CHARACTERIZATION OF JOINTS IN THE KEIMOES SUITE WITH RESPECT TO NAMAQUA DEFORMATION EVENTS

By

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A thesis submitted in partial fulfilment of the requirements for the degree
Magister Science in the department of Earth Science,
University of the Western Cape.

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November 2013

DECLARATION

I declare that ***Characterization of joints in the Keimoes Suite with respect to Namaqua deformation events*** is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Portia Leah Mokoena November 2013

Signed…………………………….

KEYWORDS

Keimoes Suite

Namaqua Natal Province

Areachap Group

Kakamas Terrane

Upington

Northern Cape

Joints

Veins

Foliations

Granitoids

Emplacement

Mohr diagrams

Rock failure

ABSTRACT

The Keimoes Suite is a group of poorly defined granitoids that characterize the Namaqua Front and Foreland zones. There is a lack of knowledge on its content and distribution. A significant amount of work has been done on the geochemical and geochronological aspects of the Keimoes Suite but no structural analysis using a comparison between joint occurrences in the suite and the country rock has been found in the literature. This study provides insight on whether these joints formed as a result of the emplacement and subsequent cooling of the granitoids or whether they are the result of later deformation processes.

This was achieved through remote sensing, detailed field mapping and structural analysis of joint data to determine the type of stress regime associated with their deformation. Eleven granitoids of the Keimoes Suite were mapped in the Kakamas-Keimoes area in the Northern Cape, South Africa. Up to four joint sets were mapped and characterized according to orientation, abutting relationship, in-filling material and spacing properties. The orientation analysis revealed two prominent joint sets (NNW and NE) that are consistent throughout the Keimoes Suite granite. However after careful analysis of their abutting relationship it has been concluded that these joints are the youngest joints formed in the Keimoes Suite. The fourth set is the E-W set which does not occur at a wide spread scale. The oldest joint set (NNE) is defined by the quartz and feldspar filling and these joints only occur in the oldest granite of the suite. Field observation revealed shear displacement, forming a conjugate joint set. This conjugate set closes at an acute angle of 60˚ and the joints displace each other. The presence of en echelon sigmoidal veins suggests these joints formed as mode II fractures and that they are tectonic joints. The dominant joint set NNW is parallel to the regional foliation, shear zones and faults which were formed during the D2 deformational vent of the Namaqua Orogeny. This NNW joint set post-dates the D2 deformational event and was formed during the D3 deformational environment of the Namaqua Orogeny.

Principal stress analysis of all the joints in the study area suggests a strike-slip environment, which coincides with the D3 deformation event of the Namaqua

Natal Province. Even though the country rock and the Keimoes Suite granites were subjected to same stress field during the D3 event, the analysis of principal stresses between the Keimoes Suite granites and the country rock reveals a slight difference in the orientation of the principal stresses. This is caused by the difference in competency between the Keimoes Suite granites and the country rock thus caused the refraction.

In conclusion Structural evidence on various members of the Keimoes Suite indicates three episodes of intrusions with respect to the D2 Namaqua deformation event based on foliation and mineral filled joints. The Vaalputs Granite is pre tectonic relative to the main D2 deformation event and the thermal peak M2 metamorphisms, while Louisvale, Kanon Eiland and Klip Kraal Granites are syn-tectonic to these deformation events. The granites that lack foliation are classified as post-tectonic granites and these are the Keboes, Kleinbegin, Gemsbokbult, Colstone and Cnydas Granites as well as the Friesdale Charnockite. However the presence of foliation in some granites suggests that a compressional episode existed for a period of time and ended sometime before the onset of the post-tectonic granites. Therefore the D2 pre-dates the last episode of Keimoes Suite granite emplacement. This study partly validates the work done by previous workers on the Keimoes Suite, although there are some slight differences which are subjected to change. Conclusion can be drawn that this study provided additional insight in the findings of other workers nonetheless also differs with some of their findings regarding the timing of emplacement of the Keimoes Suite.

ACKNOWLEDGMENT

All thanks goes to my one and only father in heaven, thank you God for the strength you have provided me throughout this project. Thank you for you endless grace, undeserved kindness and unconditional love that kept me going and focused in completing my MSc. No words are enough to express my gratitude and appreciation for everything you done for me in my entire life. You kept your promise as you said you knew me before I was born and you called me by my name. You did not just carry my burdens for me and lift me up but you assured me that your plans for me are not to harm me but to prosper me. In that I find peace and comfort and I know you love me and I thank you from the bottom of my heart.

I would like to extend my deepest appreciation to my supervisor Prof Jan van Bever Donker for his effortless time in assisting me with my work. Your patience, your guidance, your support during field mapping and thesis write up, financial support and you kindness. You made it all possible for me your input and advices is what shaped me and the outcome of this project sincerely I thank you.

I also thank my co-supervisors Dr Bailie for polishing my writing skills and for your help during field work, Dr Siad for helping me with remote sensing your great input is well appreciated.

A special thanks to the people who contributed in my work, Nompumelelo Sithole for your suggestion and availability to me when I needed you and not forgetting your encouragement and faith in me thank you my friend. Thanks to Henock Solomon, Sedzani Nethenzheni, Stephane Tsakou your valuable input this work thank you guys.

To my family my mother Sizan Ngwenya, my grandmother Esseniah Maupa, my uncles Aaron Ngwenya, John Mokoena, Stanley Mokoena and my sisters Goodness Mokoena, Sbongile Mhlotshwa, Mavis Mokoena and my brothers Xolane Mgijima, Hendry Mokoena and Terrance Mokoena for your love and support, thank you so much. Thank you for your emotional and financial supports your presence make life easier for me. Thank you for believing in me and praying for me.

Finally special thanks to my dearest friend, Xolile Godfrey Fuku thank you rato for your support, advices and inspiration. I appreciate the time you gave me when I needed it and to withstand all my moods and frustrations and I appreciate you helping hand always and for having faith in me.

DEDICATION

This work is dedicated to the Almighty God who made me who I am today and my precious mom Norah Sizan Ngwenya and sisters, Mavis Mokoena, Goodness Mokoena and Tebogo Ngwenya and my Grandmother Essenia Maupa.

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CHAPTER 1: INTRODUCTION

1. Introduction

The contact between the Archaean Kaapvaal Craton and the eastern margin of the Mesoproterozoic Namaqua sector of the Namaqua-Natal Province is perceived as marked by extensive magmatism (Cornell et al., 2006). However the precise tectonic history and evolution of the Namaqua-Natal Province along this eastern margin remain poorly understood. Numerous authors have used lithological assemblages, regional structures and metamorphism to propose various positions for the suture, as documented by Cornell et al. (2006).

According to Van Niekerk (2006), the suture occurs to the west of the Areachap Group, in an area characterised by voluminous intrusions of foliated syn-tectonic granitoids of the Keimoes Suite. Based on geochronological and geochemical data Bailie (2008) suggested that the position of this suture is located to the west of the Trooilapspan shear zone, which is the eastern margin of the Areachap Group, and which is extensively intruded by the syn-tectonic granitoids belonging to the Keimoes Suite.

However, this is not in agreement with suggestions made by previous authors, where the Brakbosch Fault is reported to be the suture between the Namaqua-Natal Metamorphic Belt and the Kaapvaal Craton (see, Cornell et al., 2006). Hence, age and nature of the Keimoes Suite serve as an important tool to determine the evolution of the suture zone between the Namaqua Sector and Kaapvaal Craton, as well as understanding the Mesoproterozoic tectonic evolution of Southern Africa.

The Keimoes Suite is a group of granitoids that are poorly defined and there is no general agreement in the literature on either its exact content or its distribution. These granitoids characterize the Namaqua Front and Foreland zones (Bailie et al., 2011; Moen, 2007), and their distribution is defined as being bound to the west by the Neusspruit Shear Zone, and to the east by the Brakbosch Fault.

The Keimoes Suite granitoids appear as intrusions into the Areachap, Korannaland and Sultananoord Groups as well as other older gneisses. According Eglington (2006) Keimoes Suite emplacement can be ascribed to the second period of intrusion that occurred at 1.03-1.08Ga. Generally this happened right after the first period of intrusion within the Gordonia and Natal sub-provinces at 1.2-.1.3Ga, and encompasses Little Namaqualand and Bushmanland.

The Keimoes Suite granitoids also characterize part of a complex group of late Mesoproterozoic intrusions of granodioritic to potassic-granite composition that occupy an outcrop belt striking approximately NW–SE to the immediate west of Upington, Northern Cape Province. These intrusions mark the contact between the Kaapvaal Craton and the Namaqua –Natal Province. Geringer et al. (1988) describe the Keimoes Suite as a composite batholith comprising a calc-alkaline suite of mid- to upper-crustal, predominantly I-type granitoids ranging in composition from quartz monzonitic to potassic.

The emplacement of this suite is related to plate tectonic processes that took place at the eastern margin of the Namaqua orogen. The suite covers an extensive distance of over 200 km from Putsonderwater, near Marydale in the southeast, to northwest of Upington beyond which it is covered by the Neoproterozoic Nama Group.

While a significant amount of work has been done on the geochemical and geochronological aspects of the Keimoes Suite by a number of authors (Barton and Burger, 1983; Stowe, 1983; Jankowitz, 1986; Geringer et al., 1987, 1988; Bailie et al., 2011; Cornell et al., 2012), almost no structural analysis using a comparison between joint occurrences in the suite and the country rock has been found in the literature. This leaves the timing of the Keimoes Suite emplacement not well understood to date. This study is aimed at providing understanding concerning the timing of emplacement of the various members of the Keimoes Suite with respect to the deformation events in the area, using structural features such as joints, veins, lineations and foliations. These structural features can be used to narrow down the timing and tectonic evolution of the western margin of the Kaapvaal Craton at its junction with the Proterozoic Namaqua Sector of the Namaqua Natal Province.

1.1. Locality of study area

The area under investigation is located near Keimoes, a small town in the Northern Cape Province of South Africa (Fig. 1.1). The study area can be easily accessed through the N14 (Fig. 1.1) which is part of the National road network that connects Upington to Olifantshoek, Kimberley and Prieska in the east to Kenhardt in the south, and to the Kalahari Transfrontier Park to the north as well as to the coast and Namibia to the west. The Keimoes Suite itself can be accessed using the sandy farm tracks.

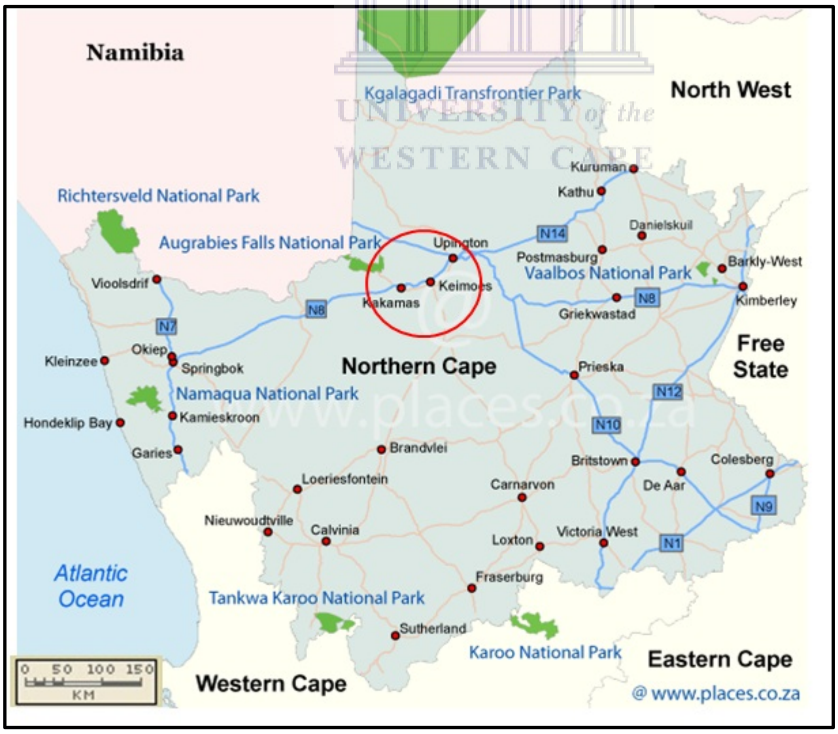

Figure 1.1 Location of study area within South Africa. Red circle represent the study area.

1.2. Literature review

This chapter presents concise results of a literature review on the subjects relevant to this research, which include joints in igneous rocks, veins, foliations and effect of pore fluid on joints. Lastly previous studies on the Keimoes Suite will also be reviewed.

1.2.1. Joints

Joints are discontinuities occurring in all rock types be it sedimentary, metamorphic or igneous rocks. They are often associated with extensional stresses. By definition a joint is a discrete brittle fracture along which there has been little or no movement parallel to the plane of fracture but slight movement normal to it (Fossen, 2010). This study is more concerned with joints forming in igneous rocks. The occurrence of joints in igneous rocks may be the result of failure under natural forces; they may be caused by shrinkage, due to cooling or desiccation, or unloading of superincumbent rocks by erosion or tectonism.

Given the above it is self-evident that there are many different types of joints such as tectonic joints, sheeting joints, exfoliation joints, cooling joints, foliation joints and parting and bedding joints and partings.

Tectonic joints are breaks formed from the tensile stresses accompanying uplift or lateral stretching, or from stress fields resulting from regional tectonic compression. High pore fluid pressure plays a major role in the formation of tectonic joints. They normally arise as planar, rough surfaced sets of intersecting joints, with one or two of the sets usually dominating in persistence (Van der Pluijm & Marshak, 2004). The only difference between tectonic joints and hydraulic joints is that hydraulic joints can also form in ductile conditions. Otherwise these types of joints are the same, hydraulic joints form at depth due to high fluid pressure whilst tectonic joints formed due to high pore fluid pressure.

Sheeting joints are further explained as sets of joints developed more or less parallel to the surface of the ground especially in igneous rocks such as granites.

This type of joints usually forms as a result of the unloading of the rock mass when it is eroded away. (Van der Pluijm & Marshak, 2004).

Exfoliation joints are products of exfoliation which is the breaking or splitting-off from the bare rock surfaces by the action of chemical or physical forces such as differential expansion and contraction during heating and cooling over the daily temperature range.

Cooling joints are defined as breaks formed as a result from cooling of igneous rocks. These joints are very common in igneous rocks

Discontinuities developed along the foliation planes in metamorphic rocks are referred to foliation joints and partings.

Neotectonic joints are joints that propagate under today's existing regional stress field. According to Frances (2007) these types of joints are hardly related to veins and strike either as parallel or enclosed acute angle with the maximum horizontal stress axis.

Figure 1.2. Sheeting joints (or exfoliation) in granite (Van der Pluijm & Marshak, 2004).

Joints often have some characteristics within the type of rock where they developed. In addition, there is also some pattern connected to the type of rock they penetrate. Therefore, the size of joint plane is strongly related to the lithology and size of the rock unit being studied. In some regions, joint patterns may record a cumulative deformation history, and consequently the rocks may record several systematic joint sets caused by temporally distinct stress fields, which produce a succession of tensile fracture events (Pastor-Galan et al., 2011). Thus, when multiple joint sets are present, caution is needed in using the spatial pattern of joints across a region to interpret tectonic history (Dunne and North, 1990; Engelder and Geiser, 1980). Different tectonic events might trigger joint formation which implies that joints existing today have formed as young fractures of later or even latest tectonic movement (Zheng and Scheidegger, 2000).

1.2.2. Jointing in igneous rocks

Joints in igneous rocks often occur as a result of cooling and contraction of magma. When studying joints in igneous rocks such as granites there are important features to consider when doing geometric description of joints within an area and these are spacing, distribution, continuity, dimension and aperture, morphology and nature of infill (Frances, 2007; Zhangerl et al., 2006). These features are helpful in establishing joint sets. According to Whitaker and Engelder (2005), a joint set provides a receptive record of the syn-kinematic stress field at the time of deformation. Three sets of joints often prevail in plutonic igneous rocks (i.e. granites, gabbros and diorites) caused by tensional forces within a rock as a result of cooling (Palmström, 1995). Two of the joints sets tend to be vertical and perpendicular to each other, whereas one will be approximately horizontal and thus more or less perpendicular to the other two sets.

To be able to determine the relative age of a joint set, it is imperative to first evaluate the spatial relationship of joints, this is mainly done by observing cross-cutting relationships between joints. There are three ways to determine relative age of a joint set and Frances (2007) lists them as follows;

- A joint that is offset by a fault, vein or stylolite propagated first
- A joint that terminates at another joint is younger and
- A large joint with a long trace that cuts traces of small sealed joints is the youngest.

Joint spacing in igneous rocks generally varies from few centimetres to metres. For instance in granite rocks, joint spacing may be few centimetres or metres and usually the spacing may remain constant over a large area. However in some cases the spacing changes in irregular manner across a single outcrop. Joints are important geological structures that are worth studying, as they not only control landscape morphology but are also known to have effect on rock strength, influence hydrologic properties (e.g. permeability) and most importantly, they can give a detailed history of stress and strain in a region.

The relationship between joints and other structures is important because it gives insight into the tectonic conditions under which joints form and the timing of joint formation with respect to the formation of other structures in a region. For example, one has to ask, are the joints parallel to tectonic foliations, and are they related to regional folds? Is there a relationship between the joints' orientation and contemporary stresses? Lastly is the spacing or style of jointing related to the proximity of faults? This information combined can unravel the tectonic history of the area.

During an orogenic event, the maximum horizontal stress is more or less perpendicular to the trend of the orogen. Consequently, the joints that form by syn-tectonic natural hydraulic fracturing are roughly perpendicular to the trend of the orogen. Because the stress state may change with time in an orogen, later formed joints may have a different strike than earlier formed joints, and the joints formed during a given event might not be exactly perpendicular to the fold trends where they form (Van der Pluijm & Marshak, 2004). Such joint patterns are typical of orogenic foreland regions, but may also occur in continental interiors. This will be discussed in detail in chapter 4.

Therefore the conclusion of joints having developed syntectonically is based on two observations: firstly, joints parallel to σ_1 direction associated with the development of tectonic structures like folds, secondly the joints may contain mineral fill which formed at temperatures and fluid pressure found at a depth of several kilometres: thus they are not a consequence of the recent cracking of rocks in the near surface (Pastor-Galan et al., 2011).

This study is interested in studying systematic joints that exist on the Keimoes granitoids, as they are likely to reflect regional tectonic stress trajectories at the time of fracturing. Unlike non-systematic joints, which only give insights into the rock strength and permeability and are therefore insignificant in providing information on regional paleo-stress orientations. Joint analysis can be useful in determining timing of deformational event related to orogenesis, for instance Pastor-Galan et al., (2011) used joint analysis to determine the timing of a bend in an orogenic belt. The authors were able to obtain some results from the joints analysis: they identified two orthogonal joint sets whereby one joint set showed change in orientation around the orogenic bend implying that this joint set formed during the formation of the orogenic belt. The other joint set post-dated the formation of the orogenic belt because there was no systematic change in orientation recorded around the bend of the orogenic belt.

1.2.3. Veins

Presence of veins in a rock indicates a distinct period of deformation during orogenesis thereby giving an idea of fluid conditions at a particular time. In general veins are extension fractures filled with minerals such as quartz or calcite but other minerals form vein filling too. Like joints, veins reflect brittle deformation, therefore are considered as common indicators of deformed rocks of all types and metamorphic grades. According to Coelho et al. (2006) and various other authors veins are a significant source of information on the deformation history of the host rock. Since they are veins formed as mode I extension fractures they can be used in the interpretation of bulk flow in kinematics. For instance Whitney and Dilek (2000) mentioned that veins provide information on the late stage deformation because the pressure and temperature sensitive minerals may crystallize from vein forming fluids under conditions not recorded by the host rock.

Given this reason, veins tend to provide information of the relation between metamorphism, fluid flow, deformation and in some cases magmatism. In addition Passchier et al. (2005) also reported that veins act as markers of deformed rocks. They stated that deformation veins in granitoid rock leads to folding and boudinage of the veins if these have a rheology considerably different from that of the host rock. In many cases though, veins and host rock tend to have similar composition and grain size, hence veins can act as markers of deformation in granitoids. Some veins start of as joints whilst other started off as faults or cracks next to the faults (Van der Pluijm & Marshak, 2004) .Coelho et al. (2006) state that the opening of veins is structurally controlled by the orientation of fractures in a volume of a rock, however pore fluid pressure and porosity also play a role. During joint formation, fluids will flow into the fracture thus the pore pressure in the adjacent rock weakens. Hence the Mohr circle will shift to the right thus away from the failure envelope, and consequently no fracture formation is possible near the initial fracture (more detail in Chapter 4).

However another fracture can only be formed outside the volume of rock with reduced pore pressure. The role played by pore fluid pressure in crustal rock in terms of deformation, faulting and earthquake processes is well addressed by previous studies. Considering work done in previous studies we also investigate if pore fluid pressure had a significant role in the formation of joints in the Keimoes Suite.

There are different types of veins developed in various modes of deformation. Ramsay and Huber (1987) identified a group of veins formed as mode I (Fig. 1.3) extension fractures (single or en echelon tension gashes, wing cracks and swordtail terminations in boudin parting surfaces) (Fig. 1. 4). These veins formed in response to combined tectonic and pore pressure. They provide significant information on the deformation history of the source rock and are therefore studied in an attempt to understand the deformation history related to the intrusion of the Keimoes Suite.

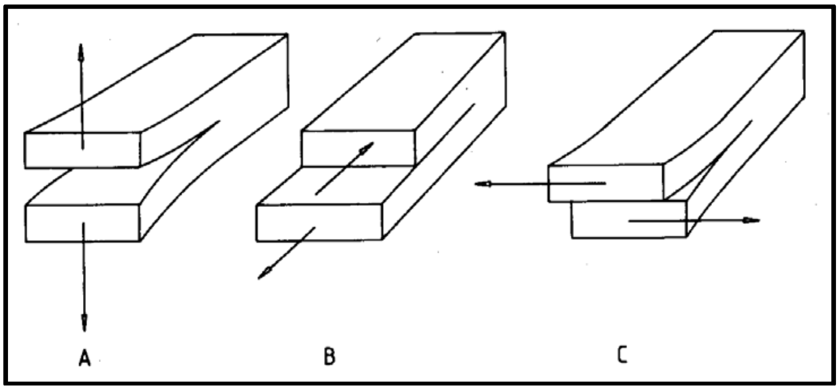

Figure.1.3. The different type of fracture mode: A) mode I, opening mode B) mode II, in-plane shear or sliding mode C) mode III, anti-plane shear or tearing mode (Mandl, 2005).

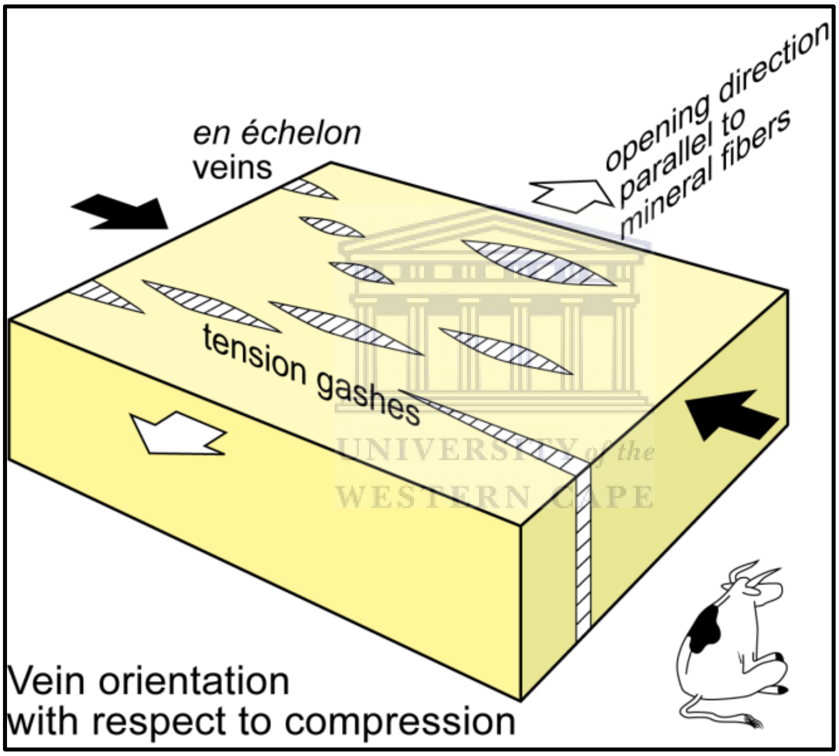

Figure 1.4. Box model showing different type of veins. (Fossen, 2010).

1.2.4. Foliations and lineation

Foliations are defined as “any planar fabric in a rock”. The type of foliation indicates the processes by which it formed. In general there are two types of foliations that develop in igneous rocks, magmatic foliation and tectonic foliations. Primary foliations form during deposition of sediments or the flow of minerals during emplacement. Generally magmatic foliation is defined by alignment of igneous minerals (usually euhedral minerals) whereby the foliation is parallel to the internal or external pluton contacts. Whereas tectonic foliation is a secondary foliation formed by tectonic stresses, and is defined by metamorphic minerals, no alignment of igneous minerals occurs. In this case foliation is locally at high angle to pluton-wall rock contacts and it is continuous with the regional cleavage (Paterson et al., 1989).

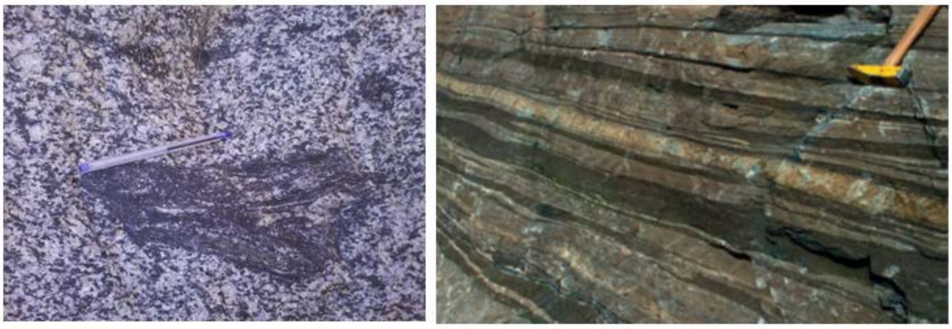

Figure 1.5. A magmatic foliation of the Straussberg granitein the Keimos Suite (b) Gneissic banding, formed during shearing of a heterogeneous intrusive complex, showing tectonic foliation (Fossen, 2010)

A review of previous studies indicates that there are four possible ways in which foliation can develop during the emplacement of plutons, however in some situations foliations can form by various combinations of the following factors:

- Flow during ascent
- Diapiric emplacement and expansion (ballooning)
- Emplacement during regional deformation
- Regional deformation post-dating emplacement

The development and distribution of tectonic foliations in plutons is facilitated by mineral proportions and existence of early-formed foliations (Paterson et al., 1989). For example the presence or absence of quartz and mica and their distribution appears to strongly influence how easily tectonic foliations form in granitoid rocks. Other factors that contribute to the development of foliations in granitoids are magmatic flow, sub-magmatic flow, high-temperature solid-state deformation and moderate- to low-temperature solid-state deformation (Paterson et al., 1989).Previous studies suggest that distinction between foliation formed by magmatic and solid state processes as well as the distinction between foliation formed during different mechanisms of granitoid emplacement are significant in understanding the timing relationships and behaviour of plutons during and after emplacement. Therefore foliation occurring in the granites of the Keimoes Suite will help in determining when the Keimoes Suite emplaced was with respect to the deformation history of the area.

Another way to understand tectonic evolution is to look at rock fabrics such as lineations which tend to reflect the strain state of rocks. This is because mineral lineation is defined by preferred orientation of minerals, particularly minerals that have a well-defined long axis, such as amphiboles. Hence their orientation often reflects the state of strain. Thus lineations can reflect strain state of rocks and are therefore a significant source of information of tectonic evolution (Pare´s and Van der Pluijm 2002).

Lineation is a common fabric element in rocks with one dimension markedly longer than the other two dimension and is often useful in unravelling the history of deformation. By definition lineation is a linear feature that occurs penetratively in a rock and includes form lineations such as crenulation, rods, elongate pebbles, and mineral elongation such as stretched grains, linear aggregates of equi-dimensional grains, and subhedral grains with an elongate crystal shape (Pare´s and Van der Pluijm, 2002).

Figure 1.6. Two perpendicular sets of mineral lineations on a fault surface in serpentinite (Fossen, 2010)

Lineations are mostly used in structural analysis to evaluate strain shear zones. Lineations such as slickenlines and fiber lineations provide important information concerning the movement and deformation of geological material, from the micro- to plate scale. In brittle regimes mineral lineations are likely to be constrained to fiber lineation, where minerals have grown in a preferred direction on fractures. Mineral fibers are common in extensional or mode I fractures and the orientation of the fiber represents extension direction (Fossen, 2010) (Fig 1.4). According to Fossen (2010) if curved fibers exist it means the extension direction has changed during the course of deformation or shear has occurred during or after the deformation of the fibers. He also mentions that it is possible to get two sets of linear structures on a single slip surface, this will reflect different movements at different times implying that stress orientation changed between different slip events. Therefore such structures can be used to reveal the relative timing of movement events.

It is well documented that joints form when magma cools for instance cooling joints which form at the surface as a result of magma cooling. Once the joints have formed they open up due to extensional stresses, then precipitation of minerals such as quartz or calcite fill up the open joints which then become cemented to form veins. The igneous processes responsible for forming joints and veins give information on the sequence of events. Therefore it can be said that the Keimoes Suite intruded first and was uplifted then it cooled down. After cooling there was a period of fracturing where the joints formed then veins were the later stage.

It is apparent that analysis of the structural features discussed above (joints, veins, foliations and lineations) plays a distinct role in understanding deformation history and also in deciphering timing of granite emplacement. For this reason this study will combine the information provided by these structural features to determine the timing of Keimoes Suite intrusion relative to the Namaqua deformational events.

1.3. Previous work on the Keimoes Suite

Publications with regard to the Keimoes Suite emplacement are limited to geochronological and isotope geochemistry aspects. About thirteen granitoids constitute the Keimoes Suite. Bailie et al. (2011) studied three of the granites and Cornell et al. (2012) studied a further two of the Keimoes Suite granitoids. Recent studies done by Bailie et al. (2011) on the southern part of the Keimoes Suite provide new geochemical, geochronological and isotope data of the Keimoes Suite granitoids. Based on their findings all three granitoids have been ascribed emplacement ages of approximately 1100Ma which coincides with the M3 metamorphism and D3 deformation event of the Namaqua Orogeny. The D3 deformational event is considered a thermal event which originated in the mantle and affected the Namaqua Natal Province at 1.1. Ga resulting in extensive magmatism (Robb et al., 1999). Bailie (2011) described the M3 metamorphism as a retrograde-to-isothermal regional contact metamorphism event that corresponds with the intrusions of late- to-post tectonic granitoids. They reported these granites as “crustally derived ferroan-A-type biotite monzogranites emplaced into a post-collision within-rift setting at approximately 1.1Ga”. This then suggests that the Keimoes Suite has been emplaced after continental collision between the Kaapvaal Craton and the Namaqua Sector. Literature reviewed reveals that the central and northern outcrops of the Keimoes Suite have granitoids that are “weakly foliated to unfoliated, medium- to coarse-grained ferroan, alkali-calcic late- to post-tectonic A-type biotite granitoids” (Bailie et al., 2011).

The weak foliations encountered on some of the granitoids may suggest that they were affected by deformation. Consequently the unfoliated granitoids were not affected by deformation, which leads to the conclusion that they are post-tectonic granitoids. Cornell et al. (2012) found similar results, he also stated that the Keimoes Suite is post tectonic relative to the 1200 Ma collision orogeny and lacks a foliated fabric that can be related to penetrative deformation. On the other hand Moen (2007) grouped the granitoids of the Keimoes Suite into pre-, syn-, and post-tectonic relative to the last foliation-forming tectonic event.

Eglington (2006) reported two periods of emplacement that occurred in the Namaqua Natal Province. He ascribed the Keimoes Suite intrusion to the second period of emplacement at approximately 1.03-1.08 Ga. These ages are younger than the D3 and M3 deformation events of the Namaqua Orogeny. Meanwhile recent studies by Cornell et al. (2012) show that the Keimoes Suite ages ranged from 1112 to 1078Ma. The Keimoes Suite is considered to have formed by melting of crustal material with a large range of crustal residence ages probably between Archaean and Mesoproterozoic (Cornell et al., 2012), this was deduced from the Hafnium (Hf) isotope data and published Sm-Nd data. According to Cornell et al. (2012) the Keimoes Suite may have formed as a multilayer crust that developed after the Namaqua collision, involving the Archaean to PaleoProterozoic Kaapvaal Craton overridden by the Mesoproterozoic Areachap and Kakamas Terranes. This study will therefore contribute in resolving the controversy by relating different theories to draw up a conclusion about the exact development of the Keimoes Suite with respect to the Namaqua deformation events.

1.4. Problem statement

The timing and tectonic evolution of the western margin of the Kaapvaal Craton at its junction with the Proterozoic Namaqua Sector of the Namaqua-Natal Province can be well defined by studying the deformation of the granitoids of the Keimoes Suite. The contact between the Kaapvaal Craton and the Namaqua Sector of the Namaqua-Natal Province is marked by the intrusion of the Keimoes Suite.

While a significant amount of work has been done on the geochemical and geochronological aspects of the Keimoes Suite by a number of authors (Barton and Burger, 1983; Stowe, 1983; Jankowitz, 1986; Geringer et al., 1987, 1988; Bailie et al., 2011; Cornell et al., 2012), almost no structural analysis using a comparison between joint occurrences in the suite and the country rock has been found in the literature. This leaves the timing of the Keimoes Suite emplacement not well understood to date.

This study is aimed at providing understanding concerning the timing of emplacement of the various members of the Keimoes Suite with respect to the deformation events in the area, using structural features such as joints, veins, lineations and foliations. These structural features can be used to narrow down the timing and tectonic evolution of the western margin of the Kaapvaal Craton at its junction with the Proterozoic Namaqua Sector of the Namaqua Natal Province.

This project entails characterization of joints occurring in the Keimoes Suite and to compare their orientation and density with those in the country rock. It will also establish whether these joints formed as a result of the emplacement of the granitoids or whether they are the result of later deformation processes. This will be achieved by using remote sensing data from satellite images and stereo-photographs, verified by field work and analysed by using statistical methods on the joints mentioned above to determine the type of stress regimes associated with their formation.

The information thus obtained will be used to relate it to various deformational events that took place before, during and after the emplacement of the Keimoes Suite. Various authors agree that the Keimoes Suite was emplaced due to compression formed by the overriding of the Kaapvaal Craton by the Namaqua plate. During that event joints may have formed as a result of the compressional stresses involved. A better understanding of these stresses can help date the timing of the Keimoes Suite intrusions. Likewise foliations and lineations can reveal the deformation history therefore stresses associated with them can be used to define the timing of the Keimoes intrusions.

The degree of foliation or lineation can give clues concerning the timing of intrusion, weakly to no foliation can be associated with late to post deformation emplacement whereas strong foliation can define a syn- or pre- deformation emplacement history. The ultimate goal of this project is to provide a detailed explanation regarding the timing of Keimoes intrusions using characterization of structural features mentioned above.

For the Keimoes Suite to have been emplaced a space must have been created for it, and the suitable scenario for this to happen is in an extensional environment whereby extensional stresses help create space for magma to intrude. Joints and veins are both mode I fractures often associated with extensional stresses in extensional environments and they both reflect brittle deformation. Joints form when the magma cools and solidifies whereas formation of veins take place after the joints have formed, indicating a second distinct deformational event. These structures are therefore significant in providing deformational history of and area. Hence they will be used to determine the timing of intrusion of members of the Keimoes Suite by relating them to the main regional deformation events of the Namaqua Natal Mobile Belt.

Recent studies have made controversial conclusions concerning the age of the Keimoes Suite, Moen (2007) suggested that they can be assigned relatively to the last foliation forming tectonic event. The members of the suite were subdivided in pre-, syn and post-tectonic based on the intensity of foliation. However this conclusion is questionable as Moen (2007) stated that foliation intensity is not exclusively determined by tectonic age, there are other factors that play a role as well.

1.5. Aims and objectives

The purpose of the thesis is to determine the relative age of emplacement of the members of Keimoes Suite. This will be achieved by using the results obtained from structural analysis of joints, veins and foliations of the Keimoes Suite as these structures can provide significant information on the history of deformation and relative timing of events. The main objectives are to:

- Provide a structural interpretation of the Keimoes Suite and Country rock with special focus on joints, veins and foliations
- Compare the Keimoes joints with the country joints and link them to Namaqua deformation events.
- Determine the relative age of the joints of both the Keimoes Suite and the country rock.

- Draw conclusions as to the emplacement time of the various members of the suite in relation to the various documented deformation events in the area

1.6. Methodology

1.6.1. Desktop study and remote sensing

Remote sensing is defined as "the technique of obtaining information about objects through the analysis of data collected by special instruments that are not in physical contact with the objects of investigation (Prost, 2001)". As such, remote sensing can be regarded as "reconnaissance from a distance," "teledetection". Remote sensing was used in this project as a tool to map possible joints occurring in the plutons of the Keimoes Suite and in adjacent country rocks. Fluids such as water and petroleum can travel along joints. Thus in areas where there is no visible outcrop one can use dry river streams to map joints. With the help of remote sensing structural features such as joints and shear zones were mapped. In this study remote sensing was used to map possible joints and identify relative joint sets occurring in the Keimoes Suite.

A thorough desktop study of the area was done which covers the geological literature and geology of the study area. All these make up the background information of the study area which was successfully obtained from previous publications and with the aid of the Google search engine. During the desktop study, remote sensing has revealed three prominent joint sets in the study area along with different shear zones. In order to validate what has been determined by remote sensing, fieldwork was conducted in the Keimoes Suite, Northern Cape. The joints encountered in the field would be characterized according to their types thereafter define the type of stress regimes associated with them whether it is extension or compression, strike-slip or combination of all. Then that information will be used to relate it to a certain event that took place during the emplacement of the Keimoes suite.

Various remote sensing methods such as satellite data and seismic surveying play a vital role in mapping and description of structures and tectonic deformation. Using satellite imagery and Google Earth software and data base, one can easily identify structural features such as faults, shear zones, folds, joints, lineations on the rocks and geological contacts. So Google Earth imagery in conjunction with satellite imagery was used to digitize possible structures such as joints, shear zones and faults existing in the Keimoes Suite.

These structures were later digitized using ArcGIS® and MOVE™ software to produce a structural geological map of the Keimoes Suite (Fig. 1.8) and from the Google Earth imagery (Fig. 1.7). The yellow polygon on the Google earth imagery represents the Keimoes Suite study area.

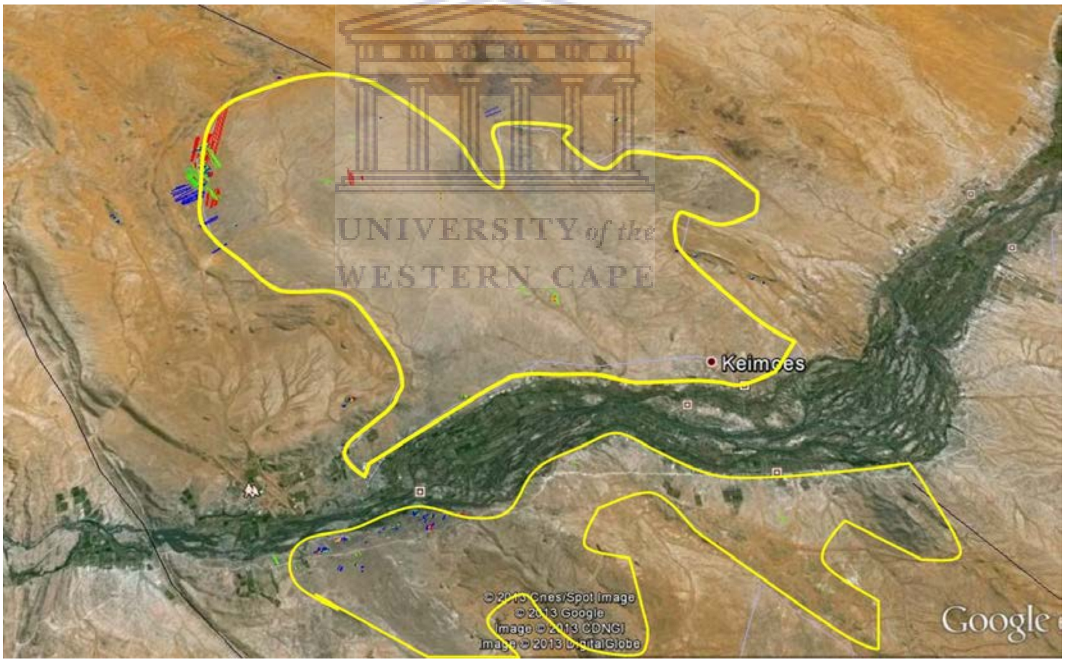

Figure 1.7. Satellite imagery of the Northern Cape. The shaded area shows the Keimoes Suite.

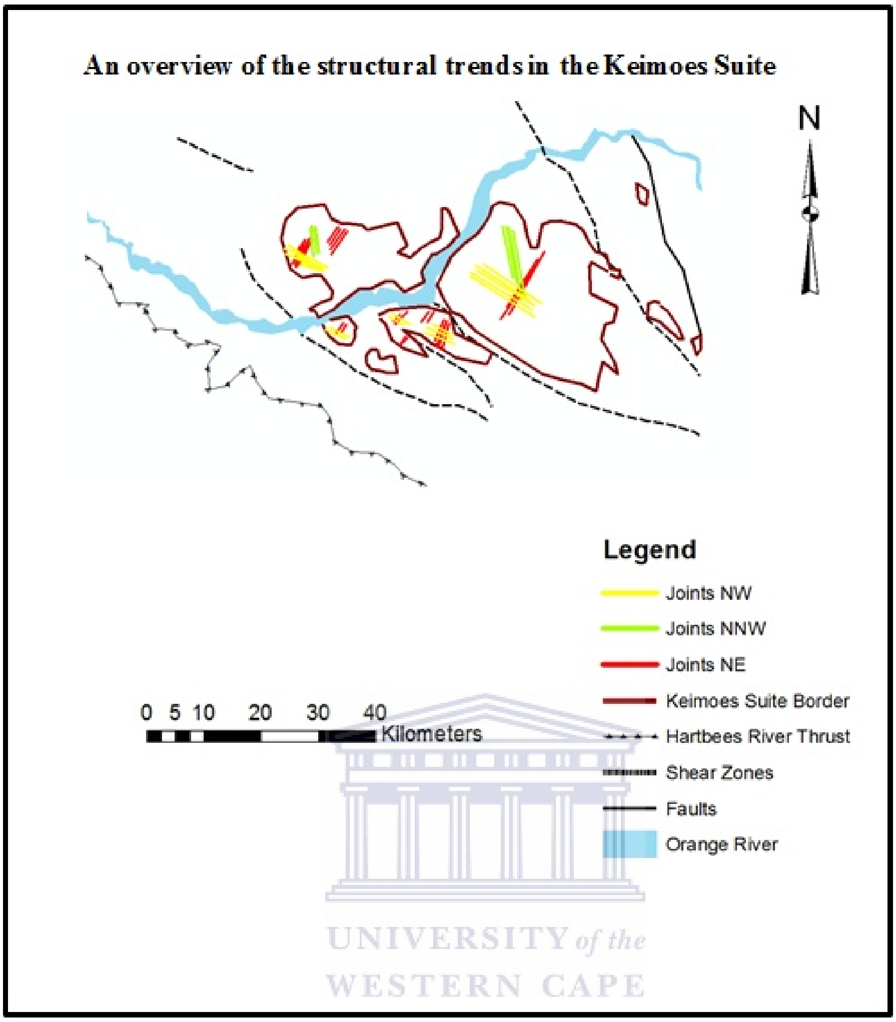

Figure 1.8. An overview of structural trends of Keimoes Suite in the Upington, Keimoes area. The area is divided by Cnydas, Neusspruit, Boven Rugzeer and Trooilapspan shear zones.

1.6.2. Field mapping

Field mapping was conducted during winter in July 2013. Descriptive analysis was carried out during field work for the purpose of identifying and describing structural features (Joints, veins, foliations) and measuring their geometry and orientation (dip and dip direction) using a Kranz compass. These structural features were mapped on both the Keimoes Suite granites and the surrounding country rock for a later comparative analysis as outlined above. The results were later displayed as stereographic plots and rose diagrams for analysis

1.6.3. Structural and tectonic analysis

Various authors reported that major tectonic structures may play an important role by creating dilational space for the emplacement of plutons. Over thousands to millions of years structural processes develop and the final product of a long deformation history can be described by means of structural datum. Horne et al (1992) conducted a study whereby they did an assessment of the structure of a batholith and the influence of primary regional structures on the localization of mineralization and emplacement of the batholith, as well as the implications for the regional tectonics.

Attitudes of prominent joints were recorded in a vast amount of outcrop locations in the studied batholith during regional mapping. They evaluated the presence of systematic joint patterns using counted density strereoplots; joint sets were identified using stereonets. The results from the stereonets revealed two NE and three NW regional joint trends within the batholith. The NW trending set was described as extension joints and attending conjugate shear joints of small dihedral angle reflecting horizontal compression. They concluded that the emplacement of the studied batholith post-dated the regional deformation of the country rocks associated with the Middle Devonian Acardian orogeny.

In this study, the emplacement history of the Keimoes Suite will be analysed by means of structural analyses following the Horne et al. (1992) approach. Stereographic projection is used to show and interpret both the orientation and geometry of structures mapped in the field. This method is quick and efficient, and the most widely used tool for presenting and interpreting spatial data.

During the desk study joints were digitized using Google Earth imagery. Four main trends were recognised for the joints, NNW, NE, and E of NE (Fig. 1.8). The orientation and density of these joints occurring in the Keimoes Suite will be compared with those in the country rock to test different kinematic models for the development of the Keimoes Suite. The field data will be plotted using Georient software and then be projected in the form of stereo-plots, rose diagrams and analysed to determine the type of stress regimes associated with the Keimoes intrusions.

