A study into the main structural features of the Namaqua region and their relation to the intrusion of the Keimoes Suite.

NOMPUMELELO SITHOLE

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

UNIVERSITY of the
WESTERN CAPE

Supervisors

Professor Jan Van Bever Donker

Dr. Russell Bailie

November 2013

Keywords

Namaqua Sector

Transpression

Tectonics

Keimoes Suite

Remote sensing

Shear zone

Fault system

Lateral escape

Pull-apart Basin

Granitic Emplacement

UNIVERSITY of the
WESTERN CAPE

ABSTRACT

The thesis provides a study into the main structural features of the Namaqua Region and their relation to the intrusion of the Keimoes Suite. This was achieved by producing a digitized map of the Namaqua Region structural framework using a LandSAT image and MOVE software for remote sensing. The structural framework showed an array of shear zones and fault systems which trend in a NW-SE direction. The validation of the sense of movement, location and orientation of the shear zones was done by field mapping. The general orientation of all shear zones was NW-SE. The sense of movement along the Neusspruit, Boven Rugzeer and Trooilapspan shear zones was found to be dextral strike slip movement and the Cnydas shear zone had a sinistral strike slip movement. The location of the shear zones were determined by analyzing the deviation in general foliation trend which was visualized using Rose Diagrams. The field data and the remote sensing were found to agree with the transpressive environment of the Namaqua Region.

The oblique collision of the Namaqua-Natal crustal block with the Kaapvaal Craton during the orogenic event at ~1.2 Ga created a compressional geotectonic setting which allowed for the intrusion of the early to late syn-tectonic Keimoes Suite granites. The lateral escape of the Namaqua-Natal crustal block took place along the western margin of the Kaapvaal Craton. This was brought on by prolonged compression which resulted in the formation of a releasing bend in the Namaqua Region. This releasing bend produced the negative flower structure with dextral shear zones which facilitated the intrusion of the post-tectonic Keimoes Suite granites.

UNIVERSITY of the
WESTERN CAPE

DECLARATION

I declare that a study into the main structural features of the Namaqua Region and their relation to the intrusion of the Keimoes Suite 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.

Nompumelelo Sithole November 2013

Signed: _______________

UNIVERSITY of the
WESTERN CAPE

ACKNOWLEDGEMENTS

I would like to acknowledge the following people;

Professor Jan van Bever Donker and Dr Russell Bailie for your extensive knowledge, advice and guidance. I would like to thank Dr Siad and Mr. Henok Solomon for helping with the remote sensing part of the study. My colleagues Portia Mokoena, Sedzani Nethenzeni and Stephen Tsakou who shared their insights through various discussions on the study and also contributed great laughs during the field work. Finally I would like to thank my mother Dolly Sithole, who was the inspiration for this MSc thesis, mom this one is for you.

UNIVERSITY of the
WESTERN CAPE

CONTENTS

UNIVERSITY of the
WESTERN CAPE

UNIVERSITY of the
WESTERN CAPE

LIST OF FIGURES

UNIVERSITY of the
WESTERN CAPE

UNIVERSITY of the
WESTERN CAPE

1. ***CHAPTER ONE: INTRODUCTION AND PREVIOUS WORKS***

1. **Introduction**

The study area is located in the Namaqua Sector of the Namaqua-Natal Metamorphic Complex, found along the western margin of the Kaapvaal Craton (Fig 1.1). The study is focused on the relationship between the regional structural framework of the Namaqua Province and the emplacement of the Keimoes Suite Granites.

The amalgamation of supercontinents is attributed to cyclic events where there are periods of crustal growth and the development of orogenic belts (Petterson, 2008). These orogenic belts are characterized by magmatism, regional metamorphism and deformation such as folding, faulting and thrusting (Petterson, *op.cit.*).

The orogenic belts can also provide information about the nature of the collision that took place whether a continent-continent or continent-island arc collisional zone (Petterson, *op.cit.*). Furthermore the orogens are divided into terranes based on factors such as tectonic framework, sense of deformation and stratigraphy with the prominent regional structural features used as the boundaries between terranes (Moen, 2007).

UNIVERSITY of the
WESTERN CAPE

The terranes of the orogens are composed of "*ocean island arcs, fragments of older continental crust, ocean floors and sediments"* which are added onto an *"older stable crustal block"* such as cratons (Petterson, *op.cit*.). This is the case with the formation of the Namaqua orogenic belt during the Mesoproterozoic basement development during the assemblage of the supercontinent Rodinia (Petterson, *op.cit.*; Schluter, 2008; Thomas et al., 1994).

This saw the *"oblique collision"* (van Bever Donker, 1991) and thrusting of the "*arcuate Namaqua-Natal Province"* onto the south western margin of the Kaapvaal Craton. (Schluter, 2008)

The study will be focusing on the structural framework of the Namaqua Province which is divided into the Richtersveld, Gordonia, Bushmanland and Kheis subprovinces and further into terranes characterized by numerous shear zones and networks of fault systems (Moen, 2007; Stowe et al., 1984)

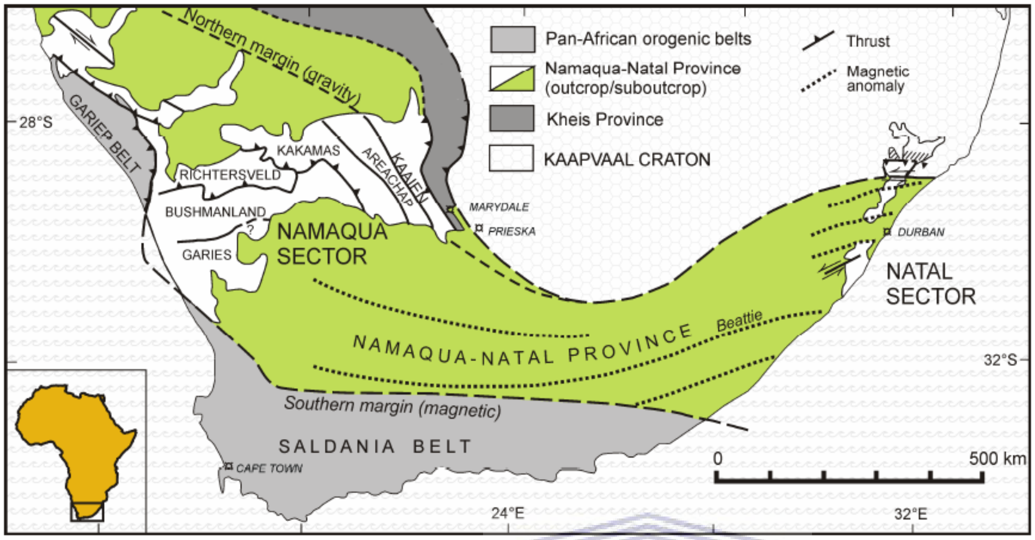


Figure 1.1: Geology of southern Africa showing the Namaqua-Natal Province, after Cornell et al., (2006)

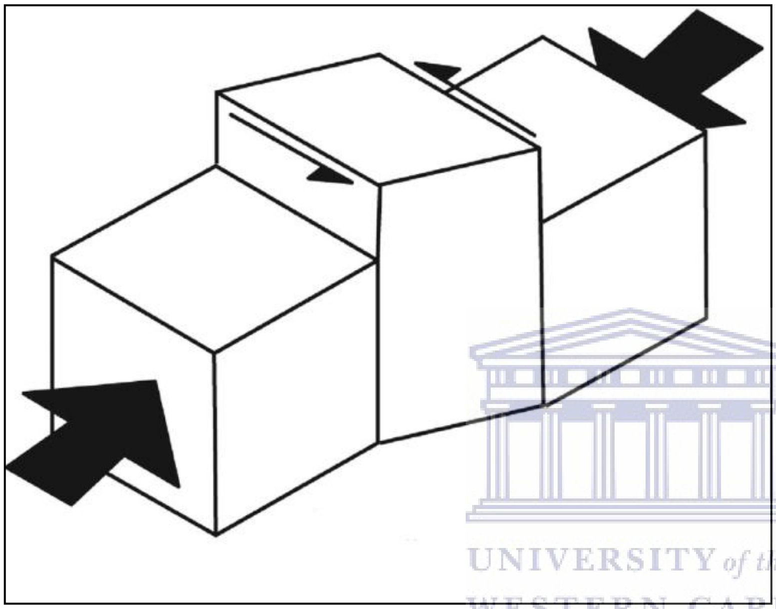
UNIVERSITY of the
WESTERN CAPE

2. Previous work

The aim of the study is to outline the main shear zones and fault systems of the Namaqua province and indicate whether these structures agree with those associated with a transpressional tectonic environment, then set up a fracture model of this sense of movement and indicate how this type of geologic setting allowed for the intrusion of the Keimoes Suite granites.

It is imperative then to understand transpressive environments and the mechanisms involved in the emplacement of granites within them, including how granitic intrusion is possible and what type of regional or local fracture systems allow for this in order to produce a model of the likely structural framework and geotectonic environment that would have allowed for the emplacement of the Keimoes Suite.

According to Marshak and Van der Plujim (2004) transpressive environments are the combination of compressional and strike slip tectonics which is associated with uplift and the formation of thrusts. The combination of strike slip tectonics with shortening is due to motion of the subducting and overriding plate not being perpendicular, so there is thrusting perpendicular to the convergent margin and horizontal shear parallel to the convergent margin (Marshak and Van der Plujim, 2004).



UNIVERSITY of the
WESTERN CAPE

Figure 1.2: Showing combination of strike slip and collisional tectonics in transpressive environment, after Henderson and Viola (2010).

This is known as oblique convergence and occurs when one landmass indents the other and continued compression introduces a strike slip component and results in lateral escape. Where blocks of crust are caught in between converging margins and are laterally squeezed out of the collisional zone (Marshak and Van der Plujim, 2004).

This can be linked to work done by van Bever Donker, (1991) into the transpressional environment of the Namaqua region and how an oblique collision model with a rigid indenter is assigned to the thrusting which occurred onto the Kheis Province. It is during this period of continued northward thrusting or orogenic development that some of the Keimoes Suite granitoids were emplaced (Geringer et al.,, 1988; Moen, 2007).

In order to establish how the Keimoes Suite granitoids were emplaced we must look into the main mechanisms associated with granite emplacement with particular reference to transpressional environments. These mechanisms are stokes diapir and fracture propagation, but it is the latter which is more accepted as it deals with the transport of magma "*along networks of pre existing fault systems and networks of active shear zones",* so as narrow channels open initial "*magma enters and solidifies and provides a form of insulation for later magma"* (Clemens, 1998).

This is further reiterated by Brown and Solar (1998) who recognize the two-end member transfer processes of "*diapiric ascent of melt through viscous rock and the ascent of melt by flow in elastic or brittle rock".* However the two-end member transfer process of melt ascent is not related to the melts associated with convergent orogens, particularly in transpressional environments as according to Brown and Solar (1998) convergent orogens are associated with a horizontal maximum compressional stress which limits or opposes the idea that melt ascends in extensional fractures that are normal to minimum compressive stress.

It is generally accepted that ascent and emplacement of melt is associated with orogenic collapse but what Brown and Solar (1998) introduce is that this is also associated with orogenic development which then implies that melt is ascending during compression.

The orientation of maximum and minimum compressive stress is fundamental in understanding how plutons are emplaced and their 3-D shape, as McCaffrey and Petford (1997) indicate that in convergent orogens plutons are "*horizontally extensive and tabular in form"*, implying that ascent is vertical and emplacement is horizontal. So the likely transportation of melt is through sheet-like flow through crustal-scale shear zone systems (Brown and Solar, 1998).

Having established that pre existing shear zones and fracture systems are the main mechanisms that allow for the ascent and emplacement of magma in transpressional environments we must now relate this to the structural framework found in the Namaqua Province

UNIVERSITY of the
WESTERN CAPE

The Namaqua Province is characterized by numerous fault systems and shear zones, which are used to delineate the tectonostratigraphic boundaries of the Bushmanland, Gordonia and Kheis subprovinces. The main structural features are the Neusspruit, Boven Rugzeer, Straus Heim, Cnydas and Trooilapspan shear zones. (Moen, 2007; Stowe, 1986; Thomas et al, 1993)

According to Moen, 2007 the Brakbosch fault splits towards Upington into *a "northward diverging array of fault zones which display evidence of the long history of episodic rejuvenation of the main structure by main transcurrent and vertical movements in ductile and brittle regimes".*

The magnitude and sense of displacement of the Brakbosch fault are somewhat controversial according to Moen, 2007 but works by Van Zyl, 1981 and Stowe, 1983 suggest a large scale dextral shear movement and a vertical displacement with the western side having moved up relative to the east.

The main structural features of the Gordonia subprovince are the easternmost Trooilapspan shear zone with a dextral displacement (Humphreys and van Bever Donker, 1987) and the Neusspruit shear zone which had the western block move up relative to the eastern block (Moen, 2007).

UNIVERSITY of the
WESTERN CAPE

There are several large shear zones identified in the Gordonia subprovince namely the Keboes, Cnydas, Boven Rugzeer and Neusspruit shear zones (Vajner et al, 1983) with work done by van Bever Donker (1983) in the Keboes shear zone region indicating there is both vertical and horizontal displacement.

The Cnydas and Boven Rugzeer shear zones have sinistral and dextral sense of movement respectively with the Cnydas shear zone postdating the youngest components of the Keimoes Suite (Thomas et al, 1994). The Neusspruit shear zone according to van Bever Donker (1983) experienced vertical displacement with the eastern block moving up relative to the western block.

The rocks in the Gordonia and Bushmanland subprovinces were subjected to a sinistral stress due to a block wedged between two dextral shear zones such as the Pofadder and Neusspruit or Cnydas shear zones this is shown by the S-shaped mega folds and a *"deviation in the regional northwesterly trend of the Namaqua province to the east of Pofadder"* (Moen, 2007).

The occurrence of numerous shear zones and networks of fault systems are related to the four major deformational events noted of the Namaqua region (Stowe, 1983 and van Bever Donker, 1991).

These multiple phases of folding can be described by referring to the work by Stowe (1983) who looked at delineating four tectonic zones on ”the Upington geotraverse” based on the type of folding, grade of metamorphism, prominent structures and the crustal movements associated with the subsequent structures. Stowe (1983) divided the geotraverse into the Namaqualand Metamorphic Complex, Namaqua Front, Namaqua Foreland and Kheis Tectonic Province zones into zones A to D respectively.

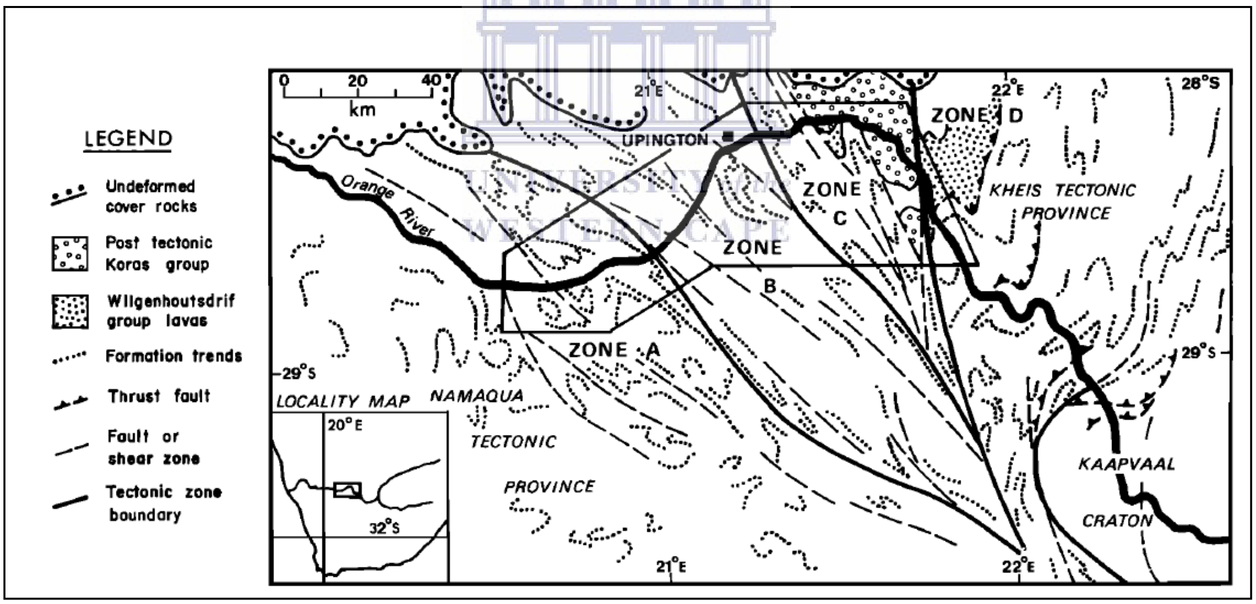


Figure 1.3: Showing the locations of the tectonic zones along Upington Geotraverse, after Stowe (1983).

The Namaqualand Metamorphic Complex is a tectonic zone panning from the Neusberg Hills to the Straussberg shear zone near Upington and is an axis of late uplift with vertical components of movement accentuated. It is also characterized by two sets of isoclinal folding F_1 and F_2 which were previously recumbent and now cross-folded into F_3 and F_4 as interference domes Stowe (1983).

The Namaqua Front is where the Korannaland sequence is tightly compressed between the syntectonic granitic plutons of the Keimoes Suite which is also a zone of intense late ductile shear, indicated by the numerous northwest trending dextral shear zones Stowe (1983).

The Namaqua Foreland is associated with the late tectonic irregularly shaped Keimoes Suite plutons which are dissected by northwest trending shear zones and thrust faults which have experienced both vertical and dextral displacement during the late stage of transcurrent deformation Stowe (1983).

These tectonic zones were all correlated using the prominent structures observed in each of the tectonic zones and what was found is that each of the four zones had transitional structures in relation to its neighboring zone. It is the early recumbent isoclinal F_2 folds which show this transitional relationship from tectonic zone to tectonic zone.

Starting in zone A these isoclinal recumbent folds alternate with narrow steep domains that have geometry identical with zone B and become isoclinal reclined Stowe (1983). Transitioning from zone B to zone C the folds become less steep to the northwest and they extend into zone D becoming broad, open northwest plunging folds that refolded the early F_1 folds and then disappear laterally to an extent of 20 kilometers Stowe (*op.cit*).

The distribution of the Keimoes Suite granites is within Zones B and C of Stowe (1983), the Namaqua Front and the Namaqua Foreland; they intrude rocks of the Areachap and Kakamas Terranes within the Gordonia subprovince and bounded by the Neusspruit shear zone to the west and the Trooilapspan shear zone to the east.(Bailie et al, 2012 and Moen, 2007)

The Keimoes Suite granites are characterized as early and late syntectonic granites and post tectonic granites by Bailie et al.,, 2012, implying that emplacement of granites took place during and after the collision of the Namaqua Province and the Kaapvaal Craton during the Namaqua Orogeny.

UNIVERSITY of the
WESTERN CAPE

3. Problem Statement

With the origin of the Keimoes Suite being vaguely related to plate tectonic processes and a period of crustal thickening (Geringer et al.,, 1988; Moen, 2007) work into whether the present day structural framework of the Namaqua Province can be related to a transpressional environment that could've facilitated the formation of large scale pull-apart basins is minimal. Therefore using remote sensing tools such as MOVE, ArcGIS and Google Earth Land SAT imagery the Namaqua Province structural framework such as; the array of shear zones, folds, domes, thrust zones and faults will be mapped and interpreted in order to show evidence for a transpressional environment, and also structural evidence that can be linked to the pull-apart basins that would've allowed for the intrusion of the Keimoes Suite granites.

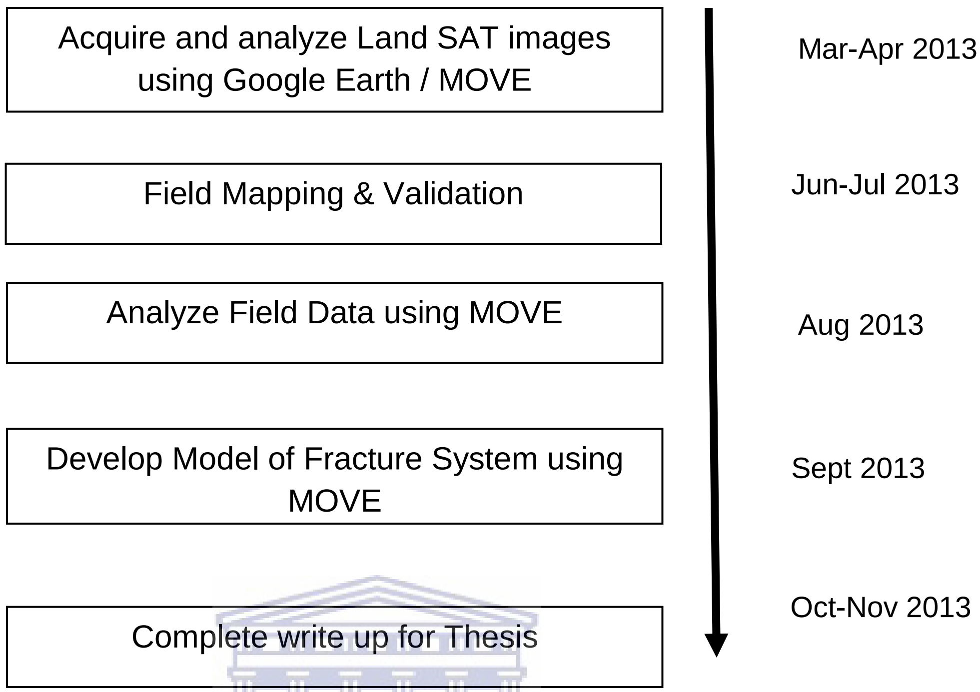
4. Methodology and Time Budget

The research will be primarily focused on analyzing the main regional structures of the Namaqua Province. In order to obtain an idea of the main structural features the remote sensing of Land SAT images will be done of the study area and the main structural features such as fault systems and shear zones will be noted, and digitized using MOVE software and Google Earth.

Then validation of remote sensed features will be done by field mapping within the Keimoes Suite. The analysis of the field obtained data includes determining the sense of movement on the main structural features such as the mega shears and establishing how the regional fabric is distorted near them in order to produce a model using MOVE software to show the relationship between the mega shears, fault systems and the intrusion of the Keimoes Suite.

UNIVERSITY of the
WESTERN CAPE

The likely time budget is indicated below in the flow chart.



