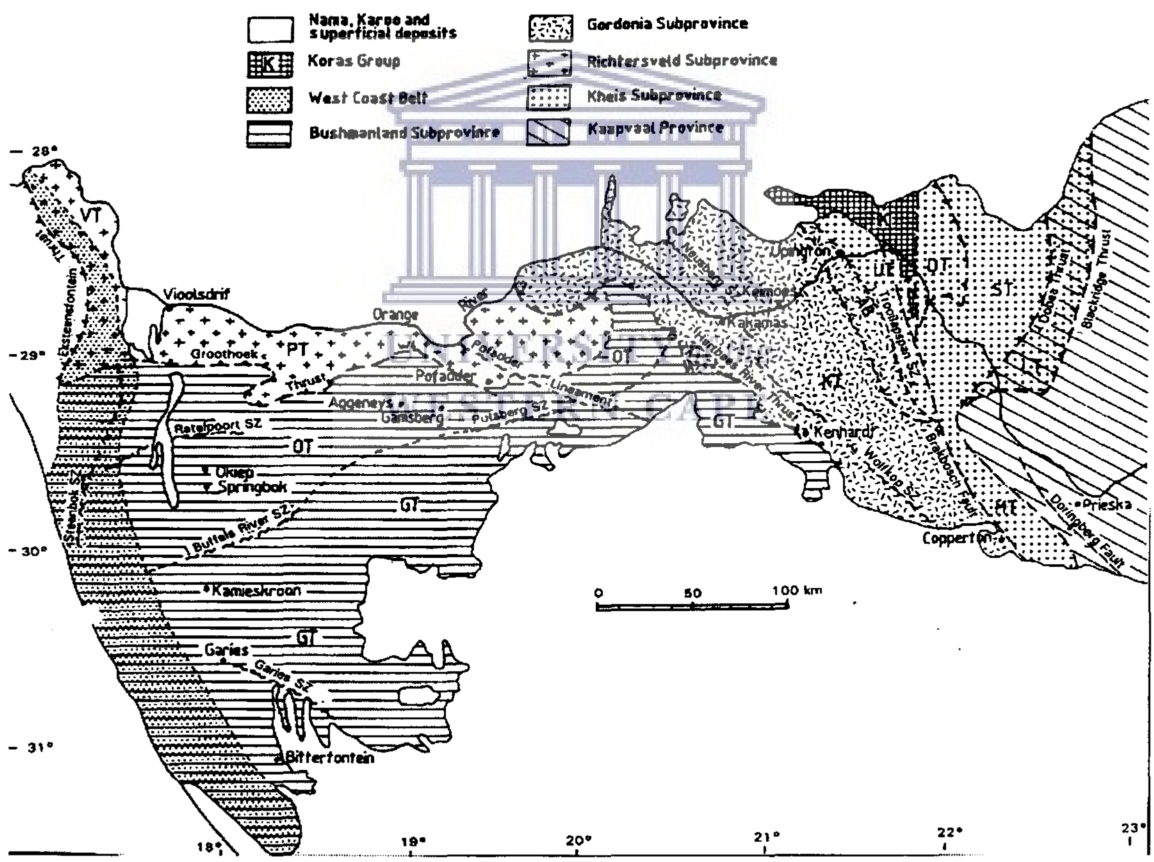



Figure 5b. The Tectonic subdivisions of the Namaqua Province (After Visser *DJL*, 1998).

### *2.5.1.3 The Okiep Copper District*

This tectonic domain is located in the west-central part of the Bushmanland Subprovince (Gibson *et al.*, 1996) and underwent high-grade metamorphism during the Namaqua deformation event (Van der Merwe, 1995). The northern boundary of this domain is the steeply dipping east trending Ratelpoort Shear zone system (Plate 2) and to the south the Buffels River shear zone. In the east it is juxtaposed against volcano-sedimentary sequences of the central Bushmanland subprovince, and in the west the Pan African west coast belt transects it (Gibson *et al.*, 1996).



Plate 2. The Ratelpoort Shear Zone north of Bulletrap.

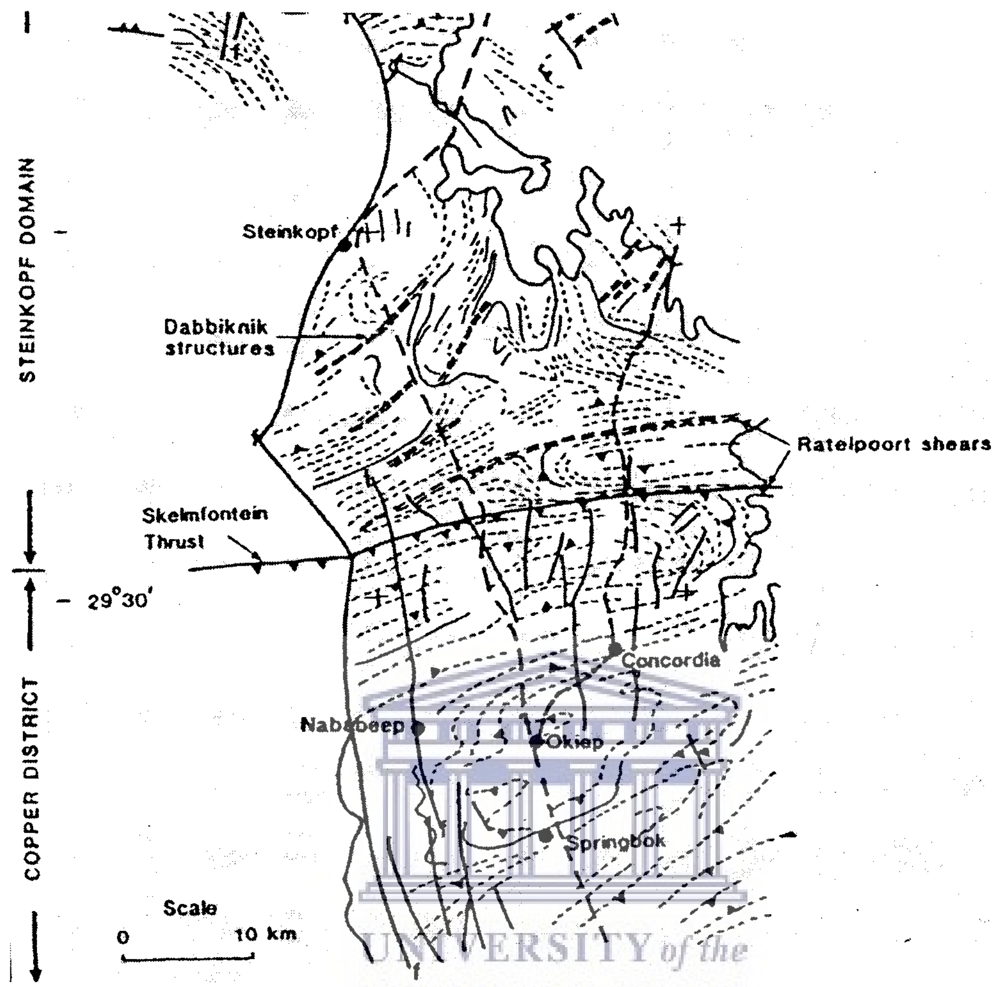



Figure 6. The Okiep Copper District (OCD) with respect to the other tectonic domains in the Namaqua Mobile belt (after Van der Merwe, 1995).

According to Robb *et al.*, (1999) the OCD includes different rock types of two main ages. These are the amphibolite-facies, granitic orthogneisses developed during the Kheis orogeny (2000- 1800 Ma), but in the case of the OCD, ~1820 Ma. The other, the Kibaran sedimentary and intrusive granitoids formed and buried at roughly 1300-1000 Ma. Blignault *et al.*, (1983), identified two main periods of igneous activity in the Namaqualand Geotransverse and environs (OCD included), namely, the 2000-1730 Ma and 1200-1000 Ma events relating to the Eburnian and Kibaran respectively.

Rocks of the Namaqua orogeny (1065 – 1030 Ma) deformed the rocks belonging to these two orogenies. Blignault *et al.*, 1983 estimated an age of 1100-1200 Ma for the OCD.

Van der Merwe (1995), subdivided the Namaqua orogeny (deformation) into an earlier forming fabric event, producing the regional foliation and lineation (Namaqua fabric, Plate 3) as well as a later period of deformation, in the form of the Skelmfontein thrust event, part of the Ratelpoort Shear Zone (Plate 2).

Robb *et al.*, (1999), identified at least three deformation events ($D_1$-$D_3$) relating to magmatic and metamorphic evolution of the Okiep Copper District (OCD). The early D1 deformation is exhibited by intrafolial folds in the orthogneisses of the Gladkop suite and metasedimentary remnants. The $D_2$ event is the dominant deformation in the OCD and is seen as a subhorizontal gneissosity in the orthogneisses of the Little Namaqualand Suite. The $D_2$ deformation formed augen textures in the orthogneisses and can also be seen as large- and small-scale isoclinal folds in the Springbok quartzite (Khurisberg Subgroup). Van der Merwe (1995) defined these stretched augen as a lineation with a prominent ENE or WSW plunging extension direction. The stresses responsible for the $D_2$ deformation continued until the intrusion of the Spektakel Suite, since the Concordia granite (lower level member of this suite) shows a poorly developed gneissosity at its base. The other members of this suite however postdate the D2 event. The D3 event had a compression stress orientated N-S and developed large-scale open folds that deformed the subhorizontal $S_2$ (formed during the $D_2$ event) fabric.

Joubert (1974b, 1971 in Visser *DJL*, (1998) termed his deformation phases $F_1$-$F_4$ which are related to the various folds formed during the deformation period of the Namaqua event. The earliest deformation ($F_1$) is indicated by discontinuous bending of banded rocks, as well as tight intrafolial folds with disjointed limbs and sharp hinge zones being deformed by later folds. The $F_2$ event (the main phase of deformation) is responsible for various folds, from recumbent to isoclinal folds with large amplitudes and short wavelengths, with rounded hinge zones to open folds. In western Namaqualand, axial planes of these $F_2$ folds are orientated WNW-ESE to NW-SE. Also, this $F_2$ phase was accompanied by large scale thrusting towards the SW and S. The third phase of deformation ($F_3$) produced large, open folds that normally trend E-W i.e. almost co-axial to $F_2$ folds. These $F_3$ folds are flexure-slip folds and their formation produced most of the movement and shearing along existing foliation planes during folding. The fourth phase of deformation ($F_4$) is recognized by monoclinal folds and associated shear zones and fractures, most of which strike NW-SE with pegmatites and quartz veins associated with these structures. In Western Namaqualand, monoclinal folds face west with the short limb on the western side. In Aggeneys they face to the east (Visser *DJL*, 1998).

The later Skelmfontein thrust (Van der Merwe, 1995), includes a family of shears representing a thrusting period in the late Namaqua event at about 1100 Ma. Later open folds fold these shears. The Skelmfontein thrust is part of the Ratelpoort shear zone, forming the contact between the OCD to the south and the Steinkopf domain to the north. Near Bulletrap (Plate 2), this zone exhibits a subhorizontal dextral sense of movement along a southerly-southeasterly dipping shear plane.



A major pulse of magmatism set to be part of the Kibaran orogeny, is represented by the intrusion of the Nababeep gneiss (Little Namaqualand Suite) at about 1212 Ma, the Modderfontein orthogneisses (~1199 Ma) and a mafic sill at ~1168 Ma. This major pulse of magmatism is thought to be part of the $D_2$ deformation or post-dates it (Robb *et al.*, 1999). Another pulse of magmatism forms part of the Namaqua Orogeny (1065 – 1030 Ma), in the form of sheet-like bodies of granite (the Spektakel Suite) at about 1064 and 1085 Ma, parallel to the $D_2$ fabrics and lithologies (Robb *et al.*, 1999).

### 2.5.2 Neotectonics

Neotectonics in Southern Africa is active along coastal regions, the continental interior, and the ocean floor between the continental margin and the South West Indian Ridge. It is accompanied by sporadic seismicity of medium intensity of usually Magnitude (M)< 6.5. Magnitude is explained as a measure of the amount of energy released by an earthquake calculated from the amplitude of the seismic waves it produces shown on a logarithmic scale (Kearey, 1996). This seismicity is caused by a NW-SE trending maximum horizontal compression ($S_H$ max) formed from southern Angola to the offshore of the Transkei basin, said to be the Wegener Stress Anomaly (WSA), and its interaction with other stress fields acting on the African plate (Andreoli *et al.*, 1996).

Seismicity in the Namaqualand can roughly be separated into three regions based on occurrence. These are: the area around Springbok, the area southeast of Springbok in the Vaalputs area and the regions east-northeast of Vaalputs (Figure 7). Seismic events are rarely M > 6. In the study area seismicity ranges between 2<M<5 with a large seismic event (M=6) recorded northwest of the area in the Port Nolloth region (op cit).



The African plate south of the equator is divided into two zones of stress orientation.
These are: **Zone 1** – predominant **NNE** directed trends as a result of the **East African Rift System** (EARS).

**Zone 2** – **NW-WNW** trends in the southern, southwestern and the southwest Indian Ocean.

A third pattern of compressional tectonism with an E-W direction for the horizontal stress is located in the western and central parts of Africa (Andreoli *et al.*, 1996).

Andersen and Ainsle (1994) identified different stress orientations in South Africa. In the Southern Cape, a horizontally east-west trending maximum compressional stress

In the Carolusberg mine in the Okiep Copper District (study area), a subhorizontal compressional NNW stress at a depth of 1572 m was recorded, which Andreoli *et al.*, (1996) linked to the ENE-WSW trending Griqualand Transvaal upwarp axis. At the Prieska mine east of the OCD and the Black Mountain Mine northeast of the OCD, a $S_H$ max with orientation NNW-SSE and WNW-ESE respectively, was recorded (Andreoli *et al.*, 1996).

