The tectono-sedimentary history of the coal-bearing Tshipise Karoo Basin

by

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Abstract

The Tshipise Basin is considered to be a fault bounded remnant of a larger Karoo aged basin that was fragmented and preserved in the outline seen today by a number of ENE-WSW and NW-SE trending basement faults. It consists of several long, narrow blocks in which the Karoo strata dip, on average, at 12° to the NNW (354). These blocks are bounded to the north by the basement faults that juxtapose the Karoo strata against the high-grade metamorphic rocks of the Limpopo Mobile Belt. The orientation and form of these faults were greatly controlled by the geometry of the metamorphic foliation of the underlying basement rocks.

The pre-Karoo topography consisted of a number of ENE-WSW trending palaeo-valleys, with drainage occurring towards the WSW. The southern-most Makhado valley contains a much thicker accumulation of sediments compared to any of the blocks to the north and is considered to have been the main depository of the Tshipise Basin. The sediment ratio maps indicate that the N-S and NW-SE trending faults influenced the deposition of most of the lower Karoo (Tshidzi, Madzaringwa and Fripp formations) and were areas of enhanced subsidence.

The coarse-grained sandstone of the Fripp Formation marks the beginning of a major tectonic event that resulted in active uplift in the SE of the basin. The thick accumulation of this unit in the Makhado Block, suggest that the faults bounding the valleys underwent movement during the pre-Fripp tectonic event. Palaeocurrent measurements in the eastern and northern part of the basin as well as the Tuli Basin indicate a unimodal transport direction towards the NW. However measurements in the central and western part of the basin deviate towards the W and SW. The change in palaeocurrent direction, from NW in the east to WSW in the west, is ascribed to the localised changes in basin relief from differential movement of the individual blocks during the pre-Fripp tectonic event.

It is either during this Fripp event, or by the time of the Klopperfontein Formation that the ENE-WSW trending faults separated the Tshipise and Tuli basins. The units above the Madzaringwe Formation are all rift-related sediments while the Bosbokpoort Formation

possibly contains a series of unconformity bounded sequences which relate to the cannibalization of the underlying strata.

Sedimentation within the basin ceased with the onset of the Karoo Igneous Province; which was a product of the splitting of Gondwana into the African and Antarctic continents. Magmatism was initially focused around at the Mwenezi Triple Junction, which firstly led to the outpouring of lava and the intrusion of the Okavango Dyke Swarm (ODS), the Save-Limpopo Dyke Swarm (SLDS) and the Lebombo Monocline. It was during this event that the vast array of dolerite sills were intruded into the Karoo sediments. The ENE-WSW trending SLDS was the first to evolve as a result of stretching and thinning of the crust in a NW-SE direction at ±182-174 Ma (NE-SW directed SHmax). This extension was roughly perpendicular to the underlying basement structures and led to the reactivation of the ENE-WSW trending faults which down-faulted and rotated the Karoo strata to the north and preserved them within half-grabens.

A second tectonic event, with a SHmax towards the NW/NNW-SE/SSE, led to some degree of inversion of the structures and is likely related to a change in the motion of the African and Antarctic continents after separation. This event probably initiated dextral transpression and compression which led to the reactivation of the primary structures (normal faults) created during the initial event to form relatively high-angled (40-60°) reverse faults across the basin. The event also led to the formation of the subtle east-west trending low-amplitude folds in the Karoo strata, preferentially localised along the ENE faults.

Drilling induced fractures and borehole breakout from the ATV logs indicates a neotectonic SHmax parallel to the underlying WSW-ENE trending basement fabric. The large and small scale structures existing in the Limpopo Mobile Belt played a significant role in the development of the Tshipise Karoo Basin. These structures shaped the depository into which the Karoo sequences were laid down, affected the sedimentation and ultimately controlled the fragmentation of this basin along these faults into the preserved blocks seen today.

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1. Introduction

1.1. Aim of the study

The main aim of this dissertation was to consolidate all previous sedimentological and structural geological research as well as results obtained from recent coal exploration activities and incorporate this with original research and field work to determine the general tectono-sedimentary history of the Greater Soutpansberg Karoo Basin with the main focus being on the Tshipise Basin (Fig. 2). Although some authors have suggested basic mechanisms for the formation of the Karoo Basin outline seen today, none has unequivocally come up with a detailed chronological sequence of events that takes all regional geological aspects into consideration.

The Main Objectives:

- As there is very little outcrop extensive use will be made of aeromagnetic surveys and geophysical wireline logging to evaluate the structural geology;
- demonstrate the role played by the mega-tectonics in the development of the basement topography and subsequent deposition of the Karoo Supergroup;
- establish to what extent syntectonic movement on the faults affected the sedimentological facies changes across the basin;
- determine local and regional changes in the character of the sedimentological units across the basin with the use of isopach diagrams derived from drilling and wireline geophysical surveys;
- define what led to the reactivation of the faults and subsequent present-day preservation of the Tshipise and surrounding Karoo basins;
- determine a chronological sequence of events to outline the structural history of the Soutpansberg Coal Basin and possibly how it relates to the other Limpopo Coal basins;
- discuss and interpret the orientations of the main structural elements, and stress field orientations that were obtained from Acoustic Televiewer (ATV) imagery and field observations.

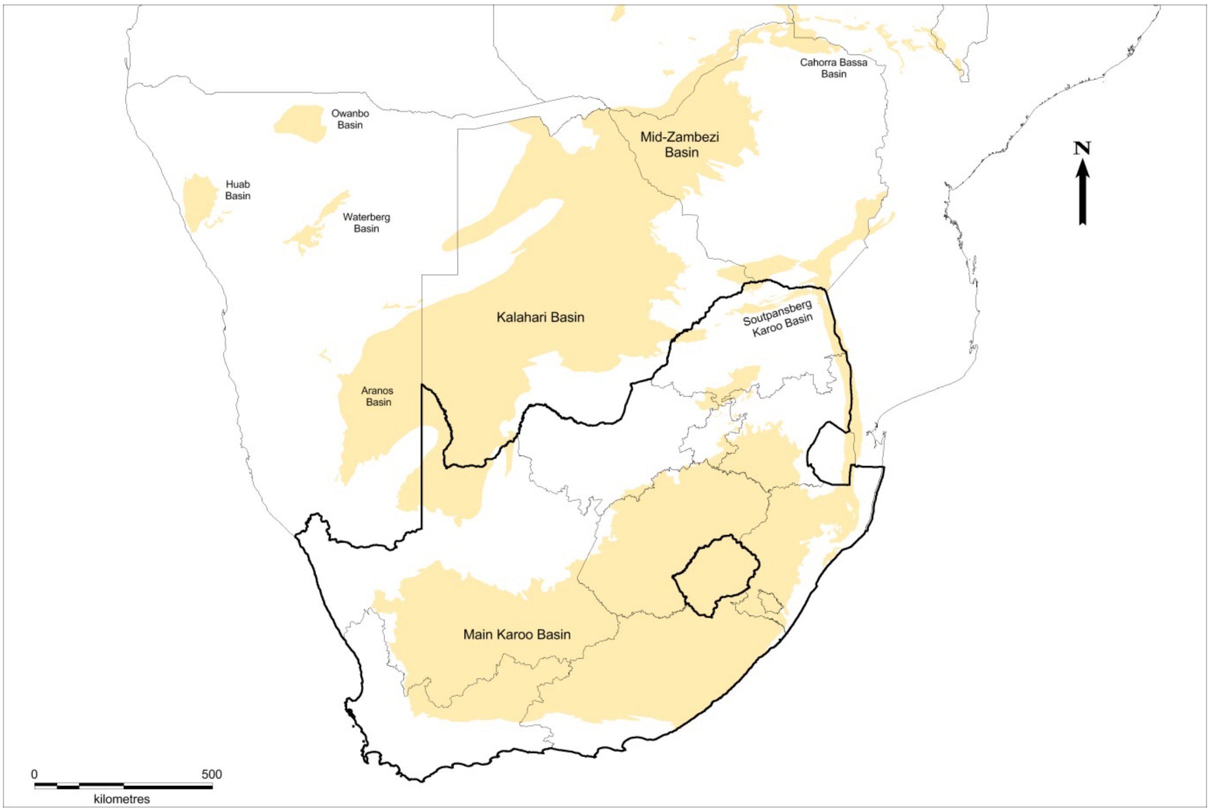


Figure 1: The distribution of the Karoo strata across Southern Africa.

1.2. Methodology

This area has been an exploration target for decades because of its potentially vast reserves of high quality thermal and metallurgical grade coal. Much of this work was done by the South African parastatal steel company, ISCOR, to assess the coal potential of the area. Most of this work was conducted during the height of Apartheid to secure the country's future potential coal needs and as a result much of this information was kept confidential. This area has only seen renewed interest and exploration within the last 2 decades. These recently drilled boreholes are an invaluable source of additional data, but have only been used to a limited extent in further defining the nature of the sedimentary fill. In addition to the boreholes being geologically logged and sampled, a number of them were geophysically logged as well. This allowed the identification of individual coal plies and where the Acoustic Televiewer (ATV) was used a structural evaluation was also made. Various high quality aeromagnetic surveys were also flown across certain areas of the basin. These were used in the identification of pre- and post-Karoo deformation structures such as faults, dykes and sills. Refer to section 1.1.3 in Appendix A for a detailed description on ATV data gathering, processing and interpretation, as well as for more details regarding the aeromagnetic survey.

A total of over 2300 boreholes have been drilled in the Soutpansberg Coal Basin, including the Tshipise Basin, since exploration began more than 60 years ago. The majority of these were drilled in the shallow up-dip flanks of the northward dipping fault blocks where coal could potentially be extracted by open-cast methods; most of the boreholes were drilled to a depth of approximately 150m. There are some however that targeted the deeper down-dip extension of the coal reserve that reach depths of 400-500m; and in a handful of cases reached depths in excess of 650m. Only a total of 1227 boreholes were considered to be appropriate to be used for the construction of isopach maps. The geological logs of these boreholes were used to determine various characteristics such as unit thicknesses, elevation and sediment ratios which were then contoured.

The author has analysed and interpreted the results of all the available datasets, which range from borehole geological logs, airborne geophysics and wireline geophysics. During the interpretation, the following actions were taken:

- mapping of all the magnetic units and major structures present in the area using aeromagnetic derivative images;
- create isopach maps of various sedimentological units in order to identify any characteristic changes in their nature across the basin (viz. clean coal thicknesses, basement to top of coal, top of coal to base of Fripp sandstone and sediment ratio maps);
- measure all secondary rock structures to determine the main structural trends, sense of movement that occurred and define the events that created them. (Viz. Field mapping, ATV structures, structures identified from LIDAR and aeromagnetic images);
- measure the main cleating directions in the coal from the ATV logs to determine the main stress tensor during and possibly after coalification;
- determine the current stress direction from Drilling Induced Fractures (DIF’s) in the coal.

1.3. The Study Area

The Greater Soutpansberg Karoo Basin is situated in the extreme north-east of South Africa, near the borders of Zimbabwe and Mozambique. It lies north of the Soutpansberg Mountain Range and extends from the town of Tolwe in the West, to the border of the Kruger National Park in the East, which stretches some 260 km East-West and is approximately 35km wide near its center (Fig 2). The nearest municipal centres are the towns of Messina and Louis Trichardt which are situated approximately 25 km north and 20km south, respectively. The Tshipise Basin forms the central part of the depository and stretches from the village of Travenna, near the Nwanedi Nature Reserve, 90km west to an area approximately 10km west of Waterpoort. The northern boundary of the study area is at the Lilliput railway siding.

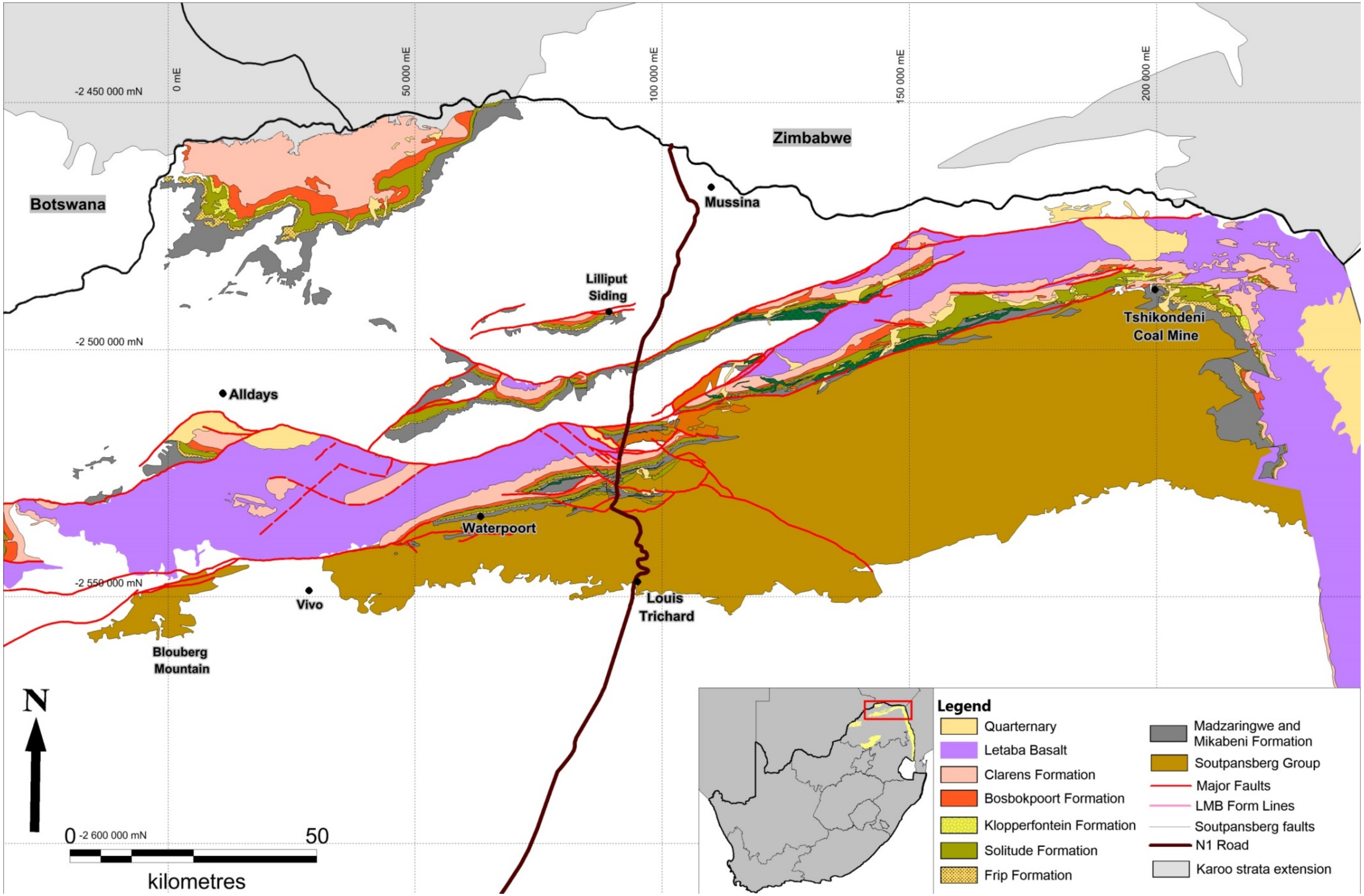


Figure 2: Regional geological overview map of the Soutpansberg Basin showing the location of the Tshipise Basin. Modified after Brandl (2002).

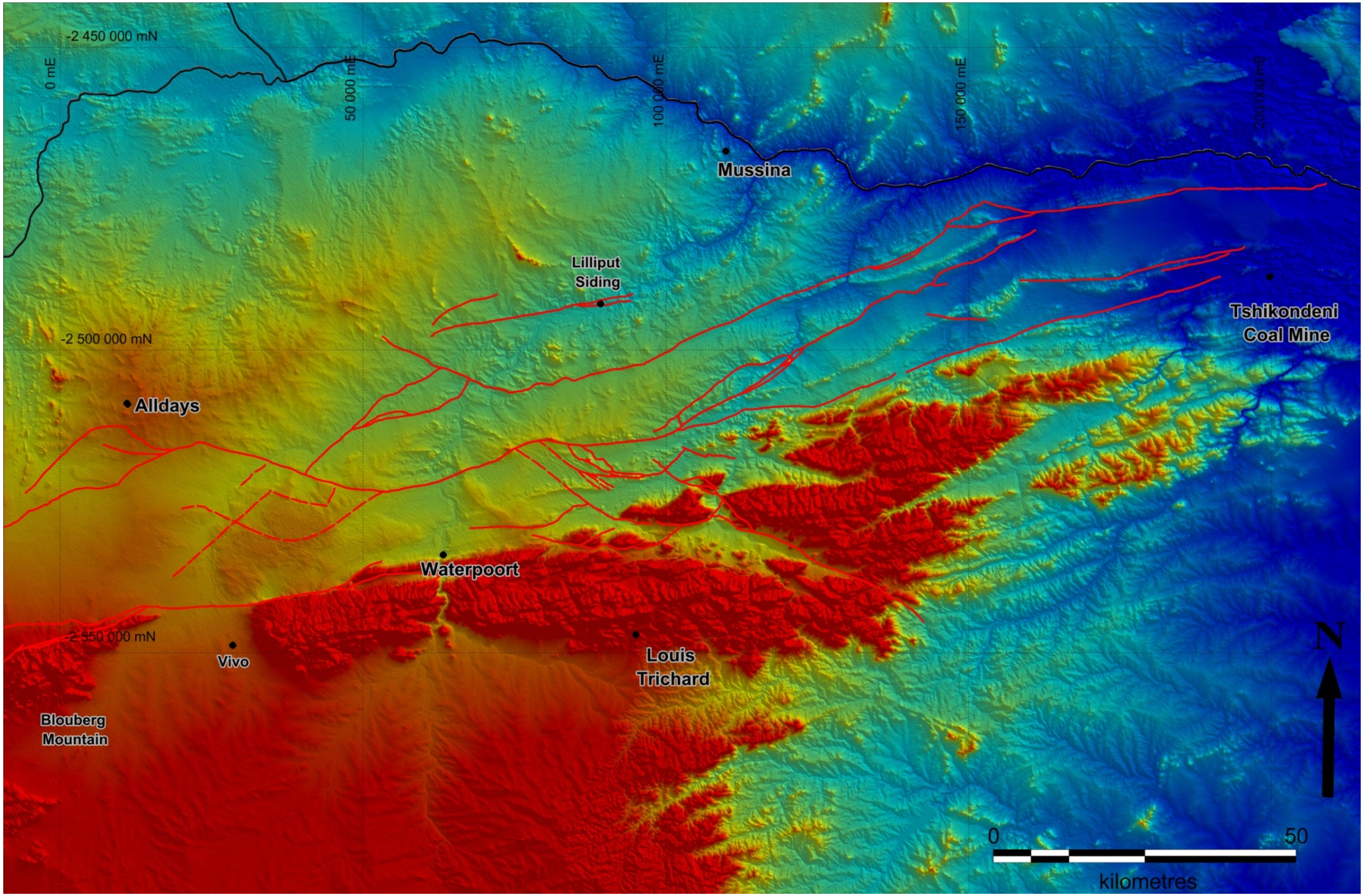


Figure 3: SRTM topographic map of the Soutpansberg mountains and study area. The red lines on the map represent the main faults bounding the Soutpansberg Karoo Basin.

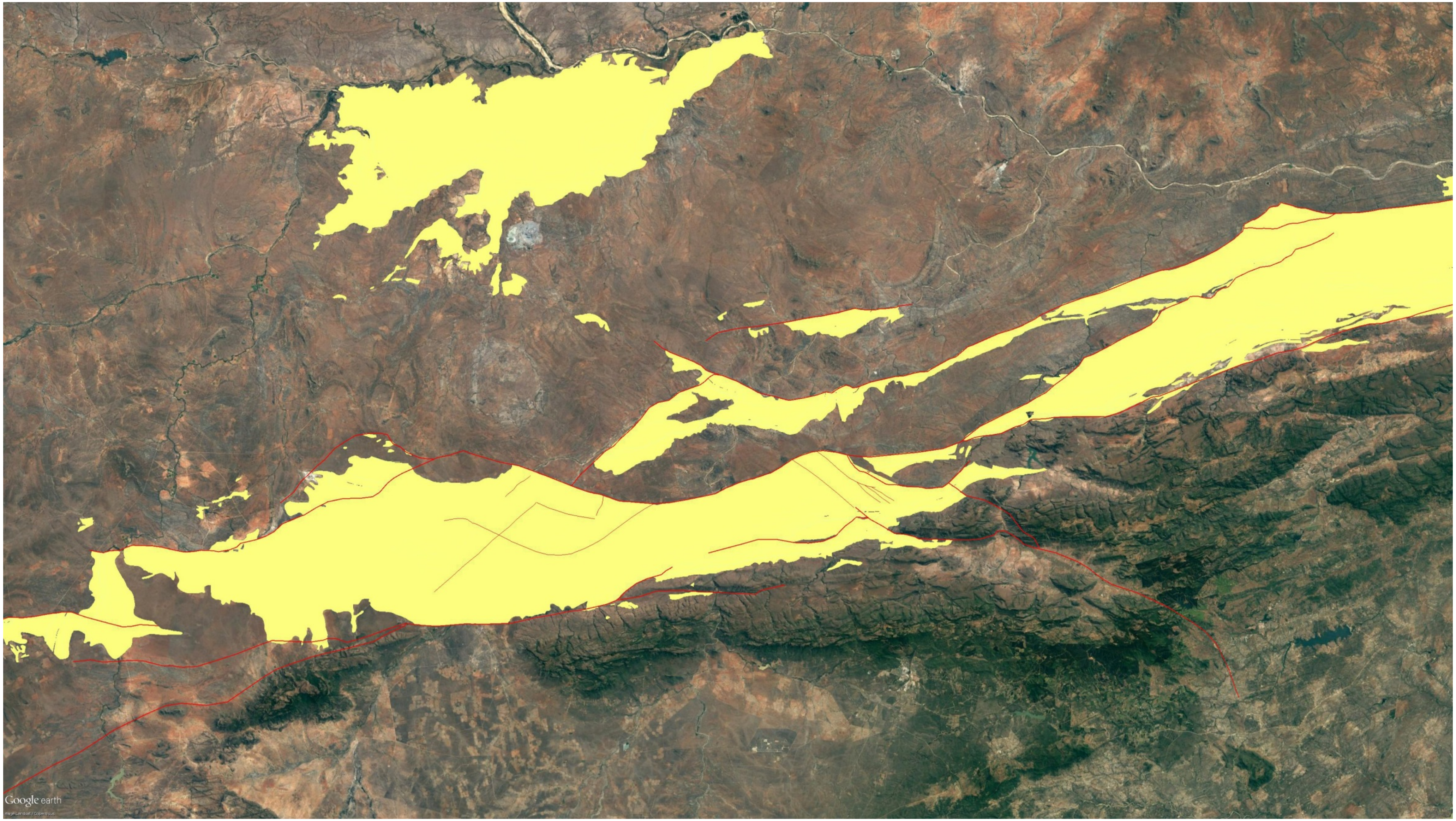


Figure 4: Satellite image showing the outline of the Greater Soutpansberg Karoo Basin and regional faults.

1.4. Topography

The overall topography of the study area is dominated by the Soutpansberg Mountain Range that suddenly gives way to a relatively flat lying area to the north, which is underlain by the Karoo sediments, basalt and Limpopo Mobile Belt lithologies (Fig 3 and 4). Outcrops of the Karoo sediments are generally restricted the arenaceous facies, including the Tshidzi, Fripp and Clarens Formations. The Clarens Formation forms long ridges across the entire length of the basin creating steep cliffs on the southern side, the highest ridge being the Bobbejaankop (200m above the valley floor) on the farm Coen Brits (Fig 38 and 68). The Fripp Formation sandstone forms small ridges in certain areas and is best developed on the farm Fripp where it forms gentle northward dipping ridges approximately 20m high (Fig 68). The Letaba basalts are deeply weathered to form flats consisting of fertile cotton soil.

The overall elevation ranges from an average of 780m in the west to 280m above sea level in the east which is clearly recognized from the SRTM image (Fig 3). Drainage in the area also occurs from west to east mostly from the Sand, Nzhelele, Nwanedzi, Mutale and Levubu rivers. These rivers generally flow northwards but tend to deviate in an eastern direction within the Karoo basin up to a point where they are able to flow through gorges carved through the Clarens sandstone to ultimately join the Limpopo River to the north (Van Der Berg, 1980). North of the study area the basement rocks of the Limpopo Mobile Belt form low undulating hills and flat valleys (Van Der Berg, 1980).

Figure 5: Soutpansberg Mountains (left) giving way to flat topography of Karoo in the Chapudi Block. The small settlement of Waterpoort is seen next to the road (R523). The main railway that meanders through the Soutpansberg Mountain is also seen to the right of the photo.

1.5. Exploration History

This coalfield has been known of since the late 1800's and commercial mining began in 1911 when the Messina Transvaal Company developed the Lilliput Mine on the Farm of Cavan in order to supply the copper smelter in the town of Messina; production ceased in 1918. Subsequent work on the coal only commenced again in 1947 when the Fuels Research Foundation took samples and reported that coal of "significant coking propensity" existed in these coal measures (Sparrow, 2011).

Between the late 1950's and 1970's, the Geological Survey, the Department of Mines and ISCOR did extensive prospecting for coal within the Tshipise Basin (De Jager 1976). ISCOR subsequently undertook detailed exploration of the entire Soutpansberg Coalfield, drilling in excess of 2000 boreholes during 1978/79 and developed the Fripp box-cut to assess the coal resource (Fig 68). This project was later abandoned in favour of the Tshikondeni project which is situated some 140km east of the town of Messina, on the easternmost extent of the coal field. This mine produced high-grade coking coal for Accelor Mittal's steel mill at Vanderbijlbark; however it closed down in 2014 and is in its rehabilitation phase. In 1983, ISCOR prepared a pre-feasibility study of the Jutland project in the Mopane sub-basin for the underground mining of coking coal in the Middle Lower and Bottom Upper coal horizons.

Trans-Natal conducted additional exploration in the Mopane Sub-basin, drilling 200 boreholes although it is unclear where these boreholes were collared (Hancox & Goëtz, 2014).

Starting in 2002 Rio Tinto and Kwezi started exploration in the Chapudi area near the town of Waterpoort and drilled more than 140 boreholes. The large ISCOR dataset containing information on the 1250 boreholes was purchased by Coal of Africa Ltd (CoAL) in 2007. This dataset forms an integral part in this study. In 2007 CoAL initiated exploration drilling on the farm Fripp and a total of 198 boreholes were completed which include 24 large diameter boreholes for bulk sampling purposes. CoAL has also initiated an exploration bulk sampling pit (Fig 6) as well as high resolution aeromagnetic, LIDAR and limited seismic surveys. In 2013 CoAL completed a 5 borehole Coal Bed Methane (CBM) project on the farm Tanga to assess the CBM potential of the coal. The Makhado Project is now in an advanced pre-feasibility stage, the new order mining right was granted in early 2015.

Figure 6: Bulk sampling pit on the farm Tanga (648) looking approximately south. The NNW dipping strata can be seen.

1.6. Previous Research

Mellor and Trevor (1908) were the first to describe the area after a reconnaissance field trip to the Soutpansberg district describing some lithological units as well as their impressions of the structures (Söhnge 1946). Certain aspects of the geology, especially the Karoo basalts were also described by Rogers (1925). In 1941 Van Eden, Van Zyl and Wessels mapped the western part of the area which Van Zyl (1950) published in his doctoral thesis. From 1948 to 1950 Visser and Coertze mapped the entire area, including the previously mapped areas Van Eden *et al.* (1956). However some of the most detailed work published on the area was that of Van Der Berg (1980) who conducted a sedimentological assessment of the area based on a limited amount of borehole core and field mapping. McCourt and Brandl (1980) and Brandl (1981) mapped the entire area and in 1997 the CGS published a 1:250 000 scale geological map based mostly on their work. This was followed by De Jager (1986), Sullivan (1995), Thabo and Sullivan (2009). Bordy (2009) conducted a sedimentological study based on a handful of boreholes from the Chapudi area that was based largely on her PhD from the neighbouring Tuli Basin, while Malaza (2013) focussed largely on the Tshipise Basin sedimentology. Several Rio Tinto employees including Broadbent (2005) and Kneale (2006) conducted research and field mapping for the purpose of writing company reports to direct their exploration efforts.

2. Regional Geological Background

2.1. Limpopo Mobile Belt. (Fig 7)

The Limpopo Mobile Belt is a broad zone of highly metamorphosed tectonites that divides the Archaean aged granite-greenstone terranes of the Kaapvaal and Zimbabwean cratons. This belt extends from the border of South Africa, Zimbabwe and Mozambique and strikes in an ENE-WSW direction through the southern parts of Zimbabwe into eastern Botswana (Johnson, 2006). The eastern end of the mobile belt is covered by the sedimentary and volcanic units of the Karoo Supergroup and obscures the junction between the Zimbabwean and Mozambique Belts while the western extremities are largely covered by the Cenozoic Kalahari Basin. The exposed ENE trending axis of the belt is close to 700km long and it varies in width between 180 and 240km (Mason, 1973). A large section of the mobile belt extends for several hundred kilometres westward into Botswana where it is covered by the Kalahari sediments.

The Kaapvaal Craton is a typical granite greenstone terrane that formed through the amalgamation of various smaller proto continents during the early to mid-Archaean whereas the Zimbabwe Craton was slightly younger and roughly half the size of the Kaapvaal Craton (Johnson, 2006). At about 2600 Ma these two continents collided along the northern margin of the Kaapvaal Craton after subduction brought the two landmasses into contact. At 2000 Ma the area underwent transpressive shearing which is considered to be the main deformational event (Kroner, et al., 1999; Xie, et al., 2017).

It was first recognised by Cox *et al.* (1965) that the belt can be divided into three east-north-east trending zones based on the lithological and deformational character exhibited by each. The three zones are the Central Zone, Northern Marginal Zone and the Southern Marginal Zone which is each separated from one another by enormous continental scale shear zones steeply dipping to the south (Mason, 1973). The two marginal zones are also separated from the cratons by large shear zones.

2.1.1. The Southern Marginal Zone

The Southern Marginal Zone is only restricted to the northern parts of the Limpopo Province and represents the granulite facies equivalents of the granitoid-greenstone assemblage that forms part of the northern portion of the Kaapvaal Craton. This was determined by isotope and geochemical comparisons. This Southern Marginal Zone is 170 km long and 45km wide and a large portion of it, including its boundary with the Central Zone, is obscured by Proterozoic sediments of the Soutpansberg Trough towards the eastern extremities of the belt. Towards the western end of the belt in Botswana, the Southern Marginal Zone is not present in outcrop and its possible development has not been constrained.

The boundary of the Southern Marginal Zone and the Kaapvaal Craton is defined by a sharp drop in metamorphic grade and coincides with the northward dipping thrust zone known as the Hout River Shear Zone (Johnson 2006). The rocks of the Southern Marginal Zone were thrust onto the Kaapvaal Craton along this zone and the timing has been constrained by zircon dates from the Matok Intrusive Complex to be between 2671 and 2664 Ma (Barton, (1992). This zone can further be sub-divided into a northern high-grade granulite zone and a southern rehydrated granulite zone separated by an ortho-amphibole isograd.

2.1.2. The Central Zone

The Central Zone is regarded as a highly complex entity that consists primarily of intensely deformed metasediments with interlayered quartzofeldspathic gneisses and mafic rocks. The metasediments were originally restricted to a sequence of meta-quartzites, magnetite quartzites, dolomites and marble that were laid down in a shallow water through-like depository of the Limpopo Mobile Belt (Mason, 1973). As the collision between the two cratons was initiated, sedimentation ceased and the sediments were subjected to extreme deformation and metamorphism; these metasediments and the associated leucogneisses are collectively know as the Beit Bridge Complex (BBC).

Apart from the metasediments there are a number of other units consisting of granitoid gneisses and ultramafic intrusions; these are the Sand River Gneiss, Alldays Gneiss, Bulai Gneiss and the Messina Layered Intrusion. The Sand River Gneiss is regarded as the oldest rock in the Limpopo Mobile Belt and were suggested by Bahnemann (1972) to represent the basement of the metasediments of the BBC.

2.1.3. The Northern Marginal Zone

This zone is similar to that of the Southern Marginal Zone in that it represents a granulite facies subzone derived from reworked granite-greenstone lithologies from the adjacent Zimbabwean Craton (Mason, 1973). The long, narrow zone is approximately 550km in length and occurs exclusively within Zimbabwe and Botswana. The granulite subzone decrease in metamorphic grade towards the north approaching the Zimbabwean Craton, however its northern contact has been defined as the Northern Marginal Thrust Zone which is a 320km long thrust-sense shear zone shallowly dipping towards the south (Mason, 1973; Johnson, 2006)

2.2. The Regional tectonic framework

The regional tectonic framework of the Limpopo Mobile Belt is construed by a number of very large ENE trending shear zones that separate the respective metamorphic provinces from each other. The boundaries between these domains, as well as those between the Kaapvaal and Zimbabwe Cratons have an inherent structural weakness and any strain built-up within the cratons would have been released within these lineaments. A number of these structures are active even to present day.

The Hout River Shear Zone is an overall steeply northward dipping reverse sense shear zone along which rocks of the Southern Marginal Zone have been thrusted southward over the low-grade cratonic rocks. In the east the geometry of the shear zone is dominantly strike-slip, whereas towards the west it is considered to be a system of frontal and lateral ramps (Smit et al., 1992) with the timing being determined to be 2671 ± 2 Ma.

The Northern Marginal Thrust Zone separates the Northern Marginal Zone from the Zimbabwean Craton and it is a shallowly southerly dipping thrust-sense shear zone. It has a strike length of 320 km and consists of several mylonitic zones tens of meters wide separated by protomylonites (Rollingson & Blenkinsop, 1995).

The Palala Shear Zone is widely regarded as the suture between the Southern Marginal Zone and the Kaapvaal Craton and extends from the eastern edge of the study area for well over 600 km to the west into Botswana where it forms part of the Zoetfontein Fault Zone. The massive shear zone is a 12km wide belt characterised by steeply dipping (60-70º) mylonites and has an outcrop length of over 25 km (McCourt, 1983). This shear zone is mostly covered by Soutpansberg and Waterberg sediments; however there is an area east of Lephalale known as the Koedoesrand window where the shear zone is exposed. Here the Palala Shear Zone forms the boundary between the Central Zone and rocks of the Bushveld Complex which could be underlain by either rocks of the Kaapvaal Craton or the Southern Marginal Zone (Mason, 1973). Its northern boundary is the Melinda Fault, a north dipping zone of fault breccia active as a normal fault in post-Karoo times; its southern boundary on the other hand is less well-defined and is taken as the Abbotspoort Fault. Two distinct episodes of deformation are recognised, one occurring at 2800 Ma and the other around 1850 Ma.

The Tuli-Sabi Shear Zone/Triangle Shear Zone is one of the largest known shear belts on the African continent and is exposed for almost its entire length varying between 5 and 50 km in width (Mason, 1973). This zone separates the Central Zone from the Northern Marginal Zone and it is known to have experienced vertical, horizontal and rotational movements at various stages. Large scale reactivation in post-Karoo times led to major displacement of the Marginal Zone and craton relative to the Central Zone; down-throws of more than 1000m to the south were identified by Mason (1973). This reactivated lineament forms part of the northern limit of the Tuli Karoo Basin.

The Tshipise Straightening Zone is characterised by a monotonous ENE-WSW trending foliation pattern that dips steeply towards SSE (Van Reenen, et al., 2004) and is possibly an eastwards extension of the Palala Shear Zone. This zone of pronounced straitening is considered to form a sinistral shear system together with the Sunnyside Shear Zone (McCourt & Vearncombe, 1987).

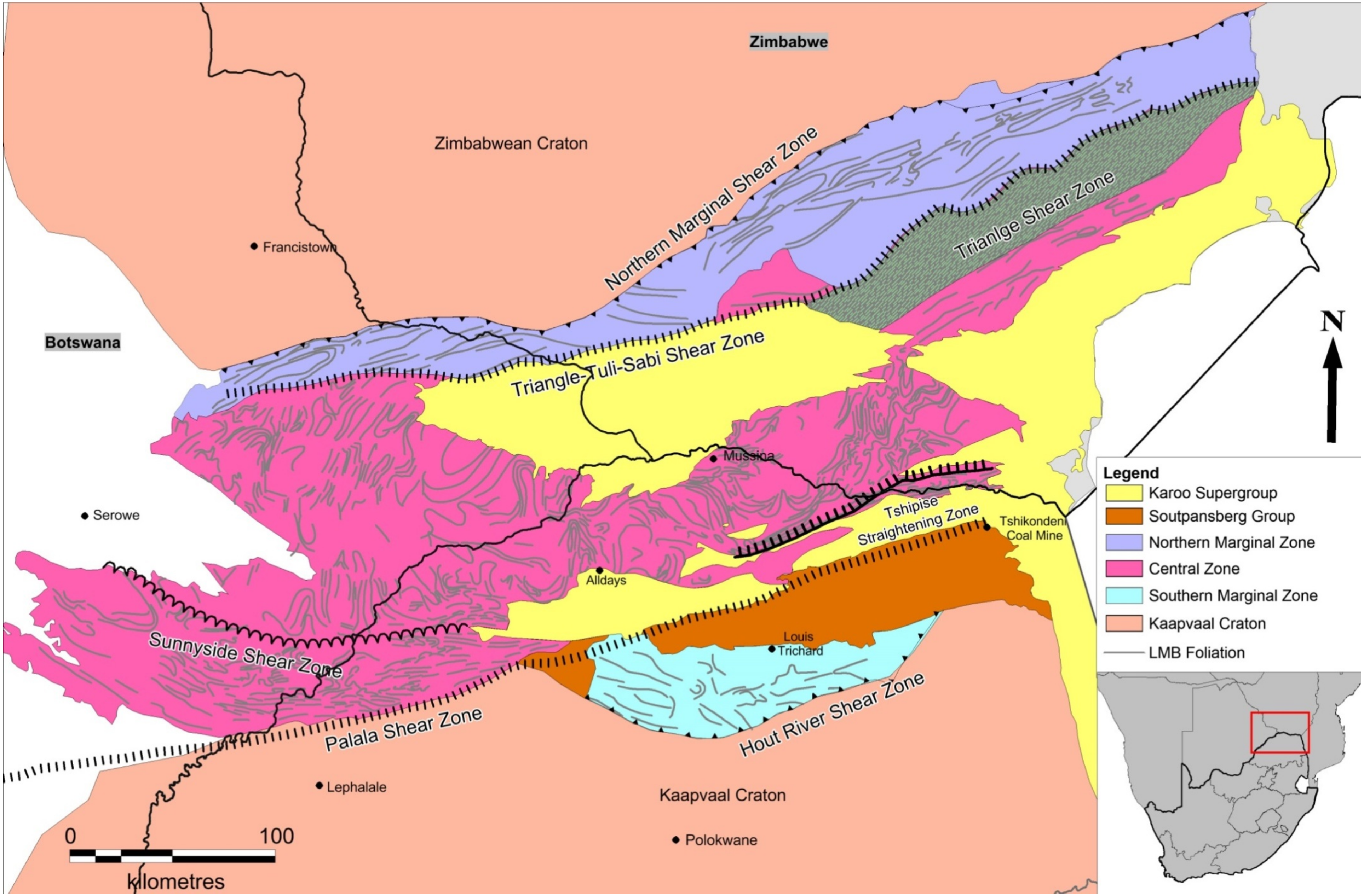


Figure 7: Regional Tectonic setting of the Limpopo Mobile Belt (Modified after Mason, 1975)

2.3. Soutpansberg Group

The Soutpansberg Group is a volcano-sedimentary sequence of rocks that unconformably overlies the high grade metamorphic rocks of the Limpopo Mobile Belt. It forms a prominent mountain range in the Limpopo Province which extends from Kruger National Park in the east to the town of Vivo in the west in an east-north-easterly direction. The terrain is characterised by a series of quartzite ridges dipping between 20° and 60° in a northerly direction and has been intensely faulted and leading to stratigraphic duplication especially in the east (Jansen, 1978; Barker, 1983). The present outline of the succession is wedge-shape (Johnson et al., 2006) with a width of 40km in the east that decreases to approximately 15km in the west.

2.3.1. Tectonic Setting

The development of the Soutpansberg Group was first described by Jansen (1975a; 1975b) who proposed that the sequence was deposited in a narrow intra-cratonic trough that developed through rifting and down-warping of basement blocks along a network of deep faults. Jansen (1975) noticed that the succession, especially the number and thickness of the lava flows in the lower portion, decreased from the east to the west which suggests that the rifting and spreading originated on the eastern edge of the Kaapvaal Craton towards a westerly direction. These basal successions are characterised by contemporaneous faulting (Jansen, 1978) which further suggests a trough that continuously evolved during the deposition of the volcanic and sedimentary sequences. Jansen (op. cit.) also found that there was no dominant transport direction.

Barker (1976) however proposed that regional uplift along the Central Zone of the Limpopo Mobile Belt led to reactivation of the existing system of large extensional ENE trending normal faults which initially formed during the accretion of the LMB. This led to the initial development of the Soutpansberg Basin which was bounded to the north by the Bosbokpoort –Limpopo fault system. Associated partial melting of the mantle occurred between 2100 and 2200 Ma and led to the outpouring of lava onto the developing basin floor. Cycles of lava flows were in many instances terminated with pyroclastic units associated with explosive eruptions followed by stages of volcanic inactivity during which sedimentation and the reworking of volcanic and pyroclastic material occurred (Sibasa

Formation) (Barker, 1983). As volcanic activity became subdued the sedimentation along the bounding faults recommenced, especially to the north, and led to the formation of the Fundudzi and Wyllie's Poort Formations. Renewed volcanism led to the formation of the Musekwa Formation which was short-lived and the final phase of volcanic activity in the Soutpansberg Group. The next phase of uplift and sedimentation commenced with the deposition of a thick sequence of clastic sediments in the Nzhelele Formation.

Cheney *et al.* (1990) however has more recently proposed that the present day exposure of the Soutpansberg Group does not define a depositional trough or aulacogen as proposed by Jansen (1975). He rather supports the conclusion of Meinster (1977) that it is merely a remnant of an originally much larger depositional basin preserved in a graben.

The SRTM image (Fig 3) of the Soutpansberg indicates that large scale faulting has occurred. The ENE-WSW trending faults, parallel to the LMB trend are abundant and were responsible for the duplication of the Soutpansberg group. The WNW-ESE trending Siloam Fault zone is a major discontinuity along which possible left-lateral strike-slip and normal movement has occurred with displacement of approximately 1500m (Brandl, 1981). This movement was as a result of a possible left-lateral wrench couple/system that occurred along the main ENE-WSW fault system (Bumby et al., 2002).

2.4. The Karoo Supergroup

The Karoo Supergroup refers to all sedimentary basins that contain fill deposited over a period of about 120 Ma during the Late Carboniferous to Early Jurassic within the Gondwana Supercontinent. This sequence of rocks is one of the most widespread stratigraphic units and covers almost 50% of the present land surface in Southern Africa.

The Main Karoo Basin is well exposed, contains the thickest and most complete record of the sedimentary succession and is the most renowned and best studied. The strata reflect a mostly continuous sequence of marine glacial, marine, fluvio-deltaic, fluvial and ultimately aeolian deposits which is very much a function of the tectonics and climate during the deposition.

The position of Gondwana relative to the earth's surface was a major contributing factor to the paleo-climate. The Main Karoo Basin was positioned near the southern polar regions during the deposition of the Carboniferous Dwyka Formation and gradually moved towards the equator with time. This cold glacial climate gave way to a more temperate one during the Permian during which plant and animal life flourished. This temperate climate changed to a hotter and drier one during the Triassic and eventually the middle Jurassic saw a very hot and arid desert climate during which the aeolian dunes preserved in the Clarens Formation were deposited. Despite the change in tectonic setting across the continent, the impact of climate proved to be a common thread on the nature of the sedimentary fill of all the Karoo basins (Bordy, 2000).

The Supergroup is appreciated for its variety of animal and plant fossils which provide distinct indications of the climate, ecology, fauna and flora of the Permian and Triassic times.

This succession reaches a maximum thickness of 8km just north of the Cape Fold Belt and gradually thins towards the north-east where the coal measures subcrop near the various coal fields of South Africa (Johnson et al., 1997).

The Main Karoo was once part of a much greater unit that stretched across the southern portion of Gondwana and is preserved today in South America (Parana Basin), Africa (Karoo Basin), Antarctica (Beacon Basin), and Australia (Bowen Basin). The formation of this sedimentary basin was initially caused by the Late Palaeozoic to Early Mesozoic subduction of the Palaeo-pacific plate underneath the Gondwana plate which led to the formation of a 6000km Pan Gondwanian Mobile Belt (Lock 1978, 1980. Winter 1984, De Wit et al 1988, Johnsonn 1991).

2.4.1. Tectonic setting

In Southern Africa, the deposition of the Karoo Supergroup is classified to have occurred in two separate tectonic settings; the Main Karoo Basin is a retroarc foreland basin while the numerous isolated basins further north are considered to be fault bounded rift and intracratonic sag basins (Rust, 1975; Watkeys & Sweeney, 1988; Johnson, 1991; Johnson et al., 1997; Catuneanu et al., 1998; Bordy & Catuneanu, 2002; Bordy, 2006).As a result of the difference in tectonic setting the Karoo sedimentary sequence in the northern basins is much thinner compared to the Main Karoo (Bordy, 2000).

The Cape Fold Belt (CFB) was formed in response to the Late Palaeozoic-Early Mesozoic subduction of the Palaeo-pacific plate underneath the Gondwana plate. As compression and orogenic loading occurred in the CFB, it led to the formation of distinct flexural provinces into which the Karoo sedimentary sequence could be deposited (Fig 8) (Catuneanu et al., 1998). Subsequently the Main Karoo Basin can be classified as a retroarc foreland system (Johnson and Beaumont 1995). The Main Karoo Basin was deposited in the foredeep and forebulge of a flexural system. A number of paroxysms were identified in the CFB which represented pulses of orogenic loading and unloading that affected the subsidence and evolution of the Karoo Basin.

The nature of these two tectonic mechanisms particularly affected the innate structures of the underlying basement (Precambrian and Archaean) which culminated in the formation of numerous individual depozones/sub-basins that followed the earlier regional tectonic trends.