UNIVERSITY of the
WESTERN CAPE

I. *CHAPTER TWO: GEOLOGICAL SETTING*

A. Regional Geology

The geology of the Northern Cape consists of Proterozoic rocks of the Namaqua Province also referred to as the Namaqua Sector (Cornell et al, 2006) Namaqua-Natal Metamorphic Complex or Mobile Belt (Moen, 2007). The rocks of the complex, which are highly deformed and metamorphosed, are traced beneath younger Phanerozoic cover to Kwazulu-Natal (Thomas et al., 1994; Moen, *op.cit*). The metamorphic grade varies from upper amphibolite to granulite facies to greenschist facies in the eastern Namaqua Sector.

The older Namaqua Sector rocks are unconformably overlain by the late syn- or post tectonic Koras Group consisting of unfolded lavas, sediments and associated intrusives (Moen, *op.cit*). To the northwest, these rocks are in turn overlain by horizontally disposed sediments of the Nama Group of Pan African age (Moen, *op.cit*). Glaciogenic sediments of the Permo-Carboniferous Dwyka Group extend northwards and cover all older formations (Moen, *op.cit*). Most of the area is covered by wind-blown sand of the Kalahari Group and underlain by extensive calcrete deposits (Moen, *op.cit*).

The Namaqua province is divided into three subprovinces namely the Richtersveld Bushmanland, Gordonia and Kheis subprovinces (Fig. 2.1), which are all bound by prominent shear zones and fault systems. It is the Gordonia subprovince which is specific to the present study.

UNIVERSITY of the
WESTERN CAPE

This study will examine the lithostratigraphy of the Korannaland and Areachap Groups of the Kakamas and Areachap Terranes respectively, which are adjacent to one another on a regional scale and which are intruded by the Keimoes Suite granitoids.

1. Bushmanland Subprovince

The easternmost Bushmanland subprovince (Fig 2.1), adjacent to the Gordonia Subprovince, is characterized by an anticlinal structure, in the easternmost portion which falls within the Upington map sheet. The Rietput Formation in the core and structurally overlain by the Kameel Puts Formation. This structure is bounded by the Hartbees River Thrust to the east and the Vogelstruisleegte fault to the west (Moen, 2007).

Kinematically these faults are presumed to be thrusts. The Kameel Puts Formation is structurally overlain by the Dröeboom Group which is bound by the Vogelstruisleegte and Swartland faults (Moen, *op.cit*). The Brakwater Metamorphic Suite constitutes the footwall of the Hartbees River thrust and is confined to the Regt Kyk dome (Slabbert et al, 1999; Moen, *op.cit*). The suite consists of quartz-feldspar-biotite gneiss with a limited range of mineralogical and textural variations.

The characteristic lithologies of the Bushmanland subprovince consist of supracrustal successions, calc-silicate, amphibolite and marble. In the Kameel Puts Formation there are boudin-like bodies of impure marble within the pink and grey gneisses of the Brakwater Metamorphic Suite (Moen, *op.cit*) .The Banksvlei Gneiss intrudes the supracrustal successions of the eastern Bushmanland subprovince and consists of a group of texturally diverse granitoid gneisses extending westwards to the Gordonia subprovince (Moen, *op.cit*).

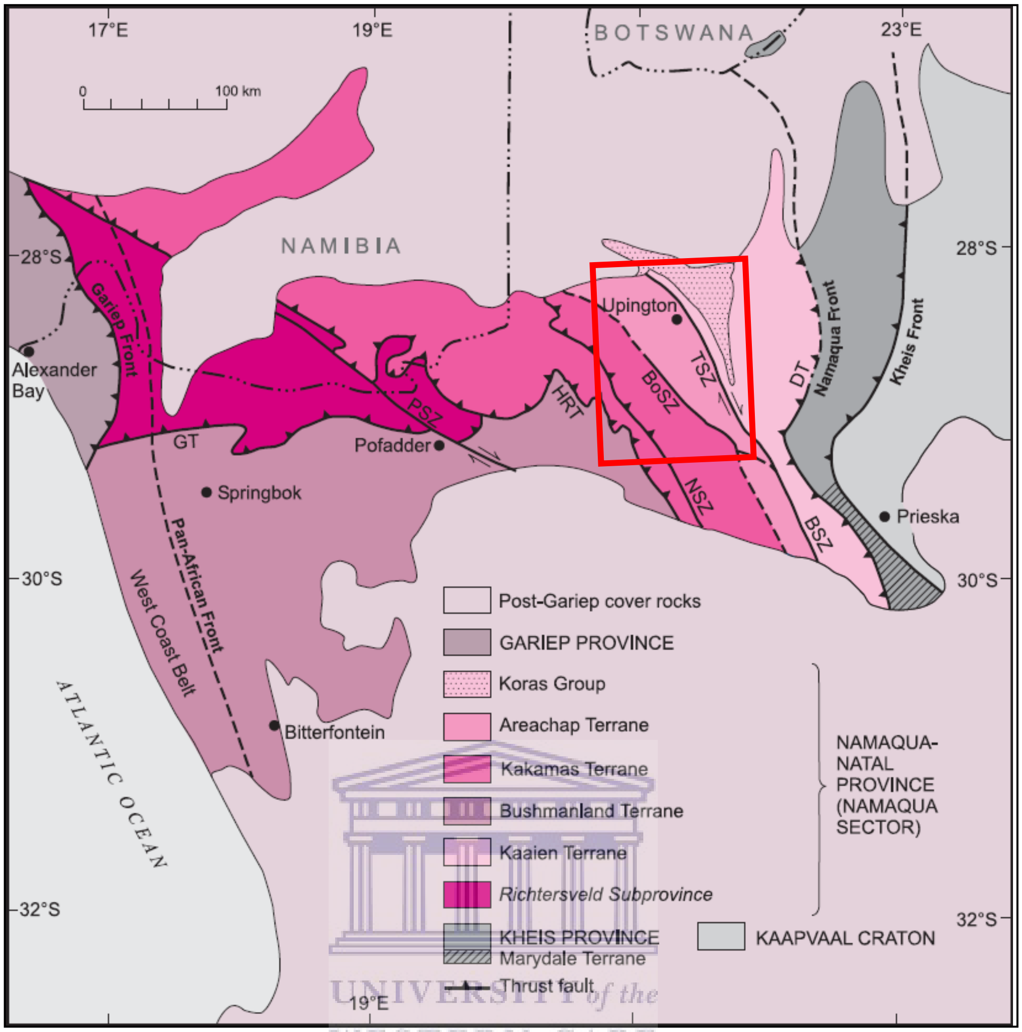
2. Gordonia Subprovince

This subprovince extends westwards from the Trooilapspan shear zone until the Hartbees River thrust (Fig 2.1) and is subdivided into two terranes, namely the Areachap and Kakamas Terranes (Moen, *op.cit*). The Areachap terrane occurs on the eastern side of the subprovince and comprises the Areachap and Korrannaland Groups and also the granites of the Keimoes Suite (Moen, *op.cit*). The Kakamas terrane occupies the western portion of the subprovince and consists predominantly of augen gneisses which underlie the Korrannaland Group and which according to Moen (*op.cit*) suggest the exposure of a deeper crustal level. There are also supracrustal successions within this high-grade terrane which are indicated by the calc-silicate rocks of the Arribees Group and migmatitic metapelites of the Hartbees River Complex (Moen, *op.cit*).

The Gordonia Subprovince was thrust eastwards at 1.24 - 1.20 Ga (Eglington, 2006) over the Kheis Subprovince onto the western margin of the Kaapvaal Craton at the onset of the 1.2 - 1.0 Ga Namaquan Orogeny, with the accretion of the Areachap Group volcanic arc onto the western margin of the Kaapvaal Craton (Moen, 2007). The thrust faults were later steepened due to late dextral transpression into sub-vertical shears such as the Trooilapspan and Brakbosch shear zone and fault. (Petterson et al, 2007; Bailie et al., 2012).

The Koras Group, which lies east of the Brakbosch fault, is represented by two virtually undeformed and weakly metamorphosed volcanic successions that are 1.17 and 1.10 Ga in age (Gutzmer et al., 2000; Petterson et al., 2007) and are thought to be the extrusive equivalents of the Keimoes Suite Granitoids (Bailie et al., 2011; Hartnady et al., 1985)

UNIVERSITY of the
WESTERN CAPE



UNIVERSITY of the
WESTERN CAPE

Figure 2.1: Tectonic subdivisions of the Namaqua Sector, after Cornell et al., 2006. GT: Groothoek Thrust, PSZ: Pofadder Shear Zone. HRT: Hartbees River Thrust, NSZ: Neusspruit Shear Zone: BoSZ: Boven Rugzeer Shear Zone: TSZ: Trooilapspan Shear Zone, BSZ: Brakbosch Shear Zone, DT: Dabep Thrust. Red box shows study area.

The Gordonia Subprovince was subjected to high-grade regional metamorphism of upper amphibolite to lower granulite facies due to several thermal events associated with the intrusion of the Keimoes Suite granitoids (Van Bever Donker, 1980 Stowe, 1983, 1986; Geringer et al, 1994; Bailie et al, 2011) This thermal metamorphism was accompanied by extensive deformation and four main metamorphic events have been recognized by Cornell et al. (1992), with the peak of metamorphism, M_2 caused by contact metamorphism due to the intrusion of the syntectonic granitoids of the Keimoes Suite (Bailie et al., 2011; Cornell et al., 1992).

Peak metamorphism was accompanied by peak deformation that gave rise to large scale tight to isoclinal subvertical folds with northwest trending axial traces. The F1 and F2 folding events were the main penetrative fabric-forming events (Bailie et al., 2011).

The later M3 metamorphism was a retrograde to isothermal regional contact metamorphic event coinciding with the F3 fold phase and intrusion of late- to post-tectonic granitoids of the Keimoes Suite. The area is transected by several shear zones from west to east that indicate regional retrograde M4 metamorphism. (Bailie et al., 2011; Geringer et al, 1986)

a) <u>*Areachap Terrane*</u>

This terrane consists of the Areachap Group volcano-sedimentary rocks with an arc-like affinity that developed due to eastward-directed subduction. These rocks were subjected to amphibolite to granulite facies metamorphism during the continental collision between the Kaapvaal Craton and Namaqua province (Bailie et al., 2011; Cornell et al., 1990, 1992; Petterson et al., 2007)

i. <u>*Areachap Group*</u>

The rocks of the Areachap Group are exposed in a 90km long northwest trending belt (Fig 2.1) from the vicinity of Upington to Kleinbegin in the southeast until terminated by the Boven Rugzeer shear zone (Moen, 2007). To the west of the Trooilapspan shear zone the belt is interrupted by a 6km wide northeast trending protrusion of Keimoes Suite granitoids which are partially rimmed by a thin layer of kinzigite (Moen, *op.cit*). To the northwest the group is unconformably overlain by glacial deposits of the Dwyka Group (Moen, *op.cit*).

UNIVERSITY of the
WESTERN CAPE

According to Geringer et al. (1994), the lithostratigraphy of the Areachap succession consists of four volcanic centers, namely the Copperton, Boksputs-Vanwykspan, Kleinbegin, and Upington volcanic centers, each distinguished according to the volcanism and type of sediment occurring within them. The general type of sediment units are a variety of gneisses occurring with calc-silicate and banded iron formations (Geringer et al., 1994).

The Areachap Group contains stratiform, volcanogenic Cu-Zn sulphide mineralization, with the southernmost deposit at Copperton being of special interest as it lies to the south of the Boven Rugzeer shear zone. Cornell et al. (1990) and Moen (*op.cit*) suggest, however, that the Copperton deposit has chemical and lithological features that set it apart from the Areachap Group in the north, and Pettersson al. (2007) and Bailie et al. (2010) have largely proved that the southern portion, around Copperton, is similar in age and lithostratigraphy as the northern portion and therefore part of the Areachap Group.

b) *Kakamas Terrane*

The terrane (Fig 2.1) is dominated by numerous intrusions along with lesser metasedimentary rocks, both of which have been subjected to varying degrees of deformation. The metasedimentary rocks include highly deformed granulite to amphibolite gneiss, calc-silicate and feldspathic quartzite and charnockites (Bailie et al., 2012).

ii. *Korannaland Group*

This group of rocks is restricted to the Gordonia Subprovince and occurs as a northwest trending belt of outcrops from an area north of Kenhardt to the eastern boundary of Riemvasmaak, where it disappears under undeformed sediments of the Neoproterozoic Nama Group (Moen, *op.cit*)(Fig 2.1). The succession consists of a variety of metamorphosed psammitic and semipelitic rocks of calc-silicate affinity with calc-silicate and marble horizons. These rocks are grouped together as the older Biesje Poort Subgroup and the younger miceaous quartzite of the Goede Hoop Formation (Moen, *op.cit*).

The Reimvasmaak augen gneiss locally intrudes the lower parts of the Korannaland Group in the Central and Melkboom domes. The Korannaland Group outcrops are fragmented by the granitoids of the Keimoes Suite, so that relationships with the adjacent Areachap Group are not clear (Moen, *op.cit*).

The stratigraphy to the west of the Neusspruit shear zone differs considerably from that to the east (Moen, op.cit). The metasediments are likewise enveloped by granitoid gneisses but the Goede Hoop Formation is absent while the Biesje Poort Subgroup is represented only by the Omdraai Formation which is a succession in which marble does not occur and calc-silicate rocks are a minor constituent (Moen, *op.cit*). The age of the Korannaland Group is debatable but Barton and Burger (1983) established an age which predates the Keimoes Suite of ~1.2Ga (Moen*, op.cit*).

3. Kheis Subprovince

According to Moen (2007) the boundaries, age and lithostratigraphy of the Kheis Subprovince have been the source of much controversy as the region consists of a unique lithostratigraphy, metamorphic grade and structural grain. Moen (*op.cit*) further characterizes the lithologies as consisting of thick successions of arenitic and metavolcanic rocks which have been metamorphosed to greenschist facies grade and overlain by unfolded lavas and arenaceous sediments of the Koras Group, with the metamorphic rocks having been subjected to polyphase deformation.

The eastern boundary is a major steepened thrust known as the Dabep fault (Fig 2.1) which is an important transition as it marks the boundary between the Kheis Subprovince and the Kaapvaal Craton (Moen, 1999, 2007). The western boundary is taken as the Brakbosch fault which is a prominent northwesterly trending fracture zone forming the western limit of the quartzitic successions in the Namaqua foreland between Copperton and Kleinbegin (Moen, 2007; Stowe, 1986). Blignault et al. (1974) and Moen (2007) suggested that the western limit of the Kheis Subprovince is the Trooilapspan shear zone.

The rocks of the Kheis Subprovince extend and appear to thicken northwards into western Botswana where they are extensively covered by the Karoo and Kalahari deposits. According to Moen (*op.cit*) the sedimentological data suggests that the arenites were deposited on a westward-expanding passive margin at the onset of a collision with a continental block ~1.35Ga ago. The western edge became the locus of basaltic and bimodal volcanism followed by downwarping and metamorphism at depths exceeding 15 kilometres (Moen, *op.cit*).

During the final convergence the Kheis rocks were folded and thrust back onto the craton and, despite substantial uplift in the west, no Archaean rocks are exposed and the nature of the Kaapvaal basement remains unknown (Moen, 2007). Considerable erosion took place before the final episode of deposition of the bimodal Koras volcanosedimentary succession (Moen, *op.cit*).

UNIVERSITY of the
WESTERN CAPE

The Vaalkoppies Group of the Kheis Subprovince is the only group of rocks which is "*extensively invaded"* by the Keimoes Suite granites (Moen, 2007). These rocks form a linear southeast-trending belt which is truncated by the Brakbosch fault, to the east of which the rocks form a prominent range of hills defining a complex antiformal structure, and to the west of which it forms a belt of low hills with the basal conglomerate of the Areachap Group found along most of the groups western boundary (Moen, 2007).

B. Local Geology

The Keimoes Suite granites are defined as a group of well-foliated to weakly foliated, non garnetiferous and non-porphyroblastic biotite, biotite-hornblende and charnockitic granitoids (Moen, 2007). The distribution of the Keimoes Suite, although loosely defined, occupies a broad belt more or less parallel to the Brakbosch fault extending westwards towards the Neusspruit shear zone (Fig 2.2).

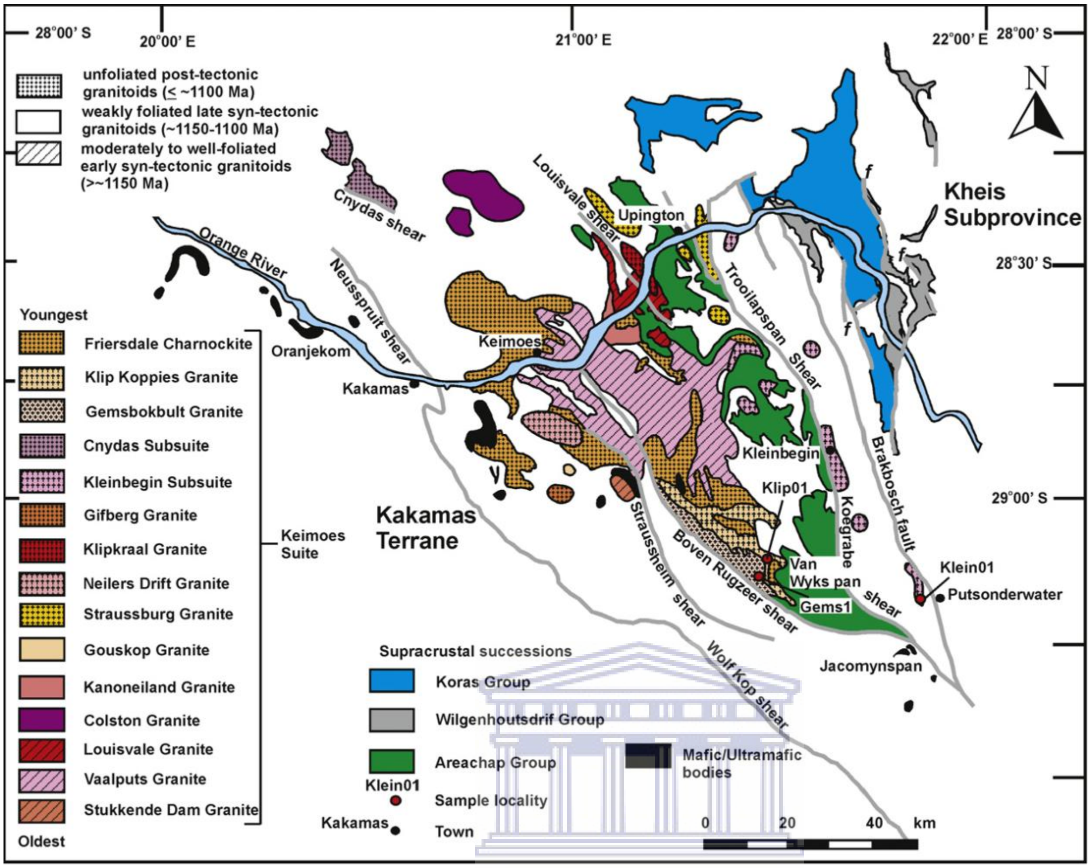


Figure 2.2: The distribution of the Keimoes Suite granites within the Gordonia Subprovince, after Bailie et al. (2011).

UNIVERSITY of the WESTERN CAPE

The components of the Keimoes Suite intrude the Sultanoord, Areachap and Korannaland Groups as well as older gneisses on a regional scale. The Keimoes Suite can be described as a composite batholith comprising a mid- to upper-crustal calc-alkaline suite of~~,~~ predominantly I-type granitoid ranging in composition from monzogranitic to potassic.

The emplacement of the suite is generally related to plate tectonic processes that took place at the eastern margin of the Namaqua Orogen. The intensity of foliation varies from one granite pluton to another, with the intensity of foliation used by some authors (Stowe, 1983; Bailie et al., 2011) to assign the timing of emplacement of the pluton relative to the last foliation-forming tectonic event.

The lithostratigraphic subdivision described is that of Moen (*op.cit*), who described the granites based on composition, texture and structural fabric, and that of Bailie et al. (2011), based on the intensity of foliation and the timing relative to tectonism of the Namaqua Orogeny.

a. <u>Vaalputs Granite</u>

The Vaalputs Granite has the widest distribution of all the Keimoes Suite granites and underlies an area of 430 km^2 (Fig 2.2). It intrudes the various members of the Korannaland Group and has good exposures. The granite is light grey in colour with a medium-grained equigranular texture and a well-developed foliation. It has sharp but generally concordant crosscutting intrusive relationships with parts of the Korannaland Group and the Riemvasmaak Gneiss.

The Vaalputs Granite contains numerous inclusions. Although lensoid mafic clots measuring a few centimetres across are occasionally present, the most common concordant lenses are those with a quartzitic composition. According to Moen (*op.cit*) these are derived from the Goede Hoop Formation and may reach several kilometres in length. A considerable portion of the pre-existing stratigraphy has been displaced by the granite so parts of the neighboring rocks now occur as macro-inclusions which are completely surrounded by granite.

The Vaalputs Granite is the oldest of the Keimoes Suite granites, due to the fact that this granite has a strong tectonic fabric, generally concordant contacts, an absence of contact metamorphism and relatively un-evolved composition it is concluded to be the oldest (Moen, *op.cit*)

UNIVERSITY of the
WESTERN CAPE

b. <u>Louisvale Granite</u>

This gneissic granite intrudes the Bethesda Formation southwest of Upington (Fig 2.2). The Louisvale Granite forms a northwest to southeast pluton, the extent of which is unknown as there are limited outcrops. It is a mesocratic to leucocratic, medium-grained granite with scattered anhedral phenocrysts. Contacts with sediments are concordant and intensely foliated. The foliation found in the Louisvale Granites is deformed in a disharmonic flow pattern. Its texture and composition suggest that it was likely emplaced during peak metamorphic conditions at a relatively deep crustal level.

c. <u>Klip Koppies Granite</u>

This granite is characterized by poorly developed foliation and potassic composition suggesting that it is a relatively late-tectonic intrusion (Fig 2.2). There is also the occurrence of muscovite and biotite in equal amounts that is unusual for the granites of the Keimoes Suite, with no contacts with the metasediments being exposed (Moen, *op.cit*).

d. Keboes Granite

The Keboes Granite is exposed in the Kanoneiland area mainly within and to the southeast of the Orange River (Fig 2.2), and intrudes the Bethesda, Sout River and Ratel Draai Formations, as well as the Louisvale Granite (Moen, *op.cit*). The exposed area of the pluton is about 35km^2 and the unit is poorly foliated and a subvertical lineation is developed locally (Moen, *op.cit*). The granite is light grey in colour and contains very few inclusions in the form of small mafic lenticles. In comparison to the Kanoneiland and Straussburg plutons the Keboes Granite is finer grained and has a lower biotite content with fewer inclusions (Moen, *op.cit*). It is considered younger than the adjacent Kanoneiland Granite, but the contact is not exposed.

e. Colston Granite

The Colston Granite crops out to the northwest of Upington, and closely resembles the Straussburg Granite (Fig 2.2). It is found in low relief areas with fragmentary exposures, intruding the metapelites of the Toeslaan Formation in the north and unconformably overlain by the horizontal strata of the Nama Group. The granite underlies an area of ~140km^2 and is likely to consist of several plutons.