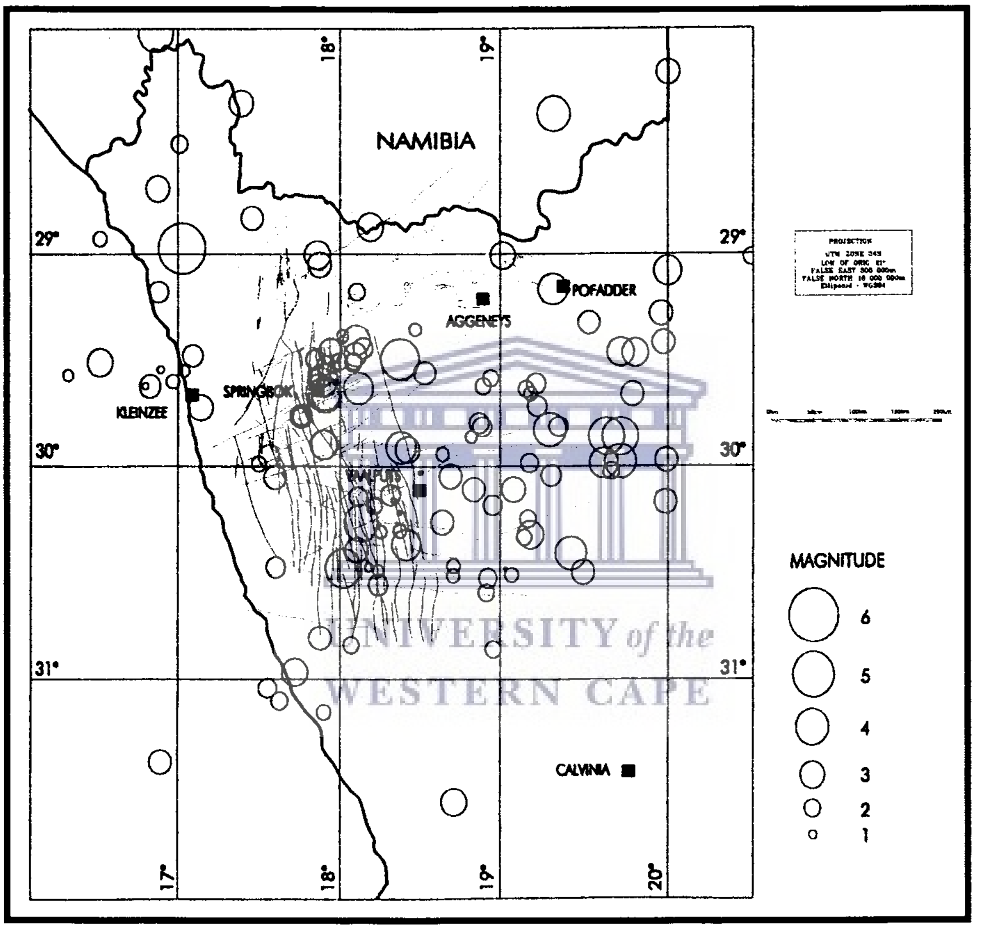



Figure 7. Seismicity and major lineaments in the study area and the regions Surrounding it from January to September 1996 (Source: Atomic Energy Corporation).

## 2.6 Hydrogeology

The area is situated in the Buffelsriver Catchment and is divided into various sub catchments (Figure 8), with groundwater flow generally difficult to determine because of the fracturing. Titus *et al.*, (2002) adopted a micro-fissured system for the crystalline rocks of Namaqualand, with the matrix constituting micro-fissures that store the water and the larger fractures transmitting the water. The fractures have a high transmissivity and low storativity and the matrix low transmissivity and high storativity, with water flowing from the matrix to the fractures if a pressure gradient exists. Midgley *et al.*, (1994) defines the water-bearing formations as being mainly undifferentiated assemblages of compact sediment, extrusive and intrusive rocks as well as porous unconsolidated and consolidated sedimentary strata.

Titus *et al.*, (2002) identified two aquifers in the Buffelsriver catchment. The first being a primary aquifer expressed as alluvial deposits in the Buffelsriver and the second comprising crystalline aquifers with joint systems, faults, shear and thrust zones which are controlled by structural features. Primary aquifers are controlled by matrix porosity. Groundwater is generally encountered in the weathered overburden, which has a low to moderate transmissivity and high storativity. The underlying fractured and unweathered crystalline bedrock has a high transmissivity and low storativity.



Generally the groundwater in the Buffelsriver catchment is saline with boreholes normally drilled in structurally controlled valleys (Figure 8b), with lower salinity waters found in the higher lying parts of the catchment. Groundwaters in the northern and central sections of the Buffelsriver catchment (i.e. study area), generally have a Na-Cl character with EC values ranging between 0-2150 ms/m (not representative of all samples). Fluoride levels are generally high in the study area and range between 0-600 mg/l (Titus *et al.*, (2002)).

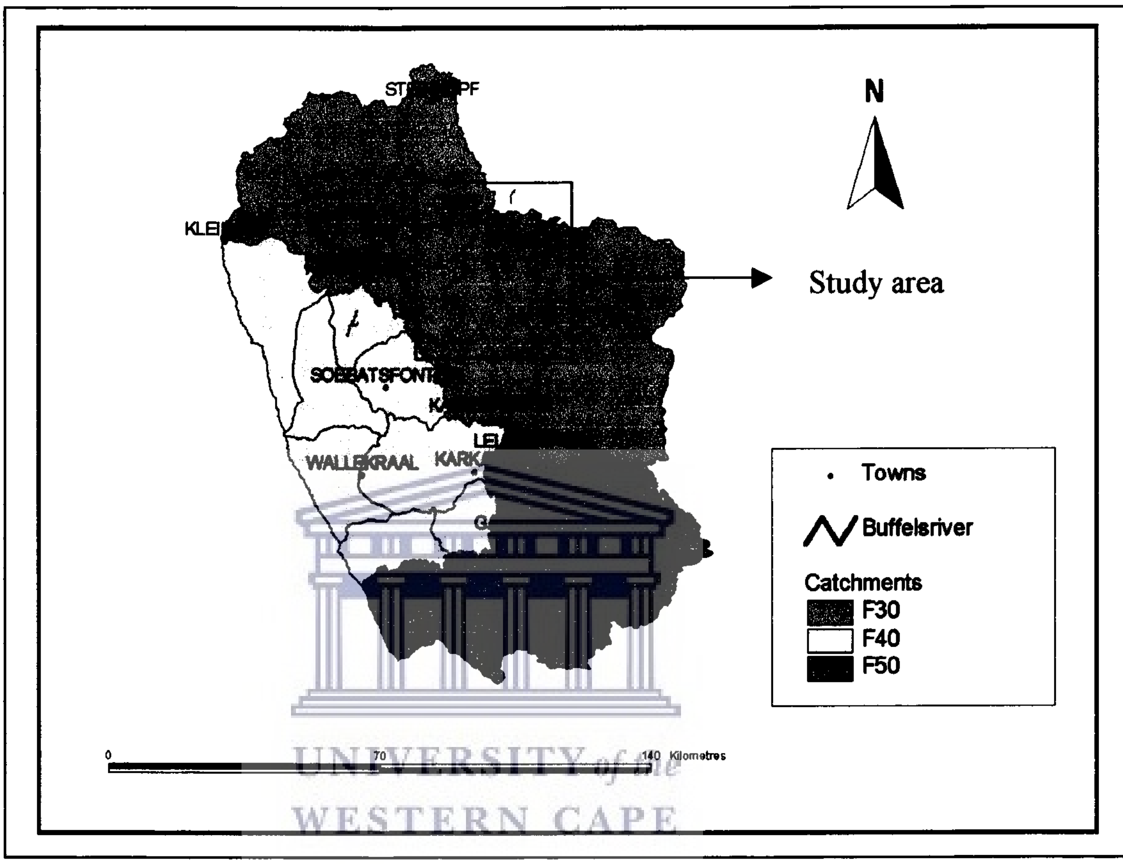



Figure 8a. The Buffelsriver catchment and its sub catchment (F30) found in the study area.

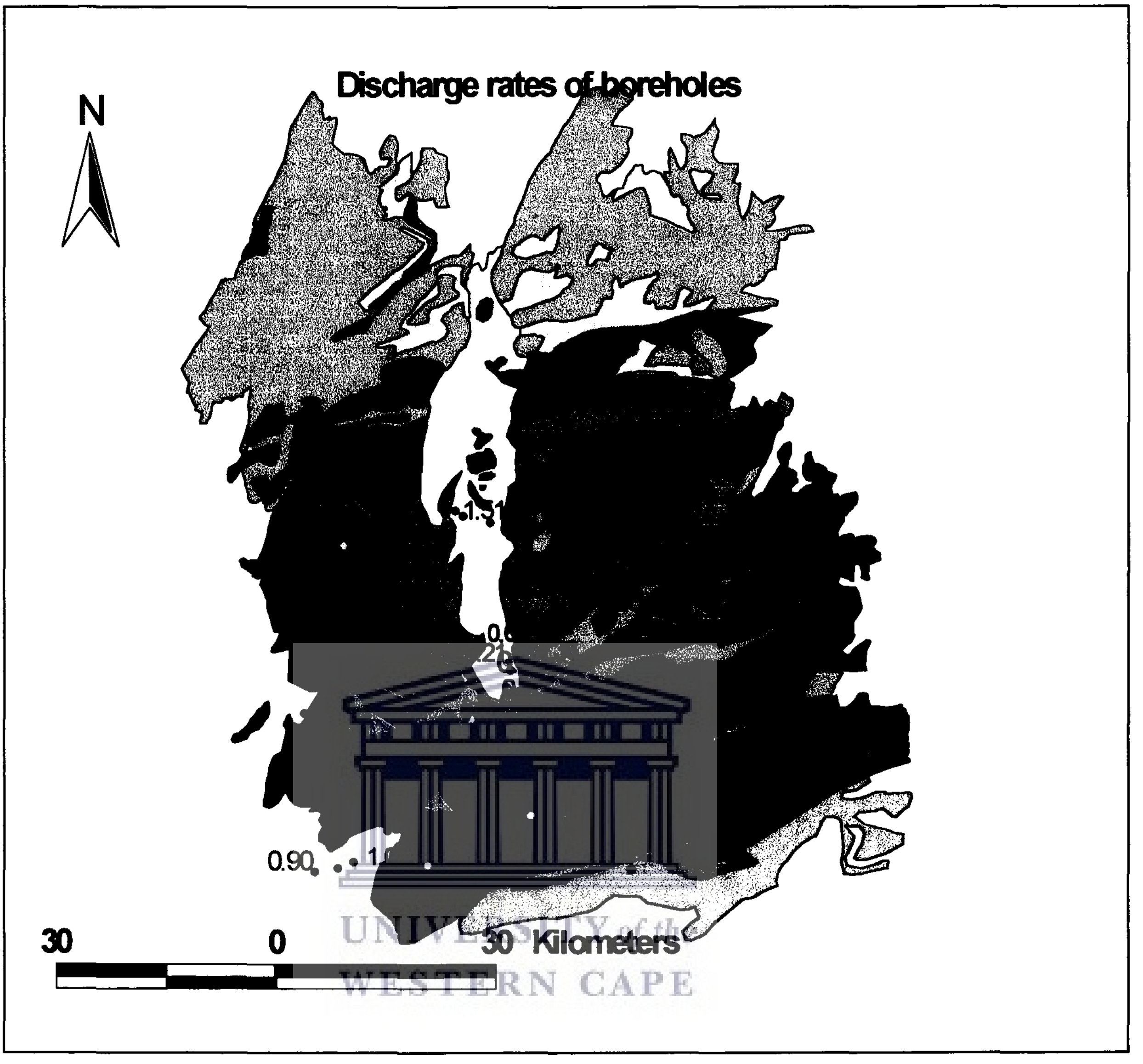



Figure 8b. Discharge rates of boreholes (l/s) related to the geology in the study area.

The data presented in figure 8b are those of 344 boreholes obtained from the National Groundwater Database (NGDB). Most of the boreholes were drilled in granite (in particular the Mesklip granite, Figure 3) and gneiss. Figure 8b indicates that the bulk of the boreholes were drilled in the south of the area, with a large number of these boreholes rendering no water. The mean depth of these boreholes is 58,06m with the deepest borehole at a depth of 196.29m, drilled in Concordia granite with a discharge rate of 0.63 l/s. Figure 8c shows the plotting of depth to yield to see if any correlation between the two data sets can be made. Figure 8c indicates that it is very difficult to see a definite correlation between the two data sets. Correlating the two sets, resulted in a correlation coefficient of -0.076565539, indicating small values of one set correlating with large values of the other (i.e. a large number of boreholes were drilled in one specific lithology, the Mesklip Granite). Generally most yields are <2 l/s. The highest yields are also recorded at depths shallower than 100m, with the highest yield of 7.38l/s recorded at 74m drilled in the Gladkop Suite. At depths greater than 100m, the yields are normally restricted to ~2 l/s except for one borehole with a yield of 2.55 l/s at a depth of 196.29m. Due to insufficient data it is not certain whether there is a possible increase in yield at depths of 200m and greater. The discharge rate of these boreholes varies between 0 and 7.38 l/s, with an average discharge rate of 0.39 l/s. Of the 344 boreholes drilled, 173 (i.e. 50.3 %) gave no water. The majority of boreholes (219) have a discharge rate of between 0 and 0.10 l/s.

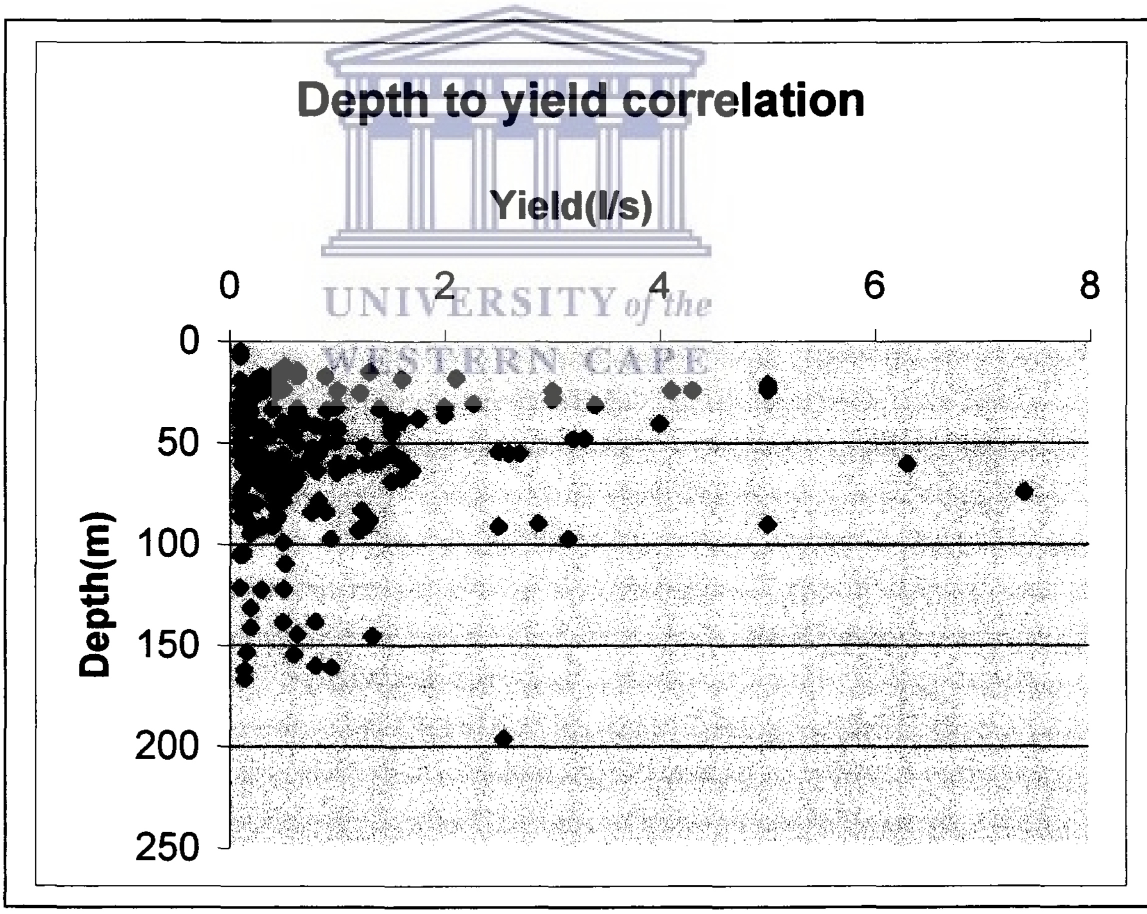



Figure 8c. A graph depicting borehole depth to yield correlation.