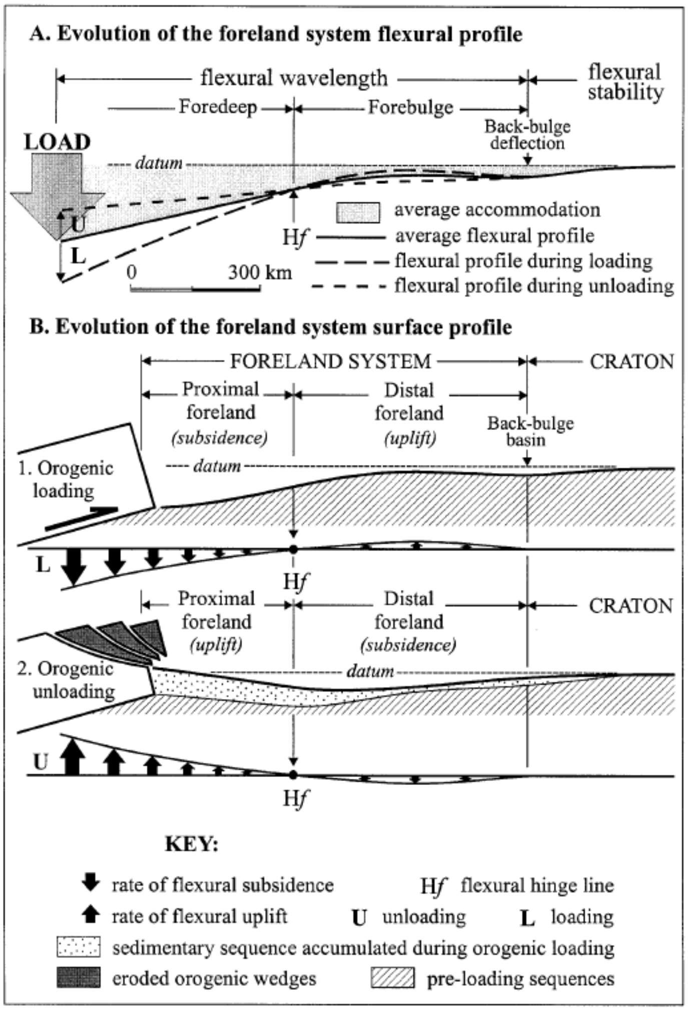


Figure 8: Regional illustration of the Karoo foreland system from Catuneanu (1998)

2.4.2. Development of Basins north of the Main Karoo Basin

According to Burke et al. (1973) the Karoo-aged basins in the Limpopo area (Tshipise, Tuli, Mopane and Nuanetsi – (Fig 44) were formed in the western arm of a Jurassic failed rift triple junction related to the breakup of Gondwana. However, the Karoo sediments were first laid down during the Permo-Carboniferous to early Jurassic, which thus precede the middle-Jurassic break-up of Gondwana. However the orientations of at least two of the failed arms were determined to have already been present in Proterozoic times and are not solely related to the Jurassic aged igneous event (Jourdan, et al., 2005; Hastie, 2014).

In the Pafuri basin further east, pre- and syn-depositional faulting has been reported with a similar ENE-WSW trend from the Tshikondeni Colliery (Sullivan et al., 1994; Sullivan, 1995; Thabo and Sullivan, 2000). However, syn-Karoo faulting has only been clearly recognized for the upper part of the Karoo succession (De Jager, 1976; Snyman, 1998; Bordy and Catuneanu, 2001) and thus extensional tectonic activities during the deposition of the lower Karoo units (i.e. Dwyka and Ecca times) are uncertain (Bordy, 2006). It is thus more likely that during the early stages of deposition, the basin was formed by a compressional tectonic regime (Catuneanu et al., 1998; Bordy & Catuneanu, 2002; Bordy, 2006). These authors suggest that the Permian sedimentary fill of Tuli and Tshipise Basins were deposited in an approximately E-W trending back-bulge region of the Karoo Foreland system (Bordy, 2000). It is expected that the pre-existing ENE-WSW trending shear zones in the LMB would have enhanced the probability of them being reactivated from the flexural tectonics taking place. This is discussed further in section 4.6.

Apart from the N-S trending Lebombo Basin, all of the Limpopo Karoo Basins are located along large E-W trending collision zones associated with the amalgamation of the Kaapvaal and Kalahari cratons. The Springbok Flats Basin occurs just south of the Thabazimbi-Murchinson Lineament whereas the Waterberg and Soutpansberg Karoo basins occur along the Palala Shear Zone (Zoetfontein/Melinda/Tshipise Fault zone) whereas the Tuli Basin is bounded to the north by the Triangle-Tuli-Sabi Shear Zone (Fig. 3). There is little doubt that these large structural lineaments played a major part in the development of the basins, whether in creating accommodation by faulting and subsidence, or just by faulting of larger Karoo units during the Jurassic into the remnants seen today.

North of the Soutpansberg and Tuli Karoo basins, the Karoo occurrences are considered to be rift-related, intracratonic basins and occur extensively in the eastern part of Africa. They extend from the Zambesi River (Cahorra Bassa Basin) to the Horn of Africa and through to the southern margin of the Arabian Peninsula. They comprise a large number of basins across Zimbabwe, Zambia, Mozambique, Malawi, Tanzania, Kenya, Ethiopia and Madagascar (Watkeys, 2011).

Towards the west of the study area, underlying almost half of Botswana lies the Greater Kalahari Karoo Basin. This basin consists of a number of sub-basins defined by local geological and facies changes (Smith, 1984). This basin is underlain by major horst and graben structures that have been intruded to a large extent by the Okavango Dyke Swarm and are thought to have been active during sedimentation of the Karoo. (Smith, 1984). This basin extends into eastern Namibia where it is called the Aranos Basin. Namibia contains two additional sub-basins called the Waterberg Basin (North of Aranos) and the Karasburg basin (South of Aranos). All of the lithofacies successions in these basins show a noticeable resemblance to each other and that of the Main Karoo Basin.

2.4.3. Overall synopses of the Karoo Igneous Province event

The Karoo Igneous Province (KIP) is best known for being one of the largest flood basalt provinces on earth (Courtillot & Renne, 2003). The main preserved volume of the province consists of lava flows, basaltic sills and dykes that extend over more than 3 x 10^6 km^2 (Cox, 1988). Associated with the flood basalt are a number of dyke swarms, the most significant being the three associated with the Mwenezi Triple Junction (Burke & Dewey J F, 1973); the Okavango, Tuli-Sabi and Lebombo dyke swarms. There is now little doubt that this event was a precursor to the eventual fragmentation of Gondwana at~167 Ma (Watkeys, 2002).

The regional distribution of igneous occurrences in Southern Africa suggest that they are mostly situated along pre-existing collision zones around the Kaapvaal and Zimbabwean cratons which have been insipient weaknesses from Proterozoic times and were also exploited during the this event.

Some of the earliest known igneous events in the Karoo Igneous Province are the diatremes/volcanic breccia pipes located south and southwest of Lesotho. These pipe-like features which are tens to hundreds of meters (exceptionally up to~ 10km) in diameter and cut the uppermost sedimentary unit (Clarens) of the Karoo Supergroup (McClintock, 2008). These bodies are thought to represent the opening phases of the Karoo Igneous Province and the Karoo basalt shows sharp, planar contacts with the underlying volcaniclastic rocks (McClintock, 2008).

Some of the most primitive rock types of Karoo magmatism are located around the Mwenezi Triple Junction and consist of Mashikiri Formation nephelinites and Letaba Formation picrites (Bristow, 1984).

The Karoo basalts were formed by successive eruptions from a suite of fissures to build up a sequence of subhorizontal lava flows that can total hundreds even thousands of meters in thickness. Geochronology indicates that the bulk of the magmatism occurred between ~ 183 Ma and ~178 Ma but continued up to 174 Ma (Jourdan et al., 2007) with the intrusion of the Rooi Rand Dyke Swarm in the southern Lebombo Monocline.

Large volumes of low-Ti, tholeiitic magmas, which characterise most of the Karoo LIP erupted within 3-4.5 Ma as continental flood basalts (CFB's), mainly in Lesotho and western Botswana that presently covers an area of at least 140 000km^2. These flood basalt possess a variation in Ti and Zr across southern Africa with basalts in the northern Lebombo and further north into Zimbabwe are high-Ti (TiO_2>2%) whereas basalts of southern Lebombo, Lesotho, central Botswana and central Namibia are low-Ti (Cox et al., 1965; Jourdan et al., 2007; Hastie, 2014)and those in Lebombo have calc-alkaline affinities (low-K tholeiites)

The continental flood basalt is considered to be a preserved remnant of a much larger body, which is very difficult to determine (Duncan & Marsh, 2006), but has been estimated to have erupted over more than 2 000 000 km^2 (Cox 1970, 1972). It was noted by Hastie (2014) that the thickest preserved sequence of basaltic lavas were in the south of Lesotho and it is significant that this, together with the volcanic breccia pipes, occur close to the southern margin of the Kaapvaal craton.

2.4.4. Dyke Swarms of the Karoo LIP

Apart from the Karoo Flood Basalts there are three main dyke swarms associated with the Karoo Igneous Province, most notably those associated with the Mwenezi Triple Junction (Save-Limpopo, Northern Lebombo and Okavango dyke swarms Fig 9) (Jourdan et al., 2004). Two of the three arms of the triple junction have hosted dyke emplacement prior to the early Jurassic and each has subsequently evolved differently.

Four more isolated swarms also occur in southern Africa (Rooi Rand, Underberg, Southern Lesotho and Southern Botswana dyke swarms (Jourdan et al., 2007; Hastie, 2014) and at least five in Dronning Maud Land (Antarctica) have also been identified. The Karoo triple junction at Mwenezi (Formerly Nuanetsi) (Cox, et al., 1965; Jourdan, et al., 2007) is situated within the Limpopo Belt and is an area where the three main dyke swarms overlap. It has long been thought to be an origin of a failed rift initiated by a mantle plume (Jourdan et al., 2004; Le Gall et al., 2002).

2.4.4.1. Save-Limpopo Dyke Swarm

This ENE trending dyke swarm is comprised predominantly of fine to medium-grained dolerite dykes emplaced within the central and western regions of the Limpopo Belt, extending for ~600km into SE Botswana (the Tuli Basin) (Hastie, et al., 2014).

This dyke swarm is 50–100km wide and comprises vertical to sub-vertical dykes that have been dated to 180.4± 0.7-178.9± 0.8 Ma, although a significant number are Proterozoic in age (Le Gall et al., 2002; Jourdan et al., 2005). Field relationships indicate that this dyke orientation predates the other two dyke swarms of the Karoo triple junction (Okavango and Lebombo dyke swarms) during Karoo magmatism, especially evident from the picrite dykes of the Mwenezi region having intruded this orientation (Watkeys, 2002). The dyke swarm underwent deep seated dilatation in a NNW-SSE direction, normal to the Limpopo trend and Save-Limpopo dykes swarm (Jourdan et al., 2005) which most likely relates to the stretching and thinning of the crust related to the split of Gondwana.

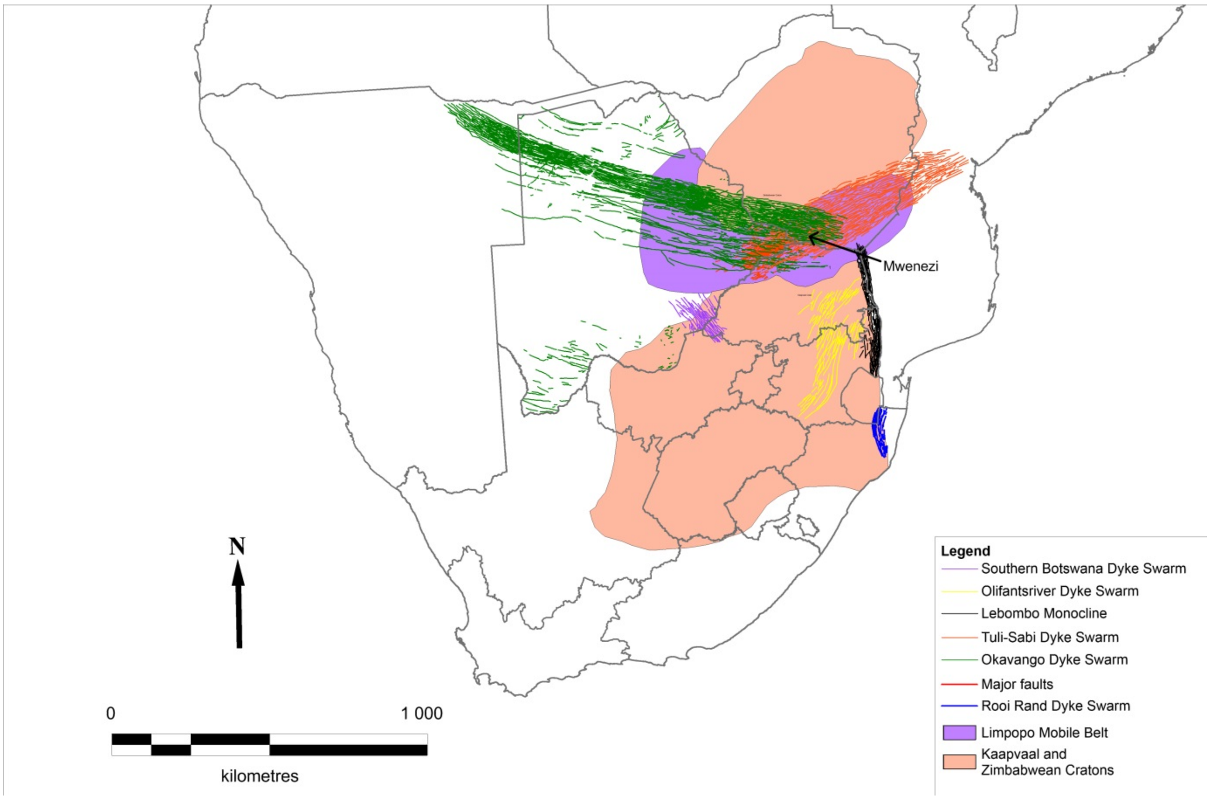


Figure 9: Regional distribution of the dyke swarms associated with the Karoo LIP. Dykes digitised from regional aeromagnetic surveys of South Africa and Botswana and from regional geological maps.

2.4.4.2. Okavango Dyke Swarm

This dyke swarm is one of the most striking aeromagnetic features in Southern Africa. It stretches 1500km from southern Angola to where it converges with the Lebombo monocline and Save-Limpopo dyke swarm at Mwenezi and is recognised as one of the largest dyke swarms on earth (Ernst & Buchan, 2001). The dyke swarm occurred over a short-lived period and did not develop into anything other than the failed arm of the triple junction (Reeves et al., 2016). It is approximately 300km wide at its southern point (Jourdan et al., 2004) and gently tapers off towards the northwest where it eventually has a width of about 40km. The orientation of this dyke swarm is considered to be a reactivated palaeo-structure present in both the Kaapvaal and the Zimbabwean cratons (Watkeys, 2002). The dyke swarm also contains a number (13%) of Proterozoic aged dykes which indicates that this orientation has been exploited prior to the Karoo magmatism (Le Gall et al., 2002; Jourdan et al., 2004). From field evidence, (Jourdan et al., 2005) inferred a NNW-SSE dilation direction for the dykes, similar to that inferred for the Save-Limpopo dyke swarm.

2.4.4.3. Northern Lebombo Dyke Swarm

This is a North-South trending dyke swarm at the eastern edge of the Kaapvaal craton and consists of several generations of feeder dykes that are hosted within the Clarens Formation as well as basaltic and other volcanic units (Hastie, et al., 2014). These dykes also intrude the basalt in other areas such as the Okavango and Rooi Rand but have no known extrusive equivalent. Two radiometric ages of 181.4±0.7 and 182.3±1.7 Ma have been recognised in the northern Lebombo Dyke Swarm (Jourdan et al., 2005). These dykes extent eastwards into Mozambique, however their magnetic expression disappears below thick Cretaceous-Cenozoic sedimentary cover below the Mozambique plains (Reeves, et al., 2016). The dyke swarm contains no Proterozoic aged dyke which suggests that this orientated dyke swarm was only developed during the Jurassic in response to E-W extension (Watkeys, 2002). Their MORB-like composition indicates it is of oceanic origin and most likely marks the initial separation and early fracturing of southeastern Gondwana (Reeves, 2000).

2.4.4.4. Rooi Rand Dyke Swarm

This dyke swarm is not part of the Karoo triple junction but has been identified as the youngest dyke swarm (173.9±0.7 Ma) in the Karoo LIP which post-date the main Karoo flood basalts (Jourdan et al., 2007). It potentially relates to the early phases of continental breakup by lithospheric rupturing caused by an upwelling asthenosphere and subsequent melting (Saggerson et al., 1983). It intruded the Sabie River Formation and Beaufort Group just west of the Lebombo Monocline and contain steeply dipping (>80°), N-S trending dykes in the central area and give way to more shallowly dipping (50°-70°) NNE-SSW striking dykes in the north (Hastie, et al., 2014).

2.4.5. Dyke flow directions

Determining the flow directions of dykes by the measurement of the anisotropy of magnetic susceptibility (AMS) has become a standard technique to determine the flow related petrofabrics. Measurements are typically made on cylindrical core samples collected from the two opposing chill margins along a dyke to determine if there is any preferred orientation of the iron-bearing minerals within the rock fabric, such as lineation and foliation (Tauxe et al., 1998; Aubourg et al., 2002).

Some AMS work has been done on the dykes in the Mwenezi Triple Junction. In the Okavango Dyke Swarm it has been identified that the injection flow directions at Thune (Botswana) appears to be sub-vertical, as well as some lateral flow to the east and west (Aubourg et al., 2008). Further to the west at Shashe (Botswana) the fabric is less well-defined and imbrication of magnetic foliation is consistent with magma injection in a westerly direction (Aubourg et al., 2008). In general the Okavango Dykes swarm flow patterns are well-defined and it is consistent with early sub-vertical flow giving way to lateral flow from SE to NW in the later dykes away from the triple junction (Hastie, et al., 2014). The Northern Lebombo Dyke Swarm show indications of vertical and lateral flow but overall indications are that mostly lateral injection has occurred from the north to the south (Hastie, et al., 2014).

2.4.6. Rifting of Southeast Gondwana

The super continent of Gondwana was created by the collision of approximately 46 smaller landmasses during several orogenies that were completed by the early Cambrian and was a complex product of more than 2 billion years of tectonic evolution (Veevers, 2003; Reeves et al., 2016). The Mwenezi Triple Junction is believed to be the first essential step in the disruption and fragmentation of the long-stable supercontinant in the early Jurassic times (Burke & Dewey J F, 1973; Cox, 1992). The ENE-WSW trending Save-Limpopo dykes swarm was the first to evolve as a result of the stretching and thinning of the crust in a NNW-SSE direction. This then evolved from an early rift to an ocean spreading centre that led to the separation of Africa and Antarctica (Jourdan et al., 2005 and Reeves et al., 2016). This rifting and spreading means that the Lebombo structure was in dextral transtension from 183 Ma until about 153 Ma (Watkeys, 2002 and Hastie, et al., 2014). The final fragmentation of the two continents only ocurred around 167 Ma (Watkeys, 2002), which implies that the NNW-SSE rifting occurred over a period stretching some 17 Ma. After separation of the continents the eastern part of Africa might have undergone minor isostatic rebound, however in general this probably marked the final stage of tectonic activity in the region up until the Miocene (25 Ma), with the onset of the East African Rift System.

2.4.7. Geochronology of the Karoo Igneous Province in the study area.

The Karoo Igneous Province, more so the dyke swarms of the Mwenezi Triple Junction, was one of the direct results of the split of southern Gondwana which ultimately played an important role in how the Limpopo Karoo basins were deformed after deposition. The location of the Save-Limpopo and Okavango dyke swarms have been exploited prior to the Jurassic KIP event occurred since a number Proterozoic aged dykes (851±6 - 1672±7 Ma) have been identified (Le Gall et al., 2002). The timing of the whole event is significant and is illustrated below:

Age of Event	Individual Events during the Karoo Igneous Province
851±6 - 1672±7 Ma	Intrusion of the Proterozoic aged dykes into the Save-Limpopo and Okavango Dyke Swarm
>183 Ma	Intrusion of the Volcanic Breccia pipes in the Southeastern Free-State (No ages but field relationships suggest they predate the outpouring of the Main Karoo basalt flows).
184.2±1.0 – 181.2±1.0 Ma	Sabie River Formation
182.3±1.0 – 181±2.0 Ma	Outpouring of the Lesotho (Main Karoo) Basalts
182.8 Ma	Outpouring of the Letaba Basalts
182.7±0.8 - 182.1±1.6 Ma	Mashikiri Formation (Nephelite) and Letaba Formation (Picrites)
182.1±0.7 – 178.0±1.6	Botswana Basalt
180.4±0.7-178.9±0.8 Ma	Save-Limpopo Dyke Swarm
181.4±0.7 and 178±1.0	Northern Lebombo Dyke Swarm
179±1.2-178.4± 1.1 Ma	Okavango Dyke Swarm
178.2±1.7 – 174.4±0.7 Ma	Mwenezi intrusions
173.9±0.7 Ma	Rooi Rand Dyke Swarm

Table 1 Timing of the events of the Karoo Igneous Province (modified after Hastie (2014).

2.4.8. Tectonic significance of the Karoo Igneous Province

The Karoo Igneous Province is considered to be the precursor or possibly opening phase of tectonism, responsible for the eventual fragmentation of Gondwana at 167 Ma (Watkeys, 2002). The collective igneous event is thought to have occurred within approximately 10 Ma (184±1.0 to 173.9±0.7 Ma). This event is considered to have created various pulses of tectonism that would have been transferred into the underlining basement structures along which large scale reactivation would have occurred. The final separation of Africa and Antarctica only occurred ±7 Ma later.

The Save-Limpopo Dyke Swarm occurs on the Limpopo Mobile Belt, a massive Palaeozoic (2700 and 2000 Ma) aged collision zone between the Kaapvaal and Zimbabwean cratons. This ENE striking metamorphic belt is a structural weakness that largely influenced the position of primitive lithologies, and idea upheld by current geochronological and structural studies (Le Gall et al., 2002; Watkeys, 2002; Jourdan et al., 2004). The Lebombo Dyke Swarm occurs at the eastern edge of the Kaapvaal Craton and is also along which rifting of Gondwana occurred. The Okavango Dyke Swarm is located in an ancient structure present in the Kaapvaal and Zimbabwean cratons (Watkeys, 2002) and also contains various Proterozoic aged dykes. This evidence clearly shows that 2 of the 3 radiating dyke swarm orientations of the triple junction were in place prior to the Karoo magmatism and were preferentially located along pre-existing crustal weaknesses (Le Gall et al., 2002; Watkeys, 2002; Jourdan et al., 2004). Rather than a single large-scale mantle plume related event that caused the Karoo LIP, Hastie 2014 rather suggests that relatively small, independent igneous centres gave rise to the various dyke swarms and associated extrusions.

Another important characteristic of the study area is the dominating presence of vast arrays of dolerite sills that have intruded the Karoo strata. The majority of them are inclined parallel to the strata and were most likely intruded prior to the tilting of the Karoo grabens. There is a significant increase in the thickness of dolerite sills towards the east, into the Pafuri Basin, as well as around the highly faulted Siloam Fault Zone near the center of the Tshipise Basin. Almost no significant sills were encountered in the northern, Jutland, Generaal and Sand River blocks (Fig. 10).

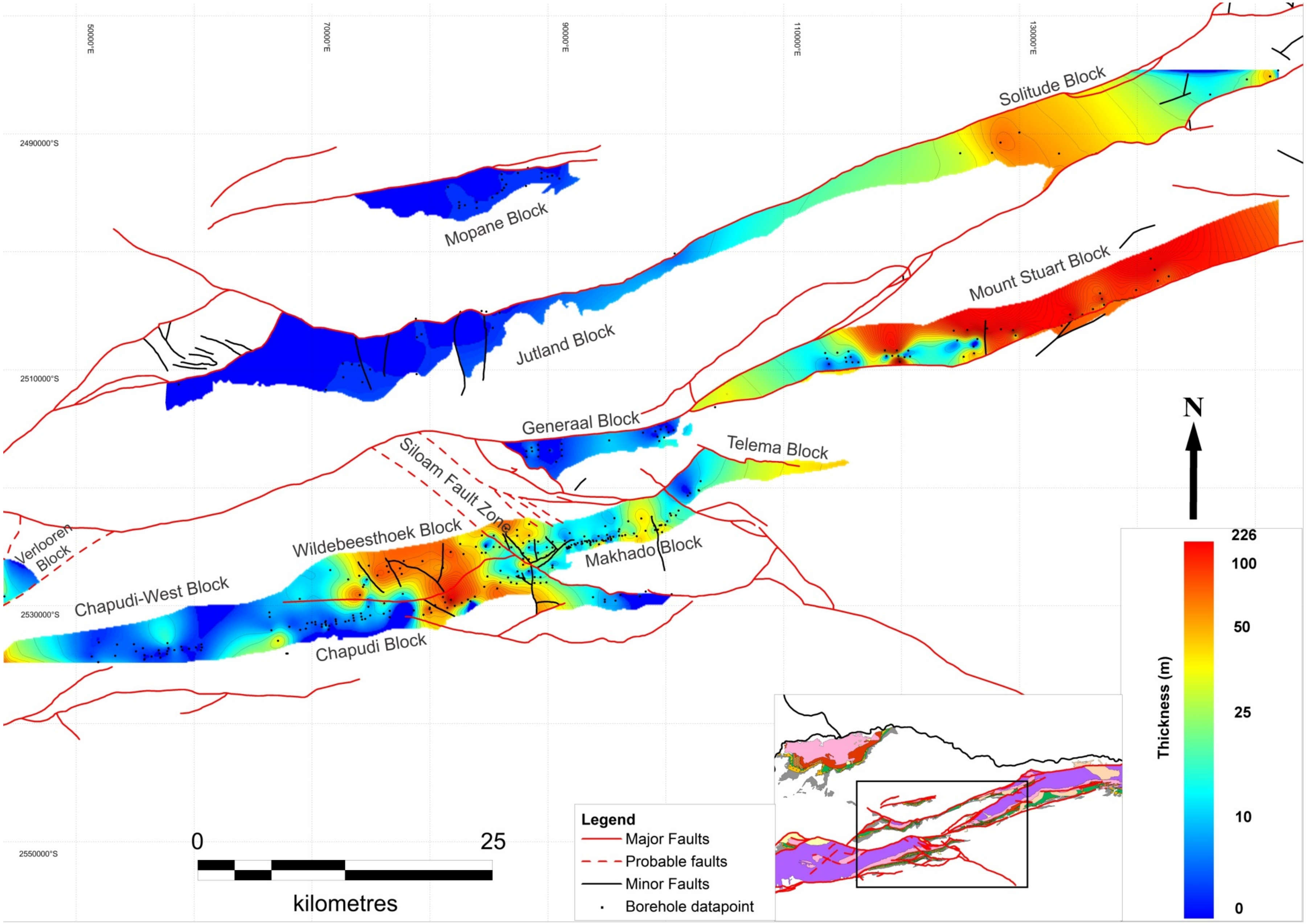


Figure 10: Isopach map illustrating the total thickness of dolerite intersected within boreholes.

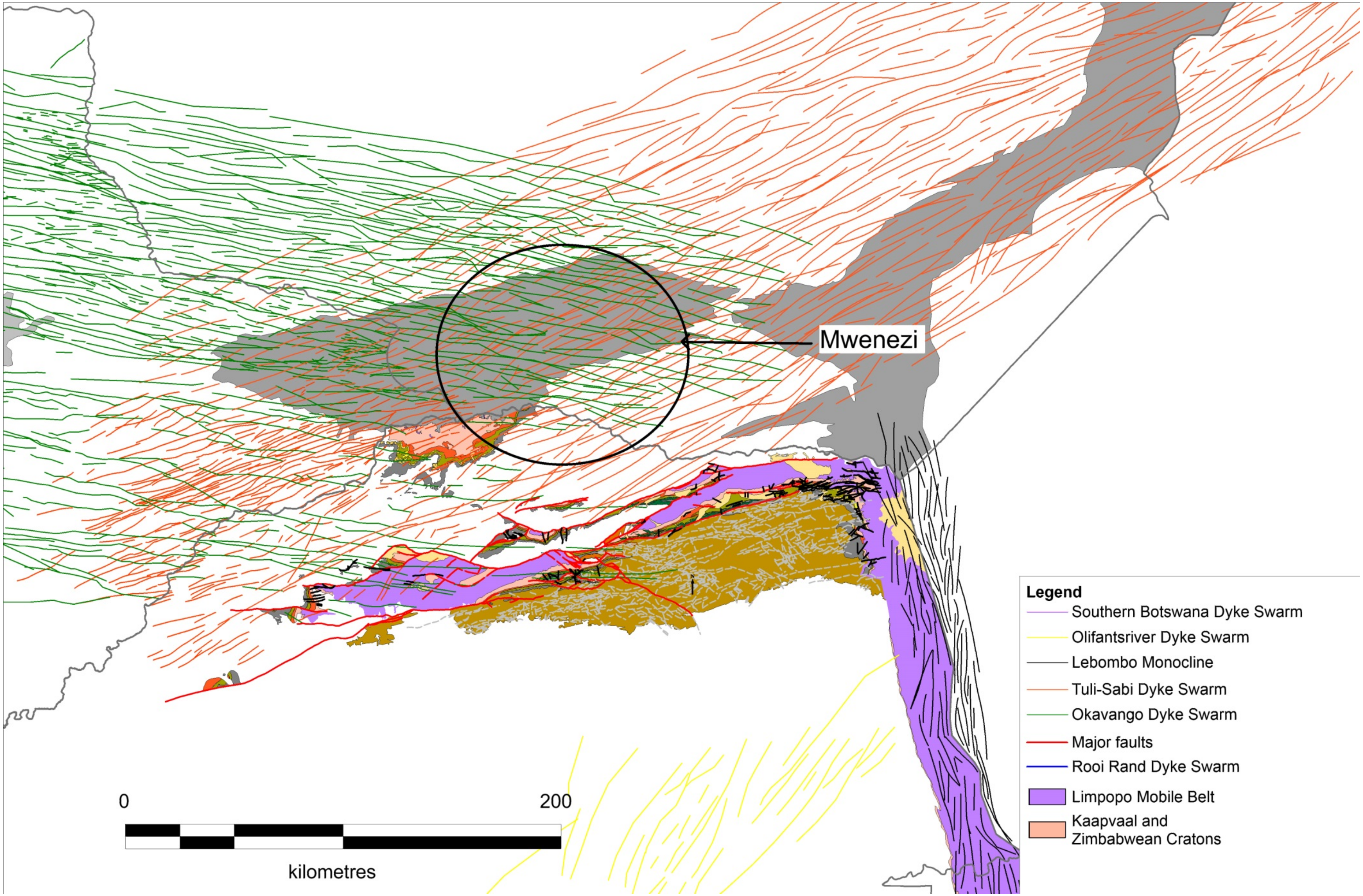


Figure 11: Position of the Karoo dyke swarms relative to the Tshipise Basin

3. The Soutpansberg Karoo Basin

The Tshipise Basin forms the central part of the Greater Soutpansberg Karoo Basin which also includes the Mopane and Nuanetsi basins (Fig 13). This basin is situated just north of the Soutpansberg Mountains and is characterised by several long narrow Karoo filled blocks orientated in an ENE-WSW direction. The extent of the original coal basin is unknown but it is estimated that it once occupied a much larger area only to be dismembered and preserved within the blocks seen today (Van Der Berg, 1980). These blocks are bounded by a number of ENE-WSW trending faults on their northern boundary along which the Karoo strata have been tilted to the NNW, and to a lesser extent WNW-ESE. These faults have a cumulative throw of several hundred meters (Cox et al., 1965; Sullivan et al.,1994; Thabo and Sullivan, 2000) with strata dipping approximately at 12° in the West and 20° in the east (Snyman, 1998).

The basin falls near the southern boundaries of both the Okavango and Tuli-Sabi dyke swarms and, as a result, the Karoo strata have been intruded by a large number of dolerite dykes and sills. These dolerite sills were intersected in the majority of exploration boreholes drilled and do affect the quality and position of the coal seams to a large extent. In general, the sills displace the overlying strata and only burn the coal units to a small extent (1m on either side of the sill contacts).

The Soutpansberg Coal Basin is bounded by a number of large ENE faults, some of which were active during the Karoo sedimentation, especially the upper Karoo, and also defined zones of enhanced subsidence. These faults were reactivated to a large extent during the Karoo Igneous event which ultimately fragmented the much larger Karoo basin into the blocks seen today by down faulting (Van Der Berg, 1980; Brandl, 1981; Bordy, 2006)

The geology of the pre-Karoo rocks shows that the ENE structures of Limpopo trend were intensely reactivated in the post-Soutpansberg, pre-Karoo period (Cox, et al., 1965). A long period of tectonic quiescence ensued before the Karoo was deposited, which meant that the pre-Karoo surface was relatively undulating yet quite subdued, similar to the present day topography (Bordy, 2000).

From the west of the basin near Waterpoort to the east at Tshikondeni there is a general increase in structural complexity, with a higher density of smaller scale faulting and an increased presence of dolerite dykes and sills.

Lithologically the Karoo sedimentary rocks are comprised of terrestrial mudstone, siltstone, sandstone, conglomerate and coal. These sedimentary rocks have been noted at depths of more than 800m in some deep boreholes as a result of the northward dip and are expected to reach depths of beyond 1000m below surface. The sedimentary strata are overlain by a thick sequence of the Letaba Basalt. In general the study area is devoid of outcrop as a result of deep weathering of the basalt and argillaceous units, and is also overlain by Cretaceous and Quaternary cover sediments in large parts. The arenaceous Clarens Formation, and to a lesser extent the Fripp Formation, outcrop readily and tend to form low lying ridges with steep southern flanks and in certain areas (Coen Britz 646) form high cliffs (200m high Bobbejaankop)(Van Der Berg, 1980; Brandl, 1981).

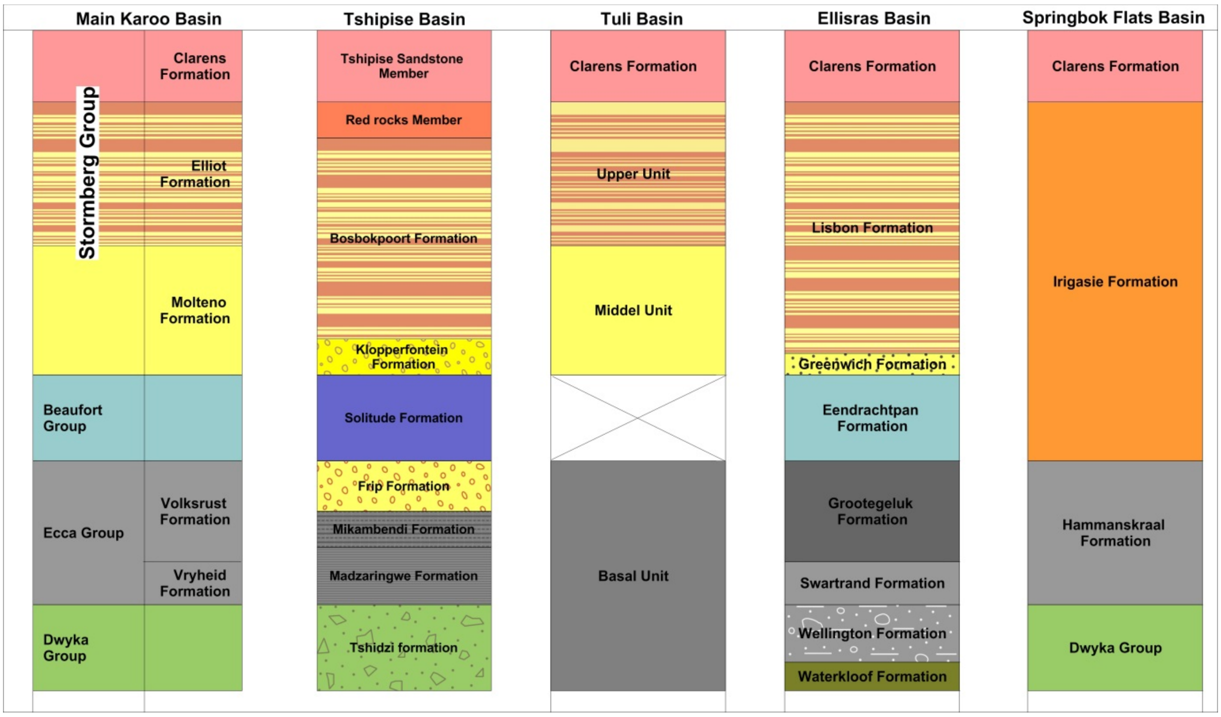


Figure 12: Stratigraphy of the Tshipise Basin relative to the Main Karoo and neighbouring Karoo basins (Modified after Bordy, 2000 and Johnson M.R, 2006)

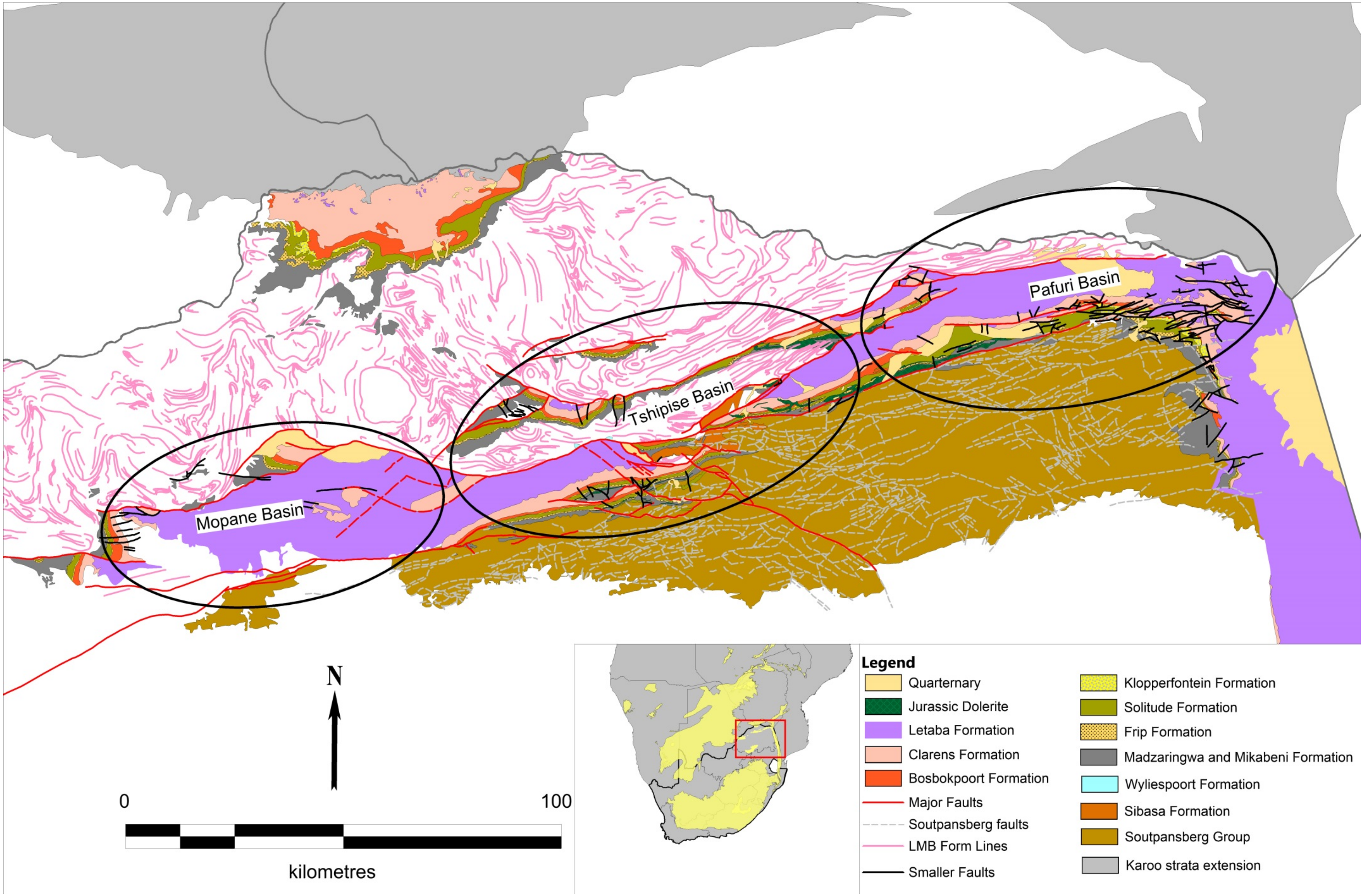


Figure 13: Subdivision of the Soutpansberg Karoo Basin into the Tshipise, Mopane and Pafuri basins (modified after Brandl (2002).

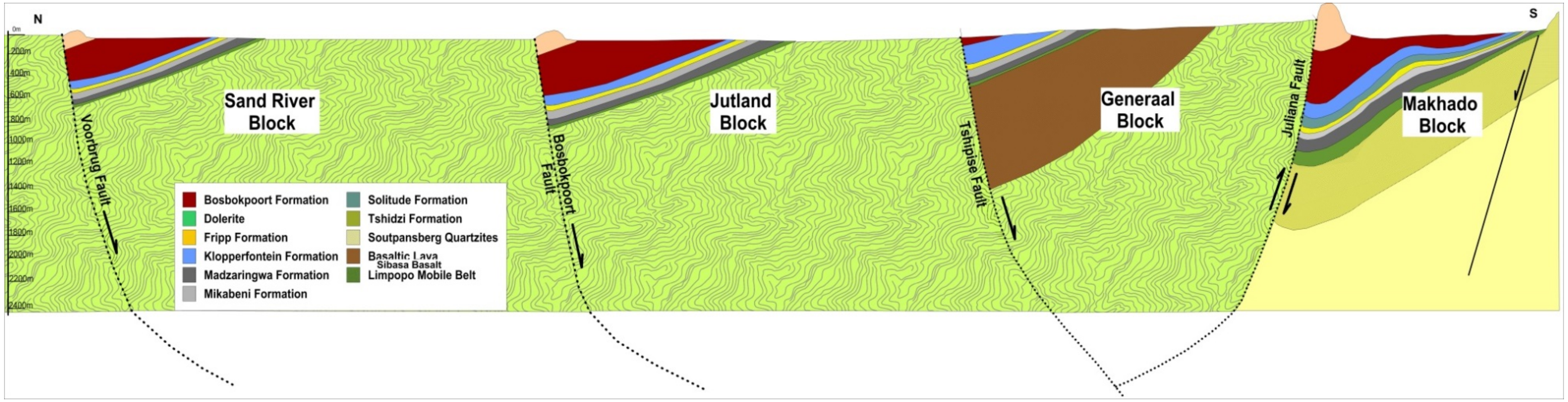


Figure 14: N-S cross-section from the Makhado block in the south to the Sands River Block in the north

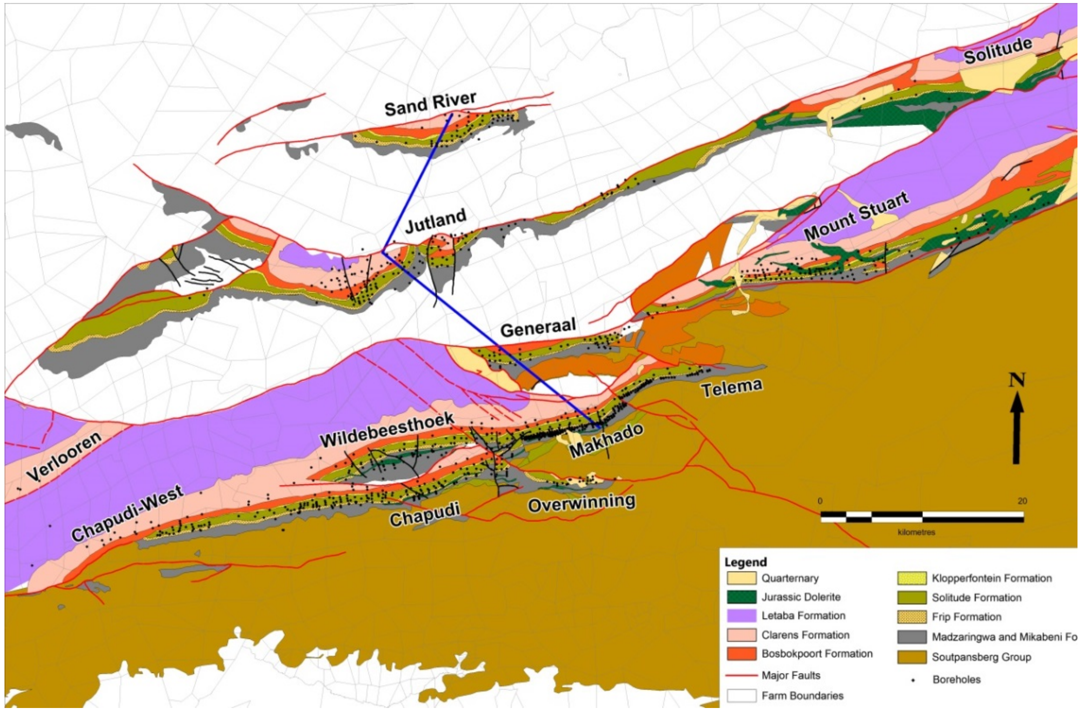


Figure 15: Subdivision of the study area into individual blocks, the blue line indicates the position of the cross-section.

3.1. Stratigraphy of the Tshipise Basin

The stratigraphy of the Tshipise Basin is a correlative succession to that of the main Karoo Basin (Fig 12). However, as a result of its different tectonic development compared to the Main Karoo basin, it is much thinner and often difficult to correlate across the region (Bordy, 2006). While the main Karoo Basin fill ranges from marine to terrestrial (flysch-molasse) succession that thickens drastically from the NE to the SW approaching the Cape Fold Belt; the Karoo stratigraphy of the Tshipise Basin consists purely of terrigenous clastic and chemical deposits (Bordy, 2006). Based on limited outcrop and borehole data from the eastern parts of the Soutpansberg Karoo Basin, the area was subdivided into a number of lithostratigraphic units by McCourt and Brandl (1980). However, Van Der Berg (1980) conducted a detailed sedimentological study on the Tshipise area and questioned the appropriateness of this, as the units have not been identified in all parts of the basin. Bordy (2006) conducted a similar study in the neighbouring and genetically related Tuli Basin towards the north and came to a similar conclusion regarding the stratigraphy. For this study the original lithostratigraphic subdivisions created by McCourt and Brandl (1980) were used.