A detailed field work was carried out within the Keimoes Suite to characterize joint and veins orientation. A total of eleven granites belonging to the Keimoes Suite were mapped and structural data collected include data of joints, foliation and veins. The collected data were presented in stereonet plots for principal stress analysis and all the results are displayed in chapter 3. Some of the Keimoes granites were not mapped due to lack of access or visible outcrop. The geometric and microstructural analyses of these structures are used to determine the timing and deformation history of the Keimoes suite.The granites are weakly foliated to well foliated and have joints displacing veins. For every outcrop mapped the joints were characterized using the following properties: orientation, spacing, shape, mineralization fillings, termination and cross-cutting relationship with other joints. Then identify the number of joint sets present. The information thus obtained will be used to relate it to various deformation events that took place before, during and after the emplacement of the Keimoes Suite.

CHAPTER 2: GEOLOGICAL SETTING

2. **Regional geology**

Introduction

South Africa experienced three orogenic events during the Proterozoic and early Palezoic era, known as Eburnean, Namaqua and Pan African episodes. The Okwa province, Kheis Province and Magondi Province formed during the Eburnean along the flanks of the Archaean Kaapvaal and Zimbabwe cratons between 2000 and 1700 Ma (Fig. 2.1). The western portion of the Namaqua-Natal Province of the mobile belt is comprised of the Richtersveld, Bushmanland, Gordonia and Kheis subprovinces. These subprovinces are dominated by supracrustal paragneisses, orthogneisses, charnockites, granitoid plutons and pegmatite belts whose metamorphic-plutonic history occurred between 1200-900 Ma (Boelema, 1994). Lastly, the Pan African Orogeny, which consists of the Damara, Saldania and Gariep Belts, which occurred during the Proterozoic to early Palaeozoic period (750-500Ma) (Boelema, 1994).

The study focuses on the Keimoes Suite which is a group of granitoids intrusions that marks the contact between the Kaapvaal Craton and Namaqua sector of the Namaqua-Natal Province. The suite belongs to the Gordonia Subprovince of the Namaqua-Natal province and it is exposed over a distance of over 200 km from Putsonderwater, near Marydale, in the southeast to the northwest of Upington in Northern Cape Province of South Africa (Bailie et al., 2011). Previous work done on the Keimoes Suite indicates that the suite covers an extensive period during the Namaquan tectogenesis with a time frame ranging from 1.25 to 1.1 Ga (Geringer and Botha, 1977; Barton and Burger, 1983; Geringer et al., 1988).

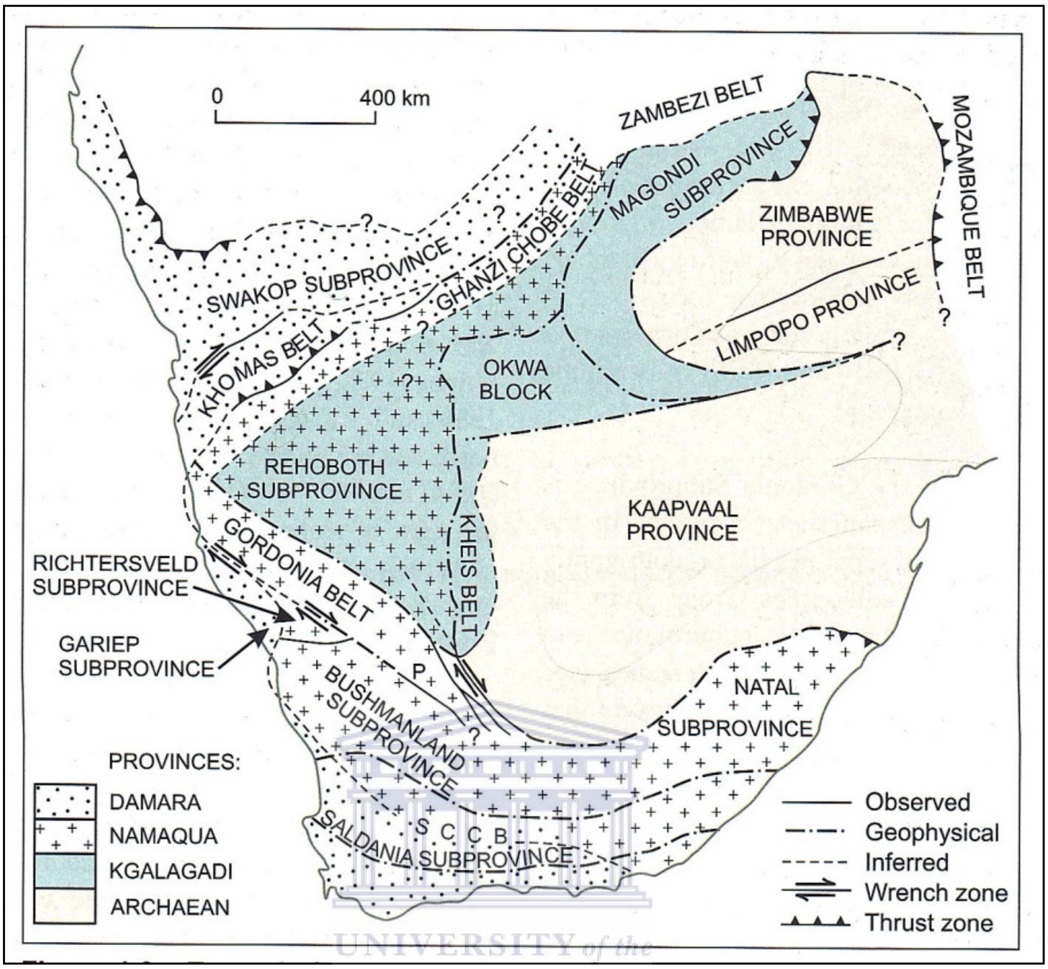

Figure 2.1. Tectonic framework of Southern Africa, (Moen 2007).

Three major tectonic crustal provinces exist in the Upington region. These encompass the Kaapvaal Craton and the Kheis and Namaqua tectonic provinces. This study will not discuss the Kaapvaal Craton and the Kheis Province as they fall outside the scope of this study. The Namaqua province will be further discussed below.

2.1. Namaqua Natal Province

There are a number of publications on the Namaqua Natal Province of South Africa regarding its geological setting. The Namaqua-Natal Province has been described as a tectonostratigraphic province that spans 1400 km across South Africa and Namibia ((Fig 2.1) Fransson, 2008). He further defines it as a 400 km wide belt flanking the Archaean Kaapvaal Craton to the north and truncated by

~600 Ma Pan-African (Gariep and Saldania) belts in the west and south (Fig. 2.2). A tectonostratigraphic province is defined as a large area of contiguous structural fabric with well-defined boundaries which formed during a certain, geochronologically defined, tectono-metamorphic event (Fransson, 2008).

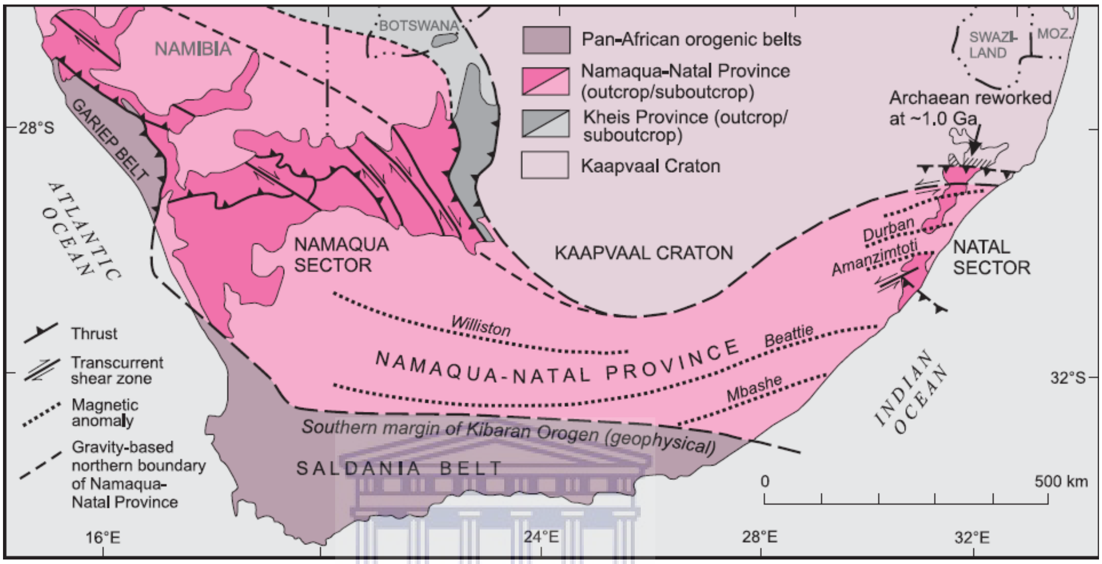

Figure 2.2. Simplified geological map of southern Africa (Fransson 2008) showing the Archaean Kaapvaal Craton and the Proterozoic Namaqua-Natal Province (in red).The Keimoes Suite granitoid suite lies on the eastern margin of the Namaqua Sector at its contact with the Kaapvaal Craton .

The Namaqua Natal Province is one of many metamorphic provinces that developed during the period of 1200-1000 Ma, which coincides with the birth of the Rodinia supercontinent (Pettersson et al., 2009, Fransson 2008.). According to Pettersson et al. (2007) the 1200-1165Ma early Namaquan event was caused by the collision and accretion of several crustal fragments or terranes with the Archaean Kaapvaal Craton to form the Rodinia Supercontinent. The Namaqua Natal Province embraces igneous and metamorphic rocks formed during the Namaquan Orogeny at approximately 1200 to 1000 Ma. These rocks crop out respectively in the Northern Cape and Kwazulu Natal provinces and are referred to as the Namaqua and Natal sectors of the Namaqua-Natal Province (Cornell et al., 2006) Fig. 2.1. Several tectono-stratigraphic terranes exist in the Namaqua Natal province - areas of common lithostratigraphic and structural fabric bounded by shear zones, which assembled during the Namaqua Orogeny. The three lithostratigraphic components are:

1. Reworked ~1.8-2.1Ga (late Paleoproterozoic) rocks.
2. Juvenile supercrustal and plutonic rocks which formed during rifting, ocean spreading and subduction phases of the Namaquan Wilson cycle (~1600 to 1200 Ma) and assembled during collision events accompanied by intense deformation and metamorphism.
3. Voluminous syn- and post-tectonic granitoids formed during the Namaquan Orogeny (1200 to 1000 Ma).

The western Namaqua sector is separated from the Kaapvaal Craton by the Kheis subprovince (Fig. 2.2). The Kheis Province comprises primarily of low-grade supracrustals in three different age intervals; ~3000, ~2000 and ~1300 Ma (Fransson, 2008). Five subprovinces have been identified in the Namaqua sector of the Namaqua Natal Province. This study follows the tectonostratigraphic terrane division of (Fransson 2008 and Cornell et al., 2006), from west to east: Richtersveld Subprovince, Bushmanland Terrane, Kakamas Terrane, Areachap Terrane and Kaaien Terrane (Fransson, 2008). All these terranes are bound by Late Mesoproterozoicshear zones and thrusts (Fig. 2.3). This study focuses on the Gordonia Subprovince, which is made up of the Kakamas and Areachap terranes and marks the easternmost portion of the Namaqua Sector at its contact with the Archaean Kaapvaal Craton (Fig. 2.3). This study will not discuss in detail the other terranes mentioned above.

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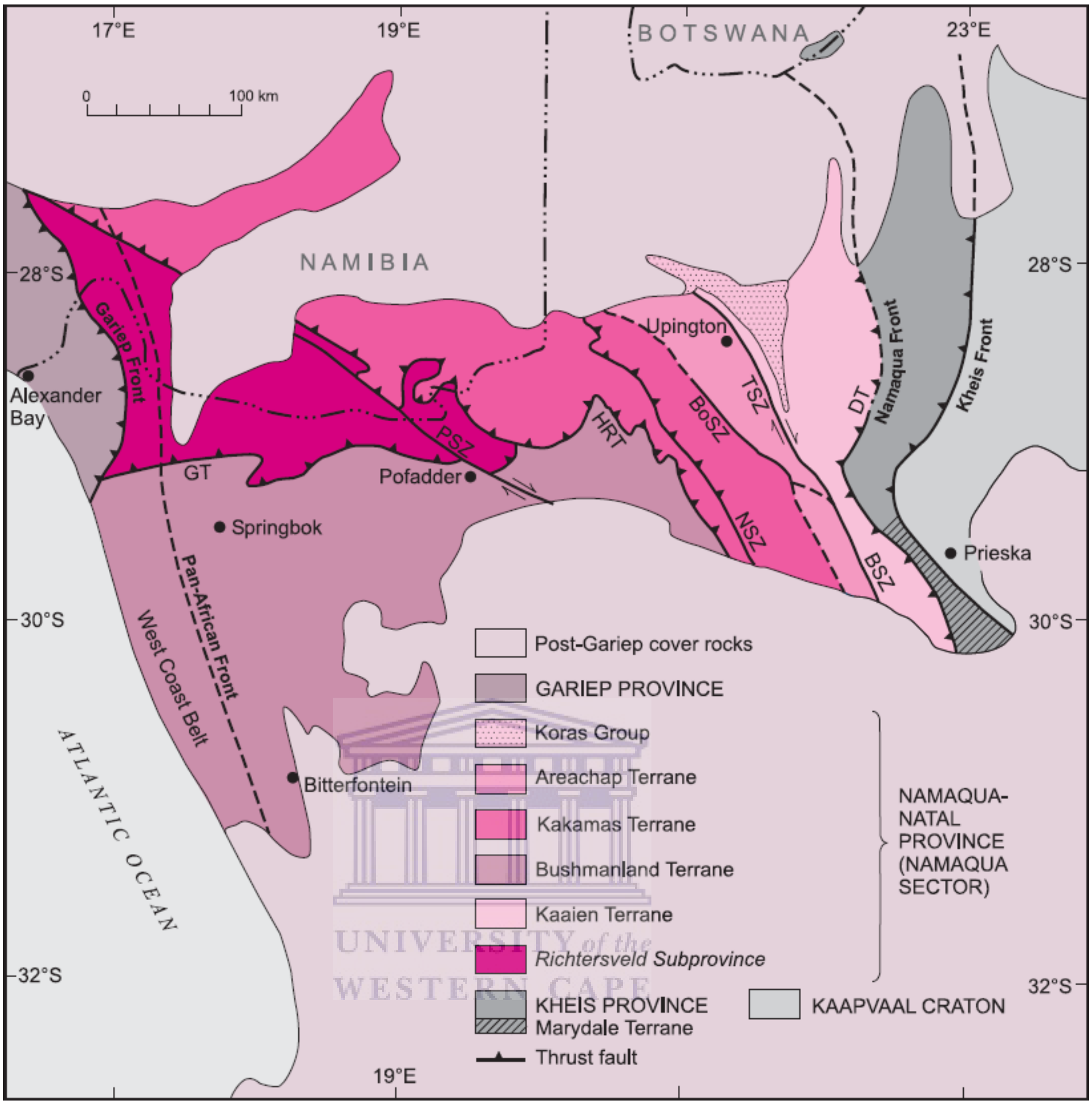

Figure 2.3.Tectonostratigraphic subdivision of the Namaqua Natal Province. BoSZ: Boven Rugzeer Shear Zone, TSZ: Trooilapspan Shear Zone, BSZ: Brakbosch Shear Zone, DT: Dabep Thrust, GT: Groothoek Thrust, HRT: Hartbees River Thrust, NSZ: Neusberg Shear Zone, PSZ: Pofadder Shear Zone. (Fransson 2008).

2.1.1. Bushmanland Subprovince

The Bushmanland Terrane is a high grade (amphibolite to granulite facies) metamorphic terrane, dominated by granitic gneisses, structurally overlain by metasedimentary sequences (Pettersson, 2008). It is located south of Richtersveld Subprovince (Fig. 2.3) and is bound to the east by the Hartbees River Thrust and consists of three groups of rocks, which are dissimilar in age and composition. According to Fransson (2008) the 1166 Ma old Kheisan granitic basement complex is the oldest unit. Secondly there are pre- and post-tectonic 1250 and 1150 Ma supracrustal sequences of sedimentary and volcanic origin. Lastly the syn- and late-tectonic (Namaquan) suites of intrusive rocks of predominantly granitic and charnockitic composition are the youngest units. The Bushmanland Terrane developed during the Namaquan orogeny. The dominant tectonic fabric in the Bushmanland subprovince is east-west, and is related to regional metamorphism at 1200 Ma (Clifford et al., 1981). In terms of deformation this terrane displays the main folding phases D2 and D3 and D1 is limited to a few xenoliths in the Achap Gneiss. Tight isoclinal E-trending subhorizontal recumbent folding with related ENE mineral lineation categorises the D2 folding phase (Pettersson, 2008).

2.1.2. Richtersveld Subprovince

The Richtersveld Subprovince is located west of the Kakamas terrane (Fig. 2.3) and is divided into three terranes, the low-grade Vioolsdrif Terrane in the centre and the high-grade Pella and Sperrgebiet Terranes to the east and west, respectively (Miller, 2012). The Richtersveld Subprovince (Fig. 2.1) is characterised by volcanic and related granitoid rocks, variably affected by low- to medium-grade metamorphism. It is bounded to the south by thrusts or shear zones which juxtapose it with the higher grade Bushmanland Terrane (Fig. 2.3). The Richtersveld Subprovince consists of arc-related Orange River Group greenschist to amphibolite grade volcanic rocks, intruded by granitoids of the Vioolsdrif Suite, both of Palaeoproterozoic magmatic age (Pettersson et al., 2009).

2.1.3 The Kaaien Terrane

The Kaaien Terrane is the easternmost terrane of the Namaqua Sector of the Namaqua Natal province (Fig. 2.3) and consists of thick folded sequence of quartzites. Pettersson (2008) mentioned that this terrane was affected by the Namaquan overprinting and is metamorphosed in lower greenschist grade. He further reported two transtensional basins formed around major strike-slip faults and the sequence of these basins were considered pre-tectonic (Wilgenhoutsdrif Group) and post-tectonic (Koras Group) in relation to the Namaqua Orogeny.

2.1.4. Gordonia Subprovince (Kakamas and Areachap terranes)

Most of the study area is situated in the Gordonia Subprovince rather than the Bushmanland Subprovince. The Gordonia Subprovince extends westwards from the Brakbosch-Trooilapspan shear zone (Fig. 2.4) and it was subjected to a period of 1.24-1.20 Ga eastwards thrusting over the Kheis Subprovince, at the beginning of the 1.2-1.0 Namaquan Orogeny with the accretion of the Areachap Group volcanic arc onto the western margin of the Kaapvaal (Eglington, 2006). Later the thrust faults were steepened by late dextral transpression into sub-vertical shears, such as the Trooilapspan and Brakbosch shear zones (Pettersson et al., 2007). Previous publications indicate that the Gordonia Subprovince suffered a high-grade regional metamorphism of upper amphibolite to lower granulite facies and several thermal events associated with the intrusion of the Keimoes Suite granitoids (Van Bever Donker, 1980; Stowe, 1983; Geringer et al., 1994).

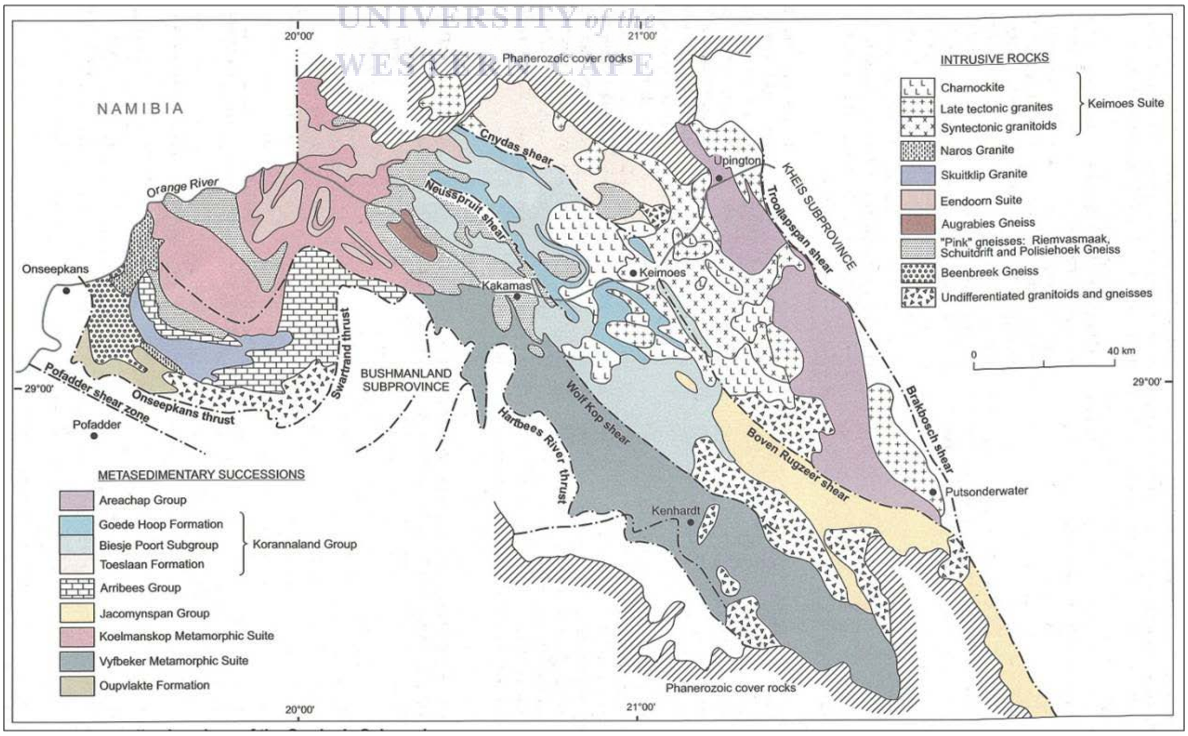

Figure 2.4. Geology of the Gordonia Subprovince (Moen, 2007).

As mentioned above, the Gordonia Subprovince consists of at least two terranes (Moen, 2007) the Areachap Terrane and the high grade Kakamas Terrane. The Areachap Terrane which covers the eastern part of the subprovince consists of Areachap Group and hosts the granites of the Keimoes Suite. Thus the Kakamas Terrane consists of the Korannaland Group and is dominated by the augen gneiss. It occupies the western portion of the Gordonia Subprovince and is separated from the Areachap Terrane by the Boven Rugzeer shear zone. (Fig. 2.4, Moen, 2007). The augen gneisses in the Kakamas Terrane suggest that a deeper crustal level is exposed which is better indicated by the presence of granulite facies metamorphosed rocks. Moen (2007) noted that the supracrustal successions of the Kakamas Terrane are characterized by calc-silicate rocks of the Arribees Group and Hartbees River Complex. The whole of the Gordonia subprovince is structurally bounded on the east by the Trooilapspan and Brakbosch shear zones and to the west by the Hartbees River and Swartrand thrusts. Distributions of the metasedimentary successions of the Gordonia Subprovince are displayed in Figure 2.4.

Table 2.1. Lithostratigraphic column of the Gordonia Subprovince (Moen, 2007)

Group	Formation(Formation)	Lithology	Age
Korannaland Subgroup	Piet Rooisbeg Formation	Quartzitic feldspar gneiss	
	Omdraai Formation	Schistose, leucocratic quartz-feldspar gneiss	
	Sandputs Formation	Quartzitic rock, calc-silicate	
	Toeslaan Formation	Aluminious gneiss(kinzigite), biotite gneiss, pelitic gneiss	
	Puntsit Formation	Calc-silicate rocks, quartzite, amphibolites and conglomerate	
	Rautenbach Se Kop Formation	Quatzo-feldspathic gneiss	
	Ganzenmond Formation	Quatzo-feldspathic gneiss, calc-silicate rocks	
	Valsvlei Formation	Quartzitic gneiss, calc-silicate rocks	
	Goede Hoop Formation	Micaceous quartzitic schist, conglomerate,sericitic quartzite	
	Sprigg Formation	Micaceous schist, quartzite, quatzo-feldspathic gneiss, quartzitic conglomerate	1150+/-13Ma (van Niekerk, 2006)
Areachap Group	Bethesda Formation	Biotite ± muscovite gneiss and schist, quartzite, amphibolites, hornblendegneiss, biotite-garnet granoblastite	
	Jannelsepan Formation	Amphibolites, pyroxene amphibolites, hornblende – biotite gneiss, calc-silicate rocks	1261Ma (Bailie, 2008)

2.1.4.1. The Areachap Terrane

Areachap terrane comprises the Areachap Group which is a narrow belt of amphibolitic grade rocks. This terrane is a highly deformed and metamorphosed volcanosedimentary succession exhibiting fragments of a 1.29– 1.24 Ga continental island arc (Pettersson et al., 2007; Bailie et al., 2011). It is situated west of the Kaaien Terrane (Fig. 2.3), dominated by a set of largely mafic to minor felsic metavolcanic rocks and metasediments which display a geochemical signature of a subduction-related arc complex (Pettersson et al., 2007). The Areachap Terrane is exposed as a 90km long northwest-trending belt from Upington to Kleinbegin in the southeast and continues until it is terminated in the Boven Rugzeer shear zone. However to the south this group extends to Copperton where it is covered by rocks of the Dywka Group (Cornell et al., 2006). This terrane has an amphibolite to granulite facies metamorphic overprint, which is commonly much higher grade than those to the east. However, the amphibolite grade stretches into the westernmost quartzites of the Kaaien Terrane and their deformational histories are related (Pettersson et al., 2007).

2.1.4.1.1. Lithology

The Areachap Group is a narrow belt of amphibolitic grade rocks and was considered a group of subduction-related formations which were accreted to the Kalahari Craton during the Namaqua orogeny (Fig. 2.2). Previous authors (Van Bever Donker, 1991; Boelema, 1994) have considered the Sprigg Formation as part of the Areachap Group. But recent studies have rejected this idea. Hence these authors proposed three formations in the Areachap Group. The amphibolites and the calc-silicate-rich rocks often comprising ferruginous chert of the Jannelsepan Formation which is now considered as the lowermost unit of the Areachap Group. This formation is in turn overlain by meta-pelitic rocks of the Bethesda Formation followed by the cross cutting kingzites of the Rateldraai Formation (Van Niekerk, 2006: Moen, 2007).

2.1.4.1.2. Structural setting

The Areachap terrane is structurally bounded to the east by Trooilapspan Shear Zone and to the west by the Boven Rugzeer Shear Zone (Fig. 2.3). Several publications indicate that the Areachap Group was subjected to several deformational events, of Namaqua age (+/-1100 Ma) as well as to the older deformation related to the Kheiss tectonic province (Pettersson and Cornell 2008).

2.1.4.1.3. *Faulting and folding*

The Areachap Group experienced tectonic events that resulted in the island-arc complex having been sandwiched between the Kheis Subprovince to the east and the Namaqua Province to the west. As a result, a number of smaller faults and shears are recognized across the Areachap Group that runs in the NW-SE direction. According to Stowe (1983) and Humphreys (1985) the network of faults divides the area into sub-parallel shear domains Fig. 2.4.

The Brakbosch fault has an along strike extent of about 220km and runs from north of Upington to south of Copperton. It forms the boundary between the Areachap Group and the Kheis Subprovince. However, other shears such as the Boven Rugzeer shear zone play a vital part in the structural setting of individual formations of the Areachap Group. The area also has faults and shears that are less significant across the group.

Stowe (1983) and Humphreys (1985) state that the Areachap group was subjected to five deformation phases and define them as follows:

- "Early deformation of the Kheis Subprovince denoted as F_1 imparts a strong penetrative S_1 foliation throughout the Gordonia Subprovince of the Namaqua Province. An example of the penetrative F_1 foliation is seen on the axialplanar cleavage in isoclinal folds at the Prieska Zn-Cu deposit.
- "The D_2 deformation is represented by NNW trends of closed F_2 syn- and antiforms.
- The D_3 deformation (F_3) may have resulted from slip on conjugate shears, varying from E-W in the north to –NE-SW in the south, as a result forming a dome and basin pattern with F_2.
- "D_4/F_4 is characterized by large-scale folds, which steepen and shear the westerly F_2 antiform limbs.
- "The last deformation, D_5, resulting in F_5 folds, includes an earlier (D_{5a}) and later (D_{5b}) deformation stage. This ended in strike-slip activity, which began during the F_2 stage, and resulted in faulting trending NNE to NW.

The results of joint analysis reveals that the principal stress is directed NE-SW.

2.1.4.1.4. Tectonic setting of the Areachap Group

Various authors, based on the metamorphic, geochemical, structural and isotopic character of the Namaqua sector of the Namaqua Natal Province, proposed different tectonic models for the Areachap Group. The structural features of the Namaqua province can be associated with eastward directed forces, which ended in subduction and collision of the Namaqua Sector and the Kaapvaal Craton.

The Areachap Group originated in a volcanic-arc environment and Thomas et al. (1994) describe this group as a sliver of juvenile oceanic crust. In addition, the tectonic evolution of the area might have developed in a trans-tensional structural environment and that deformation from F3 onward is associated with transtensional deformation (Dewey et al., 1998; Krabbedam and Dewey 1998).

Recent plate tectonic models show that the calc-silicate volcanic rocks existing in the Areachap Group rest along a destructive plate margin. Geringer et al. (1994) recognised some calc-alkaline assemblages such as low-K arc tholeiite, calc-alkaline basalt and high-shoshonitic metalavas within the Areachap Group. Radiometric dating of the amphibolites and gneisses reveals that the Areachap volcanic arc formed over considerable periods, 1275 ± 7 Ma according to Cornell and Pettersson (2007) and 1241 ± 12 Ma according to Pettersson et al., (2007).

2.1.4.2. The Kakamas Terrane

2.1.4.2.1. Lithology

The Kakamas Terrane is bounded by the Hartbees River Thrust to the West and by Boven Rugzeer Shear zone to the East (Fig. 2. 3). Main lithologies in this terrane consist of intrusions with various level of deformation and metasedimentary rocks composed of marbles, calc-silicates, sandstones, schists and metapelites (Moen, 2007). The metasedimentary rocks are folded and intruded by undeformed granites and consist of highly deformed granulite to amphibolite facies gneisses, as well as feldsphathic quartzite and charnockites both with the age span of 2.0 Ga and 1.10 Ga age (Pettersson et al., 2009).

The granite intrusions have ages corresponding to the Early and Late Namaquan magmatic events. According to Pettersson (2008) the metamorphic grade in this terrane changes from lower granulite facies to mid amphibolite facies, generally lower grade to the east. The Keimoes Suite is one of the granitic intrusions that intruded the metasedimentary rocks of the Kakamas terrane and will further be discussed on section 2.2.

2.1.4.2.2. Structural setting

According to Moen (2007) the Kakamas Terrane mostly consists of granitoids and metasediments of the Korannaland Sequence and Koelmanskop and Vyfbeker Metamorphic Suites, two high grade, commonly migmatitic and probably related suites. The Kakamas Terrane has experienced several deformation events, having at least four different fold phases. The dominant deformational event is termed D2, which is a pervasive folding phase, related to the main early Namaquan deformation and corresponds to D2 in the Bushmanland Terrane. It consists of isoclinal folds and thrusts. The doming seen in the western part of the Kakamas Terrane is attributed to the superposition of D3 open upright folds on the main isoclinal D2 fold phase (Cornell et al., 2006). D3 in the Kakamas Terrane is equivalent to D3 in the Bushmanland Terrane. Post D3-structures are related to wrenching along the major strike-slip shear zones (Pettersson and Cornell, 2008).

According to Miller (2012) deformation and metamorphism were accompanied by intrusion of extensive syntectonic, ~1.2 Ga granitoids in the Kakamas Terrane. Miller (2012) state that late, large-scale uplift of the Kakamas Terrane took place during extensive dextral shearing on the Pofadder-Tantalite Valley Shear Zone and the Excelsior-Lord Hill Shear Zone juxtaposing the high-grade rocks of this subprovince against the low-grade or unmetamorphosed rocks of the Richtersveld and Konkiep Subprovinces to the south and north, respectively.

2.1.4.2.3. Tectonic setting

Prior to the Namaquan Wilson cycle, a Kheisan Wilson cycle took place in the Namaqua sector between ~2000 and 1600 Ma, with an orogenic event at ~1750 Ma (Fransson, 2008). The Areachap oceanic basin developed due to breaking apart of the Kheis-Kaapvaal Craton. Then the rifting stopped ~ 1300 Ma and subduction of the Areachap commenced. According to Fransson (2008) the Kakamas Terrane was a small crustal fragment in the ocean basin west of Areachap island arc. She further reported that at approximately 1220 Ma the Kakamas Terrane docked with the Areachap island arc. The latter arc magmatism in the subduction moved west. Therefore continental magmatism proceeded in the Kakamas Terrane thereby resulting in the development of the Kenhardt Formation (Cornell and Pettersson, 2007).

2.1. Local geology

2.1.1. Keimoes Suite

The Keimoes Suite is a somewhat loosely defined and poorly studied group of granitoids and there is no general agreement in the literature on its exact content or distribution. The granitoids of the suite characterize the Namaqua Front and Foreland zones (Stowe, 1983), and their distribution is defined as been bound to the west by the Neusspruit Shear Zone, and to the east by the Brakbosch Fault (Fig. 2.5).

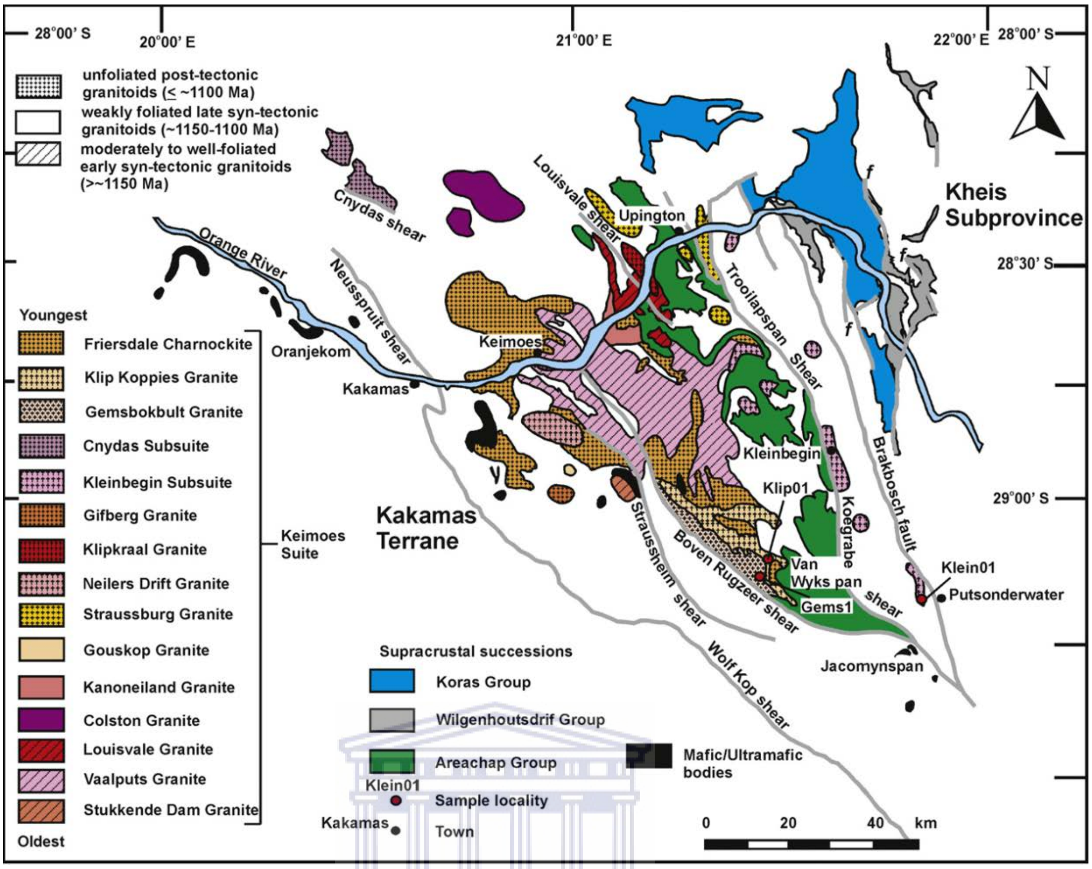

Figure 2.5. Geological map showing the distribution of granitoids of the Keimoes Suite (Bailie et al., 2011). The research excluded the Areachap and the Koras Groups.

The Keimoes Suite is described as a composite batholith comprising a calc-alkaline suite of mid to upper crustal, predominantly I-type granitoids ranging in composition from quartz monzonite to potassic granites (Moen, 2007). The emplacement of the suite is related to plate tectonic processes that took place at the eastern margin of the Namaqua Orogen. The suite covers an extensive distance of over 200 km from Putsonderwater, near Marydale in the southeast, to northwest of Upington beyond which it is covered by the Neoproterozoic Nama Group. Therefore, the suite indicates an extensive period during the Namanquaen tectonogenesis with ages ranging from 1.15 to 1.1 Ga. Various publications, reveal that emplacement of the Keimoes Suite occurred after the continental collision between the Kaapvaal Craton and Namaqua Sector as a result of crustal thickening and partial melting (Cornell et al., 1992; Eglington, 2006; Pettersson et al., 2007; Cornell and Pettersson, 2007). At approximately 1.18-1.15 Ga this collision event resulted in the generation of the syn-tectonic granitoids of the

Keimoes Suite and the peak thermal M2 metamorphism. Bailie et al. (2011) recently conducted a study on the southern portion of the Keimoes Suite and concluded that the late-tectonic and post tectonic granitoids of the Keimoes Suites such as Kleinbegin, Gemsbokbult and Klip Koppies Granites were formed during the second collision event that took place at 1013 and 1 .08 Ga. This is in agreement with previous studies on the Keimoes Suite and generally suggests that late-syn to post tectonic granitoids of the Keimoes Suite were emplaced at ~1100Ma.

The Keimoes Suite comprises a group of well foliated to weakly foliated, biotite, biotite-hornblende and charnockitic granitoids (Moen, 2007). Geringer et al. (1987) described the granitoids as coarse grained, slightly porphyritic, grey granites to medium-grained charnockitic monzogranites. The granitoid bodies vary from generally unfoliated post-tectonic granitoids in the west to foliated syn-tectonic granitoids to the east nearing Upington (Van Niekerk, 2006). SACS (1980) acknowledged that the suite is likely to include mixtures of diverse rock types not belonging to a single intrusive series and should be subdivided into more than one intrusive suite. Emplacement ages of the intrusions can be assigned to the last foliation forming tectonic event based on the degree of foliation that varies from one pluton to the next. Thus, the suite is subdivided into G1 (pre-tectonic), G2 (syn-tectonic) and G3 (post-tectonic), granites by Stowe (1983). The distribution of the Keimoes Suite granites is displayed in figure 2.5.

2.1.2. Keimoes Suite granitoids

1. **Vaalputs Granite**: This is the most distributed granite of the Keimoes Suite, occupying an area of 430km^2. It intrudes some members of the Korannaland Group and is the main component of Grey Gneiss. The Vaalputs granite is dark grey in colour with a medium-grained equigranular texture and well-developed foliation. It is composed of quartz, K-feldspar and plagioclase, surbordinate biotite, and tiny plagioclase phenocrysts (Moen, 2007). Slabbert (1987) classified the granite as a quartz monzonite based on the equal proportions of plagioclase and K-feldspar. The granite has sharp concordant contacts with

the surrounding country rocks, metasediments of the Puntsit Formation of the Korannaland Group. The Vaalputs Granite is located east of the Boven Rugzeer Shear Zone where it has a close contact relation with the Riemvasmaak Gneiss, an augen granite gneiss which occurs on both sides of the Boven-Rugzeer Shear Zone (Pettersson and Cornell, 2008).

2. **Louisvale Granite**: This gneissic granite intrudes the Bethesda Formation of the Areachap Group in a concordant lit-par-lit fashion and displays no contact metamorphism. It forms a northwest-southeast elongate pluton and, because of poor exposure away from the Orange River, it is not easy to differentiate it from the Vaalputs granite (Moen, 2007). The Louisvale granite is a mesocratic to leucocratic, medium-grained granite with plagioclase and K-feldspar varying from granitic to quartz monzonitic. This granite has intensely foliated concordant contacts with the metasedimentary rocks of the Areachap Group. The texture and composition of this granite suggest it was emplaced during peak metamorphic conditions at a relatively deep crustal level (Moen, 2007).
3. **Klip Koppies Granite**: Slabbert (1987) described this granite as a grey, poorly foliated, fine to medium-grained rock characterized by porphyritic texture and small mafic inclusions. Mineralogically it consists of K-feldspar, plagioclase, quartz, and equal proportions of biotite and muscovite. The poorly developed foliation and potassic composition suggest that it is a relatively late-tectonic intrusion. This granite carries a larger crustal component and it intrudes the Gemsbokbult Granite, based on geochemical, isotopic and geochronological data provided by Bailie et al. (2011). The relative age for this granite is approximately 1100Ma.
4. **Keboes Granite:** is exposed in the Kanon Eiland area within and to the east of the Orange River and is an intrusive into the Sout Rivier Formation of the Korannaland Group and the Bethesda and Ratel Draai Formations of the Areachap Group as well as the Louisvale granite of the Keimoes Suite. It consists of a group of meso- to epizonal potassic granites characterized by moderate to poorly developed foliation, an abundance of biotite and

sharp cross-cutting contacts. It covers an area of about 35km^2 with no visible contact with the country rock.

5. **Colston Granite**: occurs in an area characterized by low relief and fragmentary exposures. It is an intrusive into the metapelites of the Toeslaan Formation of the Korannaland Group and is unconformably overlain by horizontal strata of the Nama group in the north. This pluton has an exposed surface of about 140 km^2 and can be described as medium grained, equigranular biotite granite with numerous mafic xenoliths. These xenoliths can measure over a metre in diametre (Geringer and Ludik, 1990). The granite is composed of quartz, plagioclase, biotite and microcline. According to Geringer et al. (1987), the granite crystallized under a pressure of 5kb and can therefore be described as an epizonal intrusion emplaced in the waning stages of the Namaqua Orogeny.
6. **Straussburg Granite**: Numerous authors (Geringer et al., 1987; Van Zyl, 1981; Cornell et al., 2012) investigated this granite, and referred to it as a biotite granodiorite with minor hornblende, grading into granite, or strictly monzogranite because plagioclase predominates over K-feldspar. It contains abundant gabbroic, and fewer granitic xenoliths. Moen (2007) regarded it as late tectonic, and Van Zyl (1981) attributed the foliation to a balloonlike emplacement process rather than to regional deformation. Some metre-thick discrete shear zones clearly reflect late-tectonic block movements (Moen, 2007). The Straussburg Granite intrudes the Areachap Group supracrustal rocks. It is cut by numerous mafic and felsic dykes ascribed to the 1104 to 1092 Ma upper Koras Group. Geringer et al. (1988) correlate it with the lithologically similar Colstone Granite. Barton and Burger (1983) determined a Rb-Sr age of this granite to be 1264 ± 604 Ma, but this age is considered as too old by Cornell et al., (2012), who considers Pb-Pb ages of 1080 and 1093 Ma as more acceptable.
7. **Kanon Eiland Granite**: Like the Straussburg Granite, it is a mesocratic biotite granite characterized by a poorly developed foliation and numerous mafic and leucocratic inclusions (Moen, 2007). Good exposure can be seen at the bridge over the Orange River where sharp cross-cutting

contacts with the adjacent rocks have been observed. This granite is a late-kinematic, meso-to epizonal granite Moen (2007). Stowe (1983) regarded this granite as a post-tectonic (G3) intrusion.

8. **Neilers Drift Granite**: this granite forms an oval shaped pluton which is 6 km wide and 12 km long and is oriented in the east-west direction. It can be characterized as a mesocratic, unfoliated biotite granite that is similar to the Kanon Eiland Granite. The Friersdale Charnockite intrudes the Neilers Drift Granite, which is covered by a thin layer of sand and calcrete and is randomly exposed. According to Stowe (1983) this granite is a G2 (syn-tectonic) intrusion. Moen (2007), however, regarded it as post-tectonic based on the lack of tectonic fabric.
9. **Gouskop Granite**: this granite occupies an area of about 15 km × 3km on the farm Gif Berg 58, south of Keimoes. It crops out as prominent hills and is an intrusive into the semipelitic metasediments of the Valsvlei Formation that belong to the Korannaland Group. Slabbert (1987) described the granite as a leucrocratic, medium grained, non-porphyritic granite with moderately developed foliation. It consists of quartz, plagioclase, K-feldspar and absence of biotite, with minor zircon, hornblende and muscovite as accessory minerals (Moen, 2007).
10. **Gif Berg and Klip Kraal Granites**: These are the youngest member of the Keimoes Suite and are epizonal intrusions. The Gif Berg granite intrudes the Sandputs Formation of the Korannaland Group and is dark grey, fine to medium grained dark grey granite with foliation (Slabbert, 1987). The Gif Berg granite is the only granite of the Keimoes Suite that contains visible garnet. The modal composition is quartz, K-feldspar, plagioclase, biotite and garnet. The Klip Kraal Granite is intrusive into the Louisvale Granite and is about 500m wide and 3 km long trending in the northwest direction. It is a dark grey, unfoliated, porphyritic rock with a composition varying from quartz monzonitic through granodiorite to diorite (Moen, 2007). Based on the mineralogy and composition it is the most mafic of the granitoids of the Keimoes Suite.