## 2.7 Geomorphology

According to Partridge and Maud (1987) landsurfaces together with recent onshore and offshore stratigraphic data, can be used to reconstruct the geomorphic history of the Southern African subcontinent after the break up of Gondwanaland. This history is recorded in a series of major evolutionary stages given in Table 2. Features of the Gondwana surfaces that were of importance for post geomorphic evolution of Southern Africa are:

- The initial high elevation of the African continent.
- The existence of the Cape Fold Mountains and possibly
- The Namaqua Highlands.
- The entire westward trend of the drainage and
- The existence of Karoo rocks below most of the landsurface.

Table 2. A summary of the main geomorphic events and geomorphic manifestations in Southern Africa since the Mesozoic (after Partridge & Maud, 1987).

| **Event** | **Age (Ma)** |
|---|---|
| Climatic oscillations and glacio-eustatic sea-level changes. | Late Pliocene to Holocene |
| Post-African II cycle of major valley incision. Especially in southeastern coastal hinterland | Late Pliocene to Holocene |
| Major Uplift (up to 900m in eastern marginal areas) | Late Pliocene (~ 2.5 Ma) |
| Post-Africa I cycle of erosion | Early mid-Miocene to late Pliocene |
| Moderate uplift of 50-300m. | End of early Miocene (~18 Ma) |
| African cycle of erosion. | Late Jurassic/early Cretaceous to end of early Miocene |
| Break up of Gondwanaland through rift faulting | Late Jurassic/early Cretaceous |

# CHAPTER 3

## FIELDWORK & RESULTS

## 3.1 Introduction

This chapter presents the data and results obtained during fieldwork. It includes the methodologies used in structural geological mapping to acquire data such as fracture orientations, strikes, groundwater source identification and some important information. It is hoped that a concise explanation of data gathered, with and interpretation thereof will be made.

## 3.2 Fieldwork

### 3.2.1 Field Mapping and Methodology

A major component of the fieldwork entailed structural mapping of fractures, joints, bedding (where present) and structures such as faults and folds. Particular attention was given to establishing orientations of fractures, and to ascertain which fractures are dominant in a particular area. The structural mapping and recording of localities was done at 50000 scales on topographical sheets 2917 DA, 2917DB, 2917 DC & 2917DD (in the field) as well as on 1:60 000 aerial photographs. The 1:1000000 geological map of Southern Africa was used to identify lithologies at specific field localities.

In fieldwork, a Freiburger compass was used to measure fracture, bedding and fault orientations. These orientations were recorded in a notebook and later plotted using the RockWare Utilities software STEREO and ROSE to view the dominant orientations and strikes respectively. The data in STEREO were plotted on a equal area (Schmidt) net. The 1:60000 aerial photographs in conjunction with LANDSAT Thematic Mapper were used to identify lineaments, lineament densities as well as lineaments lengths in the study area. The lineament mapping was done under a stereoscope with tracing paper placed on the aerial photographs, which allowed for the lineaments and other structural features (e.g. folds.) to be mapped. These were then digitized using MapInfo and later viewed and manipulated in ArcView GIS version 3.1 to obtain a digitized map of the lineaments of the study area. At the same time hydrological data like borehole yield and depths, were also plotted on a geology map in ArcView, to obtain favourable localities for borehole siting.

## 3.3 Lineament Analyses

Lineament and fracture pattern mapping and identification is important in a groundwater study, since it is these features that control the location and distribution of groundwater. First, a regional lineament analysis was done using LANDSAT TM 4 to obtain large-scale features and secondly 1:60000 scale aerial photographs were used for local, and more detailed mapping. Consequently, a field study was undertaken to identify all of these features in the field and to determine the accuracy of these methods. Another important aspect of the study was to deduce the lengths of the lineaments. Due to the detailed mapping using the 1:60000 aerial photographs, 0.5km was used as the minimum lineament length. Length is important, since the shorter lineaments control local groundwater flow at or close to the surface, whilst the longer ones can be seen as deep-seated fracture systems transporting water regionally (Koch and Mather 1997).

### 3.3.1 Lineament analysis on a Regional Scale using LANDSAT TM 4

Regional lineament identification was done using LANDSAT TM 4 Scenes176/80 &176/81 with 741-band combination (Figure 9a). This produced the main distinctive lineament trends over Namaqualand and the study area. Figure 9b illustrates the major trends obtained from LANDSAT TM 4.

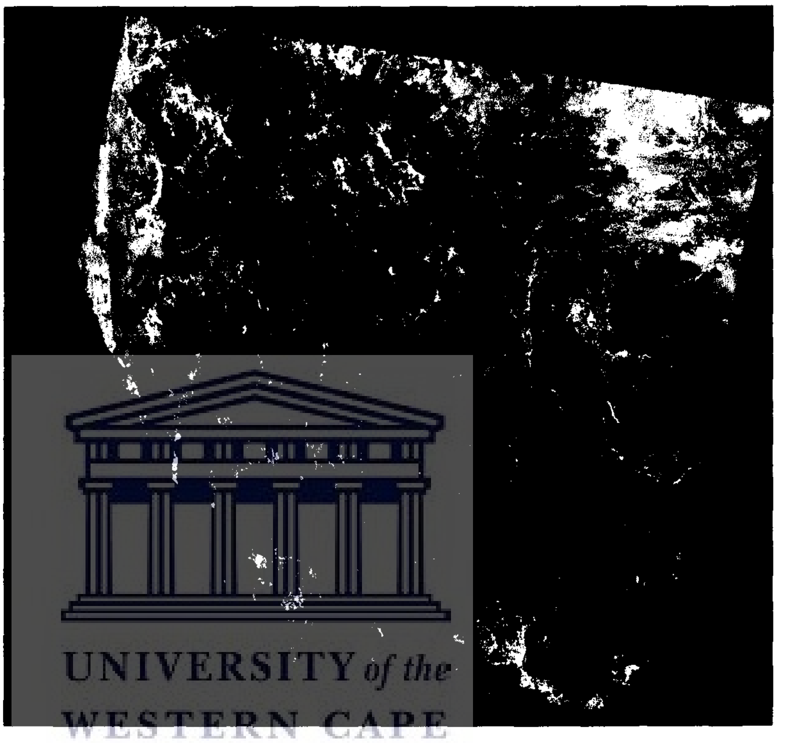


Figure 9a. LANDSAT TM 4 image scenes 176/80 and 176/81 using 741-band combination

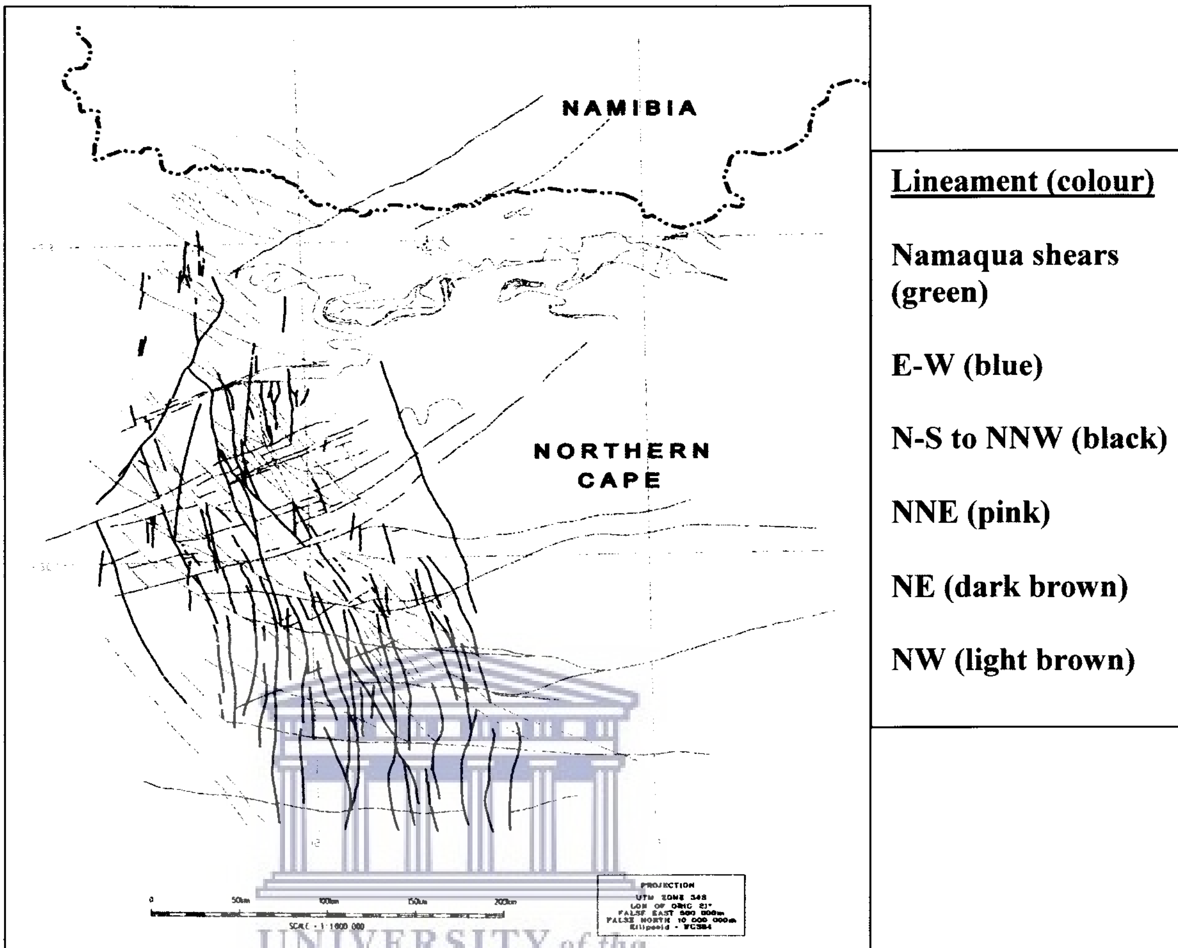





Figure 9b. The Main lineament trends in the study area obtained from LANDSAT TM 4.

The LANDSAT TM 4 revealed large lineaments stretching for vast distances over the Northern Cape. Five different lineament trends differentiated on orientation, as well as the Namaqua shears (green) were distinguished. These orientations are E-W (blue), N-S to NNW (black), NNE (pink), NE (dark brown) and NW (light brown). The Namaqua shears as part of the Namaqua orogeny, are the oldest followed by a tectonic escape phase in the form of the E-W fractures. Based on crosscutting relationships, these seemed to have been followed by the N-S fractures, then the NNE and the last fractures to have developed were the NW fractures.

### 3.3.2 Lineament analysis on a Local Scale using 1:60000 scale aerial photographs

Aerial photographs at 1:60000 scale represented an excellent opportunity as an additional tool to the LANDSAT TM4, to do in depth detailed and accurate lineament mapping because of the smaller scale. Lineaments were taken as those represented by geomorphic features such as mountains, valleys, straight river channels, fractures and tonal variations between lithologies. As an aid, roads, rivers, and towns were also mapped to help with the identification purposes of certain lineaments.

The different aerial photographs were then later mosaiced, scanned in and a physical lineament map was created. This map was then digitized using MapInfo and retrieved in ArcView. The following subsections represent the lineament map, description of lineaments, groundwater occurrence and possible conclusions that can be drawn from these maps.

#### *3.3.2.1 Lineament Map*



The 1:60000 aerial photographs revealed a complex fracture and lineament pattern in Namaqualand (Figure 9c), which is extremely important for this study, since groundwater targeting will have to be done on a local scale. In figure 9c, it can be seen that smaller networks of fractures connect large lineaments. This is a micro-fissured system with the main fractures connected by a complex system of micro fissures (Kruseman and de Ridder, 1991). Therefore the micro fissures (i.e. the matrix) will store most of the water and this will be transported by the larger fractures.

The detailed lineament mapping (Figure 9c) made it difficult to determine dominant lineament orientations in the area due to the attributed intensity of fracture systems. There is an increase in the intensity of fracturing when moving from west to east possibly due to a change in metamorphic grade (which also increases from West to East) and the different tectonic events, or a difference in geology. The area around Springbok consists mostly of gneisses part of the Little Namaqualand suite. Gneisses in general are more prone to weathering than granites; therefore the fracturing in the gneisses are more intense than that in the granites. This increase in fracture intensity is especially evident in the areas south of Springbok and near Nigramoep. There is also an increase in lineament length towards the south with lineaments ranging from 0.5km in some parts, up to 20km and greater in length. Lineaments also increase in length to a lesser extent when moving from east to west. The area around Springbok shows a remarkable absence of extremely large lineaments with respect to the rest of the area, the largest lineaments are roughly 4km in length. When comparing the lineament and geology maps, the lengths of the lineaments seem to be greater in the granites than in the gneisses, with the big lineaments "absent" in the gneisses (Figure 9c).

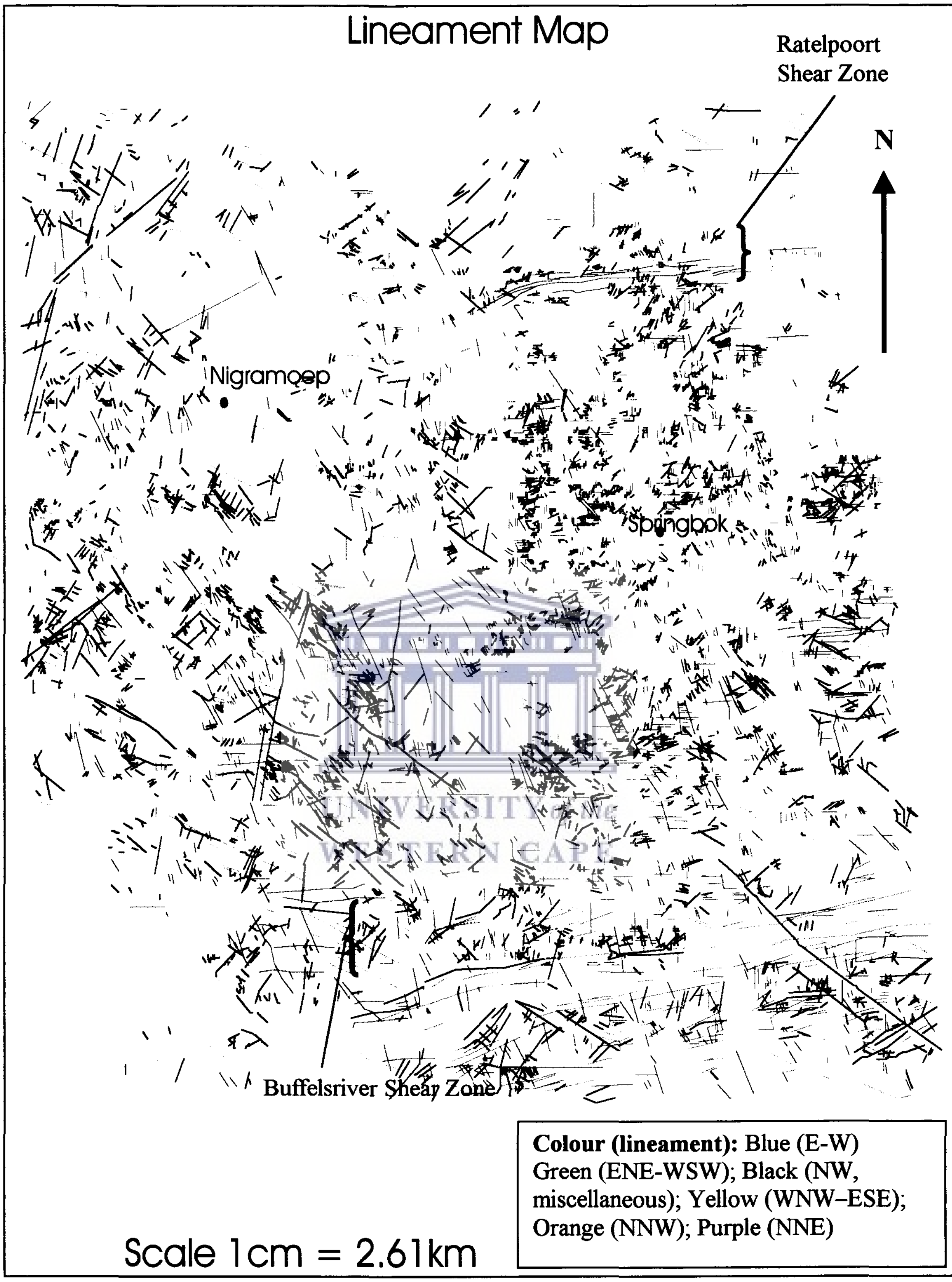



Figure 9c. A lineament map of the study area.