The sediments rest unconformably on basement rocks of the Limpopo Mobile Belt and the Soutpansberg Group rocks. There is a small angular unconformity of ~12° between the Soutpansberg Group and the Karoo Stratigraphy consistent with tilting and minor deformation of the Soutpansberg Group prior to the development of the Karoo Basin (Broadbent, 2005).

The following sections include isopach maps created from the coal exploration boreholes drilled in the area by the various exploration companies. The lithological descriptions are taken from various authors who are acknowledged in each case. The core photographs were taken in the Coal of Africa core yard at the Makhado exploration camp.

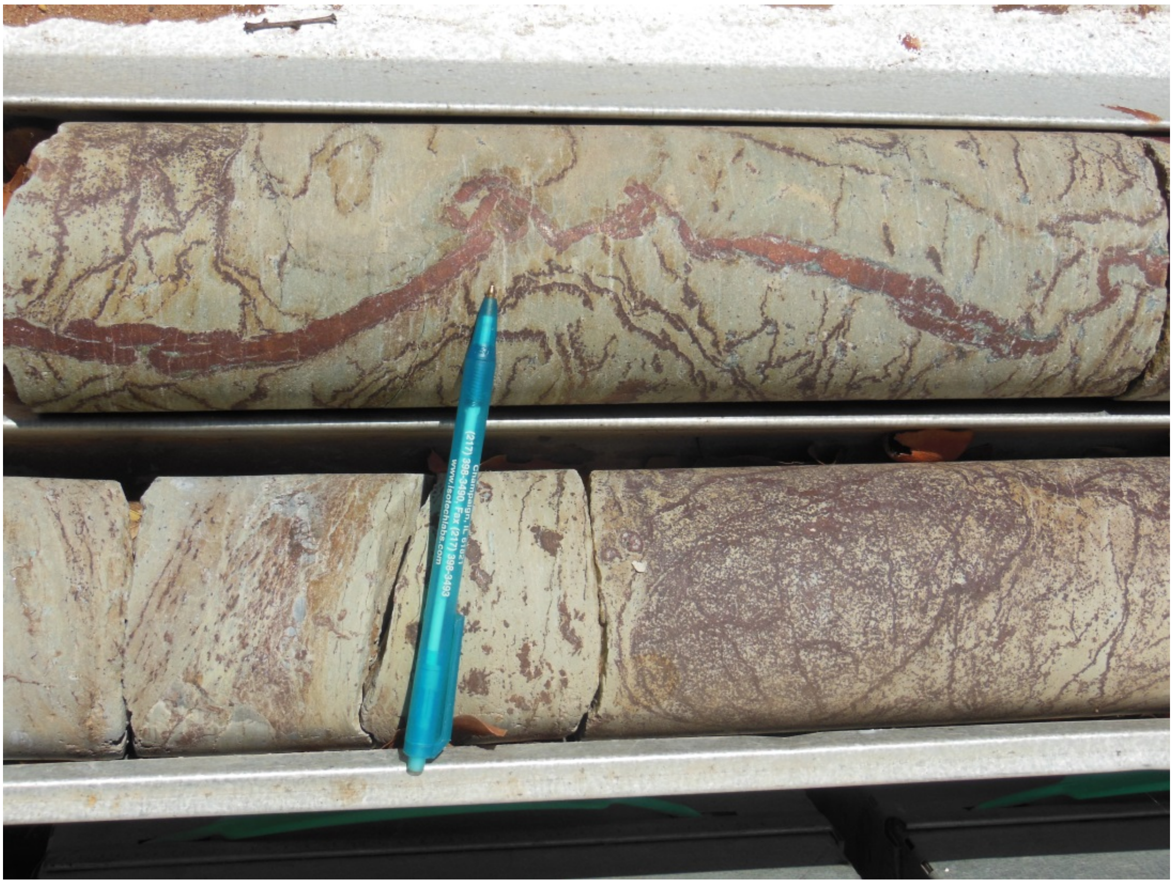


Figure 16: Highly deformed basement rocks of the LMB in core samples.

3.2. Pre-Karoo Palaeo-topography

As a result of the intensive post-Karoo faulting, it is relatively difficult to define the extent and boundaries of the basin prior to it being dismembered. Fig.19 below is an isopach map of the interval between the basement and bottom of seam 6. This coal seam is well-developed across the entire basin and is considered to be a basin wide datum. The isopach shows the presence of a deep valley/trough in the southern-most Makhado block through the presence of a noticeable increase in thickness. This image also highlights the marked variation in thickness over short distances, especially in the central part of the block. To the north, in the Generaal, Mount Stuart, Jutland and Mopane Blocks, the unit is much thinner compared to that in the southern block. Associated with these are several N-S zones where the unit is also thicker than the surrounding areas. These thickness variations correspond to the position of the post-Karoo faults, especially the N-S and NW-SE orientated structures.

Van Der Berg (1980) was the first to describe a fault bounded ridge separating the area into a southern (Makhado) and northern (Generaal, Jutland and Mopane) trough. This ridge was possibly bounded to the south by the current Juliana Fault and consisted of Sibasa Basalt. To the south of this ridge the Makhado trough was at its deepest and the basement consists of Wyllie's Poort quartzite, of the upper Soutpansberg Group, whereas the ridge consisted of Sibasa Basalt, part of the lower Soutpansberg Group. The northern Jutland and Mopane blocks consist of even older layers of Soutpansberg-aged tuff and rocks of the LMB Figure 164) (Van Der Berg, 1980). The fact that two vastly different formations of the Soutpansberg Group form the basement of the two Karoo troughs only a few kilometres apart suggest that the ridge separating the troughs was formed by up-faulting of the lower lying Sibasa Basalt. This highlights the fact that a period of pre-Karoo deformation led to the formation of ridges and valleys that would have been scoured during the early Karoo glaciation, creating basins into which the Karoo sediments could be deposited (Söhnge, 1946; Van Zyl, 1950, p108; Van Der Berg 1980). The presence of the N-S trending valleys along faults in the northern blocks suggests that they were possibly draining in a northern or southern direction and ultimately joined the main ENE-WSW trending palaeo-valleys.

3.3. Tshidzi Formation

This unit is considered to be the lower Permian Dwyka equivalent and overlies the pre-Karoo basement rocks of the Soutpansberg rocks and to a lesser extent the Limpopo Mobile Belt. The basal contact between this and the basement is often difficult to define Fig 17), especially in the areas where the basement rocks consist of basalts (Sibasa Formation) (Van Der Berg, 1980). The upper contact is a gradational one and considered to be at the occurrence of the first well-developed coal zone. The thickness of the unit varies between 1m and 162m and it is believed that the basin floor was an undulating, yet quite subdued surface that was shaped by continental-scale glaciation (Van Der Berg, 1980; Broadbent, 2005). Some authors have argued that the lack of indisputable evidence of glacial origin (striated clasts and pavements) renders the identification of these deposits as tillite and their correlation to the Dwyka of the Main Karoo Basin uncertain (De Jager, 1976). However regional palaeoclimate indicators from neighbouring regions (striated pavements in the Save Basin of Zimbabwe) and the soft sediment deformations observed around the clasts of the matrix supported breccias (dropstones) could be taken as reliable evidence of their glacial origin (Bordy, 2006).

The unit mainly consists of poorly-sorted, matrix supported conglomerates and breccias and consists of fragments of quartz, granite, quartzite set in an argillaceous to sandy matrix as well as ash-grey, well laminated mudrocks (McCourt & Brandl, 1980; Johnson M.R, 2006; Bordy, 2006). Van Der Berg (1980) sub-divided the unit into a basal arenaceous and an overlying argillaceous diamictite unit. Due to the mostly argillaceous nature of the unit, outcrop is fairly limited.

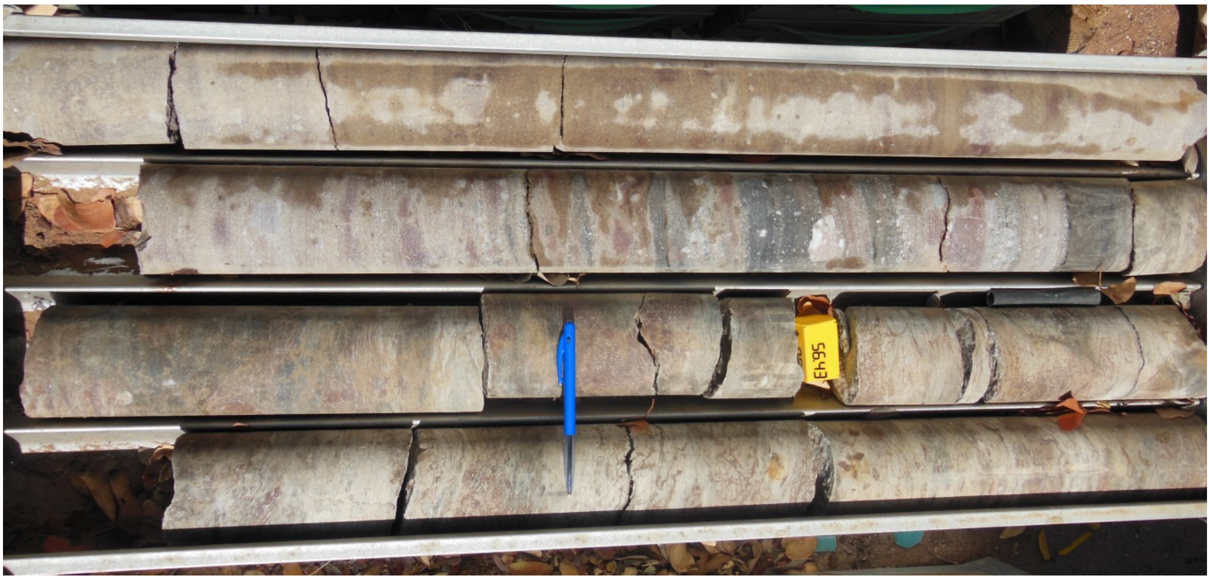


Figure 17: Gradational contact between the basement and the basal arenaceous diamictite unit of the Tshidzi Formation, blue pen is the possible contact.

3.3.1.1. Basal arenaceous diamictite unit

In general the unit consists of a basal sandy diamictite unit that has been developed across the majority of the study area that ranges in thickness from 0 to 51m with noticeable variations in thickness across relatively small distances (Van Der Berg, 1980). This sandy diamictite contains fragments of quartzite ranging in size from less than a centimetre to 2 m in diameter. In other areas fragments of pink shale, fine-grained sandstone, grey sandstone as well as weathered pre-Karoo basalt and even tuff have been seen, however they are seldom larger than 8cm in diameter (Van Der Berg, 1980). These fragments are mostly angular though smaller dropstones are well-rounded and are poorly-sorted, apart from them often increasing in size towards the base of the unit. These fragments occur in a poorly-sorted sandy matrix with very fine, white clayey layers often forming the thin undulating lamellae in the diamictite that are often folded around larger fragments, possibly as a result of compaction (Van Der Berg, 1980).

The basal diamictite unit is overlain by a coarse-grained, moderate to poorly-sorted, often upward-fining sandstone consisting mostly of quartzitic and feldspathic grains. Thin mudrock layers are present which could be associated with erosion and deposition from the reworking of existing material (Van Der Berg, 1980).

Between the farm Lukin and the Nzhelele dam, the eastern most part of the Makhado valley, this overlying sandstone changes to a very well sorted, clean, creamy coloured, medium grained sandstone with varved layers near the top. Poorly-developed upward-fining cycles are present and more apparent near the top of the sandstone unit. The parallel laminated varved layers are light grey in colour near the base and have an upward-fining character with darker coloured and finer grain-size near the top. The laminae of the varved shales are often irregular and contain a high percentage of small scale faults, possibly as a result of the rapid deposition of the upper sandy layers. This unit drastically thins from 94m to 15m in only 2 km (Van Der Berg, 1980).

3.3.1.2. Argillaceous diamictite unit

This unit occurs above the basal sandy diamictite unit and consists of diamictite interlayered with mudstone, sandy mudstone, sandstone and grit. Poorly-developed thin coal layers are often developed high up in the unit. This layer is less well-developed than the basal layer, often times only 1m thick, and the thickest occurrence is in the area where the creamy coloured sandstone occurs, Lukin to Nzhelele dam where it reaches a thickness of 68m (Van Der Berg, 1980). In general the unit comprises of fragments and grains of vein quartz as well as sandstone, dropstones and mudstone occurring in a dark grey clayey matrix. These fragments range in size from less than a cm to more than 5 cm and are poorly graded, however in some instances there is an obvious decrease in the number and size of fragments towards the top of the unit. The mudstones are grey to dark grey in colour and often very carbonaceous with thin coal layers and lamellae. Siderite nodules are common in these highly carbonaceous zones. The weathered Sibasa lavas are normally very iron rich and can be the reason for the presence of iron carbonates, siderite nodules and lenses in the clayey sediments (Van Der Berg, 1980).

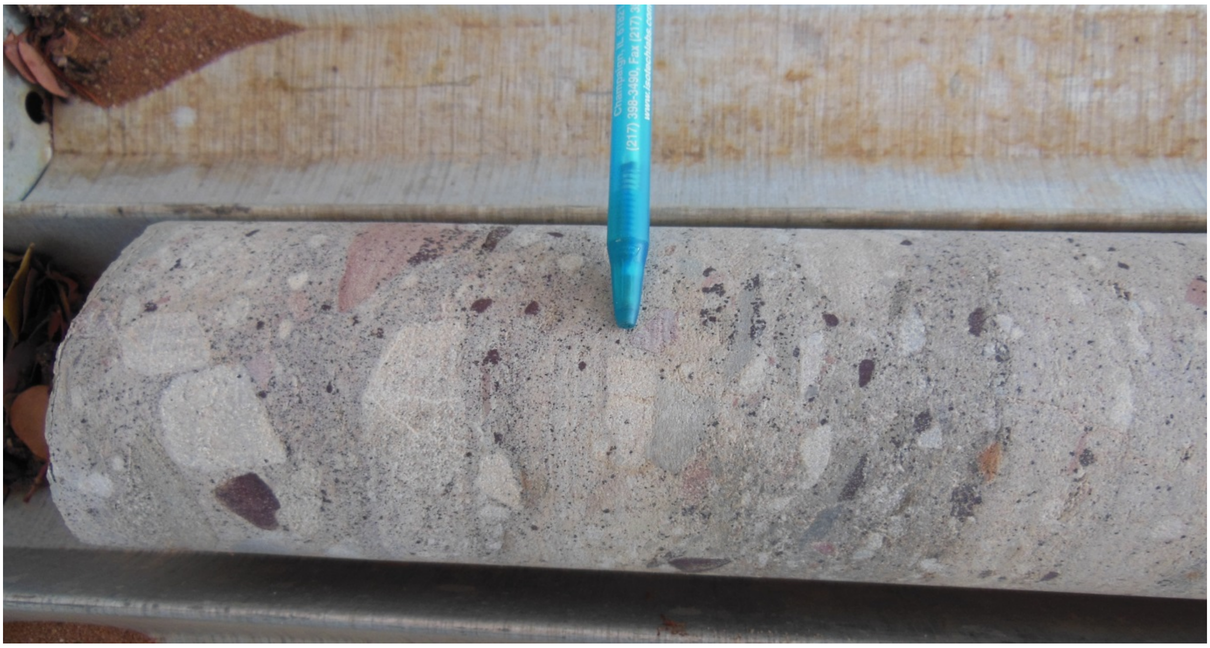


Figure 18: Lower argillaceous diamictite of the Tshidzi formation

3.3.1.3. Distribution and thickness

Fig 19 below is an isopach map of the interval between basement and bottom of the seam 6, the main coal zone. The gradational upper contact makes it difficult to define the upper limit of this formation across the entire basin and it was decided to use the bottom contact of seam 6, for the purpose of creating the isopach maps. This bottom contact of the coal seam is correlate-able across most of the basin and can be used a reliable basin-wide datum. The lithostratigraphy below seam 6 includes some coal seams (Seam 5, 4,3, 2 and 1) which are poorly-developed across the large portions of the basin and are completely absent in most of the northern blocks.

This formation varies vastly in thickness across the basin and is very much a function of the pre-Karoo basin topography and faulting. The southern-most Makhado block contains by far the thickest assemblage of this unit, especially its eastern part, on the farms Salaita (188) and Lukin (643); it has an average thickness of well over 100m. Further west towards the farms Sulphur Springs (658), Groot Geluk (711) and Castle Koppies (652) the unit shows extreme variation in thickness, from 20m to over 200m, across short distances. This area is where the Siloam Fault Zone intersects the main ENE-WSW trending fault system and where extensive post Karoo block faulting has occurred Fig. (19).

It is noteworthy to mention that the Tshidzi Formation is markedly thinner where the basement consists of basalt, which might have been basement highs at the time of deposition. This is unlike what one would expect as basalt would normally tend to weather more easily compared to the quartzite. This further suggests the area was subjected to block faulting prior to the deposition of the Tshidzi Formation, in a similar fashion to what is seen in this area today, to form a rapidly undulating basement topography.

In the blocks further north, Mopane, Jutland and Generaal Block, the Tshidzi Formation is markedly thinner and in certain cases completely absent, with coal resting directly on basement lithologies. These northern blocks do however contain a number of N-S trending zones where the Tshidzi Formation is much thicker than the surrounding areas and might represent palaeo-valleys that were present during this time. In the Jutland block, these N-S valleys are closely situated along N-S trending post-Karoo faults that have displaced the entire Karoo Sequence. The Mount Stuart block to the east show similar, yet not as well-defined, N-S zones of thicker Tshidzi Formation.

Fig 20 represents the sandstone/mudstone ratio of the stratigraphic unit below seam 6 (Tshidzi Formation) and also reflects what was seen in the Tshidzi thickness image (Fig 19). The N-S trends are seen in the Mopane, Jutland, Generaal, Makhado and Mount Stuart blocks. The central and eastern part of the Makhado block is where the greatest thickness of Tshidzi was recorded also contains the highest sandstone/mudstone ratio.

3.3.1.4. Depositional environment

This formation consists primarily of coarse-grained sediments with an origin that has been described as either a glacial, fluvio-glacial to fluvial. The basal unit is considered by Van Der Berg (1980) to be a glacial moraine that was continuously reworked by meltwater and in outcrop resembles that of alluvial fan deposits. Overlying this are coarse-grained, cross-bedded, upward-fining sandstone deposited in braided river systems that were deposited on a relatively steep gradient fed from the seasonal glacial meltwater. The general increase in clay content towards the top of the unit suggests a decrease in energy of the streams. Thin localised varved mudstone suggest the presence of small shallow lakes were water collected (Van Der Berg, 1980)

The overlying argillaceous diamictite unit is characterised by the presence of various interbedded layers of clast-supported breccias and conglomerates, mudstone and thin sandstone. The presence of dropstones and well-laminated mudstone of the Chapudi area suggest that the landscape was dotted with a number of glacial lakes whereas the clast-supported breccias have been interpreted as small debris (colluvial) fan deposits (Bordy, 2006). The thick mudstones are interpreted as being deposited within a floodplain environment where the mudflows and coarse-grained sandstone can form as a result of crevasse splays within floodplain (Van Der Berg, 1980).

Fig 19 below represents the thickness of the Tshidzi Formation where the thickest development is in the Makhado Block which rapidly thins northwards across the current position of the Tshipise and Juliana faults, into the neighbouring Generaal, Jutland and Mopane Blocks. It is also interesting that within each individual block, N-S faulting also controls the distribution of the thickness. This was possibly caused by syn-depositional faulting.

The mudstone/sandstone ratio as depicted in Fig 20 shows that the sandstone content increases dramatically where associated with this north-south faulting. This may also be indicative of syn-depositional faulting or subsidence.

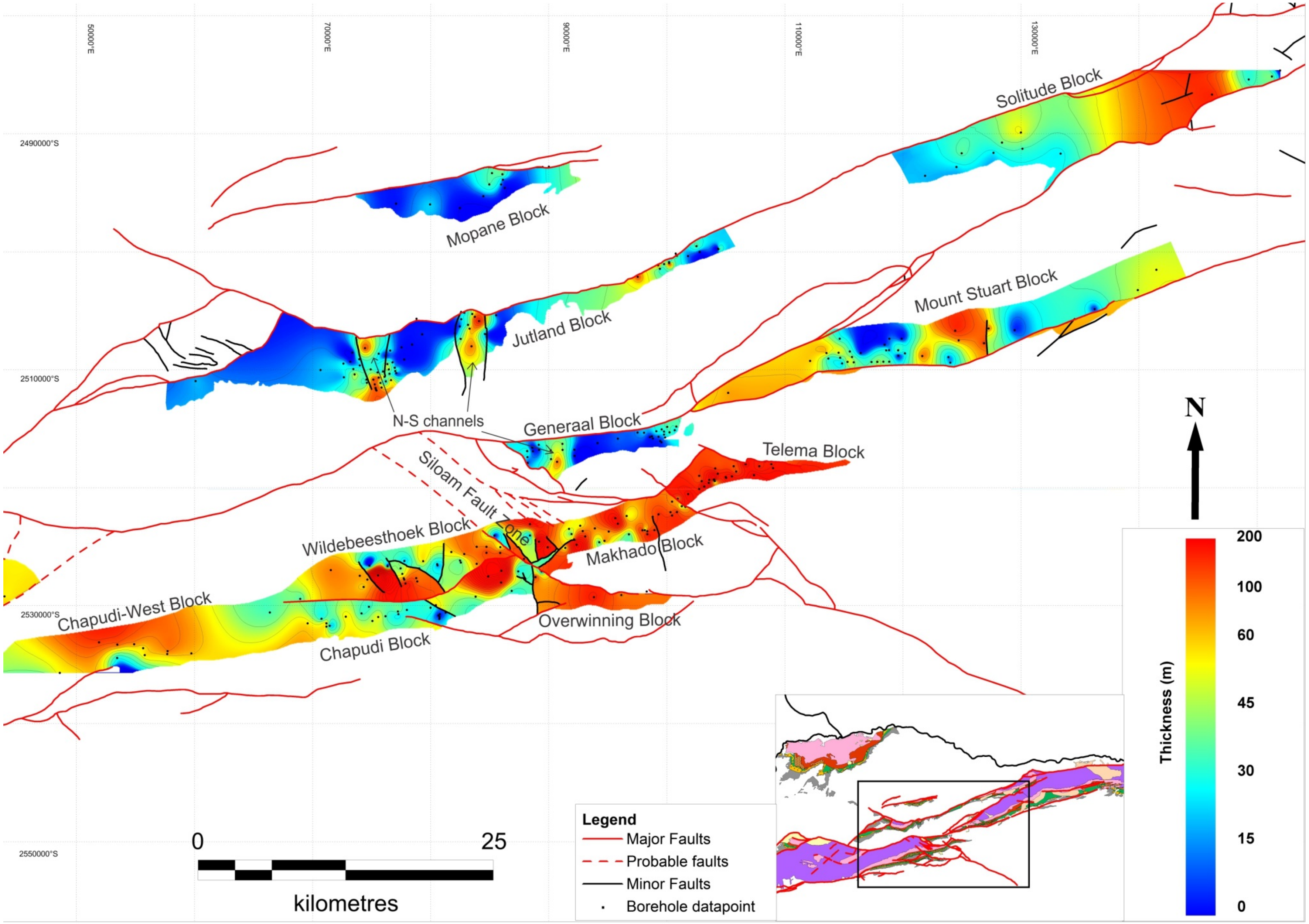


Figure 19: Isopach map of the basement to bottom of the S6 coal seam. This image illustrates the approximate thickness of the Tshidzi Formation.

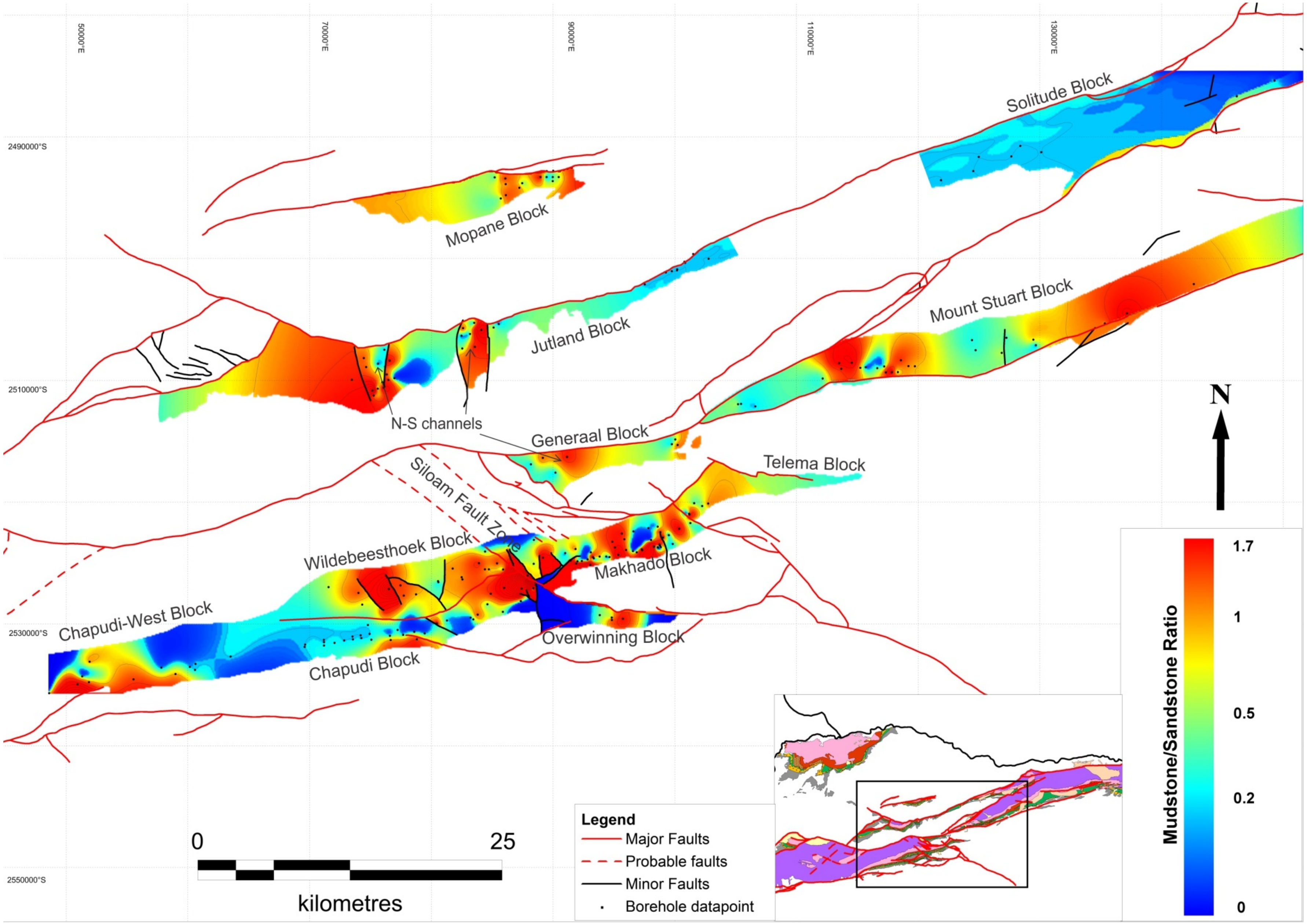


Figure 20: Mudstone/Sandstone ratio of the unit below coal Seam 6 (Tshidzi Formation)

3.3.2. Madzaringwe Formation

This Madzaringwe Formation forms the lowermost part of the Ecca Group and passes from the Tshidzi to the Madzaringwe Formation through a gradational contact (McCourt & Brandl, 1980). This unit varies between 11m and 348m thick (Fig 23) and the basal contact is taken to be the first occurrence of a well-developed coal seam. The Madzaringwe Formation consists of cyclical accumulations of alternating sandstone, siltstone, mudstone and coal layers (Truter, 1945; Van Der Berg, 1980; Bordy, 2006).

This formation is dominated by light grey to black, highly carbonaceous mudstone, coaly-mudstone and thin coal seams in the basal part of the unit followed by alternating layers of grey-black shale, brownish siltstone and laminated sandstone higher up, the proportion of silt and sandstone varies to a large degree depending on the position in the basin (Brandl, 1981). In general the unit can be referred to as mudstone with intercalated coal, silt and sandstone laminae which are usually very micaceous. There are a number of coarse-grained, poorly-sorted sand and grit layers and lenses up to 30cm thick with sharp basal and gradual upper contacts, possibly representing crevasse-splays (Van Vuuren, 1979). The mudstone layers vary in colour from light grey to black depending on the carbon content and in certain cases can be classified as "coal-shale". Siderite lenses and nodules are common and normally associated with the more carbon rich layers which tend to develop locally at similar stratigraphic horizons (Van Der Berg, 1980).

Towards the far-east of the basin (Tshikondeni area) there is a well-developed coarse grained feldspathic sandstone (<15m) in the uppermost part of the formation which is usually micaceous and contains cross-bedding (McCourt & Brandl, 1980; Brandl, 1981). This sandstone resembles that of the Fripp Formation, being comprised of quartz dominated trough cross- bedding, but located approximately 50m below the Fripp.

The coal within the Madzaringwe Formation is associated with mudstone and shales (Fig 21); however minor coarse-grained sandstones are also often present with coal making a sharp contact above it. The contacts between the coal ranges from very sharp to gradual, with gradual contacts normally associated with higher occurrence of interlaminated mudstone with a decrease in carbon content away from the coal (Van Der Berg, 1980).

The grey mudstones are normally massive and often have a mottled appearance. In the lower part of the unit especially, mudstone layers can form lenses between coal seams ranging from 40cm and 5m wide and in some cases up to 20m, and between one and 70cm thick (Van Der Berg, 1980). Compaction structures in the form of ball and pillow structures are common throughout the zone especially within shale –siltstone associations.

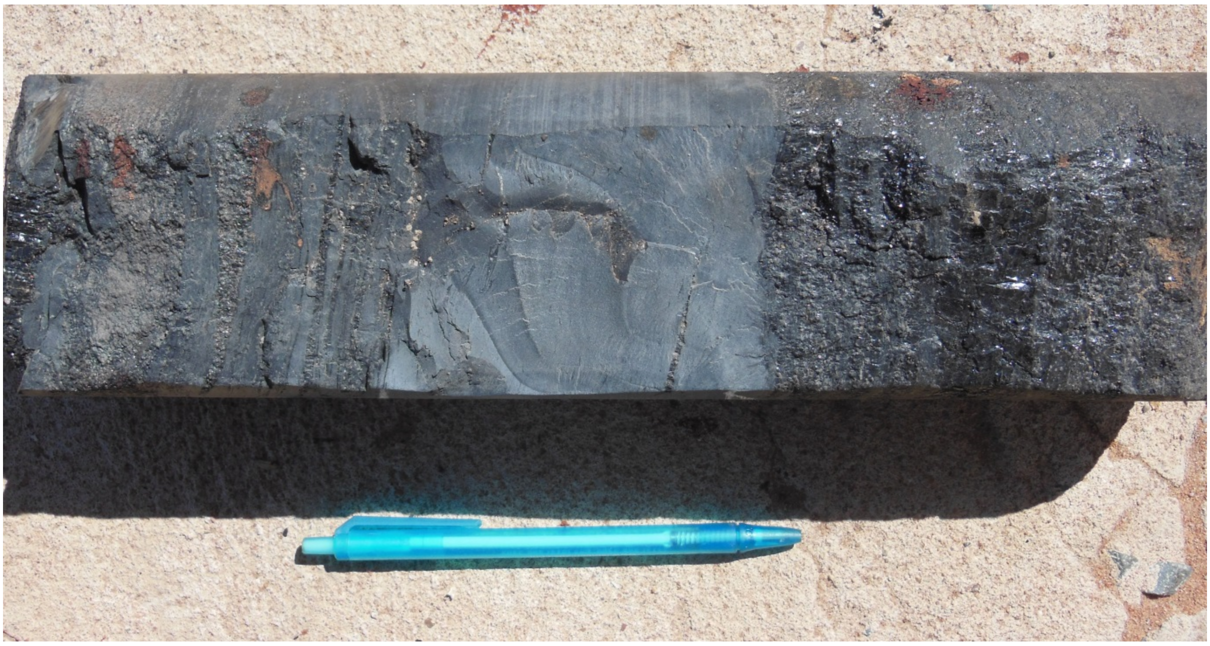


Figure 21: Bright vitrinite bands interbedded with dark grey carbonaceous mudstone typical of the Madzaringwe Formation.

3.3.2.1. Facies Description

One of the most noticeable facies changes in the unit is the increase in sandstone and overall thickening of the coal bearing unit near the eastern margin of the study area (Van Der Berg, 1980; Broadbent, 2005; Bordy, 2006). Towards the east, coarse-grained sandstone become more prominent and the coarser-grained cycles are better developed. In the east, the formation has a higher proportion of coarse sand facies, packaged into thicker units, whereas the coal seams are thinner and more massive (Broadbent, 2005).

Further west in the Makhado and Chapudi areas; the facies changes to a more mudstone-rich unit with thin sandy lenses and layers or either quartz grains distributed within a muddy matrix, in place of the sandstone layers.

The sandstone facies does not appear to be well-developed near the west of the basin, near Chapudi, but does appear to persist over a strike length of at least 20km. These sandstones have been identified at the Lilliput siding and Nakab farm with even coarse-grained conglomerates in the Madzaringwe, this suggests that the stratigraphy is more complex and not simply a 'layer cake' model as some authors have suggested (Broadbent, 2005).

In the fault blocks towards the north (Sandriver Block) the coal zones are also poorly-developed with seams of limited lateral extent between Mopane and the Brak River (De Villers, 1959). Individual coal seams in the westernmost part of the basin cannot be correlated to match any of the seams in the central (Tshipise) and eastern (Tshikondeni) regions. The poor coal development just west of Tshipise on the farm Nakab has been pointed out by De Jager (1959), and has been interpreted as an Ecca fluvial channel. Furthermore, De Jager (1959) noticed that the area between Nhzelele and the national road (N1) contain a better developed coal zone. This is the area where the planned Makhado open-cast mine is set to be opened. Much further west near Alldays, in the Mopane Basin, coal development is much more sporadic and in certain cases completely absent (De Jager, 1959).

3.3.2.2. Distribution and thickness

Fig 23 is an isopach map of seam 6 of the Madzaringwe Formation and overall it has a very similar thickness distribution to that of the Tshidzi Formation below it. The Madzaringwe Formation is overall much thicker in the southern Makhado block, especially in the east, compared to the northern Jutland and Mopane blocks. The thickness increases rapidly towards the far eastern part of the study area, in the Mount Stuart block, and is also associated with an increase in the mudstone/coal ratios (Fig 24). The effects of the N-S trending palaeo-valleys, seen in the Tshidzi Formation, are also revealed in the Madzaringwe Formation which shows an increased thickness within these valleys. Associated with these are the elevated coal/mudstone ratios (Fig 24). This is possibly the result of higher rates of subsidence in proximity to these faults.

3.3.2.3. Depositional Environment

Palaeo-environmental reconstruction of the formation indicates that the argillaceous facies of the coal bearing unit accumulated in a low energy, peat swamp environment, shielded from active sediment influx (Bordy, 2006). The arenaceous facies of the coal-bearing strata were interpreted as crevasse-splay deposits that were sourced from a main braided river channel system further to the north (Van Der Berg, 1980; Bordy, 2006). These high energy facies would have occasionally interrupted the overall quiet sedimentation regime during major flooding events. Such an Ecca-time channel was identified in an area on the westernmost part of the Mount Stuart block, on the farm Nakab (184), by the presence of thick sequences of arenaceous facies within the coal-bearing units and relatively thin coal and mudstone accumulations (Bordy & Catuneanu, 2002; Bordy, 2006). Palaeocurrent analyses of this arenaceous facies were made from the acoustic televiewer (ATV) logs from borehole 184MT004, which indicated that the main channel system had a palaeo-flow direction from the E and NE towards the WSW (Fig 22) (Bordy, 2006).

This overall drainage direction during the deposition of the Ecca coal unit is parallel to the regional Limpopo structural trend and parallel to that of the Tuli Basin to the north (Bordy & Catuneanu, 2002). Bordy (2006) indicates that the overall geometry of the neighbouring coalfields (i.e. Pafuri, Tuli) show that coal swamps formed parallel to the main river system, but distal to the areas of active clastic sedimentation.

The lateral continuity of the upper coal seams and the general decrease in the abundance of the interbedded arenaceous facies towards the top of the unit imply that these areas were progressively protected from siliciclastic input (Bordy, 2006). The protection of these areas is either as a result of progressive vertical isolation within initially low-lying, glacially carved depressions which become a raised swamp. Alternatively they might have been laterally isolated by physical barriers in the form of sediment trapping swamp-margin vegetation near the main fluvial channels (Bordy, 2006). The isopach and coal/mudstone maps in Figs.23 and 24 suggest that the both of these cases might be applicable. The thickness and lithology of the Madzaringwe Formation, especially the northern basins (Generaal, Jutland and Mopane) were controlled to some extent by N-S faulting. The increased thickness and coal/mudstone, coal/sandstone ratios (Fig 24) in these zones might indicate areas of higher subsidence and an associated increase in sediment ratios.

The overall thickness of the Karoo sedimentary rocks decreases from south to north although most units are present throughout. This thinning of the sequences possibly indicates that there was more fault related subsidence in the south than in the north. This same reasoning could also apply to the eastern area where sediments thicken markedly.

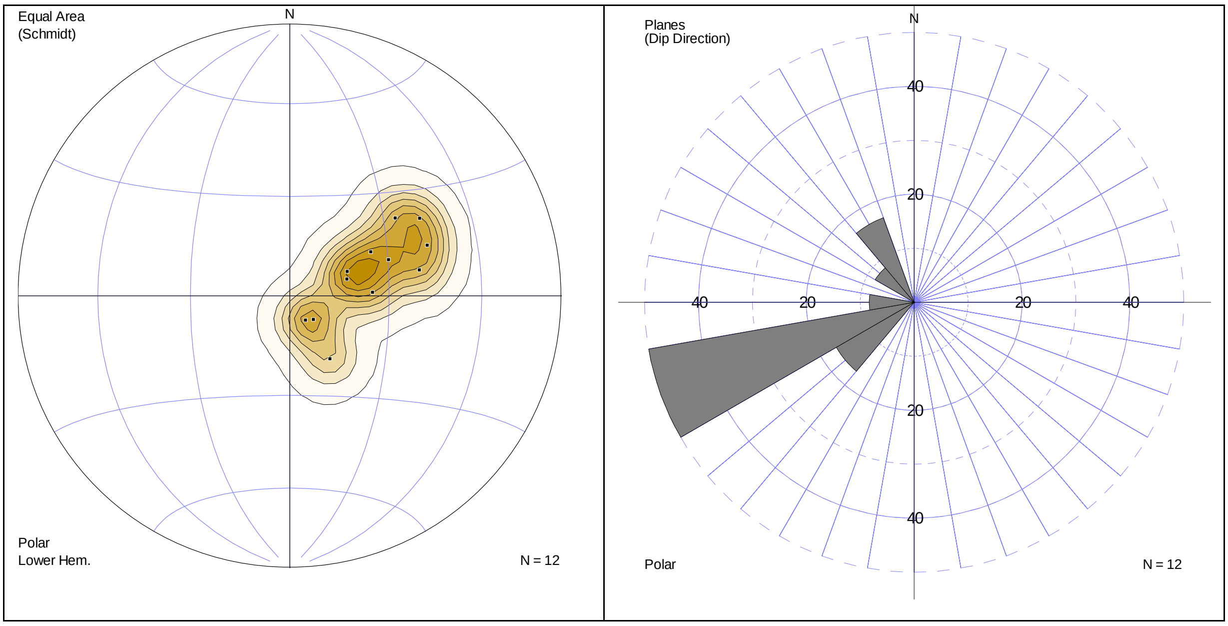


Figure 22: Borehole 184MT004 on the farm Nakab, Madzaringwe sandstone channel, cross-bedding measurements indicating a WSW transport direction. The measurements were made from the ATV log.

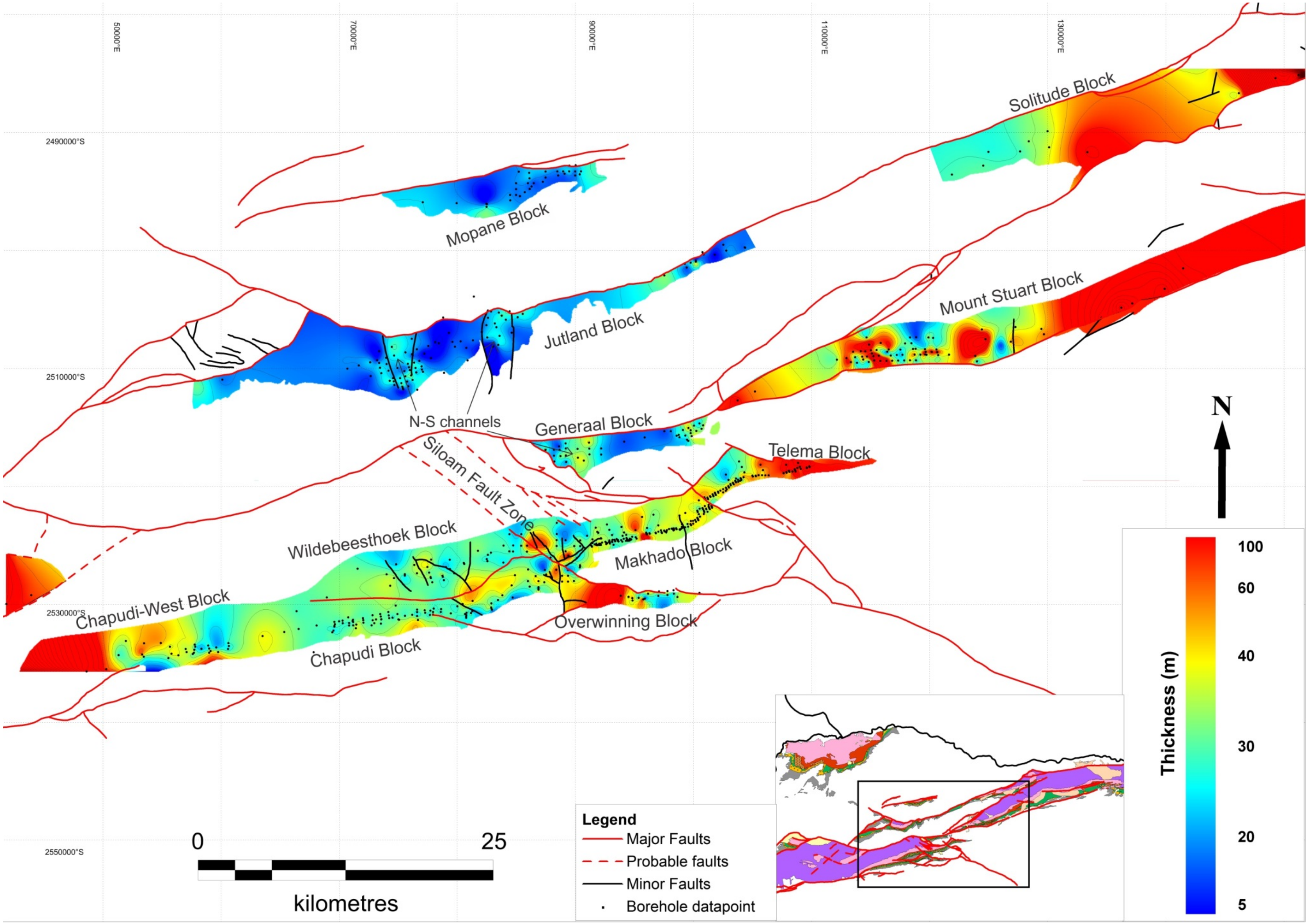


Figure 23: Isopach map of the thickness of the Madzaringwe Formation, coal bearing package.

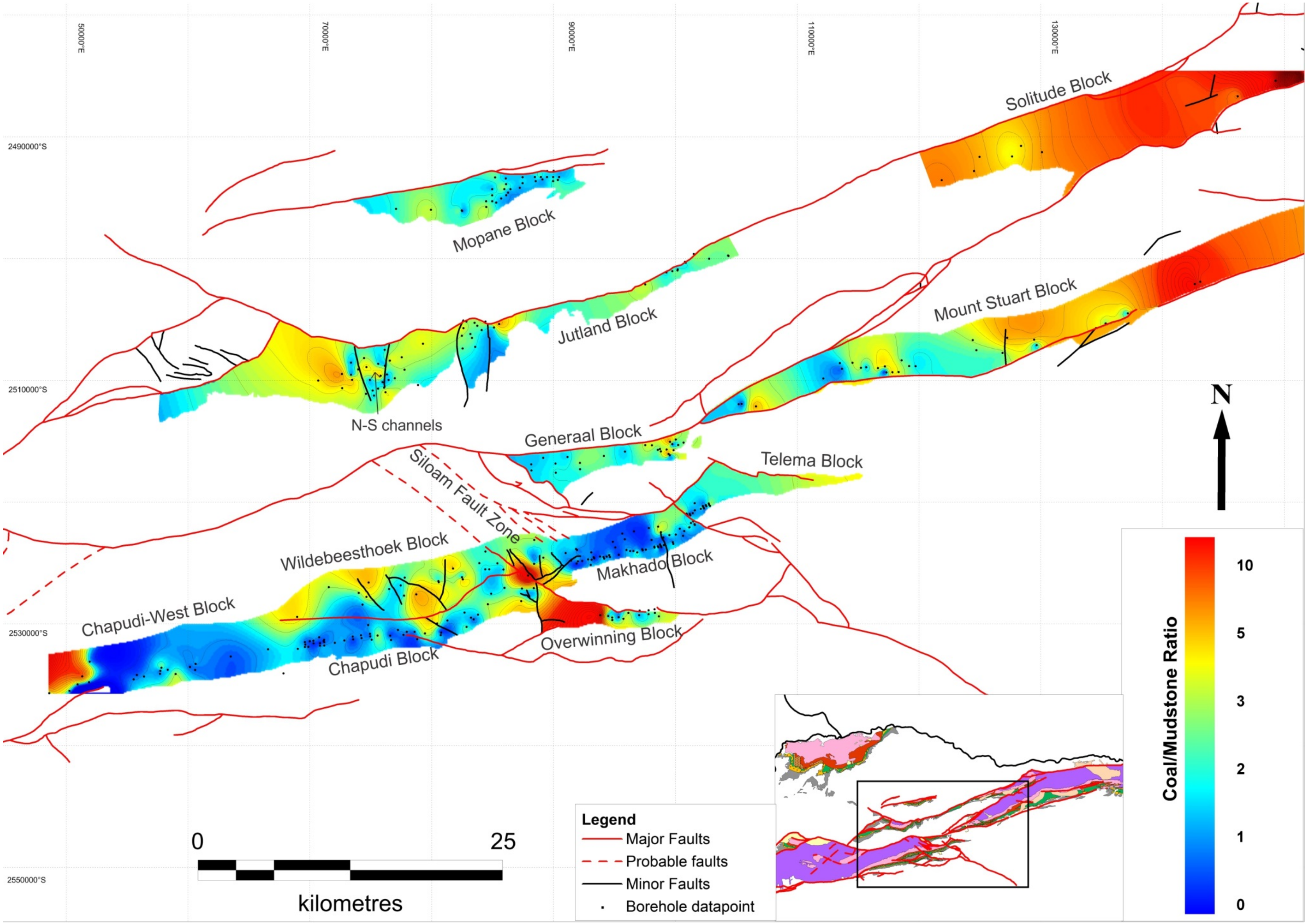


Figure 24: Coal/Mudstone ratio of the Seam 6 in the Madzaringwe Formation

3.3.3. Mikabeni Formation

This formation occurs above the Madzaringwe Formation and consists mostly of massive light grey mudstone, black carbonaceous mudstone and minor sandy layers. Thin laminae and minor coal horizons are scattered throughout the succession (Brandl, 1981), and are very often poorly-developed (McCourt & Brandl, 1980). These beds were apparently formed in a shallow-water, lacustrine environment (MacRae, 1988).