11. **Kleinbegin Granite**: it consists of medium-to coarse grained, meso- to epizonal, I-type granite. These granites have a strongly developed to absent tectonic fabric. They are leucocratic and poorly foliated to unfoliated with varying compositions and textures ranging from biotite-rich augen gneiss to fine grained leucogneiss. Moen (2007) associated this variation to the shearing related to the last movement of the Brakbosch fault.
12. **Cnydas Subsuite**: is a coherent group of post-tectonic, epizonal granitoids occurring in a triangular area extending from Lutzputs towards the northwest. The rocks are well exposed and flat-lying sediments of the Nama Group cover the subsuite. The Cnydas Subsuite has visible contact relationships with the Korannaland Group even though the group was strongly tectonised.
13. **The Friersdale Charnockite**: This forms an extensive sheet-like body in the Kakamas and Areachap Terranes. The Friersdale Charnockite is a dark grey, unfoliated rock with typical round opalescent blue quartz xenocrysts. The rock is modally a monzogranite with biotite and hornblende as the dominant mafic minerals, but minor clinopyroxene and lesser orthopyroxene, justify the name charnockite, together with its dark appearance (Cornell et al., 2012). It contains both mafic and quartzite xenoliths and intrudes all the surrounding rocks, giving rise to garnetiferous hornfelses termed kinzigites in supracrustal rocks. The northwestern lobe of the intrusion lacks pyroxene, according to Van Bever Donker (1980), and this is probably due to variable assimilation of hydrous felsic rocks. Similar, pyroxene-bearing granitoid intrusions crop out in the Cnydas area some 30 km northwest of the main Friersdale body (Moen, 2007). Barton and Burger (1983) reported an Rb-Sr age of 1085 ± 130 Ma (initial $^{87}Sr/^{86}Sr$ (R_0) = 0.707 ± 0.003) and a zircon Pb-Pb date of 1087 Ma for the Friersdale Charnockite.

CHAPTER 3: RESULTS

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3.1. Introduction

This section entails field work results of all the granites and country rocks mapped in the Keimoes Suite. All structural features observed on the granites are presented in this section. Also the results from the stereographic analysis which shows mainly the prominent joint sets and their directions respectively as well as the principal stress analysis are included in this section.

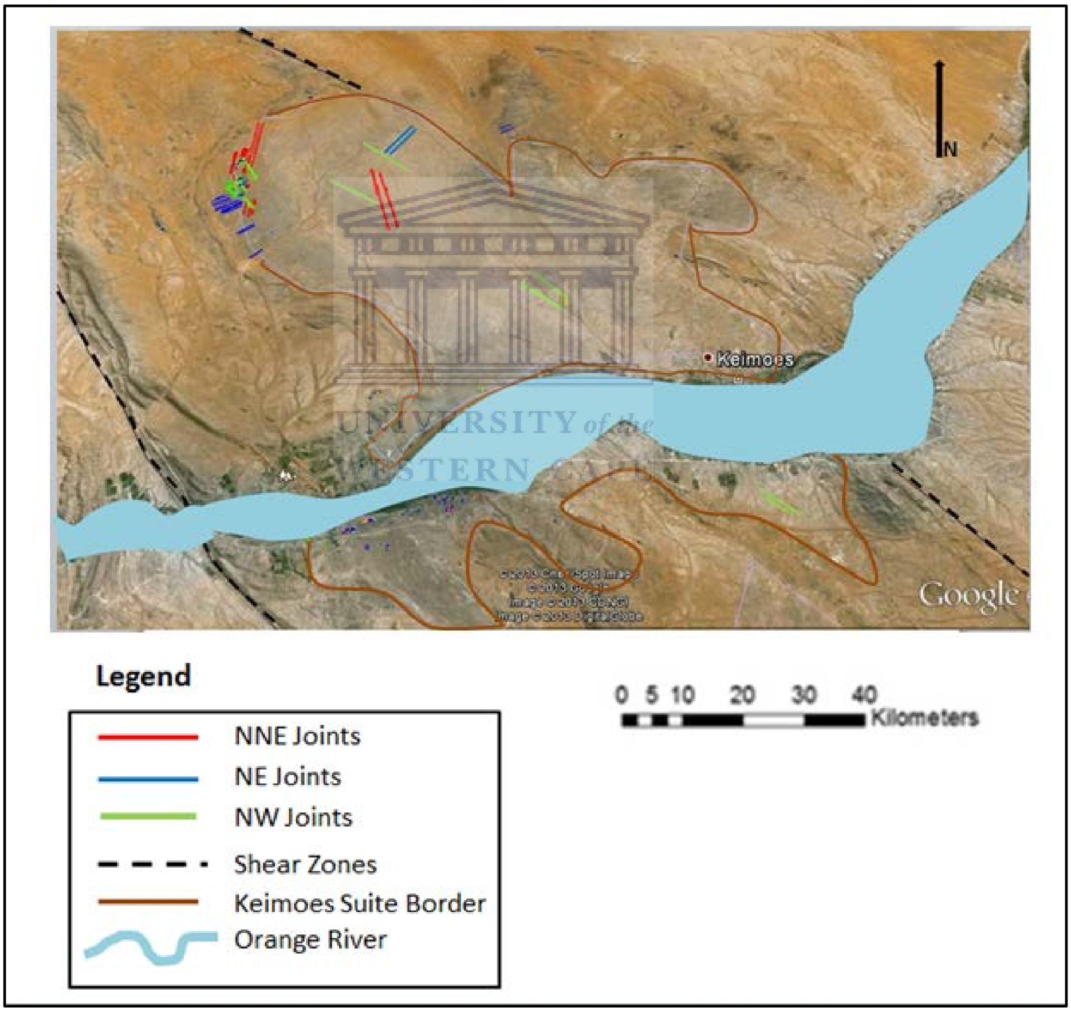


Figure. 3.1. Remote sensing image showing possible structures of the study area.

Through remote sensing significant structural information was acquired. A number of shear zones were recognised that serve as a border to the study area. The different plutons of the Keimoes Suite are widely distributed from north of the Orange River down to the southern side of the river. The remote sensing study revealed three prominent joint sets in the Keimoes Suite (Fig. 3.1), NNE-SSW, NE-SW, NW-SE.

3.2. Field observation

Based on field observation three prominent joint sets were confirmed to be in agreement with the results of the remote sensing. The systematic joint sets occurring in the granitoids of the Keimoes Suite are striking 005°-285° NNE-SSE, 335° - 165° NW-SE, and 065°-245° NE-SW however there are also some random joint sets present.

The field report is divided into three sections, section A will be the Keimoes Suite granites, section B constitute the country rocks and section C is the comparison of the country joints with the Keimoes Suite joints.

3.2.1. Section A: Keimoes Suite

1. Friersdale Charnockite

Field appearance

The Friersdale Charnockite is the most distributed granite of the Keimoes Suite. The rock is well exposed in the Upington, Keimoes and Kakamas areas. Large boulders of this granite lie along the Keimoes –Kakamas road. Good exposures are found on both southern and northern bank of the Orange River and they appear as dome or oval shaped bodies across the study area. There are also some extensive flat lying outcrops of the Friersdale Charnockite. The main characteristic of the Friersdale Charnockite is its onion skin like appearance due to weathering.. The Friersdale Charnockite is dark grey unfoliated granite. It has medium to fine grain porphyritic texture and contains among others round opalescent blue crystals. The granite has oxidised veins some of which are filled with epidote (Fig. 3. 2).

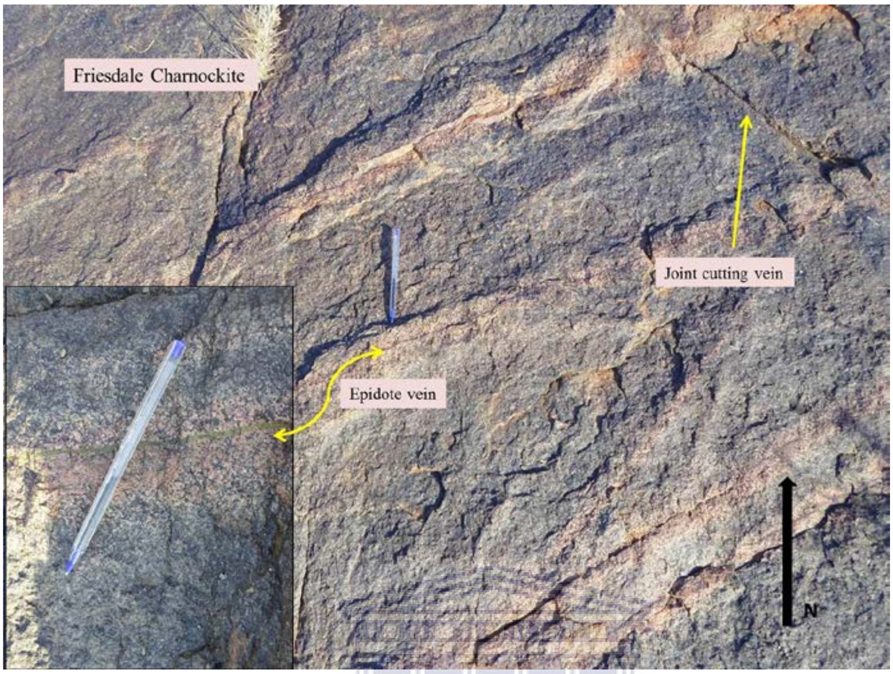


Figure 3.2. Friersdale Charnockite showing oxidised veins and epidote veins. Pen = 15cm long.

Description of structural features

About 100 joint orientation measurements were made in the Friersdale Charnockite which contains sub-parallel oxidised veins, perpendicular to the joints (Fig. 3.2). However, these veins are not displaced by the joints cutting them. Some veins are filled with greenish epidote minerals (Fig. 3.2), but they are mostly filled with leucocratic minerals such as quartz and feldspars. Prominent joint sets of the granite are striking in the N-S direction. Other orientations of joints are the NW-SE and NE-SW directions. A set of conjugate joints were identified in the Friersdale Charnockite and they strike NW-SE, NE-SW direction (Fig. 3.3).

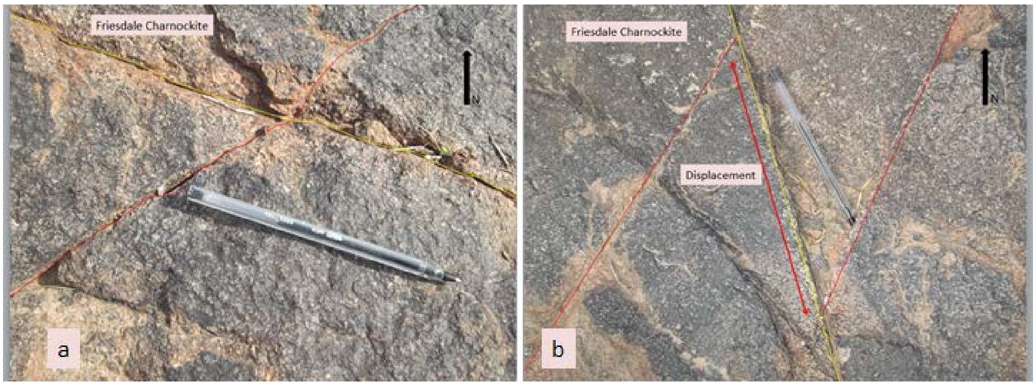
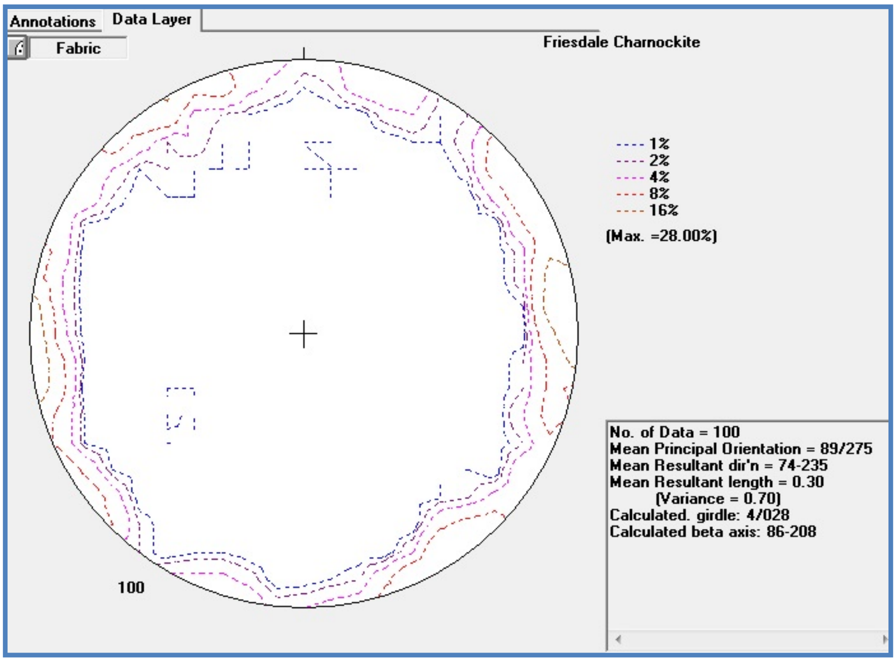


Figure 3.3. a) Conjugate joints of Friersdale Charnockite, b) Friersdale Charnockite showing joint displacement Pen = 15 cm long.

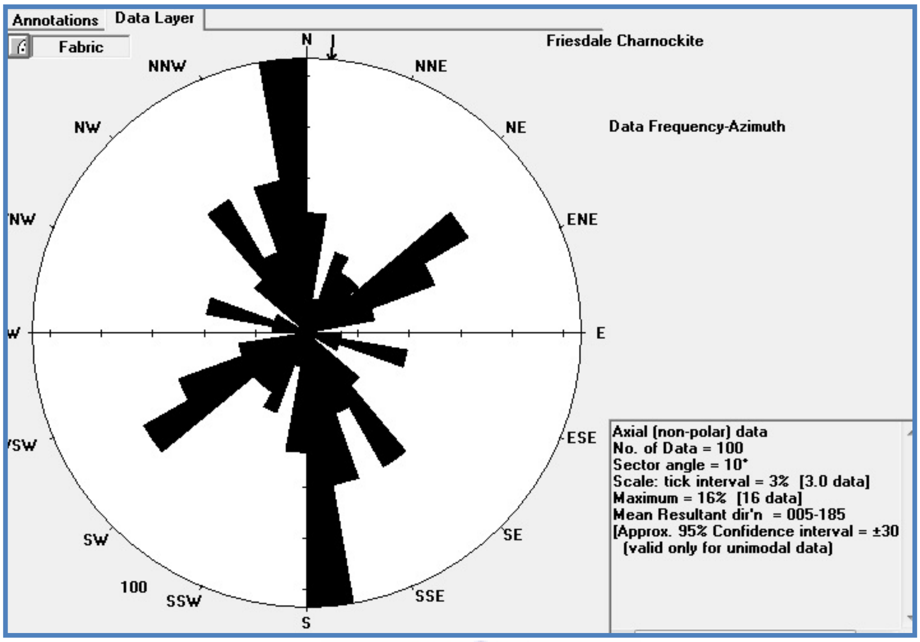
Joint analysis

The contour diagram (Fig. 3.4) does not show any clusters however there are three prominent concentrations oriented in the NE-SW, E-W and NNW-SSE corners of the diagram and this is also shown by the rose diagram (Fig. 3.5). Prominent joint sets in the Friersdale Charnockite strike 355°-175°NNW-SSE and 055°-235°ENE-WSW. Other joint sets are orientated in the 325°-145°NW-SE and 106°-285° ESE-WNW direction.



```
No. of Data = 100
Mean Principal Orientation = 89/275
Mean Resultant dir'n = 74-235
Mean Resultant length = 0.30
        (Variance = 0.70)
Calculated. girdle: 4/028
Calculated beta axis: 86-208
```

Figure 3.4. Contour diagram of pole to joints in the Friersdale Charnockite.



Axial (non-polar) data
No. of Data = 100
Sector angle = 10°
Scale: tick interval = 3% [3.0 data]
Maximum = 16% [16 data]
Mean Resultant dir'n = 005-185
[Approx. 95% Confidence interval = ±30
(valid only for unimodal data)

Figure. 3.5. Rose diagram showing strike orientations of joints in the Friersdale Charnockite.

2. Cnydas Granite

Field appearance

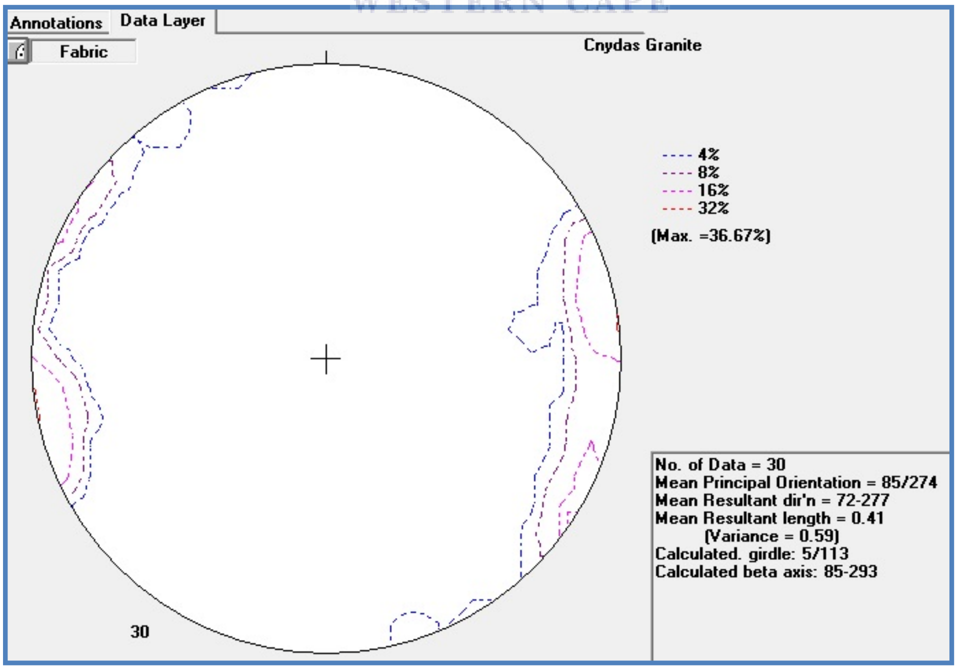
During field observation, the Cnydas granite appeared to be a medium to coarse-grained granite with no foliation. It is medium grey and contains small crystals of feldspars. Near the Cnydas shear zone the granite appears as small outcrops. Presumably good exposure of the outcrop has been eroded away. In terms of mineralogy the granite consists of quartz, feldspars, mica and a significant amount of biotite. The presence of mica gives the rock a shiny appearance. The quartzes have an opalescent blue colour like the ones found in the Friersdale Charnockite granite. However, mafic inclusions were also observed in the granite. Towards the North, the rock occurs as large boulder hills.

Description of structural features

About 30 joint orientation readings were recorded in the Cnydas granite. The granite does not really have many structural features on it, although there were a few veins which are just a few centimetres long. The veins are filled with milky quartz (Fig.3.6.). No foliation on the granite was observed.

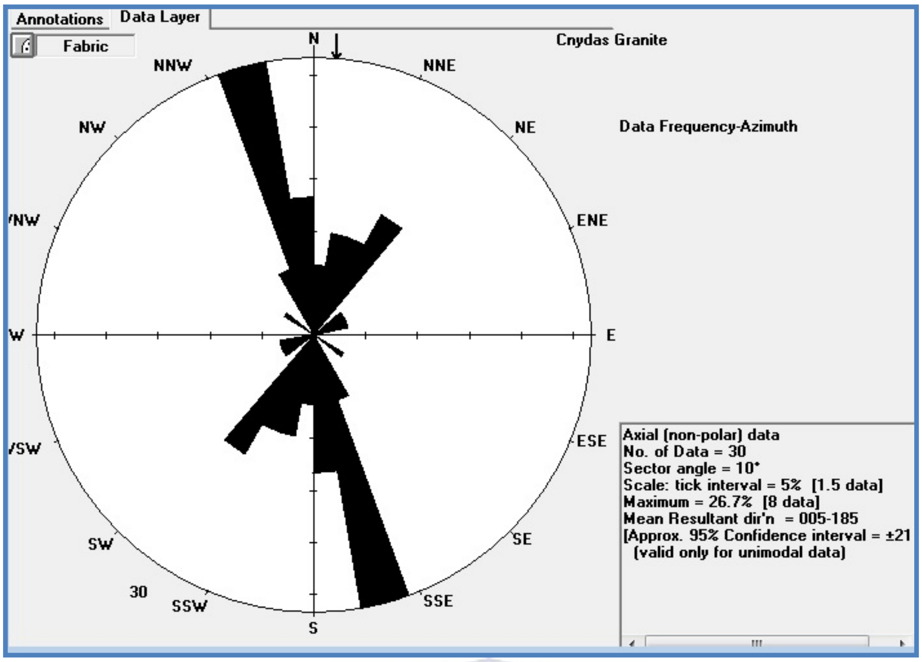
Figure 3.6. Cnydas granite with feldsphathic vein. Pen =15cm long.

The contour diagram (Fig. 3.7) shows two maxima at ENE-WSW and NW-SE direction. This indicates that there are two joint sets present in the Cnydas granite which is adequately displayed by the rose diagram (Fig. 3.8). Most of the joints in this outcrop strike at 344°-164° NNW-SSE and 035°-216°NE-SW respectively (Fig. 3. 8).



```
No. of Data = 30
Mean Principal Orientation = 85/274
Mean Resultant dir'n = 72-277
Mean Resultant length = 0.41
        (Variance = 0.59)
Calculated. girdle: 5/113
Calculated beta axis: 85-293
```

Figure 3.7. Contour diagram of pole to joints in Cnydas Granite.



```
Axial (non-polar) data
No. of Data = 30
Sector angle = 10°
Scale: tick interval = 5%  [1.5 data]
Maximum = 26.7%  [8 data]
Mean Resultant dir'n  = 005-185
[Approx. 95% Confidence interval = ±21
  (valid only for unimodal data)
```

Figure. 3.8. Rose diagram showing strike orientations of joints in the Cnydas Granite.

3. Kleinbegin Granite

Field appearance

Good exposures of Kleinbegin Granite are said to be found along the railway station. However this could not be confirmed during field mapping. Good exposures of this granite were not easily accessible as only a few small weathered outcrops along the railway station were found. The granite is biotite rich and contains quartz and feldspar grains. The biotite and feldspar form aligning bands making it granite gneiss. The granite shows randomly oriented feldspar phenocrysts which are about 0.5-1 cm in size. Some of the feldspar areas appear as plastic bands aligned with the biotite minerals. According to Moen (2007) this granite intrudes a quartzitic metasedimentary rock of the Dagbreek Formation. Although no visible contact between the granite and the country rock was observed, there were traces of the country rock on the ground. No structural features were recorded in the Kleinbegin Granite.

Figure3. 9. Photo of the Kleinbegin granite. Pen = 15 cm long.

4. Klip Kraal Granite

Field appearance

The Klip Kraal Granite is found along the Kakamas-Keimoes road approximately 10 Km from Upington. Some outcrop of this granite occurs 2 to 3 km south west of Upington along the Louisvale road where they are in contact with the amphibolites of the Jannelsepan Formation of the Areachap Group. The granite appears dark bluish in colour, but this is restricted to the presence of blue opalescence quartz grains. The granite intruded the dark amphibolitic rocks that are moderately foliated. The contact between the granite and the amphibolites is well exposed in the field. The granite furthermore contains feldspathic veins. There are light coloured magmatic flows observed on the granite.

Figure 3.10. Folded feldsphathic veins on the Klip Kraal granite. Both thick and thin veins show same deformation pattern.GPS = 10- cm long

Description of Structural features

The granite is dominated by step over joints which are oriented in the NW-SE direction. Most of the veins are perpendicular to the joints. The orientation of some of the veins is 325-145 NNW-SSE, 306-124 NW-SE. This indicates a different deformation event whereby the veins were formed at a different orientation from the earlier formed veins. The granite shows moderate foliation about 2 cm apart. The Klip Kraal Granite consists of folded M- and S- shaped feldsphathic veins. According to Passchier et al. (2005) deformation of veins in granitoids rocks ends up in folding and boudinage of the veins provided these veins' rheology is considerably different from that of the host rock. This is the case in the Klip Kraal Granite: the leucocratic folded veins have a different composition from that of the granite as the granite is mainly composed of plagioclase, hornblende and opaque minerals.

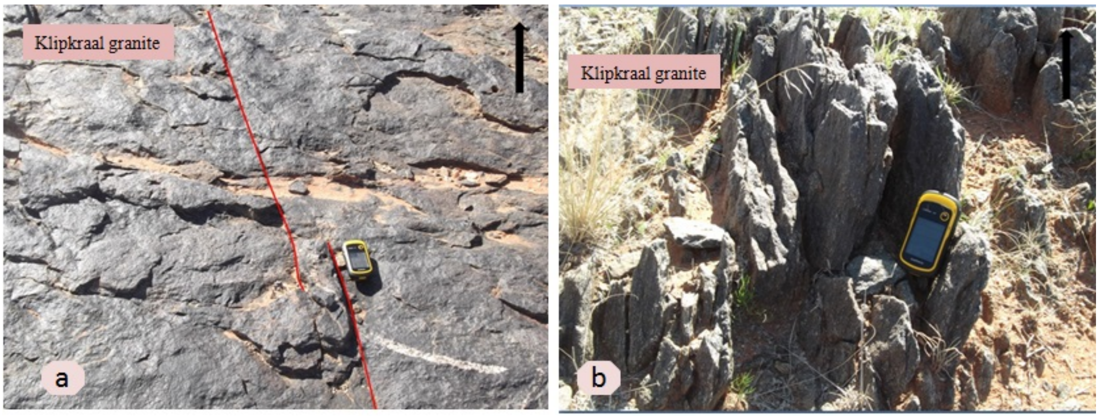
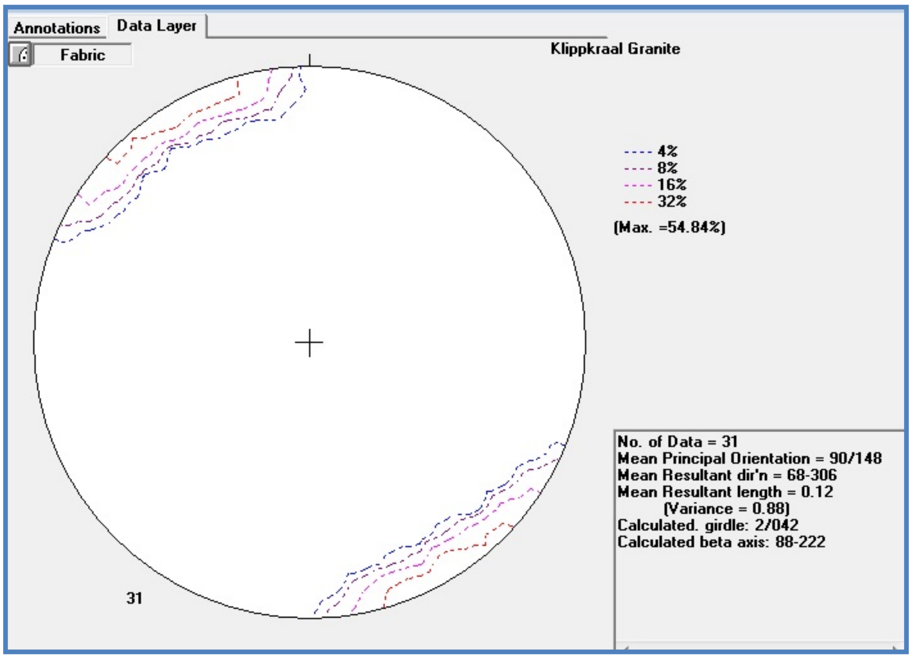


Figure 3.11. a) Step over joints of the Klip Kraal granite b) moderately foliated Klip Kraal granite.GPS = 10cm long.

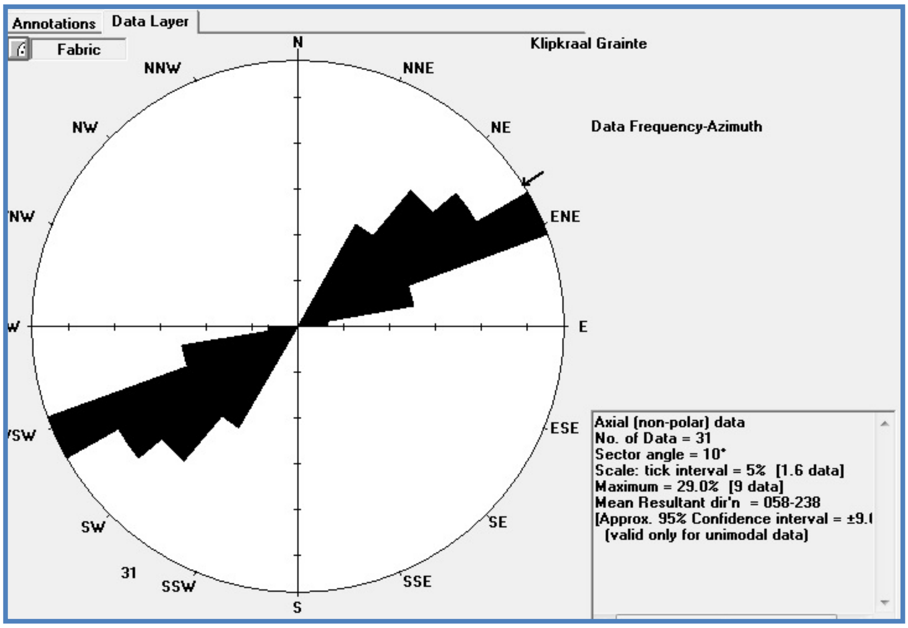
Joint analysis

The Klip Kraal contour diagram shows one cluster (Fig. 3.12). Cluster 1 has an orientation of 85/149. The mean principal orientation is 90/148 and the mean resultant direction is 68-306. This single cluster displayed by the pi diagram indicates the existence of vertical joints as displayed also by the rose diagram (Fig. 3.13).which shows only one principal direction of the joints set at 065˚-245˚ ENE-WSW.



No. of Data = 31
Mean Principal Orientation = 90/148
Mean Resultant dir'n = 68-306
Mean Resultant length = 0.12
(Variance = 0.88)
Calculated. girdle: 2/042
Calculated beta axis: 88-222

Figure 3.12. Contour diagram of poles to joints of the Klip Kraal Granite.



```
Axial (non-polar) data
No. of Data = 31
Sector angle = 10°
Scale: tick interval = 5%  [1.6 data]
Maximum = 29.0%  [9 data]
Mean Resultant dir'n  = 058-238
[Approx. 95% Confidence interval = ±9.
  (valid only for unimodal data)
```

Figure 3.13. Principal orientation of joints in the of Klip Kraal Granite.

5. Kanon Eiland Granite

Field appearance

According to Moen (2007) good exposures of the Kanon Eiland Granite are found at the bridge over the Orange River. This was confirmed during field mapping however accessing that outcrop at the bridge was difficult as there is now a fence and also the water level was an obstacle in getting to the outcrop. Therefore structural readings could not be taken at that station. As the Kanon Eiland Granite is widely distributed, most of the field mapping done on the Kanon Eiland granite was on outcrops found along the road from Louisvale heading to Kakamas.

The Kanon Eiland Granite is a coarse grained biotite granite that forms an extensive body on the southern bank of the Orange River in the Kanon Eiland area. The rock is dark grey in colour; the dark colour is defined by the abundance of biotite. It contains large biotite xenoliths with very sharp contacts (Fig. 3.14). This observation is similar to what Moen (2007) has observed as he described the Kanon Eiland Granite as having large mafic inclusions consisting of biotite and hornblende.

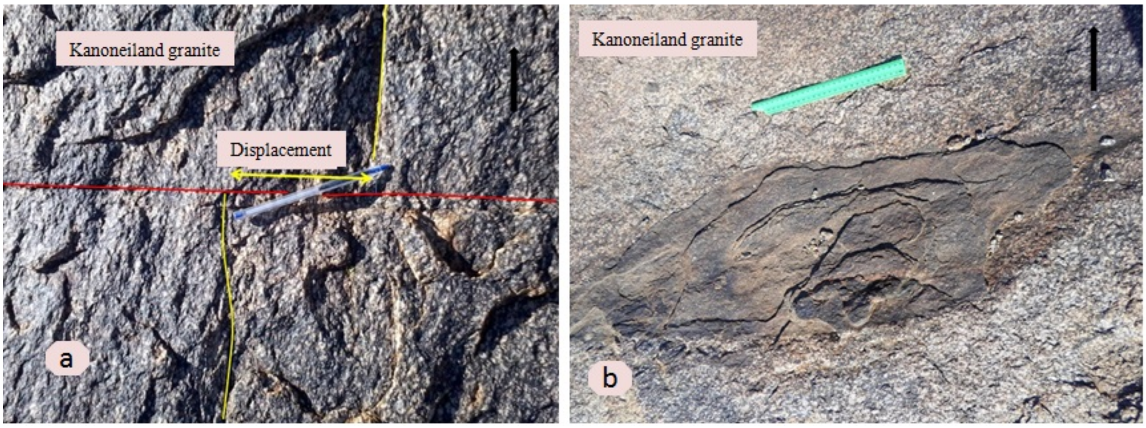
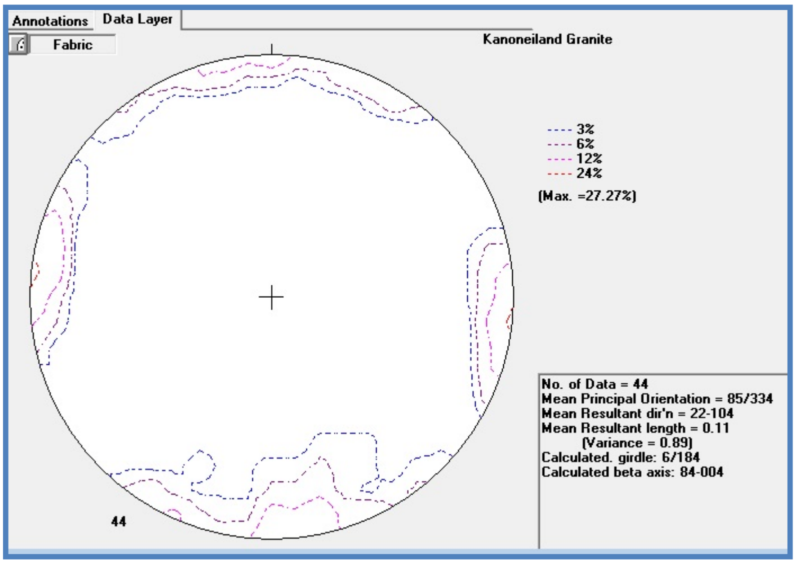


Figure 3.14.a) Joint displacement in the Kanon Eiland granite pen = 15 cm b) Mafic xenoliths on the Kanon Eiland Granite, ruler = 30 cm.

Description of structural features

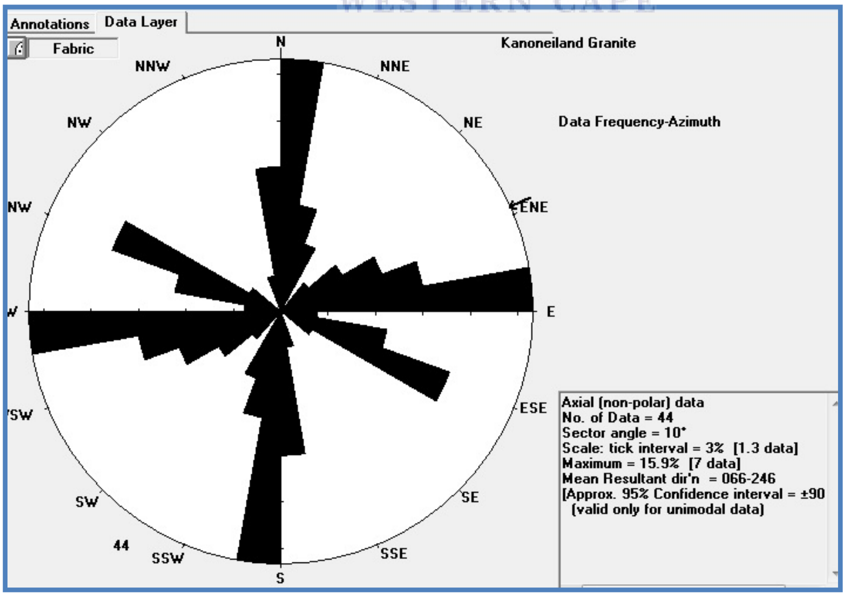
The granite contains joints displacing other joint sets. The main joint orientations are -008°-185° N-S and 085°-265° ENE-WSW. The 085°-265°ENE-WSW joint sets displaced the 008°-185°N-S, joint set (Fig. 3.14) implying that it is younger than the 008°-185°N-S set. The granite also has non-systematic joints which displace each other in some cases on the outcrop. The non-systematic joints terminate against the major joints and appear curvy in shape and are not parallel to each other. This means they are the last generation of joints in this granite as explained in chapter 4. They are orientated in the NW-SE direction. The granite is weakly foliated with a spacing of 3cm. There were no veins recorded on this outcrop.



```
No. of Data = 44
Mean Principal Orientation = 85/334
Mean Resultant dir'n = 22-104
Mean Resultant length = 0.11
        (Variance = 0.89)
Calculated. girdle: 6/184
Calculated beta axis: 84-004
```

Figure 3.15. Contour diagram of poles to joints of the Kanon Eiland Granite.

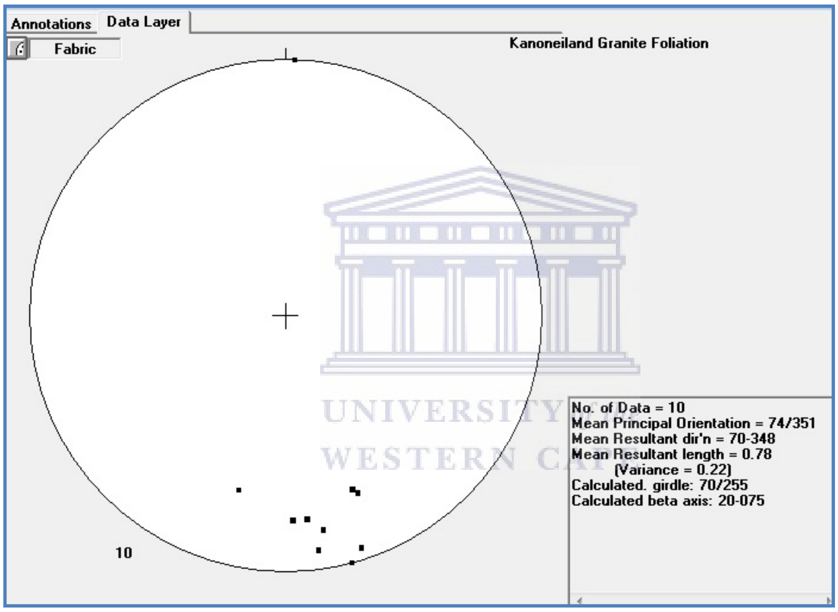
Kanon Eiland Granite contour diagram shows two clusters defined by maxima. The orientation of cluster 1 is 096/89 and cluster 2 is 177/85 (Fig. 3.15). The rose diagram (Fig. 3.16) shows the main orientation of these joints. Three joint sets were found in the Kanon Eiland granite. The principal orientations are in NS-008°-185°, EW- 085°-265° and WNW-ESE 296°-115°.



```
Axial (non-polar) data
No. of Data = 44
Sector angle = 10°
Scale: tick interval = 3%  [1.3 data]
Maximum = 15.9%  [7 data]
Mean Resultant dir'n  = 066-246
[Approx. 95% Confidence interval = ±90
  (valid only for unimodal data)
```

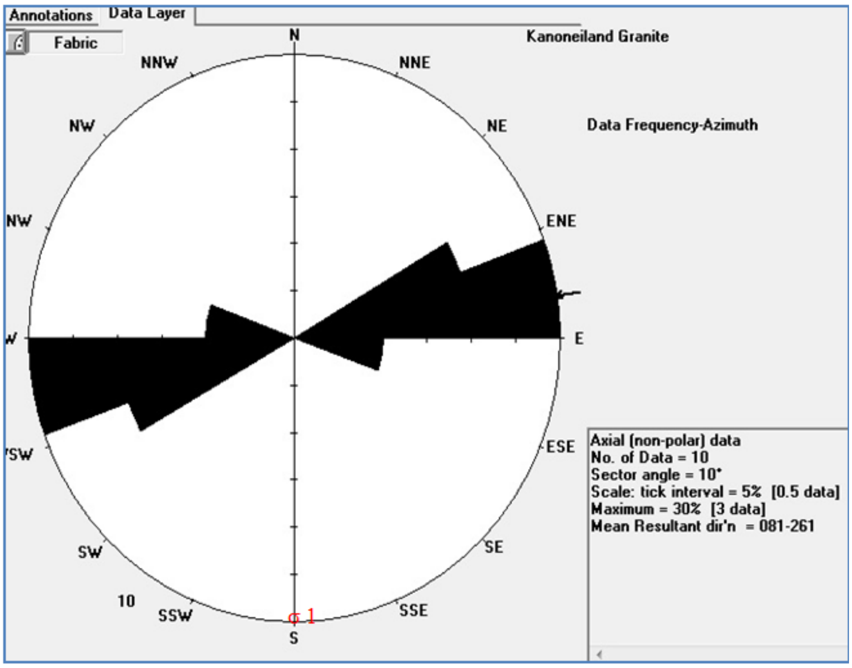
Figure 3.16. Rose diagram showing strike orientation of joints in Kanon Eiland Granite.

The contour diagram of the Kanon Eiland Granite foliation (Fig. 3.17) shows only one cluster. The pole has an orientation of 179/11. This means that the direction of dip / dip of the plane is 359/79. The mean principal orientation of the foliation calculated by the software as 354/74 and the mean resultant direction is 70-348. The strike of the main foliation is in E-W direction (Fig. 3.18). The maximum principal stress is of the foliation is 179/02 this is because the foliation is an axial planar foliation and not a fracture cleavage which behave like joints and therefore will have different sigma 1. Axial planar foliation usually forms perpendicular to the principal stress therefore it records the direction shortening.



```
No. of Data = 10
Mean Principal Orientation = 74/351
Mean Resultant dir'n = 70-348
Mean Resultant length = 0.78
        (Variance = 0.22)
Calculated. girdle: 70/255
Calculated beta axis: 20-075
```

Figure 3.17. Pi diagram showing pole to foliation in the Kanon Eiland Granite.



```
Axial (non-polar) data
No. of Data = 10
Sector angle = 10°
Scale: tick interval = 5%  [0.5 data]
Maximum = 30%  [3 data]
Mean Resultant dir'n  = 081-261
```

Figure 3.18. Principal orientation of foliation in the Kanon Eiland Granite.

6. Straussburg Granite

Field appearance

The Straussburg Granite occurs as a large extensive outcrop south of Upington, and like the Kanon Eiland Granite, contains large mafic and leucocratic xenoliths (Fig. 3.19). Moen (2007) also reported similar observations: he identified mafic and leucocratic xenoliths with preferred orientation. Some of the mafic xenoliths have feldspathic inclusions and veins cutting across them. The granite is essentially light grey in colour. Good exposures of this granite are found inside the Carpe Diem farm east of Upington. The Straussburg Granite is poorly foliated biotite rich granite. It is coarse grained and mineralogically consists of lots of biotite and some quartz, feldspars and some opaque minerals.

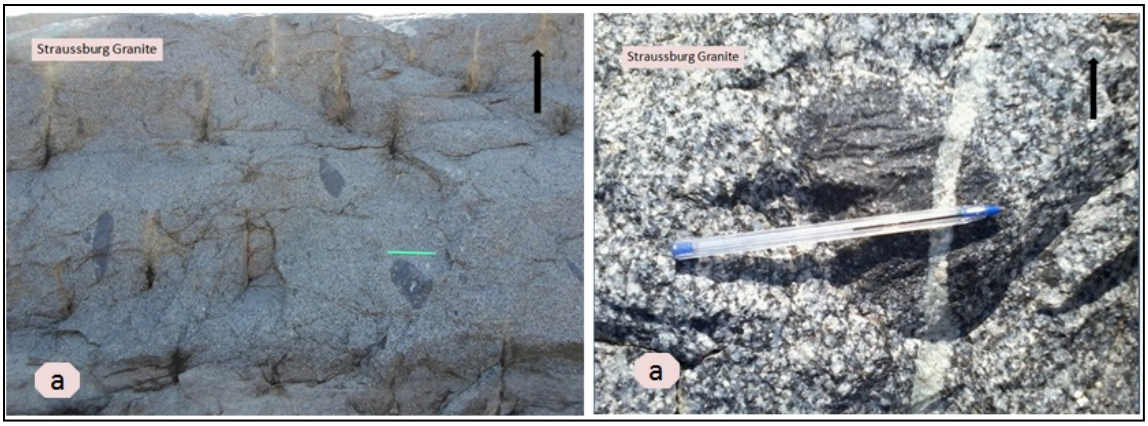


Figure 3.19. a)Mafic xenoliths on the poorly foliated Straussburg granite. Ruler = 30 cm long b) leucocratic vein cutting the mafic xenoliths. Pen = 15cm long

Description of structural features

The granite has prominent veins filled with feldspars and reddish quartz. . The veins range in sizes, some are as wide as 12 cm.The 054°-235° NE-SW joint system displaced the feldspathic vein (Fig. 3.20). The joints displace each other forming a conjugate set. The main orientation of the joints is NW-SE and NE-SW. There are also other joints trending in the E-W direction but they are not as prominent as the above-mentioned joints.