According to Moen (2007) the Colston Granite is biotite rich with weakly developed foliation in the central parts of the plutons that intensifies as one moves towards the margins of the plutons. The contact metamorphic effects are not recorded due to poor exposure. The Colston Granite is further described as an epizonal intrusion emplaced during the waning stages of the Namaqua Orogeny (Geringer et al., 1987; Moen, 2007).

f. Straussburg Granite

The Straussburg Granite intrudes rocks of the Areachap Group as a northwest elongated, oblong pluton with an exposed surface of about 175km^2 (Fig 2.2). Its eastern contact is marked by the Trooilapspan shear zone so that the intrusive relationship with the Dagbreek Formation is not exposed. The majority of the pluton is obscured by sand or calcrete.

The granite is moderately to poorly foliated with a composition that varies from granitic to granodioritic (Geringer et al., 1987; Moen, 2007; Van Zyl, 1981). The Straussburg Granite is a meso- to epizonal I-type granite. It is a that Van Zyl (1981) and Moen (2007) suggest was emplaced by an “expanding balloon” mechanism whereby the margins underwent ductile deformation and the core remained isotropic. This mechanism is also suggested for the Colston Granite.

g. Kanoneiland Granite

The Kanoneiland Granite is similar to the Straussburg Granite being that it is a mesocratic biotite characterized by a poorly developed tectonic fabric with numerous mafic and leucocratic inclusions (Fig 2.2). There are sharp cross-cutting contacts with adjacent rock units and an intrusive contact with the Louisvale Granite. This granite is regarded as a late kinematic meso- to epizonal granite and differs slightly in age from the Straussburg Granite.

h. Neilers Drift Granite

The Neilers Drift Granite forms an oval-shaped pluton which is 6km wide and 14km long to the south of Keimoes (Fig 2.2). It is a mesocratic, unfoliated biotite granite similar to the Kanoneiland Granite. It is intruded by the Friersdale Charnockite and the lack of tectonic fabric places the Neilers Drift Granite in the post-tectonic age bracket.

i. Gouskop Granite

The Gouskop Granite forms a small ovoidal pluton with a surface area of 1.5km by 3km south of Keimoes (Fig 2.2). It crops out as a prominent hill and intrudes semipelitic metasediments of the Valsvlei Formation, with no contacts observed due to poor exposure (Moen, *op.cit*).

UNIVERSITY of the
WESTERN CAPE

j. Gif Berg and Klipkraal Granites

The Gif Berg Granite occurs as an east-west orientated elliptical pluton with a surface area of 21km^2 (Fig 2.2). It intrudes the Sandputs Formation and is a dark grey, fine to medium grained and unfoliated granite (Slabbert, 1987; Moen, 2007). Inclusions of the Sandputs Formation occur in places and contacts with the surrounding metasediments are sharp. The granite displays a chilled margin indicated by a marginal reduction in grain size and the disappearance of phenocrysts towards the contacts.

The Klipkraal Granite is found as a northwest striking body intrusive into the Louisvale Granite 2km southwest of Upington and is about 500m wide and 3km long. It is a dark-grey, unfoliated, porphyritic rock with varying composition. There are no radiometric ages for the Gif Berg and Klipkraal Granites but Moen (*op.cit*) suggests that they are epizonal granitoids and are the youngest members of the Keimoes Suite

k. Kleinbegin Subsuite

The Kleinbegin Subsuite consists of numerous outcrops of granite that intrude surrounding fragments of the Dagbreek Formations metaquartzite to the west of the Brakbosch fault (Fig 2.2). Most of the granites grouped into the subsuite are relatively similar and are characterized as medium- to coarse-grained meso- to epizonal I-type granites (Moen, *op.cit*). Their tectonic fabric varies from strongly developed to practically absent and due to scattered exposures and extensive sand cover the morphology of the individual plutons is unknown.

The varying composition and textures of the Kleinbegin Subsuite is attributed to shearing associated with the late movement of the Brakbosch fault zone. The resultant fabric is more intense at lithological contacts as a result of competency differences. The variable intensity of the fabric along with retrograde mineralogy in the granites at Kleinbegin indicates a widespread, late kinematic shearing of epizonal granite.

l. "Unnamed Leucogranite/ Josling Granite"

There are scattered outcrops of even grained leucocratic gneissic texture granite to the south of Upington (Fig 2.2). These individual plutons are small to medium sized but their extent is usually obscured by sand cover. The widely separated outcrops are not identical but several factors indicate that their origin is communal (Moen, *op.cit*).

UNIVERSITY of the
WESTERN CAPE

The granites are generally leucocratic and fine grained with well-developed foliation. These granites do not resemble any of the Keimoes Suite granitoids and could possible not be a part of the unit as a pre Keimoes Suite ion age and a strong spatial association with the Jannelsepan Formation suggest the granites are related to the origin of the Areachap volcanic belt (Cornell et al., 2006; Moen, 2007).

m. Cnydas Subsuite

This subsuite**,** unlike the Kleinbegin**,** is a genetically coherent group of post-tectonic, epizonal granitoids occurring in a triangular area extending from Lutzputs towards the northwest of Upington (Fig 2.2). The rocks are generally well exposed as prominent boulder hills. The subsuite is prominently covered by flat-lying sediments of the Nama Group but some of the granite inselbergs protrude through the lower part of the succession and represent part of the pre-Nama topography (Moen, *op.cit*).

The southern boundary of the Cnydas Subsuite is strongly tectonised but intrusive relationships are still well exposed within the region of the Cnydas shear zone. There is also a 7km long north striking porphyritic dyke known as the Smalvis Dyke, which cuts through several granites of the Cnydas Subsuite and one of the youngest within the subsuite. This dyke is thought to be the feeder for the Koras Group lavas (Geringer, 1973**;** Moen, *op.cit*)**.**

n. Friersdale Charnockite

The Friersdale Charnockite is the most voluminous member of the Keimoes Suite. It forms a large continuous body to the northwest of Keimoes with more irregular bodies to the south, east and south east (Fig 2.2). The charnockite bodies are largely restricted to the synclinal and anticlinal structures (Von Backström, 1964). A large portion of the outcrop that extends northwestwards from Keimoes, however, lacks the characteristic mineralogy of a charnockite and is thus correlated with the Vaalputs Granite (Van Bever Donker, 1980; Moen, *op.cit*)

The contacts observed vary from concordant to sharply discordant and chilled margins with contact-metamorphic aureoles developed locally in rocks of suitable composition (Moen, *op. cit*). There are also charnockite dykes present within the Keimoes Suite which intrude the granites and also larger bodies of the charnockites (Moen, *op.cit*).

The charnockites form dark-grey exfoliating boulders which are well exposed; they are also unfoliated with ellipsoidal inclusions of mafic to quartzitic composition. The dyke rocks are darker and finer grained commonly with chilled margins. The charnockites overall are thought to have undergone progressive metamorphism by the emplacement of the phacoliths (Von Backström, 1964; Van Bever Donker, 1980; Moen, 2007).

III. CHAPTER THREE: REMOTE SENSING

1. Remote Sensing

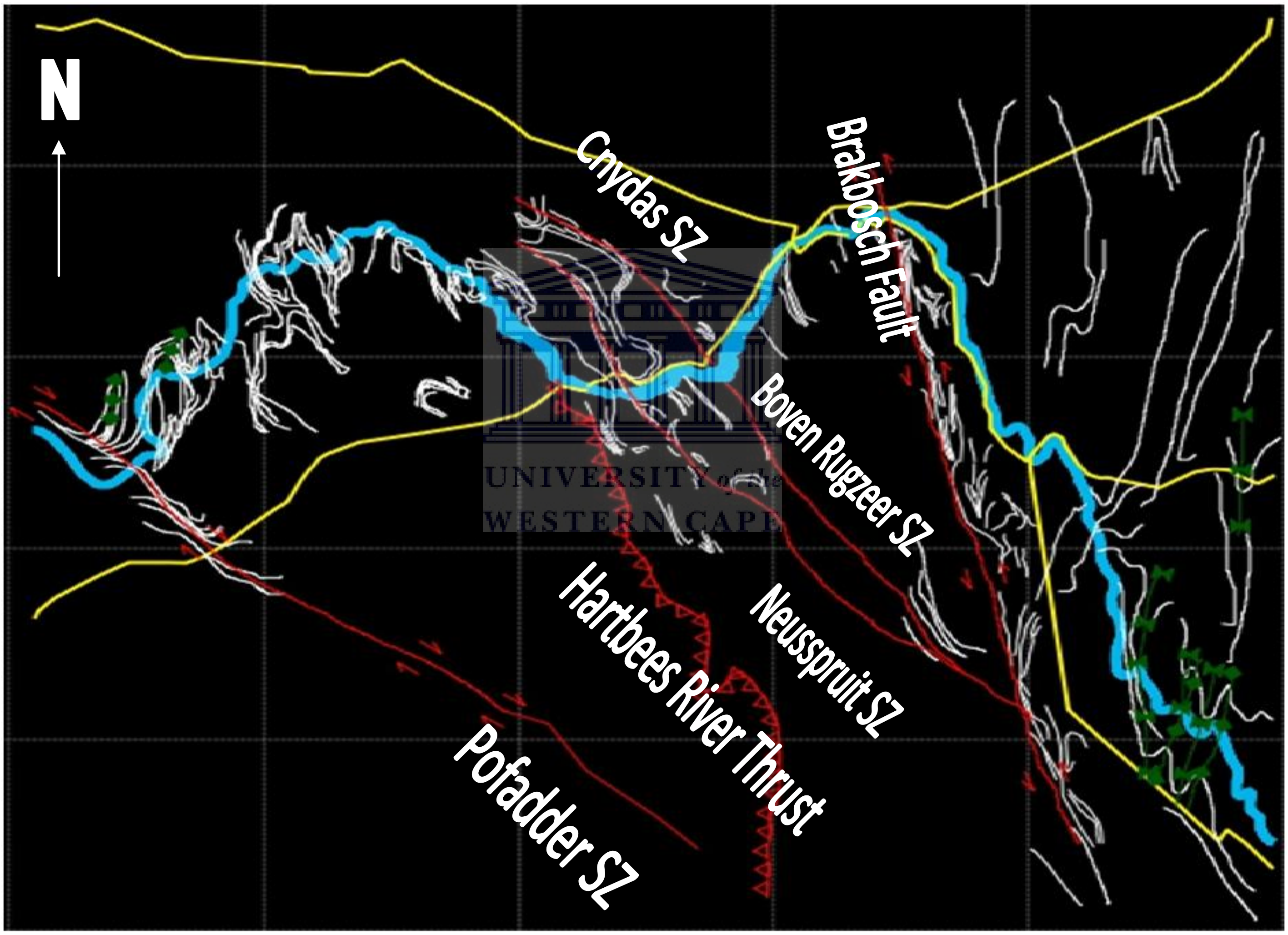
Remote sensing is the “*acquisition of information about an object without making physical contact with it”* (Schott, 2007). In the case of the study carried out of the Namaqua region the information to be acquired is the structural framework of the Namaqua region and the method used was a satellite image of the Namaqua region. The process of remote sensing includes using the satellite image to identify the regional structures of the Namaqua region and classify them accordingly in order to produce a map, and then further classifying other structural trends and features observed in the satellite image to increase the accuracy of the produced map.

The fundamental concepts of the process are digitizing and georeferencing using Google Earth and MOVE software. Digitizing was done on Google Earth and involved identifying and drawing in the prominent trends that the geology followed. The lines which show the prominent structural trends are structural trend lines and these can be interpreted to show whether there is sense of movement within that area of the Namaqua region.

UNIVERSITY of the
WESTERN CAPE

Figure 3.1: The digitizing of the structural trend lines in the Namaqua region, from Google Earth, 2013.

The next step was to import the digitized Google Earth satellite image into MOVE in order to interpret and show the sense of movement associated with the corresponding structural trend lines. The importing of the satellite image involves georeferencing which is the "*representation of the location of real world features within a spatial framework of a particular co-ordinate system, in the case of the research it is a geographic co-ordinate system using lines of longitude and latitude*". (Siad, 2012)

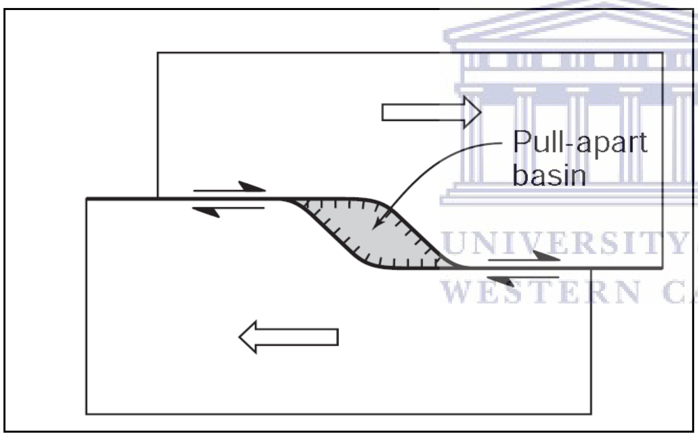


UNIVERSITY of the
WESTERN CAPE

Figure 3.2: The digitizing done on MOVE with prominent structural trends and the corresponding dextral sense of motion.

The georeferencing of the image was done using the horizontal extents; the image was extracted in a rectangular shape from Google Earth using the co-ordinates of the left top corner and right bottom corner co-ordinates and subsequently imported into MOVE.

The aim of the interpretation is to establish the structural environment from Pofadder to Prieska and determine whether there is a large scale pull-apart basin which facilitated the intrusion of the Keimoes Suite. The structural trend lines should indicate that the structural environment is a transpressional environment and within the Keimoes Suite region the structural features should indicate a pull-apart basin. This is *a “rhomboidal depression or basin which forms at a releasing bend along a strike slip fault*” and it forms when shearing and extension occur in a zone together (Marshak and Van der Pluijm, 2004).



UNIVERSITY of the
WESTERN CAPE

Figure 3.3: The formation of a pull-apart basin at a releasing bend along a strike slip fault, after Marshak and Van der Pluijm, 2004.

The area of the map is covered largely by sand and the best exposures are found along the Orange River. But using the structural trend lines observed in the produced map (figure 3.2) and previous works the individual shear zones and faults will be characterized according to the geology, deformation, metamorphism and sense of movement.

2. <u>The Pofadder Shear Zone</u>

a. Location

The Pofadder shear zone is located on the western-most boundary of the Namaqua Province and is a large regional structure with an extent larger than 500 kilometers that runs through the Bushmanland subprovince and the northern part of the Karoo basin. (Fig.3.4) (Cornell et al, 2006; Moen, 2007)

b. Sense of Movement

It is characterized by a clear dextral sense of movement when observed from satellite images, as the pre- tectonic supracrustal rocks of the Bushmanland Group show a drag in a southeast direction (Figure 3.2). (Cornell et al, 2006) There are also fold patterns north of the shear zones that are observed from the satellite image and are shown by a large anticlinal structure.

c. Geology

UNIVERSITY of the
WESTERN CAPE

The pre-tectonic supracrustal rocks of the Bushmanland Group are classified as the northern succession, with an extent from the Springbok to the Pofadder area and consist of "*basal leucocratic gneisses and overlying quartzites" (*with)" *mica-silimanite schists"*. (Cornel et al, *op.cit*)

d. Deformation

There are multiple phases of deformation and metamorphism found in the Bushmanland subprovince and those which correspond to the structural trend lines observed are D_3 and D_4. These are associated with the development of the folds and the dextral strike-slip shear system of the Pofadder shear zone. (Cornel et al, *op.cit*)

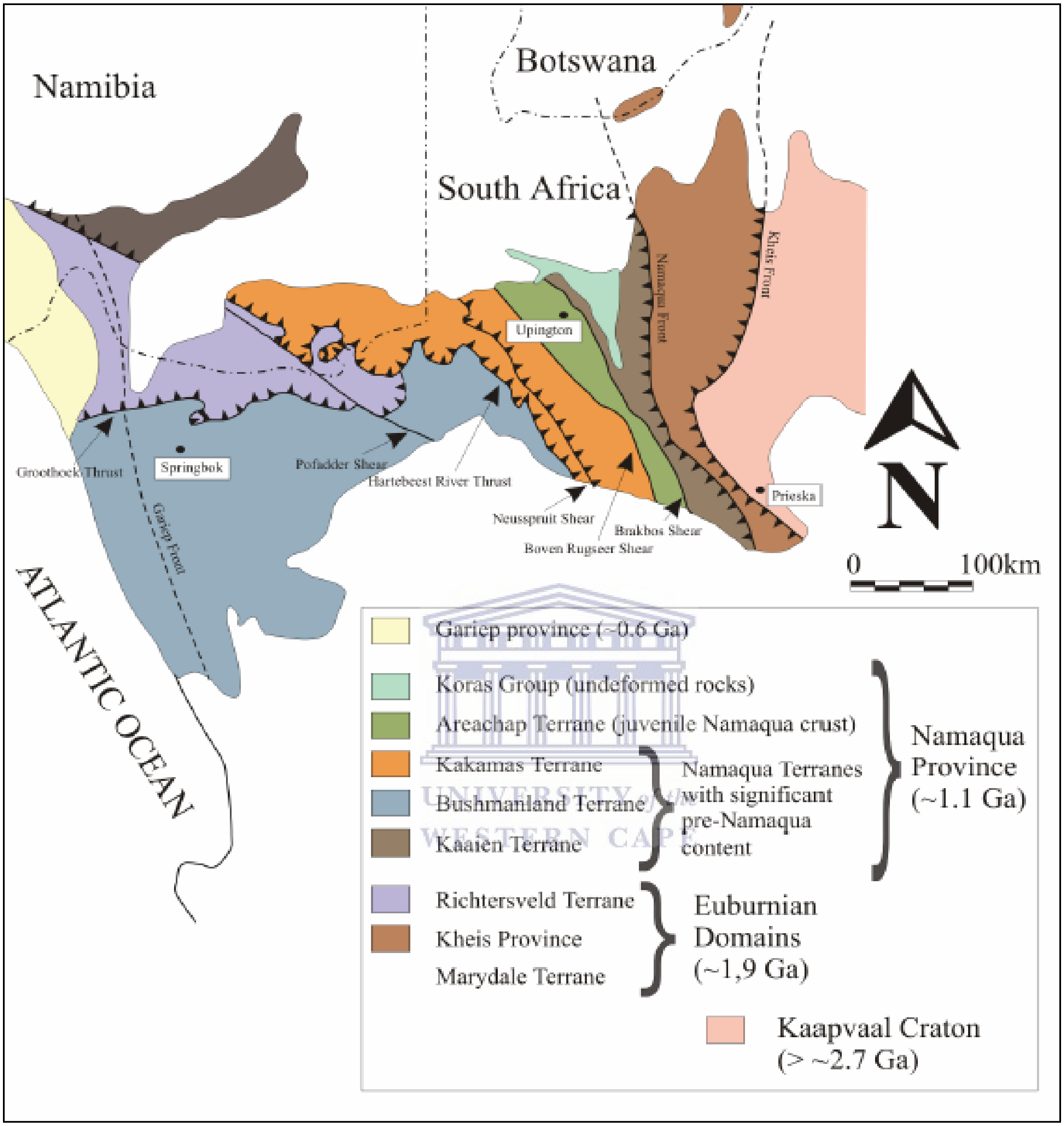


Figure 3.4: The tectonic subdivisions of the Namaqua Sector, after Thomas et al. (1994)

3. The Hartebeest River Thrust

a. Location

The Hartebeest River Thrust is the boundary which separates the Bushmanland and Gordonia sub provinces in the Namaqua Province and is identified by the Hartbees River when using a satellite image (Fig 3.4).

b. Geology

The geology of the Hartebeest River Thrust is differentiated into pre-tectonic and syn-tectonic units (Jackson, 1992). The pre-tectonic unit is the basal sequence and consists of a leucocratic and grey granite, migmatite gneiss complex that is overlain by the Hartebeest River Thrust Amphibolite Gneiss Complex. (Jackson, op.cit) There is a composite mixed syntectonic unit known as the Vyfbeker Complex that is found with the Amphibolite Gneiss Complex which is overlain by the Bushmanland Groups' quartzo-feldspathitic gneiss. (Jackson, op.cit) With the supracrustal rocks of the Korannaland Group in the northeastern part of the Hartebeest River Thrust being interlayed with the Riemvasmaak Granite Gneiss. (Jackson, op.cit)

UNIVERSITY of the
WESTERN CAPE

The upper syn-tectonic intrusive found in the Hartebeest River Thrust are correlated to deformational phases ranging from D_1 to D_4. (Jackson, op.cit) With the earliest augen gneiss correlated to D_1 being overlain by the Vyfbeker Complex during D_2 and granites related to D_3 overlain by a granite and pegmatite unit of D_4. (Jackson, op.cit)

c. Deformation and metamorphism

The Hartebeest River Thrust is a complex zone of multiple phases of deformation and folding of the rocks ranging from D1 to D4. (Jackson, op.cit) The SSW trending thrust folds found are related to deformational event D2, but were refolded in an ENE-SSW direction. (Jackson, op.cit) There is also evidence of dextral strike-slip shearing that is noted from the numerous shear zones within the Hartebeest River Thrust that are related to the neighboring Pofadder shear zone during D_4 .