Many authors do not make a distinction between the Madzaringwe and Mikabeni Formations and rather classify them under one unit (part of a larger megacycle capped by the Fripp Formation). This is understandable as Brandl (1980) came up with a stratigraphic sub-division based largely on data accumulated in the east of the basin, near Pafuri. Although these units can roughly be correlated across the basin towards the west, it has been stated by Van Der Berg (1980), Broadbent (2005) and Bordy (2006) that this subdivision may not be appropriate.

3.3.4. Fripp Formation

This stratigraphic unit forms a long narrow outcrop pattern, has a remarkable along strike continuity from east to west, and is considered to be a basin wide marker unit (Van Der Berg, 1980; Broadbent, 2005; Bordy, 2006). Based on regional observations by Visser (1984) and Bordy and Catuneanu (2004) this unit is not only recorded in this basin, but is also well-developed in all the northern Karoo basins. This unit shows a strong lithological and stratigraphic resemblance to the Middle Unit in the neighbouring Tuli Basin (Bordy, 2000).

It consists of mostly white, fine-grained to very coarse-grained, trough cross-bedded, gritty to pebbly sandstone that is very feldspathic (Van Der Berg, 1980; Bordy, 2006). This unit is defined by a very sharp basal contact and transitional upper contact with fine-grained sandstone, siltstone and mudstone occurring to a lesser degree towards the top of the unit (Van Der Berg, 1980). Thin coal layers have also been identified in a small number of boreholes. In one locality west of Tshikondeni the presence of coarse talus and boulder conglomerates (1m in diameter) have been recorded (Broadbent, 2005).

The thickness of the unit varies between 5m and 110m and overall the thickest accumulation is within the southernmost Makhado Block, on the farm Fripp (Fig 31). The isopach map shows an overall decrease in thickness from east to west in the Makhado Block; however within the Siloam Fault zone (Refer to section 7.4) and the easternmost edge of the Makhado Block (on the farm Telema), its thickness is significantly less. The Fripp thickness within the Mount Stuart block is highly variable over relatively short distances. In the northern blocks the unit is much thinner, with an average thickness of between 5-10m, compared to 60-100m within the Makhado block. Similar to the underlying Tshidzi and Madzaringwe Formation, the Fripp appears to be thicker in a number of narrow N-S zones relative to the rest of the block. This might suggest that these N-S faults controlled the thickness and facies variations of the Tshidzi, Madzaringwe and Fripp formations and led to increased subsidence in these areas.

The unit contains various fossils in the form of worm burrows (Skolithos), as horizontal and particularly vertical tubes which form white circular structures on a weathered surface (Fig 28) (Van Der Berg, 1980). Plant stem imprints also occur commonly within the sandstone whereas in the siltstone- and mudstone-rich units, Dicroidium imprints were found (Van Der Berg, 1980: p.51).

3.3.4.1. Facies description, thickness distribution and depositional Environment

An important characteristic of these sandstones is its trough cross-bedded nature (Fig 27) with troughs being 1.5m wide and 0.5m deep while the predominant direction is from E-W, ESE- WNW and NE-SW (Van Der Berg, 1980; Brandl, 1981). Soft sedimentary deformation structures in the form of dewatering structures are common and suggest that it was deposited rapidly. Rip-up clasts of this sandstone unit are also common at certain stratigraphic horizons (Fig 29).

The collective characteristics of this unit (sedimentary structures, coarse grain size and lateral continuity) suggest that it was deposited in a high energy, perennial gravel bed and braided fluvial environment (Van Der Berg 1980; Bordy 2006). Bordy (2006) indicates that the regionally determined palaeo-flow directions (NW) are perpendicular to those of the underlying coal bearing units which are parallel to the overall Limpopo trend (ENE-WSW). It is suggested that a major event of active tectonic uplift occurred in the SE to create a topographic gradient dipping to from the SE to NW (Broadbent, 2005; Bordy, 2006). The palaeo-current measurements in the east of the study area show a unimodal transport direction consistently towards the NW (Fig 30). However further west, they tend to deviate towards the W and SW, especially within the Siloam Fault Zone in the Makhado Block. On the farm Jazz (715), within the small wedge of Karoo in the SE of the Makhado Block, the transport direction is roughly towards the North. The pre-Fripp tectonic event could have created localised basin relief from differential movement of the individual blocks (Broadbent, 2005). The differential block movement appear to be more apparent in the southern and central part of the Tshipise basin (Fig 30).

In some localities, on the farm Delft (499) on the Sand River, the Fripp sandstone onlaps directly onto the pre-Karoo basement which suggests a significant palaeo-relief equivalent to the underlying formations or the event led to the erosion of the underlying Ecca and Dwyka units (Van Der Berg, 1980; Broadbent, 2005; Bordy, 2006).

Taking into account the Permian *Glossopteris* flora of the underlying Madzaringwe Formation and the apparent Triassic *Dicroidium* flora of the Fripp Formation it is very likely that the erosive basal contact of the Fripp is a major unconformity (Bordy, 2006).

Figure 25: Grit lenses and interbedded coarse-grained sandstone in the Fripp Formation.

Figure 26: Erosive surface with coarse grained conglomerates grading to mudstone and thin coal seams in the upper parts of the Fripp Formation.

Figure 27: Cross-bedding within the coarse grained pebbly sandstone of the Fripp Formation.

Figure 28: Vertical fossil worm burrows (Skolithos) within the Fripp Formation.

Figure 29: Rip-up clasts of coarse-grained sandstone within the Fripp Formation.

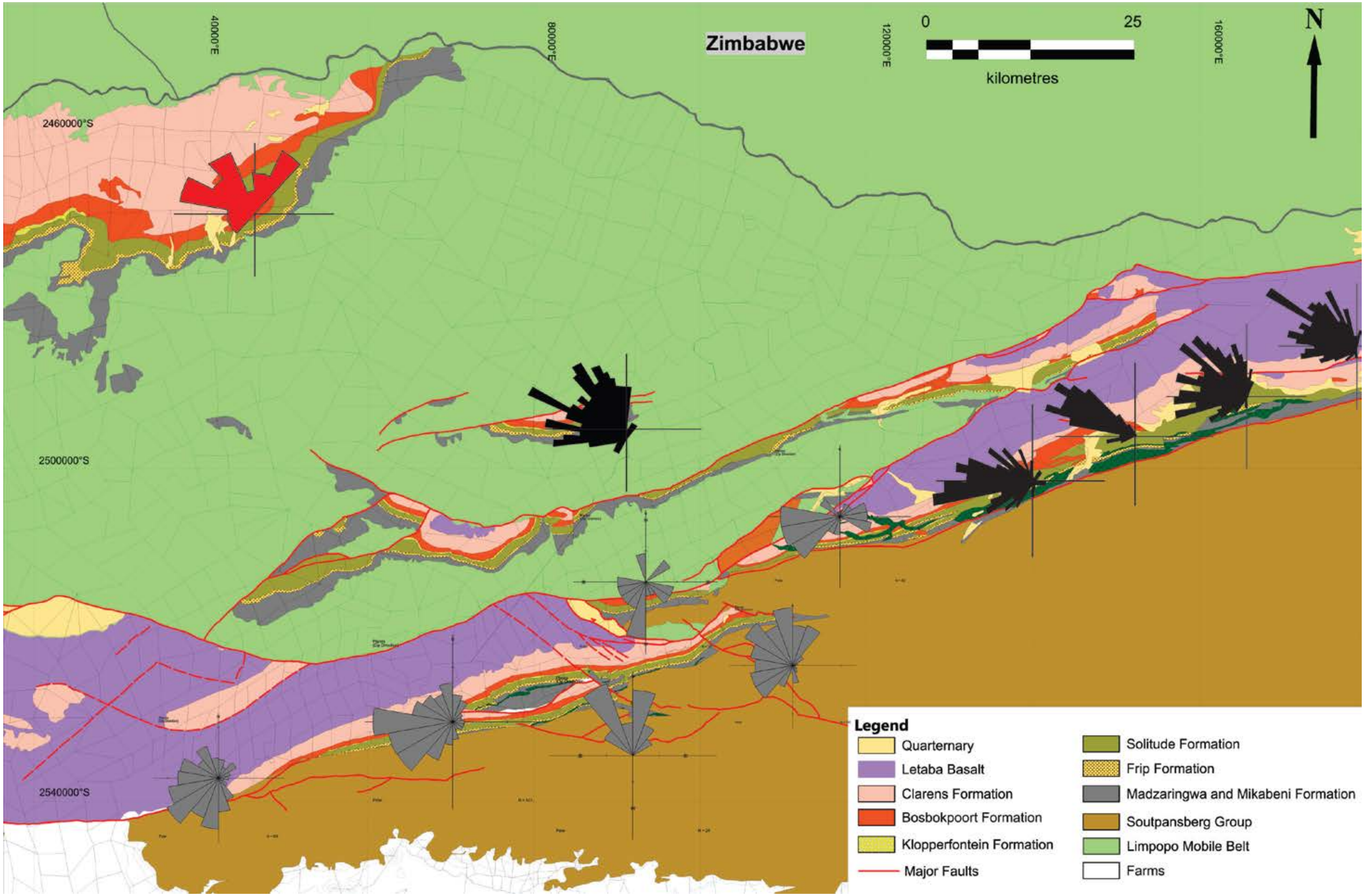


Figure 30: Palaeocurrent directions of the Fripp Formation from the ATV surveys (in grey). Stereograms in black are from Van Der Berg (1984) and the red stereogram in the Tuli Block is from Bordy (2000).

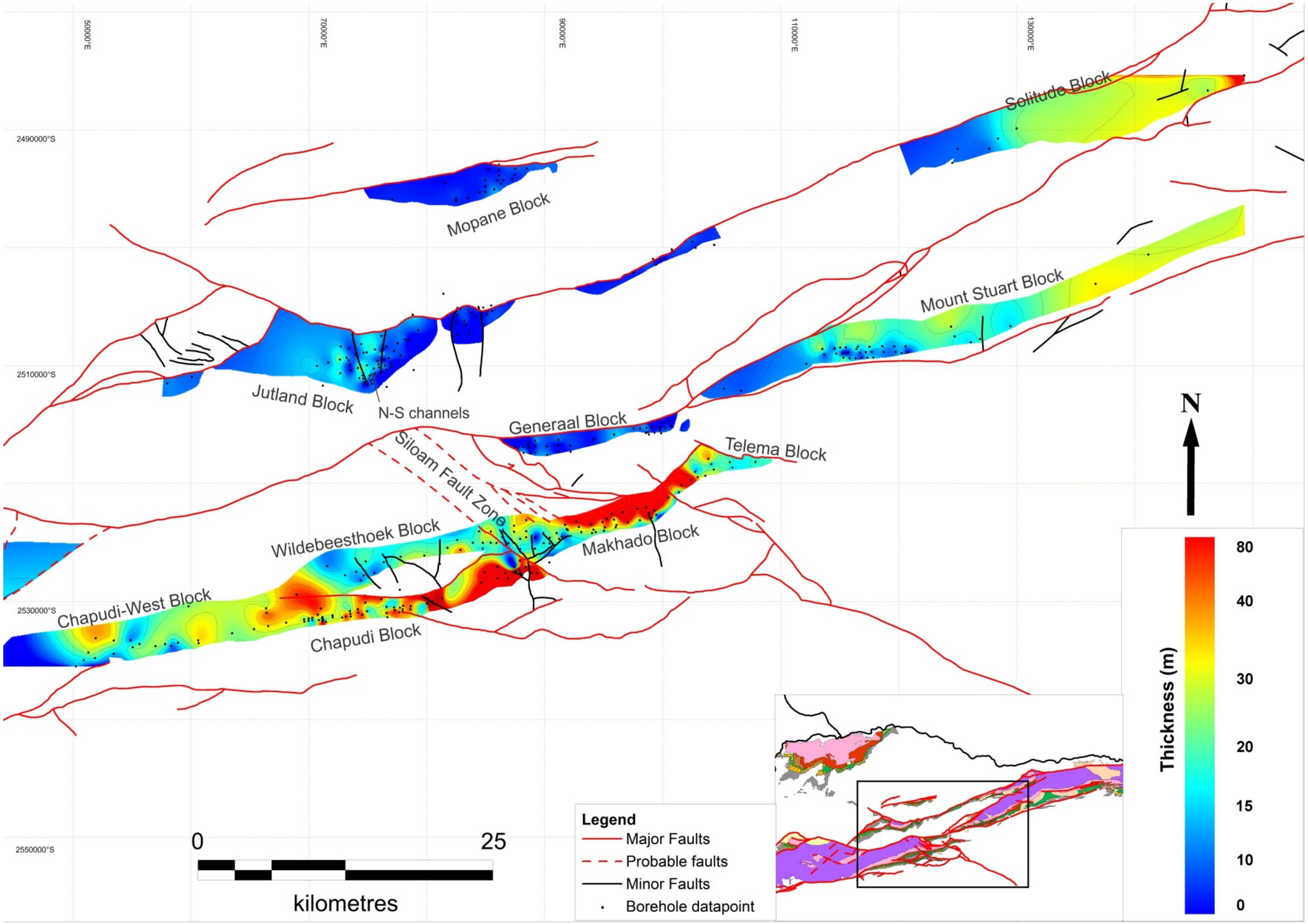


Figure 31: Isopach map of the Fripp Formation.

3.3.5. Solitude Formation

This formation is dominated by thinly-bedded purple, red and greyish coloured mottled micaceous mudstones (Fig 32–34) that are separated by thin-bedded, fine-grained, mature quartz sandstone and often contain coarse-grained units of sandstone and conglomerate (Van Der Berg, 1980; Broadbent, 2005). The mudstone at the base of the unit is dominated by purple to grey stained strata which gradually disappears towards the top and becomes redder in colour. Various carbonate (siderite) concretions which range from less than 1cm to 5cm are common mostly in the red mudstone higher up in the sequence (Fig 33). The siltstones facies consist of interbedded layers and lenses of siltstone and sandstone. These siltstones are often green in colour as a result of high percentages of the chlorite present within the matrix and can range in thickness from between 30cm to 10m in thickness (Van Der Berg, 1980). The sandstones range from fine to coarse-grained where the fine- and medium-grained types are either green or red in colour with layers reaching a thickness of 6m. The coarse-grained sandstone vary in colour from purple to green and green-grey and consist predominantly of quartz, feldspar and granite fragments (Van Der Berg, 1980). Erosive mudstone fragments are also associated with the coarser-grained sandstone and grit layers and normally associated with purple to grey-green coloured clay rich matrix. Conglomerates vary in character and are in general more abundant towards the top of a unit with thicknesses varying from 2cm to 35 cm.

The mudstones are normally massive but do in some instances contain parallel bedding. The medium to coarse-grained sandstone units do show crossbedding with cross-bed angles alternating between 10°and 30° and thicknesses between 3cm and 35cm (Van Der Berg, 1980). The medium to fine-grained sandstone units do contain parallel and ripple-cross laminations depending on the grain size with ripple-cross laminations occurring more in the coarse-grained units.

The formation is generally dominated by mudstones and rarely outcrops in the study area however it does weather to form a recessive topography and is often characterised at outcrop by reddish sandy soils and lag of angular blocky to flaggy sandstone. In the western part of the basin the unit only outcrops in selected riverbeds and excavations; however towards the east there is an increase of exposure with several sandstone horizons outcropping in the far eastern side of the basin. The sandstones contain bedding ranging from planar to low-angle hummocky –cross stratified to occasionally convolute beds with sediment injection structures (Broadbent, 2005). The base of the formation is at the first occurrence of the greenish sandstone or siltstone and can either be sharp or gradational (Van Der Berg, 1980). The upper contact is gradational and consists of upward-fining cyclical units of mud and fine to medium- grained sandstone with a gradual decrease in the argillaceous facies until it ultimately disappears (Van Der Berg, 1980). The argillaceous units are in most instances heavily bioturbated. Bioturbation is present throughout the entire zone and layers are often so disturbed that the original bedding cannot be identified. Various vertical and horizontal burrowing cylinders (Skolithos) have been identified and range from several millimetres to 1cm in width (Van Der Berg, 1980).

3.3.5.1. Facies Description

This unit consists of a range of vertical cycles with the most predominant being upward-fining and consisting mostly out of mudstone. The limited outcrop and borehole information makes it difficult to accurately determine any facies changes however Van Der Berg (1980) did notice that in the west, the unit is dominated more by mudstone rich facies whereas in the east, relatively thick coarse-grained argillaceous units are seen, especially towards the top of the succession. A limited number of palaeo-current direction measurements indicate a transport direction from the SE towards the NW (Van Der Berg, 1980). The formation possibly represents an abrupt tectonically forced drowning of the basin from the fluvially levelled unconformity of the Fripp sandstone (Broadbent, 2005).


Figure 32: Purple mudstone of the Solitude formation

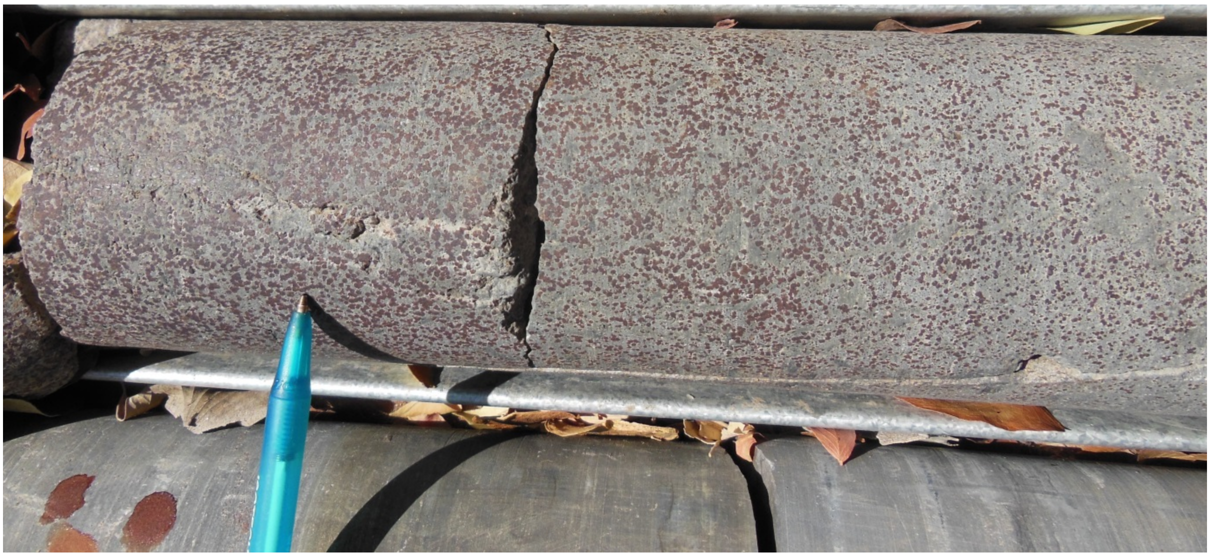


Figure 33: Small siderite nodules in the grey mudstone of the Solitude Formation

Figure 34: Mottled red and grey mudstone of the Solitude Formation

3.3.6. Klopperfontein Formation

This unit has been interpreted as the basal unit of the Elliot Formation and is the basal sequence to the Bosbokpoort Formation shale and sandstone package. Where seen, the Klopperfontein resembles the Fripp sandstone in terms of grain size, mineralogy and lithofacies types (Broadbent, 2005). The unit consists of trough cross-bedded gritty sandstone with sporadic quartz pebble lags at the bottom of the troughs. These pebbles are between 1 and 2 cm and are well-rounded. Palaeocurrent measurements are very scant and only one was measured by Broadbent (2006) which was to 080 degrees, which is in complete opposite to the dominant trend in the Fripp and Madzaringwe.

3.3.6.1. Facies Description

The unit appears to be thickest in the eastern part of the basin near Tshikondeni where it was initially described by McCourt and Brandl (1980) while in the west and south-west it is much more discontinuous. The unit passes unconformably upwards into the terrestrial sediments of the Bosbokpoort Formation. Without proper context, this unit and the Fripp Formation could be hard to distinguish. Broadbent (2006) mentioned that at ~240Ma there is a massive geodynamic change in the motion of Gondwana from north-westerly to westerly that in the context of the limited palaeo-current measurements marks a major change in basin dynamics.

3.3.7. Bosbokpoort Formation

This formation is correlated to the Elliot Formation (Redbeds) of the main Karoo basin. The unit consists of thinly-bedded fluvial mudstones and minor sandstone and mud-pebble breccias developed by the reworking of underlying mud units (Brandl, 1981; Broadbent, 2005).

The sandstones are poorly bedded and rich in clay and contain cross-bedding. At the base of the formation, the mudstones are purple and grey that becomes redder in colour towards the top. This change in colour is also associated with an increase in the occurrence of carbonate concretions (Van Der Berg, 1980). The siltstones are normally green in colour as a result of the high concentrations of chlorite in the matrix while the coarser material is much lighter in colour. These range from between 30cm and 10m in thickness and are generally massive as a result of bioturbation. The sandstones range from fine to coarse-grained where the fine to medium-grained units are green and red in colour, depending on the matrix material and can form beds up to 6m thick. The coarse-grained sandstone is purple to green to grey-green in colour and consists predominantly of quartz and feldspar fragments (Fig 35) (Van Der Berg, 1980). These sandstones are very often impure with a matrix ranging from grey, purple or green. Various conglomerate and grit layers are present consisting of quartz, feldspar, granite fragments and mudstone breccias where the clasts are no larger than 2cm in diameter and range in thickness from a few cm to 35cm (Van Der Berg, 1980). Cross-bedding occurs in the medium to coarse-grained sandstone with thicknesses between 3 and 35cm and bedding inclinations of between 10° and 30°. Parallel bedding and ripple-cross laminations occur in the fine to medium-grained sandstone. These sandstones can often appear massive, a sign of intense bioturbation. Ball and pillow structures are often present within the mudstone layers below a sandstone unit. Desiccation cracks filled with sandy to clayey material often occur in the mudstone layers and in certain instances in the siltstone (Van Der Berg, 1980).

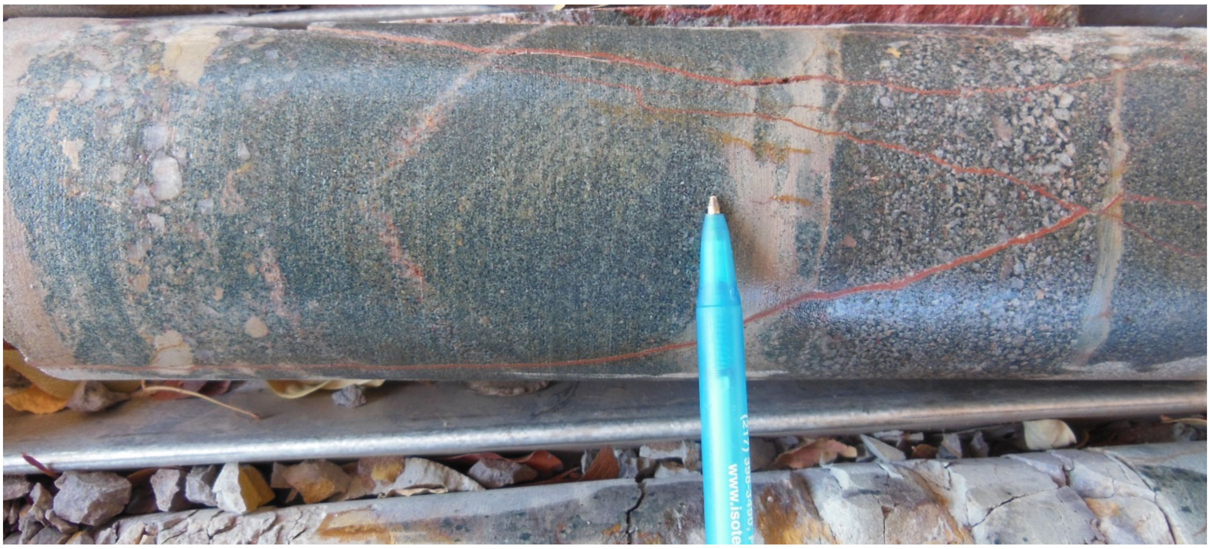


Figure 35: Green coloured medium to coarse-grained sandstone of the Bosbokpoort Formation

3.3.7.1. Facies Description

This formation consists mostly of a number of upward fining vertical cycles that range in thickness from 30 to 70 cm where the thick cycles consist predominantly of mudstone. Bioturbation is very common throughout the entire zone but does tend to increase towards the top of the siltstone unit and in many cases individual vertical and horizontal burrowing cylinders (Skolithos) can be identified (Van Der Berg, 1980).

The mudstone units contain pedogenic regolith textures, especially near the top of the formation and are considered to be a genuine red-bed sequence deposited in a semi-arid terrestrial environment, starved from major sediment input and low water inflow for an extended period of time Fig 36) (Broadbent, 2005). It is thought that the unit might represent a series of unconformity-bound sequences which developed gradually in response to tectonic uplift and structuring of the underlying units. This would have led to re-working and cannibalizing of the underlying sediments and filling of the already flat topography (Broadbent, 2005). This could explain the rather thin (80-100 meters) thickness of this unit which stretched across a timespan of approximately 30Ma.

Figure 36: Reduction root marks in the red mudstone of the Bosbokpoort Formation.

Figure 37: Massive rusty red mudstone of the Bosbokpoort Formation. This mudstone contains small quartz grains distributed in the matrix as well as purple coloured rootlets.

3.3.8. Clarens Formation

This formation is one of the most widely recognised units of the Karoo Sequence in this area and outcrops frequently to form long narrow hills that stretch across the majority of the basin (Fig 38 and 62). This unit has a thickness of approximately 120m and appears to be appreciably thicker and containing larger cross-bed sets in the east of the basin from the farm Nakab to Tshikondeni (Broadbent, 2005). This unit has been subdivided into the Tshipise Sandstone Member and the Red Rocks Member (Brandl, 1981). In some areas the Red Rocks Member is often completely absent.

This Red Rocks Member consists of fine- to very fine-grained, light red, argillaceous sandstone with irregular patches or layers of cream-coloured sandstone, whereas the Tshipise Member above it consists mostly of cream-coloured fine-grained sandstone (Johnson, et al., 2006).

This Formation lies on top of the Bosbokpoort Formation with a basal contact that ranges from sharp to gradational and as a result of bioturbation this contact is not always very clear. Van Den Berg (1984) noticed that the basal contact of the unit is almost always located at the base of the sandstone cliffs. Bioturbation is very common in the base of the unit where primary structures have been mostly destroyed (Fig 39).

The upper contact of the Formation is taken to be the base of the basalt which marks the end of sedimentation. In some cases the Clarens sandstone is locally interbedded with the basal basalt flows that suggest they overlapped in time (Van Der Berg, 1980, Broadbent, 2005).

3.3.8.1. Facies Description

Lithologically the unit consists of creamy coloured, medium-grained, well sorted, pure sandstone and often has a greenish colour at its base. The grains consist mostly of very-well rounded quartz with practically no matrix material present. These un-cemented grains are often easily detached from the surface to form a fine-grained powdery substance (Van Der Berg, 1980). Circular concretions ranging from less than a centimetre to several cm have been identified throughout and these tend to be more silicified than the surrounding lithology (Fig. 42). Large hollows tend to form in the sandstone that range in size from 1cm to several meters across and might be remnant weathering structures from the concretions (Fig 40).

The lower part of the Clarens Formation contains small to medium scaled cross-bedding ranging between 4 and 20cm thick and is often associated with parallel- and ripple-cross laminations (Van Der Berg, 1980), these are considered to be fluvial in origin (Johnson, et al., 2006). The majority of the facies observed the individual bed sets have thicknesses between 2 and 15m with very large plane-laminated moderate angle foresets (Fig 41). Irregular, intensely deformed bedding structures are relatively common in the upper parts of the zone and have been interpreted as possible flow-structures in the unconsolidated sands (Fig 43) (Van Der Berg, 1980).

The basal part of the unit contains minor upward-fining fluvial cycles, whereas higher up there are no such cycles present. The unit is fairly uniform across the basin with no major facies changes being recognised, except for local changes in thickness. The Clarens possibly represents a prograding aeolian dune-field environment across the more fluvially dominated environment with sediment transport being from NW to SE (Van Der Berg, 1980; Broadbent, 2005).

Figure 38: Clarens sandstone in the foreground and Bobbejaankop in the far upper left corner. Soutpansberg Mountains in the upper right hand corner.

Figure 39: Bioturbation in the Clarens sandstone

Figure 40: Hollows formed in the Clarens sandstone possibly from large concretions

Figure 41: Large scale cross- beds of the Clarens sandstone

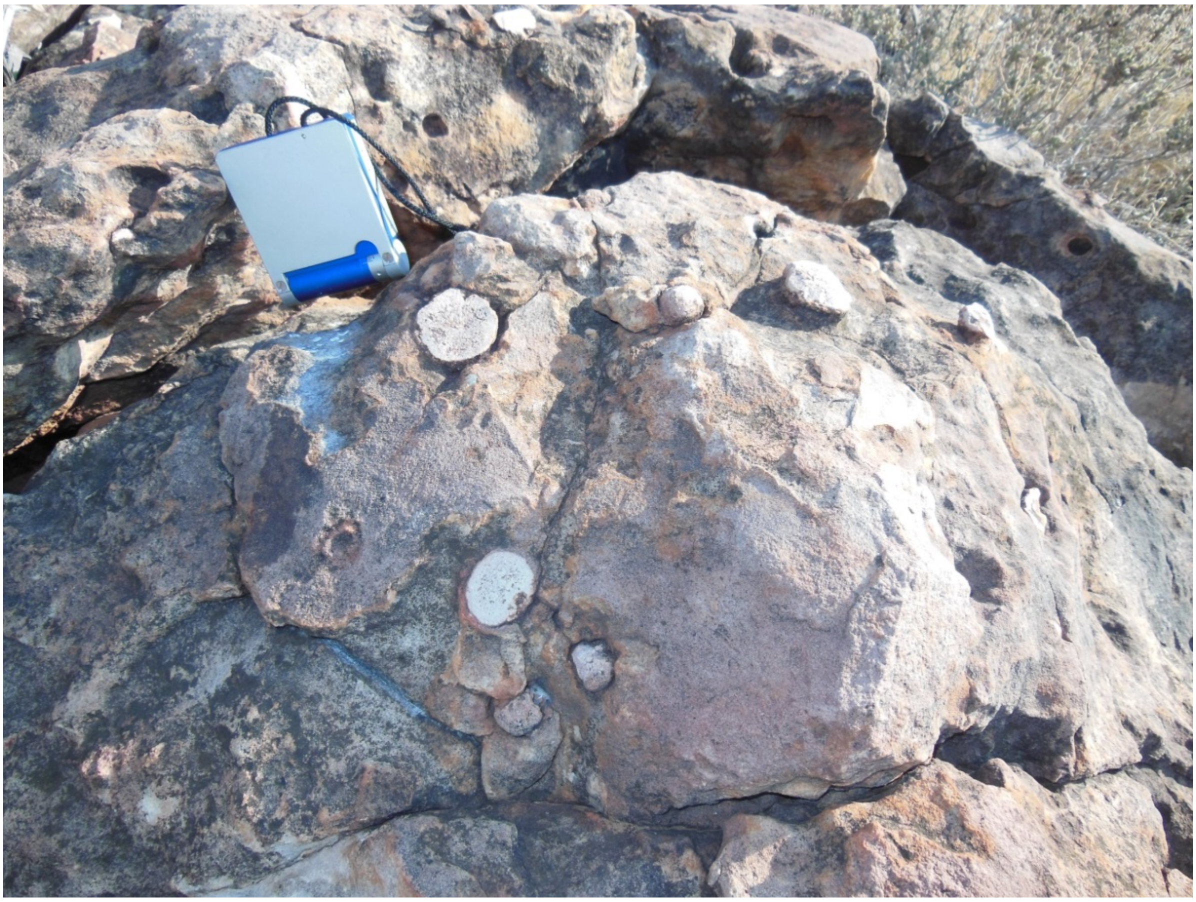


Figure 42: Circular silicified concretions in the Clarens sandstone

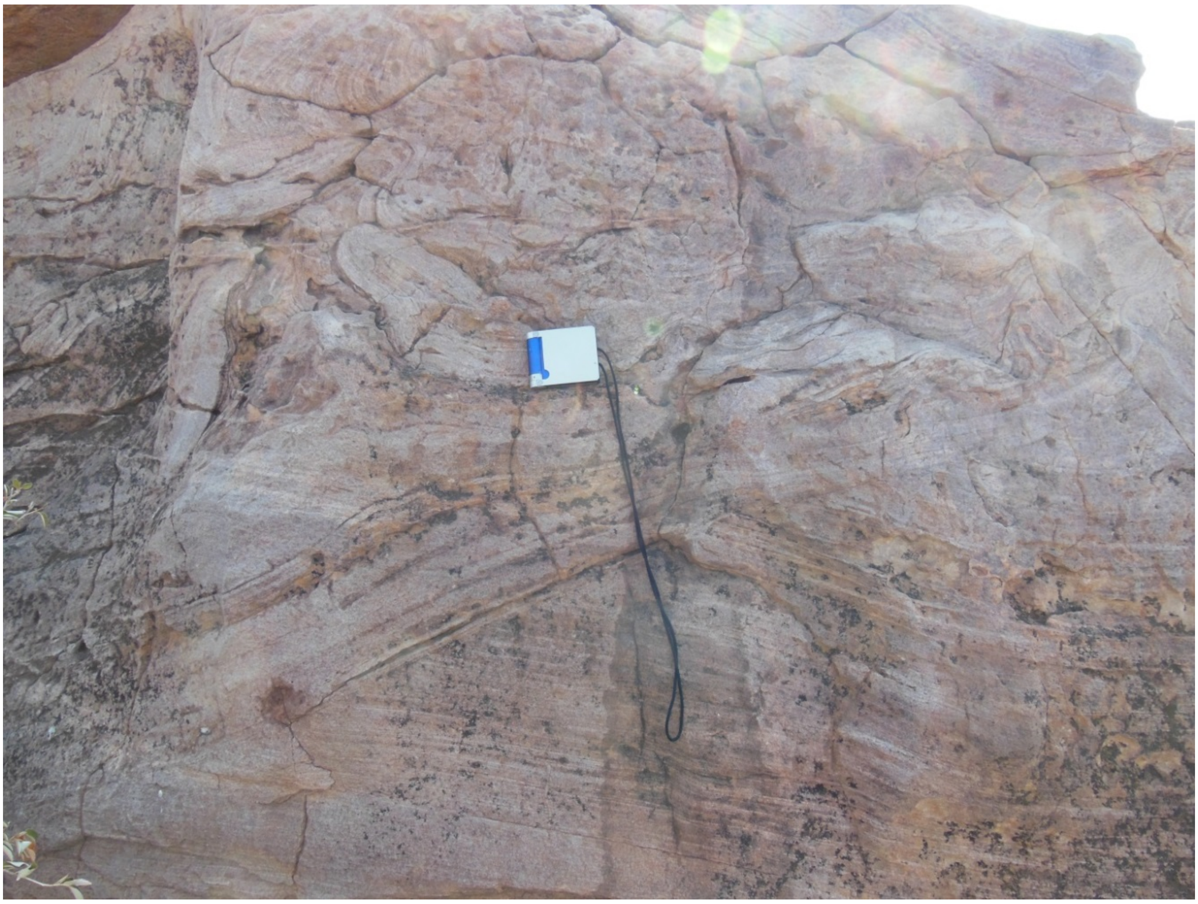


Figure 43: Irregular bedding in Clarens sandstone

3.3.9. Letaba Formation

The unit consists of a thick, stacked sequence of amygdaloidal lava flows that heralded the end of sedimentation of the Karoo Supergroup. The basal contact is sharp against the Clarens sandstone, however Du Toit (1966) and Van Der Berg (1980) points out that in some instances the sandstone units sticks out through the basalt and that topography of the floor was probably irregular.

The Letaba Formation is also associated to a large degree with numerous dolerite dykes and sills ranging in thickness, orientation and position within the stratigraphic sequence. This topic is discussed in more detail in section**Error! Reference source not found.**.

4. Neighbouring Karoo Basins

North of the main Karoo Basin, the Karoo aged basins have been preserved in a number of isolated, fault bounded grabens which have been interpreted either as rift basins or intracratonic sag basins (Rust, 1975; Watkeys and Sweeney, 1988; Groenewald et al., 1991; Johnson et al., 1996). Unfortunately it is not known to what extent these basins were connected prior to the breakup of Gondwana subsequent erosion (Visser, 1984; Johnson et al., 1996). These include the Springbok Flats, Waterberg (Ellisras), Tuli, Tshipise, Nuanetsi and Lebombo Karoo Basins (Fig 44).

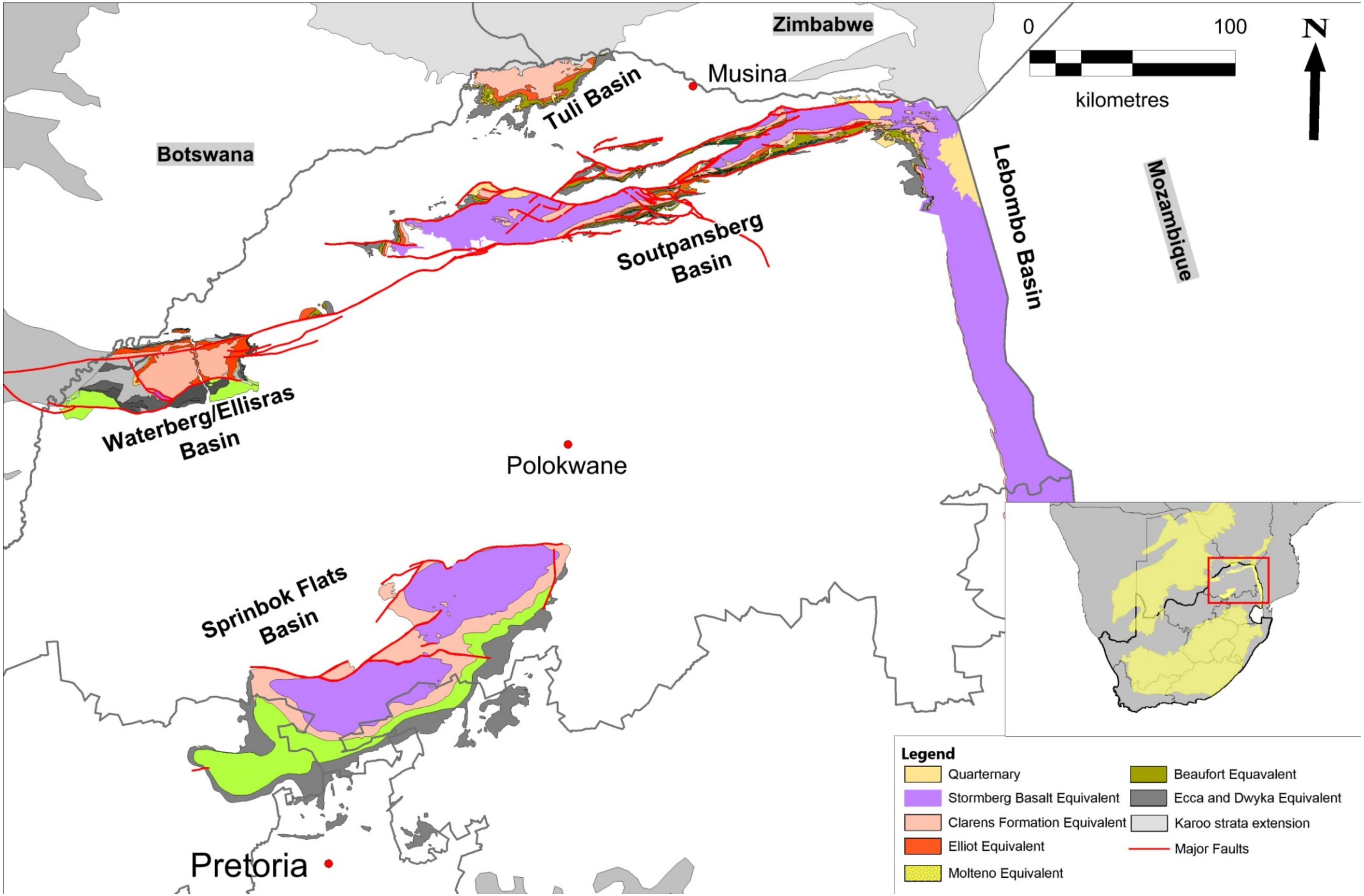


Figure 44: Location and outlines of the Limpopo Karoo Basins

4.1. Mopane Basin

The Mopane sub-basin forms part of the Soutpansberg Karoo basin and lies west of the Tshipise basin between the towns of Tolwe, Waterpoort, Alldays and Vivo (Fig 2 and 13). It has been separated from the other sub basins based mainly on lithofacies variations, especially in the lower Karoo. In general the coal measures are much thinner and occur more sporadic than in the Tshipise or Pafuri basins (Hancox & Götz, 2014). Some coal exploration work has been conducted but coal seams were found to be less than 1m in thickness. The majority of the basin is quite deep with basement lying between 200 and 700m below surface. Most of the basin is covered by the Letaba basalts with limited outcrop of the sediments occurring the in far west and north. Recent aeromagnetic surveys and subsequent drilling results have indicated that a swath of ENE - WSW trending dykes, probably associated with the ODS, that cut across the basin. Large displacements are associated with some of these dykes that have up-faulted the Clarens sandstones in the middle of the basin.

4.2. Pafuri Basin

The Pafuri basin is the easternmost extension of the Soutpansberg Karoo basin and is characterised by its highly faulted and structurally complex nature. Overall the Pafuri Basin contains a much thicker accumulation of sediments compared to the Tshipise Basin and also contains a higher proportion of arenaceous facies. This basin contains significant coal measures that are mined at the Tshikondeni colliery near the Kruger National park.

4.3. Springbok Flats Basin

This basin falls within the southern part of the Limpopo Province and consists of a northern and southern sub-basin bounded along their northern boundary by normal faults. The strata of the basin dip to the north at approximately 7-10°. In general, exposure is very poor and most information was obtained from boreholes drilled by the Geological Society and various mining companies. The basement of the coalfield is composed of granites and felsite of the Bushveld Igneous Province as well as metasedimentary rocks of the Transvaal Supergroup. The coal seams are also quite thin and also contain a large concentration of uranium in the upper most seams.

4.4. Waterberg (Ellisras) Basin

The Waterberg Basin is situated in the Limpopo Province between the town of Lephalale and the border between South Africa and Botswana, the Limpopo River. The basin is bounded in the north by the Zoetfontein fault and in the south by the Eenzaamheid fault. The NW-SE Daarby fault displaces the Karoo sequence and has up-faulted the lower coal bearing Grootegeluk formation, bringing it close to surface and making the area very suitable for shallow open cast mining.

This basin contains between 40 and 50% of the remaining coal resources in South Africa and is considered by many to be the last major coal resource in the country. This basin forms part of an easternmost embayment of the Kalahari Karoo Basin, which stretches from the Northern Cape through Botswana to the eastern part of Zimbabwe (Siepker, 1986). The Karoo sequences are generally covered by younger Kalahari Group sediments and provide for very limited exposure.

In the northern part, the basin is underlain by high grade metamorphic rocks of the Limpopo Mobile Belt, whereas in the east it is the Bushveld Complex which could have been a palaeo high during sedimentation. It is still unclear to what extent the current basin outline reflects the size of the original depository before faulting occurred.

4.5. Tuli Basin

The Tuli Basin is a large transfrontier Karoo basin that is situated in the northernmost part of the Limpopo Province, extending into Eastern Botswana and SE Zimbabwe. The outcrop of the Tuli Basin is separated from the Tshipise Basin by the highly deformed Messina Block, which could have acted as a constantly positive area during the accumulation of the Karoo strata (Cox et al., 1965; Bordy, 2000). Its northern boundary is marked by a major ENE trending fault which is continuous for about 100km. Overall the Karoo strata of the basin dips gently ($<5°$) towards the north.

During the accumulation of the Upper Unit and Clarens Formation, the Tuli Basin underwent significant tectonic movements, which led to the formation of its half-graben geometry.

4.6. Tectonic relationships of the Limpopo Karoo Basins

The Tshipise Basin together with the Tuli, Mopane, Pafuri and Waterberg Basins are all considered to have formed within an approximately ENE-WSW striking back-bulge basin in the Karoo foreland system (Bordy & Catuneanu, 2002). The main basis upon which they are classified as being part of the back-bulge basin setting is their distance away from the northern margin of the Cape Fold Belt and its relatively thin sedimentary sequence (Bordy, 2000). The orientation of the back-bulge basin is consistent with the E and NE to WSW palaeo-current measurements made within the Dwyka and lower Ecca Group equivalents of the Tshipise (Van Der Berg, 1980), Tuli (Bordy, 2000) and Ellisras basins (Faure et al., 1996).