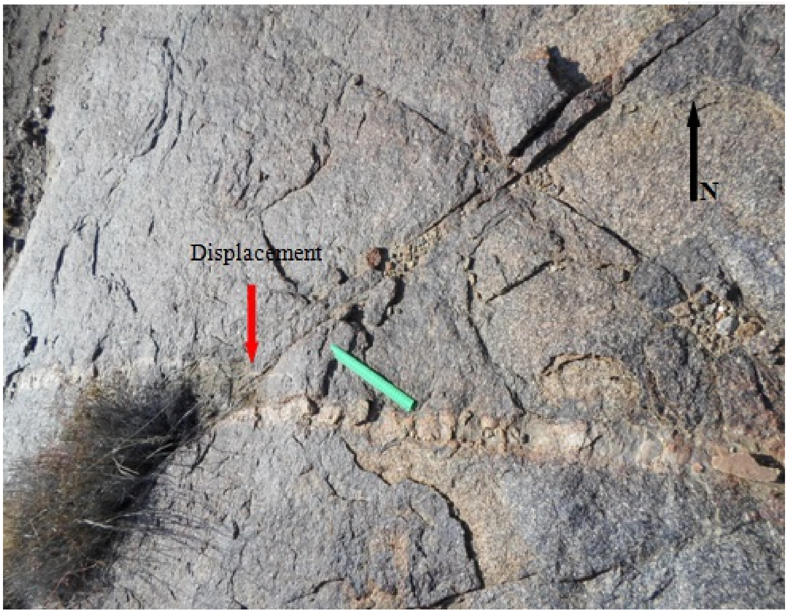
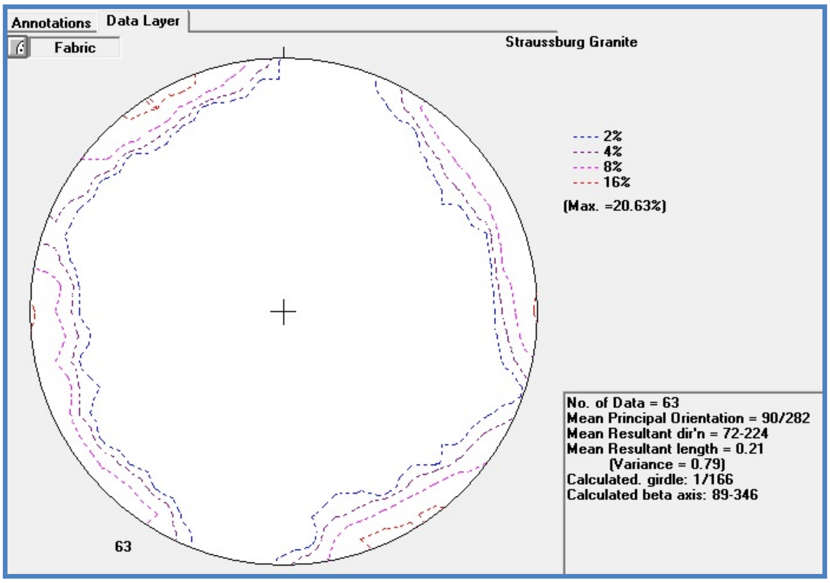
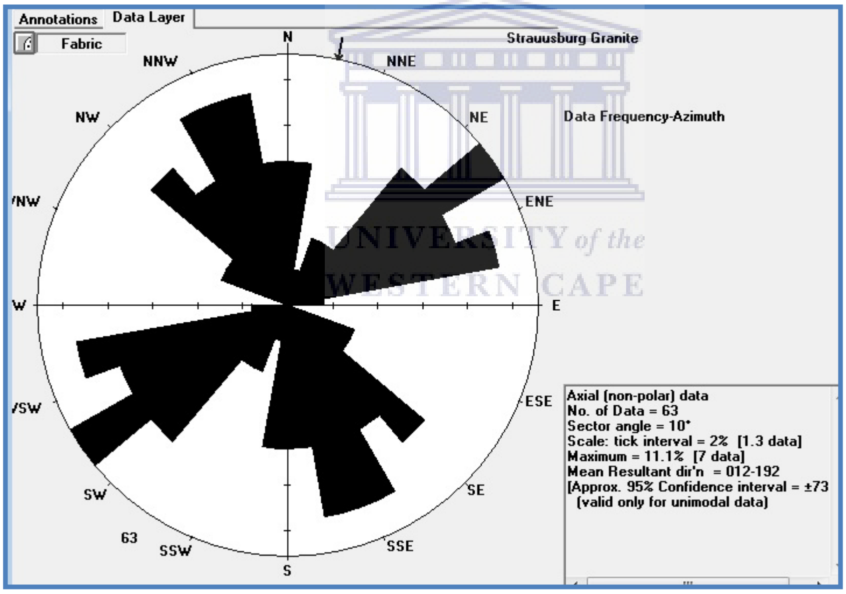


Figure 3.20. Feldspathic vein displaced by NE-SW joint in the Straussburg Granite. Rule = 30 cm long



```
No. of Data = 63
Mean Principal Orientation = 90/282
Mean Resultant dir'n = 72-224
Mean Resultant length = 0.21
        (Variance = 0.79)
Calculated. girdle: 1/166
Calculated beta axis: 89-346
```

Figure 3.21. Straussburg Granite contour diagram of poles to joints.



```
Axial (non-polar) data
No. of Data = 63
Sector angle = 10°
Scale: tick interval = 2%  [1.3 data]
Maximum = 11.1%  [7 data]
Mean Resultant dir'n  = 012-192
[Approx. 95% Confidence interval = ±73
  (valid only for unimodal data)
```

Figure 3.22. Rose diagram showing strike orientation of joints in the Straussburg Granite.

The Straussburg contour diagram shows two clusters of the maximum data points. Cluster 1 is oriented in 331/88 and cluster 2 is oriented in 063/80˚ (Fig. 3.21).Two principal orientations of joints are recognised in the Straussburg Granite. The rose diagram (Fig. 3.22) can attest as it shows joint sets in the 054°-235° NE-SW, 340°-159° NNW-SSE.

7. Colston Granite

Field appearance

Few outcrops of poor quality of the Colston granite occur along the Rooidam farm in Upington. The granite is dark grey in colour and has medium grain size texture. The Colston Granite has few mafic xenoliths and feldsphathic phenocrysts inclusions (Fig. 3.23). Mineralogically it contains an abundance of biotite and some quartz grains. The granite does not have any joints or veins in it.

Figure 3.23. Colston granite with some mafic xenoliths. Pen = 15 cm long

8. Keboes Granite

Field appearance

The outcrop is well exposed in the Kanon Eiland area and it is an intrusive to the Bethesda Formation, Sout Rivier Formation and to the Louisvale Granite. The contacts with the above mentioned formations are not well exposed as they are all weathered. The granite also occurs as large oval shaped boulders. It shows a light grey appearance with few mafic inclusions and small round feldsphathic phenocrysts. Mineralogically the granite is rich in biotite and feldspars.

Figure 3.24. Feldspathic veins on the Keboes Granite.

Description of structural features

Structurally the Keboes Granite contains joints, some of which are filled with large crystals of quartz and feldspar. The quartz veins are displaced by the 086°-266°NE-SW trending joint sets. Conjugate joint sets were also noticed on the outcrop and they are orientated in the 303°-123˚ NW-SE and 064°- 247° NE-SW, directions. Figure 3.25b shows a conjugate joint set, where normally σ_1 bisects the acute angle. These joints showed mutual displacement to each other across the Keboes outcrop. However, there were joints that were randomly orientated and they terminated against the major joint systems. This implies that they formed later than the major joints, thus postdating the major joint system. The granite is not foliated and no mineral lineations were recorded. The veins are filled with large quartz crystals and some with both quartz and feldspars. The minerals filling the veins are perpendicular to the contact and these joints can thus be described as extension joints. The veins range from 4.5 to 15 cm in width and some are over a metre apart.

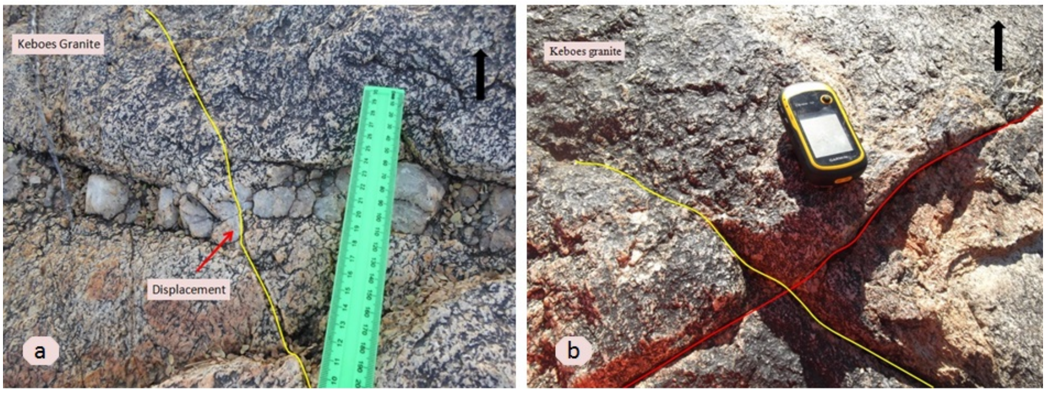
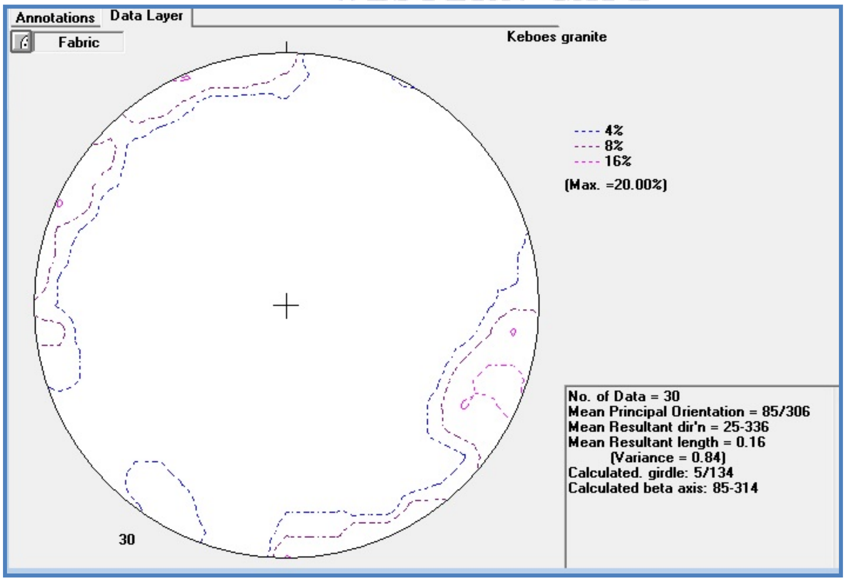


Figure 3.25. a) Joint displacing quartz vein in the Keboes Granite. Ruler = 30 cm long. b) Conjugate joints set of the Keboes granite. GPS = 10 cm long

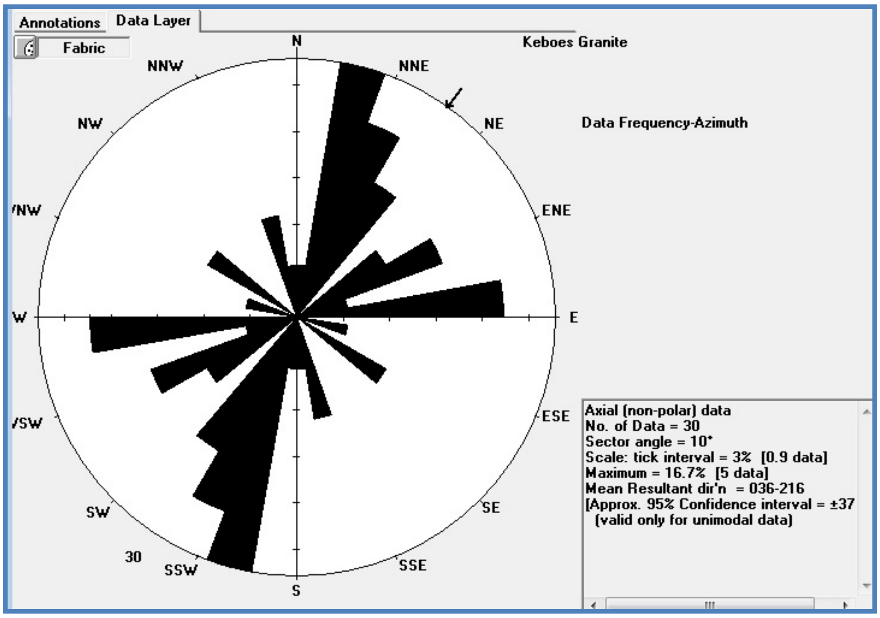
Joints analysis

The stereo plot shows upright joints, trending approximately 45 degrees and about 80 degrees (Fig3.26). The rose diagram supports this and shows two prominent joint sets in the Keboes granite (Fig3.27). The main joint system strikes 014°-194°NNE-SSW and 085°-265°E-W direction. However there are also less prominent joints present in the granite and these are oriented, 064°- 247° ENE-WSW, 303°-125°NW-SE and 345°-164°NNW-SSE directions respectively.



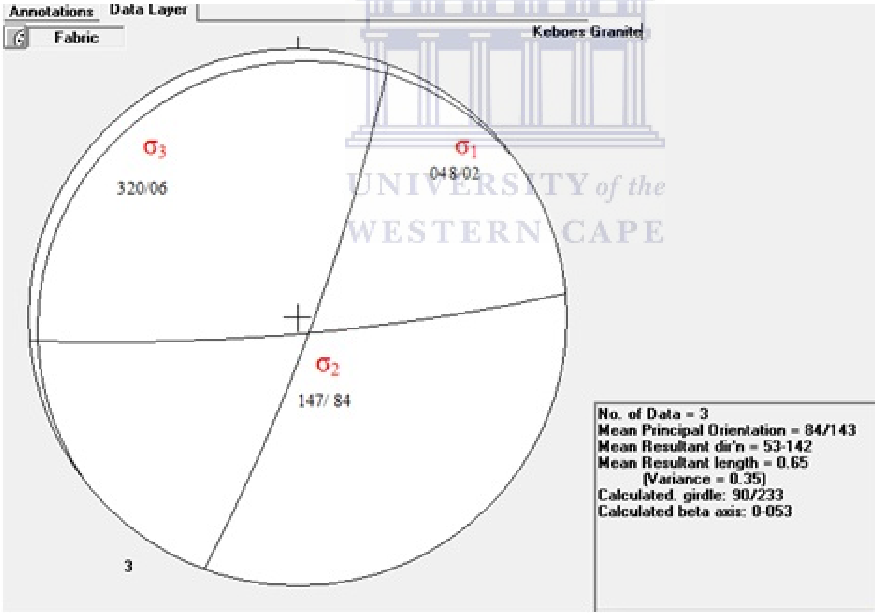
```
No. of Data = 30
Mean Principal Orientation = 85/306
Mean Resultant dir'n = 25-336
Mean Resultant length = 0.16
     (Variance = 0.84)
Calculated. girdle: 5/134
Calculated beta axis: 85-314
```

Figure 3.26. Contour diagram showing data distribution of poles to joints of the Keboes Granite.



Axial (non-polar) data
No. of Data = 30
Sector angle = 10°
Scale: tick interval = 3% [0.9 data]
Maximum = 16.7% [5 data]
Mean Resultant dir'n = 036-216
[Approx. 95% Confidence interval = ±37
(valid only for unimodal data)

Figure 3.27. Rose diagram showing frequency distribution of the strike of joints in Keboes Granite.



No. of Data = 3
Mean Principal Orientation = 84/143
Mean Resultant dir'n = 53-142
Mean Resultant length = 0.65
(Variance = 0.35)
Calculated. girdle: 90/233
Calculated beta axis: 0-053

Figure 3.28. Principal stress orientation derived from conjugate joints of the Keboes Granite.

The orientation of σ 1 is 048/02 as the acute bisectrix, σ 2 as the intersection of the two joint planes is 147/84 and σ 3 as the obtuse bisectrix is at 320/06 (Fig. 3.28).

9. Louisvale Granite

Field appearance

Good exposures of the Granite dominate in the Louisvale area, whereby some outcrops occur inside the yards of villagers .The granite encountered on the outcrop is light grey in colour caused by the abundance of feldspars. The granite is leucocratic with fine to medium sized grains which are randomly orientated. The Louisvale Granite is moderately foliated and the foliation in the granite is defined by the poor alignment of biotite and feldspar minerals.

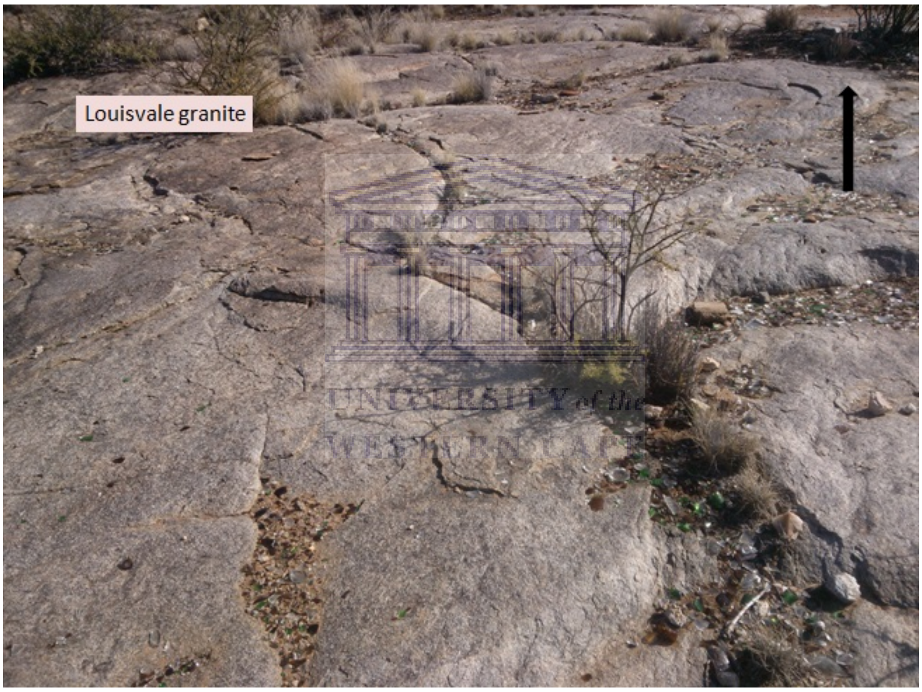


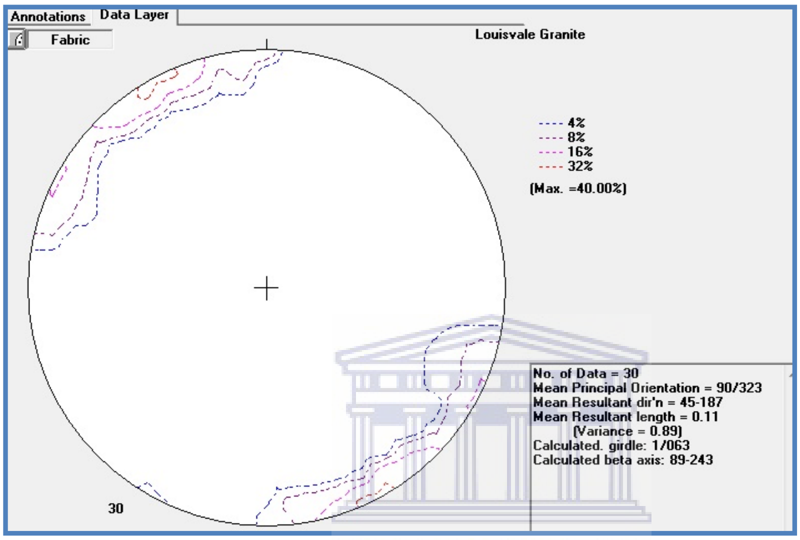
Figure 3.29. Louisvale Granite. The size of the plant is 15 cm high.

Description of structural features

The outcrop has feldspar-rich veins trending in random directions. There is no cross-cutting relationship identified between the joints and the veins. There were also step-over joints on the outcrop approximately 15 cm apart trending in the NE-SW direction.

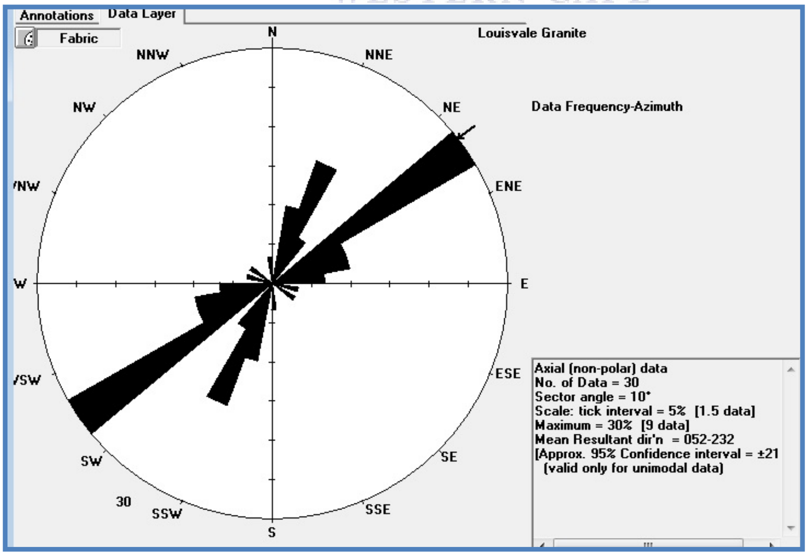
Joint analysis

Joints data of the Louisvale Granite were plotted on a contour diagram (Fig. 3.30). The rose diagram displays the direction of strike corresponding to these clusters presented in the contour diagram. The rose diagram shows that only two sets of joints exist in the Louisvale granite. Of these the main direction is at 055-235 NE-SW and the last one is more closely to the north south direction at 024-205 NNE-SSW (Fig. 3.31).



```
No. of Data = 30
Mean Principal Orientation = 90/323
Mean Resultant dir'n = 45-187
Mean Resultant length = 0.11
        (Variance = 0.89)
Calculated. girdle: 1/063
Calculated beta axis: 89-243
```

Figure 3.30.Contour diagram of pole to joints in the Louisvale Granite.



```
Axial (non-polar) data
No. of Data = 30
Sector angle = 10°
Scale: tick interval = 5%  [1.5 data]
Maximum = 30%  [9 data]
Mean Resultant dir'n  = 052-232
[Approx. 95% Confidence interval = ±21
  (valid only for unimodal data)
```

Figure 3.31. Rose diagram showing strike orientation of joints in the Louisvale Granite joints.

10. Vaalputs Granite

Field appearance

The Vaalputs Granite like the Friersdale Charnockite is widely distributed across the Upington, Kakamas and Keimoes areas. It is well exposed across the study area as large extensive outcrops and large boulders. This granite is an intrusive to the Goede Hoop, Punsit and Sout Rivier Formations (Moen 2007). The granite is light grey in appearance and is medium grained. It is well-foliated with biotite and feldspar minerals showing alignment. Mineralogically it is constituted of biotite, quartz and feldspars. Some of the joints are very wide and filled with large quartz grains (Fig. 3.32b). The red arrow indicates a new developing fracture on the Vaalputs Granite.

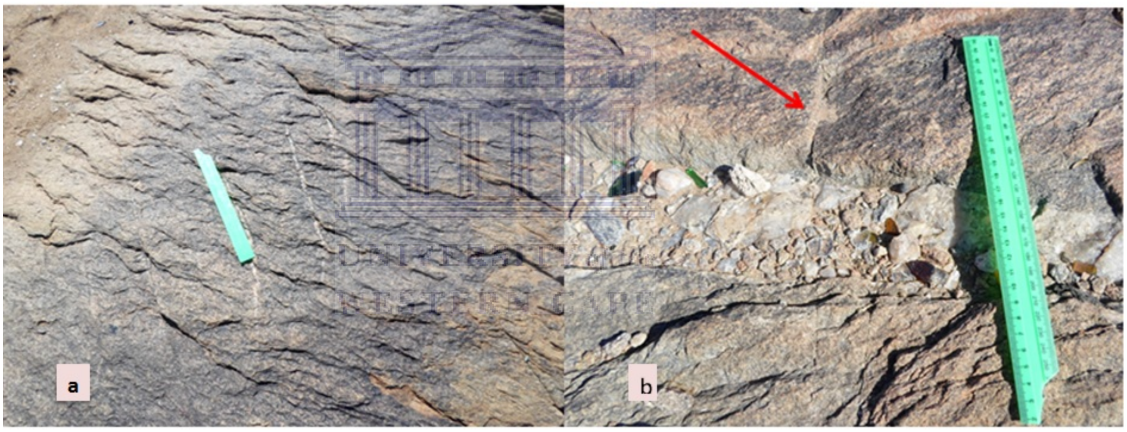


Figure 3.32. a) Sigmodial tension gash array of quartz vein b) Joint filled with blocky quartz in the Vaalputs Granite. Ruler = 3- cm long.

Description of structural features

The granite has well developed joints, the main trend of joints is in the 335-155 NW-SE direction and the less prominent is in the 235˚-054˚ NE-SW direction. The granite contains veins that are up to 15-20 cm apart, filled with quartz, and sub-parallel to each other. The quartz veins tend to thin out in the N-S direction and they show dextral rotation (Fig. 3.33). The spacing between the quartz veins increases towards the southwest.

Figure 3.33 Quartz veins showing dextral rotation. Pen = 15 cm long.

A set of conjugate joints were identified in the granite (Fig. 3.34). During field observation mutual displacement was recognized confirming these joints as a conjugate set, allowing the determination of the principal stresses (Fig. 3.37) where the principal stress σ_1 bisects the acute angle between the joints. Quartz mobilisation approximately half a metre thick is found on some Vaalputs Granite outcrops. The granite is well foliated and the foliation is mainly defined by the alignment of biotite and feldspars and is oriented in the NW-SE direction (Fig. 3.34).

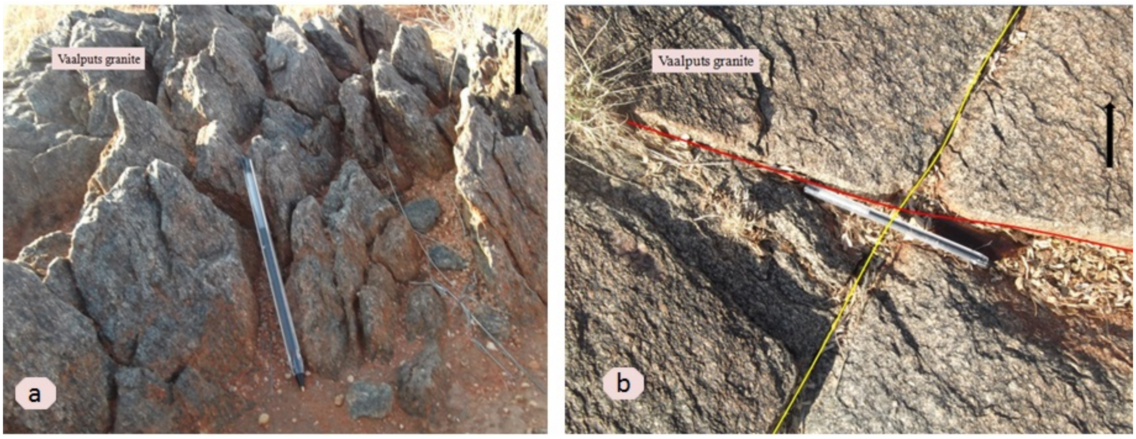
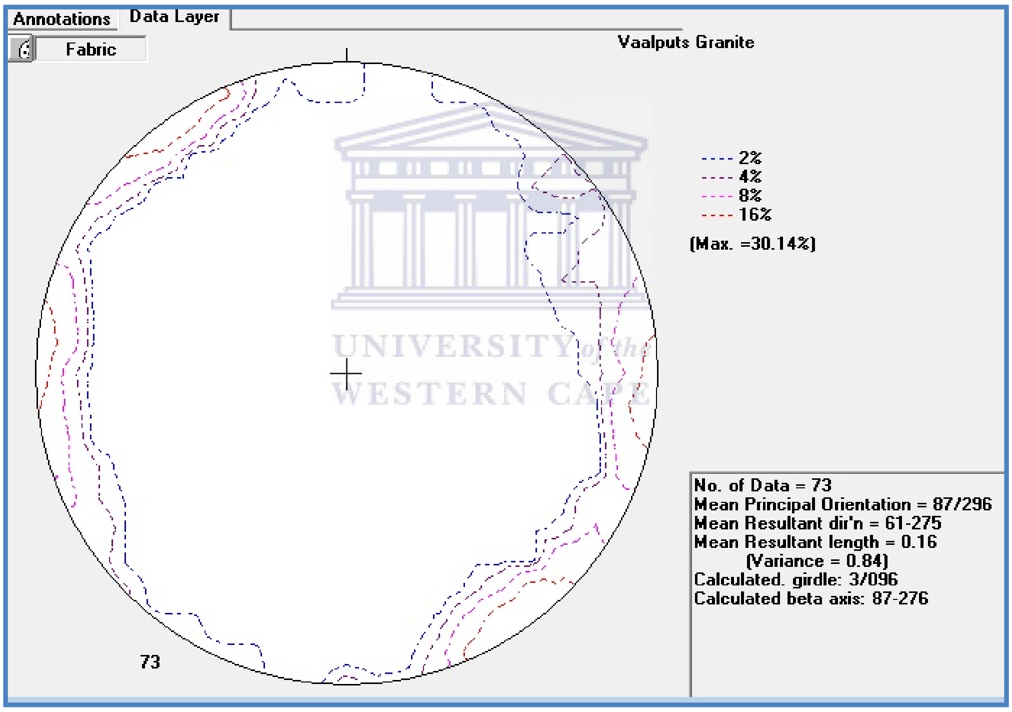


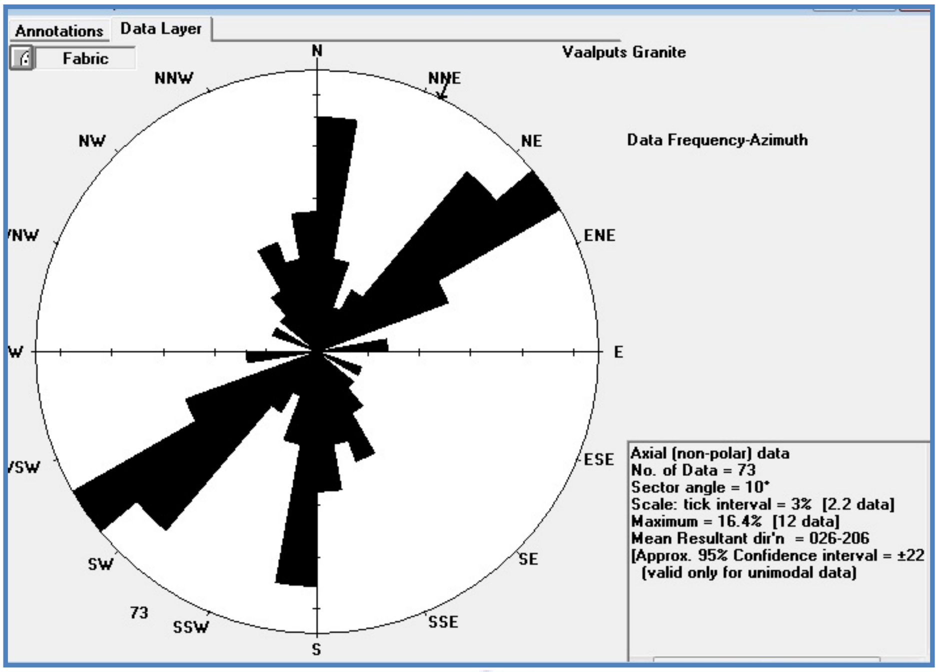
Figure 3.34. a) Foliated Vaalputs Granite b) conjugate joints of Vaalputs Granite. Pen = 15 cm long

The contour diagram of poles to joints of the Vaalputs Granite's joints does not show any distinct clusters. There are however two prominent directions defining the principal orientation of the data (Fig. 3.35). The rose diagram reveals two main directions in the 185˚-005˚ NNE-SSW and 235˚-055˚ NE-SW (Fig. 3.36) which is in agreement with what is being displayed by the contour diagram on the 16 % contours. However, there are joints that are oriented in the 335˚-155˚ NNW-SSE, 269˚-084˚ E-W direction. This might be later formed joints and are presented as outliers on the contour diagram. In the field they appear as non-persistent joints displacing the main joints.



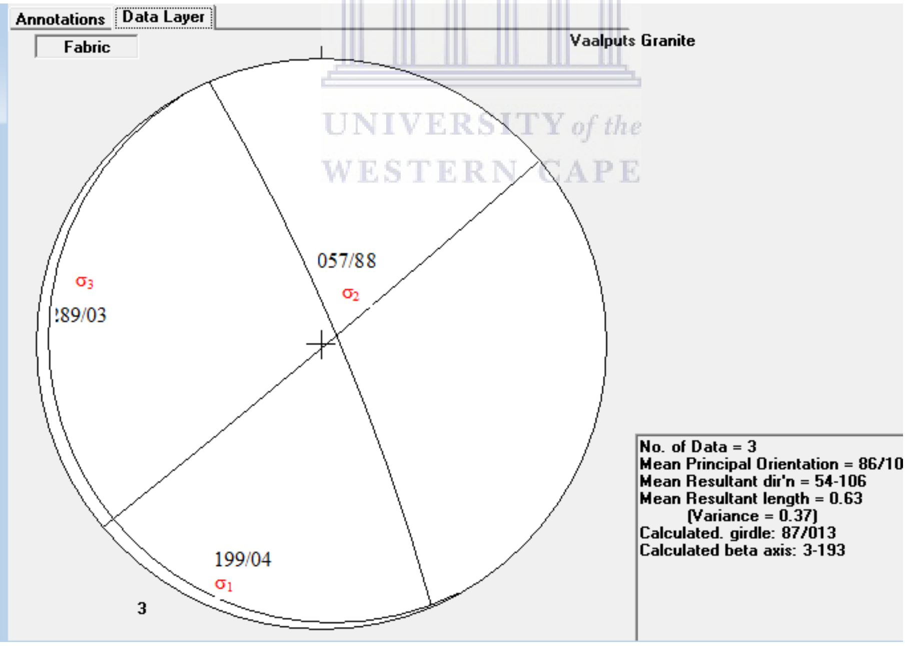
No. of Data = 73
Mean Principal Orientation = 87/296
Mean Resultant dir'n = 61-275
Mean Resultant length = 0.16
(Variance = 0.84)
Calculated. girdle: 3/096
Calculated beta axis: 87-276

Figure 3.35. Contour diagram of poles to joints of the Vaalputs Granite.



Axial (non-polar) data
No. of Data = 73
Sector angle = 10°
Scale: tick interval = 3% [2.2 data]
Maximum = 16.4% [12 data]
Mean Resultant dir'n = 026-206
[Approx. 95% Confidence interval = ±22
(valid only for unimodal data)

Figure 3.36. Rose diagram showing principal orientation of strike of joints of the Vaalputs Granite.



No. of Data = 3
Mean Principal Orientation = 86/10
Mean Resultant dir'n = 54-106
Mean Resultant length = 0.63
(Variance = 0.37)
Calculated. girdle: 87/013
Calculated beta axis: 3-193

Figure 3.37. Diagram showing principal stresses derived from the joints in the Vaalputs Granite.

Orientation of σ_1 is 199/04 and the intermediate principal stress σ 2 is 057/88 and lastly the minimum principal stress is 289/03 (Fig 3.37).

11. Gemsbokbult Granite

Field appearance

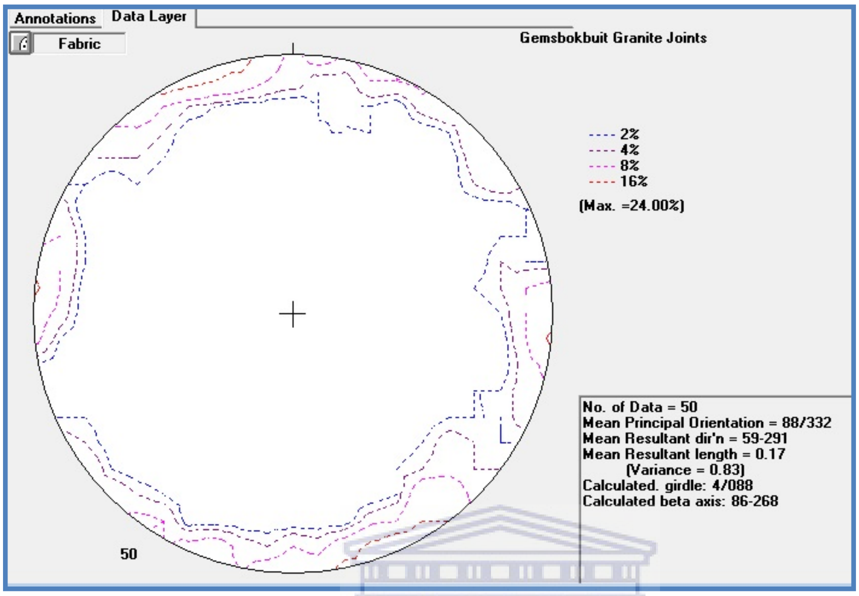
The granite appears as small bands that outcrop from the ground and continues over several farms. (Fig. 3.38).The granite is weathered resulting in a foliated appearance. This may be due to the preferential weathering of feldspars as they weather easily when exposed to different temperature conditions. During chemical weathering feldspars tend to be broken down easily forming clays or sand. The presence of mafic minerals such hornblende and amphibole causes the dark coloured appearance of the granite despite the presence of feldspathic phenocrysts.

Structural description

The Gemsbokbult Granite does not have any veins but it has significant joints.

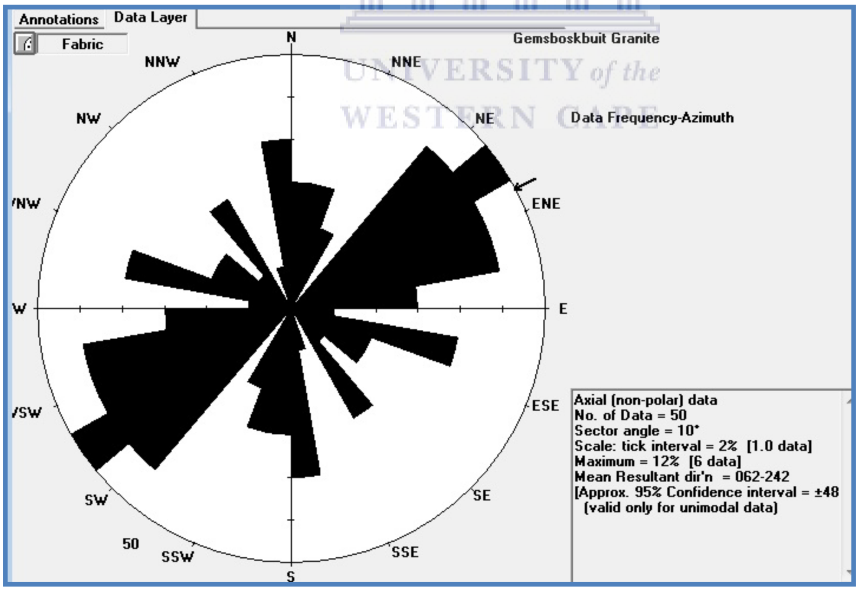
Figure 3.38. Weathered Gemsbokbult Granite. Rule = 30 cm long

The orientation diagram shows two prominent directions NNW-SSE and NE-SW (Fig. 3.39) and two minor directions NW-SE and WNW-ESE respectively. Likewise, the rose diagram of the Gemsbokbult granite shows four joint sets. The main joint set strikes in 055˚-235˚ NE-SW, 355˚-175˚NNW-SSE and the less prominent strikes at 286˚-106˚ WNW-ESE, 325˚-145˚NW-SE, and NNW-SSE, (Fig. 3.40). The Gemsbokbult Granite is not foliated although it may appear so, this foliated appearance maybe caused by differential weathering.



```
No. of Data = 50
Mean Principal Orientation = 88/332
Mean Resultant dir'n = 59-291
Mean Resultant length = 0.17
        (Variance = 0.83)
Calculated. girdle: 4/088
Calculated beta axis: 86-268
```

Figure. 3.39. Contour diagram-showing distribution poles to joints of Gemsbokbult Granite.



```
Axial (non-polar) data
No. of Data = 50
Sector angle = 10°
Scale: tick interval = 2%  [1.0 data]
Maximum = 12%  [6 data]
Mean Resultant dir'n  = 062-242
[Approx. 95% Confidence interval = ±48
  (valid only for unimodal data)
```

Figure 3.40. Rose diagram of strike trends of the Gemsbokbult Granite joints.

3.2.2. Section B: Country rocks

1. Goede Hoop Formation

Field appearance

The Goede Hoop Formation is yellowish brown in appearance. On a fresh surface, it is a fine-grained light-coloured micaceous quartzitic rock. Along the Boven Rugzeer Shear Zone station the rock changes to almost white in colour and becomes pure quartzite and then it changed back to its original colour again; this is only visible across the shear zone and is also the case at the Neusspruit Shear Zone where the formation also appears as a micaceous quartzite. The calc-silicate rocks of the Goede Hoop Formation in the Kakamas area are well foliated and the foliation is parallel to the bedding. The foliated bed planes are heavily jointed.

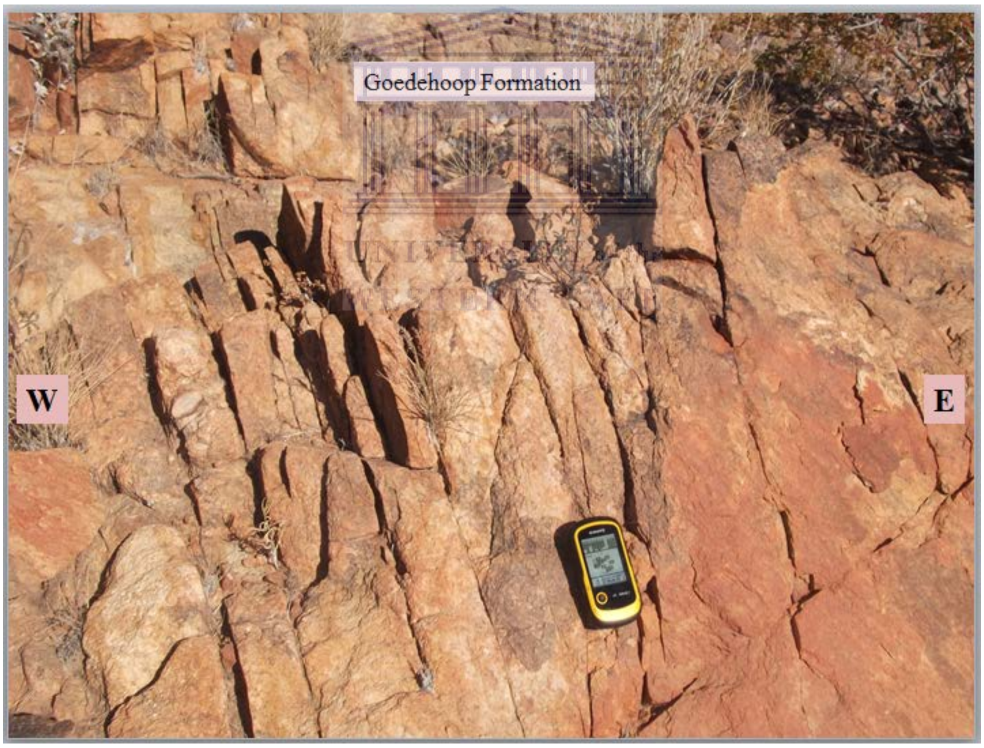


Figure 3.41. Jointed Goede Hoop Formation. GPS = 10 cm long

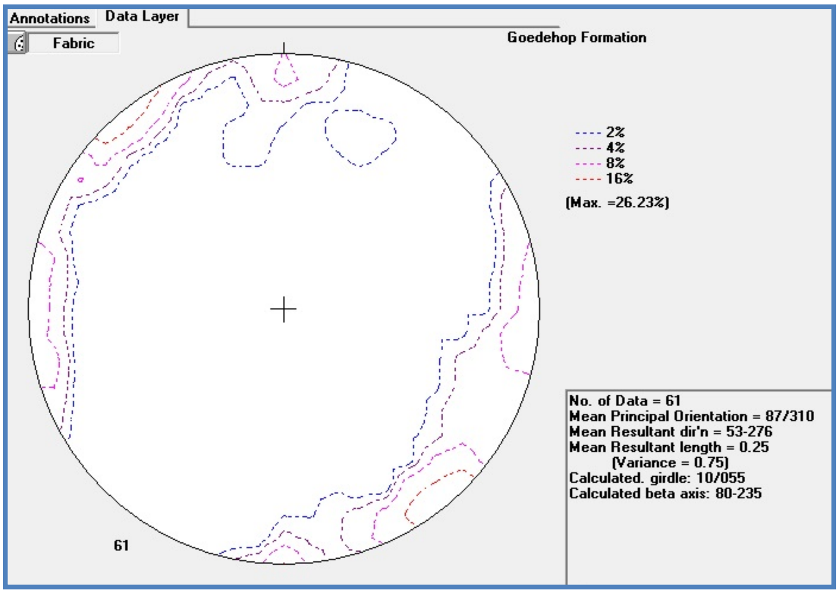
Structural description

Different sets of conjugate joints were recognised (Fig 3.42). Three joint sets exist in the Goede Hoop Formation and they are oriented in the NE-SW, NW-SE and N-S directions. The micaceous quartzite of the Goede Hoop Formation has large quartz veins broken up into boudins with the long axis in the north south direction. The quartzitic rock contains variable feldspar content. The rock appears well foliated due to the presence of mica. The formation overlies the Punsit Formation and is intruded by the Vaalputs Granite and the Friersdale Charnockite.

Figure 3.42. A set of conjugate joints of the Goede Hoop Formation displacing each other. GPS = 10 cm long.

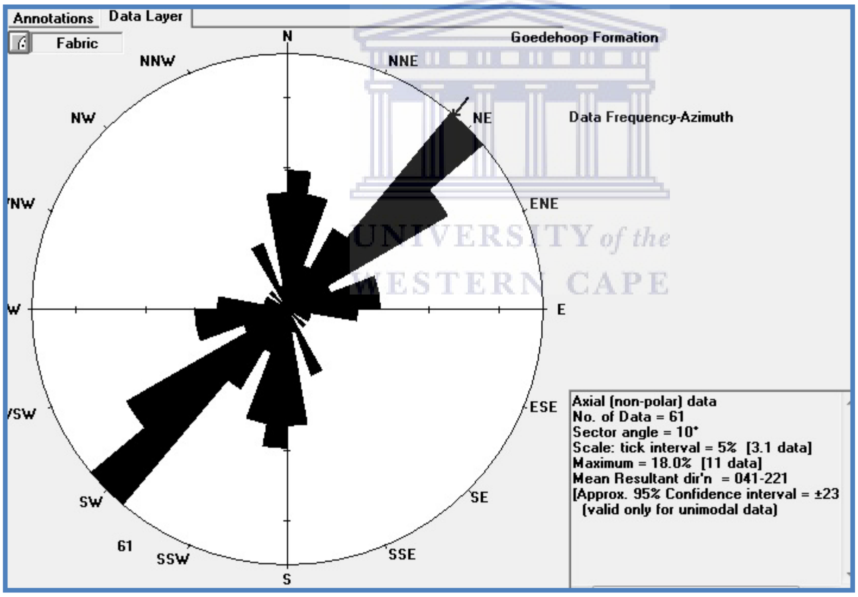
Joints analysis

The contour diagram in figure 3.43 shows distribution of poles to joints in the Goede Hoop Formation. The 16% line shows the maximum concentrations of values. The rose diagram in figure 3.44 shows the principal trend of the joints in the Goede Hoop Formation. The main principal orientation is in the NE-SW 045˚-225˚direction. Second joint set is oriented in the N-S 005˚-185˚ direction and lastly the less prominent joints are in the E-W 079˚-259˚ and NNW-SSE 155˚-335˚ direction (Fig. 3.44).