### 3.3.3 Fractures in study area 2917 DA – 2917 DD

The data collected in the study area (Figure 2) resulted in close to 2377 orientations being measured, outlined in Figure 10a below. In order to get a better view of dominant orientations, the strikes of the data were plotted using Rose diagrams (Figure 10b).

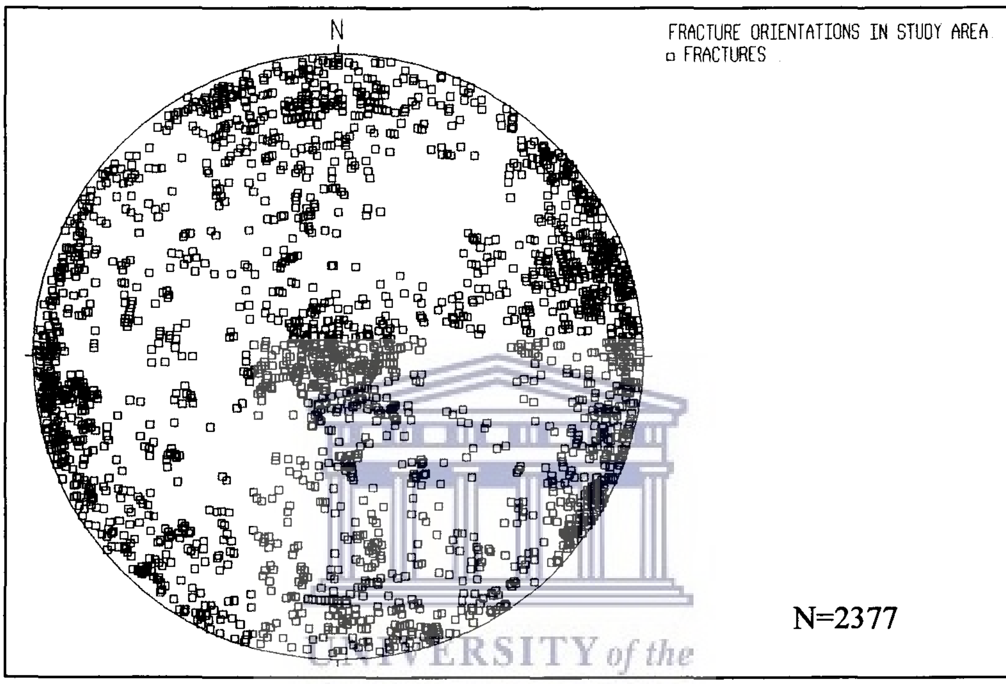



Figure 10a. Fracture orientations of data taken in the study area.

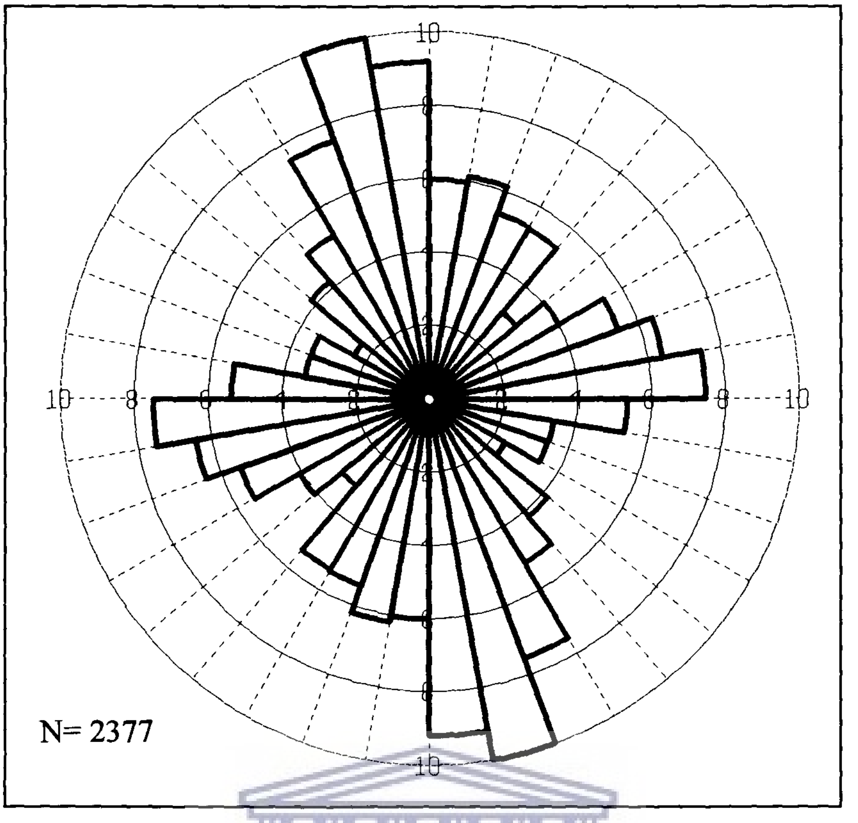



Figure 10b. Fracture strikes for the area.

Figure 10b indicates that the NNW-SSE (N10- 30$^0$W) fractures are the dominant fracture strikes with E-W strikes and ENE-WSW fractures also prevalent. This corroborates other authors like Bense ***et al.***, (1998) who concluded that the NNW-SSE direction was the preferred strike direction of fractures in the Buffelsriver Catchment. The N-S fracture system includes the N-S, NNW-SSE and NNE-SSW fractures, which generally strike 10-30$^0$ off north. This fracture system (N-S) can be classified as a fault system (Plate 3), on closer inspection done in the field. These fractures cut across most of the older fractures (plate 5).

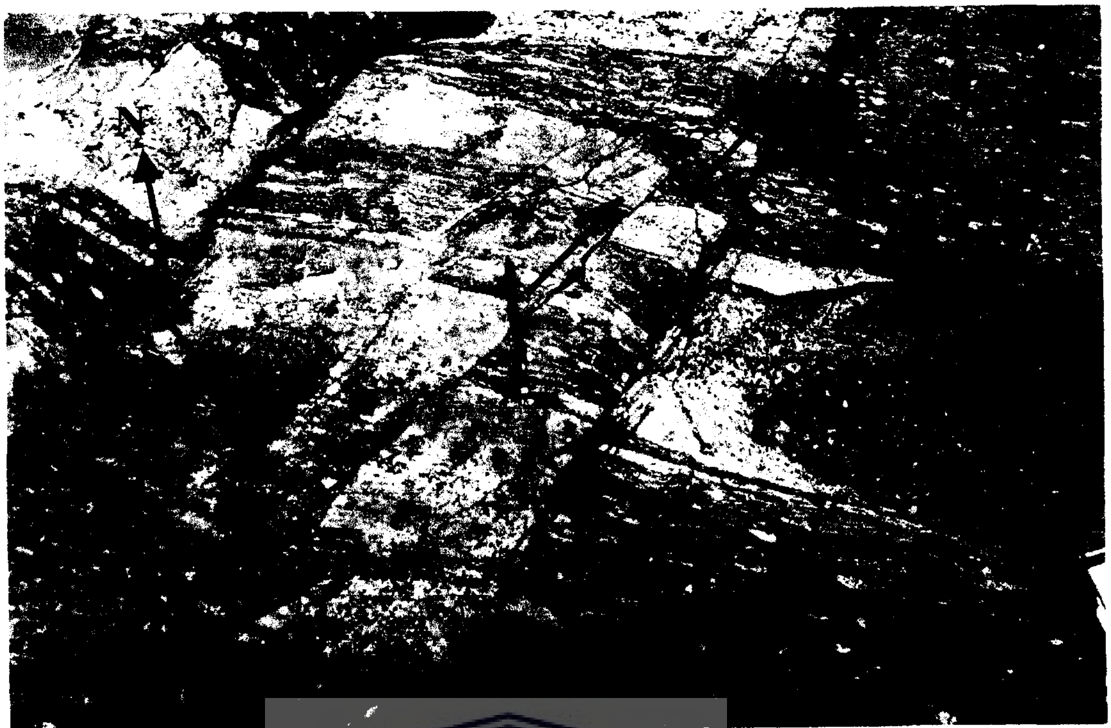



Plate 3. NNE-SSW striking fractures (thrust faults) filled with mafic material displacing older ESE-WNW vein filled (possibly Buffelsriver granite) fractures in the Buffelsriver shear zone (plate 4). The E-W Namaqua fabric in the foreground has slightly changed its orientation due to the shearing (plate 4).



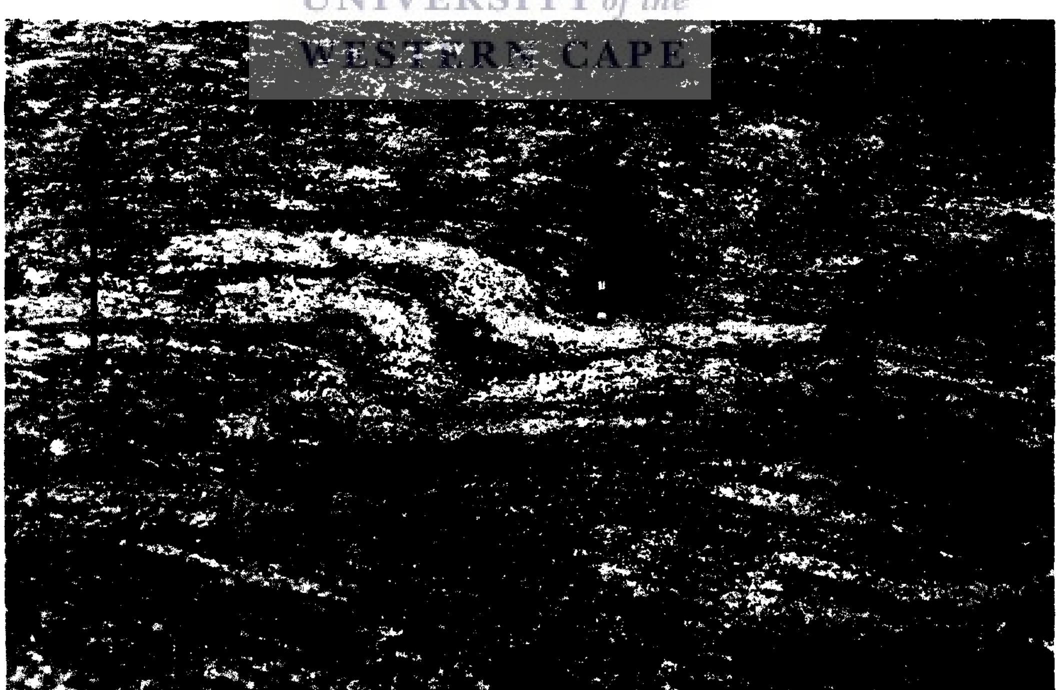


Plate 4. An asymmetric fold in the Buffelsriver Shear zone indicating right-lateral sense of shear.

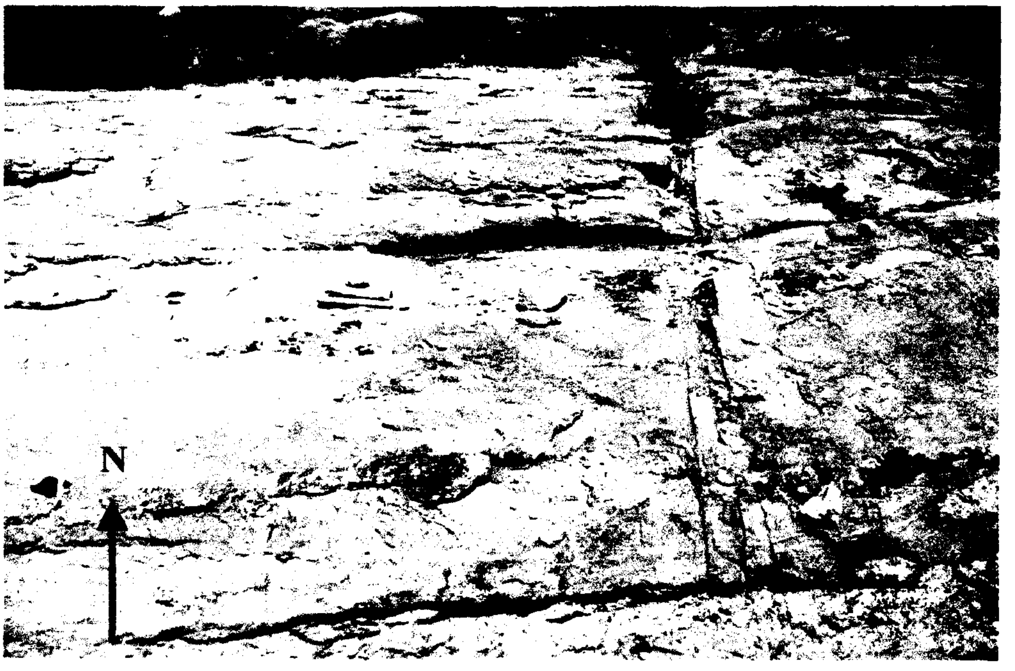



Plate 5. Older E-W fractures that were later filled by pegmatite and subsequently cut by later N-S fractures.

*3.3.3.1 Fractures in 2917 DA - SPEKTAKEL*

This area (Figure 11a) was chosen as a sub-area, since it is part of four 1:50000 topographic sheets incorporating the entire study area.