Bordy (2000) suggested that the foreland system tectonics were replaced by incipient continental extension at, or just prior to the deposition of the Middle Unit of the Tuli Basin, equivalent to the Fripp Formation in the Tshipise Basin. The Fripp, Solitude, Klopperfontein, Bosbokpoort and Clarens formations represent syn-rift deposits that accumulated in the E-W trending rift system consisting of the Tshipise and Tuli basins (Bordy, 2000).

The Fripp Formation and the Middle Unit of the Tuli Basin both have similar palaeo-current directions which imply that they were deposited in the same depository (Bordy, 2000). However, in the central and eastern part of the Tshipise Basin the transport directions deviate more towards the WSW. This change in transport direction is ascribed to the localised changes in basin relief from differential movement of the individual blocks (Broadbent, 2005), especially within the Siloam Fault Zone in the Makhado block.

Bordy (2000) describes that by the time of the Upper Unit of the Tuli Basin (Klopperfontein and Bosbokpoort equivalent), intrabasin faulting led to the formation of separate E-W trending sub-basins (Tshipise and Tuli Basins), separated by the high grade metamorphic rocks of the Messina Block (Bordy, 2000). However, the Fripp sandstone rests directly on basement lithology, on the farm Delft in the northern most Mopane block. This suggests either that the separation of the sub-basins might have started to occur during or just after the initiation of the Fripp tectonic event, or that this large tectonic event led to the removal of some of the units below it.

During the deposition of the upper units the separate sub-basins would have existed and would have experienced drainage in broadly opposite directions: Tshipise Basin from the south and the Tuli Basin from the north (Bordy, 2000).

It is not fully known to what extent these basins were connected to the Ellisras Basin to the south-west but presence of an outlier containing almost the full Karoo sequence near the town of Baltimore, halfway between the Waterberg and Mopane sub-basin, promotes the notion that these Karoo depositories were possibly connected to some degree. There are also small isolated occurrences of lower Ecca formations between the Tuli and Tshipise basin, occurring along a possible extension of the Siloam Fault Zone (Fig 13).

After the extrusion of the Letaba Basalt, the onset of the Mwenezi Triple Junction and subsequent NW-SE directed rifting, associated with the initial break-up of Gondwana ensued. The extensional tectonics have been recognized throughout the area and are thought to be responsible for the intracontinental rifting within the Archean Limpopo Belt and led to the half-graben formation of the Tshipise and Tuli Basins (Cox, 1970; Burke & Dewey J F, 1973; Smith, 1984; Van Der Berg, 1980; Watkeys & Sweeney, 1988 and Bordy, 2000).

5. Coal Characteristics in the Tshipise Basin

The overall nature of the coal changes across the basin from a multi-seam, coal-mudstone dominated unit, approximately 40m thick in the West (Waterpoort area) that consist of several discrete seams, to an overall much thicker unit containing two individual seams in the east (Tshikondeni mine) (Hancox & Götz, 2014). The transition from multi-seam to discrete seams is very sudden and adjacent to the farm Gaandrik 162, with argillaceous rocks to the west and arenaceous units to the east (Hancox & Götz, 2014). The coal bands exhibit an overall increase in vitrinite content with depth (Broadbent, 2005).

The coal-bearing units are contained within the Madzaringwe and Mikabeni formations. The basal part of the Madzaringwe Formation consists of carbonaceous siltstone and mudstone, shaly coal and thin coal seams which are overlain by a succession of alternating coal, grey black siltstone and carbonaceous mudstone and very fine to medium-grained sandstone. Only the upper third of the Madzaringwe Formation contains prominent coal seams interlayered with carbonaceous mudstone (Malaza, 2013). The Mikabeni Formation is composed of medium to dark grey siltstone, minor carbonaceous mudstone and khaki-red to grey sandstone which contain thinly scattered and most often poorly-developed coal seams.

In the study area, Rio Tinto Pty (Ltd) came up with a coal seam nomenclature that is currently used by Coal of Africa Ltd. In this naming scheme there are two sets of coal horizons that can be identified, an upper set containing 4 coal seams (7, 6, 5 and 4) (Fig 45) and a lower set with 3 seams (3, 2, and 1)**Error! Reference source not found.**. These two sets of seams correlate with the two main seams present in the Tshikondeni mine in the Pafuri Basin, in the east. In the west of the basin (Chapudi and Makhado), the stratigraphy that hosts seams 4-7 has been set to correlate with the Volksrust Formation of the Main Karoo Basin, whereas in the east, the coal poor Mikabeni Formation is correlated to the Vryheid Formation (Broadbent, 2005).

Seams 7 and 6 occur in the upper part of the Madzaringwe Formation and are the best developed seams. Seam 6 is much thicker, ranging from 30m to 38m and is considered to be the main target for potential coal extraction. Seams 5 and 4 are much thinner than seams 7 and 6 and vary in thickness (1m to 5m) and quality, and are located in the immediate footwall of seam 6. Seams 1, 2 and 3 occur below these and are poorly-developed in the majority of the area and are often difficult to differentiate.

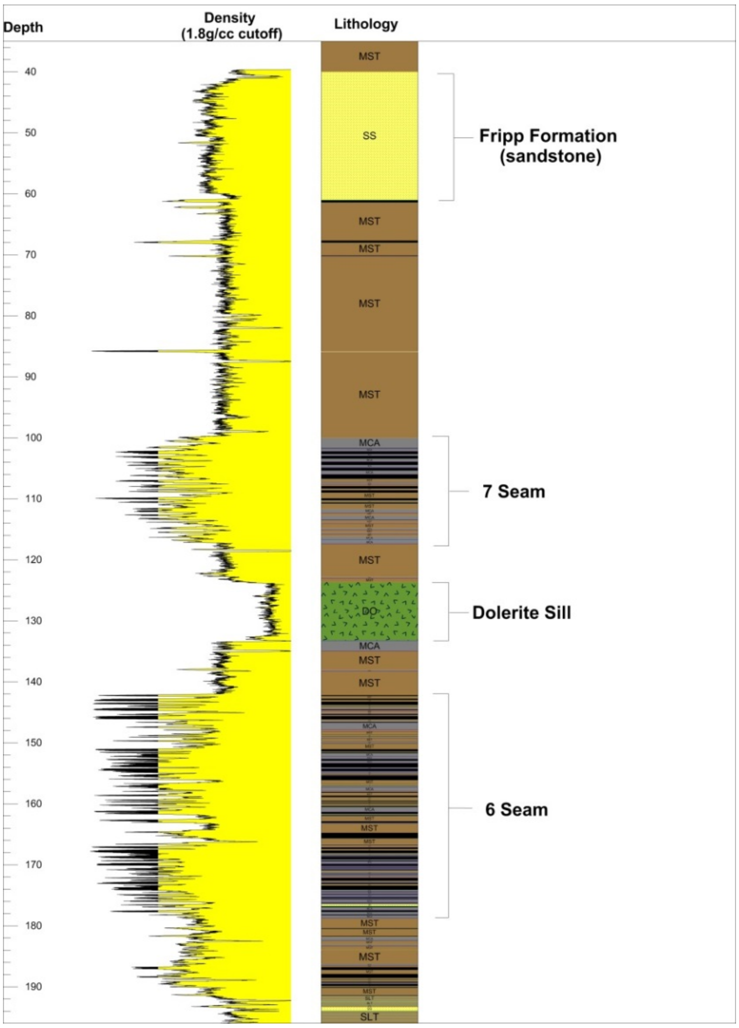


Figure 45: Wireline density comparison of seam 6 and seam 7 for borehole 649MS002 on the farm Windhoek (649)

5.1. Seam 7 (Fig 45)

Seam 7 is typically 12-15m in thickness and consists mostly of thin, poorly-developed coal seams interbedded with carbonaceous mudstone and is not economically viable in the most of the study area.

5.2. Seam 6 (Fig 45)

This seam is considered to be the most economic coal seam in the basin and as a result the vast majority of the boreholes were drilled to target this horizon. This means that the majority of the data obtained was from this seam and as a result it is the most studied and analysed of all. In general the seam contains an equal amount of coal and mudstone and has historically been the main target for coking coal. The coal can be classified as bituminous in rank with vitrinite reflectance ranging from 0.75% to 0.9% (Rio Tinto, 2007). The coal is very brittle and consists of 75% to 90% vitrinite, with liptinite, inertinite and mineral matter making up the remaining fraction of the clean coal composite (Rio Tinto, 2007). The upper coal measures show remarkable lateral continuity where the main coal seams can be traced over very large distances from either side of the basin. In general there is an up-section decrease in arenaceous facies which implies that during this time the area was increasingly protected from siliciclastic input from the surrounding fluvial environment (Bordy, 2006; Rio Tinto, 2007).

Six potential mining horizons have been identified by CoAL geologists in seam 6 and named as; Upper seam, Middle Seam, Middle lower seam, Bottom Upper seam, Bottom Upper seam, Bottom Middle seam and Bottom Lower seam (Venmyn, 2012).

5.3. Coal Rank

Coal rank refers to the degree of alteration (or metamorphism) that has occurred as coal matures from peat into different grades during the coalification process. The increase in metamorphic grade is normally as a result of an increase in burial pressure and heat over time. As the rank of coal increases, the percentage of carbon contained within it also increases, which translates to higher energy content (Thomas, 2002).

Vitrinite reflectance is a measure of the percentage of incident light reflected from the surface of vitrinite particles has been used as a tool for assessing the thermal maturity of basins and is used as a representation of coal rank. The reflectance is a function of temperature, pressure, time and type of macerals present, the effects of this on the organic macerals are not reversible and the reflectance data only marks the peak P-T regime experienced within the basin and not the timing of the event. Igneous intrusions and widely associated hydrothermal fluid pulses will affect the coal rank to a large degree, either on a localised and often regional scale (Thomas, 2002).

In the Greater Soutpansberg Basin there is a systematic increase in vitrinite reflectance from the west to the eastern part of the basin (Broadbent, 2005). There are however more complex reflectance patterns that emerge which tend to be localised around the large faults and in certain fault blocks. Reflectance values tend to increase rapidly east of the Siloam Fault Zone in an easterly direction towards Tshikondeni mine Fig 46 and 47). Broadbent (2005) also found a rapid gradient increase from west to east near the Siloam Fault Zone, which suggests that a higher palaeo-thermal gradient was associated with this structure. This increase in rank towards the east is similar to the trend observed across the rest of southern African coalfields to the south. This is a widely recognised characteristic that is associated with the increase in palaeo-thermal gradient around the east coast during the split up of Gondwana. Apart from the regional scale changes in coal rank, evidence from the borehole data suggest that reflectance values also vary with depth (Broadbent, 2005). According to Sullivan (1995) there is an increase in the rank of coal with increasing depth, however recent reflectance work conducted by Rio Tinto made it clear that a straightforward correlation with depth is not completely applicable. In a number of boreholes, profound thermal inconsistencies were recognised that were normally attributed to the proximity of dolerite sills. However dolerite sills were not intersected in all the boreholes that showed these anomalous reflectance values. Broadbent (2005) suggested that structurally or stratigraphically confined hydrothermal fluids are the only mechanism by which localised thermal variations can be produced. The microstructure of the kerogens shows intense variations over small distances which are undoubtedly associated with hydrothermal alteration (Broadbent, 2005). He further estimates that the Soutpansberg Basin may have experienced a geothermal gradient of between 60 and 80° per kilometre. Gradients like these are normally associated with shallow magma or the flux of large scaled hydrothermal fluids. The timing of this event is most likely related to the increased heat flow and intrusion of dolerite dykes and sills during the volcanism associated with the Karoo Igneous Province. Active faults, such as the Tshipise, Bosbokpoort and Siloam faults, could also have led to localised increases in thermal gradients through the fluxing of hydrothermal fluids into the surrounding lithologies (Broadbent, 2005).

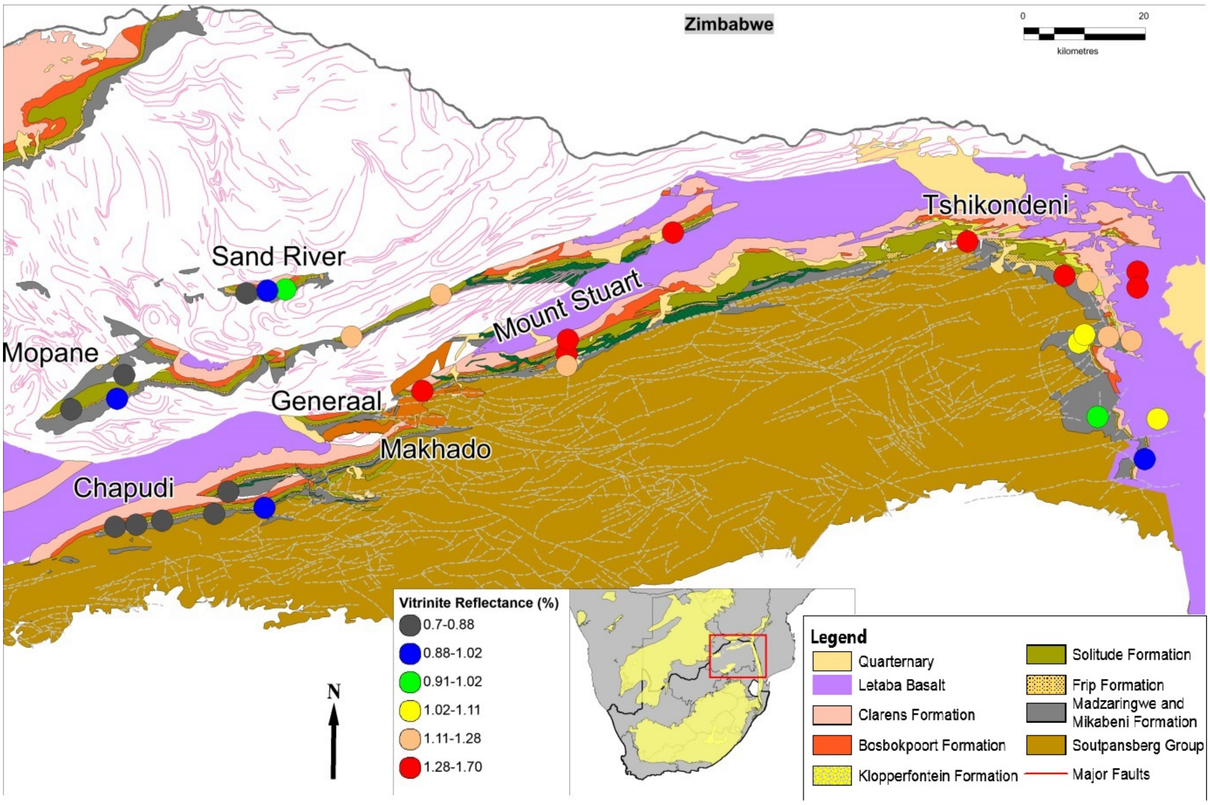


Figure 46: Regional distribution of vitrinite reflectance values of the coal samples (Modified after **(Broadbent, 2005)**

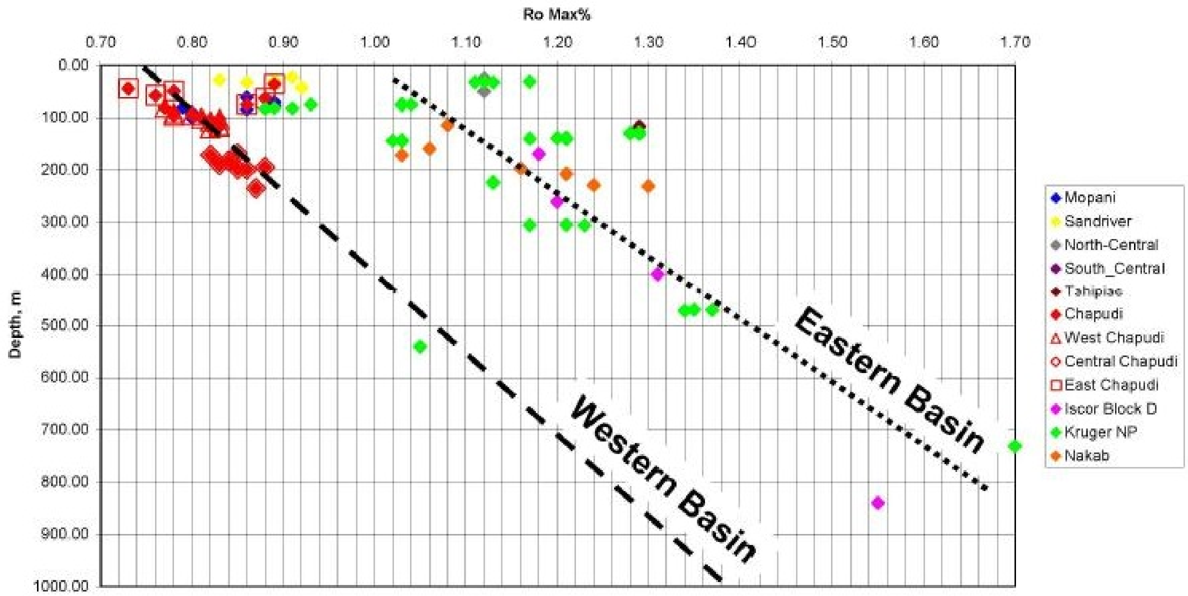


Figure 47: Vitrinite reflectance with depth of the western and eastern parts of the basin, from (Broadbent, 2005)

Figure 48: Thinly-laminated coal of the Madzaringwe Formation. Light brown siderite lenses are very common

Figure 49: Vitrinite rich coal of the Madzaringwe Formation. Coal cleats can also be seen.

6. Structural Evaluation from Airborne Geophysics

Apart from the fact that the area contains very little outcrop, the majority of the study area falls on private land, most of which are private game farms that are generally very difficult to gain access to. As a result of this the mining companies made extensive use of remote sensing surveys in the form aeromagnetic and radiometric surveys to help resolve the structural complexity of the study area. These surveys were made available to the author and are described on in this section.

During March 2008, high resolution low-level aeromagnetic and radiometric surveys were flown across a number of coal prospecting areas held by Coal of Africa (Ltd) within the Greater Soutpansberg Karoo Basin. The objectives of these surveys were to delineate the extent of the Karoo-age sediments as well as mapping the positions and extent of the Jurassic-aged dolerite dykes and sills, as well as possible faults. This high resolution imagery proved to be a very important tool in defining areas where intrusions could have potentially replaced or affect the target coal horizons.

6.1. Survey Details

The B3 survey was flown over an irregularly shaped block covering the Tanga, Generaal and the eastern portion of the Mt Stuart blocks and have dimensions of ~25km (W-E) and ~18km (N-S) covering an area of 290km^2. The survey was flown using a horizontal gradiometer magnetometer system and a 256 channel spectrometer system mounted to a B2 Eurocopter helicopter operating at airspeeds of 120km/h to 160km/h. The survey was flown at a height of between 15m and 25m with 50m flight line spacing and tie lines at a distance of 500m.

6.1.1. Aeromagnetic images and derivatives

From the magnetic data compiled, a number of derivative images were generated through data transforms and filtering routines all of which have their own applications for the geological interpretations (refer to appendix A). All of these derivatives were used in the interpretation process as each derivative appeared to enhance certain features in different rock units. The RTP VG2 image enhanced the foliation patterns within the Sibasa and Letaba Basalt and made it easier to identify its layering, as well as faults that have displaced this layering. The TMI was the only derivative image to indicate the positive and negative magnetic signatures in the Letaba Basalt on opposing sides of a fault in block 3. The horizontal gradient enhanced features covered by Karoo sediment such pre-Karoo basement dykes and post Karoo sills.

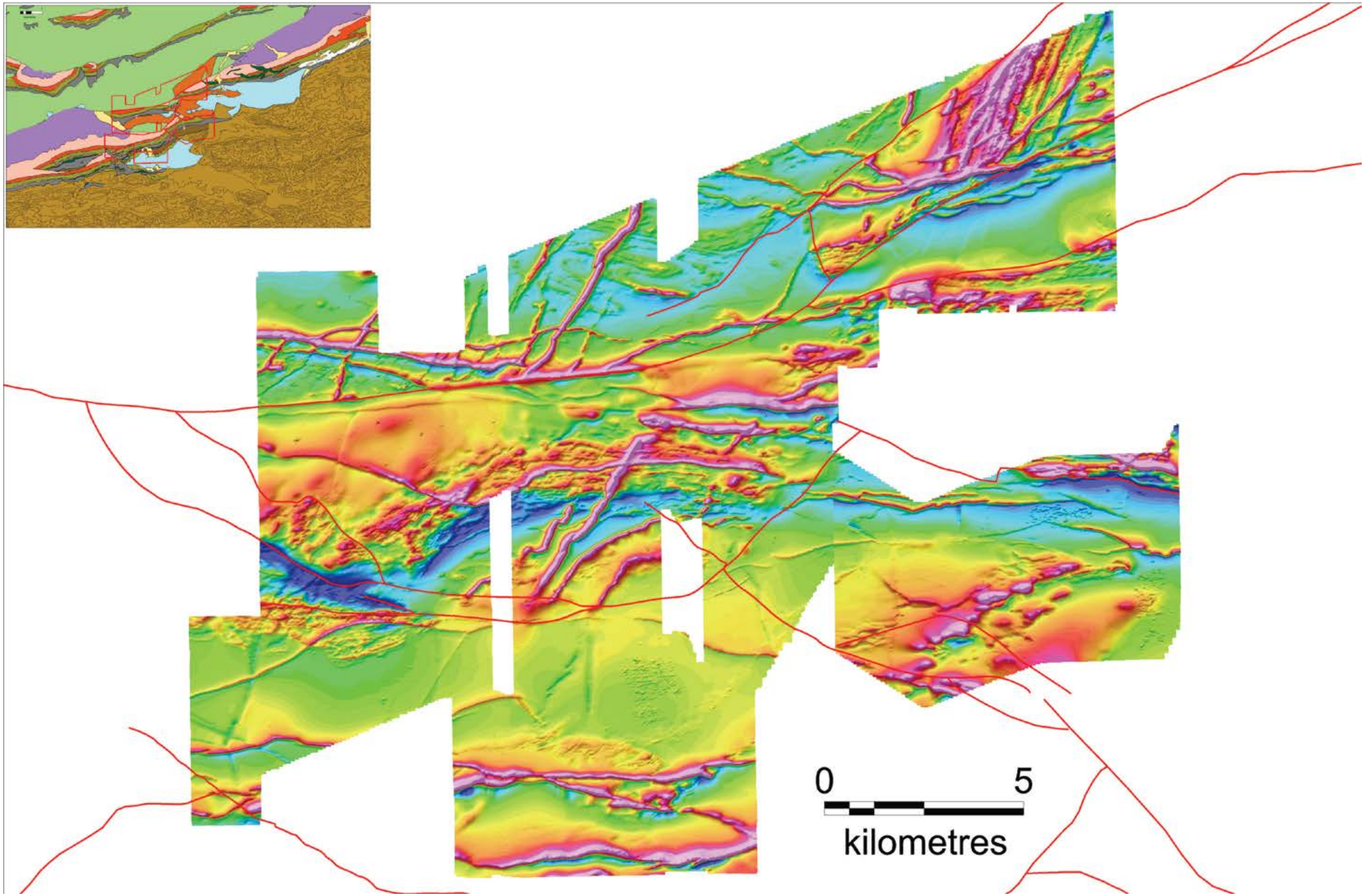


Figure 50: Total Magnetic Intensity (TMI) aeromagnetic image of the B3 block. The red lines indicate the major faults in the area.

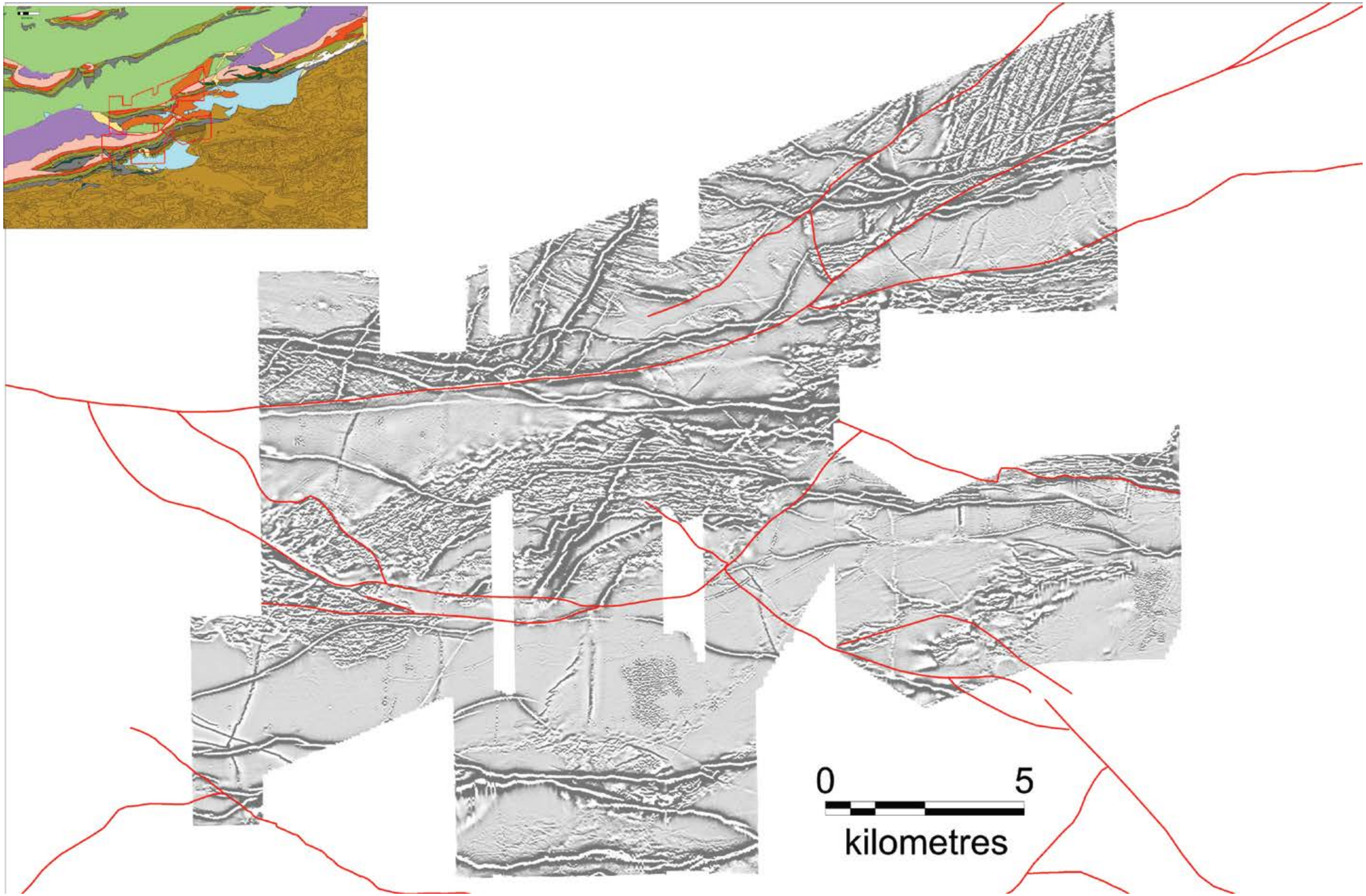


Figure 51: Vertical gradient transform of the B3 aeromagnetic survey. The red lines indicate the major faults in the area.

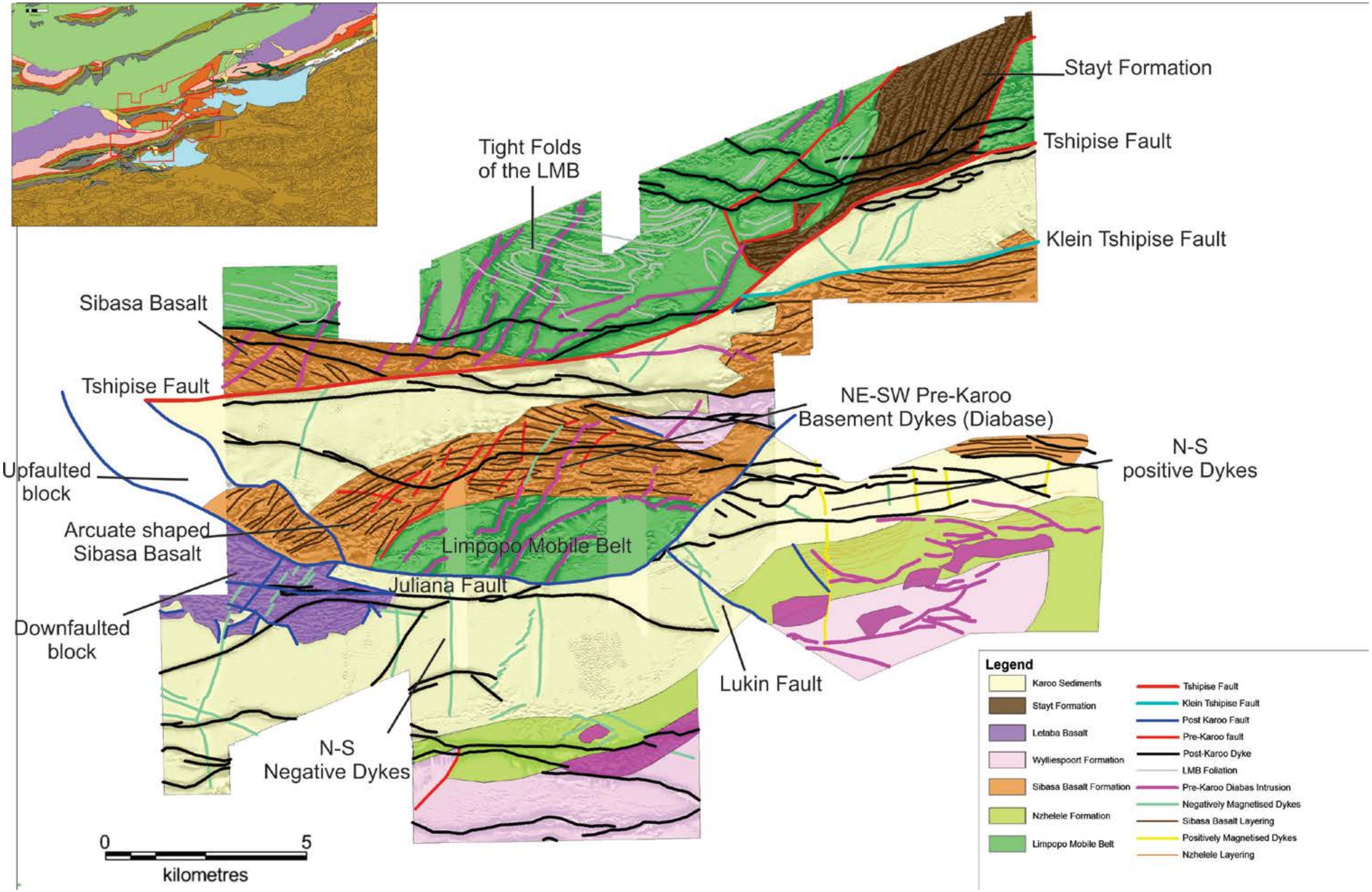


Figure 52: Geological interpretation of the B3 Aeromagnetic block

6.2. Aeromagnetic Interpretation

An interpretation of the aeromagnetic imagery was originally conducted by Brummer et al., (2010) which was mostly from a geophysical point of view; however for the purpose of this dissertation emphasis was placed more on determining the geological and structural significance of the survey. The survey not only covers the coal bearing Karoo Supergroup rocks but also various basement lithologies of the Soutpansberg Group (Wyllie's Poort, Nzhelele, Sibasa and Musekwa Formations) and the highly deformed metamorphic rocks of the Limpopo Mobile belt. Geological features, such as dykes and faults, not readily seen in outcrop or in the 1:250 000 geological maps, can be more accurately identified. The extent of Jurassic aged dolerite sills, which affect the coal bearing sequences to a large degree, can also be identified. An important aspect of the interpretation would be to define the extent of sill development and possibly being able to determine the sources of the sills in conjunction with borehole geological logs.

6.2.1. Regional Magnetic Signature

The area is underlain by a variety of rocks ranging in age, composition and structure; all of which have a unique magnetic signature and are described below.

6.2.1.1. Beit Bridge Complex (LMB)

This high-grade metamorphic unit generally exhibits structureless low magnetic intensities while in certain areas; foliation and folding patterns can be recognised. They occur throughout block 5 and a minor outlier is located in the south of block 4. This is classified by cyan blue, green and yellow colours.

6.2.1.2. Soutpansberg Group

The volcano-sedimentary sequence has two broadly different signatures which can be classified into the highly magnetic volcanic basalt units and the less magnetic sedimentary units.

- Volcanic Units (Sibasa Formation)

The Sibasa Formation is characterised by moderate to strongly magnetic, high frequency "pockmarked" pattern of positive polarity. In many instances the basaltic fabric contains lineations of higher intensity which could be the individual volcanic flows being displayed at surface as a result of rotation.

- Sedimentary Units

The sedimentary sequences of the Soutpansberg Group contain interbedded tuffaceous and pyroclastic layers which are recognised as bedding traces of low magnetic intensity. Where no such pyroclastic units exist however; the Soutpansberg sedimentary units are fairly transparent and do not exhibit much structure.

- Intrusives

Intrusives mostly in the form of diabase dykes and possibly sills are generally broad, wide and exhibit a low magnetic frequency with very high magnetic intensities. These structures are only present within the pre-Karoo Soutpansberg and LMB and it is therefore assumed that they are of pre-Karoo origin.

6.2.1.3. Karoo Sedimentary rocks

The sediments within the Karoo Supergroup are magnetically transparent and are characterised by flat and featureless magnetic backgrounds.

6.2.1.4. Karoo Basalt

The Karoo Basalt unit is very similar in appearance to the Sibasa Basalt formation by exhibiting a moderate to strong intensity, high frequency, pockmarked and "foliation" pattern. The foliation lines observed are similar to the Sibasa Formation are defined as individual lava flows of similar magnetic intensity brought up to surface as a result of the northward tilting of these blocks.

6.2.1.5. Igneous Intrusion

- Dykes

The dykes are moderately to strongly magnetic of positive polarity, and are well imaged as predominantly E-W to ENE-WSW and NE-SW narrow anomalies with HI-LO magnetic signature consistent with steeply dipping bodies (Brummer et al., 2010). There are also a number of weak, negative polarity dykes striking N-S, NE-SW and NW-SE which were emplaced at a time of magnetic field reversal at a separate, possibly later, stage.

- Sills

The sills are displayed as broad moderately magnetised units of moderate to high frequency. Their signal strength tends to dissipate towards the north as they increase in depth.

6.2.2. Faults

Faults are generally not visible in an aeromagnetic image and in general can only be identified where magnetic bodies have been displaced.
Some of the E-W and ENE-WSW trending faults in the area probably acted as conduits for dolerite to intrude through, these have been preserved as dykes and where thrusting has taken place, as sills. The majority of the NW-SE trending faults observed in the aeromagnetic image are not intruded by dolerite and it has to be assumed that this movement took place after the intrusion of these dykes.

6.3. Geological and tectonic Interpretation of the B3 Block

The most prominent aeromagnetic features observed in the image are the large E-W, ESE-WNW and NE-SW trending dykes. In many cases these dykes occupy pre-Karoo faults; however the majority of them would have been emplaced during the Jurassic igneous event. There are various negatively magnetised N-S trending dykes, the majority of which do not appear to have undergone much displacement. The highly magnetic basaltic units of the Sibasa and Letaba Formations are clearly visible and displacement within these units is fairly common.

The area was sub-divided into a number of fault blocks, mostly by the large ENE-WSW trending Tshipise and Klein Tshipise faults in the north and the Juliana and Siloam faults in the center of the map. For the purpose of this interpretation the survey area has been subdivided into a series of blocks, each defined by geological and survey boundaries, which will be each be interpreted and discussed separately.

6.3.1. Block 1 (Fig 53)

Block 1 falls within the southern part of the survey and mostly covers the northern slope of the Soutpansberg Mountains and is underlain by the Wyllie's Poort, Mabiligwe and Nzhelele Formations. These highly magnetic linear trends are possibly pre-Karoo diabase dykes that are very shallow or outcropping as indicated by the geological mapping. However, the northernmost dyke continues westwards into block 2 where it cuts through Karoo sediments and still exhibits a shallow signature.

To the north of the southern-most dyke there appears to be a weak to moderate magnetic signature decreasing in intensity towards the north. This feature is consistent with an intrusive sheet dipping towards the north and is probably a diabase sill occupying the sedimentary rocks of the Soutpansberg Group, possibly emanating from the fault to the south. This feature was confirmed by (Brandl, 2002) to be of pre-Karoo origin.

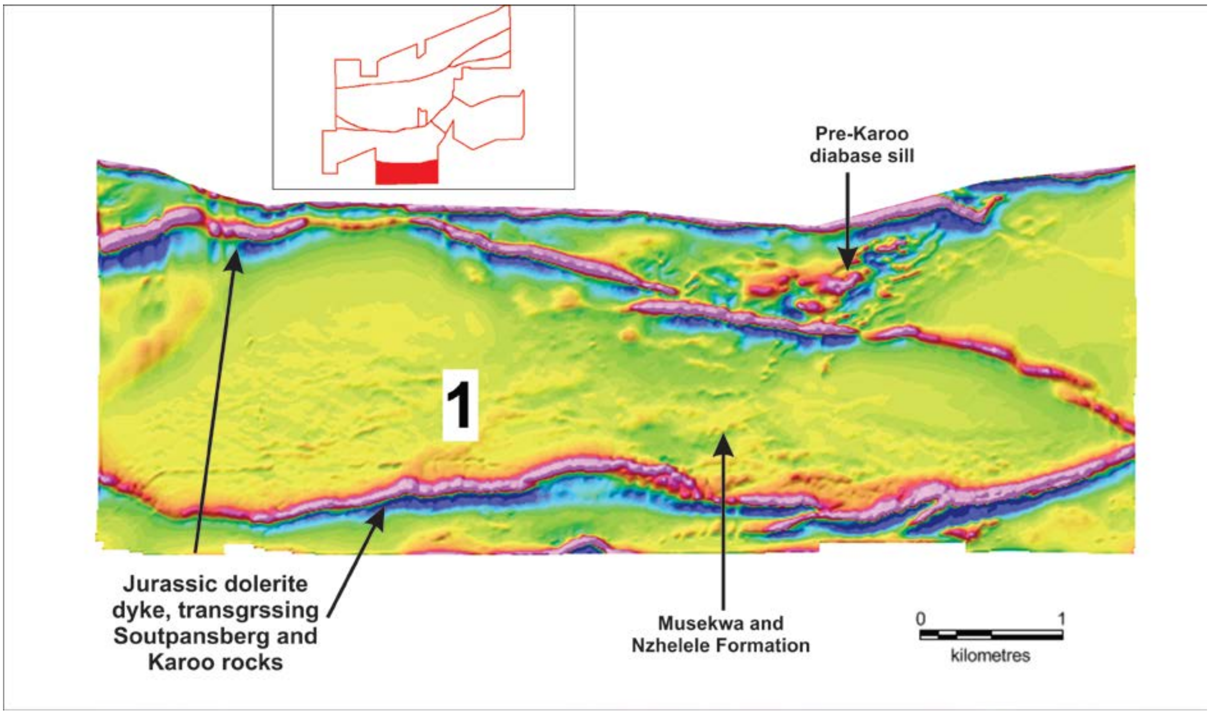


Figure 53: TMI Vertical Gradient image of Block 1.

6.3.2. Block 2 (Fig 54)

This block extends from the western edge of the survey block up to the NW-SE trending Lukin Fault. This block is almost wholly underlain by Karoo sediments that generally exhibit a flat featureless magnetic background. In the extreme NW part of the block the presence of highly magnetic, high frequency Karoo Basalt is observed. This block is bounded to the south by the E-W trending Fault 2 and to the north by the Juliana Fault.

In the north-western corner of this block a positively-magnetised unit of moderate intensity and high frequency corresponds to the Letaba Basalts. The linear structures in the basalt The positively- and negatively- magnetised dykes are clearly noted through the basaltic signature and are therefore shallow/near surface dykes. The negative dykes extend across to the blocks further north. The southern boundary of the Letaba basalt is very irregular with windows were basalt has been removed. It was confirmed by the LIDAR image that the basalt has been block faulted to a certain extent by NNW-SSE faults that were not intruded by any dolerite.

6.3.3. Block 3 (Fig 54)

This small triangular block is separated from Block 2, to the south, by a fault which is partially dyke-filled. To the north it is separated from block 4 by the NW-SE trending extension of the Juliana fault and abuts against Sibasa basalts of the Soutpansberg Group.

The block consists entirely of Letaba Basalt and is characterised by linears, approximately 50m apart and perpendicular to the dip of the blocks. These are regarded as individual lava flows expressed at surface as a result of the tilting of the blocks. The entire block is characterised by a lower amplitude and reduced short-wavelength resolution; this is normally associated with magnetic features further away from surface. This implies that the top of the Letaba Basalt, in the entire block 3, is deeper compared to block 2 to the south. This characteristic increase towards the NW of the block implies that the depth to the top of Basalt increases in this direction.

The block also contains a sigmoidal shaped dyke which could be as a result of riedel shearing formed during left-lateral shear rotation between the major bounding surfaces.

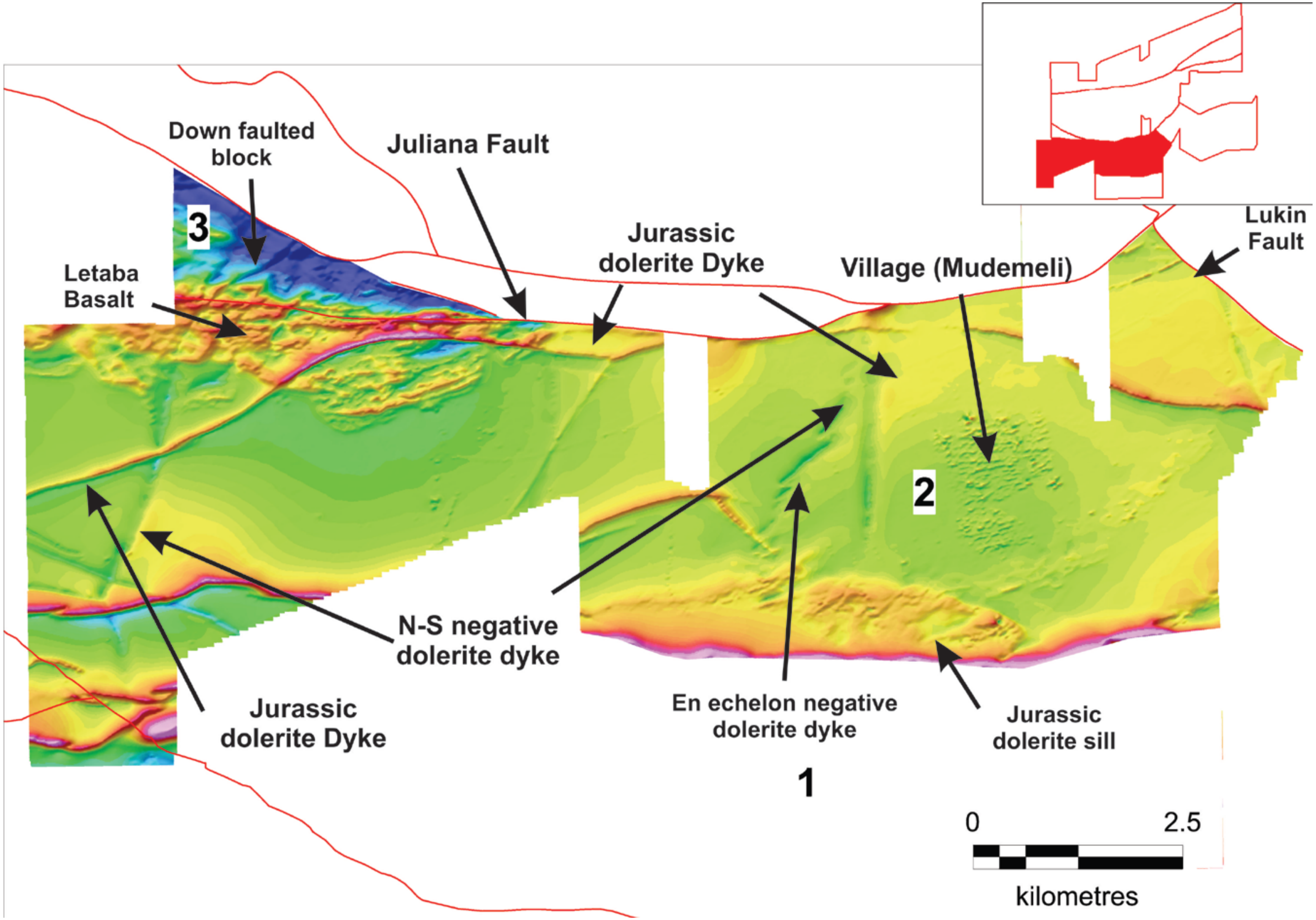


Figure 54: Total magnetic intensity (TMI) image of Block 2 and 3

6.3.4. Block 4 (Fig 56)

This block is a semi-circular shaped entity, bounded to the north by the Tshipise Fault and to the south by Juliana Fault. The majority of the block is underlain by basement rocks of the Limpopo Mobile Belt and Sibasa Formation, the latter forms a concave arc of short wavelength, high frequency, highly magnetic rocks (typical of basaltic flows) seen in all the magnetic derivatives. These Sibasa Basalt appear to have been arcuated by the folding towards the north. However the folding of the younger overlying Karoo sediments is arcuated towards the south. This leads to the conclusion that some folding took place in the pre-Karoo basement prior to the deposition of the Karoo sediments. The basement lithology of this block consists of Sibasa Basalt, part of the lower Soutpansberg Group, while the basement of the block 1 to the south consists of Wyllie's Poort Formation. This means that this block of Sibasa Basalt must have been up-faulted and brought to surface either synchronously or after the folding event.