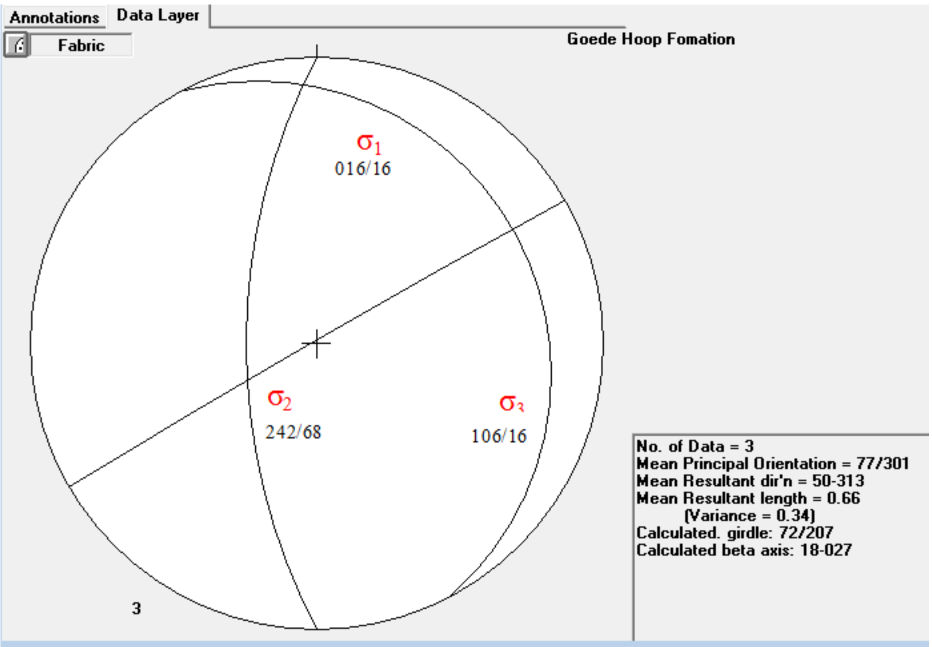
No. of Data = 61
Mean Principal Orientation = 87/310
Mean Resultant dir'n = 53-276
Mean Resultant length = 0.25
(Variance = 0.75)
Calculated. girdle: 10/055
Calculated beta axis: 80-235

Figure 4.43. Poles to joints data of the Goede Hoop Formation displayed in a contour diagram.



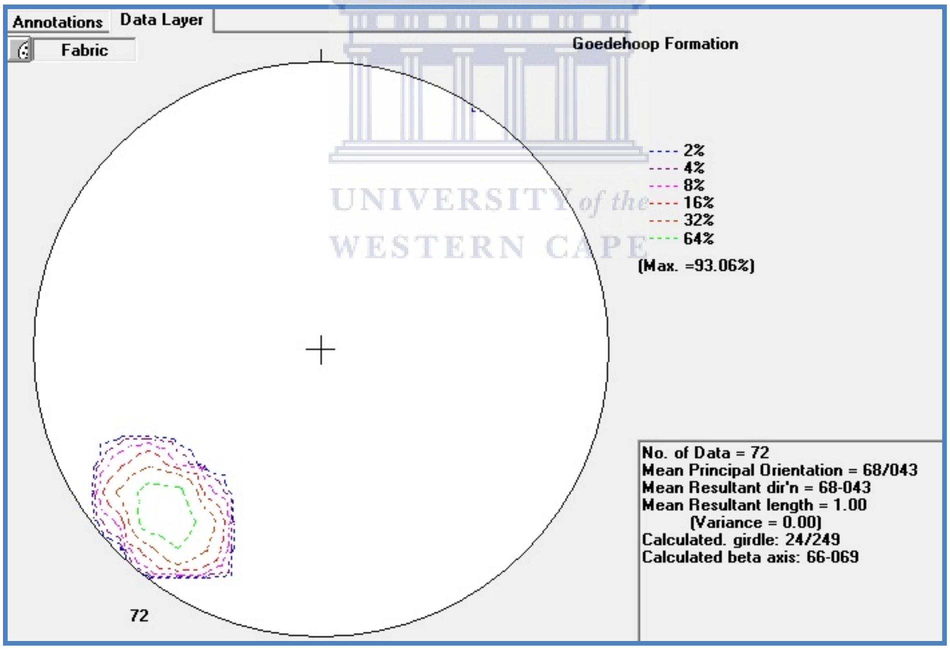
Axial (non-polar) data
No. of Data = 61
Sector angle = 10°
Scale: tick interval = 5% [3.1 data]
Maximum = 18.0% [11 data]
Mean Resultant dir'n = 041-221
[Approx. 95% Confidence interval = ±23
(valid only for unimodal data)

Figure 3.44. Rose diagram showing joint orientation of the Goede Hoop Formation.



No. of Data = 3
Mean Principal Orientation = 77/301
Mean Resultant dir'n = 50-313
Mean Resultant length = 0.66
(Variance = 0.34)
Calculated. girdle: 72/207
Calculated beta axis: 18-027

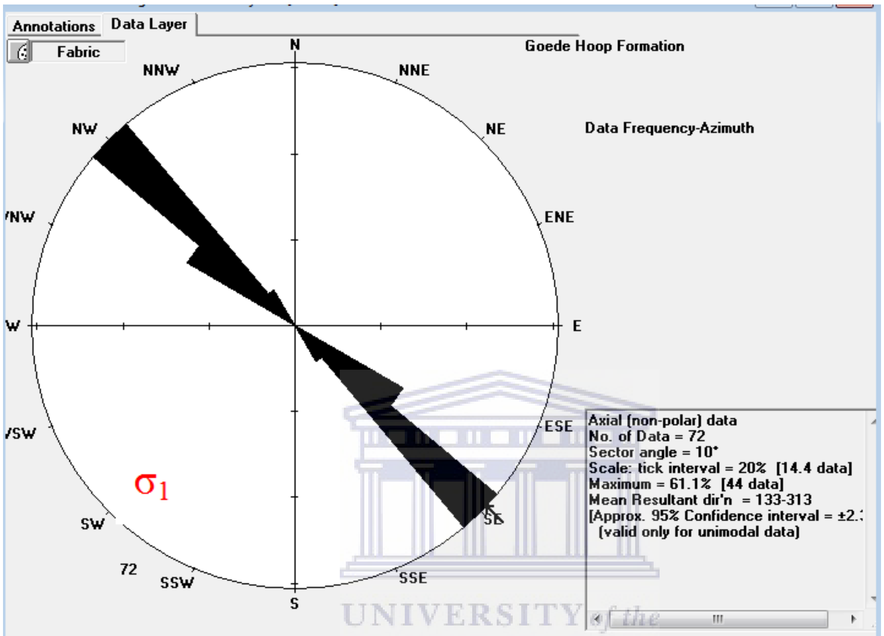
Figure 3.45 principal stress orientations of Goede Hoop Formation conjugate joints.



No. of Data = 72
Mean Principal Orientation = 68/043
Mean Resultant dir'n = 68-043
Mean Resultant length = 1.00
(Variance = 0.00)
Calculated. girdle: 24/249
Calculated beta axis: 66-069

Figure 3.46. Foliation contour diagram of the Goede Hoop Formation.

The principal analysis of joints in the Goede Hoop Formation gives a maximum principal stress of 016/16 and intermediate principal stress as 242/68 and the minimum principal stress as 1106/16 (Fig. 3.45).The contour diagram shows one cluster of foliations (Fig. 3.46). The mean principal orientation is 043/68 (dip/direction of dip) which is also the mean resultant direction. This means the foliation is oriented in one direction and the rose diagram proves this as it displays the orientation of the foliation as striking in the NW-SE 315˚-135˚ direction (Fig. 3.47). The maximum stress orientation responsible for the formation of this axial planar foliation for the Goede Hoop Formation is 225/15.



Axial (non-polar) data
No. of Data = 72
Sector angle = 10°
Scale: tick interval = 20% [14.4 data]
Maximum = 61.1% [44 data]
Mean Resultant dir'n = 133-313
[Approx. 95% Confidence interval = ±2.
(valid only for unimodal data)

Figure 3.47. Foliation rose diagram of the Goede Hoop Formation in the Neusspruit shear and the Boven Rugzeer Shear Zones.

2. Punsit Formation

Field appearance

The Punsit Formation comprises of a fine-grained quartzitic rock which grades into brown gneiss (Fig. 3.48). It appears as a light weathered calc-silicate rock with thin layers of marble and amphibolites. It consists of epidote, quartz, feldspar, opaque minerals, lenses of marble and in places skarn and wollastonite have been reported. The Punsit Formation is overlain by the micaceous quartzite of the Goede Hoop Formation.

Figure 3.48. (a) The calc-silicate rocks of the Puntsit Formation along the Keimoes road cutting, ruler = 30 cm long (b) Calc-silicate rock of the Puntsit Formation at the vicinity of the Cnydas shear zone. GPS = 10 cm long.

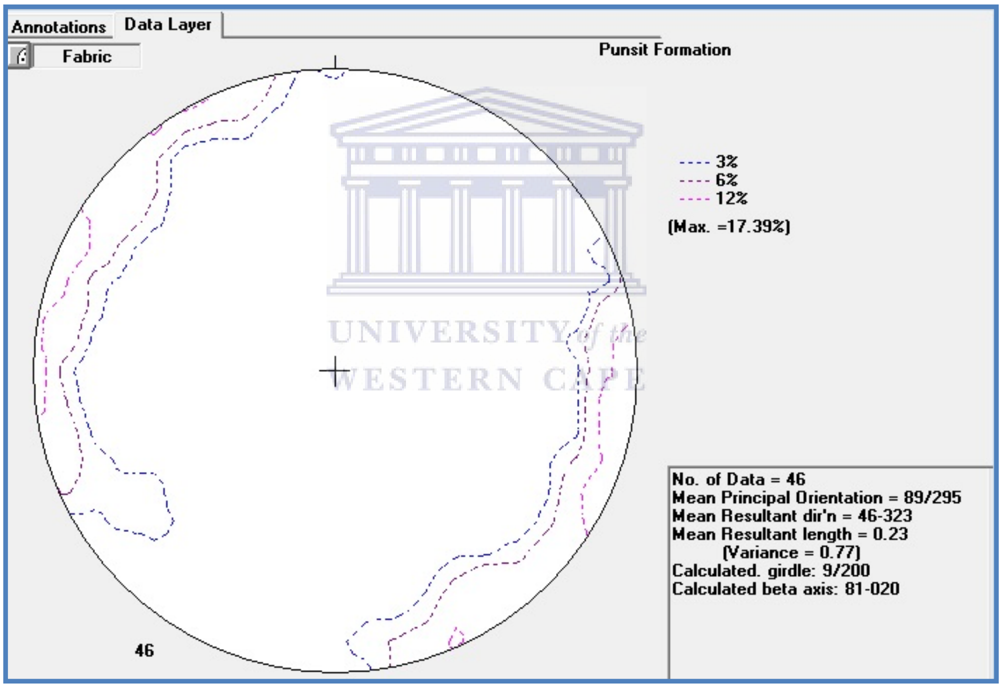
Structural description

The rock has joints that have similar orientations as those in the Goede Hoop Formation. The Punsit Formation in the vicinity of the Cnydas shear zone is strongly sheared. The calc-silicate and quartzite are folded and sheared (Fig. 3.49). The quartzitic calc-silicate of the Puntsit Formation is deformed showing folding with wollastonite in between. Moen (2007) also observed wollastonite rich limestone with calc-silicate layers showing intricate deformation patterns, which is similar to what was observed during field mapping.

Figure 3.49. Sheared Puntsit Formation. GPS = 10 cm long.

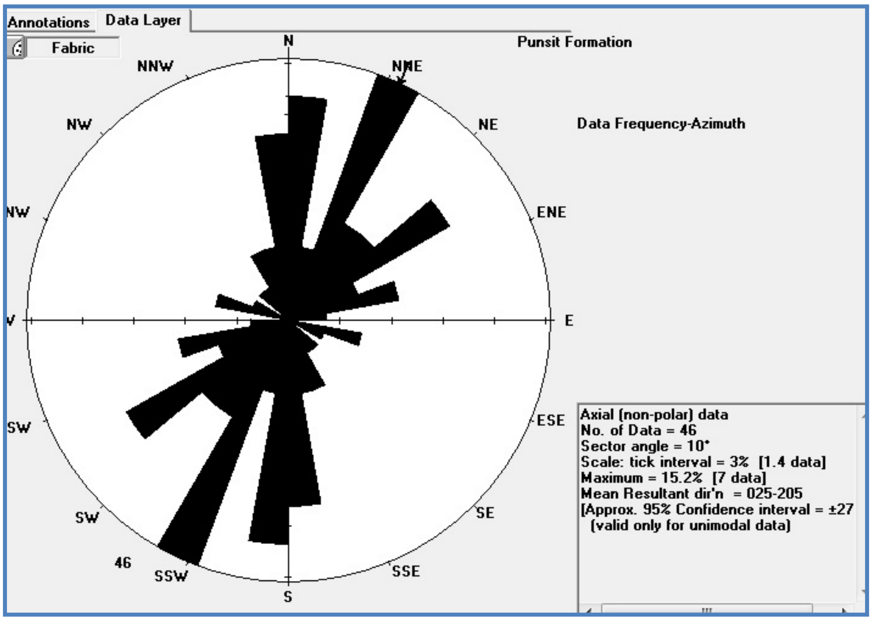
Joint analysis

The contour diagram of poles to joints in the Puntsit Formation shows pronounced concentrations in the WNW-ESE areas of the diagram, implying a joint orientation that NNE - SSW (Fig. 3.50). However the main orientations are not that clear to easily identify them on the contoured diagram. Meanwhile the rose diagram displays the joint orientation clearly. Three pronounced directions are revealed by the rose diagram (Fig. 3.51) the main directions are oriented at 025˚-205˚ NNE-SSW, 004˚-174˚N-S, 235˚-055˚NE-SW, and the least frequently occurring joints are trending at 104˚-284˚E-W (Fig. 3.51).



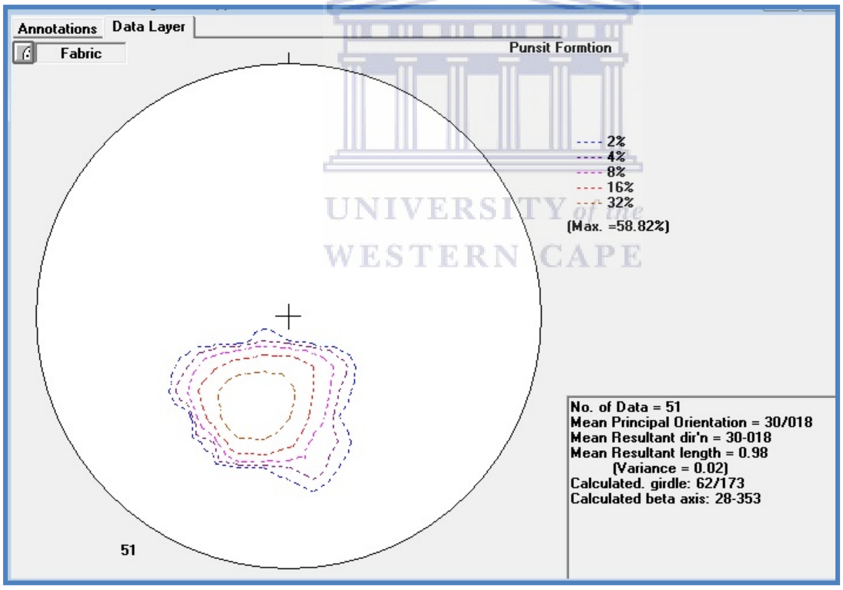
```
No. of Data = 46
Mean Principal Orientation = 89/295
Mean Resultant dir'n = 46-323
Mean Resultant length = 0.23
      (Variance = 0.77)
Calculated. girdle: 9/200
Calculated beta axis: 81-020
```

Figure 3.50. Contour diagram of poles to joints in the Puntsit Formation.



Axial (non-polar) data
No. of Data = 46
Sector angle = 10°
Scale: tick interval = 3% [1.4 data]
Maximum = 15.2% [7 data]
Mean Resultant dir'n = 025-205
[Approx. 95% Confidence interval = ±27
(valid only for unimodal data)

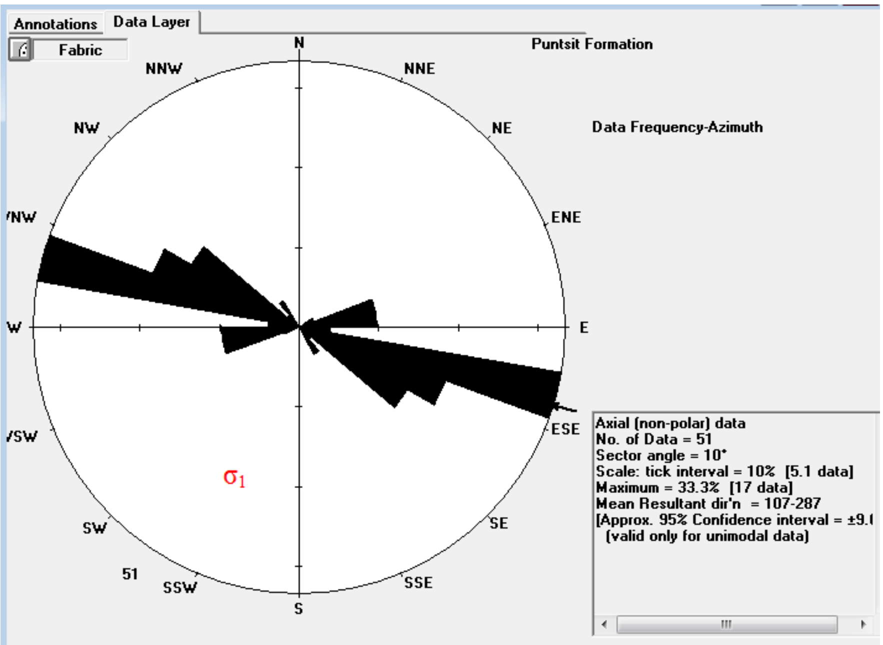
Figure 3.51-.Principal joint trends of Puntsit Formation.



No. of Data = 51
Mean Principal Orientation = 30/018
Mean Resultant dir'n = 30-018
Mean Resultant length = 0.98
(Variance = 0.02)
Calculated. girdle: 62/173
Calculated beta axis: 28-353

Figure 3.52. Foliation of the Puntsit Formation.

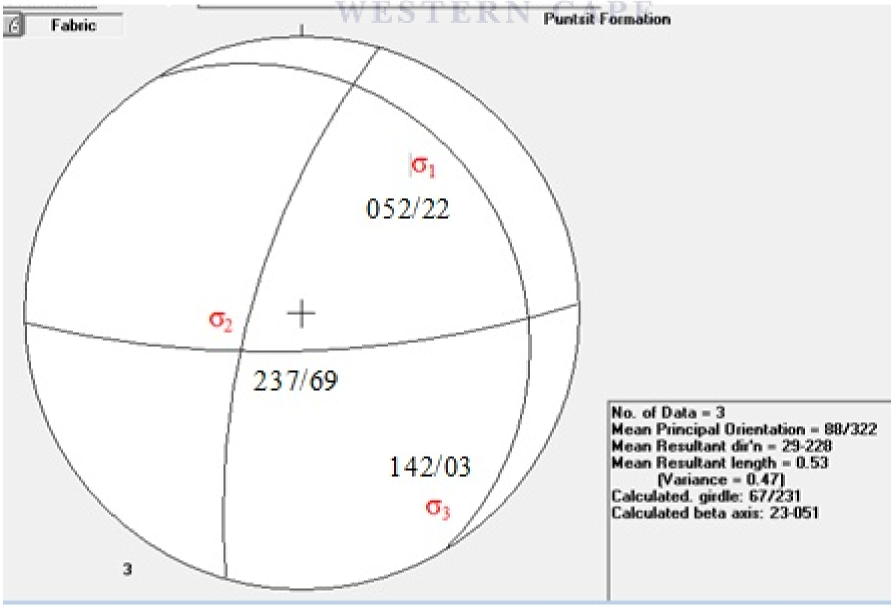
The pi-diagram for foliations in the Puntsit Formation shows one cluster (Fig. 3.52). The mean principal orientation is 018/30 (dip/direction of dip) and is the same as the mean resultant direction. The main foliation strikes in the WNW-ESE direction although there is a deviation from the main foliation. The deviation strikes in the E-W direction which could be caused by small folds in the Puntsit Formation (Fig. 3.53). Their mean resultant direction is 140-320.



Axial (non-polar) data
No. of Data = 51
Sector angle = 10°
Scale: tick interval = 10% [5.1 data]
Maximum = 33.3% [17 data]
Mean Resultant dir'n = 107-287
[Approx. 95% Confidence interval = ±9.
  (valid only for unimodal data)

Figure 4.53 Foliation trend of the Puntsit Formation.

The rose diagram above (Fig. 3.53) shows one prominent joint set. The main principal orientation is on the 315˚-109˚ WNW-ESE direction. However there are few data points which plot in the 266˚-086˚ENE-WSW direction. The axial planar foliation has a principal stress of 200/45 (Fig. 3.54).



No. of Data = 3
Mean Principal Orientation = 88/322
Mean Resultant dir'n = 29-228
Mean Resultant length = 0.53
(Variance = 0.47)
Calculated. girdle: 67/231
Calculated beta axis: 23-051

Figure 3.54. Principal stress diagram derived from joints in the Puntsit Formation.

The principal stress diagram of the Punsit Formation shows mean principal orientation of 322/88 and mean resultant direction of 29-228 (Figure. 3.54). The maximum principal stress orientation σ_1 is 052/22, σ_2 is 237/69 and σ_3 is 142/03 (Fig. 3.54).

3. Sandput Formation

Field appearance

The Sandput Formation is a feldspathic quartzite with a variety of calc-silicate minerals. The formation consists of grey to brown weathered quartzitic rock. The rock is fine grained with epidote, feldspars and calc-silicate minerals and changes to pure calc-silicate rock because of the varying concentration of the calc-silicate minerals. This makes it difficult to separate it from the Puntsit Formation. Well-exposed rocks of the Sandput Formation are found in the Cnydas Shear Zone where this formation is intensely sheared and shows mylonitisation. The sheared rock forms small folds and mineral banding. The folded minerals are greenish and light grey in colour. A dark grey folded and banded rock (this is probably the Puntsit Formation) consists of marble and wollastonite. As the rock is highly metamorphosed it is impossible to recognise the original mineralogy except for the marble and wollastonite forming thin folded bands probably defined by original mineralogical variation (Fig. 3.55).

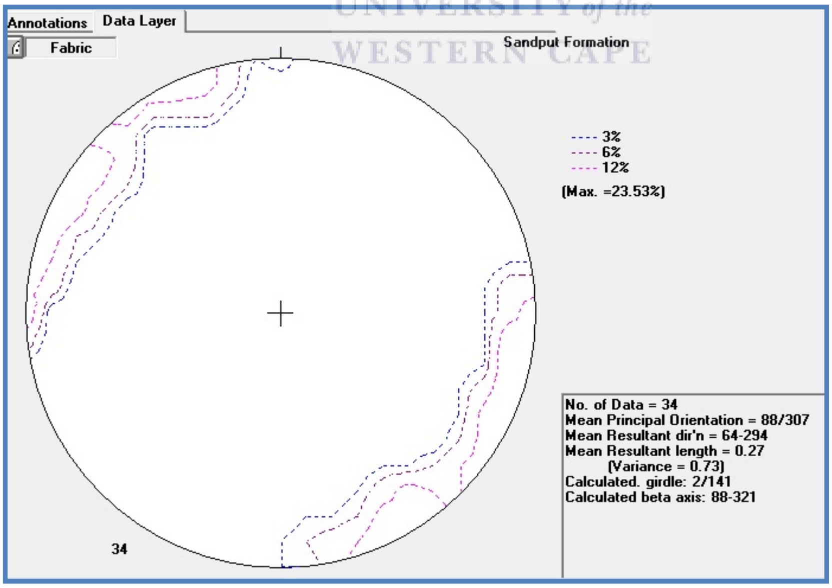
Figure 4.55. Sheared Sandput Formation at the Cnydas Shear Zone.

Description of structural features

Structurally the Sandput Formation has very thin veins on the sheared rock, and on the unsheared rock there are quartz veins. The Sandput Formation is foliated.

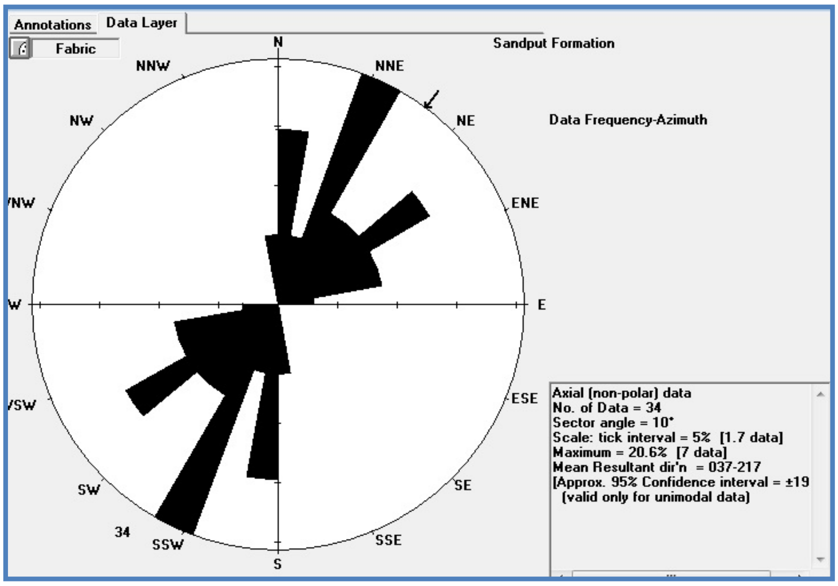
Joint analysis

Figure 56 show distribution of joint data of the Sandput Formation. Three joint sets are recognised in the Sandput Formation. The rose diagram (Fig. 3.57) shows the main orientation to be NNE- SSW 025˚- 206˚ followed by the ENE - WSW054˚-236˚ and the least prominent joint sets are oriented in the N-S 005˚-185˚ direction. The foliation contour shows one cluster (Fig. 3.58). The maximum foliation is oriented in the E-W direction, however there are foliations orientated in the NE-SW direction (Fig. 3.59). The maximum stress σ 1 has an attitude of 348/20.



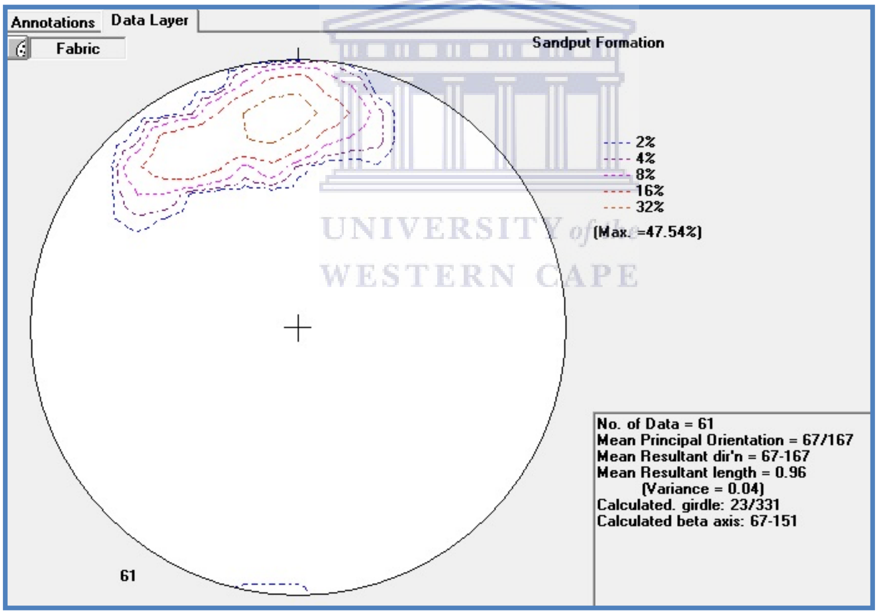
```
No. of Data = 34
Mean Principal Orientation = 88/307
Mean Resultant dir'n = 64-294
Mean Resultant length = 0.27
        (Variance = 0.73)
Calculated. girdle: 2/141
Calculated beta axis: 88-321
```

Figure 3.56. Contour diagram of poles to joints in the Sandput Formation



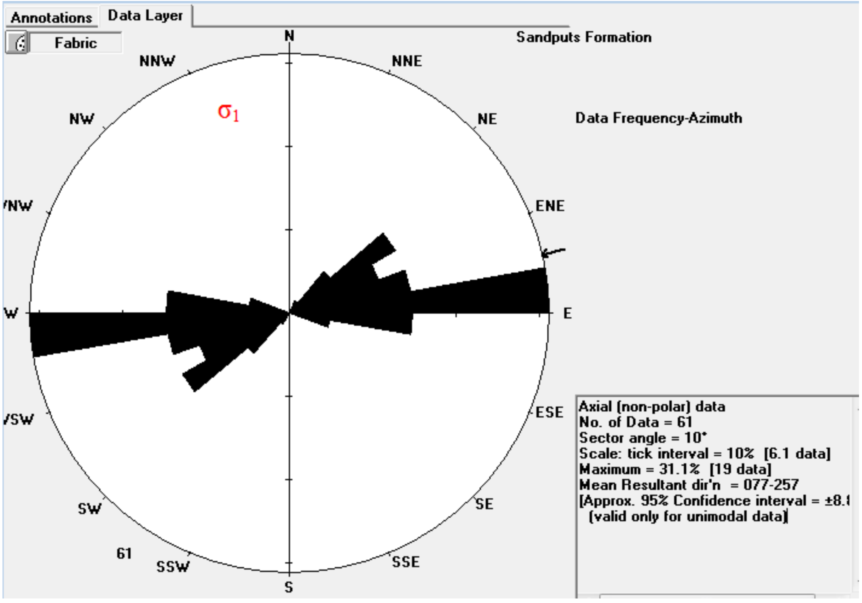
Axial (non-polar) data
No. of Data = 34
Sector angle = 10°
Scale: tick interval = 5% [1.7 data]
Maximum = 20.6% [7 data]
Mean Resultant dir'n = 037-217
[Approx. 95% Confidence interval = ±19
(valid only for unimodal data)

Figure 3.57. Strike orientation of joints in the Sandputs Formation.



No. of Data = 61
Mean Principal Orientation = 67/167
Mean Resultant dir'n = 67-167
Mean Resultant length = 0.96
(Variance = 0.04)
Calculated. girdle: 23/331
Calculated beta axis: 67-151

Figure 3.58. Contour diagram of poles to foliation in the Sandputs Formation.



```
Axial (non-polar) data
No. of Data = 61
Sector angle = 10°
Scale: tick interval = 10%  [6.1 data]
Maximum = 31.1%  [19 data]
Mean Resultant dir'n  = 077-257
[Approx. 95% Confidence interval = ±8.
  (valid only for unimodal data]
```

Figure 3.59 Rose diagram of principal trends of foliation in the Sandput.

4. Sout Rivier Formation

Field appearance

The Sout Rivier Formation is described as a paragneiss, which is a term generally used for describing gneisses derived from sedimentary rocks. Moen (2007) frequently used the term to describe metasedimentary rocks around Kakamas and to the south of Upington. During field observation the Sout Rivier Formation can be easily mistaken for a granite because of its appearance (Fig. 3.60) as it mirrors the appearance of some of the Keimoes Suite granites such as the Vaalputs granite. Therefore it is not easy to distinguish between the two as they both consist of similar mineralogy, mainly biotite and feldspars and are both foliated as well. Similar to what was observed during field mapping, Moen (2007) also concluded that the Sout Rivier Formation is of igneous origin. He concluded this on the basis that the rock lacks textural and mineralogical variation, however he also mentioned that under thin section mineralogical evidence clearly displays a sedimentary origin, which would make it a gneiss derived from a sedimentary rock.

The rock contains muscovite identified by its shiny appearance. The contact between the Vaalputs Granite and the Sout Rivier Formation has been observed as what seems to be a shear zone, defined by the presence of tension gashes on the Vaalputs Granite indicating the direction of sense of shearing. According to Moen (2007) the contact between the rocks is marked by a zone of sheared, light coloured, muscovite-bearing schist with granitic composition.

Description of structural features

On the contact zone between the Vaalputs granite and the Sout Rivier paragneiss large quartz and feldspar crystals have been observed. The quartz vein is boudinaged in the east-western direction indicating that extension was in the east-west direction and shortening was in the north-south direction. This implies that the stress field necessary to produce the vein was replaced by a different stress field perpendicular to the original stress field which caused the formation of the vein.

The paragneiss contains joints filled with reddish quartz crystals (Fig. 3.60). Step-over joints are found on this outcrop as well. The rocks of the Sout Rivier Formation are foliated which is mainly due to alignment of minerals such as biotite and feldspars. Thin quartz veins of 0.5- 1 cm width were observed to follow the foliation of the rock. Their orientation is 086-266 ENE-SWS and 053-233NE-SW. Conjugate joint set were also observed in the Sour Rivier Formation (Fig. 3.60).

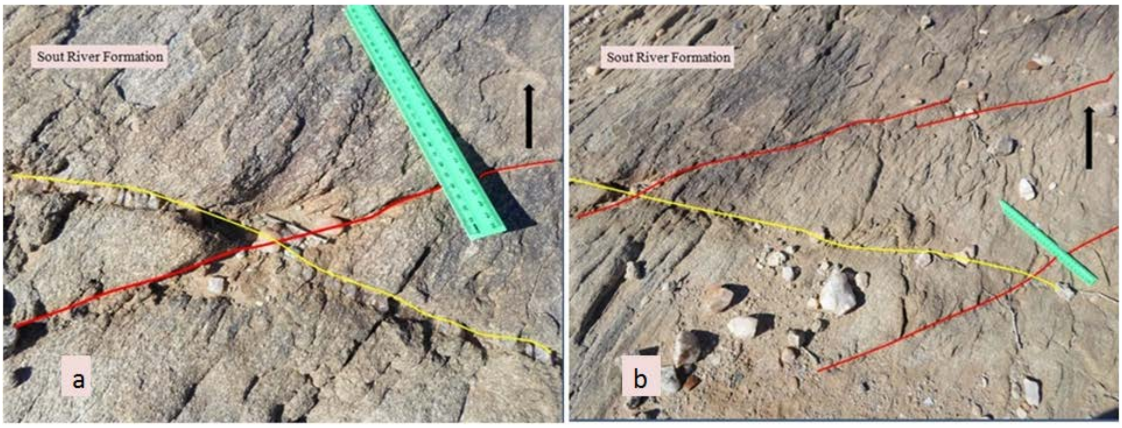
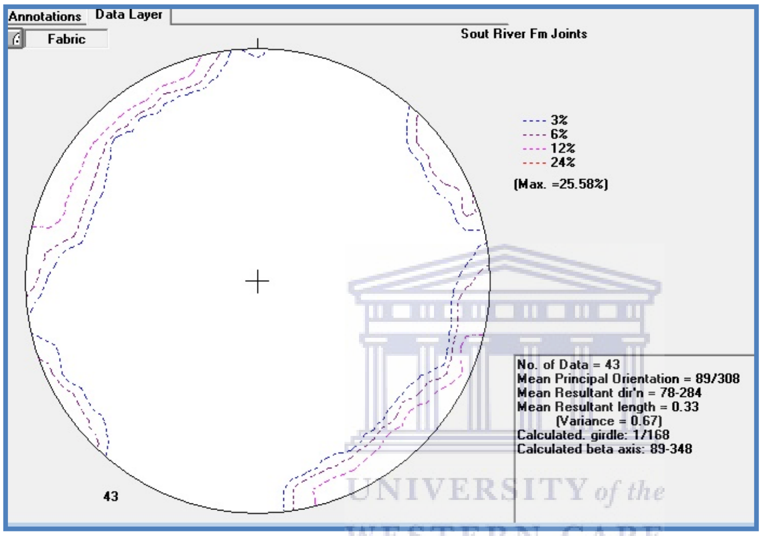


Figure 3.60 (a) Conjugate joint sets of the Sout Rivier Formation (b) Step over joints and conjugate joints. Ruler = 30 cm long.

Structural analysis

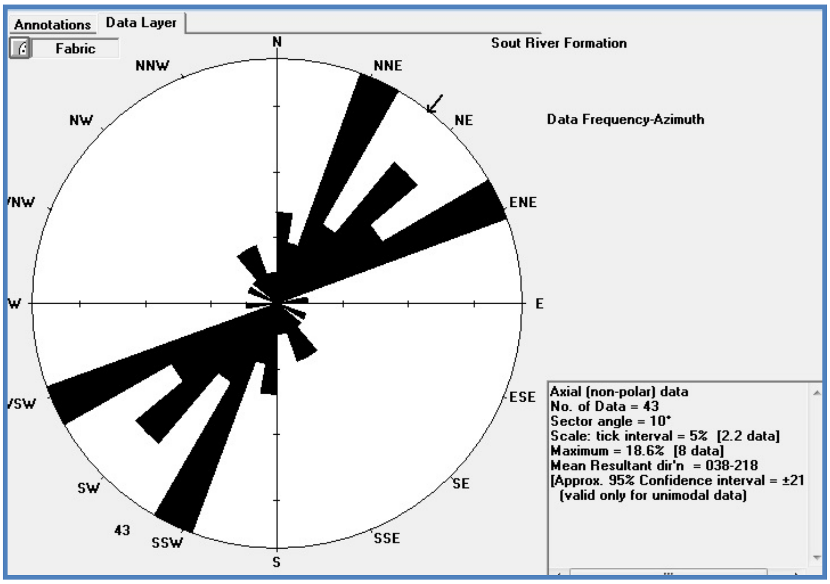
Joint analysis

The contour diagram of pole to joints (Fig. 3.61) show two prominent direction one in the ENE-WSW and the other direction is trending in the NW-SE. However the rose diagram shows three main joint sets and their orientation is 025˚-205˚ NNE-SSW, 076˚-256˚ENE-WSW and 056˚-236˚NE-SW (Fig. 3.62). The joints define a conjugate set because upon field observation they were displacing each other on several localities.



No. of Data = 43
Mean Principal Orientation = 89/308
Mean Resultant dir'n = 78-284
Mean Resultant length = 0.33
(Variance = 0.67)
Calculated. girdle: 1/168
Calculated beta axis: 89-348

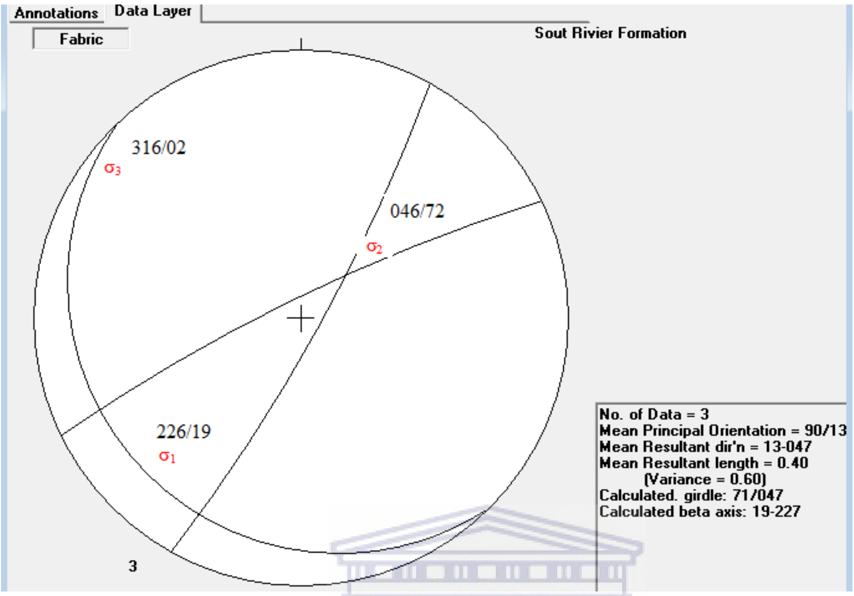
Figure 3.61. Contour diagram showing distribution of poles to joints in the Sout Rivier Formation.



Axial (non-polar) data
No. of Data = 43
Sector angle = 10°
Scale: tick interval = 5% [2.2 data]
Maximum = 18.6% [8 data]
Mean Resultant dir'n = 038-218
[Approx. 95% Confidence interval = ±21
(valid only for unimodal data)

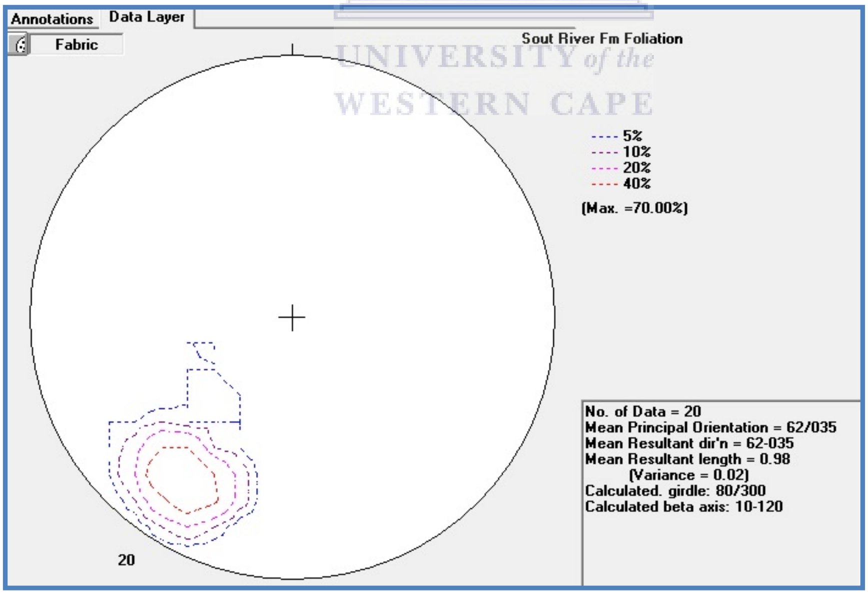
Figure 3.62 Rose diagram showing strike orientations of joints in the Sout Rivier Formation

The principal stress analysis of these joints is displayed in figure 3.63. The orientation of the maximum stress σ_1 is 226/19 and σ_2 is 046/72 and the minimum principal stress σ_3 is 316/02.



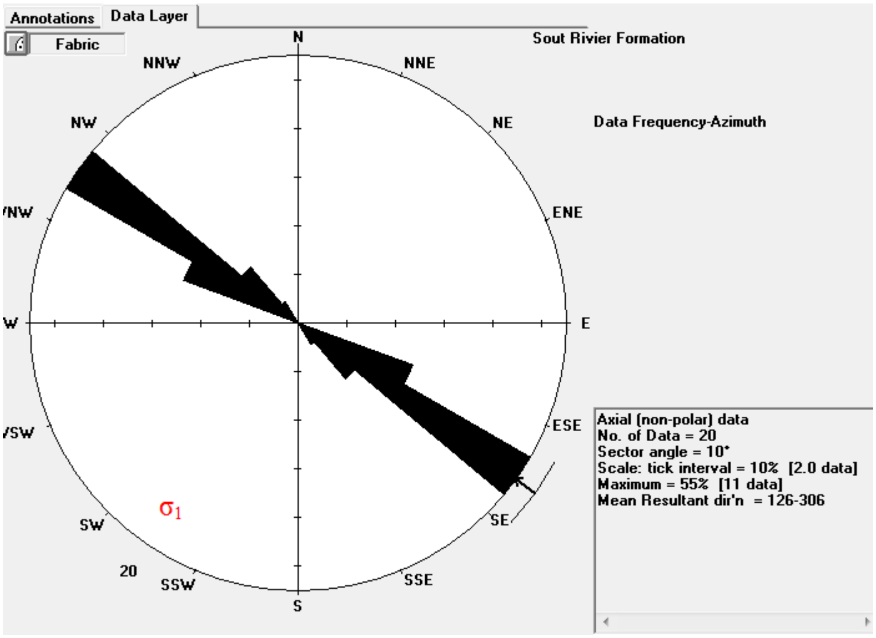
```
No. of Data = 3
Mean Principal Orientation = 90/13
Mean Resultant dir'n = 13-047
Mean Resultant length = 0.40
      (Variance = 0.60)
Calculated. girdle: 71/047
Calculated beta axis: 19-227
```

Figure 3.63 Orientation of principal stresses responsible for the formation of the Sout Rivier Formation joints.



```
No. of Data = 20
Mean Principal Orientation = 62/035
Mean Resultant dir'n = 62-035
Mean Resultant length = 0.98
      (Variance = 0.02)
Calculated. girdle: 80/300
Calculated beta axis: 10-120
```

Figure 3.64. Contour diagram of poles to axial planar foliation in the Sout Rivier Formation.



Axial (non-polar) data
No. of Data = 20
Sector angle = 10°
Scale: tick interval = 10% [2.0 data]
Maximum = 55% [11 data]
Mean Resultant dir'n = 126-306

Figure 3.65. Principal Orientation of Foliation in the Sout Rivier Formation.