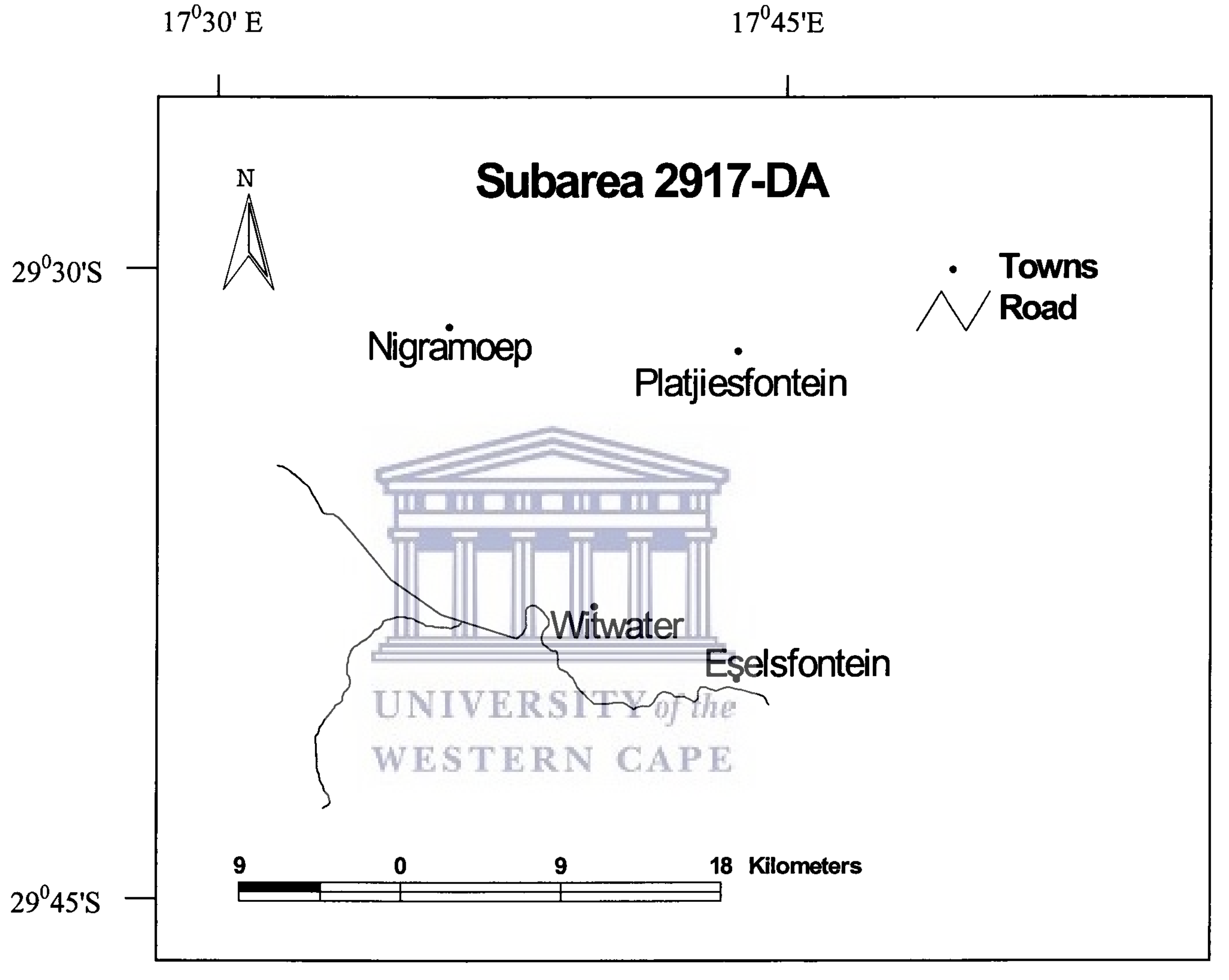



Figure 11a. Subarea 2917-DA.

The data taken in this sub-area resulted in a total of 244 orientations measured (Figure 11b). The data measured were predominantly of fractures and to a lesser extent possibly joints. The orientations of these were then plotted using RockWare Utilities software STEREO and ROSE to obtain the dominant directions, the stresses responsible for the formation of these structures, and consequently determine which of these fractures are extension fractures and which formed as a result of shearing. Figure 11b indicates that main orientations in this subarea are, the horizontal fractures, and those fractures dipping SE and ENE.

Figure 11c indicates that the NNE-SSW striking fractures dominate in this subarea, followed by the NNW-SSE and E-W fractures (E10$^0$N and W10$^0$N).

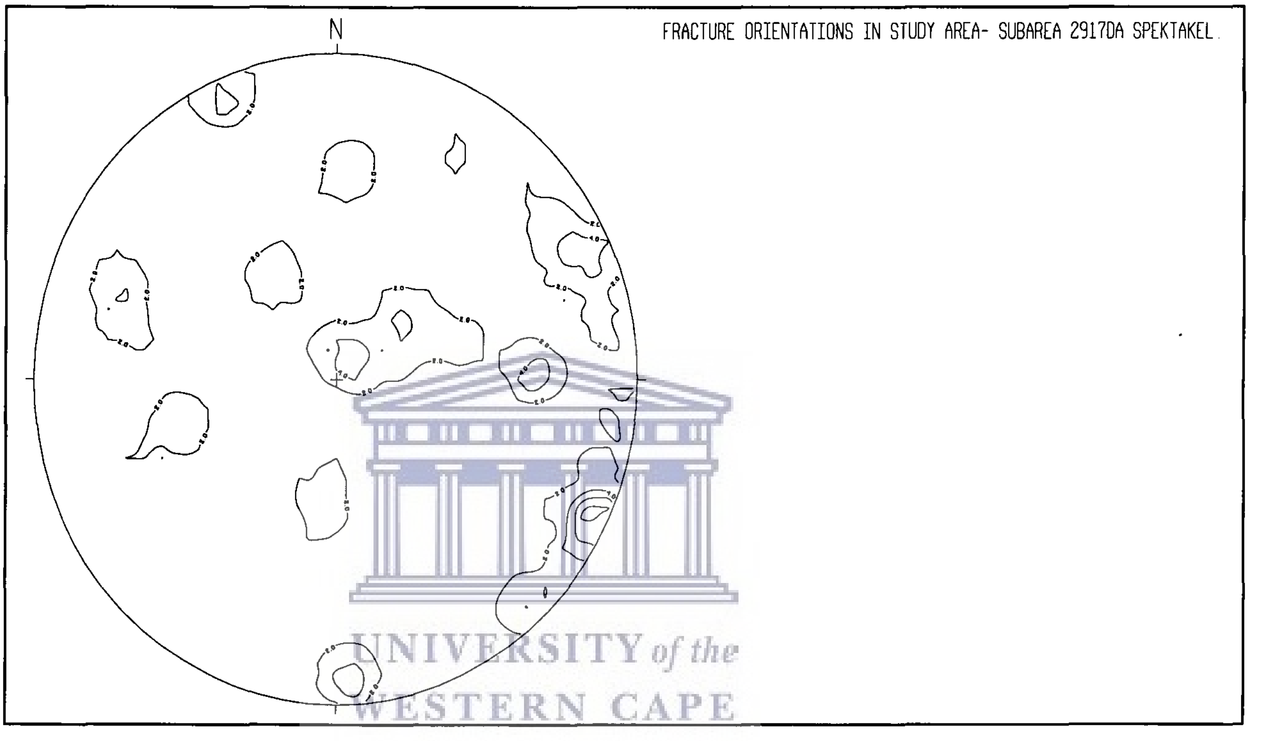



Figure 11b. Contoured fracture orientations in 2917DA – Spektakel.

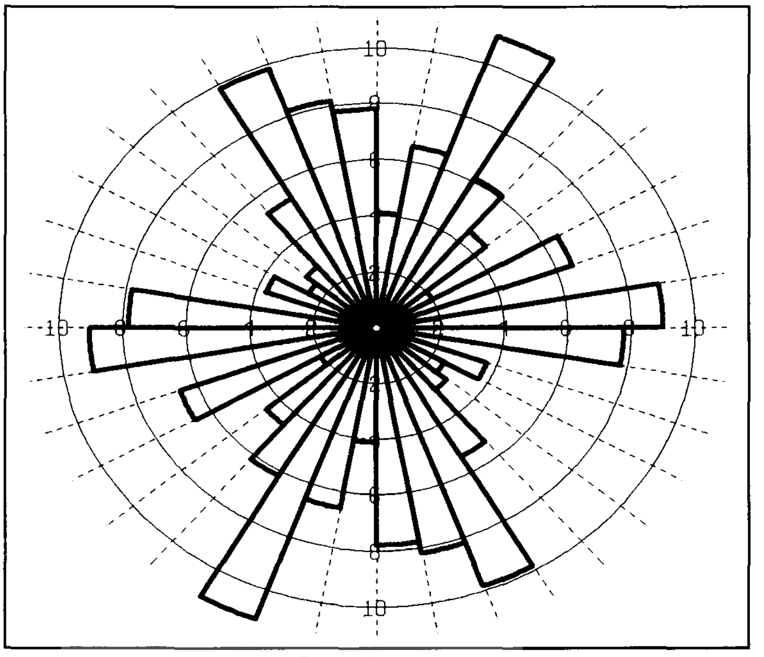


Figure 11c. Fracture strikes in 2917DA – Spektakel.

3.3.3.1.1 The Nama Sediments

These groups of sedimentary rocks are the youngest group of rocks in the study area, approximately 500-600 Ma and rests unconformably on the older rocks (plate 11). The dip of the bedding is essentially horizontal (Figure 12a). In Figure 12a the two sets of fractures, i.e. the NNE-SSW (F1) and the ENE-WSW (F2), were the only identifiable fractures found in these rocks.

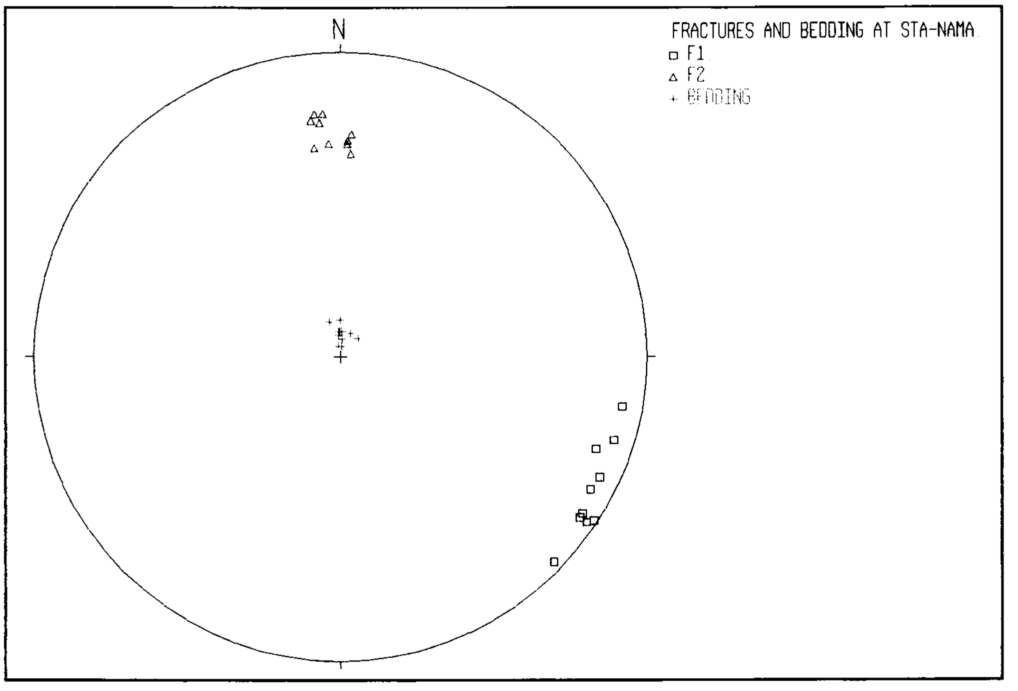



Figure 12a. Horizontal dips of the Nama sediments indicated by crosses in the center.

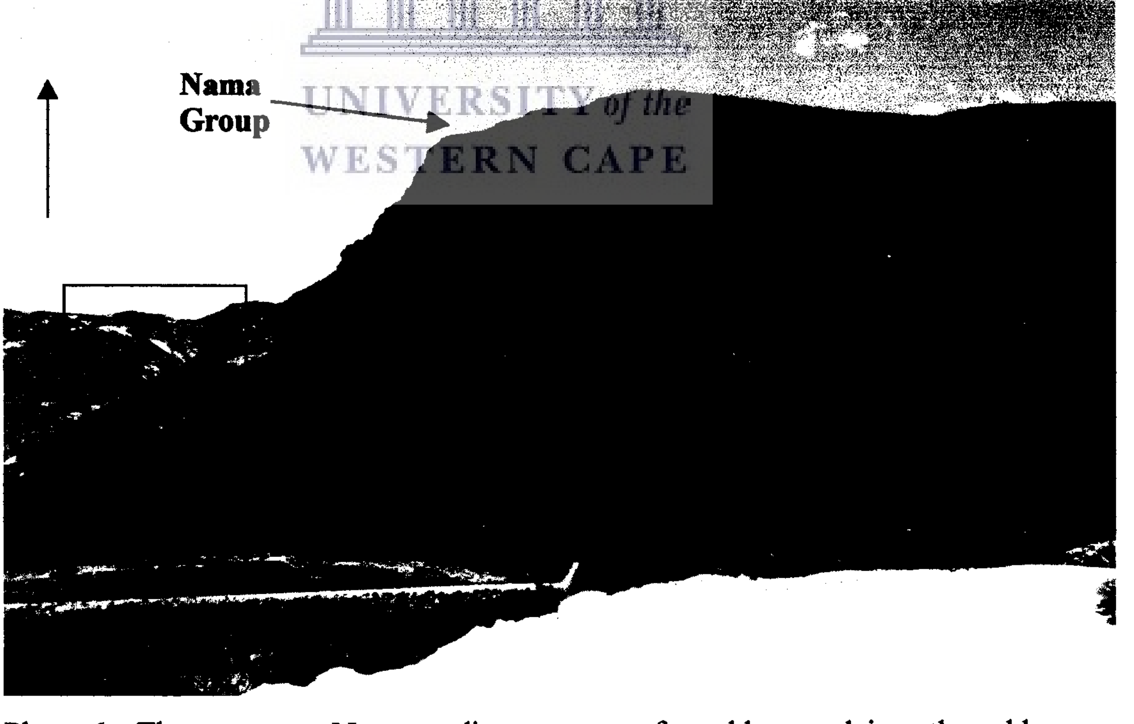



Plate 6. The younger Nama sediments unconformably overlying the older intrusive rocks in the Spektakel pass west of Springbok.

This sub-area (Figure 13a) is found in the southwestern part of the study area (Figure 2). A total of 86 data points were measured, in an extremely mountainous terrane. Figure 12b shows that the fractures in this area generally dip steeply to the NE and SE.