The Karoo sediments unconformably overly the Sibasa Basalts to the north and this normally transparent unit exhibits a magnetic intensity much higher than what would be expected. This moderately magnetic, low frequency anomaly can be ascribed to the extension of the highly magnetic Sibasa Formation beneath the Karoo sediments. This anomaly contains distinct magnetic highs and lows which negates the possibility of it being dolerite sills, which normally exhibit a flat lying, higher frequency geometry. This occurrence is observed in both the NW and NE corners of fault block 4; (Fig 56) however there appears to be a "window" of lower magnetic intensity at the apex of the concave arc (Sibasa Formation) that does not appear to be fault bounded. This possibly relates to a pre-Karoo up-faulted block of lower magnetic intensity, possibly Wyllie's Poort quartzite or LMB, which also suggests that this area was subjected to pre-Karoo Block faulting.

Furthermore some of the most dominant features observed in this block are NE-SW trending highly magnetic dykes. The nature and orientation of these dykes is unlike those of the main dyke swarms. The very high magnetic intensity of these features and the fact that these structures are only contained within the Basement lithology (Sibasa Basalt and LMB) suggest that they are pre-Karoo in origin, probably diabase dykes. One of these intrusions does appear to be displaced by NW-SE trending faults.

There are also a number of E-W trending, highly magnetic dykes that are sub-parallel to the major bounding faults of this block. These dykes appear to follow the arcuate shaped volcanic layering of the Sibasa Formation for some extent but do change orientation further west, possibly due to the intersection of the NE-SW trending fault which displaces the Sibasa Formation.

Younger negatively magnetised NE-SW trending dykes are present mainly within the Karoo sediments most of which have been deformed into sigmoids. The negative dyke occurring in the west of the block appears to displace the approximately E-W trending dolerite dyke associated with the p-fracture direction.

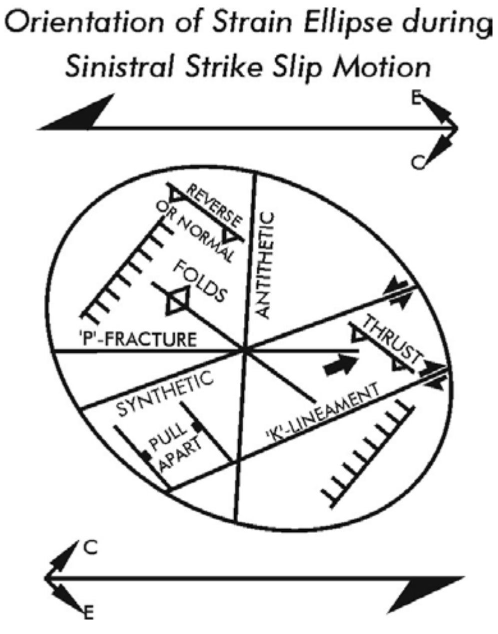


Figure 55: Example of Sinistral strain ellipse with associated structures that form (Modified after Park, 1988)

The high percentage of magnetic rocks contained within block 4, compared to other areas, makes it possible to identify the presence of faults which are not readily seen in non-magnetic rocks and can only be observed where magnetic bodies are displaced. Three sets of faults were identified in this block trending approximately E-W (associated with p-shearing), NE-SW (riedel shears) and NW-SE which is a splay fault sub-parallel to the Juliana fault in the west of the block which forms the southern bounding surface (Fig. 56). The eastern part of the block is further underlain by Sibasa basalt with elongated basalt flows and in certain cases they have been intruded by dykes. Displacement of these volcanic layers can also be seen.

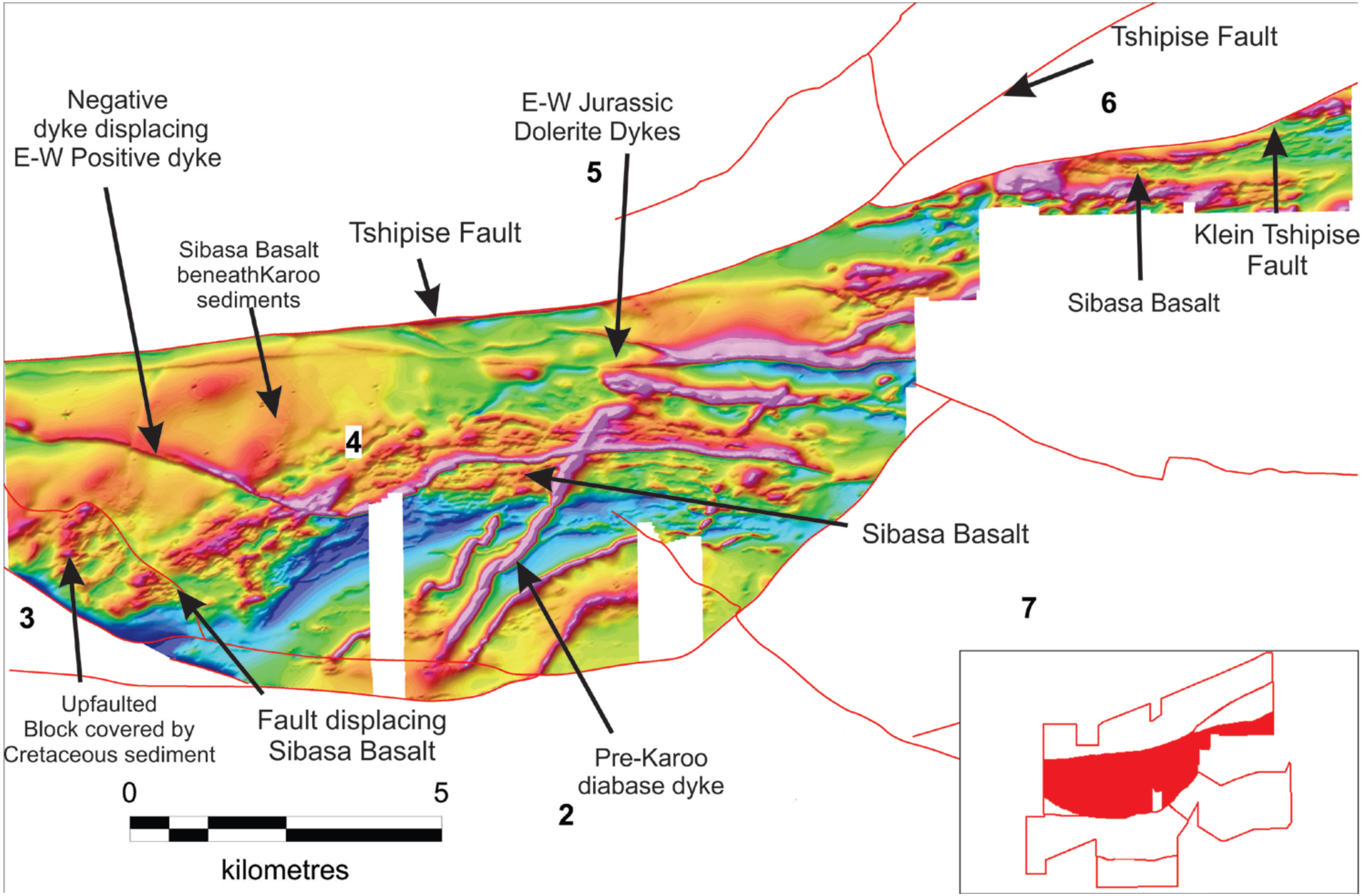


Figure 56: TMI Vertical Gradient image of Block 4

6.3.5. Block 5 (Fig 57)

This block occurs north of the Tshipise Fault and covers the northern most part of the survey area. The area is largely underlain by the low to moderately magnetised rocks of the LMB, however in the NE sector of this block the presence of the highly magnetic, high frequency, foliated signature of the Stayt Formation.

Near the center of the block, zones of moderately magnetised tight folds can be seen which are indicative of the high grade metamorphic terrane of the LMB.

This central area also has two sets of NE-SW trending dykes that are bounded to the south by the Tshipise Fault, similar to those observed in the block 4 (Fig.56). Only the lower most part of this block is covered by the survey which does not contain the northern bounding surface of this block. However from the geological mapping conducted by Brandl (2002) it is clear that the dykes extend much further north where they are bounded by the extensive ENE-WSW trending Bosbokpoort fault (Fig. 60).

In some instances these approximately E-W trending dykes tend to follow the Tshipise fault where they intersected it and also to continue on the southern side of the fault. Within the block to the east, which is underlain by Sibasa Basalts, the magnetic intensity of these dykes seems to decrease across the identified NE-SW trending fault, which they also intrude. This decrease in intensity across the fault is related to the Quaternary cover above the dyke, whereas south-east of the fault the dykes are exposed at, or are close to the surface. These E-W trending structures do displace the NE-SW dykes when they emanate from the Tshipise fault and are either young emplacements or have undergone displacement subsequent to being intruded.

The highly magnetic, banded unit in the far east of the block is the Stayt Formation and is considered to be a steeply dipping (55°) equivalent of the Sibasa Formation. The extremely high and banded magnetic nature of this unit is very distinctive and not similar to those of the Sibasa south of the Tshipise Fault. The diamond shaped area of the Stayt Formation occurs in a fault bounded block that contains LMB to the west. This block is bounded in the south by the Tshipise Fault and a parallel fault to the north. The Stayt Formation is one of only a handful of Soutpansberg outliers that occur north of the Tshipise Fault, and is by far the largest. All of these outliers are bounded to the south by the Tshipise fault and abuts against the much older LMB rocks.

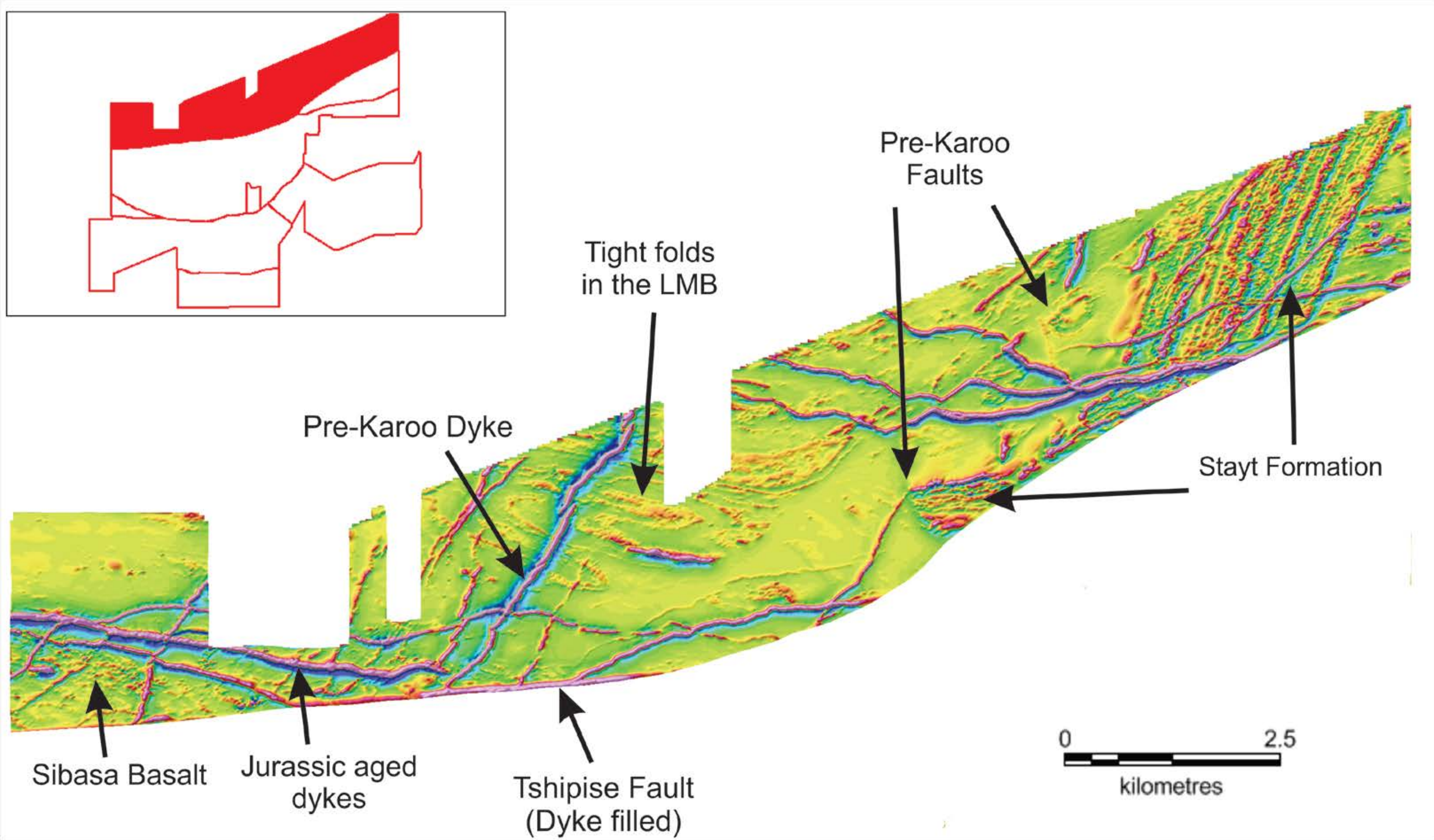


Figure 57: TMI Vertical Gradient image of Block 5

6.3.6. Block 6 (Fig 58)

This is a small block of moderate magnetic intensity within the north-western corner of the survey that is wholly underlain by Karoo sediments. This block is bounded to the north by the Tshipise fault and to the south by the Klein Tshipise fault, both of which have been intruded by dolerite to a certain extent.

A number of en echelon WSW-ENE trending highly magnetic dyke structures are observed in the north central part of the block that appear to terminate against the Tshipise Fault. These dykes are possibly right lateral Riedel shears that have been connected by the through going p-shears.

Three sigmoidal dykes of negative polarity are also observed in the centre of the block which was deformed by left lateral shearing; these dykes do not appear to have been displaced (different bounding surfaces). In addition there is one negative dyke orientated in the opposite direction and formed through right lateral movement along the bounding surfaces.

Within the far western corner of the block there two positive dykes orientated in a NNE-SSW direction, these do not appear to have been rotated or displaced.

From the RTP VG2 image, the block generally displays an underlying magnetic signature of higher frequency which could be mistaken for possible basement structures underneath the Karoo sediments. However these features are surface streams deposits which have concentrated magnetic minerals and do not reflect the underlying geology at all.

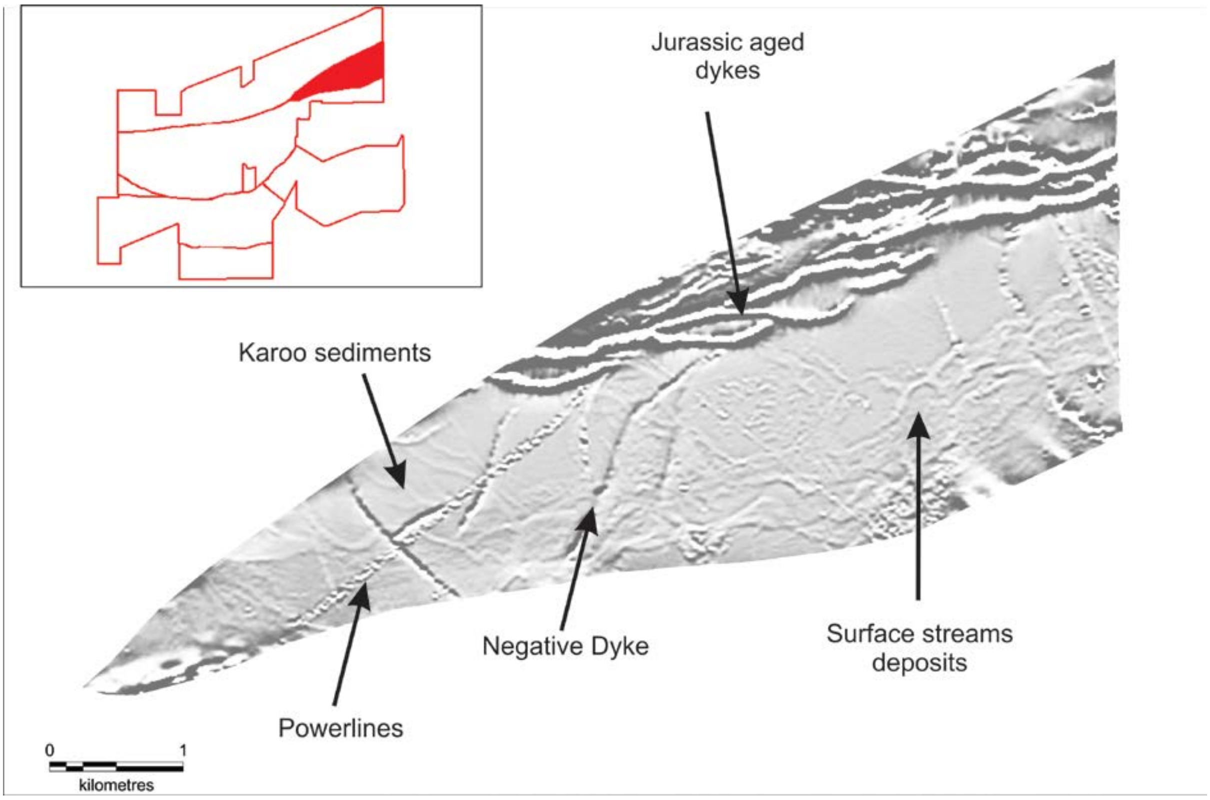


Figure 58: TMI Vertical Gradient grey image of Block 6

6.3.7. Block 7 (Telema Block) (Fig 59)

This block covers the entire south-eastern part of the survey of which the majority is underlain by the Nzhelele and Musekwa formations of the Soutpansberg Group; the Karoo sediments are only present within the very northern edge of this survey. The Nzhelele Formation consists of a red argillaceous and arenaceous upper unit (Lukin Quartzite) interbedded with layers of pyroclastic rocks; as well as the tuffaceous Mutale unit at the base. The steeply dipping (55º) pyroclastic and tuffaceous beds are identified in the TMI VG2 grey-scale image as WSW-ENE trending bedding traces and can be followed to the eastern edge of the survey. This unit has been displaced by a NW-SE trending at the western part of the block.

The highly magnetic and high frequency anomalies trending in an ENE-WSW direction in the southern part of the survey are associated with the Basaltic Musekwa Formation. A number of NW-SE trending positive polarised dykes that cut across the bedding of the Nzhelele Formation do not appear to penetrate the Karoo sediments and can be classified as diabase dykes (2 Ga). In the north-eastern corner of the survey the highly magnetised, very high frequency magnetic unit is the Sibasa Basalt which abuts against the Karoo sediments to the south separated by a WNW-ESE trending fault. A number of NNW-SSE trending faults appear to displace the E-W trending grain of the basalt.

The approximately E-W trending positively magnetised dykes (p-shear direction) have been observed in all previous blocks and occur mostly within the Karoo sediments of this block. In the southern part, one such Jurassic dyke is also present within the Soutpansberg Group and also transgresses into the Karoo. These structures are recognised at surface from the LIDAR images as linear zones of significantly less vegetation growth, approximately 20m wide and can be traced between 5 and 10km along strike.

This block is bounded in the west by the Lukin Fault which is possibly a reactivated extension of the much larger WNW-ESE trending Siloam Fault. This pre-Karoo Siloam Fault is classified as a normal fault with downwards displacement towards the NE (Barker, 1983). He recognised that the Soutpansberg Group has been down faulted by approximately 1500m which is probably pre-Karoo in age.

The Lukin Fault is a normal fault that has down faulted the Karoo sediments to the west by approximately 50m. The E-W trending dykes have been displaced and deformed into sigmoidal structures that suggest they were subjected to left-lateral wrenching along the bounding faults.

A final set of N-S trending dykes are observed throughout this block, one of which cuts across the Karoo contact into the Soutpansberg Group to the south and to the north. Apart from the previously mentioned dyke, all of these structures occur within the Karoo sediments and are bounded by the large E-W dyke structures. These dykes are both positively and negatively magnetised and do not display any form of rotation or displacement, their surface expression is also detected by the LIDAR images. The negatively magnetised N-S dykes are clearly younger than the other dykes, are probably more acidic (Granodiorite and tonalite described by Van Eden et al. [1955] near Tshipise) and have a different remnant magnetisation. These N-S dykes are possibly related to the extrusion of rhyolite, which marked the final phases of volcanic activity related to the rifting of Gondwana.

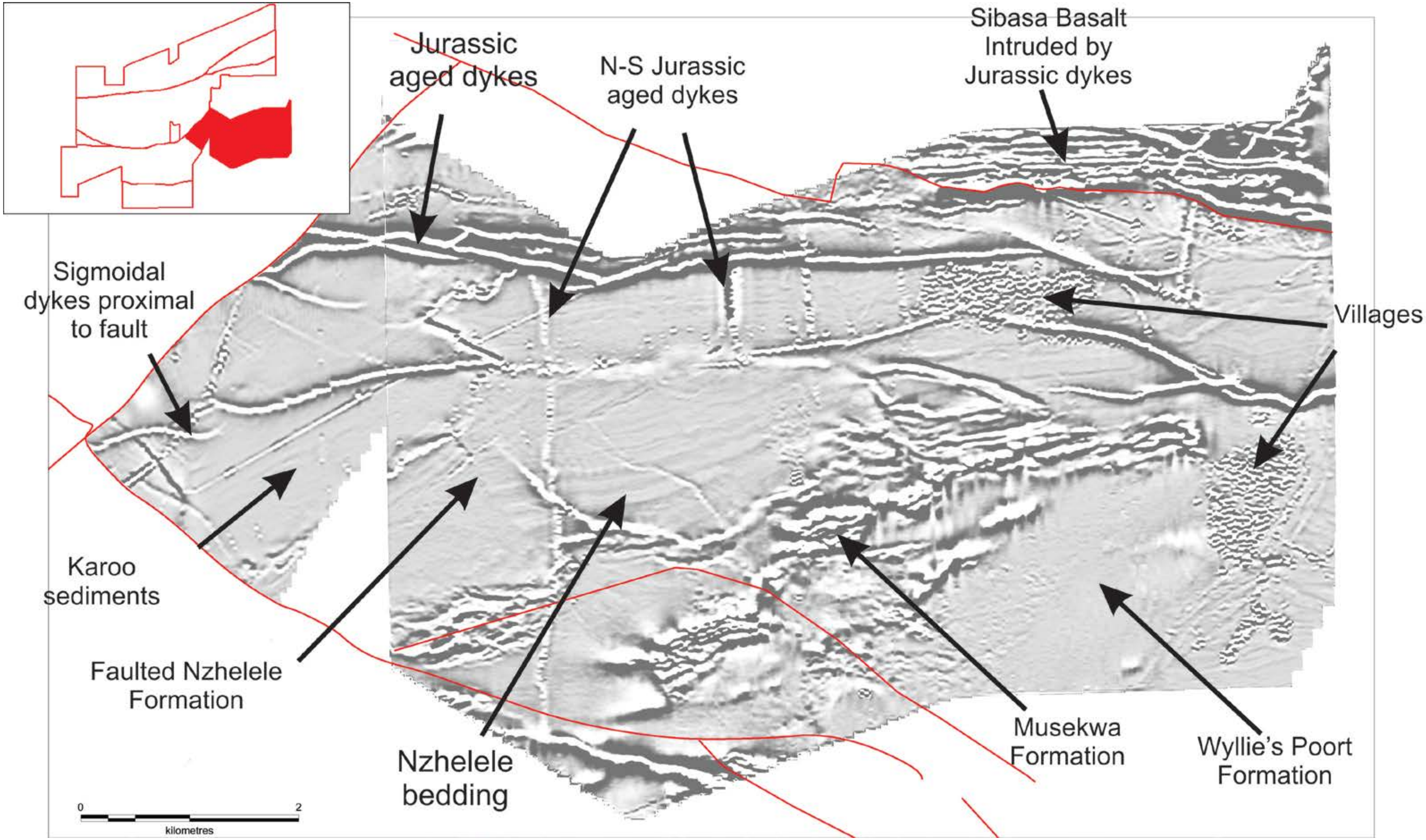


Figure 59: TMI Vertical Gradient grey image of Block 7

6.4. Discussion

The aeromagnetic survey enables the mapping of several different phases of deformation both within the basement lithologies and overlying Karoo sediments. The majority of these magnetic structures are E-W, ENE-WSW and NW-SE trending dolerite dykes formed during the emplacement of the Okavango and Tuli-Save dyke swarms associated with the Mwenezi Triple Junction. The basement lithologies in blocks 4 and 5 also contained NE-SW trending, highly magnetic dykes that have not been identified within the Karoo aged sediments and were interpreted as pre-Karoo in age. A final set of mostly undisturbed, N-S orientated, negatively magnetised dykes are interpreted as a younger phase of magmatism possibly associated with the E-W extension and split of Gondwana. NE-SW orientated faulting within the basement lithologies, is seen mostly within the Sibasa Basalt and therefore appears to be older and does not correlate with any post-Karoo deformational events.

7. Structural Characteristics of the Tshipise basin.

This structural evaluation has been derived largely from the interpretation of the aeromagnetic survey, described above, along with existing geological maps, a literature review, field mapping and wireline geophysical surveys.

7.1. Introduction

The study area has a complex structural history that is controlled by the long-lived basement structures which are remnants of the collision of the Kaapvaal and Zimbabwean Cratons to form the LMB (2.7-1.9 Ga.) This crustal weakness has been subjected to reactivation during the development and faulting of the Soutpansberg Group, and is considered to be of significance to the formation and preservation of the Soutpansberg and Karoo sedimentary and volcanic sequences.

The likelihood that all of these geological units formed as a result of a similarly orientated stress regime is very doubtful. It is rather thought that the ENE-WSW trending structures, remnant of the LMB orogeny, were episodically reactivated by palaeo-stresses of differing orientations. It is inferred that a palaeo-stress in varying directions could preferentially be transmitted into the LMB structures, reactivating them. See section 7.11 below.

Most of the structural features were digitised from published 1:250 000 geological maps, limited field mapping of the Clarens and Fripp Formations and were possible, exposures on main roads were also visited. Additional structures were digitised from the unpublished 1:50 000 geological field sheets (GCS), aeromagnetic surveys, SRTM (1arc-second) as well as from the LIDAR imagery were available.

Overall there is a remarkable similarity between the orientation of the foliation patterns of the Limpopo Mobile Belt and all the major faults present within the study area. East of the Siloam Fault Zone, within the Tshipise Straightening Zone, the Bosbokpoort and Klein Tshipise Faults show a remarkable degree of linearity. The foliation lines run parallel to the Bosbokpoort fault for almost 100km without much deviation. In the vicinity of the Siloam Fault Zone, the Tshipise and Bosbokpoort faults realigns into this WNW-ESE direction, again mirroring LMB structural architecture (Fig. 60).

The structures in the Soutpansberg Karoo Basin are all considered to be part of a right lateral wrench couple and are mostly characterised by two structural orientations, the most dominant being the ENE-WSW and the secondary orientation being the NW-SE. Further N-S, NE-SW orientated structures are present to a lesser extent.

7.2. Basin Architecture/Geometry

The present outline of the Tshipise Basin is considered to be a remnant of a larger depository, which was connected with its neighbouring basins to a certain extent and covered a much larger area. Two prominent intersecting fault systems are recognised in the study area; one being parallel (ENE-WSW) to the regional strike and the other oblique (NW-SE) to the LMB (Brandl, 1981).

The Tshipise Basin consists of a series of elongated Karoo filled blocks that are bounded mostly on their northern edges by ENE-WSW trending faults. The northern blocks, Jutland and Mopane, are smaller in size than the Makhado, Chapudi and Mount Stuart blocks in the south. Boreholes drilled into the southern blocks have intersected the coal bearing Madzaringwe Formation at over 800m in depth, and it is expected that the formation continues to well over 1000m below surface towards the NE (Fig 61).

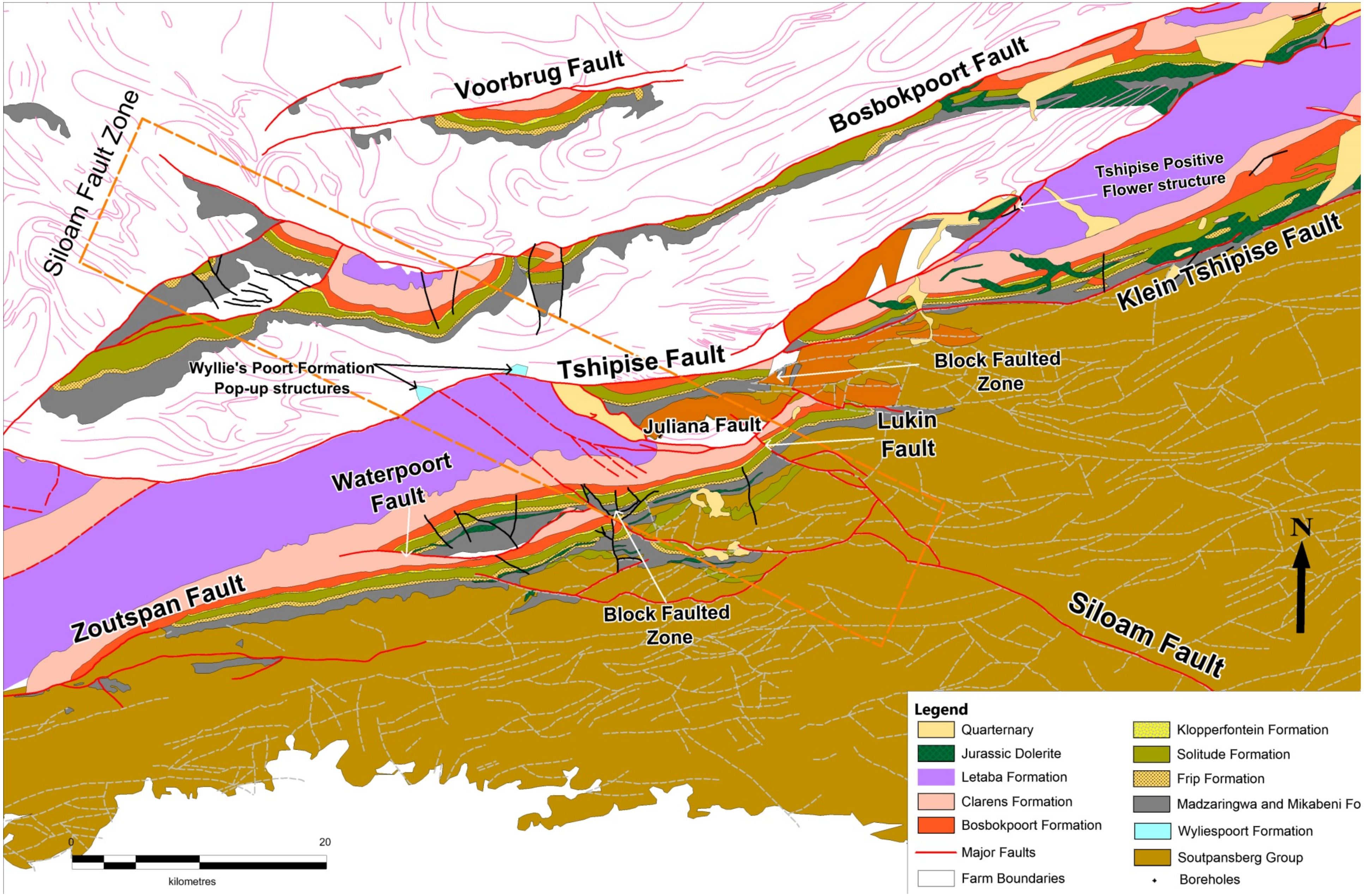


Figure 60: Geological and structural map outlining the major faults and LMB structural form outlines.

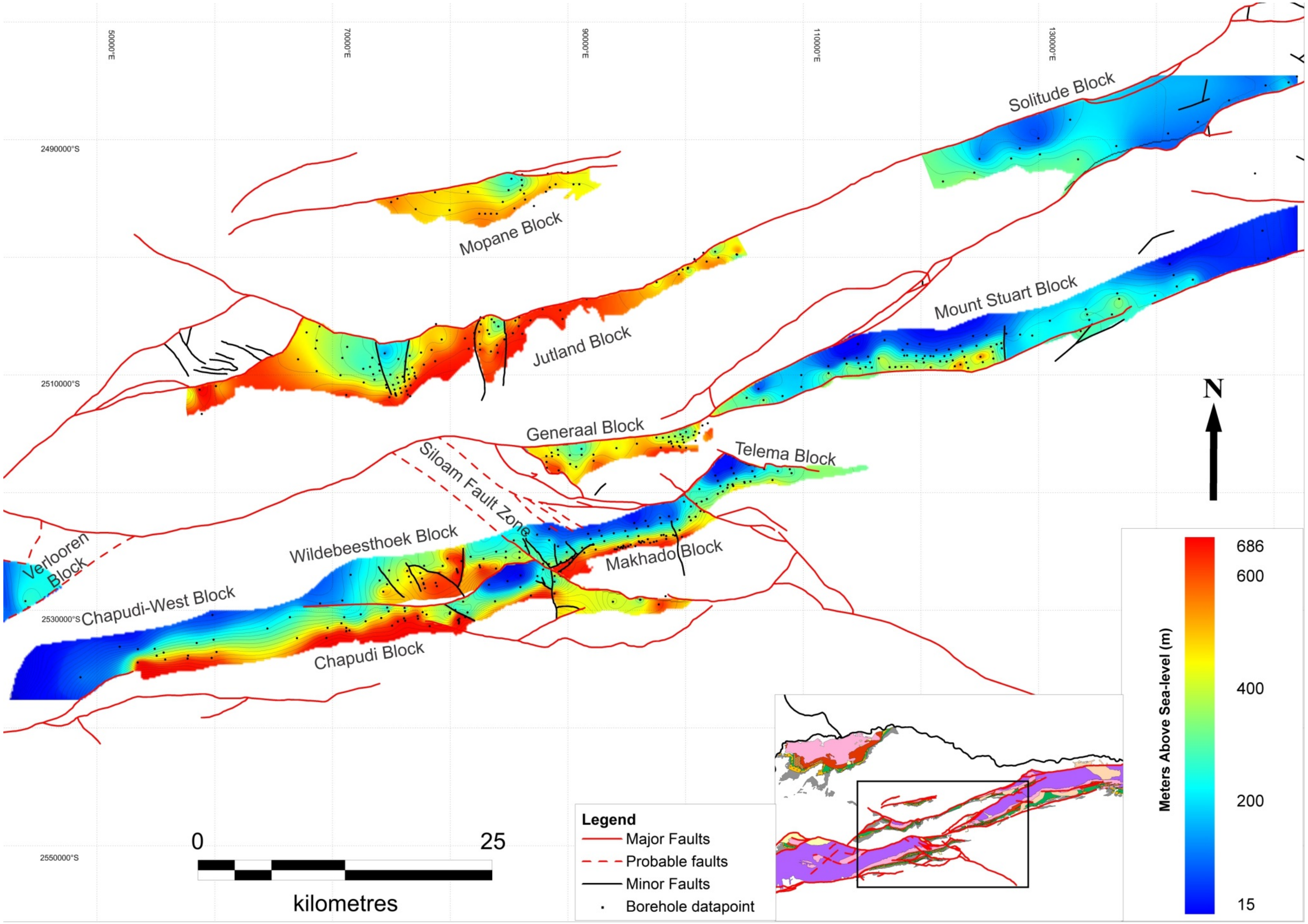


Figure 61: Elevation of pre-Karoo basement above sea-level

7.3. ENE-WSW Limpopo fault trend

These distinct faults stretch across the entire length of the basin and form the northern boundary of the majority of the Karoo filled blocks. The position and the geometry of the faults are considered to be a function of the basement fabric within the Limpopo Mobile Belt. This fault zone lies at the boundary of the Southern Marginal Zone and the Central Zone of the LMB and is possibly the NE extension of the Palala Shear Zone.

This fault orientation is recognised throughout the Soutpansberg Group and it therefore has a major control on the deposition and faulting of the Proterozoic Soutpansberg and Permo-Carboniferous Karoo basins.

These faults are mostly southward dipping, relatively low angle (40-60°) normal faults, however, a few northward dipping features have also been recognised (Broadbent, 2005). The proposed half-graben nature of the Karoo blocks means that these faults are possibly listric at depth. A number of the larger ENE trending faults have been named by Brandl (1980) which are outlined in Fig 60.

The Tshipise Fault is probably the most well-known in the area and is named after the town of Tshipise (meaning something warm), approximately 33km south of Musina, just off the R252 to the Kruger National Park. The town owns it existence to the presence of a thermal spring, which has been a tourist attraction for many years. The spring is located at the foot of a Clarens Sandstone hill in the Honnet Nature Reserve. This isolated up faulted block of Clarens is considered to be a positive flower structure formed in a right-lateral strike-slip duplex along the Tshipise Fault (G. Brandl pers. comm., 2015). Several of these duplexes are observed along the Tshipise Fault and are located where jogs are present in the fault. These duplexes are not only confined to the Clarens sandstone units but numerous outliers of the Wyllie's Poort quartzite that occur along the fault further to the west.

The fault dips to the south at around 40°-45°in the east (Brandl, 1981; Broadbent 2005) and appears to steepen to 70-80° near the western parts of the basin. This fault extends from the settlement of Lapland, in the west, more than 200km in a WNW direction where it eventually disappears 3km from the Bosbokpoort Fault. The fault is characterised by sinuous strike traces which are more apparent west of the Siloam Fault Zone. The wavelength of these fault jogs are in the order of 55km and have amplitudes of approximately 10km. A number of smaller ENE-WSW and WNW-ESE faults either extend or terminate against the Tshipise Fault. Broadbent (2005) described the possible mechanism for the sinuous traces as being the result of either E-W folding or the interaction of the two main intersecting fault systems. However it is thought that it is rather a function of the basement foliation fabric of the high-grade metamorphic rocks of the LMB. Exposure of this fault is limited; however the available aeromagnetic coverage shows that the fault is largely intruded by dolerite, almost certainly related to the Mwenezi Triple Junction.

The Bosbokpoort Fault is the northern most ENE-WSW trending fault that extends from close to the RSA-ZIM-MOZ border in the east for roughly 180km to where it ultimately terminates against the Tshipise Fault to the SW. This fault is a southwards dipping structure that has down-faulted and juxtaposed the Karoo sediments against Archaean LMB. As a result, a long thin block of Karoo sediments with a width between 1-5km has been preserved. This fault, similar to the Tshipise Fault, displays a sinuous trace in the west near the position of the Siloam Fault Zone where folding of the Karoo sediments is more pronounced in this region. The eastern part of the fault on the other hand is reasonably linear; this is again attributed to the linear nature of the foliation patterns in the basement rocks in the Tshipise Straightening Zone of the LMB. Near the westernmost part of the fault its interaction with the Siloam Fault Zone could be responsible for the sinuous nature of the fault. Duplication of the Karoo in this area could be related to pop-up structures, also possibly formed by right-lateral transpressional movement that occurred along the fault. This fault has been confirmed as being a neo-tectonic feature with movement having occurred as recently as 100 000 years ago. A 10m high fault scarp has been identified in Quaternary sediments in the far eastern part of the fault, near the Zimbabwean border (G. Brandl pers. comm., 2016). Minor seismic events have also been recorded in recent times in the proximity to this fault (Singh, et al., 2009). The neo-tectonic principle horizontal stress, discussed in section 8.3 below, was determined to be parallel to the this fault trend which would imply that the recent movement that occurred along it would most likely be normal movement on the southward dipping structure.

The Klein Tshipise Fault is located in the central to eastern part of the basin and is predominantly north facing and down-throws the Karoo sediments against the Proterozoic Soutpansberg sediments to the south. The fault extends from the farm Chase (576) in the west approximately 100km in an ENE direction to where it terminates near the Kruger National Park in the east. Towards the east the exact fault position becomes disparate and is rather associated with numerous sub-parallel smaller scaled faults. In the west the fault terminates against the Tshipise Fault. The fault is also largely filled by igneous material as seen in aeromagnetic surveys further east. The most notable characteristic of this fault is its straight/linear nature which is usually associated with normal movement (G. Brandl pers. comm., 2016) and is unlike the sinuous strike of the Tshipise fault. The reason for this is again most likely related to the linear nature of the basement foliation in the Tshipise Straightening Zone.

The Zoutpan Fault Zone lies in the western side of the basin and extends approximately 170km from the town of Tolwe in the west and bifurcates towards the east into several faults that connect to the Siloam Fault zone. Its name is derived from the salt workings on the farm Zoutpan (459) where brine leaches from the fault in the foothills of Soutpansberg Mountain. The fault is a steeply dipping normal fault that has down-faulted the Karoo sediments to the north.

Just west of the Siloam fault Zone, an extension of this fault (referred to as the Waterpoort Fault) has duplicated the Karoo sequence either through up-faulting or a southward verging thrusting (Broadbent, 2005) to form the Wildebeesthoek Block. Here the Karoo and pre-Karoo Nzhelele Formations are juxtaposed against the upper Karoo units. The geometry of this block and the fault is very similar to that of the Generaal Block approximately 15km to the NW. This Generaal block is considered to be a pop-up structure formed as a result of right lateral strike-slip movement that has occurred along the Tshipise Fault. To account for the geometry and sense of displacement seen on the geological maps, the Wildebeesthoek block had to have undergone similar movement. Karoo sediments have also been preserved high up in the Soutpansberg Mountains against the Sandriver Fault. This occurrence is only recognised west of the Siloam Fault Zone and possibly suggests that this area is tectonically younger than that to the east as Karoo sediments have not been removed (Barker, 1983).

From the regional aeromagnetics and recent drilling results the presence of additional large faults were identified not previously outlined in the geological maps. One example is in the far west of the basin on the farm Verlooren (409) where a window of magnetically transparent Clarens sandstone is down-faulted against the highly magnetic Letaba Basalts (Fig. 60). These units are separated by an ENE-WSW trending dyke along which several hundred metres of displacement has occurred. This dyke-filled fault probably continues further to the NE where is possibly emanates from the Tshipise Fault. This block of sediment is approximately 14km across from E-W and 4km from north to south and is most likely an additional graben that formed along the fault emanating from the Tshipise fault jog. More examples of additional faulting were observed further east in the Siloam Fault Zone; here the LIDAR imagery indicates the presence of NW-SE trending linears that match up with the position of previously mapped structures as well as dykes in the Jutland block. It is likely that displacement occurred along these structures which might have created additional fault blocks. These potential blocks would lie parallel to the one filled with Cretaceous sediment on the western edge of the Generaal Block. It is also at this point where two outliers of Wyllie's Poort Formation, approximately 1km wide, occur on the northern side of the Tshipise fault, considered to be positive flower structures similar to the one at Tshipise (G. Brandl pers. comm. 2015).

7.4. Secondary Fault Direction (WNW-ESE)

This is the second most prominent fault system in the area that trends between WNW to NW with throws generally to the southwest (Brandl, 1981). The most noticeable fault of this system is the Siloam Fault which is accepted to have been active in pre-Karoo times and estimated to have displaced the Soutpansberg Group by 1500m (Brandl, 1981). This fault has created major discontinuities in the Soutpansberg which cannot be explained by simple normal faulting but rather representing a major episode of possibly left lateral shearing that occurred in pre-Karoo times (Barker, 1983). Broadbent (2005) described it as a strike-slip transfer fault which formed to accommodate strain caused by the movement from the main ENE-WSW fault system. The Siloam Fault Zone is also thought to be related to the basement architecture of the LMB and in Fig. 60 it is once again seen that the fold patterns in the LMB are of similar orientation to this fault system. The sinuous traces of the larger ENE fault system are most likely related to the two fault systems that intersect in the Siloam

Fault Zone. On the farm Lukin (643) the Karoo sediments have been downthrown by approximately 50m to the south-west along an extension the Siloam Fault called the Lukin fault. The Siloam Fault is mainly observed within the Soutpansberg Group rocks and does not appear to extend further to the south or north; however its influence on the fault geometry north of the Soutpansberg Mountains is notable. The Bosbokpoort and Tshipise fault abruptly changes in orientation from ENE-WSW to NW-SE as they approach the Siloam Fault Zone. Several small blocks of the lower Karoo units (Tshidzi and Madzaringwe Formations) have been preserved to the NW along this fault trend, approaching the neighbouring Tuli Coal Basin. This reiterates the fact the Karoo depositional system between these two neighbouring basins were once connected to some extent prior to their fragmentation. The orientation of this fault zone is also consistent with the SRTM contour map (Fig. 3).

7.5. North-South faulting (Fig 60)

The N-S faulting is only seen in a handful of areas and at first glance do not appear to hold much significance. The main areas where these structures were identified were at the farm Castle Koppies (625) (Fig. 62 below) and just north of this within the Jutland Block. A similar block faulted zone was seen in the eastern part of the Generaal Block. The presence of thicker accumulations of Tshidzi Formation along the outline of these faults suggests that they were most likely present prior to the deposition of the lower Karoo. These same patterns also emerge within the overlying Madzaringwe and Fripp formations. These units also contain a higher proportion of clastic sediments in close proximity to the faults seen in the sediment ratio maps (Figs.20 and 24). These fault outlines thus represent pre-Karoo structures that were slightly active during the formation of the sedimentary basin and during the deposition of the Tshidzi, Madzaringwe and Fripp formations. When the Mwenezi Triple Junction occurred, these faults were reactivated and led to the displacement of the Karoo. This orientation is also associated with the negatively magnetised, relatively undisturbed N-S dykes identified in the aeromagnetic survey which clearly represents a different, probably younger, deformation event. The age of this post-Karoo faulting event is not definite but it is thought to have been after the intrusion of the dyke swarms and is possibly related to the final stages of rifting and separation of Africa and Antarctica at 167Ga.

Figure 62: Photograph looking westwards showing the northward dipping block faulted Clarens sandstone hills on the farm Castle Koppies 652.

Figure 63Intersection of two fault planes, the northward dipping bedding planes can also be seen at the bottom of the photo.

Figure 64: Steeply inclined beds of the Clarens Formation, dipping towards the NNW.

Figure 65: Low-angle slickensided thrust fault plane dipping towards the north-east on the farm Martha (185).