The contour diagram shows only one cluster which means there is only one direction of the foliation. The mean principal orientation and the mean resultant direction are the same: 035/62.This is confirmed by the rose diagram (Fig. 3.65) which demonstrates that the Sout Rivier Formation has a foliation trending in the 305°-125°NW-SW direction. In the Sout Rivier Formation the attitude of the maximum stress σ 1 is 219/20.

5. Bethesda Formation

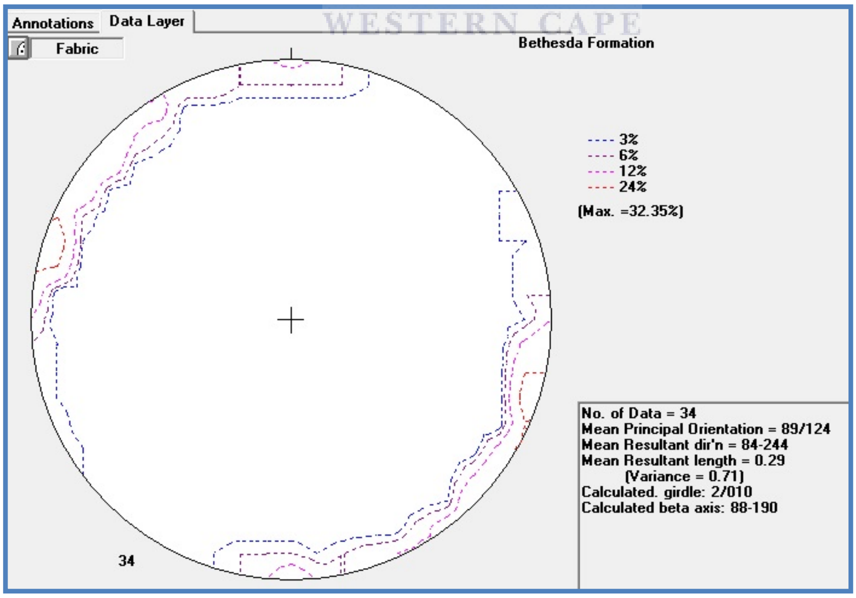
Field appearance

The Bethesda Formation is dominated by biotite gneiss and schist rocks. Although it is concealed by pegmatite in some parts good exposures are found along the road cuts less than five kilometres to the south of Louisvale. The pegmatite appears weathered on along the road cut and is mainly dominated by muscovite identified by its shinny appearance. (Fig. 3.66). Dominating mineralogy in the Bethesda Formation are quartz, feldspar, biotite and muscovite. The Bethesda Formation is intruded by Louisvale Granite. The formation is juxtaposed with a megacrystic gneiss that is light grey. There are veins randomly occurring in the rock some of which are 5-10 cm wide.

Figure 3.66. The Bethesda Formation showing shiny muscovite micas. GPS = 10 cm long

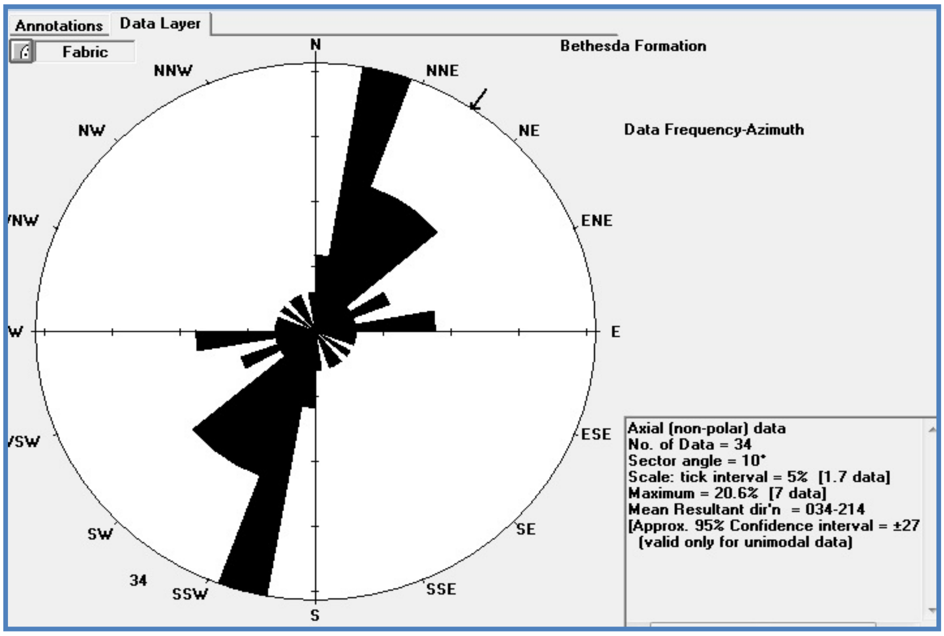
Joints analysis

The rose diagram in figure 3.68 shows one prominent joint set, striking in 014°-194° NNE-SSW and two less prominent joint sets trending in 214°-034°NE-SW, 085°-265°ENE-WSW direction respectively.



```
No. of Data = 34
Mean Principal Orientation = 89/124
Mean Resultant dir'n = 84-244
Mean Resultant length = 0.29
        (Variance = 0.71)
Calculated. girdle: 2/010
Calculated beta axis: 88-190
```

Figure 3.67. Contour diagram-displaying distribution of poles to joints in Bethesda Formation.



```
Axial (non-polar) data
No. of Data = 34
Sector angle = 10°
Scale: tick interval = 5%  [1.7 data]
Maximum = 20.6%  [7 data]
Mean Resultant dir'n  = 034-214
[Approx. 95% Confidence interval = ±27
  (valid only for unimodal data)
```

Figure. 3.68. Strike orientations of joints in the Bethesda Formation.

6. Dagbreek Formation

Field appearance

The Dagbreek Formation is a fine-grained, slightly foliated quartzitic rock intruded by the Straussburg Granite. Its colour varies from light colour to a dark red colour (Fig. 3.69). The reddish quartzite varies in grain size: the course-grained variety has feldspar crystals in it. There is also a fractured, banded black rock following the same folding of the Dagbreek quartzite. This is probably what Moen (2007) describes as a dark grey granoblastic rock that tends to form rocky outcrop and rock pavement in the same formation.

Figure 3.69. Altering quartzite of the Dagbreek Formation. (a) The quartzite is light grey to pinkish in colour (b) the quartzite from being light grey and grades to a reddish colour with black surface. PGS = 10 cm long

Structural description

The rock displays a NW-SE joint system and is intruded by the Straussburg Granite. There is a sharp contact visible between the granite and the quartzite of the Dagbreek Formation (Fig. 3.70a). No foliation or veins were recorded in the quartzite rocks of the Dagbreek Formation found in the Carpe Diem farm location.

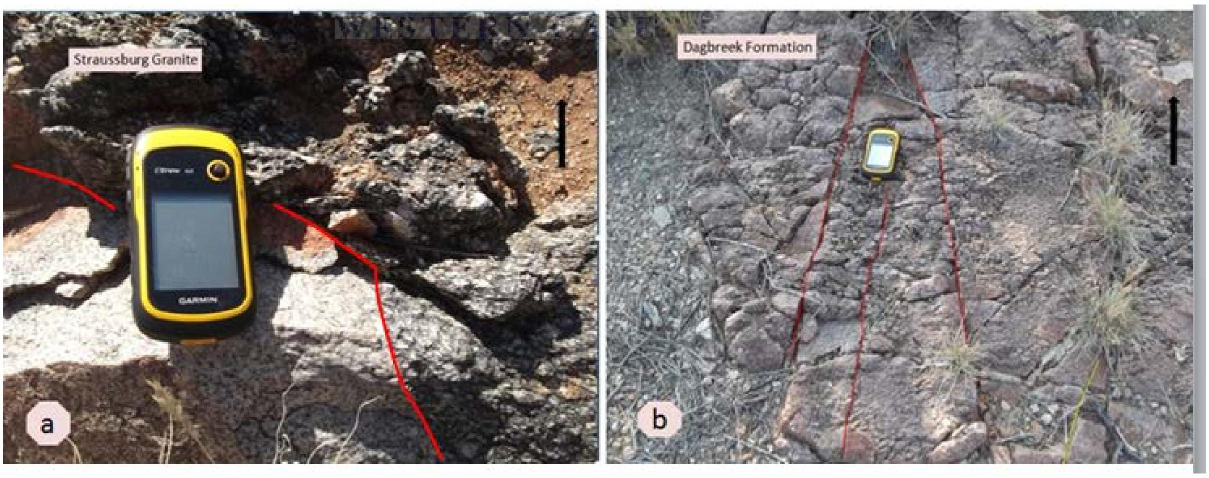
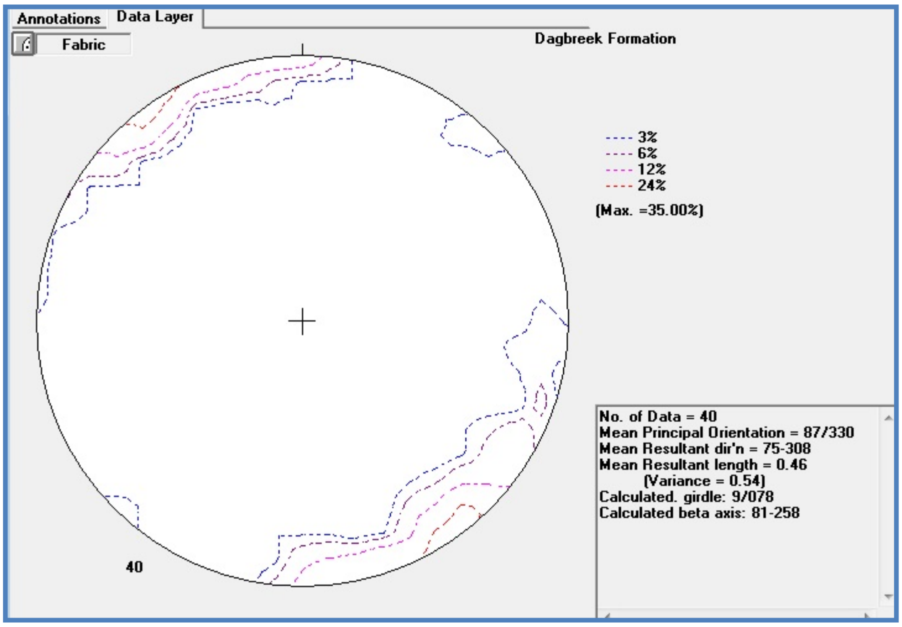
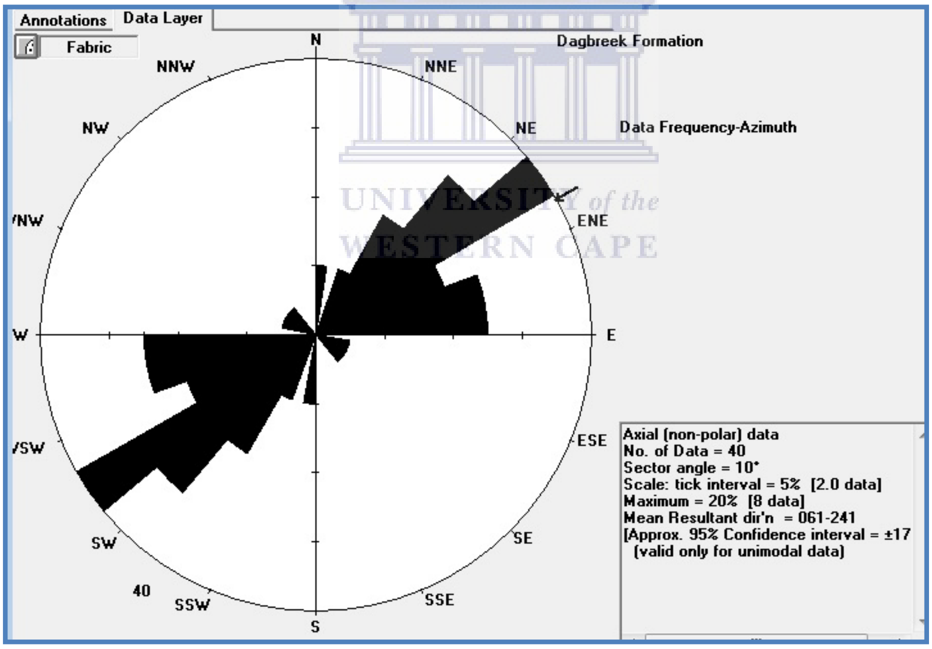


Figure. 3.70. a) Contact between the Straussburg granite and the quartzite of the Dagbreek Formation indicated by the red line b) Joints on the quartzite of the Dagbreek Formation. GPS = 10 cm long.



No. of Data = 40
Mean Principal Orientation = 87/330
Mean Resultant dir'n = 75-308
Mean Resultant length = 0.46
(Variance = 0.54)
Calculated. girdle: 9/078
Calculated beta axis: 81-258

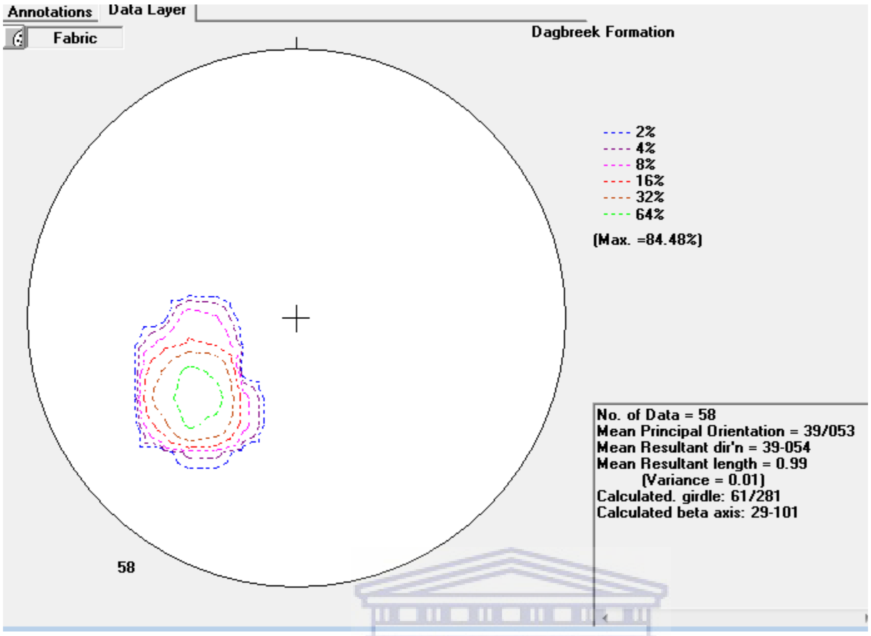
Figure 3.71. Contour diagram for poles to joints in the Dagbreek Formation.



Axial (non-polar) data
No. of Data = 40
Sector angle = 10°
Scale: tick interval = 5% [2.0 data]
Maximum = 20% [8 data]
Mean Resultant dir'n = 061-241
[Approx. 95% Confidence interval = ±17
(valid only for unimodal data)

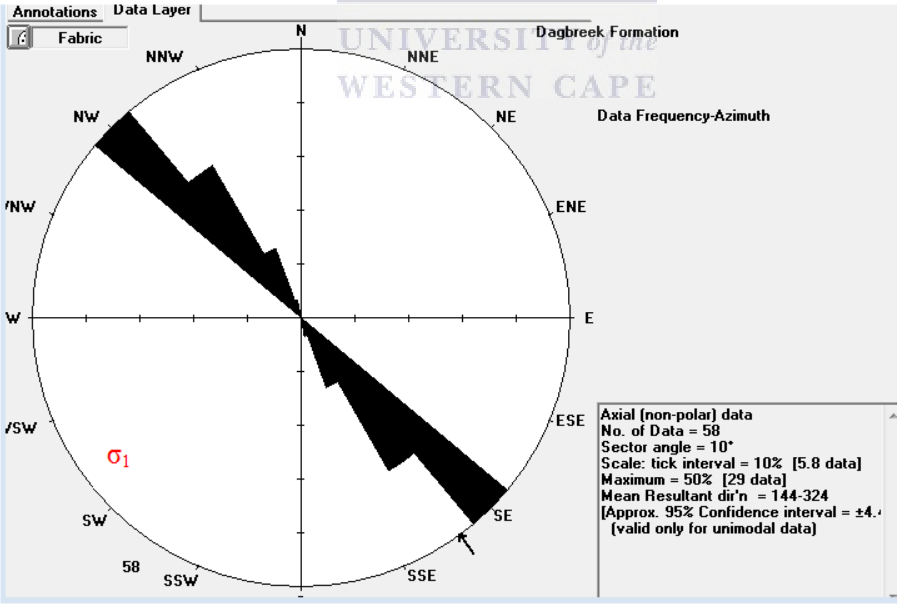
Figure 3.72. Joint orientation of the Dagbreek Formation.

The contour diagram of pole to joint for the Dagbreek Formation shows only one prominent orientation (Fig. 3.71). Rose diagram of Dagbreek joints displays two joint sets. The principal joint set strikes in the ENE-WSW 056˚-235˚ and the other joint set strikes E-W 262˚-082˚ (Fig. 3.72). The foliation contour diagram (Fig. 3.73) shows one cluster of the foliation and the mean principal stress is 053/39, and the mean resultant direction is 054/39 (Fig. 3.73). The principal orientation of the foliation is striking 315-135NW-SE. The mean resultant direction is 144/324 (Fig. 3.73). The principal stress of the axial planar foliation is σ_1 is 233/20.



```
No. of Data = 58
Mean Principal Orientation = 39/053
Mean Resultant dir'n = 39-054
Mean Resultant length = 0.99
          (Variance = 0.01)
Calculated. girdle: 61/281
Calculated beta axis: 29-101
```

Figure 3.73. Pole to Foliation in the Dagbreek Formation



```
Axial (non-polar) data
No. of Data = 58
Sector angle = 10°
Scale: tick interval = 10%  [5.8 data]
Maximum = 50%  [29 data]
Mean Resultant dir'n  = 144-324
[Approx. 95% Confidence interval = ±4.
  (valid only for unimodal data)
```

Figure. 3.74 Trend of the Foliation of the Dagbreek Formation in the Neusspruit Shear Zone.

3.2.3. Section C: Comparison of structural analysis between Keimoes Suite and country rocks

Joints comparison

Some granites of the Keimoes Suite have similar joint trends with each other and in some cases the trend is the same as the adjoining county rocks.

Table 3.1 shows the main orientation of joints of the Keimoes Suite, listed in order of the principal direction and age of granite.

Name of granite	**Orientation from**	**Orientation to**
Vaalputs	SSW-18 SW-235	NNE-005 NE-055
Louisvale	SSW-205 SW-235	NNE-025 NE-055
Straussburg	SW-235 NNW-340	NE-055 SSE-160
Keboes	SSW-196 WSW-265	NNE-016 ENE-085
Klip Kraal	SW-245	NE-065
Kanon Eiland	SSW-185 WSW-265 WNW-295	NNE-005 ENE-085 ESE-115
Friersdale Charnockite	NNW—335 SW-235	SSE-175 NE-055
Gemsbokbult	SW-235 NNW-355 WNW-286	NE-055 SSE-175 ESE-106
Cnydas	NNW-345 SW-215	SSE-165 NE-035

The Cnydas, Gemsbokbult, Straussburg Granites and the Friersdale Charnockite show similar joint trends: they all have their maximum direction in the NNW-SSE and also in the NE. This is in contrast to some of the granites such as the Kanon Eiland, and Gemsbokbult Granites who have their maximum direction in the SSW-NNE such as the Vaalputs, Keboes and the Louisvale granites. Kanon Eiland, Straussburg and Gemsbokbult Granites show the same trends as their main joints are trending NS-EW (Table 3.1). The Louisvale, Keboes and Vaalputs Granites show results closely related to those of the country rocks (Goede Hoop, Puntsit, Sandputs, Dagbreek and Sout Rivier and Bethesda Formations) (Table 3.2).The NNE joint set is common in Vaalputs, Louisvale, Kanon Eiland and Keboes Granites. Meanwhile the NE joint set orientation is present in all the granites except in the Keboes and Kanon Eiland. Straussburg, Gemsbokbult, Cnydas granites as well as the Friersdale Charnockite have the NNW joint set. However the other granites also have this NNW joint set but is not displayed in the table because they are not the prominent joints in those particular granites. Lastly the less prominent ENE joint set is only found on the Keboes and the Kanone Eiland granites. It is clear that certain joint sets exist in some granites that can be useful in determined their relative age by grouping them according to the joint sets present in them.

Table 3.2 Main orientation of joints sets in the country rocks.

Name of Formation	Orientation from	Orientation to
Goede Hoop Formation	SW-225 SSW-185	NE-045 NNE-005
Puntsit Formation	SSW-205 S-174	NNE-025 N-004
Sandputs Formation	SSW-206 WSW-236 SSW-185	NNE-026 ENE-056 NNE-005
Dagbreek Formation	SW-235	EN-056
Sout Rivier Formation	SSW-191 WSW-256 SW-205	NNE-025 ENE-076 NE-056
Bethesda Formation	SSW-194	NNE-014

They all have their maximum orientation in the NNE, NE and ENE directions. Their joints show the same orientation which could mean that they are of the same generation. What has been observed on the rose diagrams is that most of the joints from the granites and the country rocks joints are trending in the NE, NNE and ENE directions. Meaning the joints from the granites and the country rock are related and were formed by the same deformation event.

Principal stress comparison

When comparing the maximum stress of foliations and the principal stress of both the granites and the country rocks it seems that there is a strong relationship between them. The foliation measured in this study area is an axial planar foliation, forming perpendicular to the direction of principal stress. Therefore it gives the direction of shortening in this area. The principal stress of most country rocks is almost similar except for the Sandputs Formation which has principal stress of 348/20. The Dagbreek Formation has principal stress of 233/20, Goede Hoop Formation is 225/18, Sout Rivier Formation is 219/20 and Puntsit Formation is 200/45. Comparing this to the Keimoes Suite granites, the Vaalputs and the Keboes granites show similar principal stress to the country rocks. The principal stress of Keboes granite is 227/01 and Vaalputs granite is 210/02.

Presence and absence of foliation

The presence and absence of foliation can help in determining the relative timing of intrusions of the Keimoes Suite. Among the Keimoes Suite granites not all of them are foliated, some granites show strong to moderate foliation and some are not foliated at all. Strong to moderate foliation was observed on the Vaalputs, Kanon Eiland, Louisvale, Klip Kraal, Keboes, and Straussburg Granites where the foliation is mainly defined by the alignment of biotite and feldspars respectively. In contrast to the Friersdale Charnockite the Gemsbokbult, Kleinbegin, Cnydas, and Colston granites are not foliated. There is a clear distinction of the Keimoes Suite granites that were emplaced and affected by different deformational events that took place in the Namaqua Natal Province. The details of the different deformation events that affected the Keimoes Suite will be discussed in chapter 4.

CHAPTER 4: DISCUSSION

The study is about characterization of joints in the Keimoes Suite with respect to Namaqua deformational events

4.1. Structural analysis and interpretation

4.1.1. Characterization of joints

As defined before joints are tension fractures in brittle rocks along which no shear has occurred. They form at low pressure and are found in every rock type. Joints of the Keimoes Suite granites and the country rock were characterized based on their orientation, spacing and attitude, continuity, aperture, nature of infill. These features altogether are useful in determining joints that comprise a set. Frances (2007) mentioned that microstructural analysis of a joint surface can be used to describe further joint morphology and therefore providing information on the mode of fracturing.

Systematic joints are defined as planar joints that constitute a family of joints in which all the joints are parallel or sub-parallel to one another, and preserve approximately the same average spacing throughout the observed region (Van der Pluijm & Marshak 2004). Figure 4.1 shows the relationship between systematic and non-systematic joints. Non-systematic joints have irregular spatial distribution, they are never parallel with neighbouring joints and are non-planar. These types of joints often terminate at other joints and in most cases non-systematic and systematic joints tend to exist in the same outcrop.

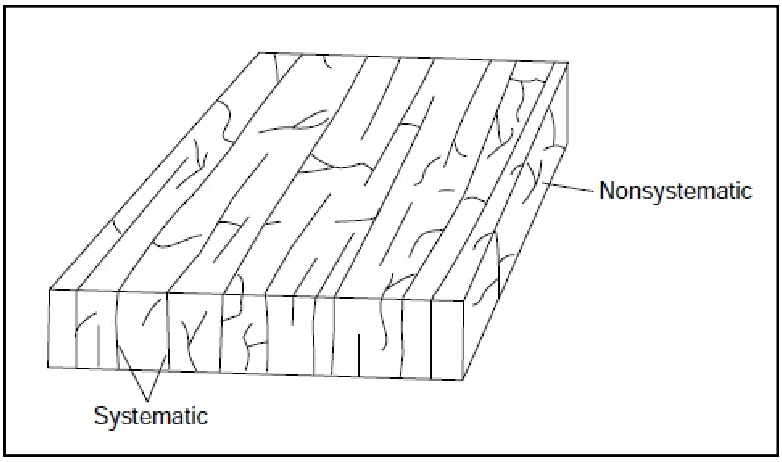


Figure. 4.1. A block diagram showing occurrence of both of systematic and non-systematic joints in a body rock (Van der Pluijm & Marshak 2004).

During field observation, step over joints, joints filled with secondary minerals and joints that unfilled with minerals were encountered. While systematic joints dominate in the Keimoes Suite granites, non-systematic joints were however recorded in few granites in the area. Keboes, Friersdale Charnockite and Vaalputs Granites exhibit systematic joints. For instance in the Friersdale Charnockite the non-systematic joints terminate at the systematic joints (Fig. 4.2). It is therefore concluded that the systematic joints in the Friersdale Charnockite are the first generation and the non-systematic joints are the second generation as seen on (Fig. 4.2) they terminate at the main joints. The main orientation of the systematic joints strikes 065°-245° -NE-SW in all different Friersdale Charnockite bodies that were mapped, in both Keimoes and Kakamas areas.

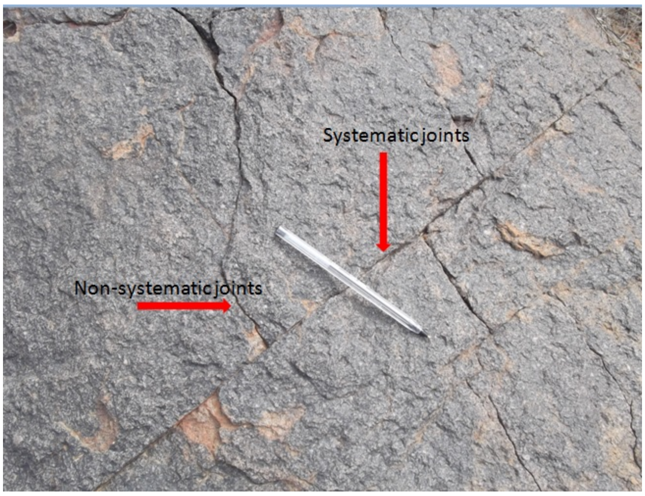


Figure 4.2. Non-systematic joints terminating against the systematic joints in the Friersdale Charnockite.

4.1.2 Joint sets

A group of systematic joints is termed a joint set. When two or more joint sets intersect at a constant angle they define a joint system. The angle between two joint sets within a joint system is the dihedral angle (Van der Pluijm & Marshak 2004). If the two sets are mutually perpendicular (i.e. a dihedral angle of 90°) they are called orthogonal whereas they are called conjugate if they intersect with a dihedral angle between 30° to 60° which is an acute angle (Van der Pluijm & Marshak 2004). The significance of both orthogonal and conjugate joints is that the joints displaced each other meaning that they formed at the same time (Fig. 4.3). Conjugate joint sets are composed of two coeval joints that commonly enclose an acute angle of 60^{o}, while conjugate hybrid joints enclose an angle between 1 and 60° (Fransson, 2008).

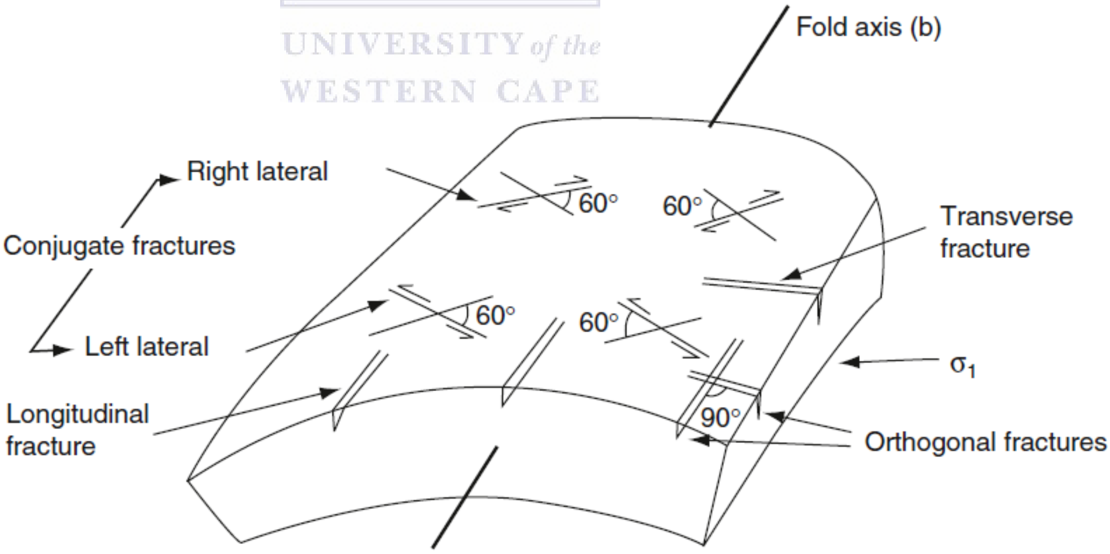


Figure 4.3 Conjugate joints and orthogonal joint sets (Singhal and Gupta, 2010). The conjugate joints set close at angle of 60˚.

By definition a conjugate fault set is a cross-cutting set of fault planes which ideally intersect at angles of 60° and 120°, and have both left-handed and righthanded shear senses (Allaby, 2008). The line of intersection is parallel to the direction of intermediate principal stress (σ_2). The maximum principal stress bisects the acute angle and the minimum principal stress bisects the obtuse angle (Fig. 4.3). There are two ways of determining if conjugate joints exist in an area, the first one is to measure the angle between the joints displacing each other. And the second method is to do principal stress analysis by plotting field measurements and if σ_2 is at the centre of the diagram it illustrate the presence of conjugate joints. Conjugate joint sets are associated with strike-slip stress. Riedel shears, which are brittle shear fractures, form at an acute angle to the direction of shortening as a result of the same strike-slip stress field as the conjugate joints.

Previous field studies by some workers reveal that rocks are always jointed in one favoured direction and host joint sets. In many cases there seem to be two or more prominent sets and one or more minor set frequently occurs, while random joints may be present as well. This is the case in the granites of the Keimoes Suite. Six possible joint sets were identified in the Keimoes Suite granites. However, three prominent joint sets dominate and seem to be present in all the granites, sub vertical joint sets 065°-245° NE-SW, 325˚-145˚NW-SE; 355˚175˚ NNW-SSE - the least prominent sets are 008°-185°N-S 085°-265° E-W, and 024^{o}-205^{o} NNE-SSW. Same orientation of joint sets occurring in the Keimoes Suite granites were also observed in the country rocks and these are: 336˚-146˚NW-SE; 053˚-235˚NE-SW and 086˚-262˚ENE-WSW. This led to the conclusion that the joints formed in the Keimoes Suite relate to the joints formed in the country rocks.

4.1.3 Description of joints

Joint analysis and interpretation will focus only on the most prominent joint sets which are the most frequent occurring joints in both the Keimoes Suite and the country rock. The NE-SW joints will be called trend 1 (T1), NW-SE T2, NNW-SSE-T3 and N-S-T4 joints. Cross relationship between T1 and T2 are more common in most of the Keimoes Suite granites and hence they form conjugate relationships. However, the T4 and T2 also show a similar cross cutting relationship as the T1 and T2 joints. These joints are of the same generation. The most dominant conjugate set is formed by T1 and T2 across the study area. Significant displacements on some of the joint sets were identified. For instance in the Kanon Eiland Granite T3 joints are displaced by T4 joints and in the Friersdale Charnockite T1 joints displace the T2 joints. The T3 joints are the only joints which are filled with quartz, feldspar and epidote mineralization especially in the Straussburg Granite and Friersdale Charnockite, as well as the Vaalputs and Keboes Granites. This means they are the older set of joints in the area. This is concluded on the fact that the later joints which are not filled with minerals displaced the T3 joint filled with minerals. Also due to the fact that these joints were opened for some time and later minerals such as quartz, feldspars and epidote precipitate in the fracture and sealed the open fracture to form the formed veins. The later joints that offset these veins are therefore younger as they came after the veins were formed. In both Keboes and Straussburg Granites the T1 displaces the T3 quartz filled joints, implying that the T1 joints postdate the T3 joints. The NE-SW T1 and NW-SW T2 trending joints appear undisturbed across the study area. The ENE-T4 joints are the least prominent joints in the area and are not filled with any minerals; however, some non-systematic joints are terminated against the T4 joints.

4.1.4. Country rock

Three prominent joint sets were present in the country rocks, NE-SW, NW-SE, and N-S trending joints. These three joint sets coincide with the joints found in the Keimoes Suite. However, no joint sets filled with minerals were recorded except for the conjugate system of the Sout Rivier Formation. In the Sout Rivier Formation the conjugate joint sets trending in the NE and NW directions are filled with blocky quartz veins. In this formation step over joints were also present and appear to be closely spaced with no mineral filling in them. The oldest joints in the Sout Rivier Formation are the ones filled with minerals. The step over joints are the last generation of joints to form in the formation. Also similar behaviour of the N-S trending joints in the Goede Hoop Formation exists whereby the N-S joints are closely spaced and the NE-SW joints are terminated by the N-S joint sets.

4.1.5 Joint orientations (attitude)

The results from the stereonet analysis of the contour plots of the attitudes of prominent joints reveals 5 significant steeply dipping joint trends existing in the Keimoes Suite. However the NE-SW and NNW-SSE joint trends dominate the stereoplots of almost all the data sets. Their joint trends are listed in order, T1-NE, T3-NNW, T2-NW, T4-ENE T6-E-W and T5-NNE. According to Palmstrom (1995) high to very high dips (60- 90^o) and low dips (0-30^o) prevail over intermediate dips in a large number of geological settings, especially in intrusive rocks. Similar results were found in the study. During field investigation steeply dipping joints having high dips of 70˚-90˚ were recorded. About 80% of the Keimoes Suite granites have the NE trending T1 joints this is also deduced from the rose and contour diagrams.

4.5.6. Joint spacing

Joint spacing in igneous rocks varies from a few centimetres to metres resulting in irregular spacing of joints. The magnitude of joint spacing in igneous rock is controlled by the degree of tectonic activity. Other factors that control the joints spacing in igneous rock are the mechanical properties of the rocks, the strain rate and the fluid levels present within the rock (Van der Pluijm & Marshak 2004).

In granites, joint spacing often follows roughly long-normal frequency distribution. For the same lithology joints tend to be more closely spaced. This is due to the fact that a joint relieves tensile stress in the layer over a lateral distance proportional to the joint length (Gross et al., 1995). According to Gross et al. (1995) since joints stop at layer boundaries which are the rock discontinuities, the longer joints in thicker layers need to be spaced less frequently. Joint spacing can also be influenced by stress reduction which prohibits new joints formation nearby the existing joints. For instance, in sedimentary rocks lateral extent of this stress reduction shadow increases with joint height, which corresponds to bed thickness. Mineral composition controls rock strength; rocks containing quartz are the strongest followed by calcite and other minerals.

The mechanical properties of a rock, such as mineralogy, composition and grain size tend to control the strength of the rock. Kemthong (2006) reports that the strength of an igneous rock decreases with increasing grain size. Hence mechanical properties of the rock influence joints spacing such that stronger, more brittle rocks have more closely spaced joints than weaker rocks. Likewise rocks with low tensile strength show more joints than stiffer lithologies, because strain is the same along layers of different types. However higher stresses are required to achieve the same amount of strain in the stronger layers. Therefore, strong layers fracture less frequently. This response, though, is mainly sensitive to local pore fluid pressure. Because when a joint forms, fluids flow into the fracture and the pore pressure in the adjoining rock reduces. Then the local Mohr circle moves away from the failure envelope (Fig. 4.16), and no fracture is possible near the initial one. A new fracture can be possible beyond the volume of rock with reduced pore pressure. Thus minimum spacing depends also on the permeability of the rock (Fossen, 2010). Increasing the strain rate strengthens the rock. By contrast, reduced or low strain rate will weaken the rock. Fossen (2010) said this is because crystal plastic processes can then easily keep up with the applied stresses. Therefore joint spacing in a fracture set decreases with increasing total strain, increasing number of loading cycles, and decreasing strain rate.

In igneous rock normally three sets of joints form caused by tensional forces set up in a rock body as a result of cooling (Zheng and Scheidegger, 2000). Two of these joint sets are vertical and perpendicular to each other whereas the other joint will be more or less horizontal. During field observation it was recorded that joint spacing differs in all the Keimoes Suite granites: in some granites the joint spacing and orientation is constant while in other granites they are not. For example, the Friersdale Charnockite (Fig, 4.2) has constant orientation but the spacing is not constant. The other granites of the Keimoes Suite have irregular joint spacing and they are oriented in different directions. The spacing of the step over joints of the Klip Kraal granite is approximately 10 cm apart. Similar joint spacing between the step over joints of the Sout Rivier Formation was found.

4.1.7 Jointing pattern

Palmstrom (1995) recognises two types of joint intersection geometries, namely the orthogonal class (+ intersection) and non-orthogonal (X-intersection). Both types are divided into three groups (1), all joints are persistent, (2) some persistent, some not, (3) all joints are non-persistent. Most of the joints observed during field investigation are systematic and step over joints although there are non-systematic joints present in some parts of the study area. Non-orthogonal joints, also termed conjugate joint sets, were found in some granites of the Keimoes Suite and in their country rocks. Also it was observed that persistent and non-persistent joints exist. In the Keboes Granite non-persistent joints terminate against persistent joints, as is the case in the Friersdale Charnockite and Kanon Eiland Granites. The intrusion of magma into the country rock is caused by stress and some of the stress remains active after the magma has solidified (Horne et al., 1992). As a result the stress causes the present solid igneous rock to fracture as joints.

4.1. Veins in the Keimoes Suite

Veins are defined as extension fractures filled with mineral deposits, generally quartz or calcite and other minerals such as epidote and oxides, and one of the most common features in deformed rocks of all types and metamorphic grades. Veins are thus taken as evidence for movement of fluids along fractures. Opening of veins is structurally controlled by orientation of fractures in a volume of rock but other parametres, like pore fluid pressure or porosity, are also important (Coelho et al., 2006). Two types of veins can develop in both compressional and extensional regimes and these are blocky veins and fibrous veins (Fig. 4.4).

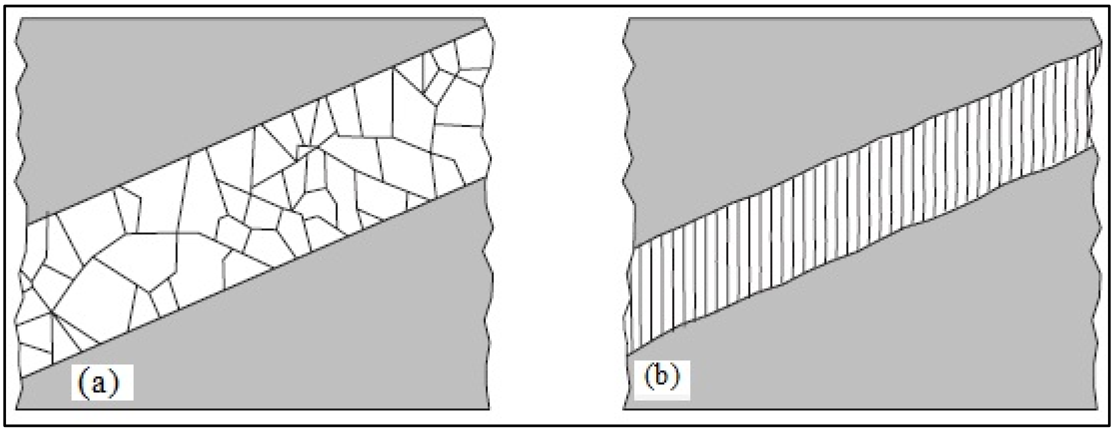


Figure 4.4. Two types of veins occurring in rocks (a) show blocky vein type (b) fibrous vein type (Van der Pluijm & Marshak 2004).

Occurrence of blocky veins in rocks implies that the vein was an open fissure at the time of mineral precipitation. This is likely to happen only in veins formed near the surface, where the rock is able to allow a cavity to stay open or fluid pressure is sufficient to hold the fracture open that previously formed vein fill later recrystallized to form blocky crystals (Van der Pluijm & Marshak 2004). The Mohr diagram demonstrates that an increase of pore fluid (Pf) will cause the whole Mohr circle to shift to the left; however, its diametre will not change (Fig. 4.16) and when the circle reaches the failure envelope, shear failure occurs regardless of whether the relative values of σ_1 and σ_3 are unchanged. This suggests that a differential stress that is insufficient to break a dry rock may break a wet rock if the fluid in the wet rock is under sufficient pressure. Hence an increase in pore pressure effectively weakens a rock (Van der Pluijm & Marshak 2004; Brannon, 2003 and Fossen, 2010).

Fibrous veins are known to form as a result of a crack-seal process. This is when in an unbroken rock containing a pore fluid with dissolved minerals, the fluid pressure becomes so great that the rock cracks which initiates a slight opening. Thus the crack will be filled with fluid because of imbalance between the fluid pressure within the open crack and the pores of the surrounding rock, thereby, resulting in a decrease of dissolved material; the minerals precipitate thus sealing the crack. Fibrous veins filled with quartz or calcites are important because they provide useful information about the progressive strain history in a rock. Most of the Keimoes Suite granites exhibit blocky vein types where sometimes are being displaced by joints. The blocky veins of the Keimoes Suite granites are mostly filled with quartz and some are quartzofeldspathic veins (Fig. 4.5). The Friersdale Charnockite contains fibrous veins (Fig. 4.6), filled with epidote minerals.

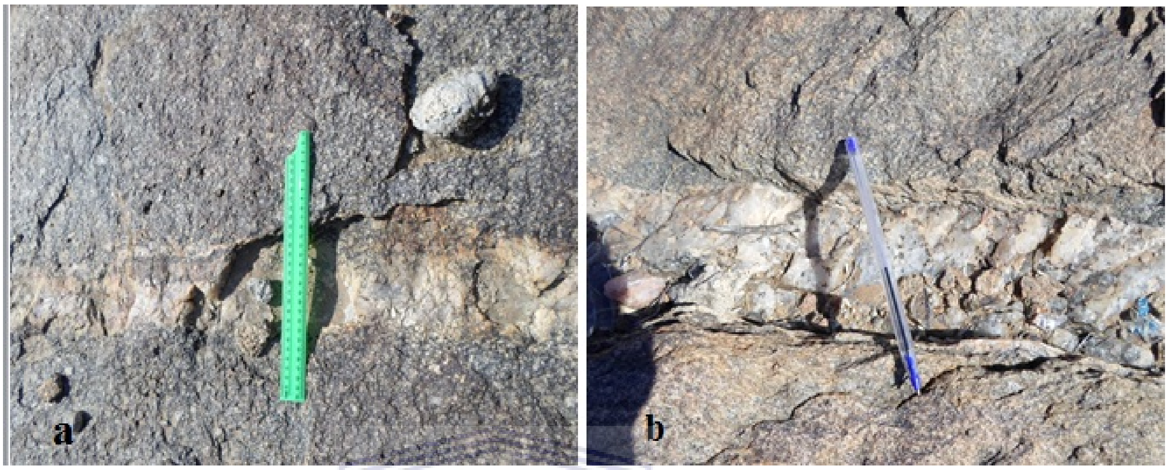


Figure 4.5. (a) Blocky quartzo-feldspathic vein of the Straussburg granite Ruler = 30 cm long (b) Blocky vein filled with quartz in the Vaalputs granite. Pen = 15 cm long

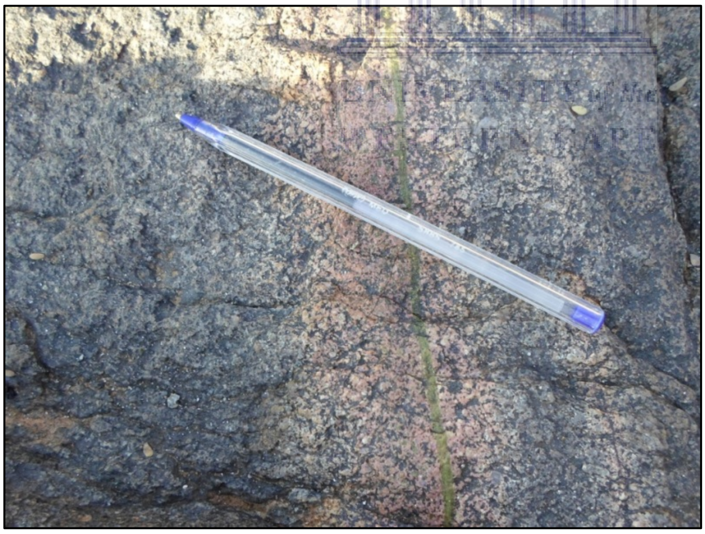


Figure 4.6. Fibrous vein of the Friersdale Charnockite filled with epidote minerals. Pen = 15 cm long

Tension gashes, named en échelon veins, were identified in the Keimoes Suite granites. Generally both tension gashes and veins belong to mode I fractures formed in response to combined tectonic and pore pressure. According to Ramsay and Huber (1983), tension gashes, wing crack and swordtail termination in boudin parting surfaces are common indications of veins developed as mode I extension fractures (Fig. 4.12). Hence they are used in the interpretation of bulk kinematics and are an important source of information on the deformation history of the host-rock. However pure tension of opening mineral space for deposition may be controlled by Riedel (R) and anti-Riedel ($R^{\prime}$) conjugate shears (Fig. 4.7).