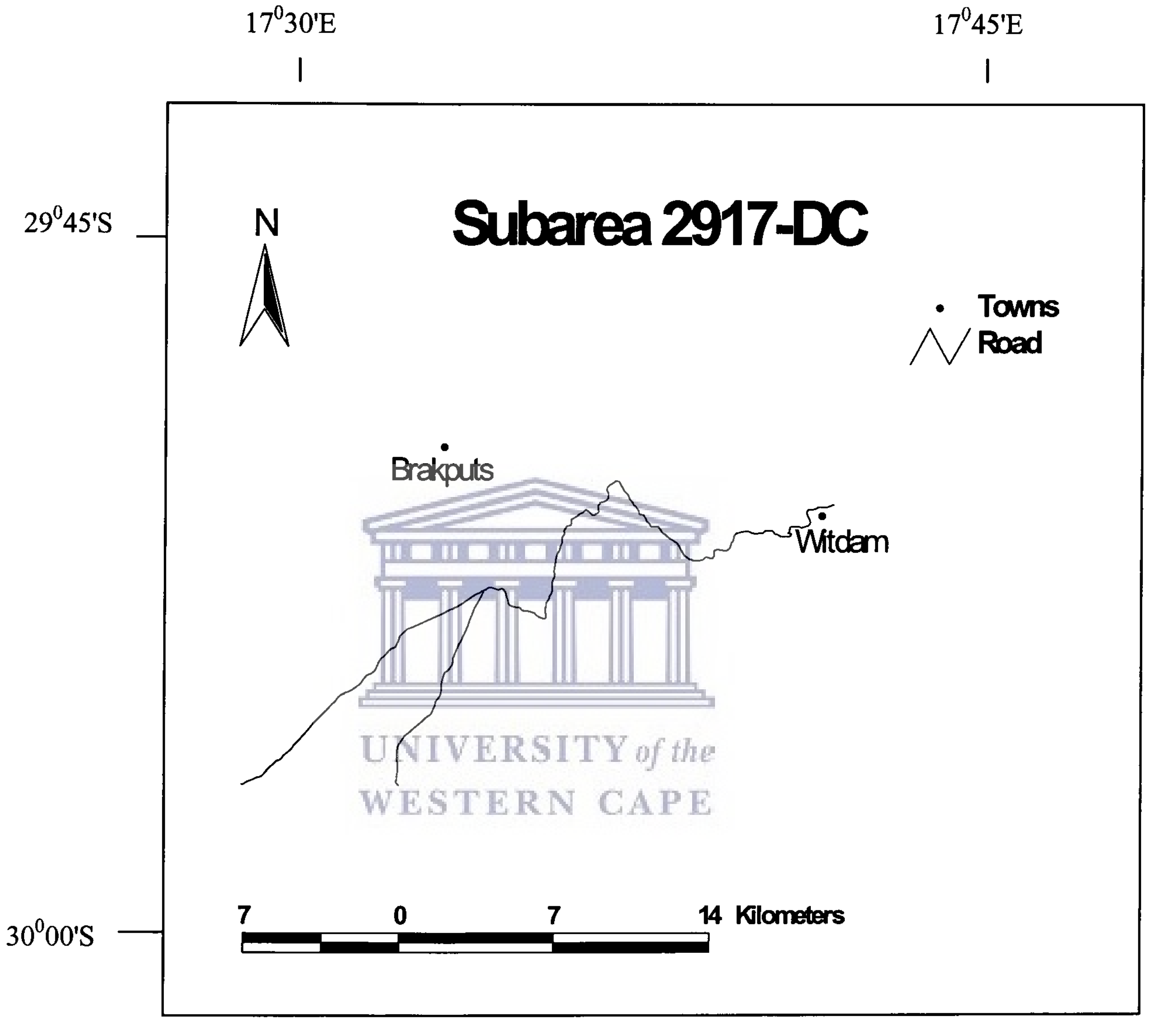



Figure13a. Location of subarea 2917 DC.

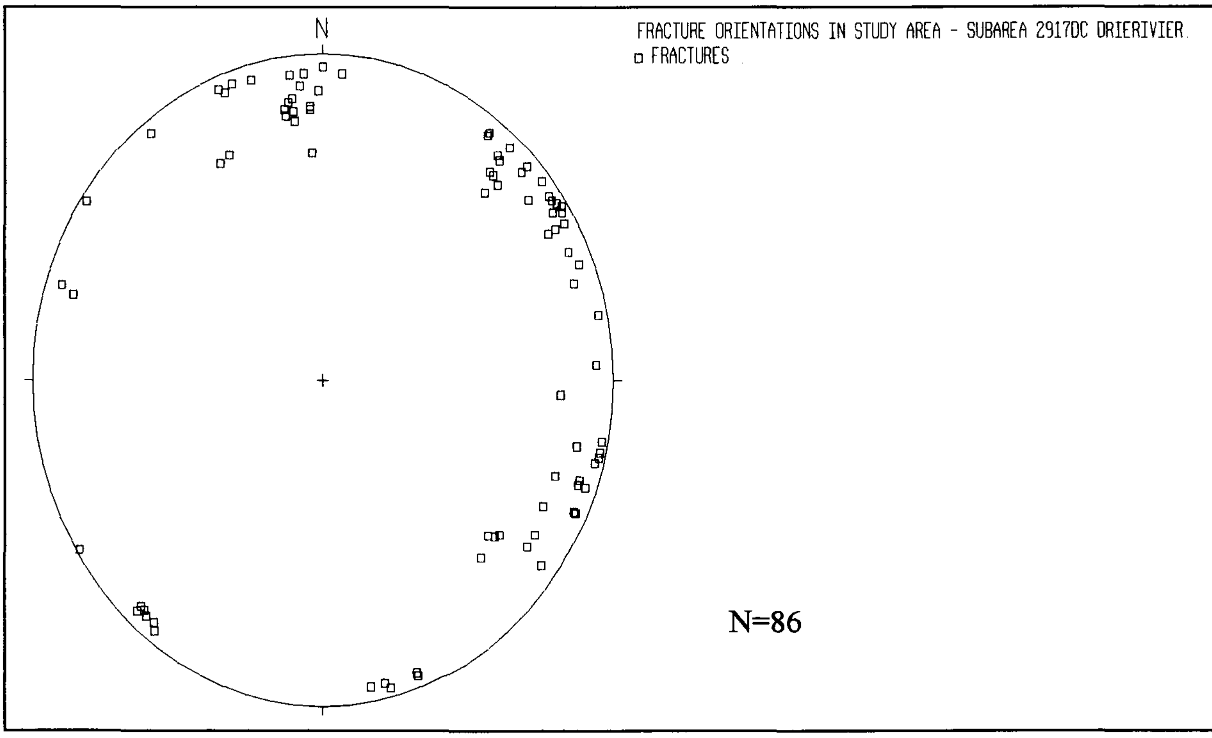



Figure 13b. Stereographic projections in subarea 2917 DC – Drierivier.


Plate 7 . An example of the cross cutting relationships of different fracture orientations found in this subarea. The E-W striking fracture has been filled with quartz, and was subsequently cut by the later N-S and NW-SE fractures.

*3.3.3.3 Fractures in 2917 DB – SPRINGBOK*

This subarea (Figure 14a) situated in the northeastern section of the area (Figure 2), encompasses all the major towns of the area like Springbok, Okiep and Nababeep. Most of the data (Figure 14b) were taken along the N7, major roads in the area, and outcrops, totalling 971 readings. The N-S fractures (Figure 14c) are the preferred orientation in this sub-area, with a weak E-W peak with respect to the N-S fractures. The N-S fractures include the NNW-SSE and NNE-SSW (10-30$^0$ off the N-S axis). The N-S fracture system is mostly seen in this part of the area, and was generally accompanied by intrusions of mafic material along them, as shown in Plates 2 & 6. The dominance of the N-S system is affirmed with 17 of the 33 localities in this area incorporating strikes related to this system. Other fractures include the ENE-WSW (plate 8) and WNW-ESE striking fractures.

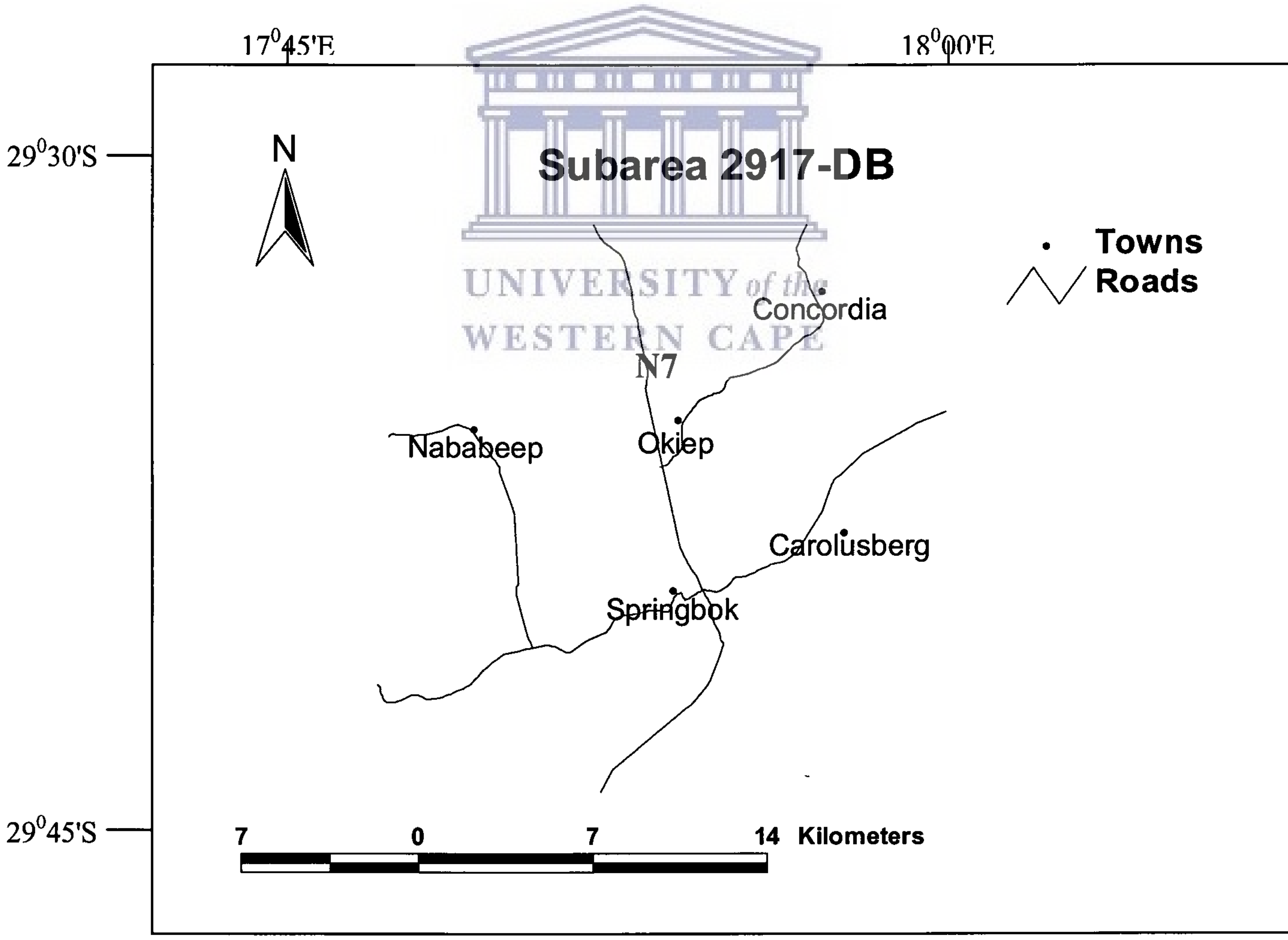



Figure 14a. Subarea 2917 DB.

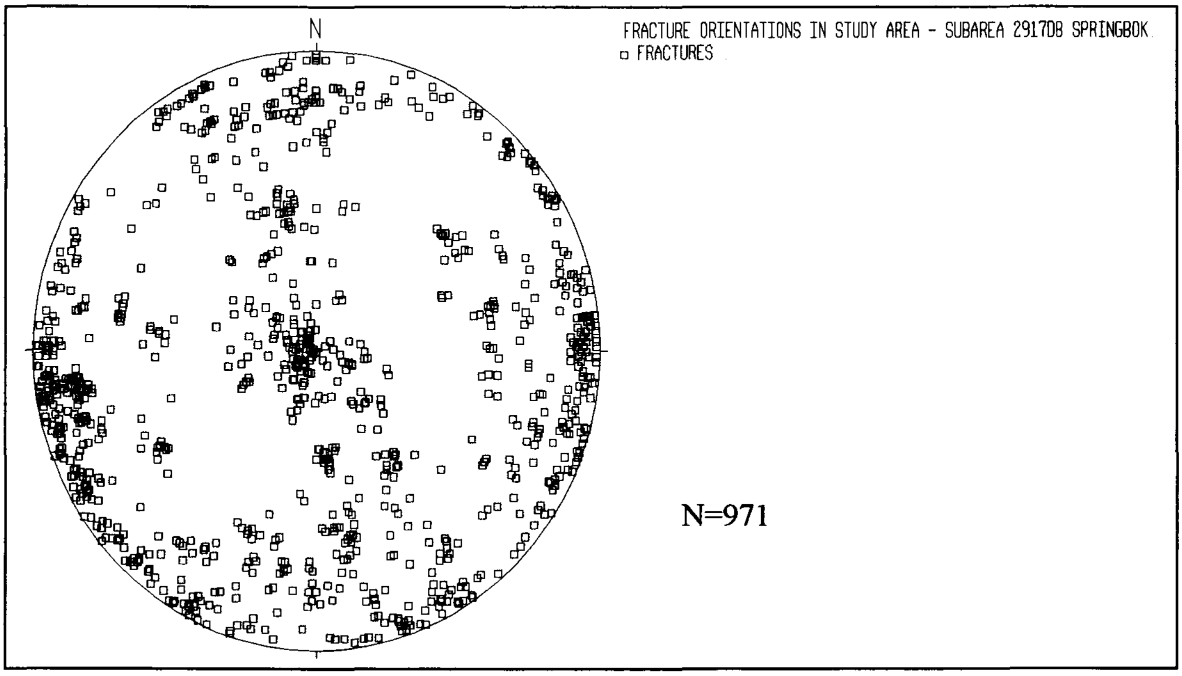



Figure 14b. Fracture orientations of stations in 2917DB – Springbok.



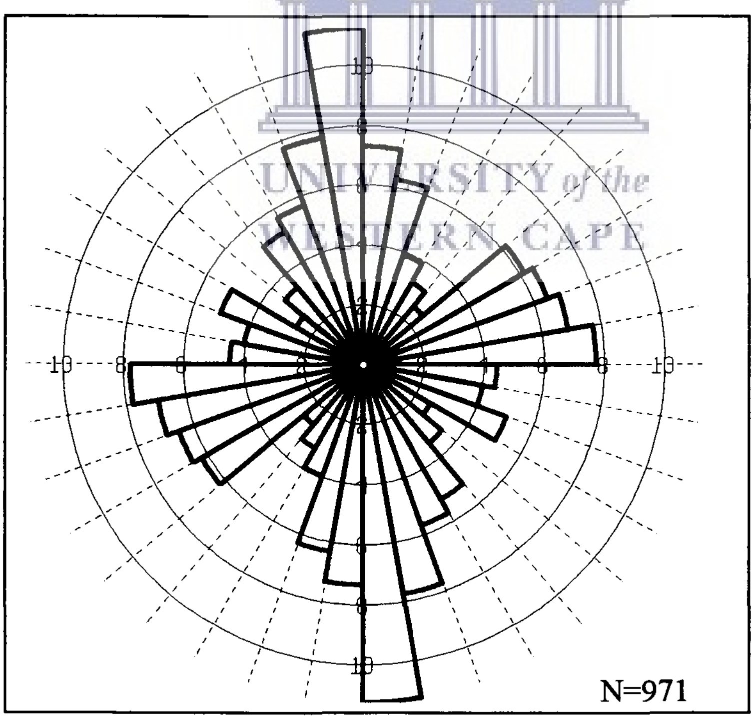



Figure14c. Rose diagram of fractures in subarea 2917 DB – Springbok.