4. The Neusspruit Shear Zone

a. Location

The Neusspruit shear zone is found within the Gordonia Subprovince and is of significance as it is the eastern limit of the regional migmatisation and marks the western limit of the Keimoes Suite Granites (Fig 3.4) (Moen, 2007).

b. Sense of movement

The sense of movement is not visible from the satellite image, but a prominent linear northwest trending feature is observed which marks the Neusberg Mountains north of the Orange River. According to Moen (op.cit) the sense of movement can be deduced regionally by referring to the contrasting intrusive bodies of the Keimoes Suite and the Reimvasmaak Gneiss found on either side of the Neusspruit shear zone. The contrasting intrusive bodies suggest dextral strike slip movement as the western block moved up relative to the eastern block. (Moen, op.cit)

c. Geology

UNIVERSITY of the
WESTERN CAPE

The geology of the Neusspruit shear zone is only restricted to the older Puntsit Formation and the younger Goedehoop Formation of the Korannaland Group. The latter consists of muscovite-bearing quartzite and schist which is found as linear ridges and hills along the shear zone. (Moen, op.cit) The Puntsit Formation has the greatest distribution and consists of dark weathering calc-silicate rocks with layers of marble and amphibolite. (Moen, op.cit)

d. Deformation and metamorphism

There is evidence of folding found in both the Puntsit and Goedehoop Formations which is correlated to the Namaquan Orogeny; these formations are also intruded by the Keimoes Suite Granites.

5. The Boven Rugzeer Shear Zone

a. Location

The Boven Rugzeer shear zone is found within the Gordonia Subprovince and is marked by the intense deformation of the Puntsit Formation (Fig 3.4) (Moen, op.cit).

b. Sense of Movement

The shear zone can was outlined during remote sensing of the satellite image and was found to be a linear northwest trending feature and according to Moen (2007) it has dextral strike slip movement.

c. Geology

The geology found along the Boven Rugzeer shear zone is the Korannaland Group, Keimoes Suite granitoids and the Areachap Group further south of the shear zone. (Moen, op.cit) The rocks of the Korannaland group are the Puntsit and Goedehoop Formations which are intruded by the early, syn and post—tectonic granitoids of the Keimoes Suite. (Moen, op.cit)

UNIVERSITY of the
WESTERN CAPE

d. Deformation and metamorphism

The intense deformation that demarcates the shear zone south of the Orange River is related to the intrusion of the Keimoes Suite Granitoids during the Namaquan Orogeny with high grade regional metamorphism from upper amphibolite to lower granulite facies. (Bailie et al, 2012; Moen, op.cit)

6. The Cnydas Shear Zone

a. Location

The Cnydas shear zone is located north of the Orange River and from remote sensing seems to line up with the Boven Rugzeer shear zone south of the Orange River within the Gordonia subprovince of the Namaqua Province.

b. Sense of movement

The sense of movement cannot be deduced using remote sensing as there is no clear evidence of a dragging effect of structural trend lines. The shear zone is noted as a linear feature trending northwest which seems to connect to the Boven Rugzeer Shear zone. According to Moen (2007) the sense of movement of the Cnydas shear zone is sinistral suggesting the eastern block moved up relative to the western block.

c. Geology

The geology found along the shear zone is the Puntsit, Sandputs and Goedehoop Formation of the Korannaland Group which are intruded by the late syn-tectonic Keimoes Suite Granites. (Bailie et al, 2012; Moen, 2007) However the distinction between the Puntsit and Sandputs Formation is not clearly defined as these formations have interbanding and gradational contacts. (Moen, 2007)

The late syn-tectonic granitoid of the Keimoes Suite which is adjacent to the shear zone is known as the Cnydas Subsuite which consists of an unfoliated, coarse grained diorite known as the Cnydas East Granodiorite. (Moen, op.cit) This Granodiorite has a highly sheared boundary with the Korannaland Group where wollastonite rich limestone with calc-silicate layers show intricate deformation patterns as well as small scale folding. (Moen, op.cit)

d. Deformation and metamorphism

There is intense deformation and metamorphism noted along the Cnydas shear zone shown by the anastomosing belts of rock observed by Moen (op.cit).

UNIVERSITY of the
WESTERN CAPE

7. The Brakbosch Fault

a. Location

The Brakbosch fault is found within the Kheis Subprovince of the Namaqua Province and is a prominent northwest trending linear feature (Fig 3.4).

b. Sense of Movement

The sense of movement was clear during remote sensing to be dextral as the eastern block of the fault has moved down relative to the western block. This is clear from the dragging effect shown by the structural trend lines. The Brakbosch Fault from remote sensing seems to be the most prominent feature within the Namaqua region and study area as it has an array of shear zones and faults that are connected to it.

The shear zones of the study area show a general pattern and trend that converges towards the Brakbosch Fault and so it is interpreted in figure 3.2 that the Neusspruit, Cnydas and Boven Rugzeer shear zones are connected to the Brakbosch Fault. The Pofadder shear zone also with the same trend may connect to the Brakbosch Fault further south of the mapped area.

UNIVERSITY of the
WESTERN CAPE

c. Geology

The geology that is along the Brakbosch Fault is the Brulpan, Vaalkoppies, Wilgenhoutsdrif and Koras Groups. The basal Vaalkoppies Group consists of metapelites, schist and quartzite of the Dagbreek Formation and the massive quartzite with interbedded phyllites and minor schist of the Sultanaoord Formation. (Moen, 2007)

The Brulpan Group overlies the Vaalkoppies Group and consists of "*sericitic quartzites*" which are overlain by the volcanogenic Wilgenhoutsdrif Group. The Koras Group unconformably overlies the Wilgenhoutsdrif Group and the granites and gneisses associated with the Namaqua orogeny, this Group consists of unmetamorphosed volcanic and sedimentary rocks. (Moen, op.cit) *d. Deformation and metamorphism*

The Koras Group has little or no evidence of deformation and metamorphism in certain areas but where it is found there is evidence of open folds and synclinal structures which are not correlated to the Namaqua orogeny. (Moen, op.cit)

As the individual shear zones and faults have been characterized it is important to look at the overall patterns and to give a summary of observations done during remote sensing.

8. Interpretation of Remote Sensing

The structural trend lines between the Pofadder shear zone and the Hartbees River Thrust include fold interference patterns, anticlinal structures and domes. The western boundary of the map is the Pofadder shear zone which has a dextral strike slip sense of motion, which is indicated by the pattern which the structural trend lines make north of the Orange River compared to the pattern they make south of the Orange River.

The area between the Neusspruit and Boven Rugzeer shear zones has fold interference patterns north of the Orange River and south of the Orange River it shows linear trend lines which correspond to the respective shear zones. The Straussheim shear zone further south of the Neusspruit shear zone is not visible due to the lack of outcrops in that area. The region between the Boven Rugzeer shear zone and the Brakbosch Fault has minimal outcrops making it difficult to identify the Trooilapspan shear zone using remote sensing.

The eastern boundary of the map is the Brakbosch Fault which has an array of linear structural trend lines south of the Orange River. North of the Orange River there is folding as evidenced by the presence of antiforms and synforms. The evidence of the dextral sense of motion is shown by the structural trend lines which are dragged from the area north east of the Orange River to south of the Orange and are then included into the linearly arranged trend lines of the Brakbosch Fault.

The shear zones within the Namaqua sector also show a NNW west dragging pattern from the north of the Orange River which deviates south of the Orange River to a north-

UNIVERSITY of the
WESTERN CAPE

south direction then trending in a NW direction as most converge towards the Brakbosch Fault.

The map (Fig 3.2) has allowed for the general overview of the prominent structural trends within the Namaqua region and allowed for the establishing of the prominent strike slip boundaries, the Pofadder shear zone and Brakbosch Fault along with the Hartbees River Thrust, Neusspruit, Cnydas and Boven Rugzeer shear zones. However the sense of movement along the three shear zones is not clear as there is no structural evidence that is identified from remote sensing that can be used. The lack of outcrops further north and south of the Orange River also contributed to the lack of structural evidence which resulted in the Trooilapspan and Straussheim shear zones not being identified from remote sensing.

From the interpretation it can be concluded that there is evidence of strike slip tectonics which are indicated by the numerous shear zones and the sense of motion observed from the Pofadder shear zone and the Brakbosch Fault and there is also evidence of compressional tectonics indicated by fold interference patterns, domes, antiforms and synforms as well as the Hartbees River Thrust.

UNIVERSITY of the
WESTERN CAPE

The interpretation and the map (Fig 3.2) of the structural framework of the Namaqua region do agree with a transpressional environment.

Therefore the identification of the Trooilapspan and Straussheim shear zones and the sense of movement along the Neusspruit, Cnydas and Boven Rugzeer shear zones is done and established.

IV. CHAPTER FOUR: FIELD WORK AND MODELLING

A. Field Work

The purpose of the fieldwork is to establish the shear zones that were not observed during remote sensing and to validate their sense of movement. In doing so the study will show that the shear zones that are found within the Gordonia Sub-province provided the zones of crustal weakness that facilitated the intrusion of the Keimoes Suite.

In order to show evidence of shearing at the Neusspruit, Cnydas, Straussheim, Boven Rugzeer and Trooilapspan shear zones within the study area the regional trend of the foliation had to be established by taking readings along traverses which ran across the shear zones. These readings were then used to establish whether there was a deviation from the regional foliation trend. (Graham and Ramsay, 1967) Structural evidence such as micro- shear zones and boudinage structures within the outcrops in the vicinity of the shear zones were used to delineate the likely sense of strike slip movement. The rock descriptions and presence of structural data were recorded at the stations which ran across the traverses at all shear zones.

The readings of the foliation were taken using a Krantz compass (The Krantz compass is a structural compass modeled on the Klar compass which records direction of dip and dip in one movement, like the Breithaupt and Freiberger structural compasses) and analyzed by rose diagrams using strike and dip with GEOrient software, these readings were then correlated with the geological map sheet of Upington in order to note any deviations in the general trend in foliation from the Neusspruit, Straussheim, Boven Rugzeer, Cnydas and Trooilapspan shear zones. The study area was divided into areas which were placed so as to cut across the shear zones in order to compare the trend of the foliation across them for any changes in trend as described by Ramsay and Graham.

It was noted during field validation that there were shear zones which follow the geological contacts of the metasedimentary rocks; shear zones that border plutons of the Keimoes Suite and the shear zones related to the Riemvasmaak Gneiss which predates the Keimoes Suite. Below are the descriptions of these relationships.

UNIVERSITY of the
WESTERN CAPE

1. Neusspruit shear zone

Location: The Neusspruit shear zone is located 13 kilometers from Kakamas in the Northern Cape, it transects the Orange River from the north at 28°38’40”S, 20°38’10”E and south at 28°57’4”S, 21°02’56’E as shown in the map of the field validation area.

Rock description: The rocks found at this shear zone from oldest to youngest are an Amphibolite Biotite Gneiss, (Tsakou, 2013 pers comm.) Puntsit Formation and Goedehoop Formation. The Puntsit formation is a quartz rich and mafic calc silicate rock and is seen in field observation to be interfingering with the younger micaceous quartzite of the Goedehoop Formation at this station (Moen, 2007). It is characterized by a dark weathering surface and consists of a mixture of manganese and iron minerals with a fine grained texture and a lighter colour on fresh surfaces (Moen, 2007). There is mineral banding and evidence of epidote is observed at its gradational contacts with the Goedehoop Formation (Moen, 2007).

In field observation the Goedehoop Formation’s micaceous quartzite that is found along the Neusspruit shear zone is characterized by its shiny mica and lightly coloured weathering surface. It is well foliated, fine grained and light grey to white in colour with an abundance of feldspar clasts, ranging from 0.1-3cm in width closer to the contact with the Puntsit Formation. The lesser deformed Goedehoop Formation has preserved cross bedding and pebble horizons. (van Bever Donker, 2013 pers comm..)

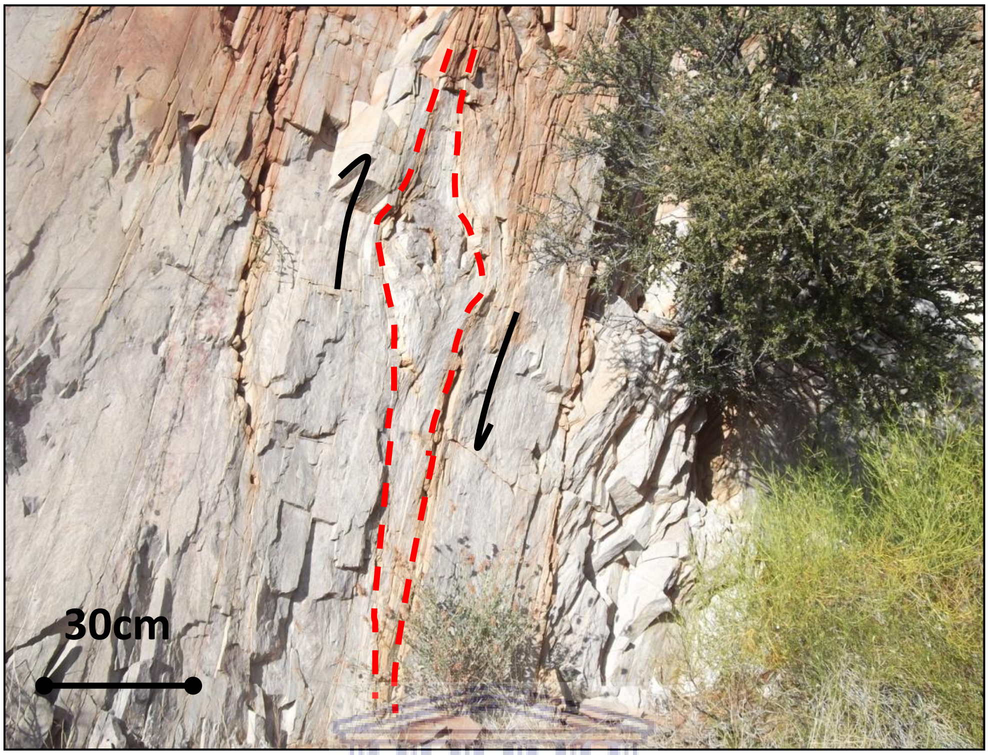
UNIVERSITY of the
WESTERN CAPE

Structural data: As determined from field observations.

The Goedehoop and Puntsit Formation have prominent joint sets and a well developed foliation that trends in a NW-SE direction that is 133- 313 strike direction. The foliation varies in spacing from 1cm to 20cm wide and there are feldspar clasts observed in the Goedehoop Formation ranging from 0.1-3cm in length. There is evidence of dextral movement and clockwise rotation observed in the Puntsit Formation at a road cutting running across the shear zone. (Figure 4.1) There are also slicken lines which indicate direction of movement (Figure 4.3) and displaced joints observed that indicate there was a period of movement after joints formed. (Figure 4.2).

Deviation from regional foliation trend: The Neusspruit shear zone is the geological boundary between metasedimentary rocks of the Puntsit and Goedehoop Formation and the Reimvasmaak Gneiss. The general trend in foliation is NW-SE, with readings taken trending in a 133 – 313 degrees strike direction; this is shown as the most prominent direction in Figure 4.4. The traverses which were done at stations on either side of the Orange River where the shear zone crosses the Orange River show an average deviation of 5-10 degrees north in the general trend of the foliation.

EAST



WEST

Figure 4.1: Dextral rotation in feldspar porphyroblast found close to Neusspruit shear zone. Image is a vertical surface.

UNIVERSITY of the
WESTERN CAPE

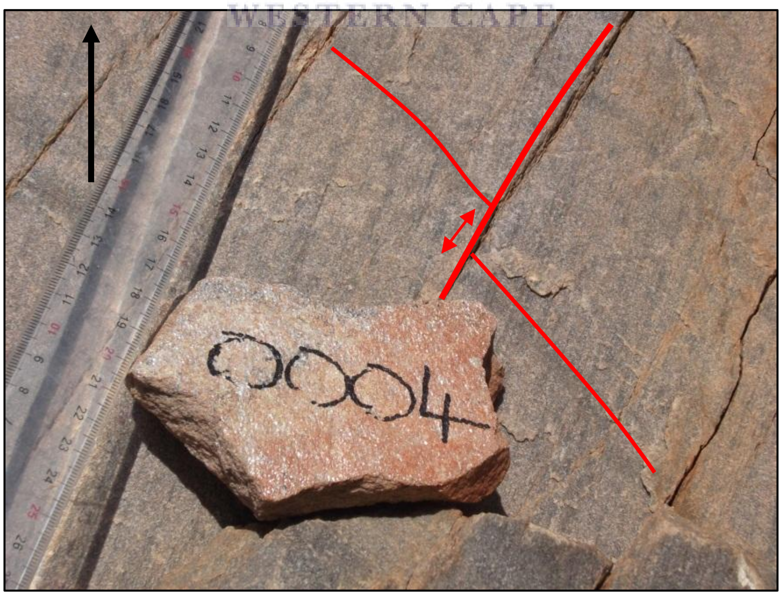


Figure 4.2: Displaced joints in Puntsit Formation close to Neusspruit shear zone, indicating there was a later stage of movement after the joints formed. Image is a horizontal surface

Figure 4.3: Slicken lines found in the Puntsit Formation show that there was an easterly direction of movement, which can account for the deviation in general foliation trend. Image is a vertical surface.

UNIVERSITY of the
WESTERN CAPE

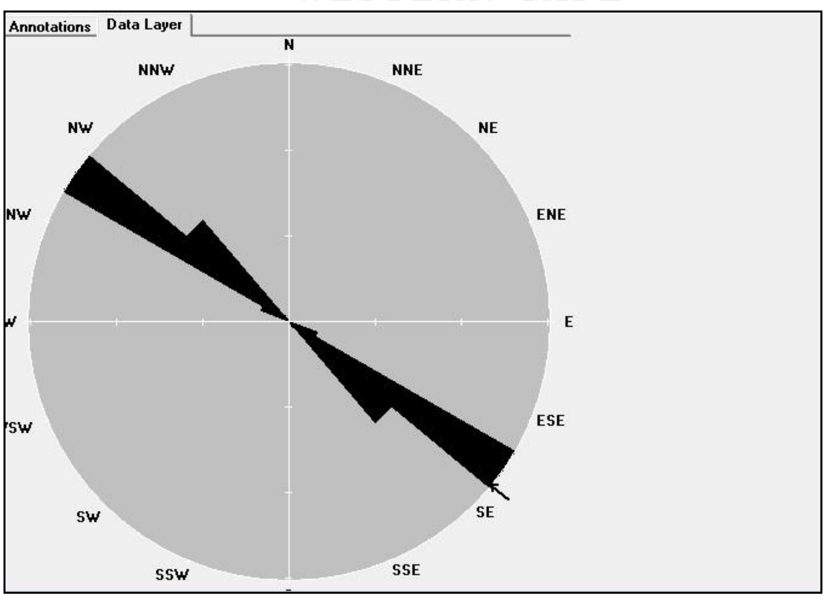


Figure 4.4: Rose diagram showing NW-SE regional foliation trend at the Neusspruit shear zone.

Figure 4.5: Quartz vein being dragged into the shear zone. The GPS used for scale is 10x5cm and the image is taken on a horizontal surface.

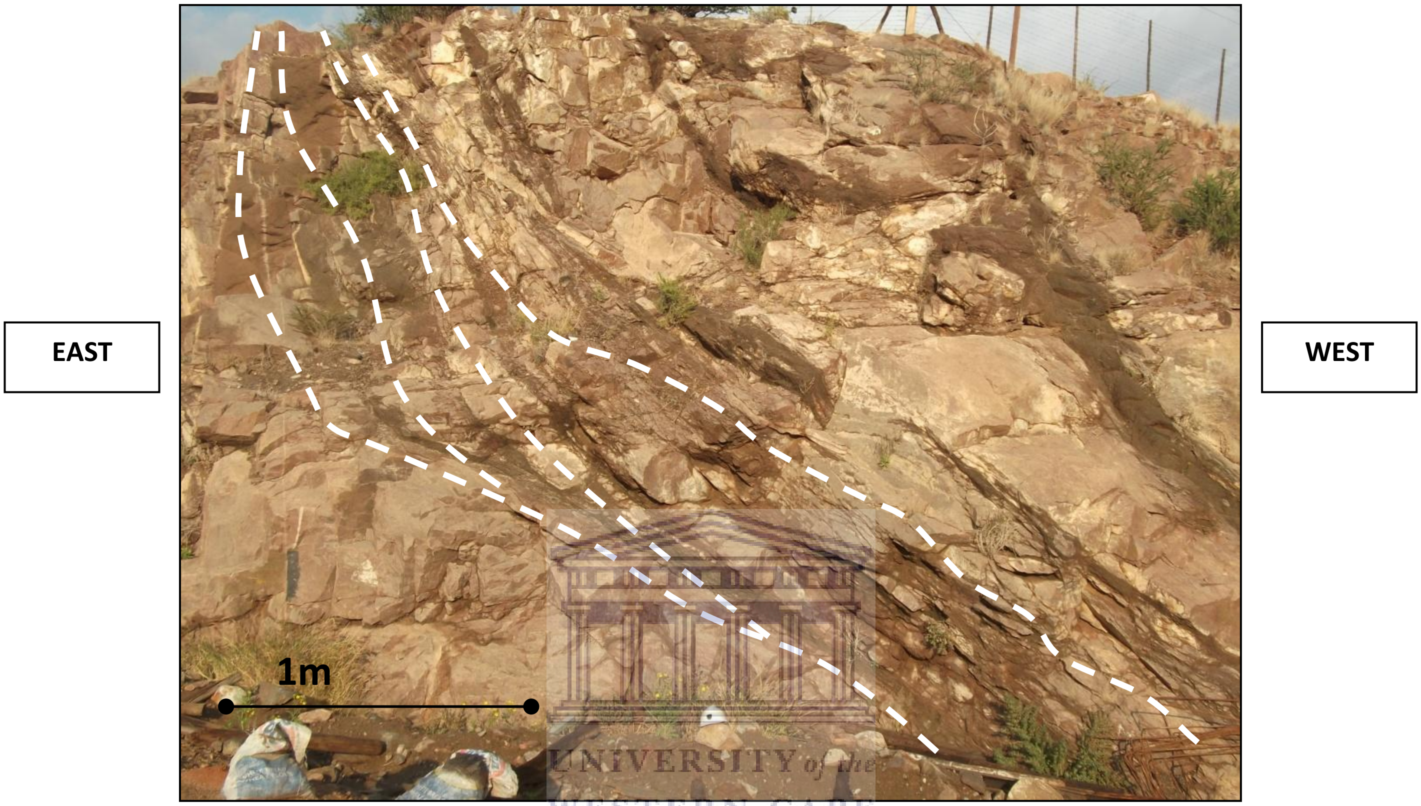
UNIVERSITY of the
WESTERN CAPE

2. **Boven Rugzeer shear zone**

Location: The Boven Rugzeer shear zone is located eight kilometers from Keimoes in the Northern Cape, it is found south of the Orange River from 28°44’27”S, 21°02’09”E to 28°57’39”S, 21°16’12”E as shown in the map of the field validation area.