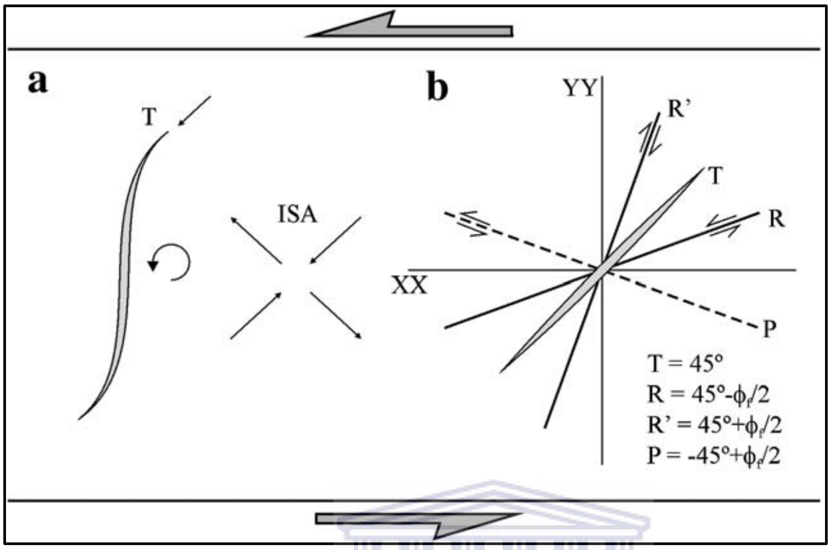


Figure 4.7. The tips of small tension gashes spread in a direction perpendicular to the incremental principal extension (Coelho et al., 2006).

En échelon veins are planar, regularly spaced and equally parallel in an overlapping or staggered arrangement (Fig. 4.8). Each vein is relatively short but collectively they form a linear brittle shear zone defined by two parallel, non-material enveloping surfaces. The strike of the individual veins is oblique to the linear zone as a whole, which is taken as a discrete, potential fault zone. En échelon veins are inclined against the sense of shear in agreement with extension fractures being initiated normal to the incremental extension within the fault zone (Van der Pluijm & Marshak, 2004).

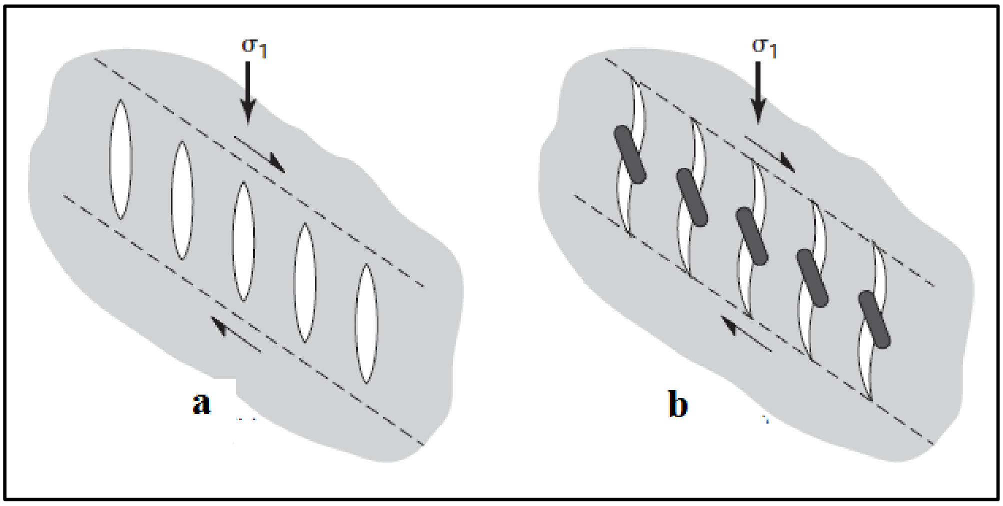


Figure 4.8. Development of sigmoidal tension gash array in a brittle shear zone. a) Formation of en échelon tension gash array and b) formation of sigmoidal en échelon veins, as a result of the rotation of the older, central part of the veins and growth of new veins (Van der Pluijm & Marshak 2004).

The Vaalputs Granite of the Keimoes Suite contains en échelon veins which are sigmoidal in shape. This is caused by the rotation of the central part of the vein while the vein was lengthening at the time of deformation (Fig. 4.9). The sense of rotation of the central part of the vein with respect to the tips indicates the sense of shear.

Figure 4.9. En échelon veins in the Vaalputs granite. Ruler = 30 cm long.

4.2.1. Orientation of veins

Veins occurring in the Keimoes Suite are oriented in various directions. Veins in the Straussburg Granite are perpendicular to the joints and parallel to each other. Veins mapped during the field investigation were plotted in a rose diagram to obtain their orientation. Six sets were recognised. However, there are two sets of veins which are pronounced and are consistent in 90% of the stereoplots (Fig, 4.10). The prominent vein sets trend in the NE-SW and NNE-SSW direction respectively.

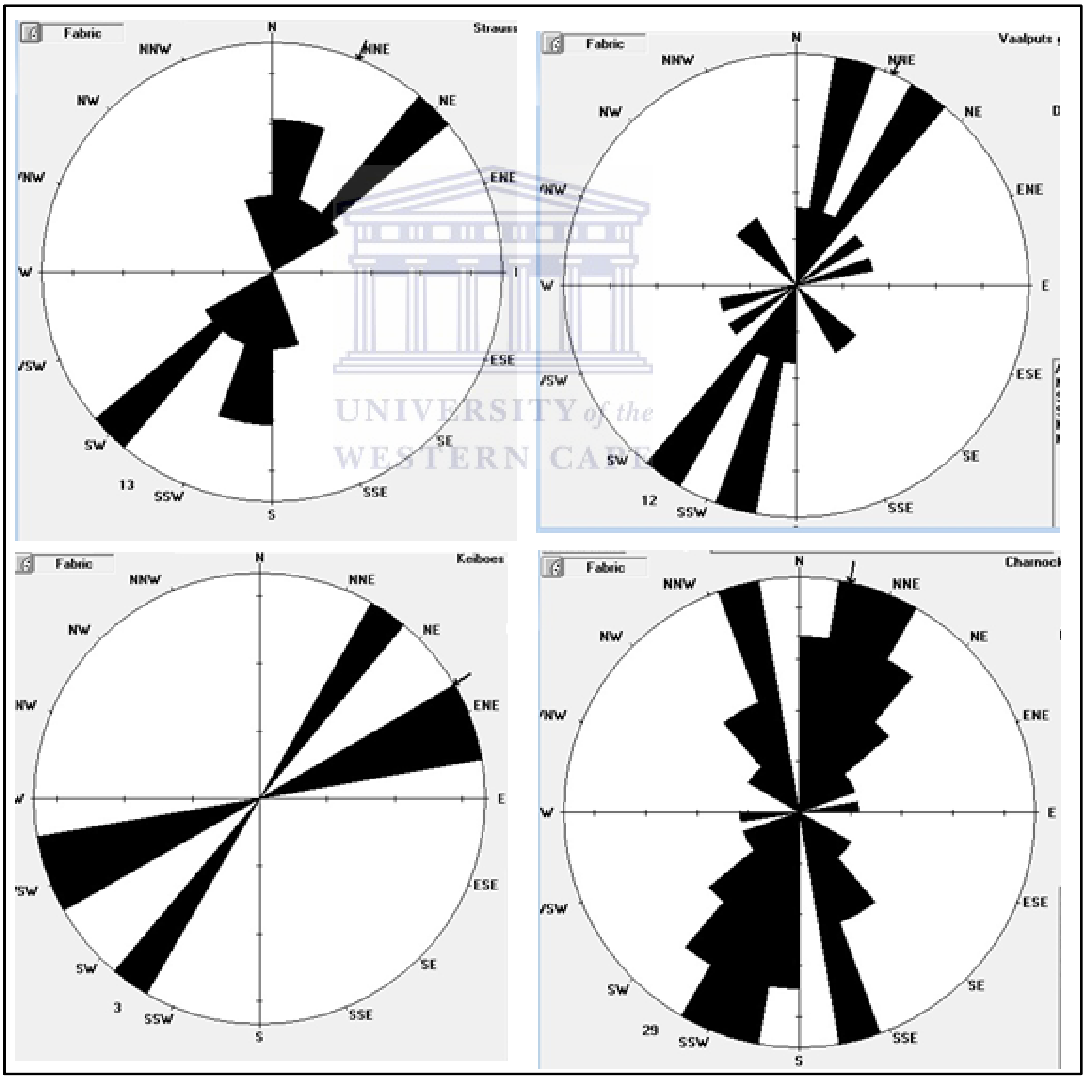


Figure 4.10. Rose diagram showing orientation of the veins in the Keimoes Suite. (a) Straussburg Granite (b) Vaalputs Granite (c) Keboes Granite (d) Friersdale Charnockite.

Both rose diagrams of joints and veins display similar results in terms of prominent joint set. The NE-SW trend is the common prominent orientation in both cases. The NNE-SSW dominant vein set coincides with the less prominent joint set T5-NNE-SSW of the Keimoes Suite granites.

4.3. Application of Mohr diagrams

In 1882 a German civil engineer Otto Mohr developed a graphical technique to represent stress and strain in a circle and it is referred to as a Mohr circle. The Mohr circle is basically a way to determine the shear and normal stress for a pair of stresses oriented obliquely to the plane in question (Brannon, 2003). The Mohr stress diagram provides an easy way to visualize mean stress and difference in stress or deviatoric stress and relate these stresses to deformation. In the Mohr diagram the horizontal and vertical axes represent the normal (σ_n) and shears (σ_s) stresses that act on a plane through a point (Fig. 4.11). The value of the maximum and minimum principal stresses (σ_1 and σ_3, also symbolized σ_1 and σ_2 for two dimensional cases) are plotted on the horizontal axis, and the distance between σ_1 and σ_3 defines the diametre of a circle centered at $((\sigma_1 + \sigma_3)/2.0)$ (Fossen 2010).

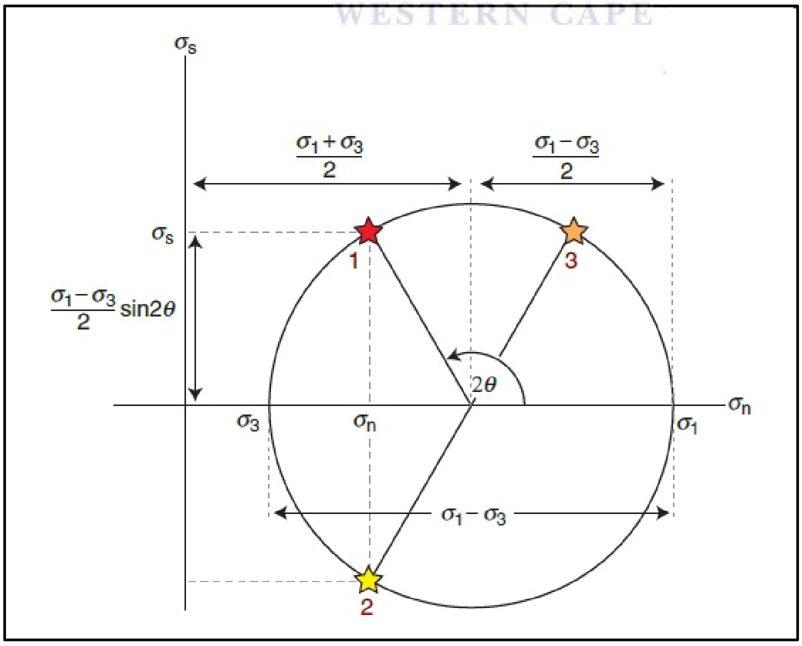


Figure 4.11. The Mohr circle where ϴ is the angle between the largest stress and a given plane. Plane 1 and 2 have same normal stress but different shear stress. Plane 1 has positive shear stress and plane 2 has negative shear stress. Plane 1 and 3 have same shear stress but different normal stress. σ_1 is the maximum principal stress and σ_3 is the minimum principal stress. Refer to text for discussion of the diagram (Fossen, 2010).

In general a rock's response to stress depends on the level of stress or amount of accumulated strain, temperature, strain rate and various properties of the rock such as anisotropy, pore fluid pressure and confining pressure. Under a brittle condition rock fracture depends on the differential stress ($\sigma_1 - \sigma_3$) and the mean stress ($\sigma_1 + \sigma_3$)/2; this is applicable to a rock with a constant temperature and constant positive confining pressure. Therefore, for fractures to form the differential stress must exceed the strength of the rock. The strength of the rock is controlled by the confining pressure or depth of burial. Therefore increasing of the confining pressure makes it necessary to increase the differential stress in order to fracture a rock. To display graphically how rock fails or fracture, a Mohr diagram can be used to show the physical stress conditions under which the above mentioned factures formed.

4.3.1. Mode of fracturing

Generally rock failure takes place in two different modes; shear bands and tensile fractures. Fractures such as joints are common and extensive features in rocks. There are several processes that relate to their origin and are therefore connected to the geological history of the area. Joints are produced by stresses which have various origins such as (a) tectonic stresses related to the deformation of rocks; (b) residual stresses due to events that happened long before the fracturing; (c) contraction due to shrinkage because of cooling of magma or desiccation of sediments; (d) weathering, in which dilation may lead to irregular extension cracks and dissolution may cause widening of cavities, cracks (Singhal and Gupta, 2010). Fractures are generally divided into three classes:

Shear joints- could or could not display displacement\ and are co-genetically developed in conjugate sets with a dihedral angle $2\Theta > 45^\circ$. In the field shear joints may appear as conjugate joint sets implying that there was shearing.

Dilational (extension) joints– are tensile in origin and usually develop perpendicular to the bedding plane and are open fractures with no evidence of shear movement.

Hybrid joints display features of both shear and extensional origin. They may occur in conjugate sets with a dilational angle of less than 45° and are interpreted as failure surfaces initiated in the transition from tensile to shear failure. They may be filled with various minerals and may display some shear displacement.

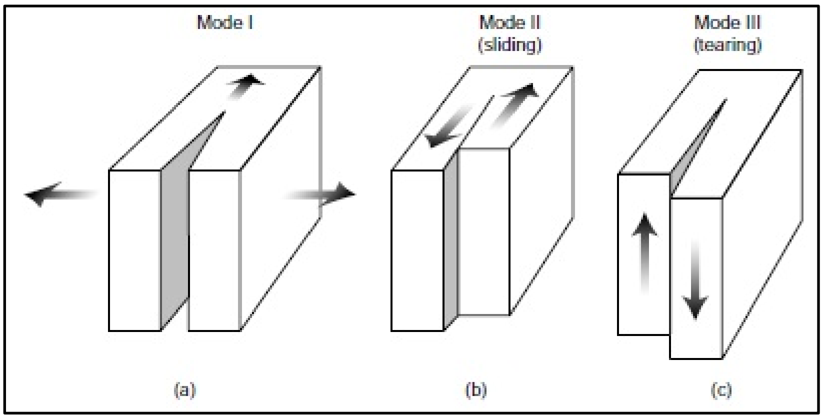


Figure 4.12. Block diagrams showing three modes for development of joints. (a) Mode I is a tensile joint, (b) Mode II is shear joints and (c) Mode III is hybrid joints (Van der Pluijm & Marshak 2004).

Extension (tensile) fractures are usually referred to as Mode I (Fig. 4.12), where the displacement is perpendicular to the walls of the crack. Whereas mode II is known as the sliding mode it represents shearing or sliding movement and the shear is perpendicular to the edge of the fracture (Fig 4.12). Mode III is tearing mode whereby the rocks on one side of the crack moves similar to the direction parallel to the fracture front (Van der Pluijm & Marshark, 2004).Joints in the area can be attributed to Mode II fractures. The evidence supporting this is the presence of conjugate joint sets and also that most joints are tight, they are not open although some joints which were open are now filled with minerals. More evidence is provided by the data analysis where the principal stress diagram shows a conjugate set, which further reveal a strike-slip environment.

The joints filled with quartz and feldspars could have started off as Mode I fractures but then later precipitation of minerals sealed the opening and formed veins. During Mode I displacement tensile cracks form parallel to the principal plane of stress that is perpendicular to the σ_3 direction, and can thus grow without changing orientation. These types of fractures tend to form at low confining pressures deep in the lithosphere, where high fluid pressure reduces the effective stress. Thus the reduced strength of a rock facilitates hydraulic fracturing. Hydraulic fracturing is when pore pressure in a rock causes tensile cracks to spread, although none of the remote stresses are tensile, because pore pressure can heighten a crack-tip tensile stress that surpasses the magnitude of σ_3 (Van der Pluijm & Marshak, 2004). On a Mohr diagram hydraulic fracturing can be epitomised by the shift of Mohr's circle to the left (Fig 4.13). according to Van der Pluijm & Marshak, (2004) it is not necessary for a rock to be overpressured in order for a natural hydraulic fracture to take place, however a certain condition must be met where *Pf* must equal or exceed the magnitude of σ_3.

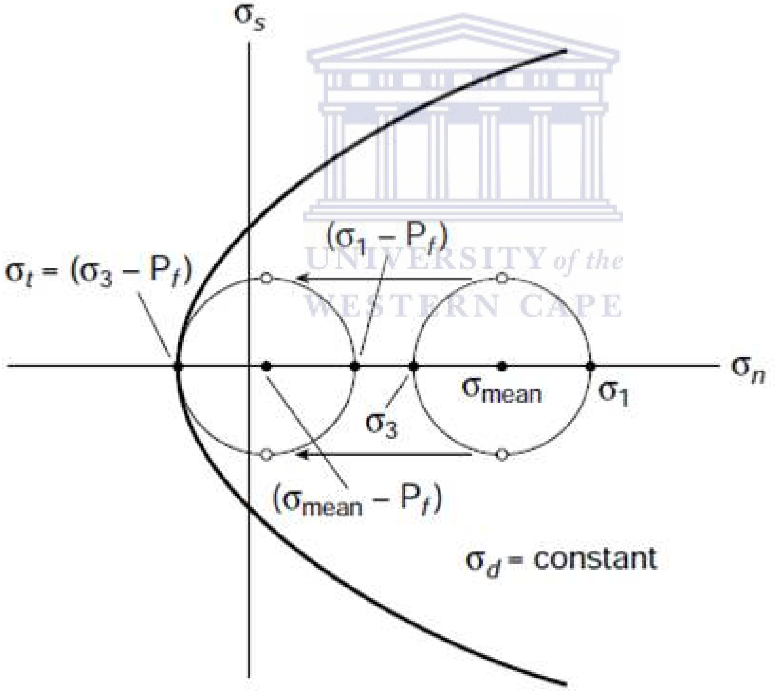


Figure 4.13 A Mohr diagram showing hydraulic fracturing whereby an increase in pore fluid (P_f) pressure shifts the Mohr's circle to the left along the horizontal axis without changing the size of the Mohr circle (Van der Pluijm and Marshak 2004).

4.3.2. Prediction of rock failure using the Mohr diagram

In general Mohr diagrams are used by both engineers and geologists for determining stress and strain under various conditions. Mohr diagrams in geology are used in determining rock failure, to explain the reactivation of pre-existing planes, to perform strain analysis and representation of tensors. The Mohr diagram presents normal and shear as well as the greatest and least stresses on a Mohr circle in two-dimension and three-dimension for a given set of principal stresses.

It appears that rock failure at specified σ_3 and σ_1 will occur when the stresses are negative. Generally in geology rocks are weakest under tension, which plots on the left side of the vertical axis of the Mohr diagram (Fig 4.14 b). For compression the Mohr circle plots on the right side of zero (Fig. 4.14a).

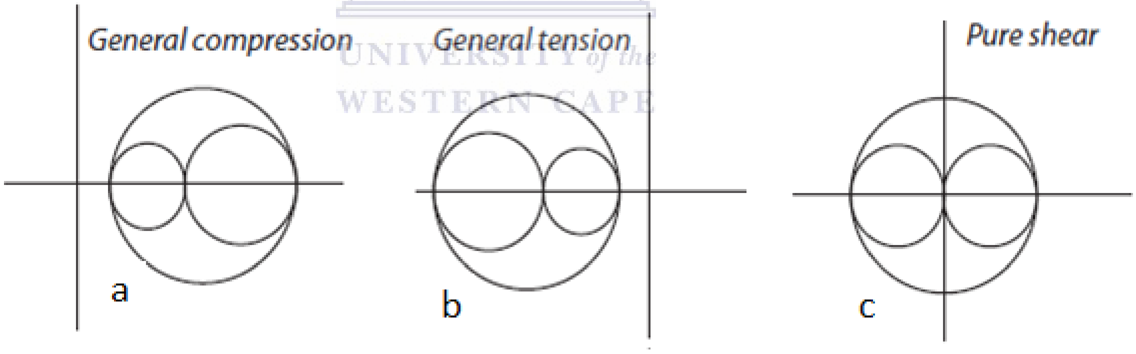


Figure 4.14 Mohr circle representations of 3 dimensional stress: The three circles in the Mohr diagram correspond to the σ1, σ3; σ1, σ2; σ2, σ3 pairs (Fossen, 2010).

Various authors have demonstrated by the use of experiments that the shear stresses needed to produce failure increase with increasing confining pressure. Rocks cannot withstand large tensile stresses; hence the failure envelope has a parabolic shape (Fig. 4.15). The parabolically shaped envelope separates two regions, the inside of the envelope where both normal and shear stresses applied to the rock can be supported and the rock will not fail, and the other region outside this envelope which represents a region of failure or fracture.

Principal stresses, maximum shear stresses and stresses on an inclined plane can be easily calculated using the Mohr circle. The Mohr diagram can be used to show how rock failure occurs. The Mohr circle shows the initial state of stress with zero pore fluid overpressure. As the pore-fluid pressure increases homogenously by an amount of ρ, the radius of the Mohr circle remains constant and the circle is displaced to the left until it touches the failure envelope (Fossen, 2010). Depending on the location where the circle touches the failure envelope, the formation of shear bands or tensile fractures takes place at different angles termed θ along the failure envelope (Fig. 4.15).

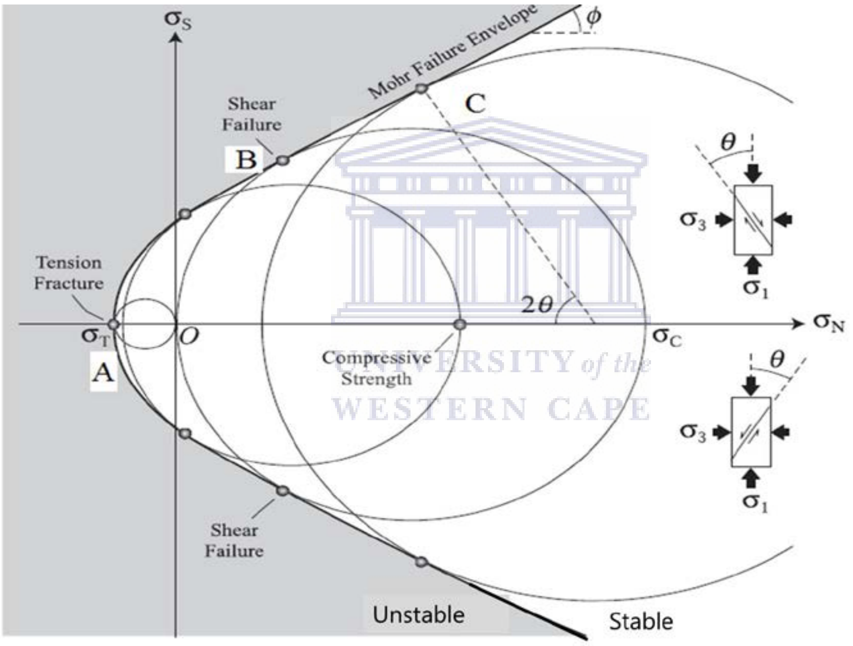


Figure 4.15. A Mohr diagrams showing rock failure conditions.

A Mohr diagram was used to explain how the Keimoes Suite joints formed (Fig. 4.15). The curve ABC is a Mohr failure envelope. The stress circles intersecting the Mohr envelope at points A, B and C indicate different failure conditions of the rock. The principal minimum compressive stress for A is negative and the shear stress is zero, meaning extension without shearing, and therefore it leads to dilational failure. In condition ‘C’, a typical conjugate shear failure takes place, as both normal stress and shear stress have positive values. In the Mohr diagram, ‘B’ represents a condition where there is a positive maximum principal compressive stress σ_1 and a zero minimum principal compressive stress σ_3, i.e. the effective normal stress (Fig. 4.16) perpendicular to the fracture plane is positive (compressional). This can be attributed to high fluid pressure conditions at depth. Hence, there is a tendency for such shear fractures to open and also get filled with minerals (Singhal and Gupta, 2010).

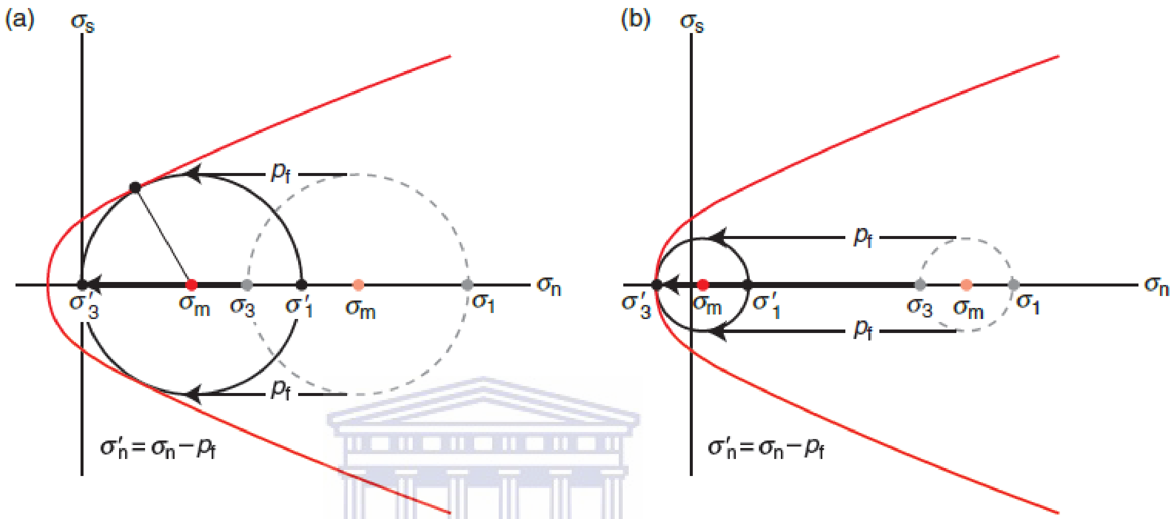


Figure 4.16. The diagrams show the effect of increasing pore fluid pressure P_f in a rock. a) The Mohr circle is moved to the left (the mean stress is constant but the effective stress is reduced) and a shear fracture will form if the fracture envelope is touched while $\sigma3$ is still positive. b) A tensile fracture forms if the envelope is reached in the tensile field (low differential stress) (Fossen, 2010).

Recent studies show that the use of the 3-dimeansional Mohr diagram is useful in explaining the mechanism of faulting and reactivation of pre-existing faults. Xu et al. (2010) state the two tri-axial conditions as: (a) $\sigma1$, $\sigma2$, and $\sigma3$ have non-zero values; and (b) $\sigma1 > \sigma2 > \sigma3$, and can be tensile or compressive. Based on the measurements of in-situ stress it indicates that the crustal stress is generally in a three-dimensional stress state. Hence mechanical behaviour of crustal rock should be explained using a three-dimensional Mohr diagram.

Based upon their findings they discovered that on a three-dimensional Mohr diagram, a point is defined by three Mohr circles. This point has combined both the normal and shear stresses. However, in real space four planes exist with the same normal and shear stresses only if the signs are not taken into account. This means that the four planes may be reactivated, if a point on the diagram is located above the critical slip line. They further stated that the planes may also be reactivated as a result of changes in the intermediate principal stresses. The tangent solid line represents the failure envelope. Above this line there is stress difference sufficient to start slip for a range of pre-existing plane orientations (Xu et al., 2010). The states of stresses are unstable in this region, and slip or failure will occur, while below the envelope fracture or slip will not occur.

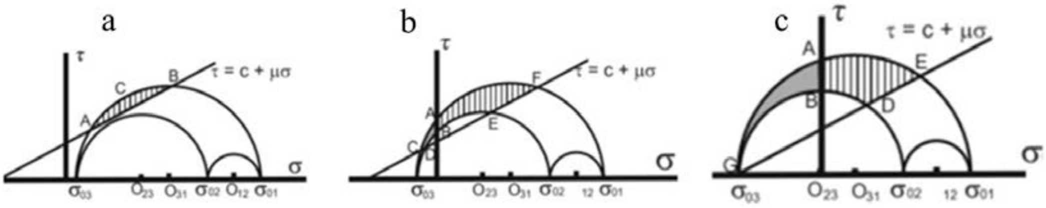


Figure 4.17. Four types of reactivated planes according to the normal and shear stress on the planes. When all principal stresses are greater than zero, the normal stress on the planes is positive (Fig. 4.17a). If the minimum principal stress is less than zero, other types of reactivated planes may appear (Fig. 4.17b, 4.17c). On one type of plane, only shear stress exists (points on line AB). On another type of plane, the normal stress is negative (grey area in Figures 4.17b, 4.17c). Specially, for point G, there is only extensional stress. In Figure 4.17 τ is the magnitude of the shear stress and σ is the normal stress on the pre-existing plane; C is the shear strength on the pre-existing plane when σ is zero, and μ the coefficient of friction on the pre-existing plane. O12, O31, O23 represent three families of concentric circles in the $\sigma_1\sigma_2$, $\sigma_3\sigma_1$, and $\sigma_2\sigma_3$ planes (Xu et al., 2010).

In the Mohr diagram (Fig. 4.17), Xu et al. (2010) identified four types of reactivated planes:

- First type of plane: the normal stress is compressional and is denoted by the hatched region
- Second type of plane: the normal stress is absent and only shear stress is active. These planes are represented by points on the line AB in Figure 4.17b and 4.17c.
- As for the third type of plane, the normal stress is tensional to them, and these planes are represented by the grey shaded area (Fig. 4.17b & 4.17c)
- The forth type of plane is vertical, whose strike is parallel to the maximum principal stress (σ_1) and perpendicular to the minimum principal stress (σ_3). Only tensional stress exists on these planes; there is no shear stress, for instance the planes at G (Fig 4.17c) are this type of plane.

4.3.3. Effects of pore fluid pressure in fracturing

Van der Pluijm & Marshak (2004) define the pore pressure as an outward push opposing inward compression from the rock. So if it happens that the pore fluid pressure is more than the least compressive stress σ_3 in the rock, tensile stress at the edge of the crack oriented perpendicularly to σ_3 direction is enough for the crack to propagate. Step over joints are a product of pore fluid pressure. Step over joints form when one joint dies out where another, parallel, but non-coplanar one initiates. The region between the endpoints of two parallel but non-coplanar joints is called the step over area (Van der Pluijm & Marshak 2004). Such joints exist in some of the Keimoes Suite granitoids. (e.g Klipp Kraal Granite, Fig. 4.18b)

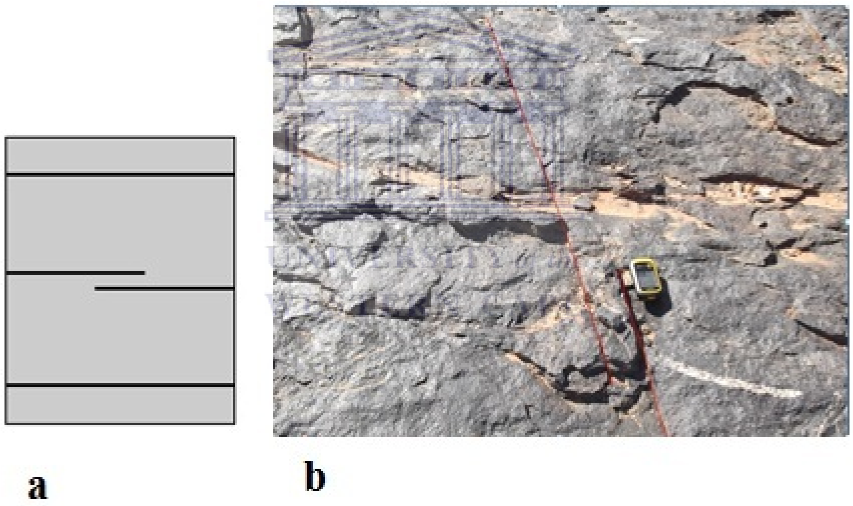


Figure 4.18 (a) Map view sketch illustrating how joint spacing is fairly constant because joints that grow too close together cannot pass each other and form a step over geometry (after Van der Pluijm & Marshak, 2004), (b) Step over joint in the Klip Kraal Granite of the Keimoes Suite.

Van der Pluijm & Marshak (2004) state that fluid flowing into joints has the ability to increase the fluid pressure to an extent that the joint begins to grow

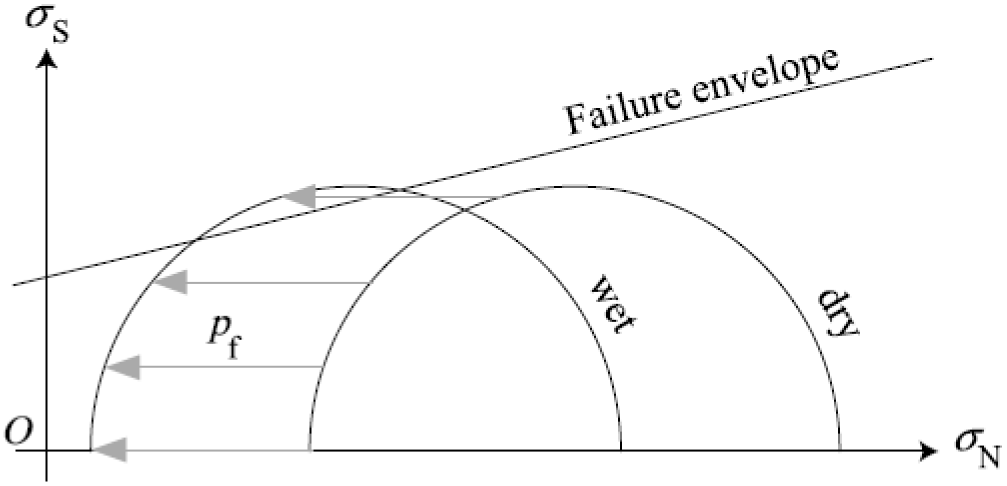


Figure 4.19. Mohr diagram showing the failure condition and effect of increasing pore-fluid pressure (after Eaton, 2011).

In the Mohr diagram (Fig. 4.19) an increase of pore fluid pressure (P_f) depresses the principal stresses acting on the body and moves the corresponding Mohr circle to the left. The dry rock is stable on the right of the Mohr circle meaning there will be no fracture taking place since it does not reach the Mohr envelope. Whereas in the same rock volume, when subjected to high fluid pressure, the Mohr circle will shift to the left and the rock becomes unstable as soon as it touches the Mohr envelope (Doglioni and Caraminati, 2008). Eaton (2011) considers pore-fluid pressure as an important factor for understanding the onset, distribution and termination of induced seismicity due to injection of fluids into the subsurface. He states that injection of pore fluid reduces the effective normal stress, and if the normal stress is reduced sufficiently then basic Mohr-Coulomb failure theory predicts brittle failure of the rock mass (Fig 4.19). Thus joints driven by high fluid pressures tend to grow in a start-stop manner and consequently their surfaces show many arrest lines. Arrest lines, also known as ripple or rib marks, initiate when the propagation of a fracture decreases in velocity, stops and moves on again. Closely spaced rib marks can indicate slow propagation velocities. The presence of arrest lines indicates a simultaneous stop of the fracture front (Ziegler, 2010).

According to Van der Pluijm & Marshak (2004) there are many reasons that influence the formation of step over joints. The reasons that cause joints to stop growing are listed below.

Van der Pluijm & Marshak (2004) state that joints stop growing if:

- the joint grows into a region where energy at the crack tip can be dissipated by plastic yielding,
- the joint propagates into a rock with a different stiffness or tensile strength
- The joint tip enters a region where the stress intensity at the crack tip becomes too small to drive the cracking process.

The decrease in stress intensity may be due to a decrease in the tensile stress magnitude in the rock, or due to an increase in compressive stress that holds the joint together.

Fossen (2010) defines the Mohr failure envelope as the envelope or curve in the Mohr diagram that describes the critical states of stress over a series of differential stress values, irrespective of whether it follows the Coulomb criterion or not. The Mohr envelope, indicated by an arrow in Figure 4.19, separates the stable field, where the rock does not fracture, from the unstable field, which is in principle impossible because fracture prevents such states of stress occurring because the rock would have failed by fracturing before such stress state is reached.

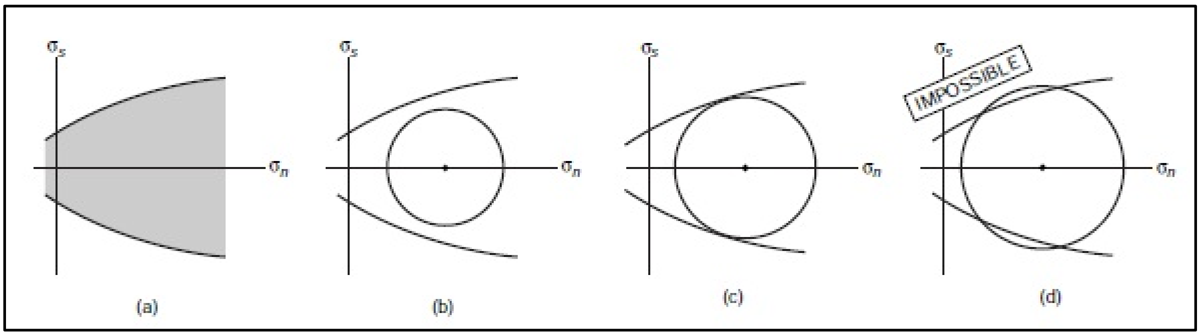


Figure 4.20. (a) A brittle failure envelope as illustrated on a Mohr diagram. The shaded area in (a) indicates stable stress states, whereas the envelope (outside the shaded area) indicates stress states that are unstable. (b) A stress state that is stable, for the Mohr circle, which passes through values for σ1 and σ3 and describes the stress state, falls entirely inside the envelope. (c) A stress state at the instant of failure. The Mohr circle touches the envelope. (d) A stress state that is impossible (Van der Pluijm & Marshak 2004).

Figure 4.20c shows the critical condition whereby rock is at the verge of failure and it is highly possible that it will fracture. Once that happens the Mohr circle can never pass the Mohr envelope because it has reached the unstable field, and, according to Fossen (2010), at that state the stress is higher than that required for failure; therefore this is an impossible situation. This is not entirely true since the orientation of the plane relative to the principal stresses is critical. Parts of the stress circle can exist above the failure envelope as it is only a graphical representation. For instance, the plane denoted by the green line in Fig. 4.21 plots below the failure envelope. At this point the relative shear and normal stress traction associated with this plane are significantly below the failure envelope so that it is stable. However, if the plane was sitting anywhere between the purple lines (marked as unstable ranges), the shear stress would be above the failure envelope and slip would occur.

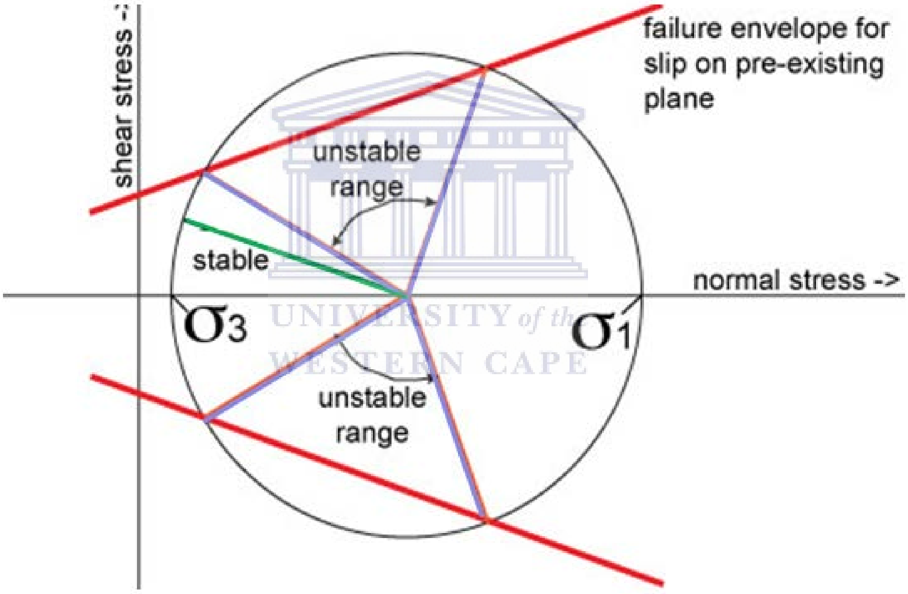


Figure 4.21 Mohr diagram displaying rock failure at a specific point. The red lines represent the failure envelopes for a specific plane or anisotropy in a rock. (i.e. a joints surface or slaty cleavage). The purple lines represent the limits of the unstable field. (Modified from Maher, M.,H. D. Jr, n.d)

4.3.4. Failure mechanism responsible for the formation of Keimoes Suite joints

The Mohr diagram demonstrates different failure mechanisms for rocks under a given normal and shear stress. Most of the Mohr diagram outlined above explains the formation of joints in the Keimoes Suite. The overall joints in the Keimoes Suite are formed as mode II fractures. Mostly they are shear joints formed in a strike-slip environment, but also step-over joints were identified during field mapping. The Keimoes Suite joints were initiated at the end of the D2 event and the beginning of the D3 event. This was still a ductile environment at this time as D3 folds have been reported by various authors. Consequently the granites are still behaving in a plastic manner. For joints to form under those conditions, high pore fluid pressure must be involved. This is demonstrated by most of the Mohr diagrams outlined above. For instance during ductile conditions the Mohr diagram still plots to the right away from origin. As pore fluid pressure is increased in the granite the mean stress remains constant but the effective stress will be reduced hence shear fracture forms as predicted by the Mohr-Coulomb diagram (Fig. 4.16) The diagram in Figure 4.19 predicts a failure of a wet rock saturated with fluids, this will cause the Mohr diagram to move to the left and as soon as it reaches the failure envelope, fracture will initiate.

The failure mechanism that was also responsible for the formation of step-over joints that were identified in some members of the Keimoes Suite is the effect of pore fluid pressure. This particular Mohr diagram predicts that rocks which are saturated by pore fluid will fracture. As the fluid pressure increases in the granites the Mohr circle slowly shifts towards the origin, the moment it touches the failure envelope meaning that the fluid pressure exceeds the cohesive strength of the rock, failure occurs thus step over joints in the Keimoes Suite were formed. Also under these conditions the veins in the Keimoes Suite formed which might have started off as Mode I fractures. In unbroken rock containing a pore fluid with dissolved minerals, the fluid pressure becomes so great that the rock cracks which initiates a slight opening. This crack will be filled with fluid because of imbalance between the fluid pressure within the open crack and the pores of the surrounding rock, thereby, resulting in a decrease of dissolved material; the minerals precipitate thus sealing the crack. This mechanism is applicable for the Keimoes Suite veins which formed near the surface, where the granite was able to allow a cavity to stay open or fluid pressure was sufficient to hold the fracture open that previously formed vein fill later recrystallized to form blocky crystals. Examples of blocky veins are to be found in the Vaalputs, Straussburg and Keboes granites.

The conjugate shear joints of the Keimoes Suite can also be predicted by the σ_1 Mohr-coulomb failure criterion (Fig. 4.15). According to this criterion shear stress needed to initiate a shear fracture is proportional to the normal stress across the fracture surface. A conjugate shear fracture, one with right-lateral shear sense and one with left lateral shear sense may form. These two fractures are separated by an angle of $\leq 60^\circ$ corresponding to the tangency points on the circle representing the state stress at failure with the Coulomb failure envelope (Van der Pluijm & Marshak, 2004). The shear failure will occur at point B (Fig, 4.15) as the Mohr circle reaches the failure envelope thus conjugate joints set of the Keimoes Suite formed under these conditions.

Shear failure will occur even if the relative values of principal σ_1 stress and minimum stress σ_3 are unchanged. This implies that differential stress that is not enough to break a dry rock may break a wet rock (Fig. 4.16), if the fluids in the wet rock are under sufficient pressure. Therefore increasing pore fluid pressure effectively weakens the rock. This is the case in the granites which are affected by high pore fluid pressure: they become weak and the joints in the Keimoes Suite formed.

Granites are not very porous like sedimentary rocks, they are intact therefore shear fracture in granites formed when the pore pressure pushed open microcracks which combined to form a rupture at smaller remote stresses. Likewise increase in pore fluid pressure effectively decreases the shear stress necessary to starts frictional sliding on a pre-existing fracture, as pore fluid pressure reduced the normal stress across the fracture surface.

4.2. Relative timing of Keimoes Suite joints

Assessing the spatial relationships of joints helps to determine the relative age of joint sets. Joints formed in the same deformation event are likely to have the same orientation~~,~~ Rocks, however, experience different stress regimes during their history with the result that several fracture sets are overlain on each other to produce fracture networks. The relative ages of different joints of the Keimoes Suite were deduced based on their cross-cutting relationships.

According to Van der Pluijm & Marshak (2004), the principal stresses are reoriented near an early joint, which is a free surface unable to support a shear stress within the rock and, thus, is a principal plane of the stress ellipsoid. Therefore later joints bend (Fig. 4.22) into an orientation at right angles to the earlier ones as they approach them and abut against these. For that reason younger joints are shorter. It was noted during fieldwork that where early joints were found to be long and fairly continuous, these early joints will stop propagation and alter the orientation of later ones, as explained above. In the case of the younger joints they commonly terminate against older joints (Fig. 4.22) because extension fractures cannot propagate across other, older extension fractures, as explained above. The diagram also show that under positive compressive stress no fracture will occur as that region is considered the safe stable zone.