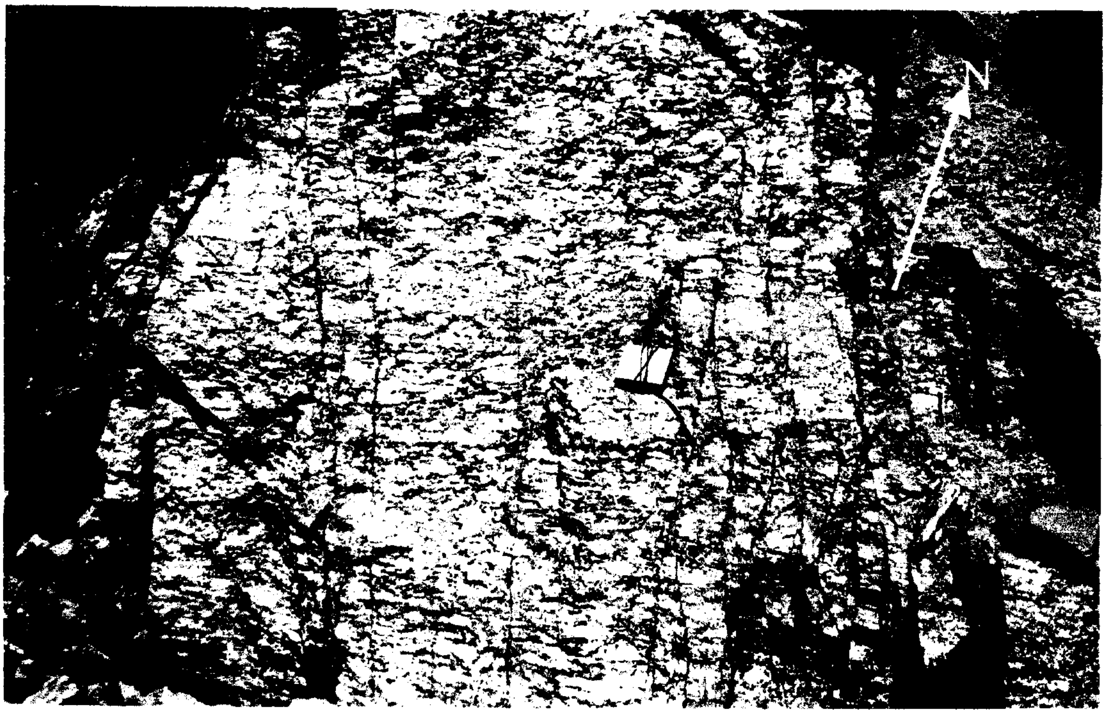



Plate 8. Indicates the N-S fracture system with strikes N-S, NNW and NNE.

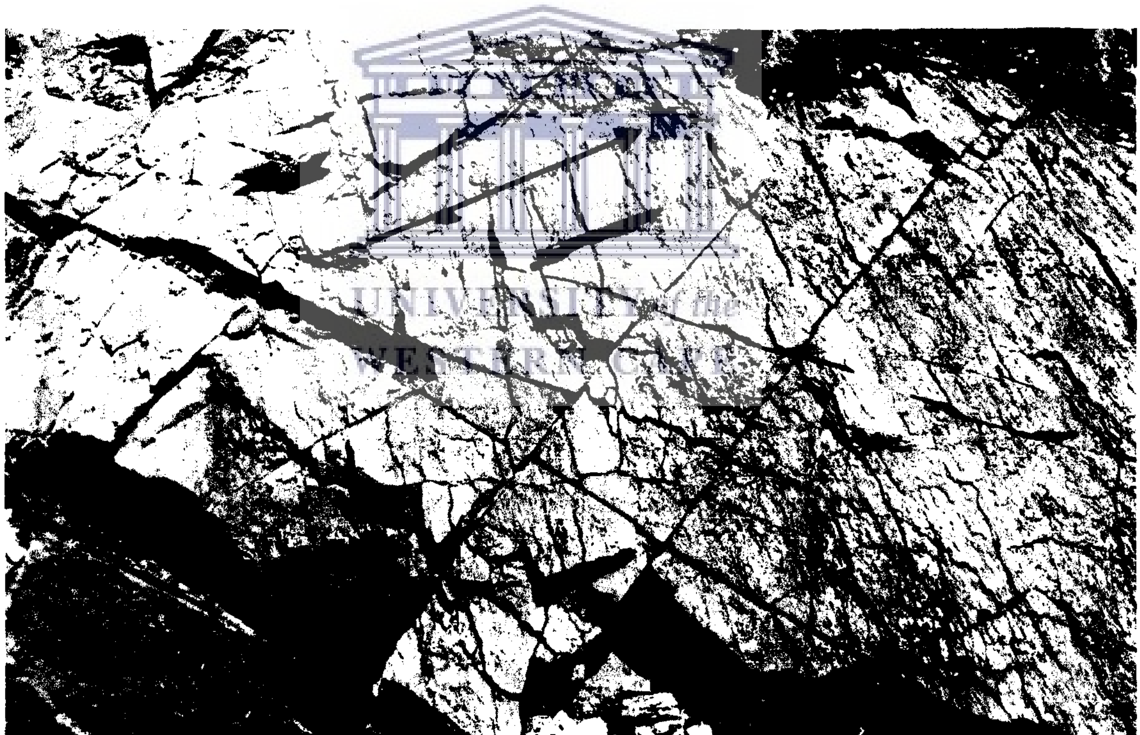


Plate 9. An extremely fractured outcrop of Nababeep Gneiss with NNW-SSE, ENE-WSW and WNW-ESE striking fractures outside the town of Nababeep. The Namaqua fabric has slightly changed its orientation (normally E-W) to a WNW-ESE due to shearing. This shearing appears to have been north northwesterly directed.

*3.3.3.4 Fractures in 2917 DD – MESKLIP*

This southeastern section of the study area (Figure 15a) includes approximately 924 fracture orientations of 30 localities illustrated in Figure 15b.

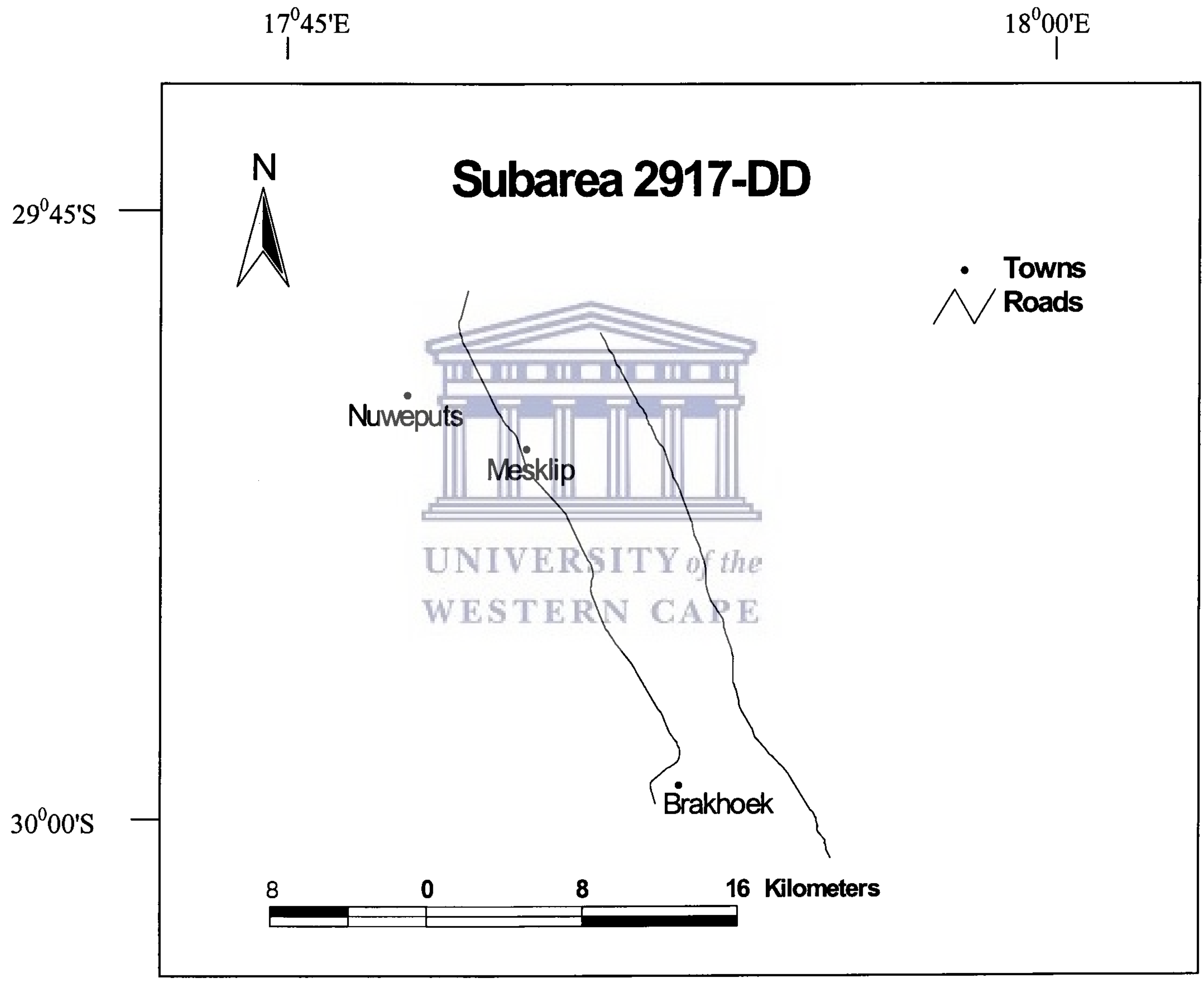



Figure 15a. Subarea 2917 DD.

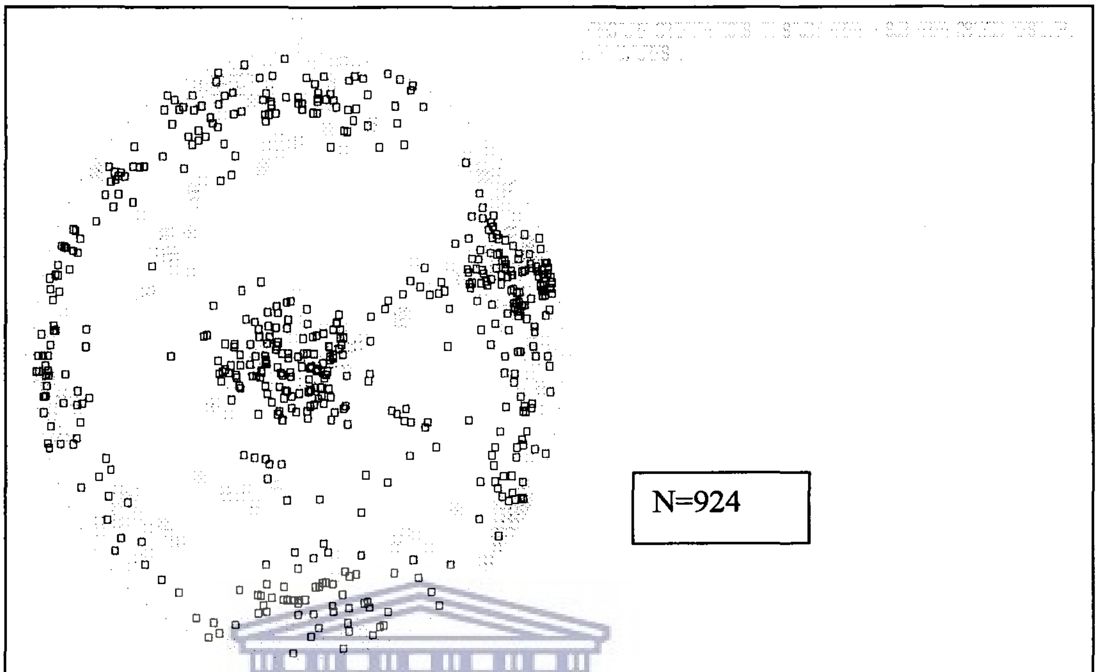



Figure 15b. Fracture orientations of 2917 DD – Mesklip.

Figure 15b illustrates that the data includes a wide selection of orientations in the study area. The strikes of these data points are given in Figure 15 c below, the dominant strike being NNW-SSE and peaks of NNE-SSW and ENE-WSW (plate 10). In Figure 15d were these data points are contoured, the dominant fractures are the horizontal fractures (plotting in the center), the ENE-WSW and the N-S fracture system.

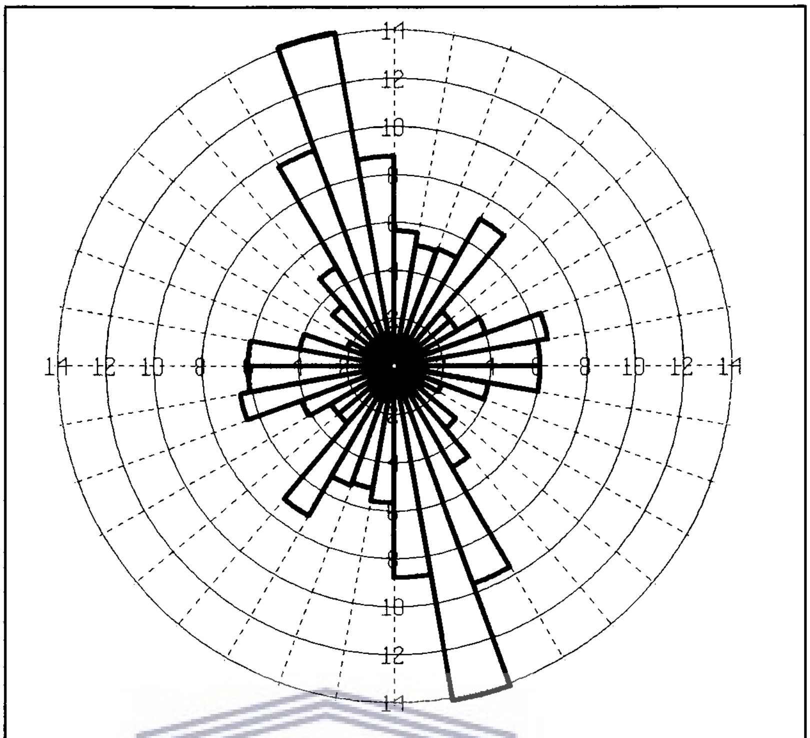



Figure 15c. Fracture strikes in subarea 2917 DD – Mesklip.