Rock description: The formations affected by this shear zone are the Sandputs Formation, Puntsit Formation, Riemvasmaak Gneiss and Vaalputs Granite. The Reimvasmaak Gneiss is distinguished by its pink weathering colour and granular or augen texture (Moen, 2007). The Puntsit Formation and Vaalputs Granite observed at this station are similar to that which has been described above. The Sandputs Formation is a grey to brown quartzo-feldspathitic calc-silicate feldspathic and calc-silicate with distinct laminar texture and has a gradational contact with the Puntsit Formation. (Moen, *op.cit*)

Structural data: There are boudinage structures and a dextral shearing pattern observed from the foliation at a road cutting located north of the shear zone. (Figure 4.6)



UNIVERSITY of the
WESTERN CAPE

Figure 4.6a: Anastomosing shear zone observed from road cutting outside Keimoes, above the Boven Rugzeer shear zone. Image is taken from a vertical exposure.

Figure 4.7: Boudinage structures observed at the Boven Rugzeer shear zone. Image was taken on a horizontal surface and the GPS used for scale is 10x5cm.

Deviation from regional foliation trend: The Boven Rugzeer and Straussheim shear zones show a minimal deviation in regional foliation trend.

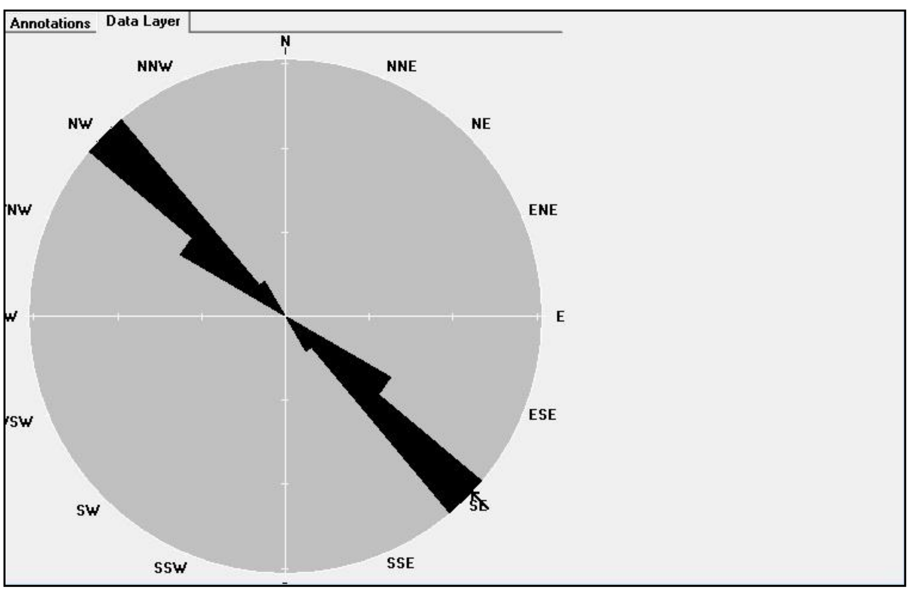
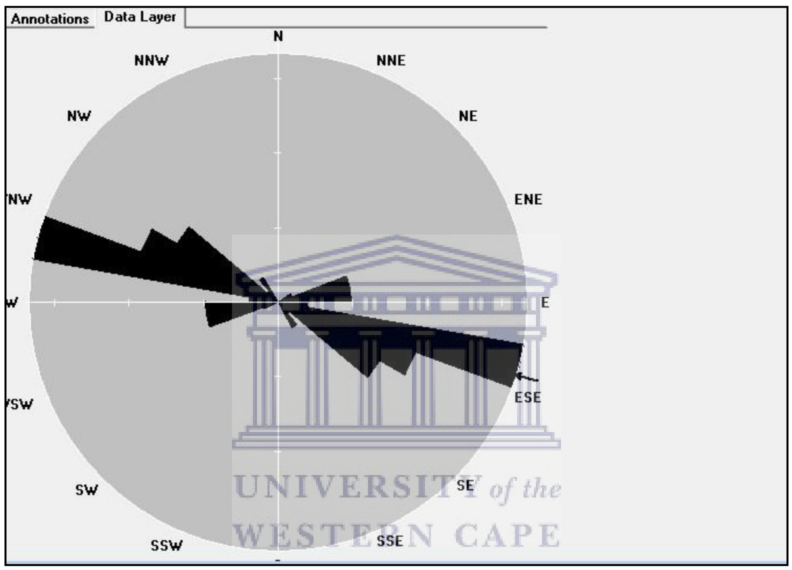


Figure 4.8: Rose diagram of the regional foliation trend at the Boven Rugzeer shear zone.

There was a clear deviation observed from the readings taken at the road cutting above the Boven Rugzeer shear zone (Figure 4.6): while the general foliation direction is NW-SW , the observed orientation is ENE-WSW closer to the shear zone, this is also shown in the rose diagram below (Figure 4.8) as the regional foliation trend of 107-287 degrees deviates to 077- 257 degrees.



UNIVERSITY of the
WESTERN CAPE

Figure 4.9: Rose diagram of the deviation of the regional foliation at road cutting outside Keimoes, Northern Cape.

3. **<u>Trooilapspan shear zone</u>**

Location: The Trooilapspan shear zone is located seven kilometers from Upington in the Northern Cape, it transects the Orange River from the north at 28°24’43”S, 21°17’06”E and south at 28°55’18”S, 21°39’55”E as shown in the map of the field validation area.

Rock description: The Dagbreek Formation of the Vaalkoppies Group shares an intrusive geological contact with the Straussburg Granite of the Keimoes Suite along the Trooilapspan shear zone north and south of the Orange River. (Moen, 2007)

The Straussburg Granite observed is poorly foliated, coarse grained and biotite rich granite with quartz inclusions and is obscured at some exposures by sand and calcrete.

(Moen, 2007)The contact between the Dagbreek Formation and the Straussburg Granite lithologies wasn't observed.

Field observation shows the Dagbreek Formation as a light coloured, medium grained quartzite that is slightly banded and displays a platy foliation. It grades onto a bluish-grey intensely fractured quartzite. This then in turn begins to grade into a dark-grey banded gneiss and there are also lenses of amphibolite and serpentinite. As the metasedimentary Dagbreek Formation grades into banded gneiss there is a change of colour and large clusters of rose quartz and black to greenish mineral nodules orientated N-S ranging from 1-2cm in length. These changes were observed at a road cutting south of the Orange River

Structural data: The Dagbreek Formation has transecting quartz-filled veins that have been displaced at the base of the outcrop. There are also large rotated feldspar porphyroblasts that show a dextral sense of movement.

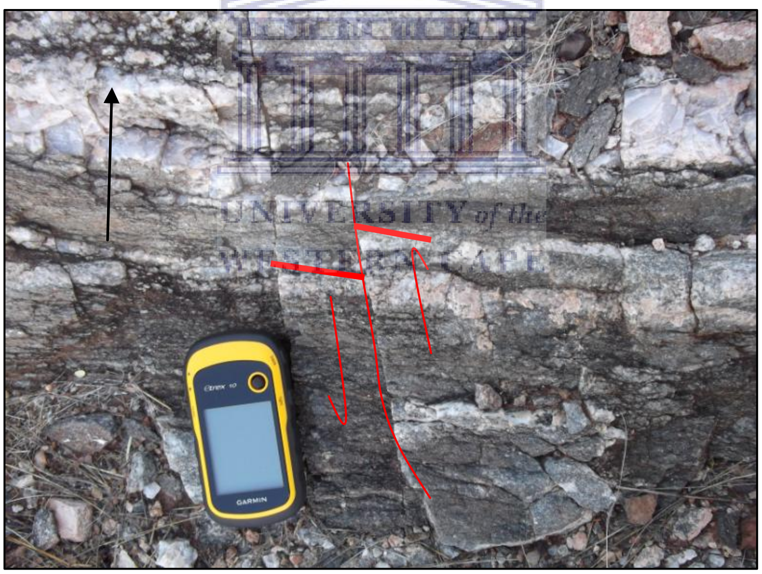


Figure 4.10: Displaced veins at Trooilapspan shear zone. Image taken on a horizontal surface.

Figure 4.11: Quartz porphyroblast showing dextral vorticity at Trooilapspan shear zone. The GPS used as a scale marker is 10x5cm. Image taken on a horizontal surface.

Deviation from regional trend: The deviation in the regional foliation trend was validated and showed readings decreasing towards a northerly direction, this is observed from (figure 4.11) which shows readings moving towards a northerly to southerly direction. There was evidence of large amounts of quartz mobilization found in the country rock.

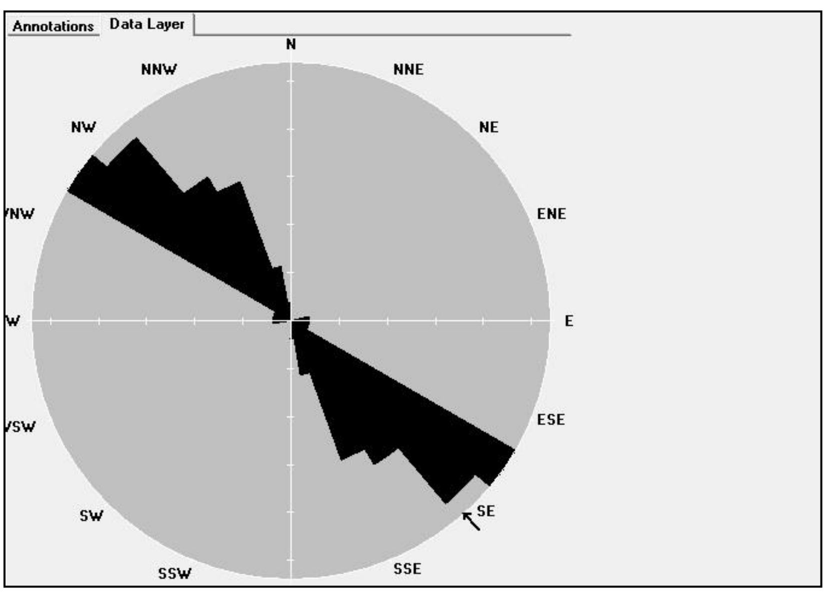


Figure 4.12: Rose diagram of the regional foliation at the Trooilapspan shear zone.

4. Cnydas shear zone

Location: The Cnydas shear zone is located 31 kilometers from Kakamas in the Northern Cape from 28°23'43"S, 20°28'53"E to 28°31'17"S, 20°45'E as shown in the map of the field validation area.

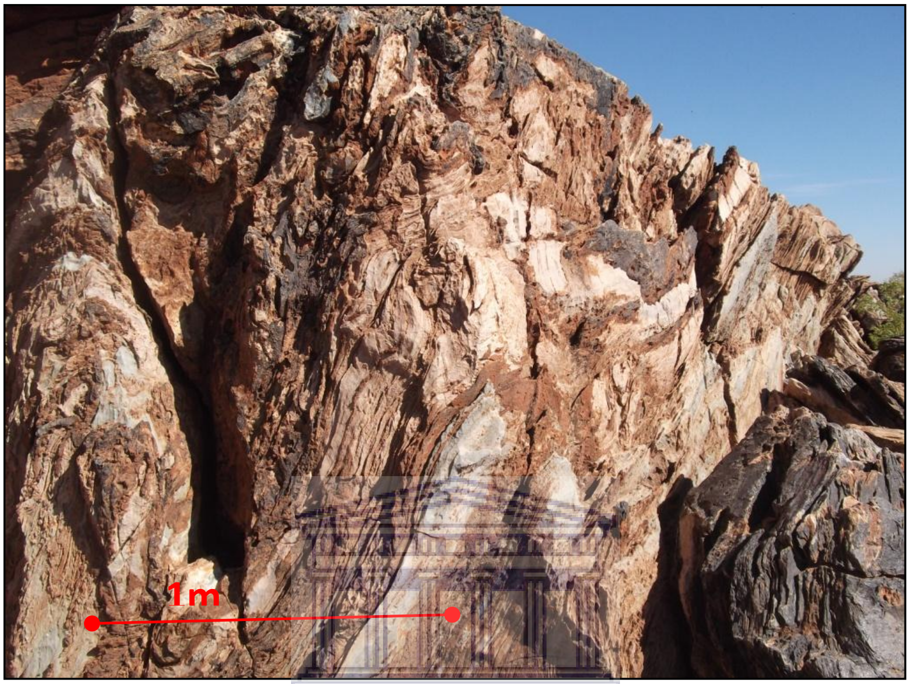
Rock description: The validation of the Cnydas shear zone was done at the contact of the Cnydas subsuite and Sandputs Formation (Moen, 2007). The shear zone is located along the contact of the Sandputs Formation and the oldest unit of the Cnydas Subsuite; the Cnydas East Granodiorite is an unfoliated, coarse grained rock with an equigranular texture and mafic inclusions (Moen, *op.cit*). The Sandputs Formation at this station is a reddish schist which grades vertically into a succession of dark-grey laminated quartzitic, schistose calc-silicate rocks quartzite, schist and calc silicate rocks. (Moen, 2007) There is intense shearing observed at this station.

Figure 4.13: Ptygmatic folds observed in the Sandputs Formation at Cnydas shear zone. The GPS used as a scale marker is 10x5mm and the image is taken on a horizontal surface.

Structural data: There is a prominent foliation in the Sandputs Formation trending in a NW-SE direction, with ptygmatic folds.

Deviation from regional trend: The Cnydas shear zone is also located in an area where the regional foliation trend is NW-SE and the foliation measured along the traverses done shows a significant deviation in foliation trend into a ENE - WSW direction of 077- 257 degrees as shown in the rose diagram below.

EAST

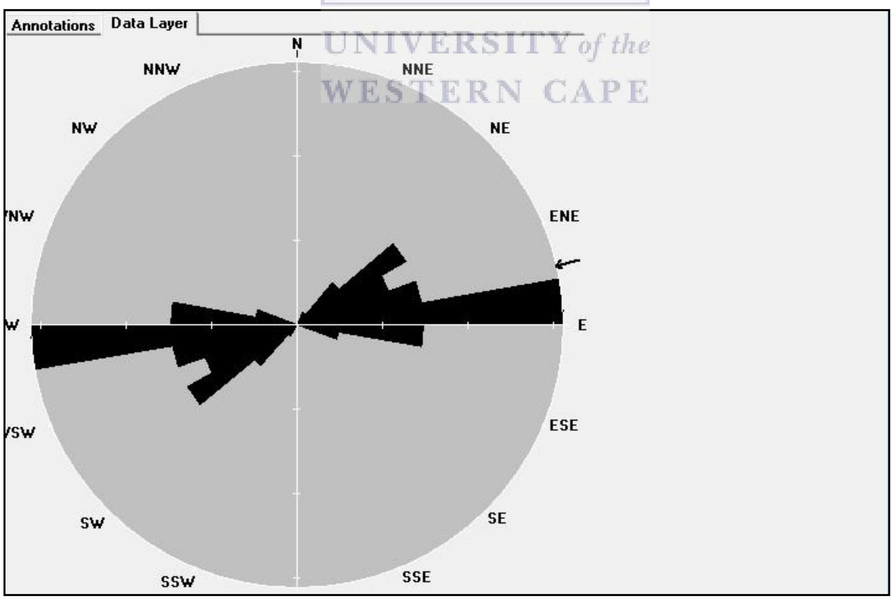


WEST

UNIVERSITY of the
WESTERN CAPE

Figure 4.14: Intense shearing at Cnydas shear zone of Sandputs/ Puntsit Formation.

Figure 4.15: Pinch and swell structures with flow structures found at Cnydas shear zone.



UNIVERSITY of the
WESTERN CAPE

Figure 4.16: Rose diagram of the regional foliation at the Cnydas shear

There were also outcrops observed in the field that had clear evidence that shearing has taken place: firstly the Dyasons Klip Gneiss which showed a minor shear zone with a dragging effect and displacement. The second were the Curries Camp and Klip Bakken Gneisses that had large clusters of quartz mobilization which is indicative of movement and change in orientation of foliation. The rock descriptions and structural data follow below;

5. **Dyasons Klip Gneiss:**

Rock Description: This is an Amphibole- Biotite gneiss (Moen, 2007) with feldspar porphyroblasts which are rounded with varying sizes from 32x17mm and 4x2mm . The following observations were done during field work, the phenocrysts are orientated in a NE-SW direction. Most of the outcrop is transected by pegmatite veins consisting of quartz and feldspar with a chilled margin with increasing mafic bands. The pegmatite veins are trending northeast and are displaced by a later joint set that trends southeast.

Structural Data: There is a dextral shear zone with a minimum displacement of 2metres .There is also an area where movement is left lateral and in the centre of the outcrop there is no indication of movement.

UNIVERSITY of the
WESTERN CAPE

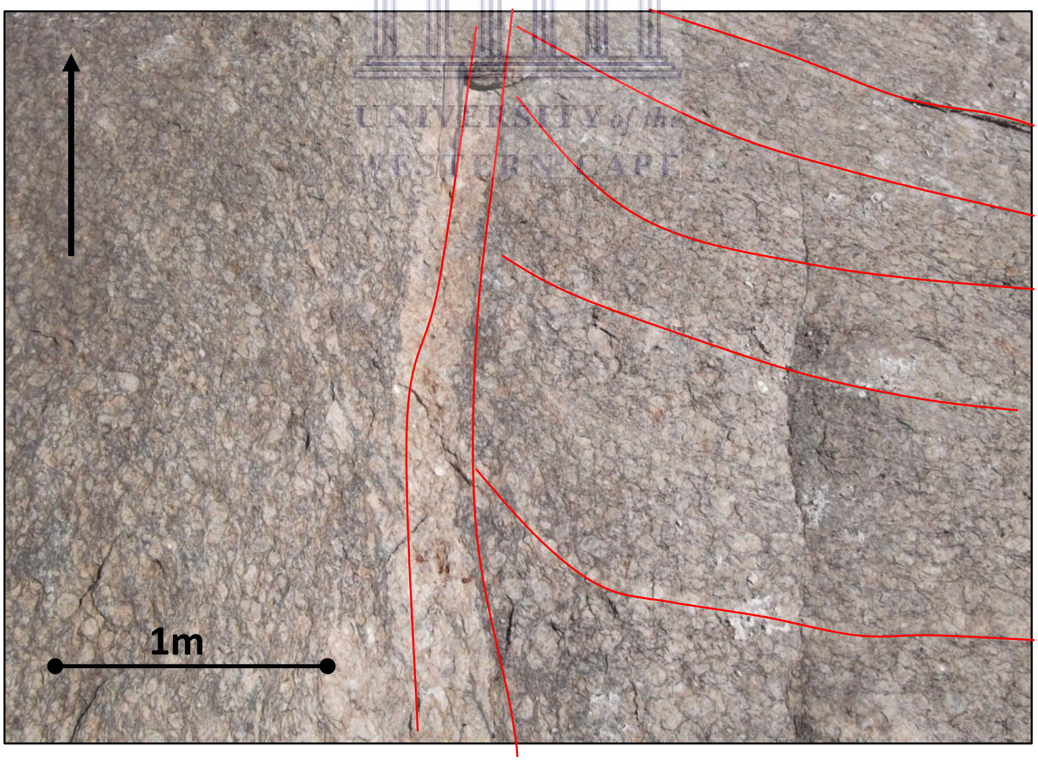


Figure 4.17: Shearing found in Dyasons Klip Gneiss.

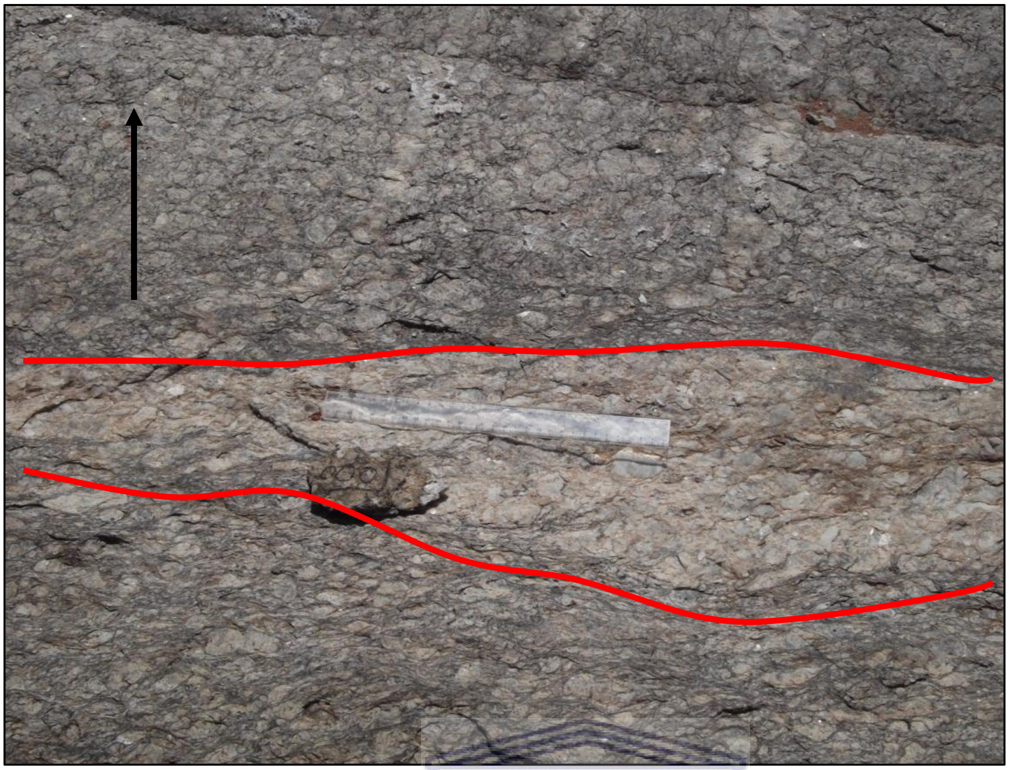


Figure 4.18: Quartz vein observed in Dyasons Klip Gneiss.