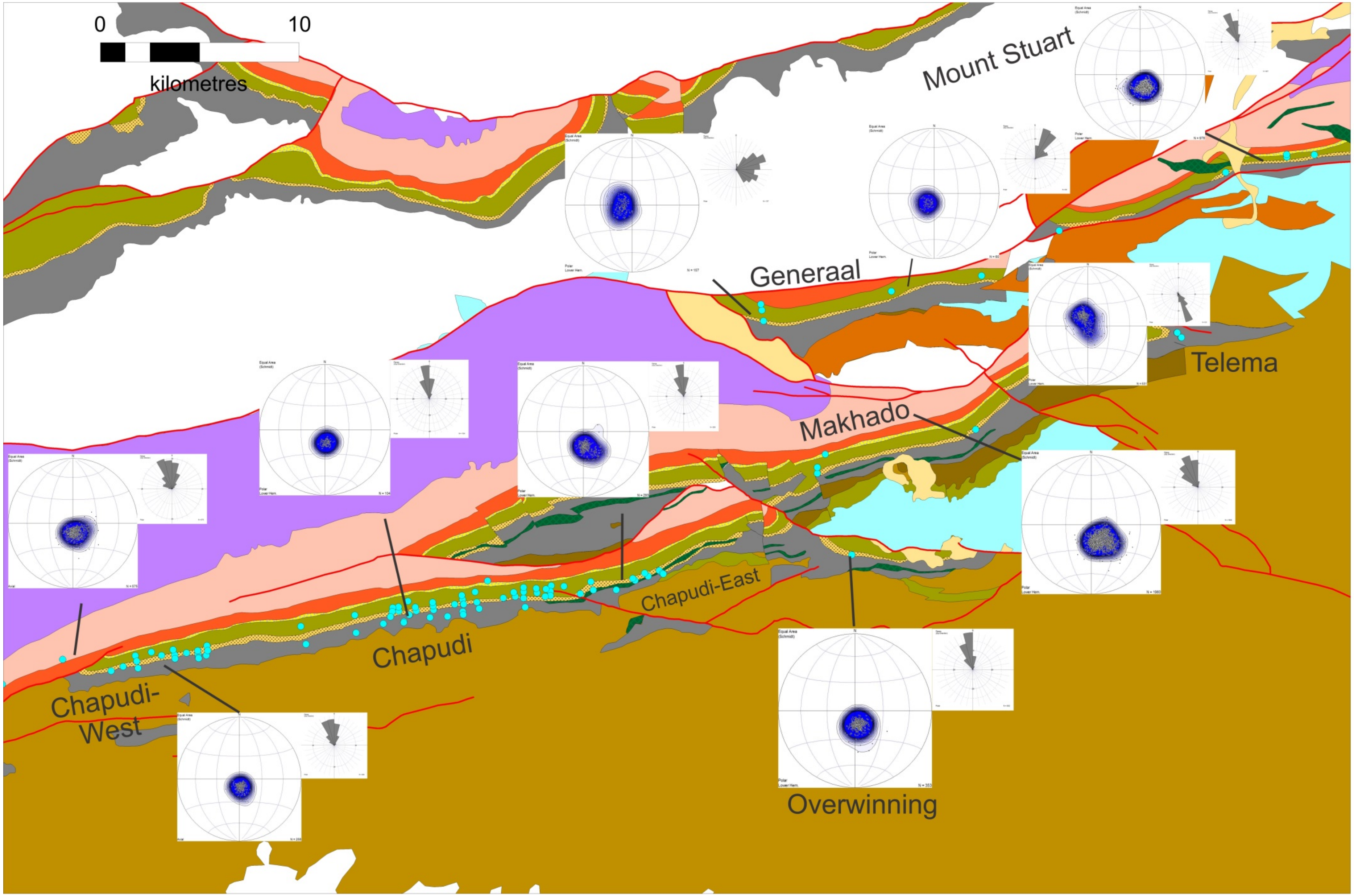


Figure 66 ATV Bedding measurements on regional structural domains

7.6. Half-graben rotation

Almost all the Karoo strata from the individual blocks dip relatively consistently towards the NNW; apart from a handful where localised folding has occurred along faults. This is attributed to block rotation associated with rifting and extension that occurred along most of the large ENE-WSW trending faults. The rotation that has occurred within these blocks is not straight forward; the blocks in the north are bounded by a fault along their northern boundary whereas some of the southern blocks (Generaal, Mount Stuart, Wildebeesthoek and possibly Chapudi and Makhado) are fault-bounded to the south as well. The northern flanks of the Soutpansberg Mountain are normally covered with alluvial debris which makes the identification of faults along the foot of the mountain very difficult. To this end it is disputable whether the rotation along the blocks was as a result of down faulted grabens, rotation of half-grabens along their northern boundary faults or whether it is a combination of both.

The average dip of the Karoo bedding is about 12°NNW; however in some domains their inclination could be as steep as 20-30° (Fig 66). These blocks dip fairly constantly towards the NNW (345°), perpendicular to their northern bounding faults. The average bedding within the Generaal Block however, dips towards the NW (40°) and is most likely associated with localised folding of the strata in proximity to the bounding faults.

7.7. Reverse/Thrust Faulting

A large number of fault slickensides and lineations measured indicated that they underwent reverse movement (Fig 65). The majority of these faults were at relatively high angles (40-80°) and were most likely formed by some degree of inversion which led to reverse movement to occur along the pre-existing normal faults.

The Tshipise Hill, which consists of highly faulted Clarens sandstone is considered to be one such example. Palaeostress analysis conducted on the hill suggests that a N-S orientated compressional event led to its formation (Rousseau, 2015). The N-S compressional stress tensor was possibly caused by right lateral strike-slip movement along the Tshipise Fault which was translated into reverse movement to form a positive flower structure along a jog.

The Klein Tshipise Fault, in the Nuanetsi Game Reserve, also had steeply dipping (60-70°) faults, the majority of which underwent reverse movement.

In the Generaal Block, the Juliana Fault again displays a reverse sense of movement. The fault dips at approximately 50° towards the NE where the Clarens bedding, normally dipping to the NNW, has locally been drag folded along the fault towards the south, confirming the reverse sense of movement. The high angled nature of these reverse faults possibly indicates that they were normal faults formed during extension that were reactivated, or they were formed synchronously as part of the right lateral wrench.

The results from the palaeostress analyses in section 8.3 below indicates that one of the deformational events had a NW/NNW to SE/SSE directed SHmax which is correctly orientated to cause right lateral wrenching to occur.

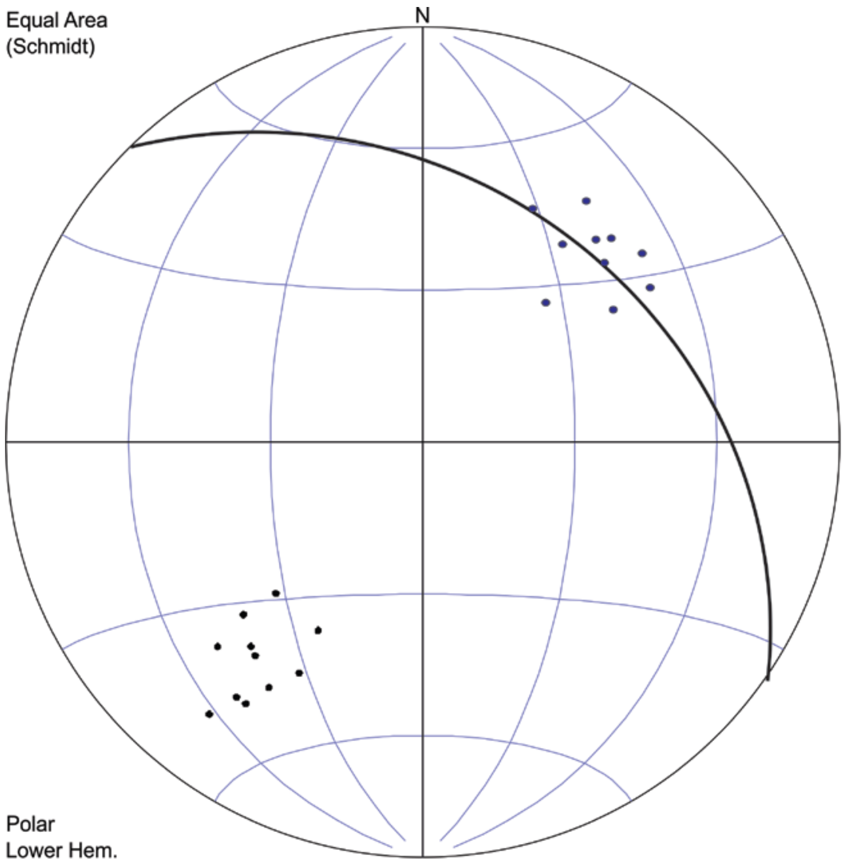


Figure 67: Poles to planes of the Juliana Fault (black points), and plane plotted together with their lineations (blue dots), on the farm Juliana (647). The sense of movement is hanging wall up which makes this is a relatively steeply dipping reverse fault. This fault abuts the Clarens sandstone, to the south against the LMB rocks to the north.

7.8. E-W trending folds

From the map patterns observed in the Tshipise Basin (Figure 60) subtle east-west trending, low amplitude folds, with wavelengths of several kilometres are visible along the Tshipise, Bosbokpoort and Voorbrug faults. These have also been identified by Broadbent (2006) who interpreted them as strike-limited basin inversion structures which are preferentially localised against the large ENE trending faults. It is likely that these folds were formed by right-lateral transpression focused along the fault planes, most likely in response to the NW/NNW – SE/SSE directed compression.

7.9. Roll-over anticline

In the Makhado Block, recent drilling results indicated the presence of a possible roll-over anticline. The cross-section, in figure 65, is based on boreholes drilled in the deeper part of the block and clearly shows that the strata do not just continue with depth but are rather folded, either from the initial normal movement of the Juliana fault, or reverse movement.

7.10. Pop-up Structures

As mentioned in section 7.3, several pop-up structures have been identified along the Tshipise Fault and are normally located along jogs within the fault, these include the Tshipise hill as well as several outliers of the Wyllie's Poort quartzite that occur along the fault further to the west. The Generaal and Wildebeesthoek blocks are also possibly up-faulted structures.

7.11. Palaeostress analysis

A palaeostress analyses was originally conducted by (Malaza, et al., 2015), however (Fagereng & Hodge, 2015) highlighted a number of inaccuracies from his interpretations and conclusions. As a result of these confusing results a palaeostress analyses was conducted in conjunction with the field mapping. The majority of the fault measurements indicate a maximum horizontal stress (SHmax/σ_1) towards the NW/NNW-SE/SSE; roughly perpendicular to the strike of the Limpopo trend, a second SHmax direction trending NE-SW was also identified. The results from this analyses indicated that there are localised variations in the stress orientations which indicates that the area was most likely subjected to multiple reactivation events. The NE-SW trending SHmax is possibly from the initial NW-SE directed extension related to the breakup of Gondwana; which was most likely also the event which led to the formation of the half-grabens in which the Karoo sediments have been preserved. The second set of measurements indicating NW/NNW to SE/SSE directed SHmax is most likely related to a subsequent event, possibly some form of inversion, related to a change in motion of the African and Antarctic plates after them separating. The second deformational event would have reactivated a large number of primary structures created during the initial event and also create additional structures. This would explain the reverse sense of movement recorded for the majority of the faults mapped in the study area. A number of these faults dip at relatively high angles (40-60°) and possibly represents normal faults created during the first deformational event that were reactivated to form high-angle reverse faults. The Juliana Fault is such an example and is also associated with a low-angle thrust fault.

Figure 68: Aerial photograph of the Mudimeli village in the Makhado Block looking towards the NW. The image shows the Fripp box-cut in the foreground with the Fripp Formation ridge behind it and Clarens sandstone ridge (Bobbejaankop) in the background.

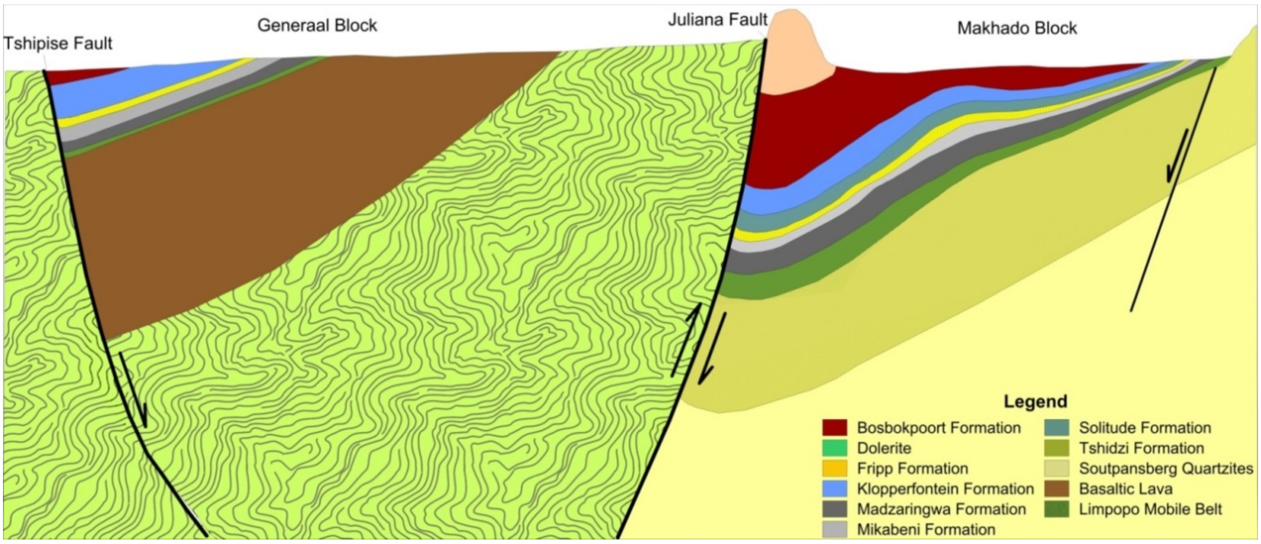


Figure 69: Sketch Cross-section across the Makhado block to the Generaal block, in the North. Localised drag folding is noted, as well as a roll-over anticline in the Makhado Block. Not to scale

8. Acoustic Televiewer Structural Measurements made in the Tshipise Basin

In the study area a large number Acoustic Televiewer (ATV) wireline surveys were conducted in the boreholes. The majority of the boreholes were relatively shallow (±60m), however numerous deeper boreholes were also logged and some of which even intersected the overlying Fripp Sandstone in which cross-bedding could be measured. Most of the ATV surveys were conducted in the boreholes drilled in the Chapudi exploration block between 2002 and 2004; however a handful of boreholes in the Makhado, Generaal, Overwinning and Mount Stuart blocks were also logged. No ATV borehole logging was conducted in the northern, Jutland or Mopane blocks. Unfortunately the borehole core were discarded after being sampled and could not be used to verify the presence or nature of the structures detected or determine the sense of movement on the faults. The author had to solely rely on his own discression to classify and 'pick' the structures from the logs.

All of the ATV measurements (picks) were made and corrected (to true north and for borehole deviation) in the software Wellcad 4.4. These measurements were then imported into stereographic projection software (Spheristat 3.0) where the data was interpreted and stereograms created of the data. Unfortunately the ATV imaging tool can only detect structures with an inclination less than 85° and many sub-vertical structures beyond the range of this tool will go undetected. In certain stereograms the detection limit window of the tool can also be seen.

The ATV measurements provide a good overview of the structural state that the Karoo strata is in although it has to be said that certain aspects of structural measurements could not be ascertained from just the logs themselves. The presence of faults could only be noted when the image displayed visible displacement in the strata. The positive aspect about these logs however was the large amount of measurements that could be made in a relatively short amount of time and across a large area. These measurements also provided data points on farms where access was not possible during the writing of this dissertation.

8.1. Regional Structural Interpretation

Fig 70 below illustrates the regional distribution of the structural measurements made from the ATV logs. Generally the structures reflect the orientations of the large faults situated in the vicinity of the boreholes and are dominated by the ENE-WSW striking structures seen throughout the basin, these structures dip on average at between 45 and 60° to the SE. Further east, towards the Siloam Fault Zone, in the Makhado, Overwinning and Mount Stuart exploration sections a set of strongly developed low-angled structures dipping between 20 and 35° are developed to the NW. These are likely to be conjugates to the prominent south-easterly dipping structures as they have the same strike direction.

In the far western part of the Tshipise Basin, the rock mass appears to be much less fractured and faulted than that near the center and east of the basin. The ATV logs of the boreholes in the westernmost parts did not contain many joints or faults and in general the rockmass is relatively unfractured, especially when situated some distance from faults. Across the Soutpansberg Karoo Basin there is an increase in faulting and tectonism from west to east with an associated increase in dolerite sill occurrences. The Siloam Fault Zone is a major structural entity that would have played a major part in the development of the basin. The NW-SE striking fractures are prominent within the Siloam Fault Zone; however in Chapudi East this orientation is detected and is possibly related to the presence of the Sand River Fault Zone.

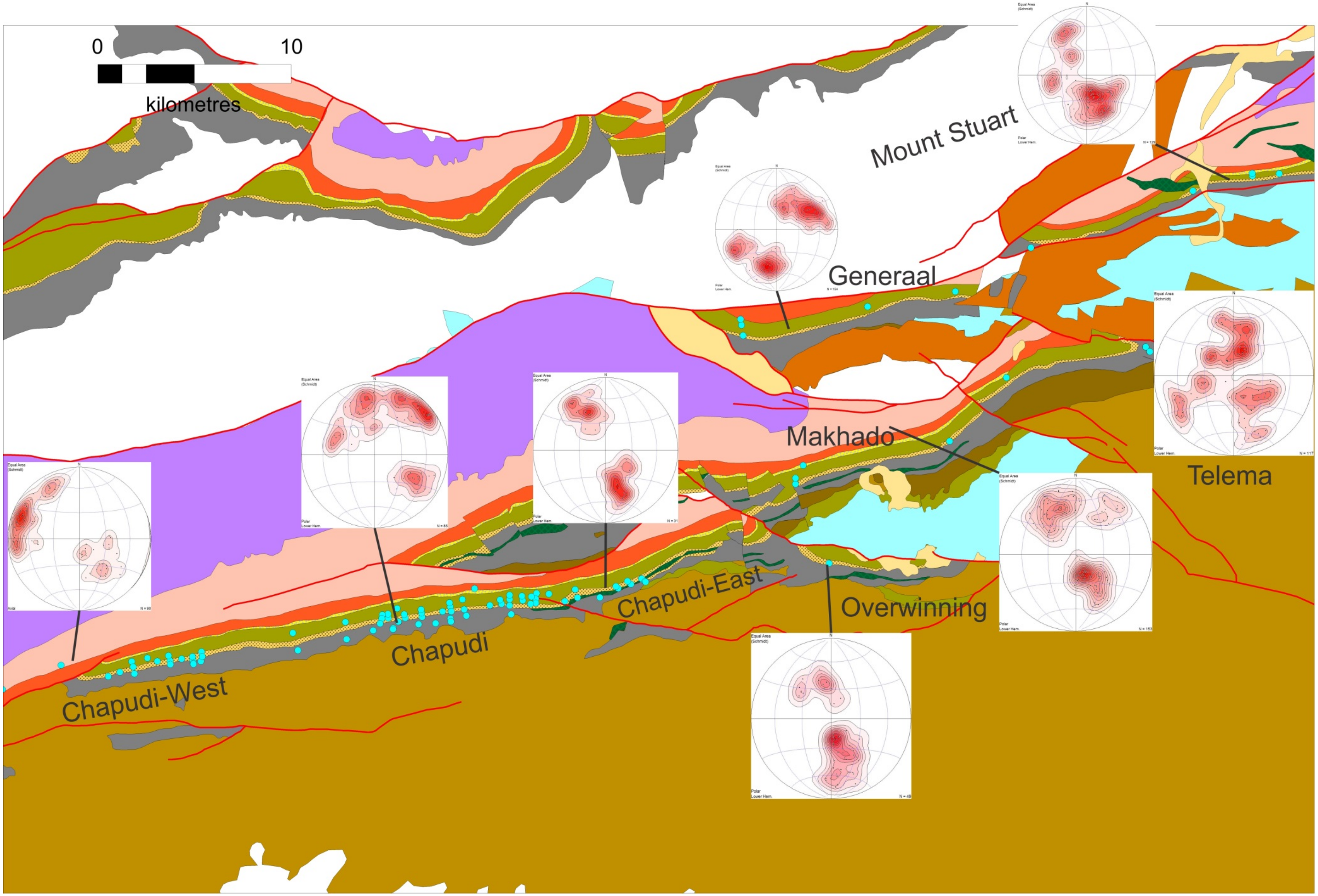


Figure 70: ATV structural measurements of all secondary planar structures, i.e. faults and joints, of the regional domains in the Tshipise Basin. The blue dots represent the boreholes.

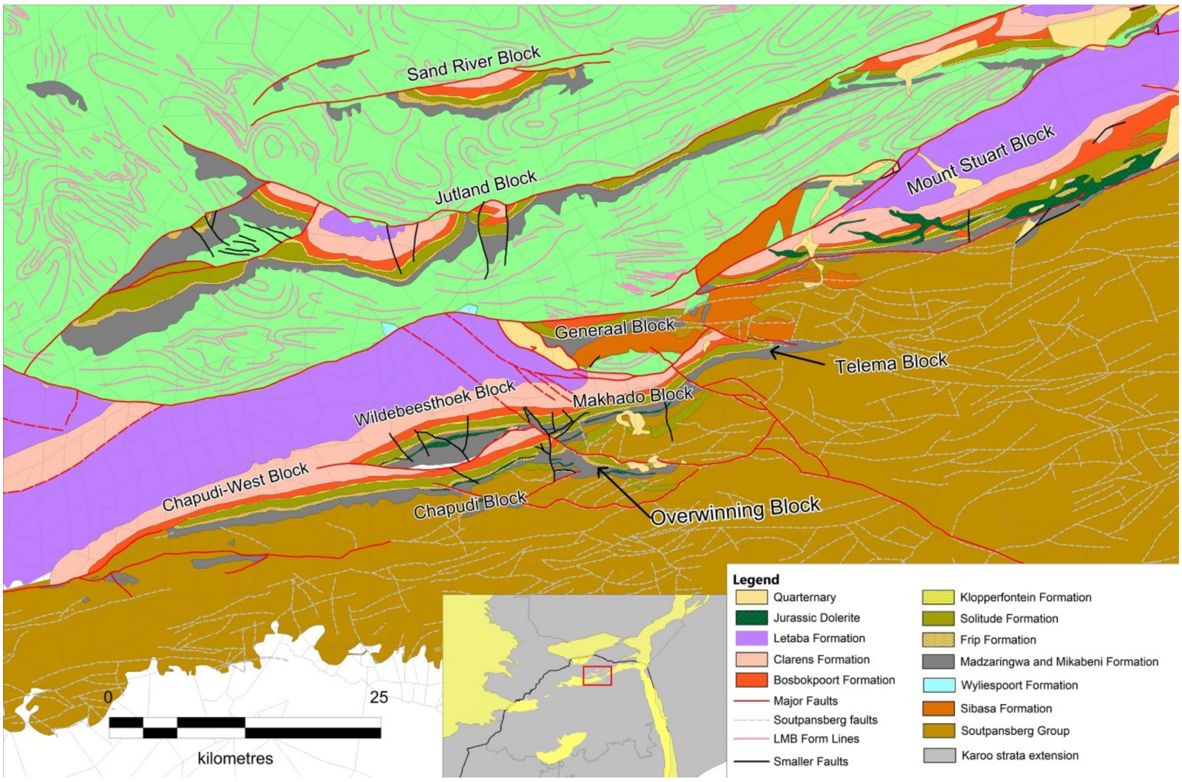


Figure 71: Structural domains used from ATV measurement classification.

8.2. Structural Domains

The boreholes in which the ATV measurements were made stretched from the western edge to the eastern edge of the southern-most block of the Tshipise Basin, approximately 80km. It was decided to group the measurements into domains of similar orientations. This approach was useful in interpreting the large amount of measurements made from the numerous boreholes.

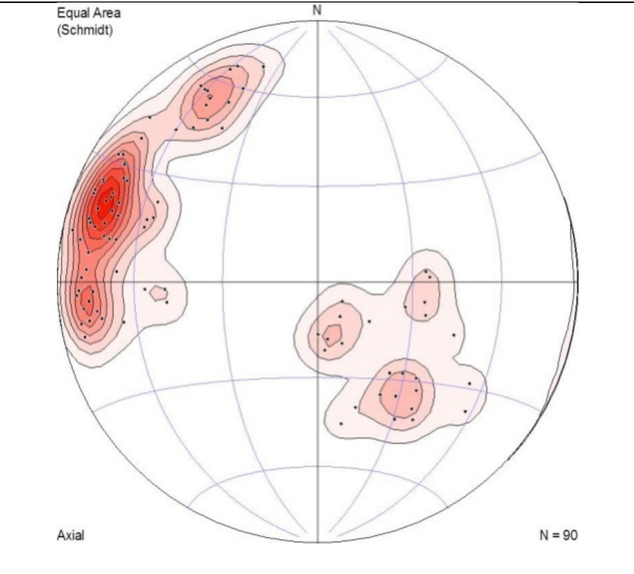
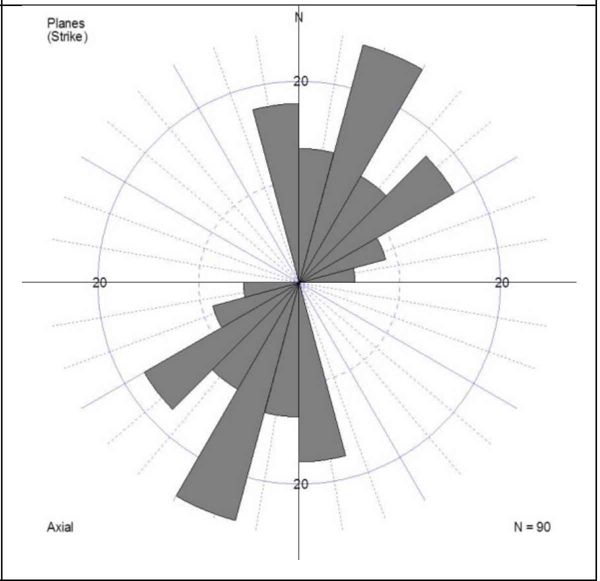
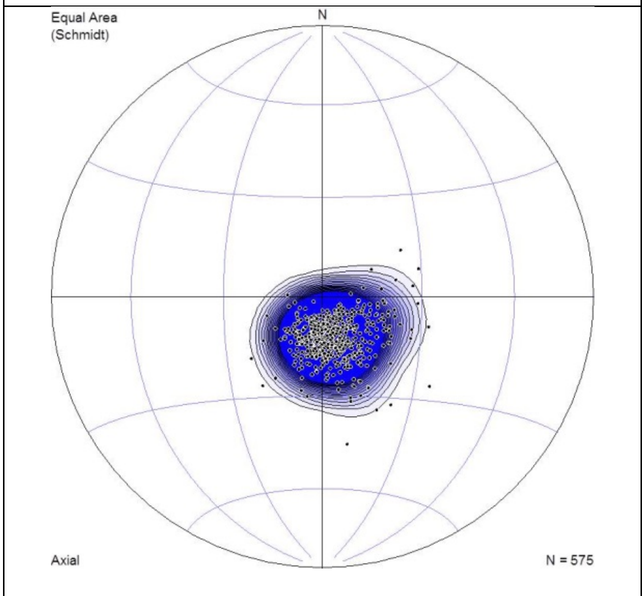
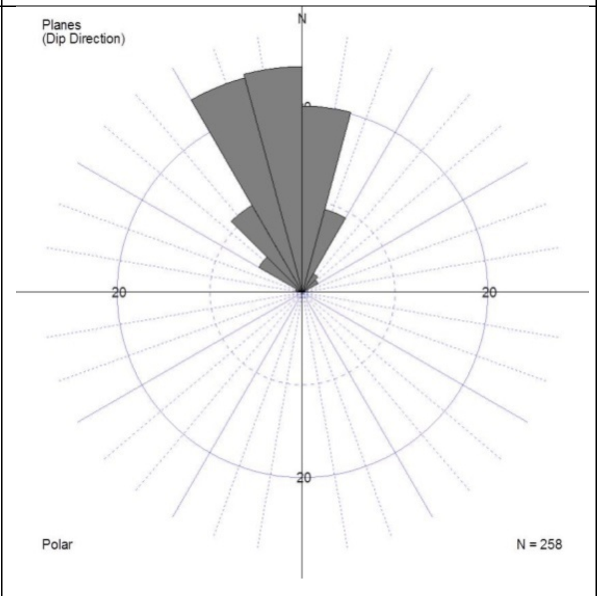
The tables below contain the set of measurements that were made for each domain. These measurements include the fractures (a collective term for all joints and faults), bedding, sandstone cross-bedding (mostly collected from the Fripp Formation), cleat orientations and drilling induced fractures.

8.2.1. Chapudi West

This area lies in the westernmost portion of the Tshipise Basin, bordering on the Mopane Basin (Fig 71). The fractures in this domain are mostly steeply dipping to the SE and a less prominent conjugate set of low angle fractures (Fig 72 A). The fractures in this domain have a dominant NNE-SSW strike not seen in any of the other domains and are ascribed to the change in orientation of the Zoutspan Fault or possibly by other faulting not noted on the geological maps.

The bedding of this area has a mean value of 12° dipping towards the NNW (354°) (Fig 72 B). The cross-bedding measurements were rotated back to their original position prior to the northward tilting of the block. Fig 72 C shows the cross bedding measurements of the Fripp Formation having a dominantly SE transport direction.

The cleat orientations were also rotated and fig 72 D shows their orientation in the original bedding being dominantly NE-SW with a lesser developed butt cleat striking E-W. Only a limited amount of coal cleats could be measured in this area.

<table>
<tr><td colspan="2">Chapudi-West ATV measurements</td></tr>
<tr><td>A)Fractures (poles to planes)</td><td>Fractures (Strike direction)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>B)Bedding (poles to planes)</td><td>Bedding (Dip direction)</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

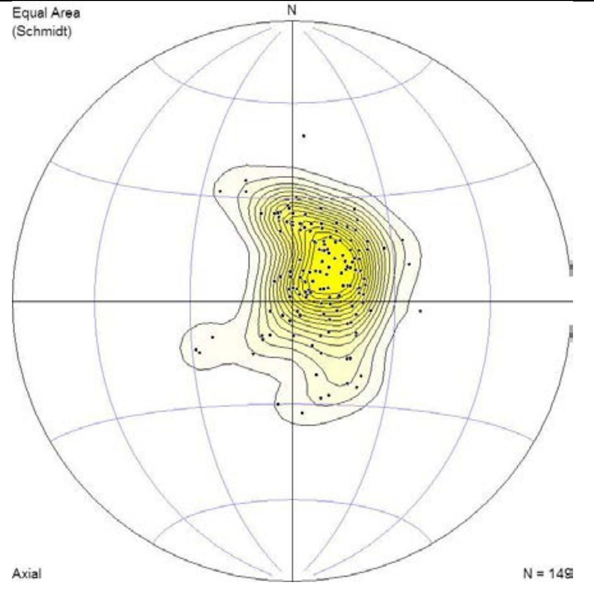
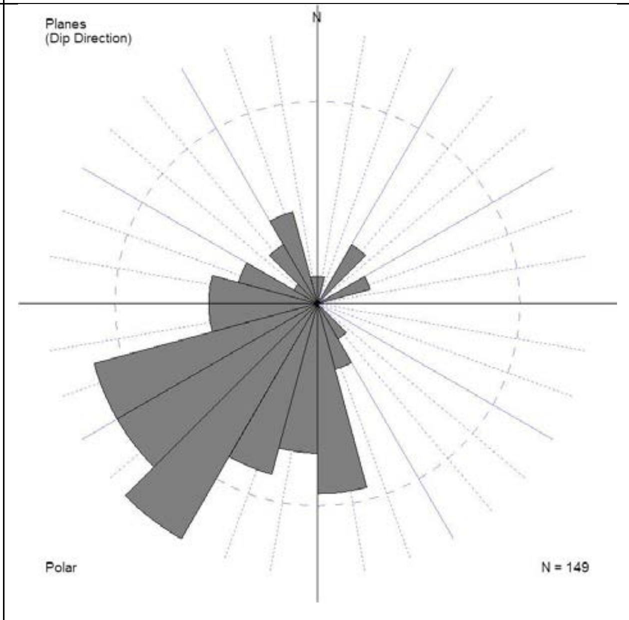
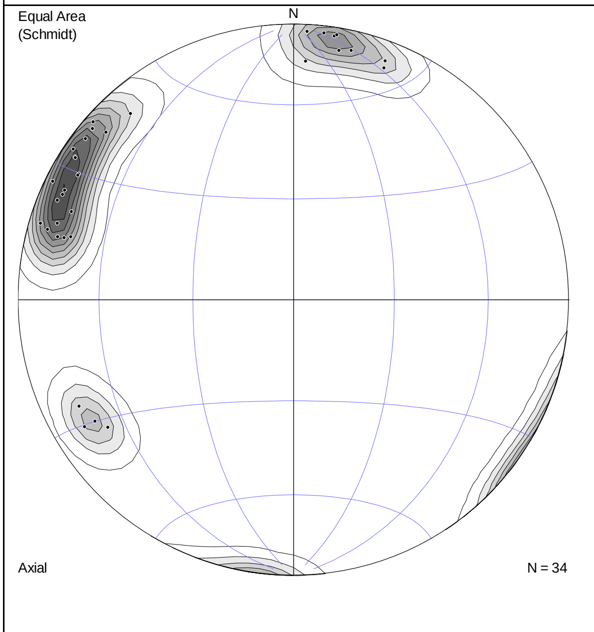
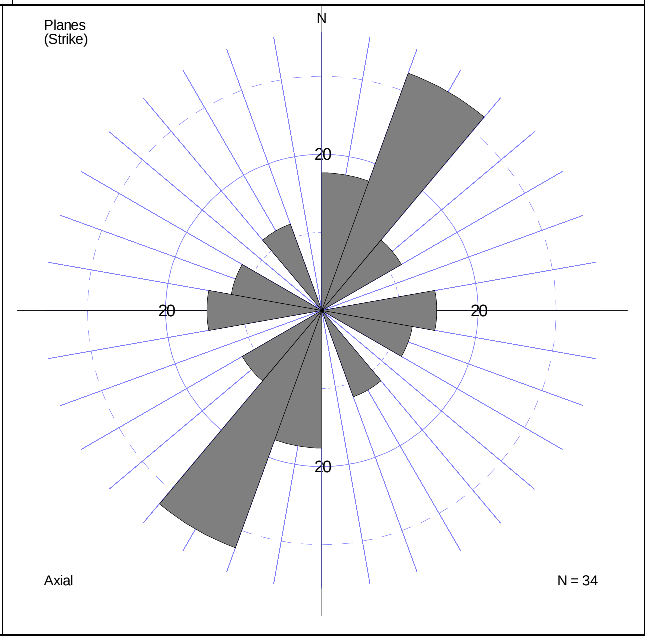
C)Sandstone bedding (Poles to planes)	Sandstone Bedding (Dip-direction)
	
D) Cleats (poles to planes)	Cleats (Strike-direction)
	

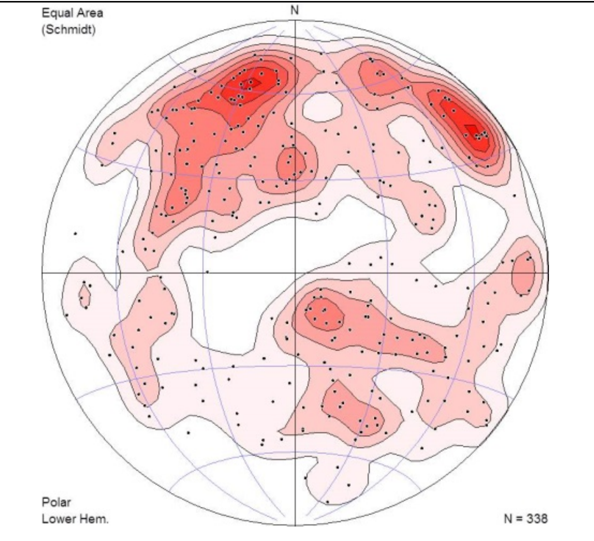
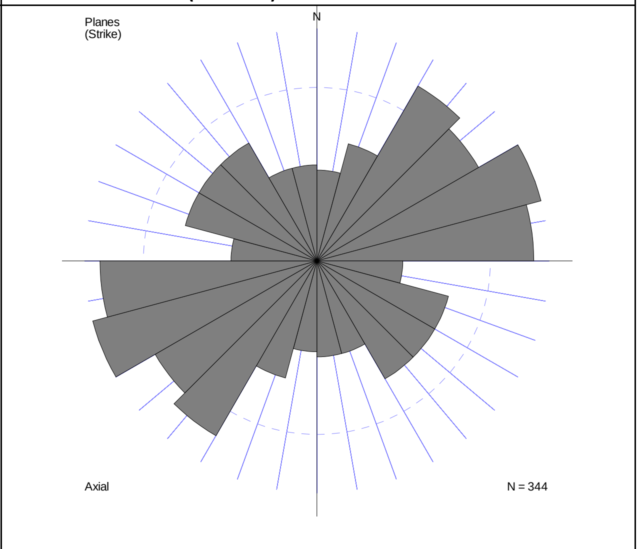
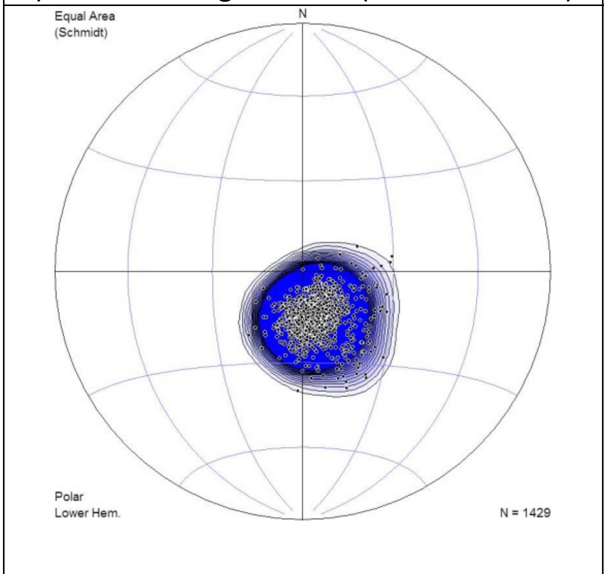
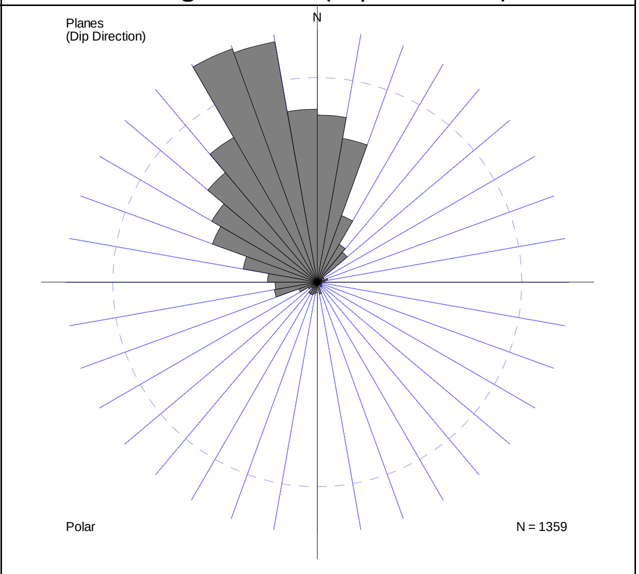
Figure 72: Chapudi West ATV measurements. A) Fractures B) Bedding C) Sandstone Bedding D) Cleats

8.2.2. Chapudi Central

This domain lies between the western and eastern Chapudi domains and contains the majority of the measurements that were made. This domain contains two dominant fractures sets, a NNW-SSE and NE-SW striking direction. The first set (NNW striking) dips to the SE (60°) and has a less well-developed low-angle conjugate pair. The second set (NE-SW striking set) dips at a steep angle to the SW with no apparent conjugate set.

The bedding in this domain dips at approximately 16 degrees to the NNW (356°) (Fig 73 B). The Fripp cross-bedding data shows a transport direction ranging from north to south-west, with the dominant direction being west.

The cleat measurements (shown in Fig 73 D) have two directions, one being the dominant NE-SW striking face cleat set and the other being the less well-developed NW-SE striking set, possibly the butt cleats.