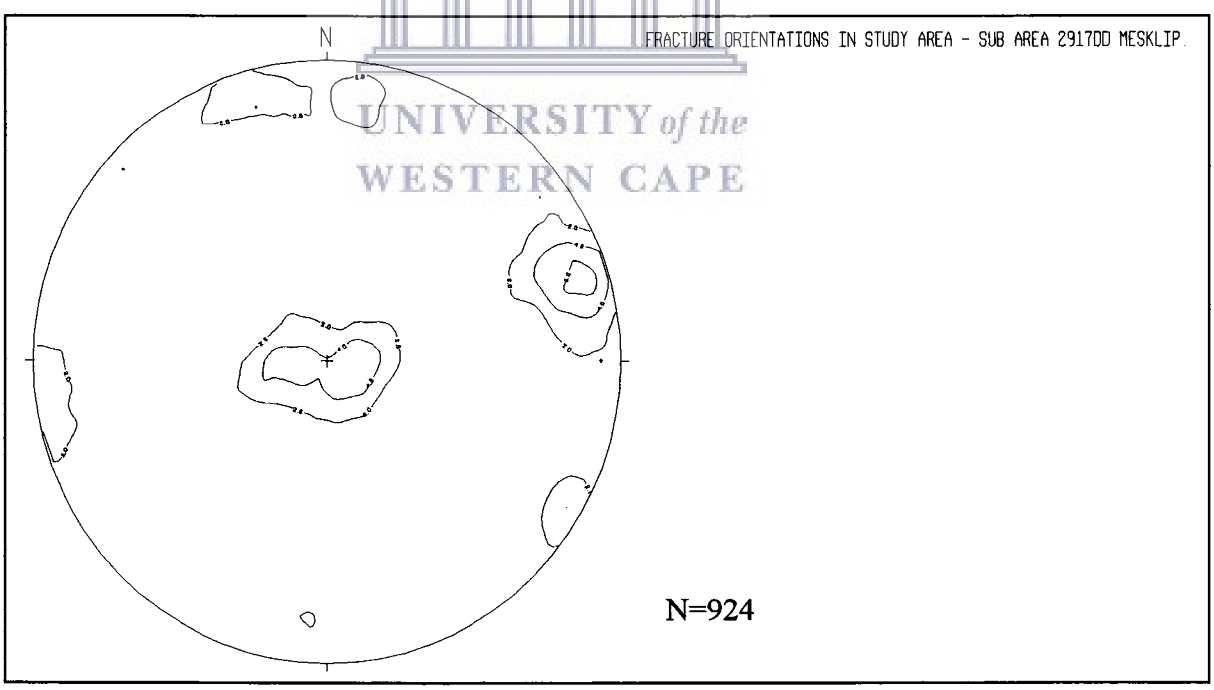



Figure 15d. Contours of the fracture data in subarea 2917 DD – Mesklip.

Plate 10. ENE-WSW fractures cutting across vein filled NNW-SSE fractures at the contact between Khurisberg and Mesklip granite in the south of the area.

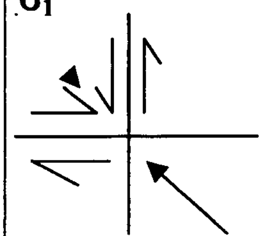
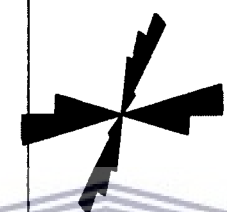
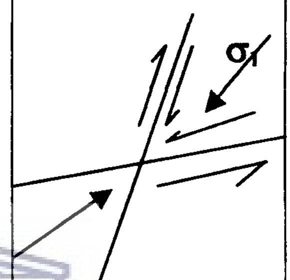
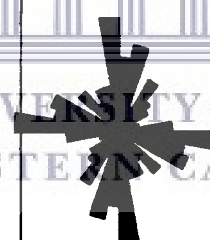
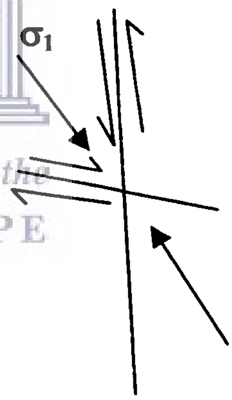
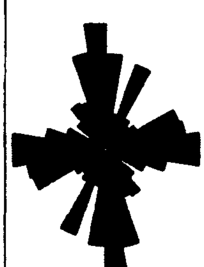
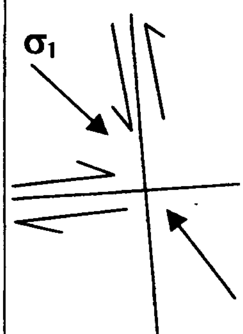
## 3.4 Stresses in the area 2917 DA-DD related to the different tectonic events.

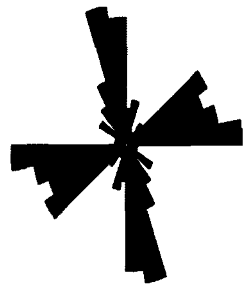
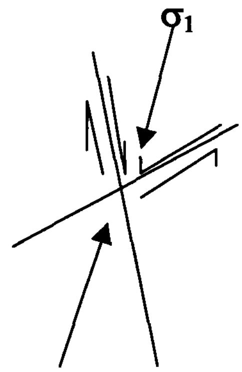
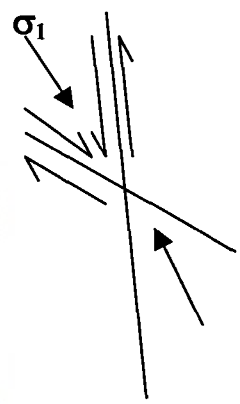
In order to determine the stress directions that have prevailed in the area, the different tectonic orogenies and events had to be identified and distinguished. At the same time the data collected in the field, had to be incorporated into these events. Robb *et al.*, (1999), established rock types of two main ages in the Okiep Copper District (OCD). These are the amphibolite-facies granitic orthogneisses developed during the Kheis orogeny (2000- 1800 Ma), and the Kibaran sedimentary and intrusive granitoids formed and buried at roughly 1300-1000 Ma. These rocks were then deformed by the later Namaqua orogeny. The two main tectonic events in the area, are $D_1$ and $D_2$ (section 2.5.1.3) which forms part of the Kheis and Kibaran orogenies respectively. $D_1$ deformation is exhibited by intrafolial folds in the orthogneisses of the Gladkop suite and metasedimentary remnants (Khurisberg subgroup). The $D_2$ event is the dominant deformation in the OCD and is seen as a subhorizontal gneissosity in the orthogneisses of the Little Namaqualand Suite. The Kibaran and Namaqua orogenies seem to overlap, with the age of the Namaqua orogeny set at ~1200Ma.

The $D_1$ and $D_2$ events were then later followed by the deposition of the Nama sediments at ~550 Ma, rendering it an age of Late Proterozoic – early Phanerozoic. The most recent events followed these. Using the above information and the fracture data obtained during fieldwork, it was possible to some extent, to show the evolution of the stresses that affected the different rocks in the area.

Table 3 illustrates the different ages of events, the events itself and the ROSE diagrams of the fracture data related to these events. The stresses were then calculated using the ROSE diagrams, based on a method used by Fernandes and Rudolph (2001). Basically this method entails distinguishing the different tectonic events, calculating the fracture patterns using ROSE software, and using these to deduce the stress directions from basic theory, i.e. $\sigma_1$, bisects the acute angle between your two dominant fracture sets, and $\sigma_3$ the obtuse angle (between the two dominant fracture sets), and $\sigma_2$ perpendicular to these stress axes. Through these processes, a rough estimate of the stresses pertaining to a particular event in a specific area, can be determined.

Table 3. Stress evolution in the area, with its resultant shear and extension fractures.

| Age | Events | | Fracture Patterns | Shear fractures and $\sigma_1$ directions | Extension Fractures |
|---|---|---|---|---|---|
| Neotectonic | | | (Inferred from literature) |   | NW-SE |
| Late Proterozoic to early Phanerozoic | Nama Sediments | |  |   | ENE-WSW |
| Proterozoic | D2 | Modderfo ntein Gneiss |  |   | NW-SE |
| | | Nababeep Gneiss |  |   | NW-SE |

| Age | Event | | Fracture Patterns | Shear Fractures and $\sigma_1$ direction. | Extension Fractures |
|---|---|---|---|---|---|
| Proterozoic | D1 | Gladkop Suite |  |   | NNE-SSW |
| | | Khurisberg Subgroup |  |   | NNW-SSE |



Since the stress directions have been established, it is important to identify the extension fractures (parallel to the $\sigma_1$ direction), in terms of groundwater, since it is these fractures that are set to control groundwater flow.

# CHAPTER 4

## DISCUSSION AND CONCLUSION

The stress fields in the study area have changed from NNW-SSE in some of the oldest rocks, to a NW-SE neotectonic stress field defined by Andreoli *et al.,* (1996). The NW-SE stress field is defined as the Wegener Stress Anomaly. This neotectonic stress field varies slightly within the area. At the Carolusberg mine in the study area, a subhorizontal compressional stress field orientated in a NNW direction at a depth of 1572m was recorded which Andreoli *et al.*, (1996) attributes to the ENE-WSW trending Griqualand Transvaal upwarp axis.

Table 3 indicates that in between this time range of stress fields, the NNE-SSW, NW-SE and ENE-WSW stress fields also operated. After the formation of the Khurisberg subgroup, which was subjected to a NNW-SSE stress field, the Gladkop Suite intruded at about 1800 Ma and underwent NNE-SSW compression. The formation of the Little Namaqualand Suite saw two of its members, the ~1212 Ma old Nababeep Gneiss and the ~1199 Ma Modderfontein Gneiss experiencing a NW-SE compressional stress. After the intrusion and formation of the Little Namaqualand Suite, the area experienced a relatively quiet period. This stage of relative calm, was interrupted by the deposition of the Nama sediments during the late Proterozoic to early Phanerozoic, at ~550 Ma. The deposition of the Nama sedimentary rocks saw the stress field change from NW-SE to ENE-WSW, due to the Pan-African event.



The occurrence of the various stress fields naturally resulted in different fractures forming, whether it was shear or extension fractures. The fact that the NW-SE stress field had operated in the past and also is the present day stress field, meant that these fractures are not only favourable for groundwater location, but also must have seen a variable degree of reactivation since they were already in extension. So, in essence, the NW-SE fractures should be targeted in search of groundwater.

Figure 10b indicates that the main fractures obtained from field data in the area, are the NNW-SSE and E-W fractures. Field evidence shows that the NNW-SSE fractures are part of the N-S fracture system, which also includes N-S strikes and sometimes NNE (plate 7) and NNW strikes and was intruded by dykes along them. Field evidence also indicated that this fracture system is actually a family of faults displacing older rocks. These fractures dominate in most of the area except for subarea 2917-DC, where these fractures are almost absent. According to Bense *et al.*, (1998), dykes at about 800 Ma intruded these fractures. Joubert (1973) explains that these fractures have been reactivated along existing lines of weakness at ~500-600 Ma. At present there is also a school of thought attributing these N-S fractures to the breakup of Gondwana with its associated continental rifting and the opening of the Atlantic between ~140-110 Ma.

Fracture relations in the field indicate that the N-S fracture system cuts across most of the other fractures found in the intrusive rocks and the metasedimentary rocks, except for those in the Nama sediments. The N-S fractures are present in the older intrusives but not in the younger 500-600 Ma Nama group. One possible reason could be that these fractures were just overlooked in the field. The most probable explanation though, would be that the N-S fractures are post Intrusives and pre Nama, thereby explaining their absence. Since Joubert (1973) describes these fractures to have undergone reactivation at 500-600 Ma, it would be absent in the Nama, since the Nama was roughly formed at that time. Therefore one would tend to lean towards a pre Nama age for these N-S fractures rather than a post Nama age.



The older E-W fractures found in the gneisses of the Little Namaqualand Suite in the area are believed to be part of the Namaqua orogeny. This orogeny was preceded by a collisional/ accretional phase seen by the shearing (green) in the north (Figure 9b), and was followed by a tectonic escape phase indicated by the larger E-W fractures (Figure 9 b & c). The Neotectonic Stress field in the area is NW-SE. What became clear during fieldwork and the ensuing processing of field data was an almost clear absence of these NW-SE fractures taken in the field except for 2917 DC. In the field there is a dominance of structures attributed to brittle deformation in this subarea (2917 DC) with almost no sign of the structures formed by ductile deformation, as is the case in the rest of the area. These increases in brittle behaviour and NW orientation of fractures are illustrated in Figure 9c.

In trying to deduce the relative ages of these fractures, it became quite clear that formation of these fractures would have to be related to the different orogenies, since the same fractures appeared through time owing to similar stress fields. So, when looking at the Kheis orogeny, one would assume that the NNW-SSE fractures are the oldest since they parallel the applied stress direction. The resulting shear fractures i.e. the N-S and WNW-ESE fractures, will then follow the NNW-SSE fractures. The fractures that formed after these appeared to have been the ENE-WSW, NNE-SSW and NE-SW fractures based on Table 3.

During the Kibaran and Namaqua Orogenies, the NW-SE fractures are assumed to be the oldest since it is the oldest stress direction in this deformation event. These fractures were then followed by shear fractures with strikes orientated NNW-SSE, E-W and WNW-ESE. These fractures were post dated by the ENE-WSW fractures which were probably formed during the Pan-African at ~550Ma years.



The Remote sensing on the other hand, provided a more detailed insight, on a regional and local scale, filling the gaps that could otherwise not have been covered by the fieldwork. In contrary to the LANDSAT TM 4 and field mapping, the lineament map (Figure 9c) revealed lineaments in great detail as to be expected due to the larger scale of the aerial photographs. This detail, however, became the drawback, since no general trends of lineaments could easily be identified. Nevertheless, the main directions in the field and those identified on the LANDSAT were highlighted. Usually, the lineaments increase in length from north to south. There is also an increase in the intensity of fracturing moving from W-E, which can be attributed to the various degrees of metamorphism. The metamorphic grade increases from the coast moving inland (SACS, 1980). The highest intensity of fracturing seen in the east of the area around Springbok (Figure 9c) coincides with a higher degree of metamorphism in this vicinity in the area. The increase in fracturing may also be due to different geological units and the degree of weathering. Gneisses dominate the area around Springbok, whereas further south and west, granites tend to dominate. Since gneisses generally weather more easily than granites, the fracturing in these will tend to be more intense than in the granites. Hence, infiltration of water into the gneisses should be more rapidly with these fractures storing more water. The lengths of these lineaments serve as an indication of whether particular lineaments can be seen as regional water carriers or local carriers, assuming that the larger lineaments are set to be an indication of regional deep groundwater systems and the smaller lineaments indicative of shallow groundwater systems (Koch *et al*., 1997).

When drilling boreholes in Namaqualand or aiming to do so, past research suggests that the best system to drill a relatively successful yielding borehole would be the weathered fractured system. Yields in excess of 7l/s were recorded in this system. This said, as with life there are no guarantees. A large number of boreholes drilled in this system came up empty handed, due to factors such as differential weathering, changing stress fields and its resultant fracture systems.



Fracture systems control groundwater flow, and since the stress fields have changed over time, different extension fractures were groundwater carriers through time. So, knowing deformational events, the stratigraphy belonging to these events, fracture patterns obtained from field data and lineament analyses and using stress fields, one can begin to predict the location of fractured aquifer systems.

Therefore taken into account the regional neotectonic stress field (set to be NW-SE) and past stress fields, the topography of the area, since these fractures need to be in valleys, weathering, lineament maps and the geology of the area: It is recommended that boreholes should be drilled in either the Gladkop Suite, Gneisses belonging to the Little Namaqualand Suite and/or the sedimentary deposits in the form of the Nama rocks, where the present day and past stress fields should be applied in order to establish past and present extension fractures favourable for groundwater location.

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