UNIVERSITY of the
WESTERN CAPE

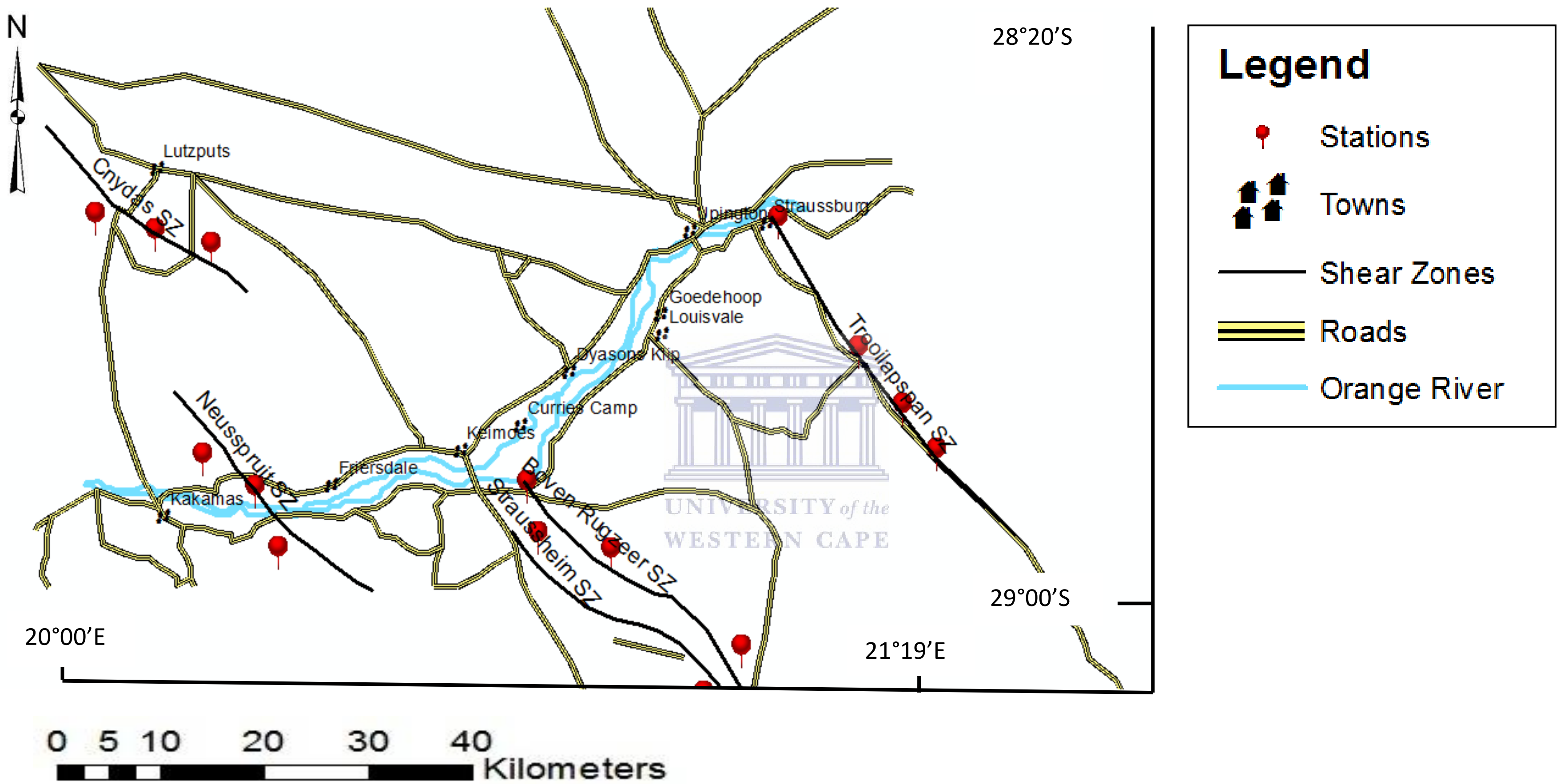
6. Curries Camp and Klip Bakken Gneisses

Rock Description and Structural Data: This is a Biotite Gneiss (Moen, 2007) with large clusters of quartz indicative of movement and change in orientation of foliation. (Figure: 4.19) It is also characterized by large augen shaped feldspar megacrysts and a well developed foliation.

Figure 4.19: Quartz mobilization, Curries Camp.

A field map of the study area was completed in order to record all information found by field validation. This map includes the stations used, the traverses done across shear zones, the general orientation of the foliation observed and recorded, the sense of strike slip motion observed through structural evidence at the various shear zones and the main roads used to get to the stations.

7. Map of the Field Validation Area



UNIVERSITY of the WESTERN CAPE

B. Modeling

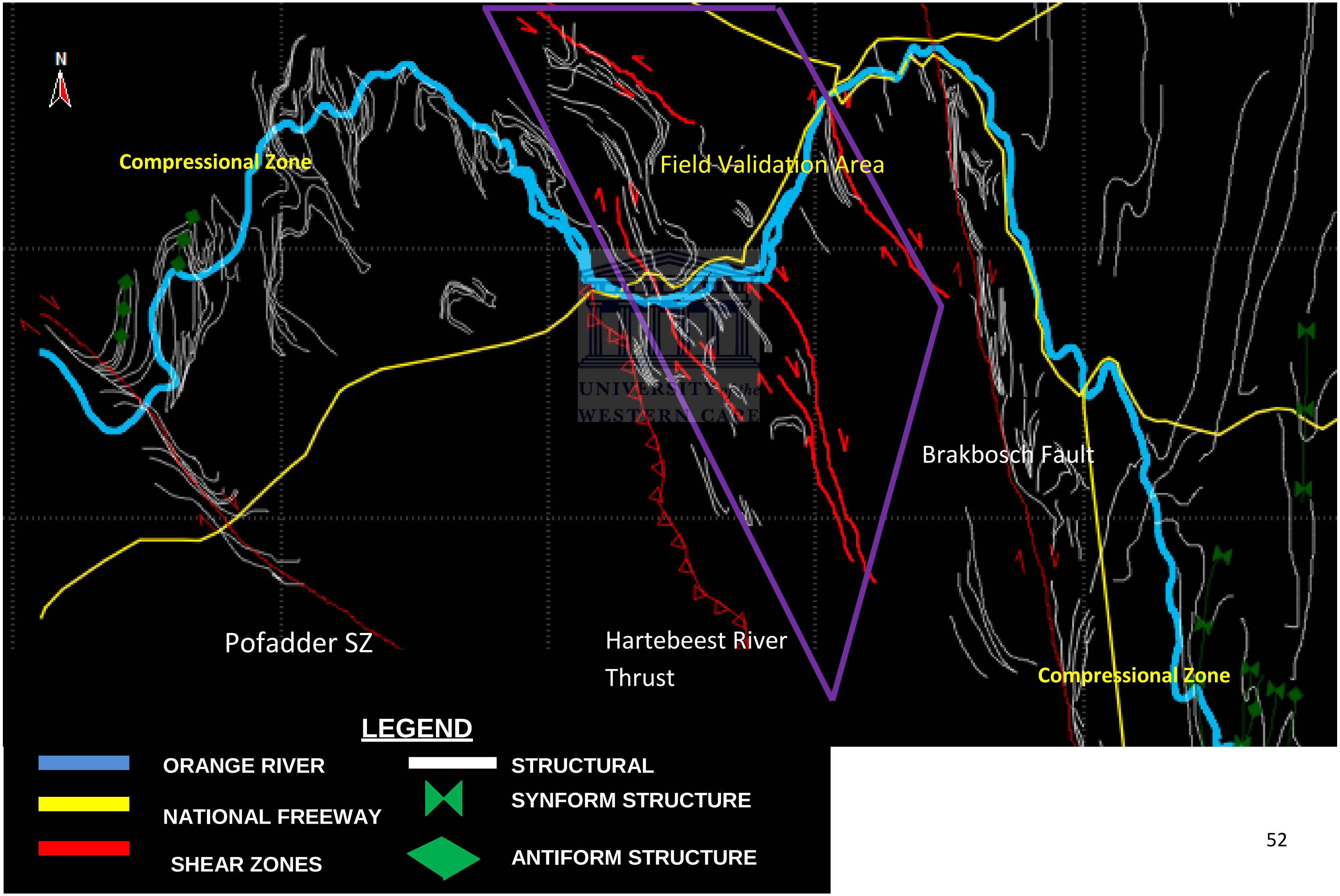
The field data acquired from field validation allows for information to be added to the previous model of the structural framework of the Namaqua Province done by remote sensing. This field data includes; sense of strike slip motion observed at the shear zones by structural evidence and the location of shear zones not previously shown by remote sensing.

The shear zones not found by remote sensing were the Straussheim and Trooilapspan shear zones however during field validation using the geological map of Upington the Straussheim shear zone was found at 28°50’ S and 20°45’E exposed on a road cutting on the southern side of the Orange River. The Trooilapspan shear zone was found at 28°35’S and 21°10”E at a road cutting south of the Orange River. Both shear zones were mapped at numerous stations so as to follow their trend further south of the Orange River.

These coordinates allowed for the digitizing of the shear zones using the previously georeferenced image used during remote sensing, then with structural evidence obtained during field work the sense of strike slip motion was also put in.

UNIVERSITY of the
WESTERN CAPE

1. <u>**Model of the Structural Framework in the Namaqua Province.**</u>



The Neusspruit, Boven Rugzeer and Cnydas shear zones were also validated in the field by going to the locations established during remote sensing and using the geological map of Upington, their locations were found to correspond to the remote sensing map along with the structural trend lines that were used to outline them during remote sensing.

The sense of strike slip motion observed at the Neusspruit, Straussheim, Boven Rugzeer and Trooilapspan shear zones is dextral while the Cnydas showed sinistral movement. The model shows zones of compressional and strike slip tectonics in the Namaqua Province. This is based on the correlation between the structural trend lines that were digitized over the satellite image of the Namaqua Province, the geological map of Upington and previous works. To the west of the image there is a major dextral shear zone (Pofadder SZ) and towards the east a large area of fold interference patterns, bound by a prominent thrust zone (Hartebeest River Thrust) further east.

There are then an array of dextral shear zones south of the Orange River and a sinistral shear zone north of the Orange River where field validation took place. The Brakbosch Fault marks the end of dextral strike slip motion south of the Orange River. This fault was not validated during field work as the dextral sense of movement was observed during remote sensing. The area southeast of the Brakbosch Fault showed fold structures such as synforms and anticlines with fold axes observed during remote sensing to be orientated N-S and NE-SW and this indicates another compressional tectonic zone.

UNIVERSITY of the
WESTERN CAPE

This will be used as evidence of the transpressional geotectonic environment that exists in the Namaqua Province and will be discussed with regards to how this environment could have allowed for the Keimoes Suite Granites to intrude.

V. CHAPTER FIVE: DISCUSSION AND CONCLUSIONS

A. Discussion

The aim of the study is to establish whether the numerous shear zones within the eastern Namaqua Sector indicate if there was a structurally generated zone of weakness which formed in the transpressional environment of the Namaqua Sector that allowed the Keimoes Granite Suite to intrude. In order to achieve this, remote sensing of the eastern Namaqua Sector was done; however, in the region where the Keimoes Granite Suite is found remote sensing could not be done as there was a scarcity of geological outcrops at the remote sensing scale. It is this region which was validated by field work and mapping. The mapping was done as traverses across the major shear zones and in zones where the shear zones showed a significant change in direction.

The relationship interpreted from field data is that there are mainly dextral shear zones, with the exception of the Cnydas shear zone which is sinistral, and that within this block, from the Neusspruit shear zone to the Trooilapspan Shear zone there is dextral strike slip movement. The events found in the geologic time scale of the Namaqua Sector which are associated with the formation of the shear zones and their rotation is D_4, where late stage dextral shearing occurred on a large scale during the deposition and intrusion of the Koras Group and Keimoes Granite Suite (Jacobs et al., 1993; Miller, 2008).

This was due to the continued northeast to southwest directed compression with the shape of the adjacent Kaapvaal Craton presenting an indentor which propagated the transcurrent shear system (Cornell et al., 2006; van Bever Donker, 1991). This suggests that the Namaqua Sector was subjected to a period of compression which was followed by strike slip tectonics as, with continued compression and time, this compressional stress was released laterally and formed these dextral shear zones.

This is better explained by understanding plane stress in a two dimensional surface (Fig 5.1). In vector analysis when there is a force oblique to a surface, it is resolved by a force perpendicular and one parallel to the surface (Van Bever Donker, pers comm). The vector normal to the plane is the normal stress (σ_n) and the vector component parallel to the surface is the shear stress (σ_s) (Huber and Ramsey, 1983).

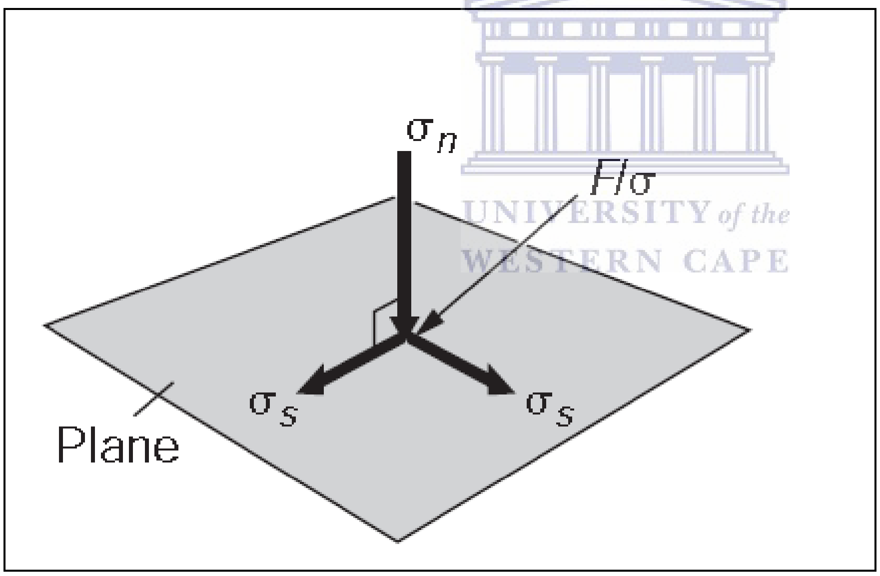
The formation of strike slip motion due to continued compression is indicative of a transpressional environment, and is also confirmed by Vajner (1974a) who concluded that there was dextral rotation of the Namaqua block relative to the craton which produced a transpressional regime, thereby causing the en echelon arrangement of fractures and the dominantly dextral movements of its component faults.

To understand the development of transpressional environments we must first look into the processes that account for the field evidence such as the vorticity structures found

UNIVERSITY of the WESTERN CAPE

at the shear zones along with the overall dextral rotation of the Areachap Terrane as indicated by the dextral shear zones. The next step is to relate these to the greater picture of a transpressional environment and determine where these dextral shears and processes fit within this geotectonic setting. Then finally it must be assessed whether a transpressional environment would have allowed for the formation of a structurally generated zone of weakness such as pull-apart basins which facilitated the intrusion of the Keimoes Granite Suite.

The processes that account for the field evidence are block rotation due to translation and lateral escape. The presence of vorticity structures and the mainly dextral shear zones within the Areachap Terrane show that there is rotational torque on the area. This can only be accommodated by subdividing the area into small strips with strike-slip movement between them. This creates many strike slip faults which slip past each other and change a rectangular area into a parallelogram (Fig 5.2). This produces translation between the shear zones and the rotational effect of the Areachap Terrane (van Bever Donker, pers. comm)



UNIVERSITY of the
WESTERN CAPE

Figure 5.1: Two dimensional stress acting on a planar surface with normal stress (σ_n), shear stress (σ_s) and force (Fσ), (after Marshak and Van der Pluijm, 2004).

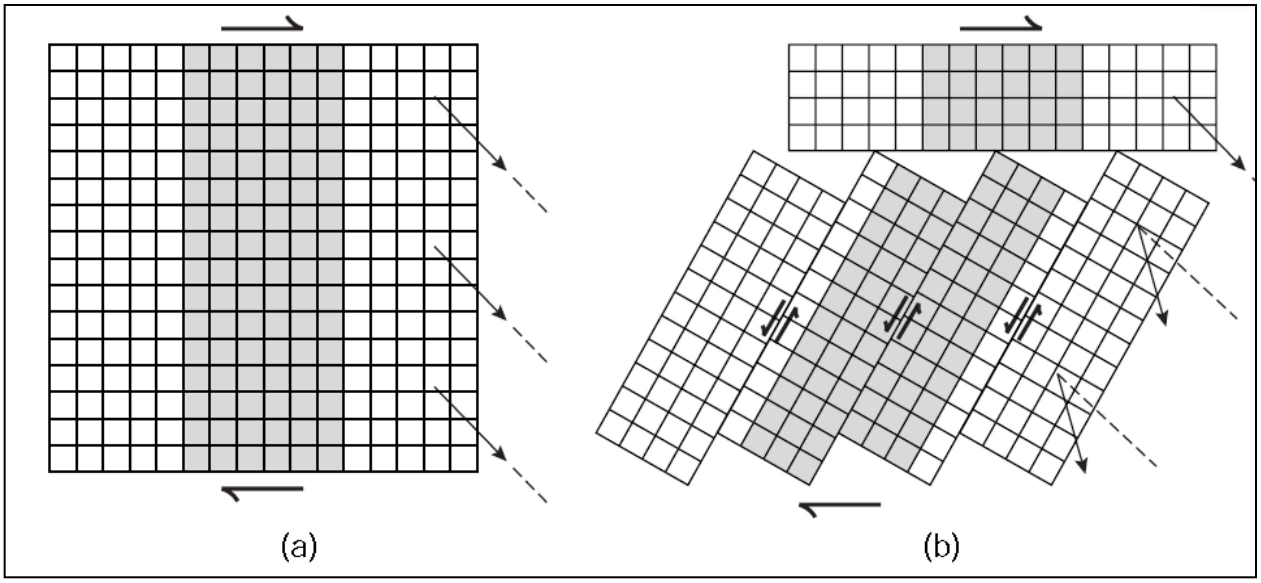


Figure 5.2: The block rotation in a dextral strike-slip zone. (a) The grid is subjected to dextral simple shear and (b) The grid is divided into blocks which are bound by strike slip faults (after Marshak and Van der Pluijm, 2004).

UNIVERSITY of the
WESTERN CAPE

1. <u>Block rotation due to translation</u>

In order for crustal blocks to be rotated there needs to be large amounts of stress or force applied, as, according to Marshak and Van der Pluijm (2004): *"deformation of a body occurs in response to forces"*. In order for translation of a block to occur there is no change in the shape of the block as it moves, as shown in Fig 5.2 and Fig 5.3. The translation of a block occurs when rotation and distortion are zero.

The other components of deformation include rotation and distortion where rotation is the spin of a body around an axis and distortion is the complete change in shape (Marshak and Van der Pluijm, *op.cit*). In order to understand the components of deformation Marshak and Van der Pluijm (*op.cit*) describe the relationship of deformation and strain by pointing out that deformation is the *collective "displacements of points in a body*" when there is "*transformation from the initial to the final geometry of a body*".

This can be shown by the four corners of a square, where during translation of the square the corners would be displaced and have new positions, the length from the initial positions of the four corners of the square to the new positions are noted as displacement vectors and it is the sum of these that denotes which component of deformation such as translation, rotation or distortion occurred (Marshak and Van der Pluijm, 2004). Using this, rotation can be described as when the translation and distortion components acting on a body are zero (Marshak and Van der Pluijm, 2004).

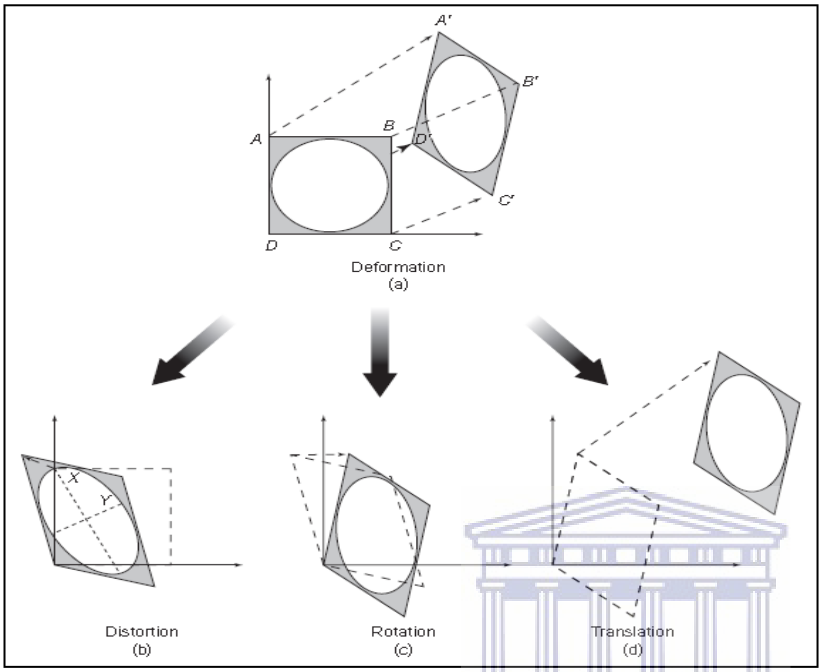


Figure 5.3: The three components of deformation (after Marshak and Van der Pluijm, 2004).

UNIVERSITY of the
WESTERN CAPE

2. Transpressional Environments

The next process to address is that of lateral escape. It is synonymous with transpressional environments and indentation escape tectonics as it is the point where continued compressional tectonics results in a strike slip component. It is imperative to firstly establish how transpressional environments develop; secondly what the processes are that lead to indentation and lateral escape tectonics, and thirdly what structural evidence there is to prove that escape tectonics has occurred.

Transpressional environments are primarily compressional environments where there are three stages of collisional tectonics, namely pre-collision and initial interaction, abortive subduction, suturing and crustal thickening, and, finally, extensional collapse (Marshak and Van der Pluijm, 2004). In transpressional environments there is a period of regional strike slip faulting and lateral escape that is included. These four stages of development will be described and correlated to the Namaqua Sectors geology and structures.

a. Pre-collision and Initial Interaction

The initial interaction prior to collision includes taking note of factors such as the relative motion between colliding blocks which influences the type of structures that form, as in frontal collision thrust faults develop with their movement perpendicular to the edge of the colliding zone (Marshak and Van der Pluijm, 2004). In the case of oblique collisions there are thrust and strike slip faults which develop and the colliding blocks move together (Marshak and Van der Pluijm, 2004).