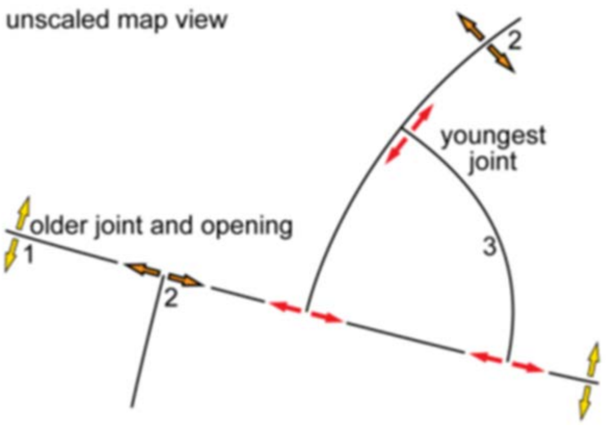


Figure 4.22 Butting relationships between joint generations with stress perturbation close to pre-existing joints (Fossen, 2010).

The Vaalputs, Keboes, Louisvale and Straussburg Granites all have joints filled with blocky vein in common. These granites are all foliated, with the Straussburg Granite showing magmatic foliation as well. In all four granites these mineral filled veins are offset by later unfilled joints which imply that the mineral filled joints are the oldest joints. This is the case throughout the study area: the unfilled joints postdate the mineral filled joints. However, the other granites do not have the mineral filled joints which suggest that they were emplaced after the Vaalputs, Louisvale, Keboes and Straussburg Granites respectively. Some of these granites do have joints and some display a fair amount of joints that are not so well developed as in the previous four granites.

The Friersdale Charnockite was emplaced after the Vaalputs, Louisvale, Keboes and Straussburg Granites. This conclusion is based on the nature of joints and the lack of foliation. The Friersdale Charnockite has veins filled with epidote, as opposed to the other veins occurring in the area which are filled with quartz and feldspar.

There is a clear differentiation of granite emplacement episodes. In this study the granites that do not have joints and foliations, for instance, are considered as the post-tectonic intrusion episode. Based on field observations, the Colston, Cnydas and Kleinbegin Granites and Friersdale Charnockite can be considered as the post-tectonic intrusions. This is attributed to the fact that they do not show significant structural features such as joints, foliations and veins like the other granites in the area. Some of the granites do show faint developing joints or fading veins, showing that these structures are still in the maturing stage. For instance, the Klip Kraal and Gemsbokbult Granites show a fair amount of jointing in them, but the Gemsbokbult Granite is not foliated. The joints in the Klip Kraal Granite can be considered as formed at the same time. Since these joints do not show any cross-cutting or intersection relationship at all they are simply sub-parallel to each other.

The Straussburg and Kanon Eiland Granites are older than the Colston Granite because they are moderately foliated and the Colston Granite is not foliated at all (Table 4.1). The N-S trending joint sets are found in the Friersdale Charnockite and Vaalputs Granite, as well as their country rocks *viz.* the Goede Hoop and Puntsit Formations respectively. Also, the Straussburg Granite has similar joint sets as its country rock, the Dagbreek Formation. This is the same with the Sout Rivier and Bethesda Formations, which are intruded by the Keboes Granite, and have the NNE trending joints. However, the Sout Rivier Formation is also intruded by the Vaalputs Granite, and shows different joint sets, namely the youngest joint set (the NE set) in this formation which coincides with the NE trending joints in the Vaalputs Granite. This means that the NNE and the ENE trending joints formed prior to the Vaalputs intrusion. In summary, considering all the joints occurring in the study area, it appears that the same joint sets exist in both granites and their country rocks.

This was the case in the Keboes granite and Friersdale Charnockite. In the Keboes Granite NE trending joints terminate against the NNW trending joints meaning they are later formed joints and they postdate the NNW joints, whereas in the Friersdale Charnockite non-systematic joints were generated after the systematic joints. The non-systematic joints were terminated at the systematic joints. In Table 4.1 the oldest joint set is termed Joint 1, followed by Joint 2, and the youngest joint set is termed J3.

Table 4.1. Chronological order of the Keimoes Suite granite emplacement based on joints and foliations. Number of x indicates intensity of foliation in the granites. The letter p for joints means that joints have been recorded.

Granite	Foliation	Joints 1-NNE	Joints 2-NE	Joints 3-NNW
Vaalputs	xxxxx	P	p	p
Louisvale	xxx	P	p	P
Straussburg	xx	P	p	p
Keboes	x	P	p	
Klip Kraal	x		p	p
Kanon Eiland	xx		p	
Friesdale Charnockite			p	p
Gemsbokbult			p	p
Cnydas				p
Colston				
Kleinbegin				

Based on the joints and degree of foliation the Keimoes Suite granites can be grouped into three episodes of emplacement. The Vaalputs and the Louisvale granites can be classified as early syn-tectonic granites. These granites have strong to moderate foliation and all joint sets are present in them. The Vaalputs granite is the oldest granite in the Keimoes Suite. Syn-tectonic granites are the Klip Kraal, Straussburg, Kanon Eiland and Keboes granites. This is based on their weak foliation, and, since the Kanon Eiland and Klip Kraal granites do not have Joint 1 they are younger than the Keboes granite. The post-tectonic granites are the Friersdale Charnockite, Gemsbokbult, Colston, Cnydas and Kleinbegin granites. These granites lack foliation and they only have the later formed joints sets Joint 2 and Joint 3.

4.5. Comparison of principal stress of the Keimoes Suite and the country rocks

Principal stress analysis helps in determining the type of environment in which the joints have formed. The results of the principal stress analysis of the joints are displayed in Figure 4.23. The relationship between the mapped joints and the principal stress is given in Figure 4.24 and the possible environment where these particular joints have formed. For instance, joints formed under a compressional environment will produce a strereoplots where σ_3 is vertical. For extensional environments the stereoplot will have σ_1 in the centre i.e. vertical and in strike-slip environments σ_2 is vertical.

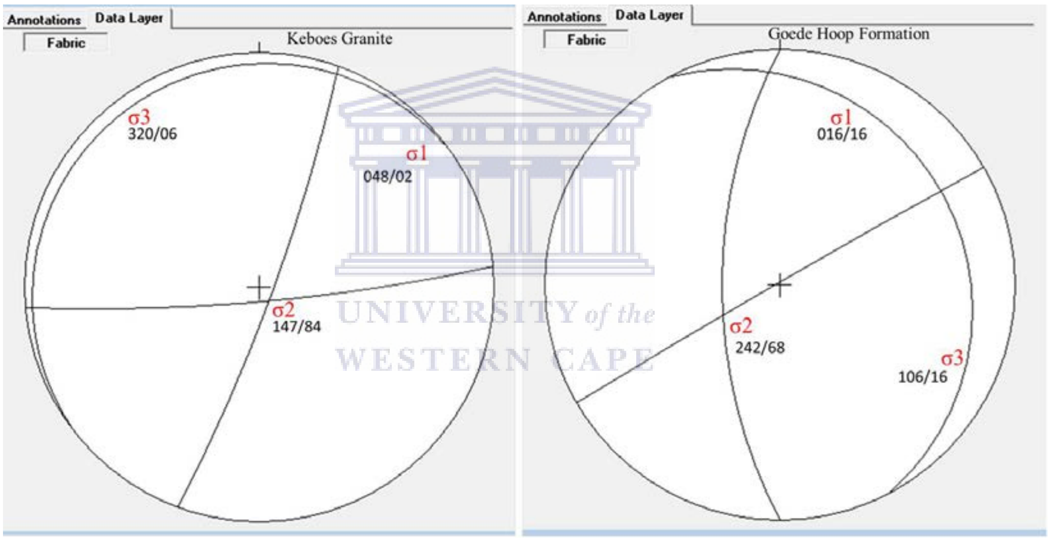


Figure 4.23. (a) Principal stress analysis of the Keboes granite (b) Principal stress analysis of the Goede Hoop Formation.

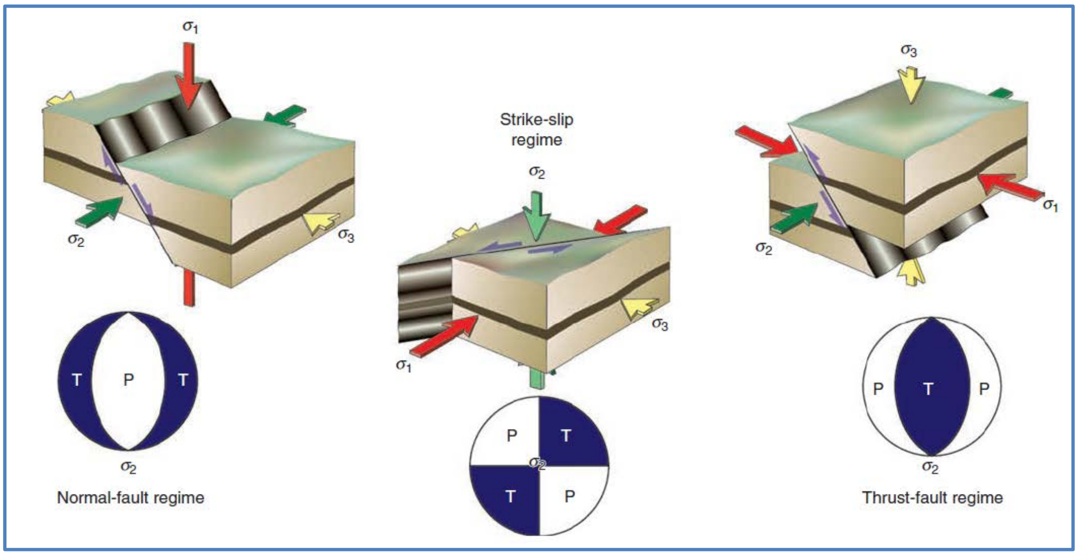


Figure 4.24. A relationship between joints and principal stress (Fossen, 2010)

The principal stress analysis diagram in Figure 4.23 and Table 4.2 shows a strike-slip tectonic environment. This means that the joints mapped across the study area are related to a strike-slip regime where σ_2 is vertical and σ_1 and σ_3 are both horizontal. Both principal stress analyses of the Keimoes Suite joints and the country rock joints indicate that the joints are related to a strike-slip environment (Table 4.2).

Table 4.2 Principal stress orientation of the Keimoes Suite granites and their country rocks

Granites	**σ 1**	**σ 2**	**σ 3**
Vaalputs Granite	199/04	057/88	289/03
Keboes Granite	048/02	147/84	320/06
Friersdale Charnockite	128/16	308/75	216/01
Straussburg Granite	090/04	236/86	000/02
Cnydas Granite	005/02	282/79	094/10
Formations			
Sout Rivier Formation	226/19	046/72	316/2
Goede Hoop Formation	016/16	242/68	106/16
Puntsit Formation	052/22	237/69	142/03

4.5.1 Change in stress field between the country rocks and the Keimoes Suite granites

Vaalputs granite has same stress field orientation as the country rock Sout River Formation. For both of them σ_1 is located in the SW. However the Vaalputs Granite as well as the Friersdale Charnockite are both intrusive to the Goede Hoop Formation and they show different stress field of σ_1 in the Goede Hoop Formation is situated in the NE and as for the Vaalputs Granite it is situated in the SW and the Friersdale Charnockite σ_1 is in the SE. Although the granites and the country rocks were affected by the same phase of deformation the later D3 which was responsible for the formation of joints in these rocks in a strike-slip environment. The different orientation of the principal stress in all the granites and the country rocks might be caused by this D3 event which was also associated with formation of strike-slip faults. Strike-slip faults may cause blocks to rotate due to differential slip along these faults this is probably what happened here as Moen (2007) reported a horizontal displacement along the Neusspruit Shear Zone between the Goede Hoop Formation block and the Keimoes Suite block.

Stresses acting on a formation vary in origin, size and direction. In-situ vertical stresses stop primary from the weight of overburden. Horizontal stresses also have a gradational component that could be enhanced by tectonics, thermal effects and geological structures. Lithology, pore pressure and temperature are factors known to have great influence on magnitudes and orientations as well as the degree which the rock reacts to stress. Hence the magnitude and orientation of stresses on earth vary with the structural dips of the formation which in turn rotates principal stresses from vertical and horizontal orientations. Cook et al. (2007) Further reported that existence of faults, salt diapirs, mountains and other complex structures also play a role in the change of stress field in rocks. The Goede Hoop Formation was affected by shearing that was activated during the D3 deformation event. These events are associated with major movement along shear zones. This might be the result of the different stress field between the Goede Hoop Formation and the Friersdale Charnockite. As stated by Cook et al., (2007) that stresses on regional structures such as faults may cause a shift in stress field in rocks. According to Moen (2007) the Cnydas Shear Zone is young and post-dates the younger members of the Keimoes Suite. This implies that the shearing could have caused the shift in the stress fields recorded in these rocks.

4.5.2. Competency difference between country rocks and the Keimoes Suite

Marmo and Wilson (2000) state that shear fractures entering relatively competent layers are refracted toward the normal to the bedding interface about an axis defined by the line of intersection of the bedding with the shear fractures. The angle of deflection is administered by the angle of incidence and the refractive index of the more competent layer. Maximum refraction arises where the intermediate principal stress σ_2 lies parallel to the layering. If the maximum principal stress σ_1 is perpendicular to the layering, shear angles become smaller where the faults pass from less competent into more competent layers. If σ_1 is parallel to the layering, the angles become larger in more competent layers than in less competent layers. For other stress orientations, refraction effects are smaller, except that no refraction occurs where σ_2 is perpendicular to the layers.

As outlined above it is clear that competency difference between layers results in refraction. This is the case in the study area. Both the country rock and the Keimoes Suite granites were subjected to same stress field that formed during D3 event. However the analysis of principal stresses between the Keimoes Suite granites and the country rock reveals a slight difference in the orientation of the principal stresses probably caused by refraction of the stresses at the interface between these rocks, which may be the result of competency difference between the Keimoes Suite granites and the country rocks.

4.6. Keimoes Suite Joints relative to regional deformational events

According to Van der Pluijm & Marshak (2004) rocks will be affected on a broad scale by compressive tectonic stress during a collisional orogenic event. Joints will form on foreland margins of an orogen during orogeny. If these joints are parallel to the σ_1 direction associated with regional structures such as folds, faults and shear zones it can be concluded that they are syn-tectonic joints. The orientation of the latest joint set (NNW) is parallel to the regional foliation and the main shear zones in the area. This joint set is considered to be the youngest based on the abutting relationship with other joints in the granites and are found in all the Keimoes Suite granites (Table 4.1).Thus, these joints can be called post-tectonic joints with respect to the D2 deformation event of the Namaqua Orogeny. Tectonic joints, according to Frances (2007), form at depth in response to high pore fluid pressure and tectonic stresses before the rocks were unearthed. Also, if joints contain minerals which formed at temperatures and fluid pressures at depth, this implies that they are not a result of recent cracking of rocks in the near surface. These joints will be called hydraulic joints, which form at depth due to high fluid pressure. The veins found in the Keimoes Suite imply that there was a second generation of deformation that took place after the earlier joints in the granites were formed. The earlier joints became sealed by the precipitation of quartz and feldspars thereby resulting in the formation of veins. These veins are found in the Straussburg, Keboes, Louisvale and Vaalputs granites Therefore, the veins indicate the oldest joints in the Keimoes Suite and they are oriented in the NNE direction.

The principal stress analysis revealed two possible tectonic events that could explain when the Keimoes Suite intruded. The conjugate joint sets found on four of the Keimoes granites (i.e. Vaalputs, Straussburg, and Keboes granites and Friersdale Charnockite) indicate a strike-slip environment. Similar conjugate joint sets were also found in the country rocks (Goede Hoop, Puntsit, Bethesda and Sout Rivier Formations; Fig. 4.23).

In a strike-slip environment σ_2 is vertical and σ_1 and σ_3 are horizontal (Fig. 4.24). Fossen (2010) states that bends in a strike-slip environment can produce either contraction and extension components depending on the sense of slip and stepping whether it is left or right oriented. These are referred to as transtension and transpression. Transpression is a compression due to strike-slip and transtension is extension due to strike-slip. Basically both transtension and transpression are due to strike-slip tectonics. Based on the compressional event D_2 that caused the foliation in some members of the Keimoes Suite granites and the joints that affected all the Keimoes Suite granites which were formed during strike-slip event

D3, a conclusion can be reached that a transpressional environment existed in the area under consideration.

4.6.1. Deformation history in the Namaqua Natal province

From literature review all the eastern terranes (Kakamas, Areachap and Kaaien Terranes) of the Namaqua Natal Province have experienced a similar structural evolution. They all have four folding phases related to four deformational events, D1-D4, where D1 is related to the S1 fabric and is partly overprinted by the main deformational event D2 (Miller, 2012). The main deformational event D2 caused isoclinal local to regional scale NNW-SSE trending folds; according to Pettersson (2008) this is related to the main Namaquan tectonism. The D2 deformation event was then followed by the D3 event characterized by wrench faulting near major shear zones. The last deformation event, D4, is related to NW trending movements of sub-vertical shear zones and faults related to compression from the SW and affected by the geometry of the wedge shaped Kaapvaal Craton.

4.6.2. Deformation history of the Keimoes Suite

The Keimoes Suite is bordered by NW and NNW trending structures such as the Neusspruit Shear Zone and the Brakbosch Fault. Considering the results of structural analysis of the Keimoes Suite, this leads to a clear deduction of the tectonic environment of the area. The principal stress analysis reveals a strike-slip regime whereby σ_2 is vertical, and σ_1 and σ_3 are almost horizontal and perpendicular to it.

The findings from the Keimoes Suite investigation agree with literature. Van Bever Donker (1990) reported a strike-slip and compressional environment for the Areachap Group. The Keimoes Suite granites intrude the Areachap and the Kakamas Terranes. The joints of the Keimoes Suite relate to a collision event accompanied by isoclinal folding of rocks of the Areachap and Kaaien Terranes resulting in the closure of the Wilgenhoutsdrif depositional basin (Pettersson et al., 2007). There is a general consensus among various authors (Pettersson, 2008;

Bailie et al., 2011; Pettersson and Cornell, 2008; Miller, 2012; Eglington, 2006 and Pettersson et al., 2007) that the D2 is the main deformational event that was responsible for the isoclinal local to regional scale NNW-SSE trending folds.

The D2 deformational event took place approximately at 1.18-1.15 Ga. Eglington (2006) further reported two major period of granitoid intrusion that occurred at 1.15 Ga and 1.03-1.08 Ga which were both regional extent. The Keimoes Suite intruded during the second period of intrusion which took place a 1.03-1.08 Ga.This event is the second major magmatic event that intruded into a tensional setting, affecting the eastern Namaqualand, Kakamas, Areachap and Kaaien Terranes (Pettersson and Cornell, 2008). The stresses which were released during this magmatism in the tensional environment contributed to the formation of the Keimoes Suite joints.

Literature review further reveals that the collision between the Areachap and Kheis-Kaapvaal Craton led to intense deformation and medium to high grade metamorphism in both sectors. This resulted also in extensive crustal melting and generation of voluminous granitoid magmas (Fransson, 2008). This could be the ideal situation when the magma of the Keimoes Suite was generated.

The shear zones forming a border around the Keimoes Suite were created by lateral escape of the Areachap volcanic arc. This happened after the long period of collision where there was no more crustal shortening taking place through low angle-thrusting and crustal thickening (Fransson, 2008). According to Fossen (2010) and Van der Pluijm and Marshak (2004), lateral escape is defined as a process whereby two converging continents cause blocks of crust caught between the colliding masses to become squeezed laterally out of the zone of collision.

Most of the Keimoes Suite joints relate to the pull-apart basins formed due to post collision strike-slip movements (Patterson et al., 2007), such as those into which the Koras Group bimodal volcanic rocks were emplaced. Therefore the tectonic stresses that were responsible for the Keimoes Suite joints correspond with the tectonic activity that was mentioned in the literature review.

Passchier and Urai (1988) state that since every progressive step of deformation overprints older effects, all data must be retrieved from the final rock fabric in order to reconstruct the deformation history of an area. In this study the joints and foliation are used to reconstruct the deformation history of the Keimoes Suite.

According to Passchier and Urai (1998) there are two methods that can be used to obtain data on the deformation paths from the final fabric: one is determination of the mechanism of fabric development in order to correctly interpret fabrics in terms of flow or deformation parametres. The second one is development of a theoretical background showing how the variation of parametres with time influences finite deformation.

In the Keimoes Suite, fabric elements that were recorded are foliations, folded veins, as well as fibrous veins and joints. These elements were used to depict the deformation history in the Keimoes Suite and to determine the relative timing of emplacement of the granites. Within the study area some granites were found to be unfoliated while others were foliated. This means that the Keimoes Suite granites were affected by different deformational events, so giving the relative timing of emplacement.

Not all the granites were affected by the foliation developed during the D2 deformation event. The oldest joints in the Keimoes Suite are striking in the NNE direction termed Joint 1. These joints are filled with quartz and feldspar. Precipitations of these minerals in the NNE joint sets indicate that these joints were formed during greenschist facies condition at temperatures above 300C˚ just after the peak of the thermal M2 metamorphism (Miller, 2012).

Bailie et al. (2011) reported M2 metamorphism to have been caused by contact metamorphism reaching temperature of 700-800 ˚C at pressure of 4.5kba as a result of the intrusion of the syn-tectonic granitoids of the Keimoes Suite. The peak M2 was accompanied by the peak D2 deformation event that formed large scale tight to isoclinal sub-vertical F2 folds with NW-trending axial traces. Therefore the Vaalputs Granite is the oldest granite of the Keimoes Suite based on its intense foliation that was formed during the D2 deformation event. Toward the end of the M2 metamorphism and D2 deformation event of the Namaquan orogeny the Straussburg, Kanon Eiland, Louisvale, and Klip Kraal Granites were emplaced as they show moderate to weak foliation compared to the Vaalputs Granite.

The Vaalputs granite is the oldest granite of the Keimoes Suite and it is considered pre-tectonic with respect to the D2 deformational event and the M2 metamorphism. This agrees with the literature where Bailie et al. (2011) report that continental collision between the Kaapvaal Craton and the Bushmanland Subprovince of the Namaqua Sector gave rise to extensive magmatism and the peak M2 metamorphism. This is when the above mentioned granites were emplaced and the metamorphism ended. The degree of foliation in the Straussburg, Kanon Eiland, Klip Kraal, Louisvale and Keboes granites allows us to classify these granites as late-syn-tectonic.

The emplacement of the Friersdale Charnockite, Kleinbegin, Gemsbokbult, Colston and Cnydas Granites post-date the D2 deformation and M2 metamorphism event. Therefore these granites are post-tectonic with respect to the D2 event. All these granites were not affected by this event. This is supported by the absence of foliation in these granites and the lack of NNE joint sets. It appears that there was a second episode of vein deformation and this affected only the Friersdale Charnockite; the joints in the Friesdale Charnockite are filled with epidote although this granite is not foliated but the presence of these veins differentiate the intrusion age of the Friersdale Charnockite from that of the other granites. The epidote filled joints in the Friersdale Charnockite are older than the NNW and NE joint sets respectively. However, the Friersdale Charnockite, Colston, Cnydas, Kleinbegin, Gemsbokbult granites are post-tectonic with respect to the D2 deformational event.

The second generation of joints is Joint 2, the NE set which occurs in all the granites, and post-dates the NNW joint set. The NNW and NE joints sets are not filled with minerals; the same was observed in Joint 2, which is the NE set. The joints in the Keimoes Suite are sub-vertical dipping (70-90^{o}) which means they are either strike-slip shear joints or mode I tensional joints, but as shear displacement was noticed during field mapping these joints can be classified as mode II fractures, being strike-slip and the tensional option can be discarded. From the principal stress it was apparent that they formed in a strike-slip environment. This coincided with the D_3 (F_3) deformation events which may have resulted from slip on conjugate shears, varying from E-W in the north to NE-SW in the south. Post D3-structures are related to wrenching along the major strike-slip shear zones resulted in faulting trending NNE to NW. The strike-slip event was the last deformation event to occur in the Keimoes Suite. All the joints were formed in this environment and they are found in all the granites of the Keimoes Suite.

4.6.3. Comparison of relative ages with previous studies

Based on the foliation Bailie et al. (2011) grouped the Vaalputs and the Louisvale Granite as early syn-tectonic granites and consider these granites to be well foliated. They further reported that these granites were probably emplaced during the D2 deformation event. The moderate to foliated granites are grouped as syn-tectonic and Colston Granite falls under this group. The younger member of the Keimoes Suite are grouped as post-tectonic based on the fact that they are not foliated and they intrude older members of the Keimoes Suite. According to Bailie et al. (2011) the post tectonic granites are Klip Kraal, Keboes, Kanon Eiland, Gemsbokbult Granites as well as the Friersdale Charnockite. These intrusions of post-tectonic granites were associated with the M3 metamorphism and D3 deformation around 1100Ma.

Cornell et al. (2012) dated the Straussburg Granite and the Friersdale Charnockite using the zircon U-Pb emplacement. Their results showed that the Friersdale Charnockite is the youngest member of the Keimoes Suite which is in agreement with what Bailie et al. (2011) reported, and the Straussburg Granite is older than the Friersdale Charnockite. These data by Cornell et al. (2012) and Bailie et al. (2011) coincide with some conclusion of this study. However, they consider both these granites as post-tectonic with respect to the ~1200Ma collision of the Namaqua orogeny. Based on the similar major element composition and normative mineralogy they are both classified as monzogranites. They are not in agreement with other authors who classified the Straussburg Granite as late syn tectonic based on the granite being foliated. They consider the foliation in the Straussburg granite as formed during magma emplacement in contrast to main deformation D2 event. As a result they provided precise age for the Straussburg as 1090Ma.

It is well demonstrated that foliation in the Keimoes Suite plays a role in determining relative age of emplacement for granites with respect to deformation events. There is however an alternative way to determine relative age of emplacement of granites. Using joints occurring in granite can provide relative timing of granitoids and be able to link to regional deformation event that affected the granitoids. The main aspect of this work was to determine the relative timing of Keimoes Suite emplacement with respect to the Namaqua deformation events using joints occurring in the granite. Successfully the members of the Keimoes Suite were grouped into three categories, early syn-, late syn- and post-tectonic relative to the D2 deformation events. This grouping was based on foliation like previous studies did and reinforced by making use of the various types of joints. The results from the joints show similar results from literature. Three joint set were used to date the granites, the NNE-J1 is the oldest joint set and NE-J2 and NW-J3 are the youngest joints respectively. All three joints sets were found on the Vaalputs, Straussburg, Keboes and Louisvale Granites.

The Vaalputs Granite was considered early syn-tectonic with respect to 2 deformation based on the joints present and the degree of foliation. This is in agreement with what has been reported by Bailie et al. (2011) and Cornell et al. (2012).The Kanon Eiland and Klip Kraal Granites are younger than the Vaalputs, Straussburg, and Louisvale Granites based on the absence of joint 1, but are older than the Gemsbokbult, Kleinbegin, Cnydas, and Keboes Granites as well as the Friersdale Charnockite based on the occurrence of both Joint 2 and joint 3 and the presence of foliation in the former as opposed to the latter.

The post-tectonic granites are the Gemsbokbult, Kleinbegin, Cnydas, Colston Granite and the Friersdale Charnockite because J1 pre dates J2 and J3 in these granites and they are not foliated. Although Bailie et al. (2011) considered the Keboes and the Klip Kraal Granites as post tectonic however they did not provide precise ages for these granites. Their conclusion was based on the intrusive relationship with the older members of the Keimoes Suite granites. In this study they were found to fall under the late syn-tectonic group based on the various joints as outlined above. Then precise age for these granites needs to be done using accurate methods such as the Zircorn dating. In closing this project was able to provide another alternative method from the existing ones for determining relative timing of emplacement of granites.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The overall joints in the Keimoes Suite are formed as mode II fractures. Mostly they are shear joints formed in a strike-slip environment. The evidence that supports the Mode II fractures is the presence of conjugate sets and sigmoidal veins indicating the sense of shearing, as well as the tightness of these joints. The Keimoes Suite joints were initiated at the end of the D2 event and the beginning of the D3 event. This was still a ductile environment at this time as D3 folds have been reported by various authors. Consequently the granites are still behaving in a plastic manner. For joints to form under those conditions, high pore fluid pressure must be involved. This is demonstrated by most of the Mohr diagrams outlined in the study. For instance during ductile conditions the Mohr diagram still plots to the right away from origin. As pore fluid pressure is increased in the granite the mean stress remains constant but the effective stress will be reduced hence shear fracture forms. Therefore pore fluid pressure played a major role in the formation of these joints in a strike-slip environment.

The D2 deformation event is characterized by compression and isoclinal folds. The foliation mapped here coincided with the regional shear zones, meaning that they were controlled by regional structures as they show the same orientation in the NW and NNW direction as the regional sub-vertical shear zones as well as the folds.

5.1.1. Timing of emplacement using foliation

The source of magma for the Keimoes Suite granitoids is believed to be formed during the collision between the Namaqua block and the Kheis-Kaapvaal Craton which caused intense deformation and medium to high grade metamorphism. The emplacement of the Keimoes Suite granite took place in three distinct episodes, early syn-, late syn- and post tectonic with respect to the D2 deformational event.

The early- and late syn- tectonic granites of the Keimoes Suite show some similarities which make it difficult to distinguish between the two. However, the Vaalputs Granite is considered the early syn-tectonic granite with respect to the D2 deformational event based on strong foliation in the granite. The weaker foliation is what separates the late syn-tectonic granites from the early syn-tectonic Vaalputs Granite. The late syn-tectonic granites are the Kanon Eiland, Straussburg, Louisvale, Keboes and Klip Kraal Granites. The post tectonic granites are based on the absence of foliation, such as the Colston, Gemsbokbult, Kleinbegin, Cnydas Granites and the Friersdale Charnockite. These granites are not foliated, and are, therefore, considered post-tectonic granites with respect to the main D2 deformation event.

5.1.2. Timing of emplacement using joints

Three sets of joint were used to determine the relative timing of the Keimoes Suite granites. Joint set 1, which strikes in the NNE direction, is the oldest joint set in the Keimoes Suite. This is attributed to the fact that it is filled with quartz and feldspar and, in some cases, epidote, and was offset by the later formed joint sets joint 2 and joint 3. Only the Vaalputs, Straussburg, Louisvale, Keboes and Louisvale Granites display joint 1. However, the Keboes Granite is the only unfoliated granite among these granites making it younger than the foliated granites; the Joint 1 post-dates the foliation event in these granites. Joint 2 striking in the NNW direction, and Joints 3, striking in the NE direction, are the prominent joints occurring in most of the granites.

The relationship between the NE and NNW striking joints is confusing as it is hard to tell which one came first as they displace each other in different members of the Keimoes Suite meaning they formed at the same time but later than joint 1. The Kanon Eiland and Klip Kraal Granites are younger than the Vaalputs, Straussburg, and Louisvale Granites based on the absence of joint 1, but are older than the Gemsbokbult, Kleinbegin, Cnydas, and Keboes Granites as well as the Friersdale Charnockite based on the occurrence of both Joint 2 and joint 3 and the presence of foliation in the former opposed to the latter. Here Joint 1 pre-dates

Joint 2 and joint 3. Therefore the Gemsbokbult, Kleinbegin, Cnydas, Colston Granites and the Friersdale Charnockite are the youngest granites of the Keimoes Suite based on the joint occurrence. Seeing that all the Keimoes Suite granites are jointed this means they were all affected by the same stress field, however on different occasions. The principal analysis of the joints revealed a strike-slip environment which coincided with the D3 event characterized by wrench faulting near major shear zones.

In conclusion, the joints in the Keimoes Suite formed as a result of later deformation processes, in this case the D3 deformation event associated with a strike-slip environment.

5.1.3. Sequence of deformation events that affected the Keimoes Suite

The sequence of deformation events in the Keimoes Suite is as follows: first intense magmatism and deformation accompanied the collision event between the Areachap volcanic arc and the Kheis-Kaapvaal Craton. During the collision event the oldest early syn-tectonic Vaalputs Granite was emplaced. Continuing deformation resulted in the foliation developed in the granite. Subsequently the late syn-tectonic granites were emplaced and affected by the reduced degree of deformation which resulted in weak foliation in the granites.

The emplacement of the late-post tectonic granitoids of the Keimoes Suite can be correlated with the closing stage of the folding event between 1.18 Ga and 1.75 Ga prior to the development of transcurrent shears. Subsequently the D3 deformation event, characterized by wrench faulting near major shear zones, took place around 1.10 Ga. This ended in strike-slip activity, which began during the F_2 stage, and resulted in faulting trending NNE to NW. The strike-slip deformation event was the last event affecting the Keimoes Suite.

Structural interpretation of the Keimoes Suite and the country rock with special focus on joints, veins and foliation provided meaningful results. Through joint analysis, the results indicated a strike-slip environment. The foliation in some of the Keimoes Suite granites implies that there was a compressional environment that resulted in the formation of foliation. Since not all granites are foliated it means they intruded after the foliation forming event but they have joints formed in a strike-slip environment. It suggests that strike-slip deformation events succeeded the compressional event.

Both the country rock and the Keimoes Suite granites were subjected to the same stress field that governed the D3 event. However the analysis of principal stresses between the Keimoes Suite granites and the country rock reveals a slight difference in the orientation of the principal stresses. This is caused by the difference in competency between the Keimoes Suite granites and the country rock which caused the refraction of the joints leading to the slight differences in the resultant interpretation of the stress fields.

This work partly corroborates the findings that were reported by various authors (Bailie et al., 2011and Cornell et al., 2012) who did work in the same area. This study and their finding is in agreement that the Keimoes Suite granitoids can be grouped into early syn- late syn- and post-tectonic with respect to the D2 deformation event. Bailie et al. (2011), Cornell et al. (2012) and this study show that Vaalputs Granite is the oldest member of the Keimoes Suite and that the Friersdale Charnockite is the youngest member. There are some overlaps between the studies as most of the Keimoes Suite granites are classified similar. However there is a contradiction in some cases such as for the Straussburg, Klip Kraal and Keboes Granites.

Cornell et al. (2012) considered the latest as post tectonic granites based on precise dating and here in they were grouped as late syn-tectonic granites based on foliation and jointing. Also Bailie et al. (2011) considered Klip Kraal and Keboes granites as post-tectonic based on intrusive relationship with the older granites of the Keimoes Suite. They did however not provide precise ages for these granites nor is there an existing age of emplacement of this granite in literature. The relative age provided for these granites in this work will remain unchanged. Klip Kraal and Keboes Granites can now be considered as late syn-tectonic granites and Straussburg Granite can therefore be accepted as post- tectonic as Cornell et al. (2012) provided precise age for this granite to be 1090Ma.

5.2. Future work and recommendations

Although this study managed to provide information on the relative timing of the Keimoes Suite emplacement with respect to the Namaqua deformation events, there is still a lot of work that needs to be done on the Keimoes Suite. More work needs to be done in terms of clearly classifying the granites, as some granites appear the same as their neighbouring granites~~,~~ in terms of mineralogy and appearance. The Keimoes Suite granites host veins filled with different mineralogy and texture. These veins can provide information on the different temperature conditions and deformation episodes that occurred in the granites which, in turn, may help to determine the timing of emplacement of the various members of the Keimoes Suite more accurately. However the most accurate and precise way of determining the ages of emplacement of the Keimoes Suite granites and the deformation events that affected them is to use the ion-probe technique of zircon dating. This technique allows precise age determination of rock-forming events in complex metamorphic areas such as the Namaqua Natal Province. Since there are only few Keimoes Suite granites that were dated using this technique it is recommended that the remaining Keimoes Suite granite be dated as well to get their precise age of emplacement.

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APPENDICES

APPENDIX A: Raw Data of Joints Measurements

Keimoes Suite

Table 1: Keboes granite

Dip	Direction	Dip	Direction	Dip	Direction
66	302	89	154	85	150
74	37	80	298	70	290
90	160	90	334	85	34
89	278	75	282	83	355
70	300	80	76	85	120
87	284	89	20	85	90
85	78	89	321	86	167
80	281	80	178	85	123
79	266	70	293	82	175
85	110	70	354	90	124

Table 2: Cnydas Granite

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
90	290	80	252	79	291	85	347
82	216	82	265	80	74	85	141
82	285	90	267	60	254	50	304
86	271	85	259	80	83	66	271
90	250	90	121	89	73	85	75
85	255	90	333	85	281	85	299
85	80	90	125	85	248		
80	304	87	263	90	300		

Table 3: Gemsbokbult Granite

Dip	**Direction**	**Dip**	**Direction**	**Dip**	**Direction**
85	137	85	336	90	270
85	336	82	102	89	107
89	166	86	327	85	342
85	145	65	196	85	325
85	155	85	323	90	341
90	340	75	138	90	177
90	343	70	320	85	160
85	38	85	12	89	167
90	207	89	20	86	271
90	147	75	255	85	195
90	178	80	320	89	283
75	313	85	325	70	264
87	270	89	93	85	233
72	300	85	89	86	233
89	46	90	277	85	176
90	26	90	298	90	213
89	60				

Table 4: Klip Kraal Granite

Dip	**Direction**	**Dip**	**Direction**	**Dip**	**Direction**
89	322	85	320	85	160
89	311	85	340	85	320
90	330	90	325	90	155
86	327	85	338	90	344
85	131	90	345	90	154
89	305	85	332	85	155
90	306	90	155	89	152
90	321	90	319	90	170
85	126	90	330	80	171
85	150	85	137	85	162
89	125				

Table 5: Louisvale Granite

Dip	Direction	Dip	Direction	Dip	Direction
85	330	70	291	89	308
85	338	85	110	90	118
80	359	88	199	90	65
85	150	90	290	67	54
88	342	80	169	89	220
90	156	74	289	88	310
85	344	90	141	90	261
90	150	90	326	85	159
90	327	85	150	89	146
85	116	89	354	90	142

Table 6: Kanon Eiland Granite

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
85	176	85	286	85	96	75	266
89	266	85	93	90	147	85	205
90	162	86	95	89	210	82	352
85	276	85	355	90	220	69	358
89	102	89	253	90	201	89	356
85	116	85	342	89	136	89	339
85	113	90	182	89	196	64	338
75	26	90	345	90	100	62	339
85	92	60	15	90	144	90	86
90	194	74	350	89	270	89	29
85	106	69	354	89	172	90	280

Table 7: Vaalputs Granite

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
90	91	86	289	90	134	90	125
90	82	85	102	89	142	89	136
70	270	85	250	85	226	86	154
85	327	90	204	89	319	85	148
86	239	80	325	84	339	85	155
75	252	89	337	89	279	90	153
70	236	89	311	90	330	86	180
89	294	90	140	90	327	86	174
86	260	89	298	89	141	69	319
90	275	82	331	86	314	80	326
87	270	90	149	89	318	86	328
79	302						

Table 8: Straussburg Granite

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
86	135	89	345	85	62	89	225
75	317	89	153	90	139	84	142
85	117	87	338	86	232	90	96
85	322	87	165	89	246	85	260
89	344	89	91	89	157	90	260
89	249	89	265	85	226	89	127
84	341	89	139	85	150	86	91
84	104	90	260	86	236	77	89
85	29	89	249	90	257	87	144
84	41	89	220	69	235	89	155
84	74	86	245	85	329	89	329
79	342	90	239	90	159	90	277
89	210	89	307	89	218	85	140
90	90	89	300	85	270	85	248
89	224	70	345	84	175	89	230
74	74	90	270	87	329		

Table 9: Friesdale Charnockite Granite

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
85	235	84	127	86	155	85	259	90	234
85	156	52	188	86	200	90	156	85	262
84	320	89	146	86	266	85	165	85	260
85	198	64	159	90	260	90	116	85	265
90	145	80	250	89	266	89	271	80	258
75	142	70	318	89	285	80	281	90	280
80	85	89	232	90	90	90	278	85	326
89	85	89	242	89	85	90	200	90	304
89	269	85	327	85	70	85	100	85	194
89	119	89	156	90	45	85	293	85	320
89	15	80	260	85	183	85	291	86	256
89	322	90	115	90	266	85	280	85	224
45	54	85	320	85	130	89	160	90	145
85	257	90	279	89	339	85	249	90	84
83	170	90	85	85	83	80	234	89	265
90	233	90	130	89	334	90	265	90	232
85	325	90	150	80	210	85	237	89	350
65	144	90	90	85	235	89	270	89	330
80	202	90	75	85	20	85	230	85	170
85	245	85	269	85	50	89	253	79	280

Country rocks

Table 10: Sandput Formation

Dip	Direction	Dip	Direction	Dip	Direction
72	306	75	300	65	312
80	180	60	170	85	189
79	312	79	345	80	320
60	207	65	200	70	288
85	322	89	330	85	330
85	320	70	270	85	336
79	315	85	325	75	178
82	316	65	230	79	280
70	290	55	290	89	304
89	320	85	130		

Table 11: Dagbreek Formation

Dip	Direction	Dip	Direction	Dip	Direction
85	191	80	309	89	322
65	356	85	333	90	320
85	298	86	347	85	150
85	140	85	324	85	336
70	324	90	180	90	332
80	279	85	330	90	329
85	170	89	319	90	350
90	324				

Table 12: Bethesda Formation

Dip	Direction	Dip	Direction	Dip	Direction
90	328	89	280	90	154
90	341	90	298	90	105
90	240	88	283	90	335
85	271	90	180	90	310
90	282	90	262	85	136
85	180	90	185	85	140
90	130	85	250	90	290
90	132	89	220	89	281
85	130	90	192	90	289
90	305	90	295	80	112
85	117	85	139	85	281
90	351				

Table 13: Puntsit Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
90	277	85	250	85	134	84	272	85	293
75	125	80	264	90	275	85	328	85	77
80	135	74	300	90	279	90	334	82	84
90	115	82	67	80	330	84	302	79	324
74	205	86	301	75	270	80	108	90	135
80	322	79	75	75	346	80	160	85	162
82	265	69	20	80	290	85	116	85	156
70	327	89	342	86	263	85	120	72	119
40	19	85	353	67	49	80	99	67	60
25	12	85	280	90	292				

Table 14: South River Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
75	304	90	295	85	277	90	316
80	110	85	234	90	310	90	330
75	115	79	111	85	243	85	155
85	160	85	310	90	135	85	120
85	284	85	335	90	210	85	255
90	230	90	340	90	295	90	270
90	155	80	338	90	231	90	335
90	246	85	340	85	316	90	314
90	280	85	354	85	300	85	319
90	144	85	327	76	119	90	115
90	280	82	320	85	145		

Table 14: Goede Hoop Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
72	306	89	330	75	178	90	250	85	184
80	180	70	270	79	280	90	322	89	85
79	312	85	325	89	304	89	333	85	150
60	207	65	230	85	130	89	257	90	283
85	322	55	290	70	290	80	135	85	142
85	320	89	320	82	316	80	95	90	95
79	315	65	312	85	115	85	323	85	342
75	300	85	189	85	175	89	270	85	244
60	170	80	320	90	181	85	82	85	285
79	345	70	288	80	139	85	129	70	353
65	200	85	330	90	277	59	167	85	138
85	132	85	336	89	274	84	95	89	82

APPENDIX B: Raw Data of Foliation Measurements

Table 1: Kanon Eiland Granite

Dip	Direction	Dip	Direction
85	342	82	352
90	182	64	338
90	345	69	358
60	15	62	339
74	350	69	354

Table 2: Sout River Formation

Dip	Direction	Dip	Direction	Dip	Direction
60	39	65	28	60	44
60	36	60	25	60	40
60	28	70	30	74	50
60	21	73	35	60	31
70	31	40	35	70	43
65	35	65	37	75	35
33	60	63	34		

Table 3: Dagbreek Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
55	36	69	30	50	38	55	37	50	38
58	40	75	31	45	36	55	38	55	42
55	42	55	40	45	40	50	40	45	40
50	43	55	38	45	44	65	35	45	37
75	53	55	35	50	40	50	40	45	36
70	30	55	42	50	40	55	44	45	40
70	36	55	38	45	45	70	34	50	44
70	30	50	45	45	35	50	42	50	45
70	34	55	42	55	37	51	46	45	38
70	28	55	40	55	38	55	45	45	40
50	43	60	36	45	40	45	45	45	40
50	45	45	35	50	44				

Table 4: Puntsit Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
70	165	70	145	65	153	70	178	60	179
65	167	75	138	65	156	62	171	70	177
60	173	65	130	70	154	75	170	60	168
60	172	65	134	80	185	75	172	65	175
65	180	65	140	80	189	70	178	70	165
65	200	70	145	75	189	62	171	70	170
65	149	60	165	75	189	65	170	70	168
65	145	70	140	75	182	65	172	75	175
65	148	70	145	75	190	70	174	70	174
70	142	65	148	75	183	65	185	64	154
70	155	65	150	75	172	70	185	65	155
60	171	65	155	75	172	70	195	65	177
65	195								

Table 5: Goede Hoop Formation

Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction	Dip	Direction
45	70	40	70	54	70	42	70	50	65
41	70	42	65	37	70	35	70	48	70
40	70	38	65	44	70	35	70	42	70
44	65	46	66	48	70	35	74	44	65
38	70	46	65	51	70	40	70	41	70
55	65	45	70	46	70	45	70	46	70
42	68	45	70	52	70	45	72	46	65
36	70	43	68	45	70	43	71	52	65
35	70	45	61	45	72	35	70	35	65
46	68	51	70	40	74	45	70	45	65
40	70	47	66	40	65	42	70	45	65
42	70	46	70	38	65	36	70	50	60
37	65	45	65	44	70	49	68	51	75
37	70	38	65	47	65	43	65	46	62
41	68	41	70						

APPENDIX C: Raw Data of Keimoes Suite Veins Measurements

Table 1: Straussburg Granite

Dip	Direction	Dip	Direction
84	229	85	214
84	228	90	355
75	165	89	196
89	204	75	231
79	229	85	180
78	189	73	190
89	196		

Table 2: Vaalputs Granite

Dip	Direction	Dip	Direction
85	199	75	79
80	192	81	220
79	190	70	214
75	195	80	204
70	235	89	144
79	135	89	214

Table 3: Friesdale Charnockite Granite

Dip	Direction	Dip	Direction	Dip	Direction
66	200	80	265	80	10
89	185	80	307	80	210
79	199	85	20	70	350
85	184	85	17	85	334
85	40	85	153	70	144
85	133	69	170		

Table 4: Keboes granite

Dip	Direction
85	244
85	260
78	212