The shape of the colliding blocks and the degree of lateral confinement of the crustal block to be indented are also factors which influence the shape of orogens that develop. In addition, the physical characteristics of the colliding blocks, such as temperature, thickness and composition also affect the type of collision that takes place (Marshak and Van der Pluijm, 2004; Cobbold and Davy, 1988).

The first stage in pre-collision includes the moving of continent A and continent B together and the subduction of the oceanic lithosphere attached to continent A underneath continent B. The type of margins existing are a passive margin with sedimentary basins which have developed along continent A and an Andean-type convergent margin with a volcanic arc along continent B.

UNIVERSITY of the
WESTERN CAPE

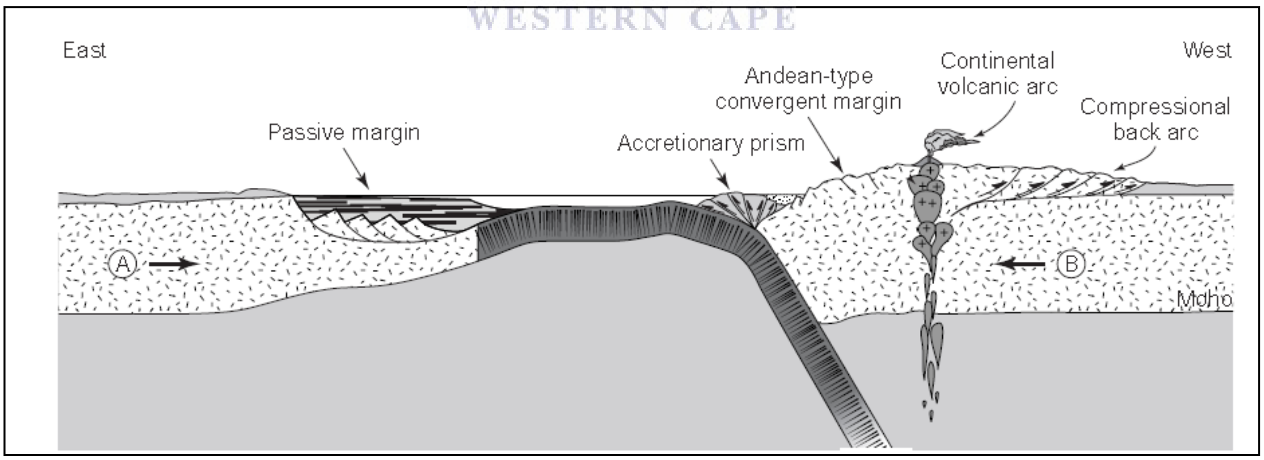


Figure 5.4: Pre-collision stage of continents A and B (after Marshak and Van der Pluijm, 2004).

Continent A starts to bend as it is pulled into the subduction system by the down-going plate causing an extensional environment on the down-going plate and the formation of normal faults trending parallel to the edge of the margin.

b. Abortive subduction and suturing

As there is continued convergence the surface of continent A's continental shelf becomes the floor of the trench and the turbidites that are derived from the margin of continent B and its volcanic arc bury the now eroded surface of the continental shelf. This forms a major unconformity which defines the contact between the passive margin basin sedimentary sequence and the turbidites. There is the development of a fold thrust belt as the strata on the down-going plate consist of well stratified sedimentary beds of the former passive margin basin. The thrusts propagate into these beds producing a fold thrust belt that grows into the foreland of continent A with time.

As the thrusts propagate into the foreland of continent A there is also a slice of oceanic crust that once separated continent A from continent B that is included. This forms a suture which appears in the orogen as a piece of highly sheared mafic and ultramafic rock and defines the boundary between rocks of continent A and of continent B on either side (Figure 5.5).

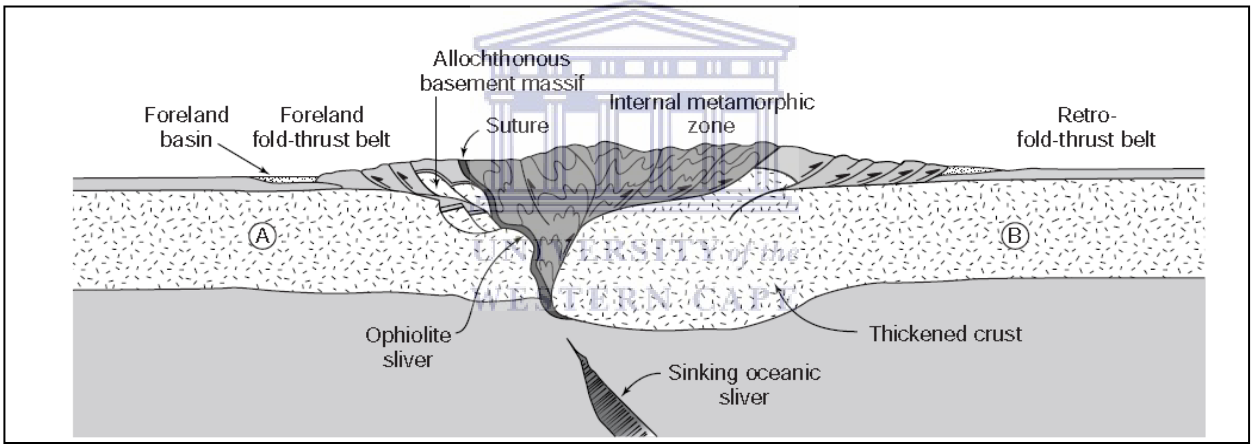


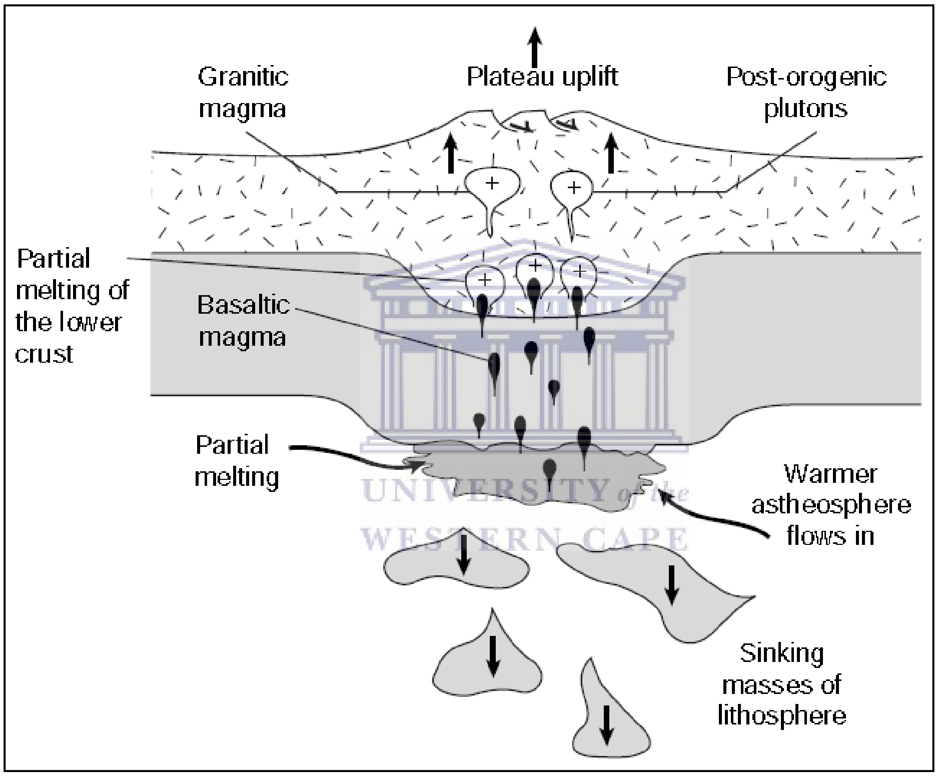
Figure 5.5: Abortive subduction and suturing (after Marshak and Van der Pluijm, 2004).

There is also the reactivation of normal faults to reverse faults as basin inversion occurs and the thickening of crust which increases ductile folding and produces large, tight and isoclinal folds, with shearing producing mylonites and regional metamorphism that produces gneisses and schists.

c. Crustal thickening and Extensional Collapse

Crustal thickening occurs as compression ensues but *"as a consequence, the differential stress developed in the orogen due to the weight of overlying rock exceeds* *the yield strength of the rock at depth, and the rock begins to flow and develop horizontal extensional strain" (*Marshak and Van der Pluijm, 2004).

The rock at depth is warmer and weaker as there are higher temperatures and ductile conditions there, while the rock in the upper crust is cooler and brittle due to brittle conditions. The upper crust rocks experience rupturing and the development of normal faults as there is extensional collapse and the lower crust experiences decompression which triggers the partial melting of the deep crust and the underlying asthenosphere producing magmas *(*Marshak and Van der Pluijm, 2004).



UNIVERSITY of the WESTERN CAPE

Figure 5.6: The emplacement of magma during ductile extensional collapse (after Marshak and Van der Pluijm, 2004).

d. Regional strike-slip faulting and lateral escape.

The development of strike slip faulting within collisional tectonics is brought on in the early stages of collision where the relative motion vector of the colliding blocks is not perpendicular, such that the collisional boundary between these blocks is oblique (Marshak and Van der Pluijm, 2004). In this case the relative motion between the two plates is an important factor which is "*divided into a component of dip slip motion which* *is perpendicular to the margin and a component of horizontal shear or strike slip faulting which is parallel to the margin"* (Marshak and Van der Pluijm, 2004). This would then result in crustal blocks caught between colliding masses been squeezed out of the collision zone along strike slip fault boundaries in a process called lateral escape (Marshak and Van der Pluijm, 2004). This is a process which is important to the development of the shear zones found in the study area and the understanding of which is essential to the study in order to correlate what was found in the field to the overall structural framework of the Namaqua Sector.

An important aspect to lateral escape is the degree of confinement that exists between the indentor crustal block and the continental margin, as these influence the direction of lateral escape and the type of structures that form (Cobbold and Davy, 1988). In the following three scenarios, convergence is from west to east.

There are three types of lateral confinement; strong, moderate and weak lateral confinement. In strong lateral confinement there is only crustal thickening which is localized in front of the indentor and results in a northward propagation of thrusts in the uppermost layer in east-west directed convergence. In moderate lateral confinement, with indentation occurring along the eastern margin of the crustal block, there is crustal thickening and lateral escape occurring in similar proportions (Cobbold and Davy, 1988). The crustal thickening is concentrated in a plateau area in front of the indentor whilst lateral escape is facilitated by a main left lateral thrust zone that joins the western corner of the plateau to the eastern continental margin. The thrust zone is divergent in a northeast to southwest direction (Cobbold and Davy, 1988).

In weak lateral confinement, also occurring at an eastern margin, the lateral escape is in an eastward direction with reverse faults and rifts forming, along with crustal thickening near the indentor (Cobbold and Davy, 1988). There is a left lateral thrust zone which develops between the indentor and the unconfined margin which separates the area of eastwards escape from undeformed continental material (Cobbold and Davy, 1988).

The best example of modern day indentation and lateral escape is of the collision between India and Asia during the development of the Himalayan mountain belt. This was simulated by Marshak and Van der Pluijm (2004) using a wood block representing the rigid craton of India which is pushed into the clay cake representing the soft crust (in relation to the Indian craton) of Asia, while there is a rigid block representing western Asia that constrains the clay cake and an unconstrained eastern side of the clay cake representing the Pacific Ocean. What is observed over time is that as the wooden block moves northwards, or as the Indian craton indents Asia there are strike slip faults which develop in Asia and large crustal blocks or pieces of the clay are pushed eastwards.

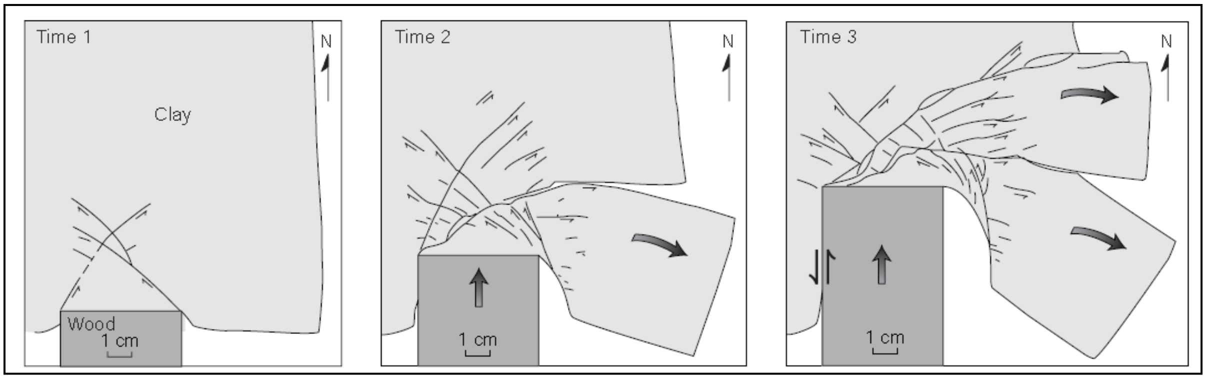


Figure 5.7: Model of indentation and lateral escape tectonics, as represented by the collision of India with Asia (after Marshak and Van der Pluijm, 2004)

As lateral escape occurs, crustal blocks are rotated and release structures develop, such as large scale strike slip fault systems that are terminated by minor fault systems with extensional or compressional components (Marshak and Van der Pluijm, 2004).

These minor fault systems are known as transcurrent faults as they diverge into an "*array of smaller faults*" which can be reverse or normal faults resulting in folding and uplift on one side of the large scale strike slip fault, and tilting and subsidence on the other (Marshak and Van der Pluijm, 2004). These are known as releasing and restraining bends. The formation of these fault bends is due to the deviation of the strike of a fault plane from the regional displacement vectors.

Figure 5.8 shows a strike slip fault that strikes in an east west direction and that is parallel to the regional displacement vector, but where the strike of the fault plane is not parallel a fault bend with either an extensional or compressional component develops.

A releasing bend develops at a fault bend with an extensional component; this is due to the opposite walls of the fault pulling away from each other. Thus normal faults develop and there is subsidence of the crustal block that is adjacent to the fault bend so that pull-apart basins form (Fig. 5.8a). A restraining bend develops at a fault bend with a compressional component; this is due to the fault segment inhibiting motion and the opposite sides of the fault push together thus causing crustal shortening and the formation of fold thrust belts (Fig 5.8b) (Marshak and Van der Pluijm, 2004).

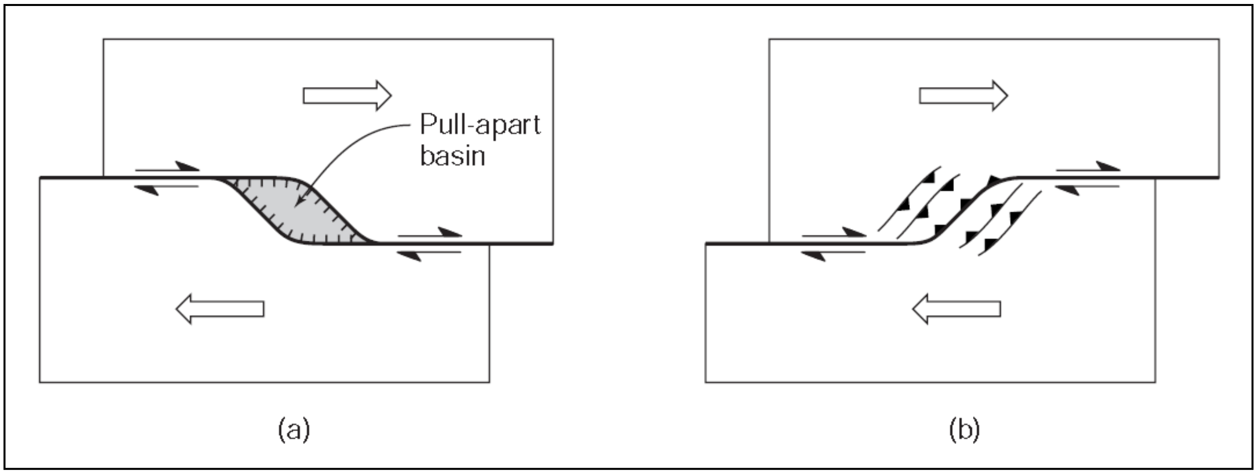


Figure 5.8: The development of fault bends with (a) an extensional component and (b) a compressional component, (after Marshak and Van der Pluijm, 2004).

The displacement that occurs due to crustal shortening and crustal extension in restraining and releasing bends in regional strike-slip faults produce positive and negative flower structures in map view (Fig 5.9).

The formation of positive flower structures is when there is a compressional component acting on the fault bend and fold thrust belts develop (Fig 5.9 a). In negative flower structures there is an extensional component acting on the fault bend and there is crustal subsidence and extension (Fig 5.9b) (Marshak and Van der Pluijm, 2004).

WESTERN CAPE

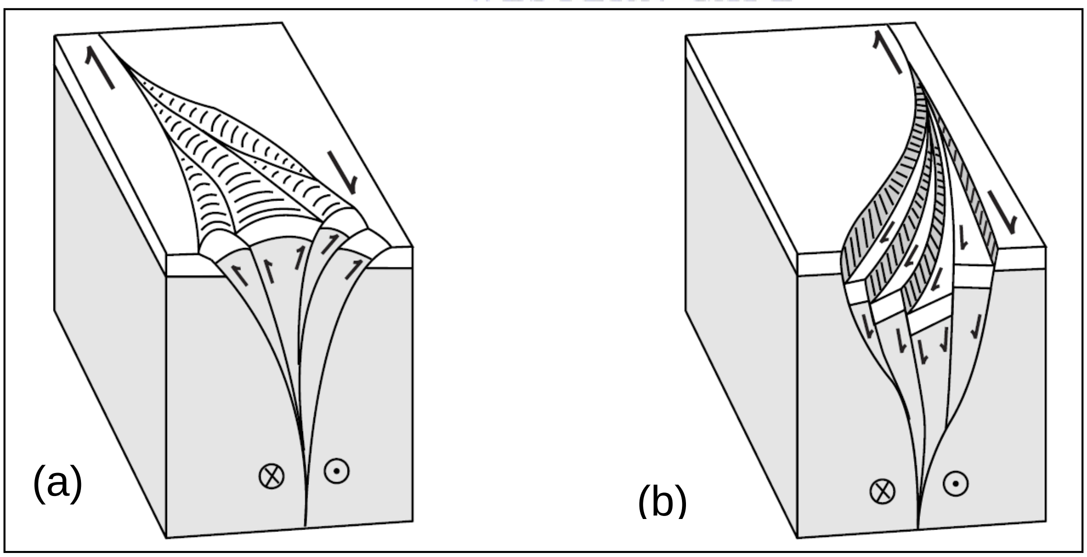


Figure 5.9: The formation of a positive flower structure (a) and a negative flower structure (b) along a dextral strike slip fault (after Marshak and Van der Pluijm, 2004).

3. Interpretation of the regional and local geology

The discussion has given an overview of the development of a transpressive environment and the major processes which account for the structures observed during field work and remote sensing. The interpretation will link the development of a transpressive environment with the regional and local geology and produce a geologic sequence of events of the Namaqua Sector.

The first stage of a transpressive environment is the oblique convergence of the two continents, such as the Namaqua crustal block and the Kaapvaal Craton. The Namaqua crustal block was the subducting plate with a passive margin and the Kaapvaal Craton was the Andean-type convergent margin. According to Cornell et al. (2006), the Kheisan age Brulpan and Vaalkoppies Groups were deposited on continental crust and deformed in a continental margin environment. They were deposited on the western margin of the Kaapvaal Craton. The Areachap Terrane has subduction-related geochemical signatures (Geringer et al., 1986) and points to an arc-related setting with massive sulphide deposits (Cornell et al., 2006).

Moen (1980) proposed an active plate margin for the Wilgenhoutsdrif Group in which deposition took place above a westward-subducting plate. A back-arc environment in a convergent margin setting was suggested for the Wilgenhoutsdrif Group with the Areachap Terrane representing the arc, which initiated the Namaqua Orogeny at ~1.2Ga. Further convergence led to the accretion of the arc, the back-arc complex and the latter's Kheisan floor with the Kaapvaal Craton during the Namaqua Orogeny (Cornell et al., 2006).

UNIVERSITY of the
WESTERN CAPE

The continued compression subjected the rocks of the Namaqua crustal block to be thrust over the Kaapvaal Craton and regional metamorphism and deformation to occur. These deformational events are referred to in the literature as D1 and D2, which were the earliest fabric forming episodes and which produced isoclinal, non-cylindrical folds and southwest directed thrust and nappe development. The third deformational phase comprises open to partially upright folds related to the D3 event (Stowe, 1983, 1986).

During continued compression there is basin inversion which reactivates normal faults into reverse faults (Marshak and Van der Pluijm, 2004). This can explain the sinistral movement of the Cnydas shear zone and imply that it may be older than the dextral shear zones which form as part of orogenic collapse. However this can only be validated by further field work in the area as solving this riddle fell outside the scope of this project.

As convergence continues and subduction stops there is the thrusting of the slice of oceanic lithosphere which separates the geology of the two crustal blocks. This is known as a suture zone which Cornell et al. (2006) suggested to be the serpentinite lenses accompanying the Brakbosch-Blauwbospan fault system which may be interpreted as a possible suture zone between the Areachap and the Kheis Province.

There is an increase in crustal thickening after subduction occurs as the weight of the fold thrust belt exceeds the load that the lower crust can withstand and decompression of the lower crust takes place (Marshak and Van der Pluijm, 2004). This decompression triggers partial melting of the deep crust and the underlying asthenosphere which produces magmas which intrude the upper crust (Marshak and Van der Pluijm, 2004).

The Keimoes Suite granites are differentiated according to the timing of intrusion relative to the Namaqua Orogeny into early, late syn-tectonic and post-tectonic granitoids. According to Geringer et al. (1988) the well foliated metamorphosed granitoids of the Keimoes Suite are mostly syn-tectonic and this along with their geochemical signature suggests that they formed by melting following collision and crustal thickening as they show evidence of experiencing much of the deformational history of the Namaqua region (Stowe, 1983; Van Zyl 1981) (Fig 5.10).

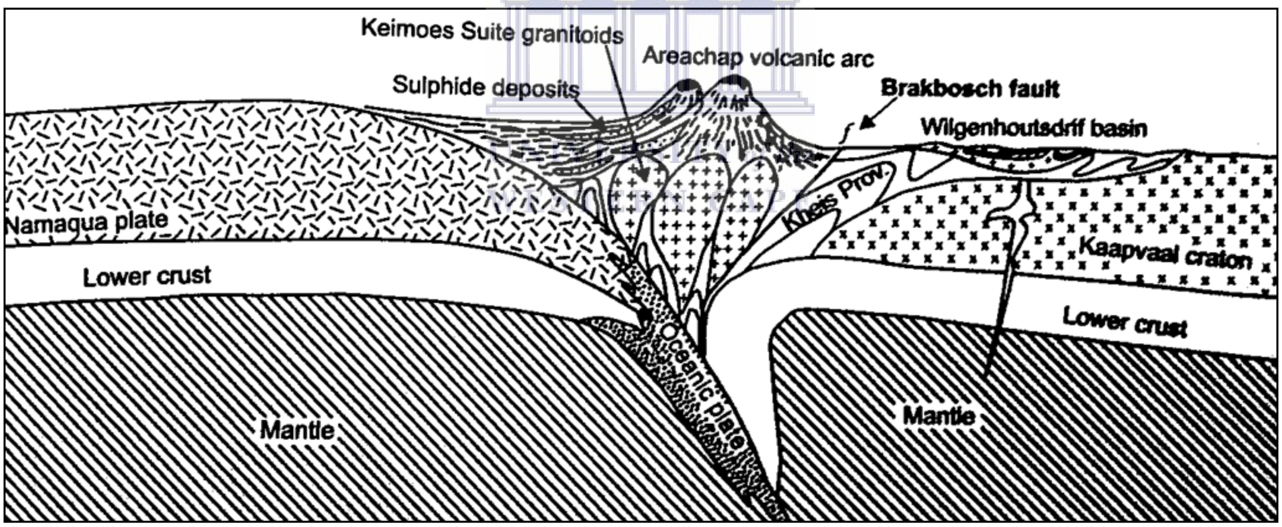


Figure 5.10: The emplacement of the early to late syn-tectonic Keimoes Suite granitoids (after Geringer et al. 1986).

The change of the geotectonic environment from a compressive to transpressive environment was brought on as the response to continued crustal shortening as the "*thrust planes were locked and steepened"* (van Bever Donker, 1991). As the Namaqua crustal block continued to collide with the Kaapvaal Craton the environment changed to a compressional environment with a strike slip component as the Namaqua crustal block escaped laterally. A large transcurrent strike slip fault developed on the margin of the Kaapvaal Craton and the Namaqua crustal block with sinistral strike slip faults on the eastern margins (Natal Sector) and dextral strike slip faults on the western margins (Namaqua Sector) (Fig 5.11) (Miller, 2012).

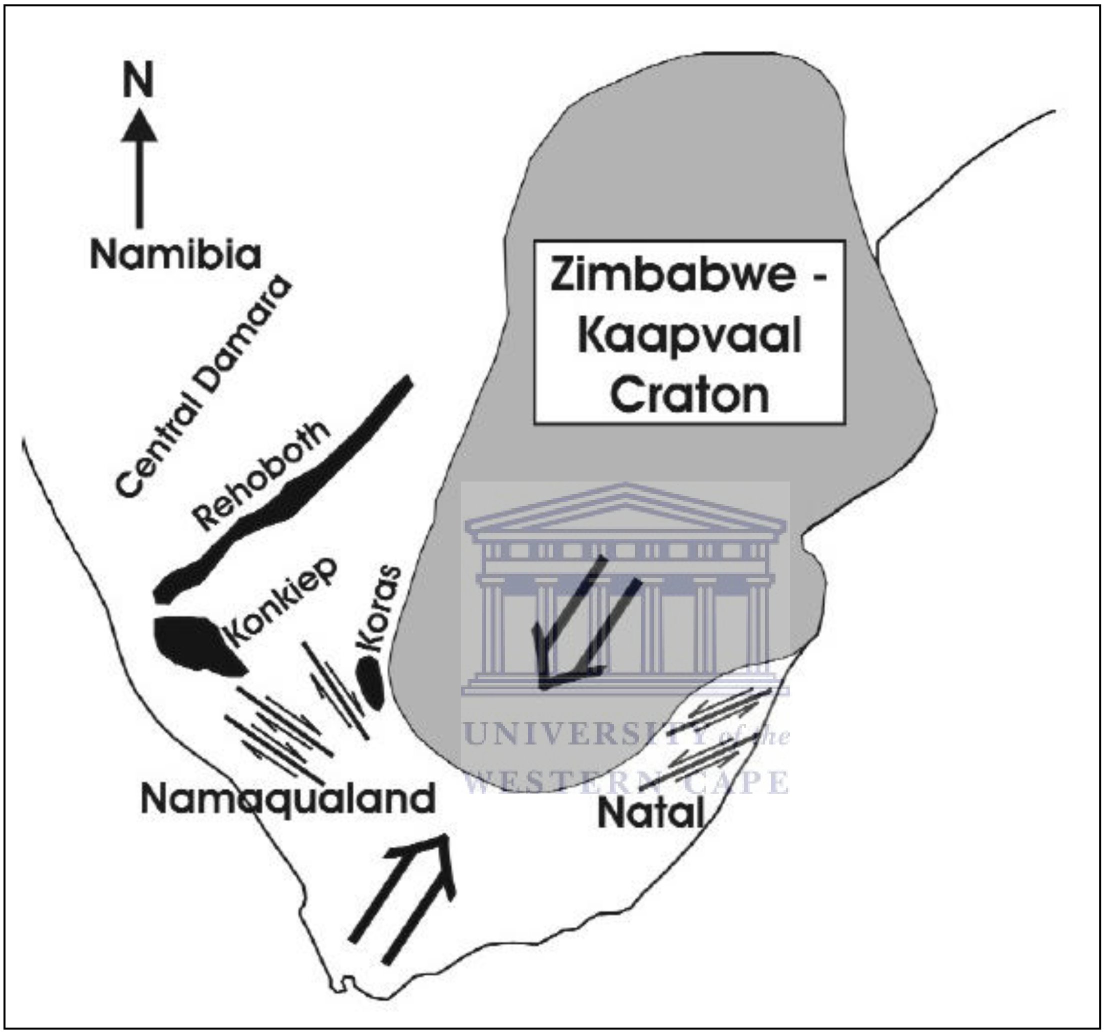


Figure 5.11: The development of dextral strike slip faults along the western margin and sinistral strike slip faults along the eastern margin of the Kaapvaal Craton due to lateral escape from the continued NE-SW compression of the Namaqua-Natal continent (after Miller, 2012).

The development of dextral strike slip faults in the Namaqua Sector due to continued compression would indicate that the fault bend within the Namaqua Sector has an extensional component. The presence of an extensional component within the Namaqua Sector would develop large scale pull-apart basins as the opposing walls of the fault plane would be pulling away from each other and create crustal subsidence.

This would have formed a transtensional structural feature such as a negative flower structure that would include features such as a pull-apart basin with normal faults and graben structures that which would have allowed for the intrusion of the post tectonic Keimoes Suite granites (Fig 5.12) and the extrusion of the synchronous Koras Group bimodal lavas at 1.17 and 1.10 Ga (Bailie et al., 2012).

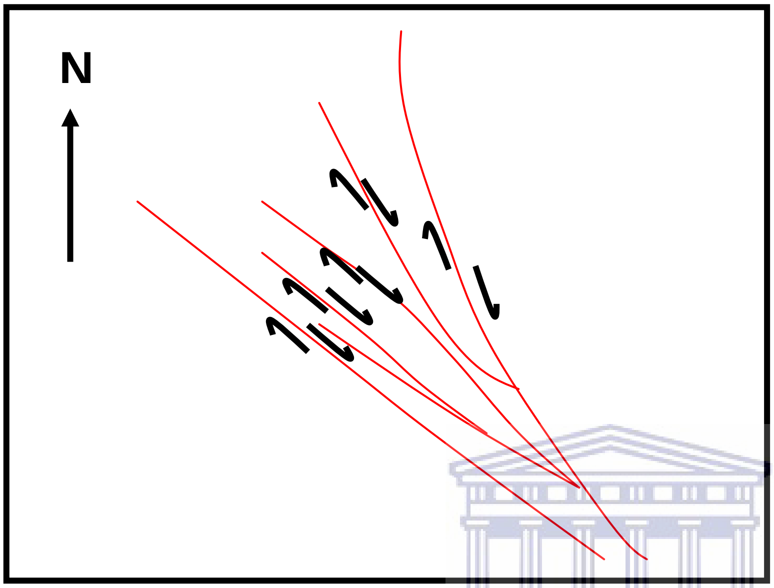


Figure 5.12: The overall pattern and general trend of shear zones within the study area, indicating a negative flower structure done by digitizing of a LandSAT image.

UNIVERSITY of the
WESTERN CAPE

The literature makes reference to an extensional period after the Namaqua Orogeny during the deposition of the Koras Group which is deposited in large scale gradually deepening grabens within pull-apart basins (Cornell et al., 2006, Jacobs et al., 1993, Miller, 2012). This is important as the age of the Koras Group (1.17 Ga) correlates with the syn-tectonic or younger Keimoes Suite granitoids which intrude the Areachap and Kakamas Terranes (Barton and Burger, 1983; Botha et al., 1979; Miller, 2012).

According to Cornell et al. (2012), and from other studies there are two suites of granitoids, one of about 1.17 to 1.15 Ga that are syn-tectonic (synchronous with the older 1.17 Ga portion of the Koras Group), and a younger, largely post-tectonic series of granitoids that intruded around 1.10 Ga, synchronous with the younger, upper part of the Koras Group

This means there was a period of extension which occurred across all three terranes, including the Kaaien Terrane, and that the younger unfoliated granitoids of the Keimoes Suite with slightly foliated margins and metamorphic aureoles were intruded as melts of the supracrustal rocks (Cornell et al., 2006; Miller, 2012).

The regional geology and structural framework of the Namaqua Sector agrees with a transpressive environment and the environment allows for the intrusion of the Keimoes Suite granitoids during and after the Namaqua Orogeny. An overview of the geological sequence will be given.

4. Sequence of geologic events in the Namaqua Sector

- Oblique collision of the Namaqua continent with the western margin of the Kaapvaal Craton during the Mesoproterozoic Namaqua Orogenic event at ~1.2Ga.
- Intrusion of the syn-tectonic Keimoes Suite granites during the Namaqua Orogenic event due to crustal thickening.
- Collision of the Namaqua continent with a southwest directed pointed indentor of the Kaapvaal Craton created southwest directed thrusting and nappe-like folds.
- Continued NE-SW orientated compression resulted in lateral escape of the Namaqua Sector along the western margin of the Kaapvaal Craton and the formation of an array of large scale dextral strike slip faults in the Namaqua Sector.
- The Kaaien, Areachap and Kakamas Terranes are rotated.
- The formation of an array of strike slip faults with an extensional component forms pull-apart basins across the three rotated terranes.
- The post-tectonic Keimoes Suite granites intrude the Areachap and Kakamas Terrane sedimentary rocks and the Koras Group volcanosedimentary rocks are deposited in half graben and graben structures in the Kaaien Terrane.
- There is erosional exhumation, uplift, cooling and retrograde metamorphism.

UNIVERSITY of the
WESTERN CAPE

The dextral shear zones in the study area correlate to D_4 (Stowe, 1983) and show evidence of rotation due to continued compression of the Namaqua Region and the Kaapvaal Craton. The negative flower structure the shear zones display validate a transpressional geotectonic environment for the Namaqua Region and show that a pull-apart basin developed in the Kakamas and Areachap Terranes which would have allowed for the Keimoes Suite granites to intrude.

B. CONCLUSION

The thesis aimed to provide a study into the main structural features of the Namaqua Region and their relation to the intrusion of the Keimoes Suite. The Keimoes Suite granites were emplaced during and after the Namaqua Orogenic event. The granites emplaced during the orogenic event were due to continued crustal thickening, decompression and partial melting of the lower crust and asthenosphere. The post-tectonic granites were emplaced in the pull-apart basins or zones of structural weakness that formed as a result of the lateral escape of the Namaqua-Natal region.

The continued compression of the Kaapvaal Craton and the Namaqua-Natal Sector produced a releasing bend in the Namaqua Region and a restraining bend in the Natal region. This allowed for the formation of dextral and sinistral faults which later became the regional shear zones observed in the structural framework.

The relation of the main structural features to the intrusion of the Keimoes Suite is shown by the geometry of the shear zones in the Namaqua Region. The shear zones found within the area of the Keimoes Suite granites produce a negative flower structure, which forms as the opposing walls of a fault plane pulling away from each other and created a basin with normal faults. These normal faults developed as crustal subsidence occurred and allowed for the intrusion of the Keimoes Suite granites.

UNIVERSITY of the
WESTERN CAPE

REFERENCES

Bailie, R., Gutzmer, J., Rajesh, H.M. and Armstrong, R., 2010. Age of ferroan A-type post-tectonic granitoids of the southern part of the Keimoes Suite, Northern Cape Province, South Africa. Journal of African Earth Sciences, 60, 153-174.

Bailie, R., Gutzmer, J., Rajesh, H.M. (2012). Bimodal volcanism at the western margin of the Kaapvaal Craton in the aftermath of collisional events during the Namaqua-Natal Orogeny: The Koras Group, South Africa. Precambrian Research, 200-203, pp. 163-183.

Barton, E.S., Burger, A.J. (1983). Reconnaissance isotopic investigations in the Namaqua mobile belt and implications for Proterozoic crustal evolution- Upington geotraverse. In: B.J.V. Botha (Editor), Namaqualand Metamorphic Complex. Special Publication of the Geological Society of South Africa. 10, pp. 173-191.

Blignault, H.J., Jackson, M.P.A., Beukes, G.J., Toogood, D.J. (1974). The Namaqua tectonic province in South West Africa. In: Contributions to the Precambrian geology of southern Africa. Bulletin, Precambrian Research Unit, University of Cape Town, 15, pp. 29-48.

Botha, B.J.V., Burger, A.J., Grobler, N.J. (1979). New U-Pb age measurements on the Koras Group. Cape Province and its significance as a time reference horizon in the eastern Namaqualand. Transactions of the Geological Society of South Africa, 82, pp. 1-5.

Brown, M., Solar, G.S. (1998). Granite ascent and emplacement during contractional deformation in convergent orogens. Journal of Structural Geology, 20 (9/10), pp. 1365-1393.

Clemens, J. (1998). Observations on the origins and ascent mechanisms of granitic magmas. Journal of the Geological Society of London, 155 (5), pp. 843– 851.

UNIVERSITY of the WESTERN CAPE

Cobbold, P.R., Davy, P. (1988). Indentation tectonics in nature and experiment. 1. Experiments scaled for gravity. Bulletin of the Geological Institutions of Uppsala, N.S., 14, pp. 129-141.

Cornell, D.H., Griffin, G., Humphreys, H.C., Kroner, A. (1990). Age of origin of the polymetamorphosed Copperton Formation, Namaqua-Natal Province, determined by single-grain zircon Pb-Pb dating. South African Journal of Geology, 93, pp. 709-716.

Cornell, D.H., Thomas, R.J., Moen, H.F.G., Reid, D.L., Moore, J.M., Gibson, R.L., (2006). The Namaqua-Natal Province In; Johnson, M, R., Anhaeusser, C.R., Thomas, R.J (Editors.), The Geology of South Africa. Geological Society of South Africa, Johannesburg, Council for Geoscience, Pretoria, 325–379.

Eglington, B.M. (2006). Evolution of the Namaqua-Natal Belt, southern Africa – a geochronological and isotope geochemical review. *Journal of African Earth Sciences* **46**, 93-111.

UNIVERSITY of the
WESTERN CAPE

Geringer, G.J., Botha, B.J.V., Pretorius, J.J., Ludick, D.J. (1986). Calc-alkaline volcanism along the eastern margin of the Namaqua Mobile Belt, South Africa – a possible middle Proterozoic volcanic arc. *Precambrian Research* **33**, 139-170.

Geringer, G.J., De Bruiyn, H., Schoch, A.E., Botha, A.E., Van der Westhuizen, W. A. (1987). The geochemistry and petrogenetic relationships of two granites and their inclusions in the Keimoes Suite of the Namaqua Mobile Belt, South Africa, Precambrian Research, 36, pp. 143-162.

Geringer, G.J., Bottha, B.J.V. and Slabbert, M.J. (1988). The Keimoes Suite- a composite granitoid batholith along the eastern margin of the Namaqua mobile belt, South Africa. South African Journal of Geology, 91 (4) , pp.465-476.

Geringer, G.J., Humphreys, H.C., Scheepers, D.J. (1994). Lithostratigraphy, protolithology and tectonic setting of the Areachap Group along the eastern margin of the Namaqua Mobile Belt, South Africa. South African Journal of Geology, 97 (1), pp. 78-100.

Graham, R.H., Ramsay, J.G. (1970). Strain variation in shear belts. Canadian Journal of Earth Sciences, 7, pp.786-813.

Gutzmer, J., Beukes, N.J., Pickard, A., Barley, M.E. (2000). 1 170 Ma SHRIMP age for the Koras Group bimodal volcanism, Northern Cape Province, South African Journal of Geology, 103 (1), pp. 32-37.

Hartnady, C., Joubert, P., Stowe, C. (1985). Proterozoic crustal evolution in south-western Africa. *Episodes* **8**, 236–244.

Henderson, I.C., Viola, G. (2010). Inclined transpression at the toe of an arcuate thrust: an example from the Precambrian 'Mylonite Zone' of the Sveconorwegian orogen. Geological Society, London, Special Publications, 335, pp. 715-737.

Huber, M.I., Ramsay, J.G. (1983). The techniques of modern structural geology, Academic Press Limited, London, pp.174-178.

Humphreys, H.C., van Bever Donker, J.M. (1987). Aspects of deformation along the Namaqua Province eastern boundary, Kenhardt District, South Africa. Precambrian Research, 46, pp. 39-63.

Jacobs, J., Thomas, R.J., Weber, K. (1993). Accretion and indentation tectonics at the southern edge of the Kaapvaal craton during the Kibaran (Grenville) orogeny. *Geology* 21,pp. 203–206.

UNIVERSITY of the
WESTERN CAPE

Marshak, S., Van der Plujim, B.A. (2004). Earth Structure: An introduction to structural geology and tectonics, W.W. Norton and Company, New York, pp. 673.

McCaffrey, K.J.W., Petford, N. (1997). Are granitic intrusions scale invariant?. Journal of the Geological Society, 154 (1), pp. 1-4.

Miller, R, McG. (2008). The Geology of Namibia. Volume 1, Archaean to Mesoproterozoic. Geological Survey, Windhoek, Namibia.

Miller, R, McG. (2012). Review of Mesoproterozoic magmatism, sedimentation and terrane amalgamation in southwestern Africa. Geological Society of South Africa, 115 (4), pp. 417-448.

Moen, H.F.G. (1980). Petrology and tectonic setting of the Wilgenhoutsdrif Formation, Northern Cape Province. M.Sc. Thesis, University of the Orange Free State, South Africa, pp 287. (Unpublished).

UNIVERSITY of the
WESTERN CAPE

Moen, H.F.G. (1999). The Kheis Tectonic Subprovince, southern Africa: A lithostratigraphic perspective. South African Journal of Geology, 102 (1), pp. 27-42.

Moen, H.F.G. (2007). The Geology of the Upington Area, Council of Geoscience, Pretoria.

Pettersson, A., Cornell, D. H., Moen, H. F. G., Reddy, S., Evans, D. (2007). Ion-probe dating of 1.2 Ga collision and crustal architecture in the Namaqua-Natal Province of southern Africa. *Precambrian Research* **158**, 79-92.

Petterson, A. (2008). Mesoproterozoic crustal evolution of Southern Africa, M.Sc. thesis, University of Gothenburg, Sweden. (published).

Schott, John Robert (2007). Remote sensing: The image chain approach. (2nd ed.). Oxford University Press.

Schluter, T. (2008). Geological Atlas of Africa. Springer, Berlin, 230-239 pp.

Siad, A.M. (2012). Spatial data and maps, course notes, University of the Western Cape, Belville.

Stowe, C. W. (1983). The Upington geotraverse and its implications for craton margin tectonics. In: Botha, B. J. V. (Editor), Namaqualand Metamorphic Complex. Johannesburg: Special Publication of the Geological Society of South Africa **10**, 147-171.

Stowe, C.W. (1986). Synthesis and interpretation of structures along the north-eastern boundary of the Namaqua Tectonic province, South Africa. *Transactions of the Geological Society of South Africa* **89**, 185-198.

UNIVERSITY of the
WESTERN CAPE

Thomas, R.J., Cornell, D.H., Moore, J.M., Jacobs, J. (1994). Crustal evolution of the Namaqua-Natal Metamorphic province, southern Africa. South African Journal of Geology **97(1)**, 8-14.

van Bever Donker, J.M. (1980). Structural and metamorphic evolution of an area around Kakamas and Keimoes Cape Province, South Africa. Bulletin. Precambrian Research Unit, University of Cape Town, 28, 165pp.

van Bever Donker, J.M. (1983). The Neusspruit lineament, Upington geotraverse, possible boundary between the Namaqualand Metamorphic Complex and the Namaqua front. In: B.J.V Botha (Editor). Namaqualand Metamorphic Complex. Special Publication. Geological Society of South Africa, 10,pp. 193-198.

van Bever Donker, J.M. (1991). A synthesis of the structural geology of a major tectonic boundary between a 1000 m.y. mobile belt and a 3000 m.y. craton. In: R.D.

Hatcher, Jr and L. Zonenshain (Editors). Accretionary Tectonics and Composite Continents. Tectonophysics, 191, pp. 359-370. ‘

Vajner, V. (1974). The tectonic development of the Namaqua Mobile Belt and its foreland in parts of the Northern Cape. Bulletin, Precambrian Research Unit, University of Cape Town, 14, pp. 201.

Von BackstrÖm, J.W. (1964). The geology of an area around Keimoes, Cape Province with special reference to phacoliths of charcnockitic, adamellite-porphyry. Memoir, Geological Survey of South Africa, 53, 218pp.

Van Zyl, C.Z. (1981). Structural and metamorphic evolution in the transitional zone between craton and mobile belt, Upington geotraverse. Bulletin, Precambrian Research Unit, University of Cape Town, 31, 243pp.

UNIVERSITY of the
WESTERN CAPE

UNIVERSITY of the
WESTERN CAPE