Chapudi-Central ATV Measurements	
A) All fractures (Poles to Planes)	All Fractures (Strike)
	
B) Main Bedding of Strata (Poles to Planes)	Main Bedding of Strata (Dip direction)
	

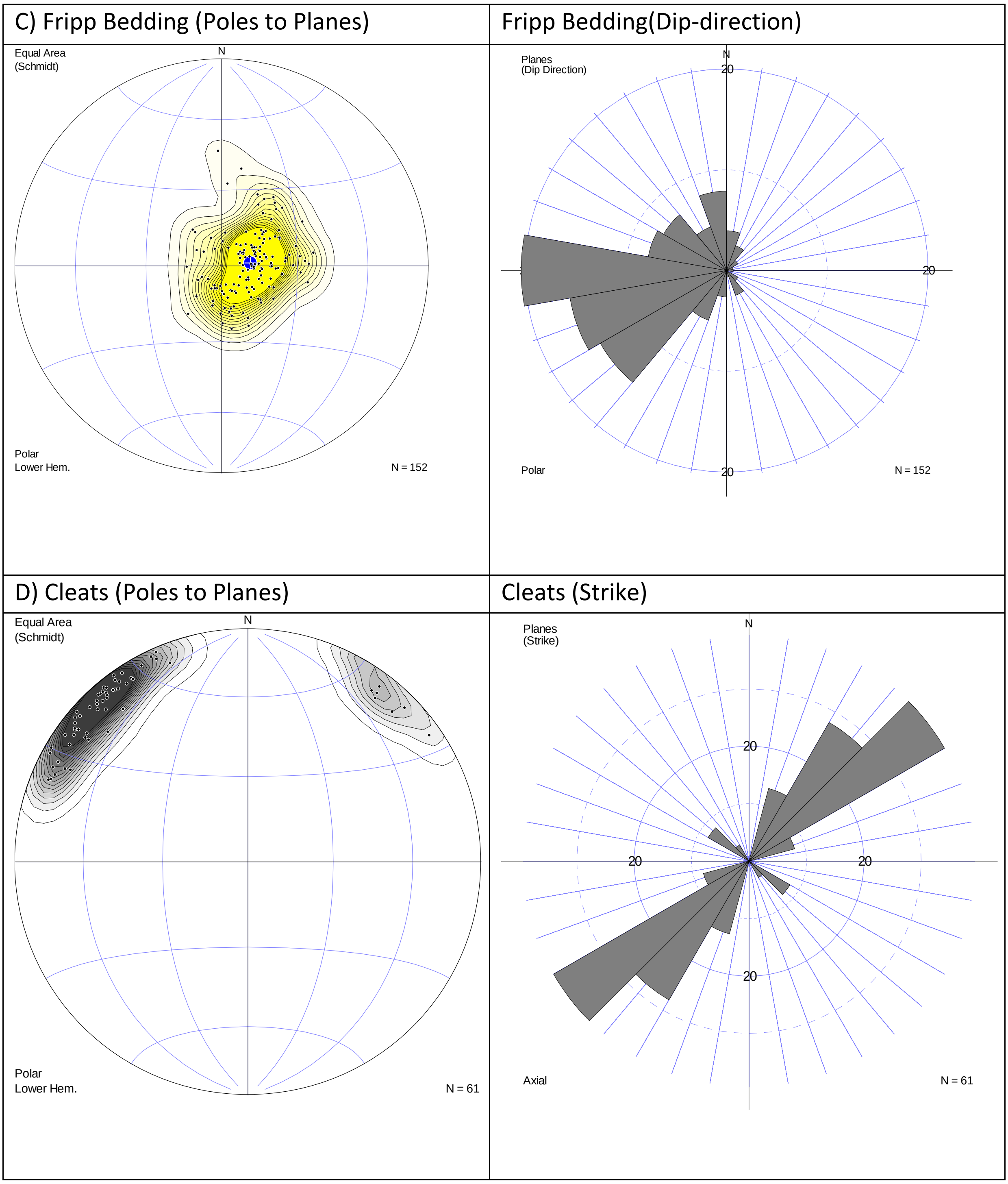
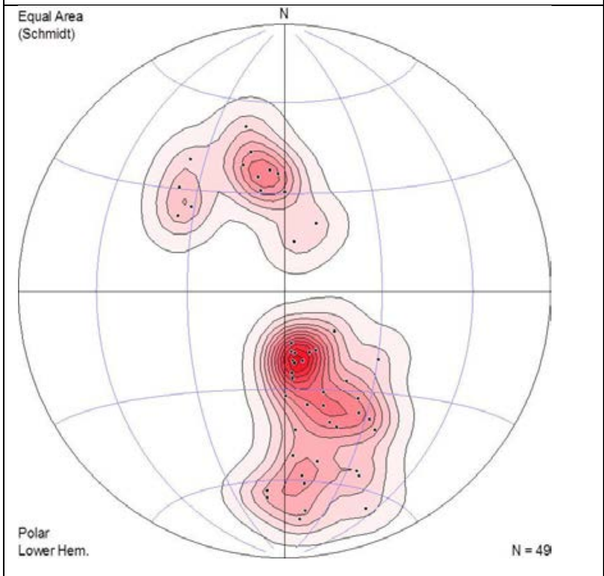
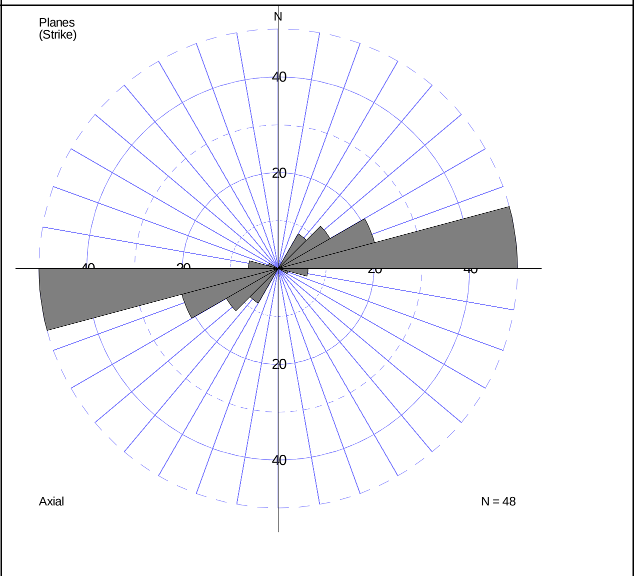
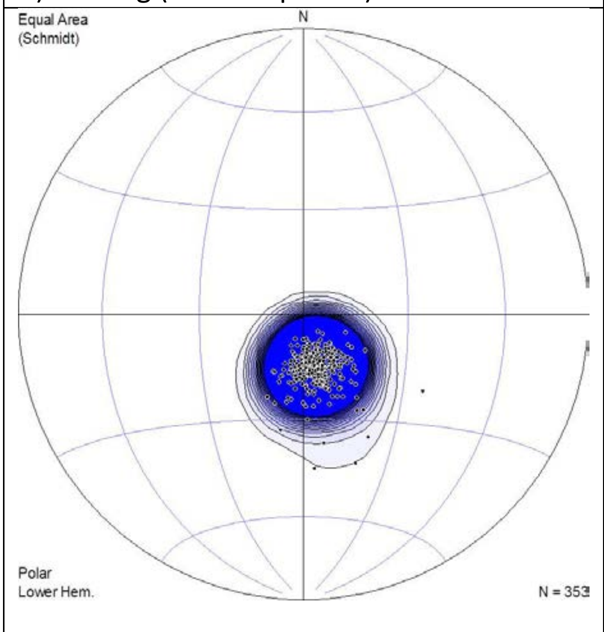
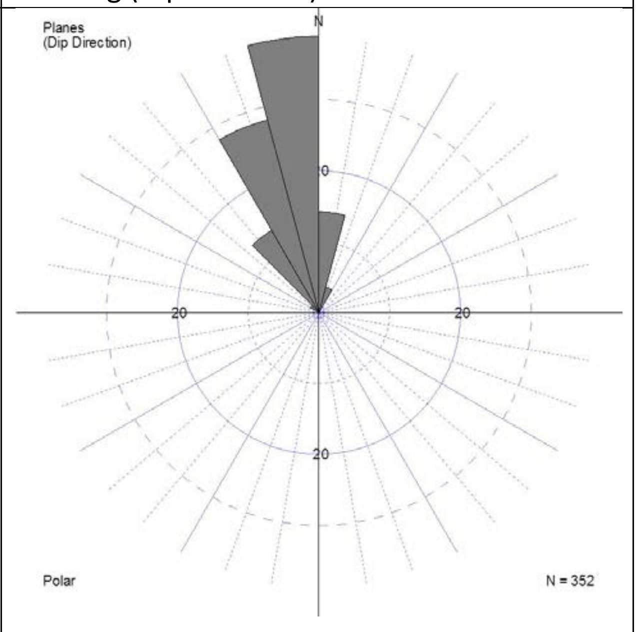
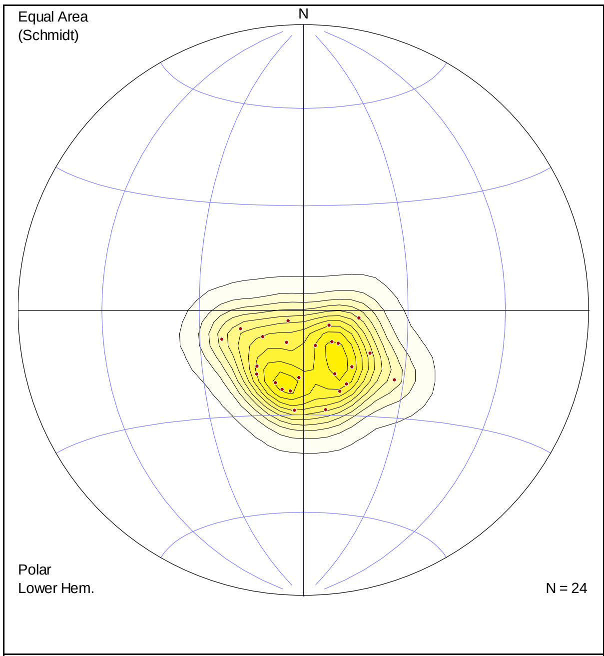


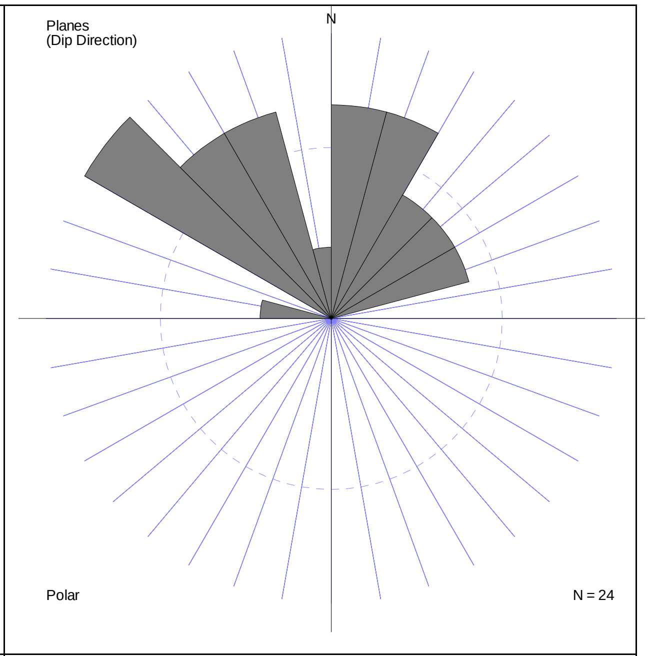
Figure 73: Chapudi Central ATV Measurements. A) Fractures B) Bedding (Strata) C) Sandstone cross-bedding D) Cleats

8.2.3. Overwining

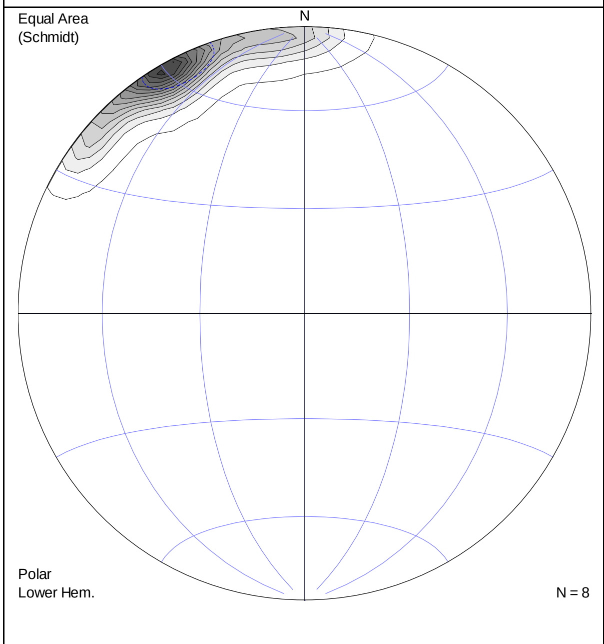
The Overwining domain is bounded to the north by an E-W fault, associated with the Siloam Fault Zone, which juxtaposes a narrow wedge of Karoo sediments against the Wylliespoort Formation to the north. The stereogram in Fig 74 A shows one conjugate set of structures dipping at a relatively low to intermediate angle of between 20 and 40° to the north and the south. The north dipping set is better developed than its southern counterpart and appears to contain a wider range of dips. The bedding is very similar to the previous areas and dips at a mean value of 15° to the N (348°) Fig 74 B. The Fripp sandstone measurements on the other hand show a transport direction ranging from the ENE to the NW (Fig 74 C).Only one set of cleats were made in this domain striking in an ENE-WSW direction.

<table>
<tr><th colspan="2">Overwining ATV Measurements</th></tr>
<tr><td>A)Fractures (Poles to planes)</td><td>Fractures (Strike-direction)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>B)Bedding (Poles to planes)</td><td>Bedding (Dip-direction)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>C)Sandstone Bedding (Poles to planes)</td><td>Sandstone bedding (Dip-direction)</td></tr>
</table>





D)Cleats (poles to Planes)	Cleats (Strike-direction)



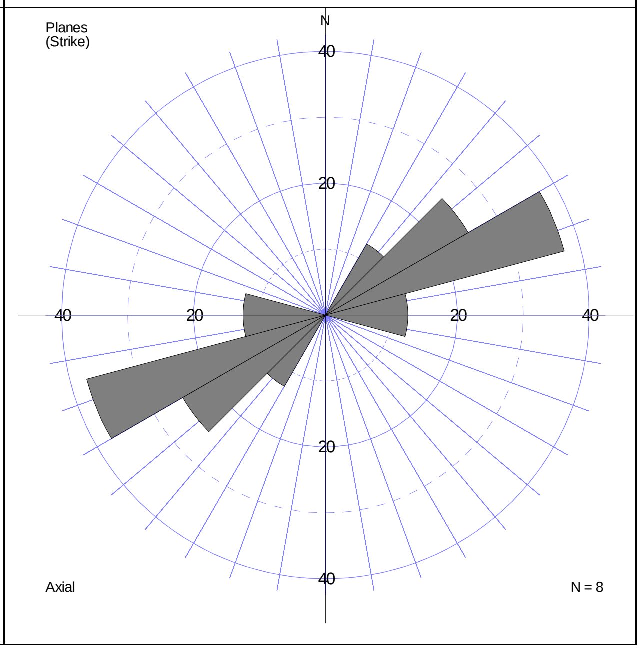


Figure 74: Overwining ATV Measurements. A) Fractures B) Bedding (Strata) C) Sandstone cross-bedding D) Cleats

8.2.4. Makhado

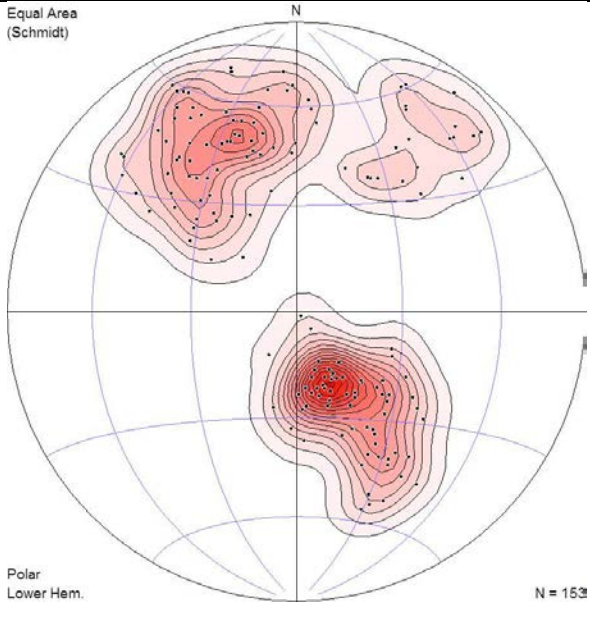
The Makhado Block is situated within the Siloam Fault Zone and the stereogram in Fig 75 A displays the characteristic ENE-WSW trending conjugate set of north (20-50°) and south dipping (30-70°) structures. A second set of NW-SE striking structures, dipping at approximately 30 and 75° are present which is the direction of the Siloam Fault Zone. These structures were especially prominent on the western part of the block on the farm Windhoek 649 where the Karoo strata is heavily block faulted. On the farm Castle Koppies (657) and Sulphur Springs (658), the intense faulting is seen on surface by the displacement of the Clarens sandstone hills (Fig 62).

The mean bedding in the Makhado block dips at 19° to the NNW (339°) and is somewhat steeper compared to the domains further west. There are minor occurrences of southward dipping strata normally in close proximity to faults. The cross-bedding measurements in the Fripp sandstone indicate a transport direction ranging from NNW to SE (Fig 75 C).

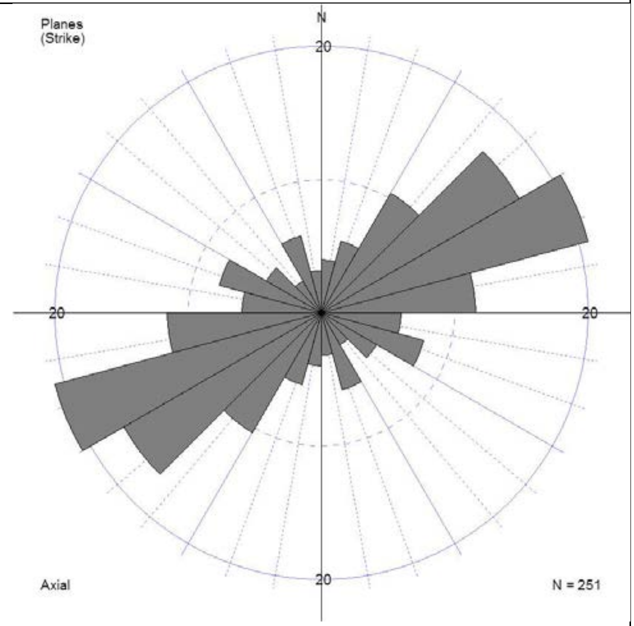
The cleat measurements show a dominant NE-SW trending face cleat orientation with a minor NW-SW set butt cleat set (Fig 75 D).

Makhado block ATV Measurements

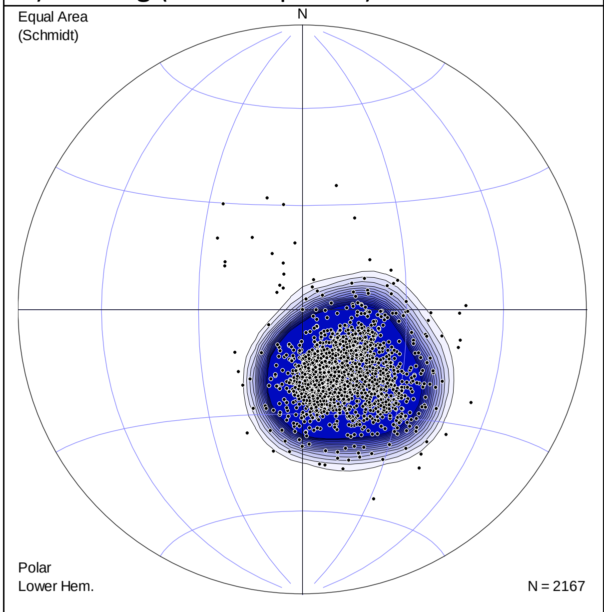
A)Structures (Poles to planes)



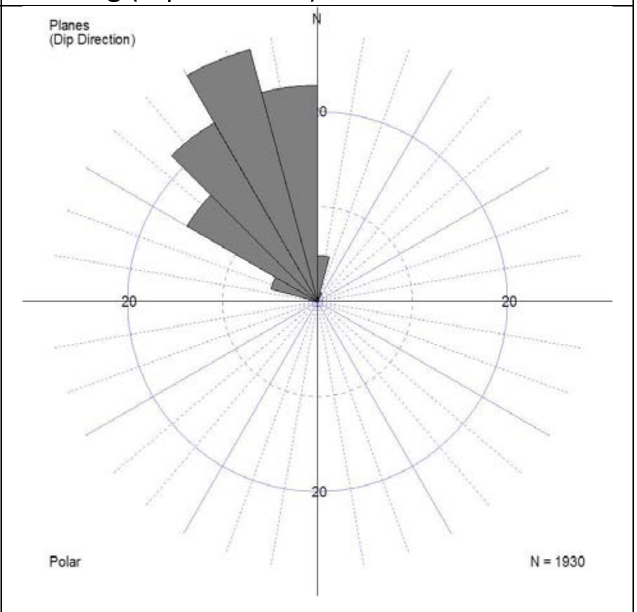
Structures (Strike-direction)



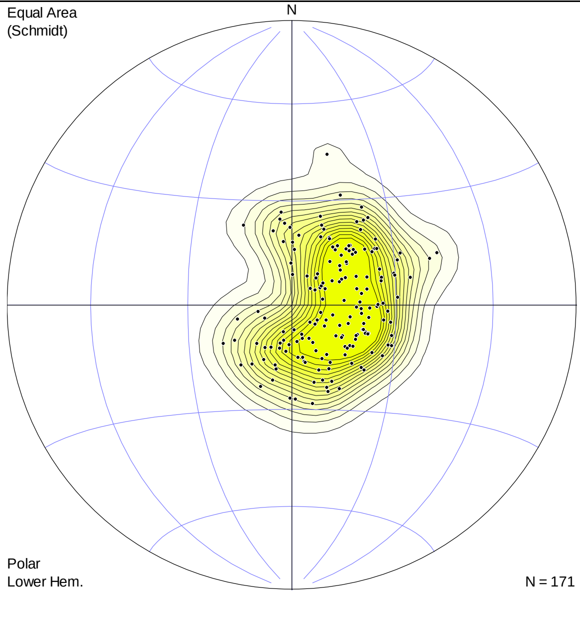
B)Bedding (Poles to planes)



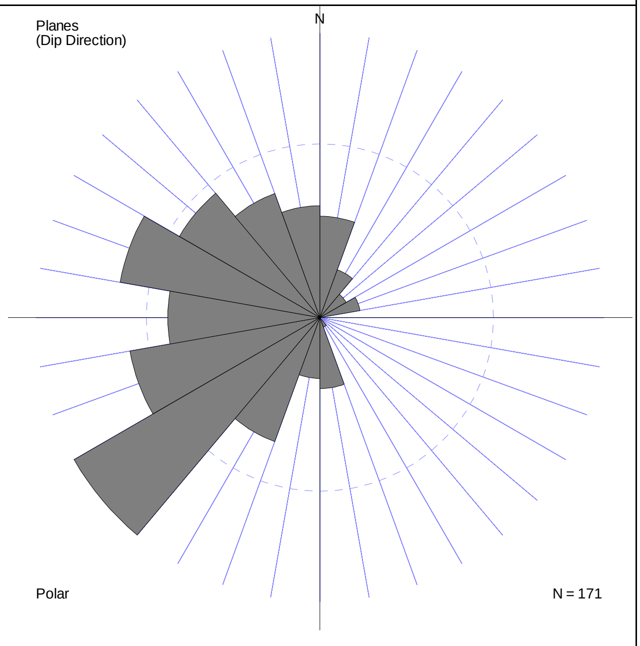
Bedding (Dip-direction)



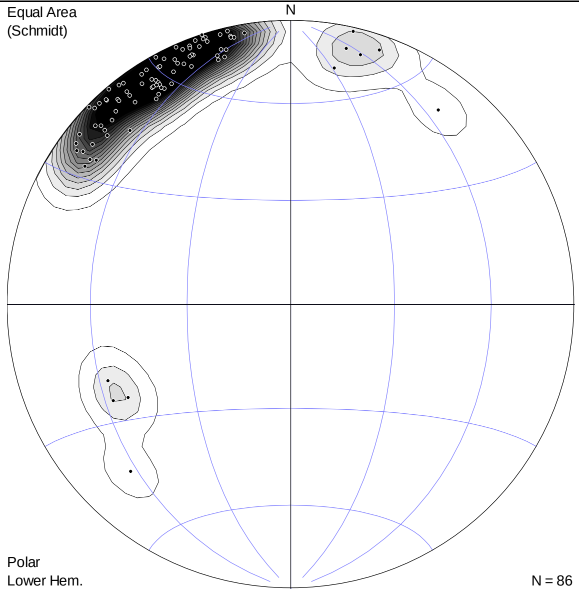
C) Sandstone cross-bedding (Poles to planes)



Sandstone cross-Bedding (Dip-direction)



D) Cleats (Poles to planes)



Cleats (Strike Direction)

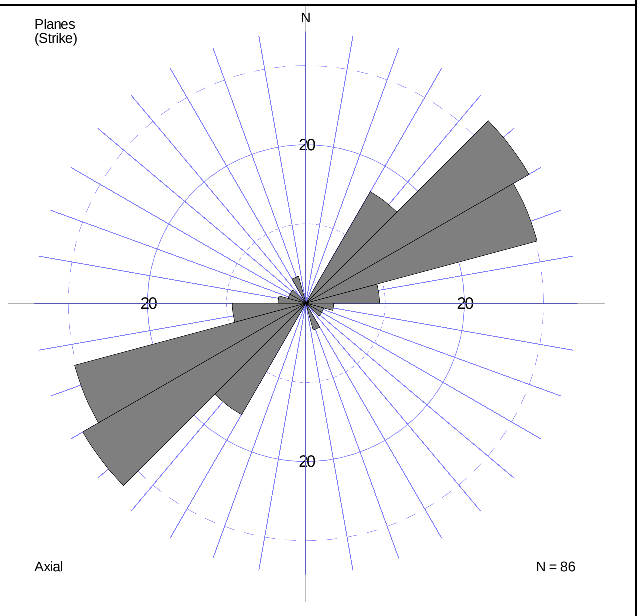


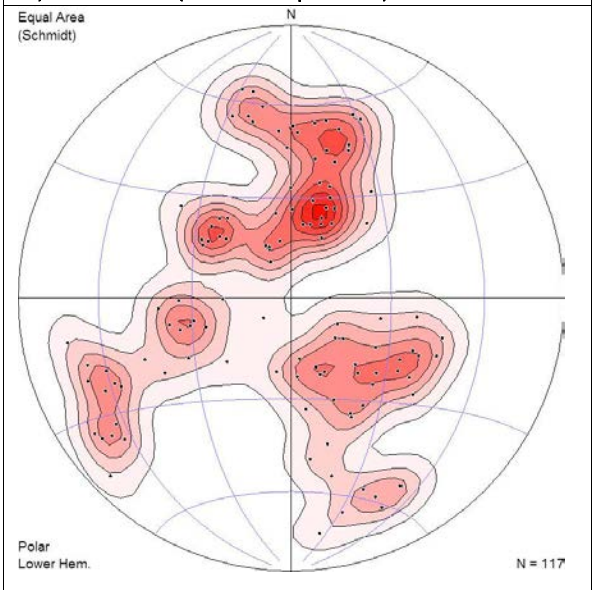
Figure 75 Makhado ATV Measurements. A) Fractures B) Bedding (Strata) C) Sandstone cross-bedding D) Cleats

8.2.5. Telema Block

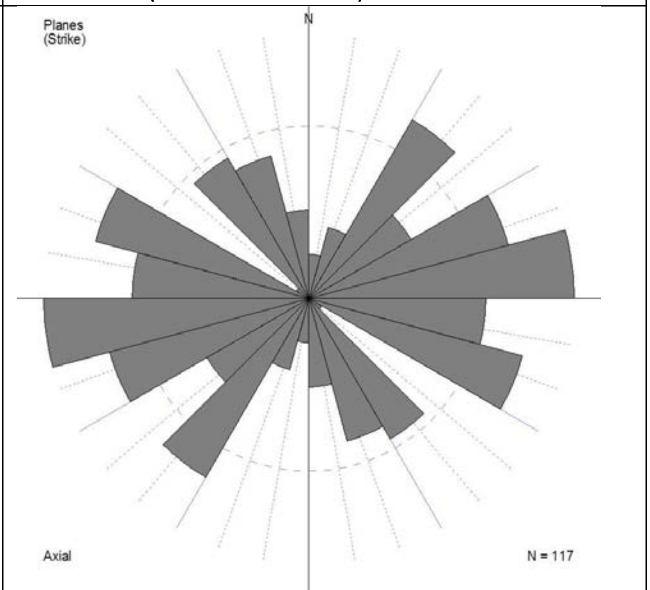
The Telema block lies just east of the Makhado block and gently thins eastwards where it is eventually juxtaposed against WNW-ESE trending fault. The structural measurements made in this area reflect this large fault. The bedding measurements dip mostly towards the SSE however it was noted that the measurements in the bottom half of the borehole were dipping in the opposite direction (NNW). The depth at which the orientation of the measurements change indicate the presence of a fault which has rotated the beds towards the opposite direction.

Telema Block ATV measurements

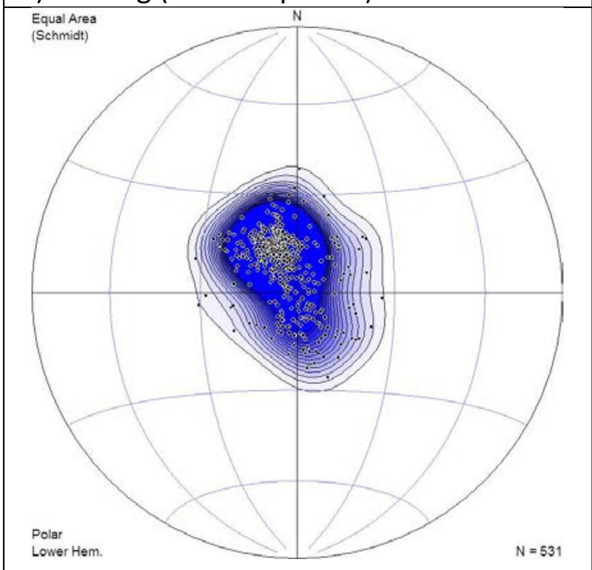
A)Fractures (Poles to planes)



Fractures (Strike-direction)



B)Bedding (Poles to planes)



Bedding (Dip-direction)

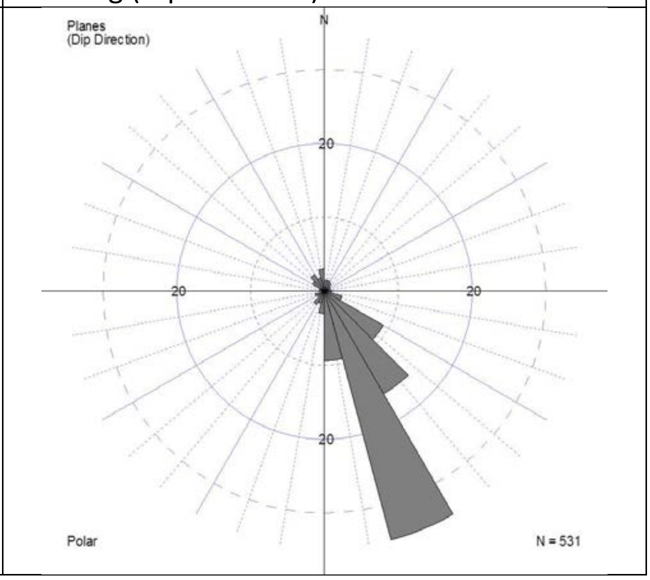


Figure 76 Telema and Gray ATV measurements A) Fracture B) Bedding

8.2.6. Generaal

The Generaal Domain is situated north of the Makhado Block and possibly represents a large pop-up structure bounded between the Tshipise Fault (to the north) and the curved Juliana Fault (to the south). This block is also unique in that it contains one of the only occurrences of LMB lithologies south of the Tshipise Fault. The eastern edge of the domain is highly block faulted and both the basement and Karoo lithologies are folded. The arcuate shaped Sibasa Basalt fold patterns possibly pre-date the folding in the Karoo sediments.

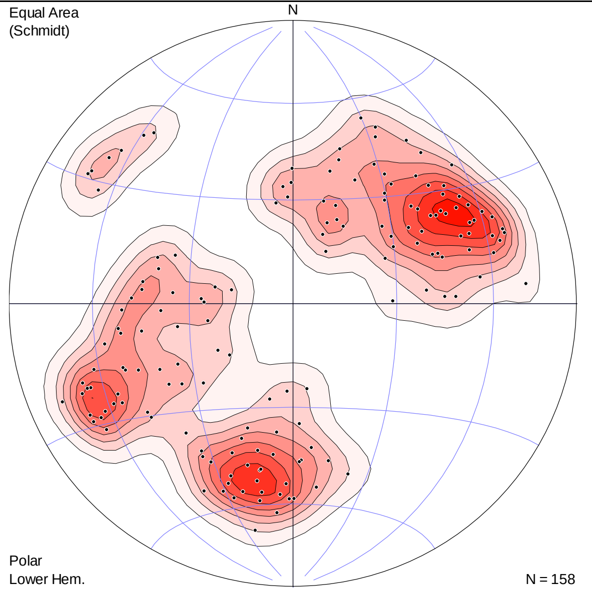
This domain consists broadly of two different sub-domains. The first is within the central and eastern part of the block which shows a higher fracture occurrence than the western part and is dominated by the conjugate set of NW-SE striking fractures, characteristic of the Siloam Fault Zone. A second set of moderately steep (40-60°) NNE dipping fractures are seen, possibly associated with the southern bounding Juliana Fault. A third set of moderately eastward dipping (20-60°) fractures are also present. Lastly, a minor set of steep SW dipping (60-65°) structures is seen, possibly related to the Tshipise Fault.

The bedding measurements in the eastern and central part of the block dip towards the NNE (019°) at a mean dip of 12°. In the western part of the domain, two boreholes (587MS003 and 587MS002) approximately 300m apart contain strata dipping to the SE and ENE respectively (Fig 77 B, D and E). This might be as a result of folding in the Karoo strata, the fold having a NNW striking fold axis.

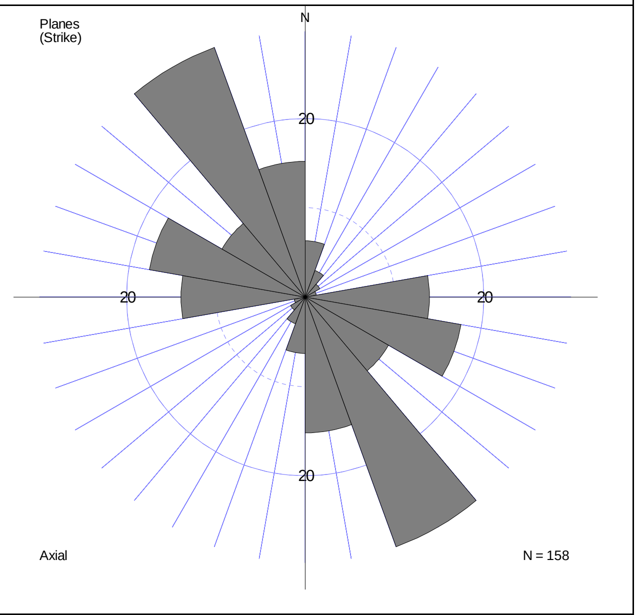
The measurements made here are very similar to the fault measurements made in the Clarens Formation in the southern bounding Juliana fault. The field measurements indicated reverse movement on both of these fault sets (Fig 67) associated with drag folding.

Generaal ATV measurements

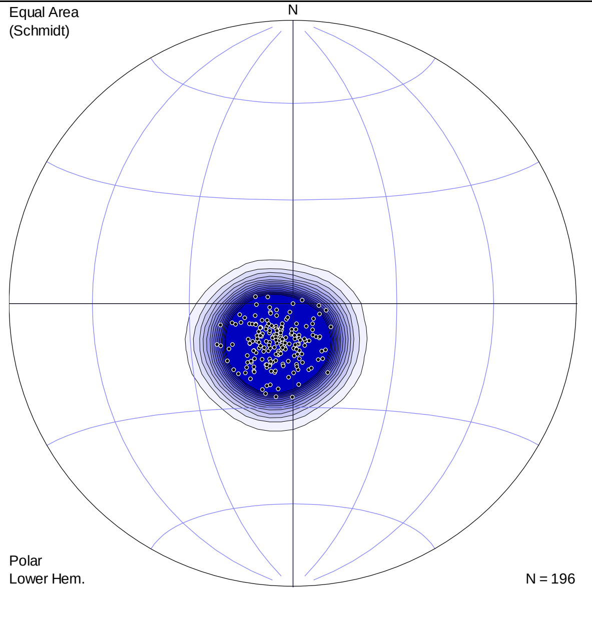
A) Eastern and Central sub-domain, fractures



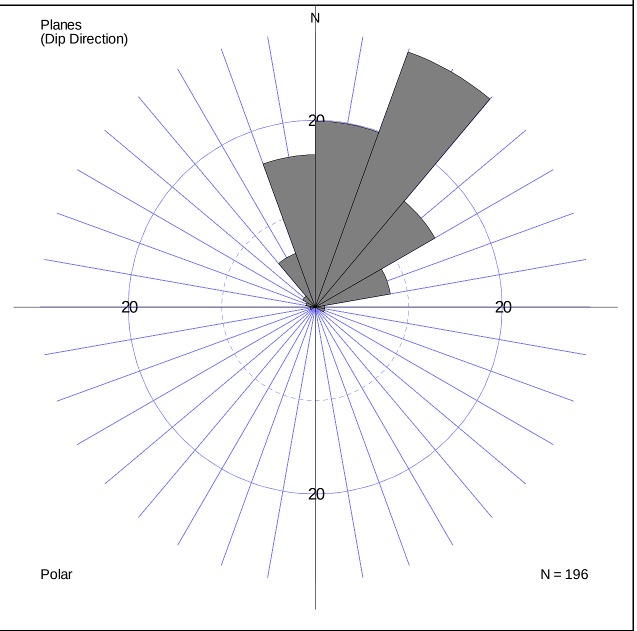
Fractures strike direction

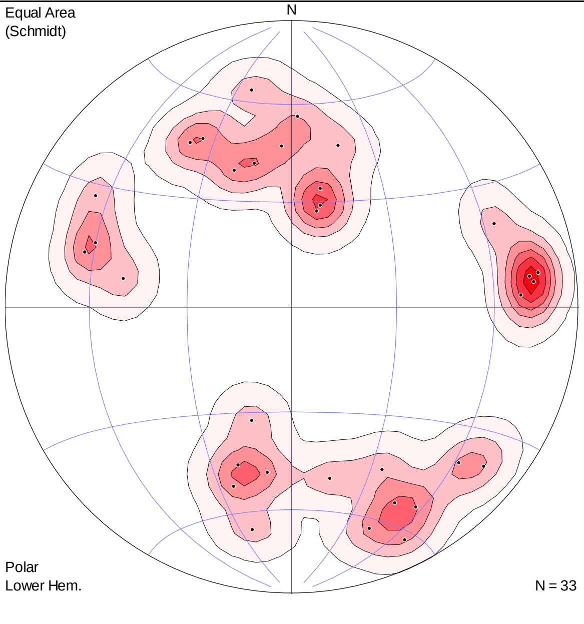
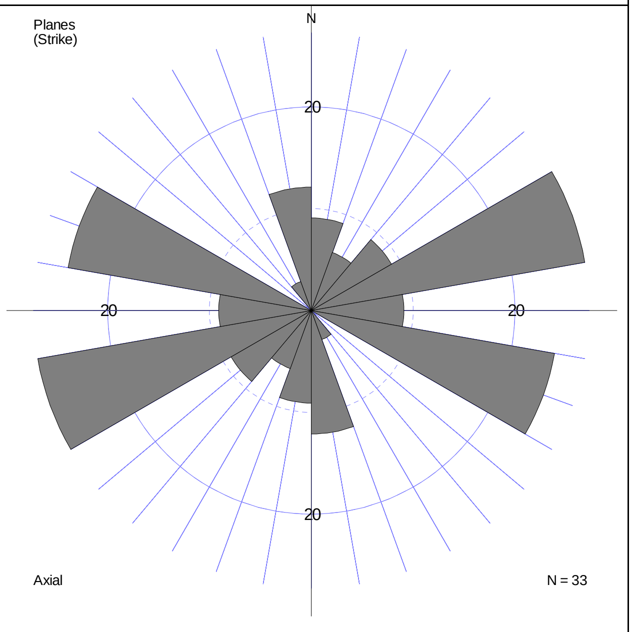
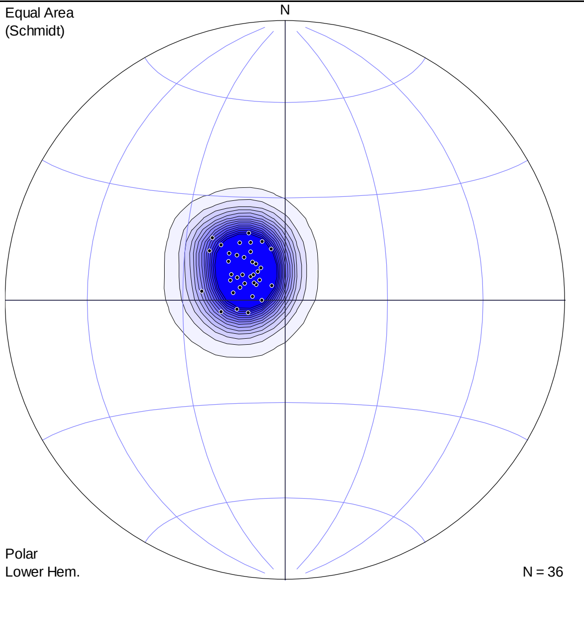
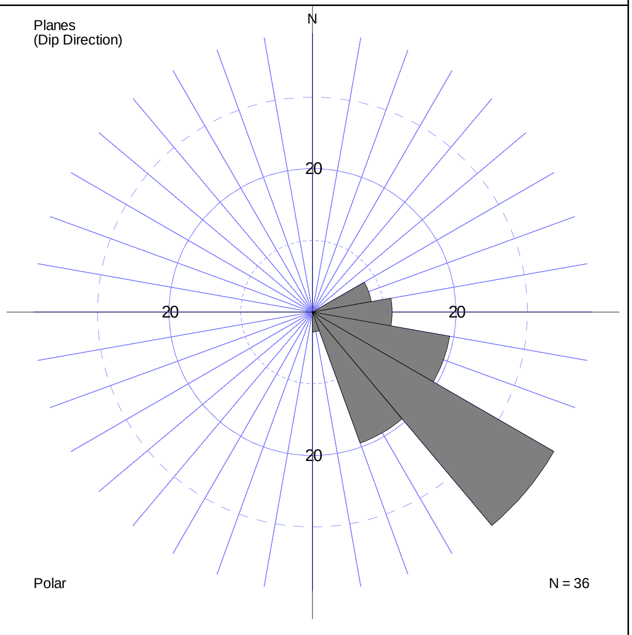


B) Eastern and Central sub-domain, bedding



Bedding dip direction



C) Western domain, Fractures	Fractures Strike direction
	
D) Western Domain borehole 587MS003 bedding	Bedding Dip direction
	

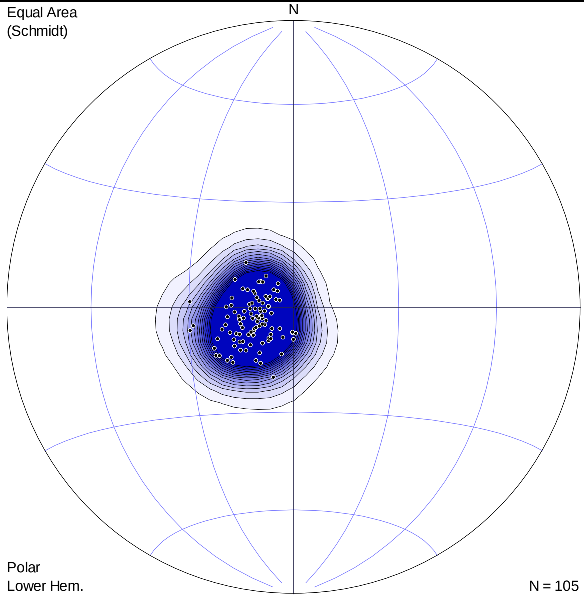
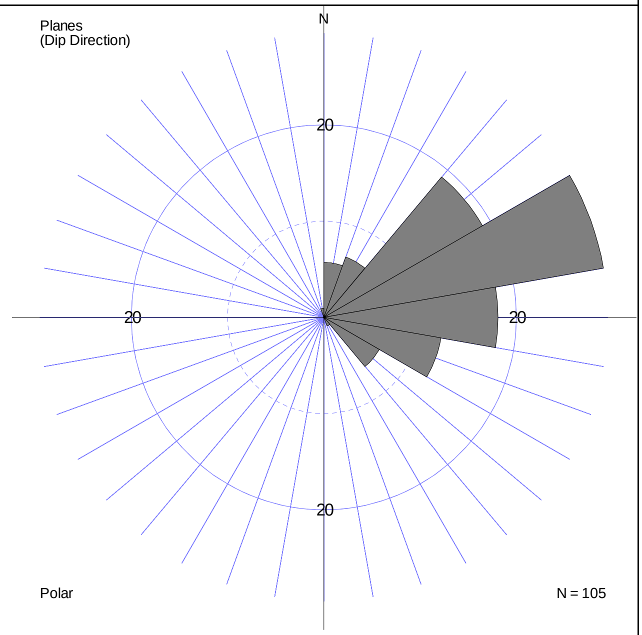
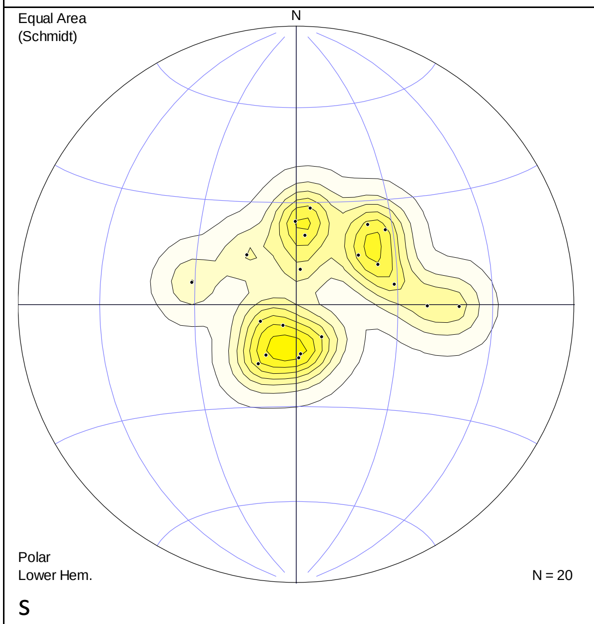
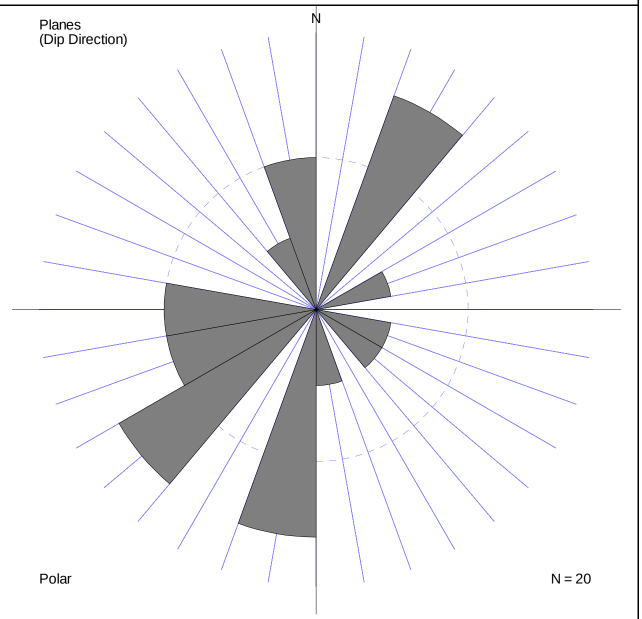
E) Western Domain borehole 587MS002 bedding	Bedding Dip Direction
	
F) Sandstone bedding (Pole to planes)	Sandstone bedding (Dip-direction)
	

Figure 77 Generaal ATV Measurements. A) Fractures in eastern domain B) Bedding in in eastern domain, C) Fractures in eastern and central domain, D) Bedding in western domain, F) Sandstone cross-bedding

8.2.7. Mount Stuart

This domain occurs within the easternmost part of the Tshipise Basin and also lies east of the Siloam Fault Zone.

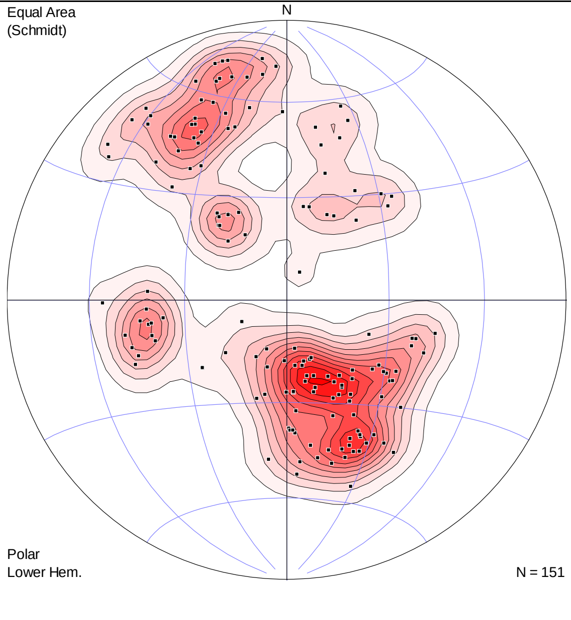
The fracture measurements made in this domain are dominated by the ENE-WSW striking set. The conjugate set of fractures dip to the south at between 45 and 75° and to the north at between 25 and 60°. A minor set of structures dipping at approximately 45° to the east are also present (Fig 78A).

The bedding measurements indicate that the strata dip towards the NNW (339°) with a mean dip of 16° (Fig 78B). On the farm Nakab 184, the strata dip more towards the north with an average dip of 17° to the north (003). This farm is at the junction of the Tshipise and Klein Tshipise fault and these changes in dip probably indicate folding limited along the Tshipise fault. The borehole on this farm (184MT004) has very thin coal measures developed within the Madzaringwe Formation and rather contains coarse-grained sandstone and siltstone units with a palaeo-current direction towards the ESE. These palaeo-current measurements are some of the only transport direction points measured within the lower Ecca unit of the Tshipise Basin. The Fripp Formation has a transport direction ranging from NW to SW with the most dominant direction being W.

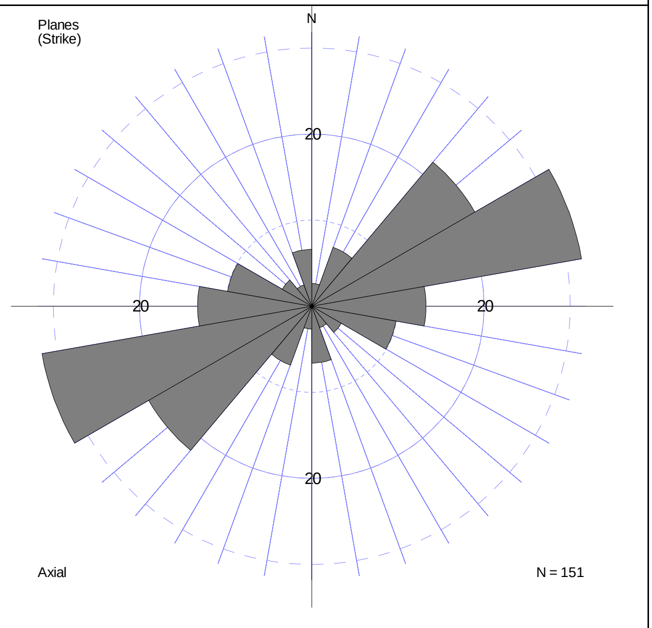
One set of cleats were identified in the area striking in an ENE-WSW direction. This is the average strike for the main cleating direction seen throughout the entire Tshipise Basin, with slight variations seen throughout.

Mount Stuart ATV Measurements

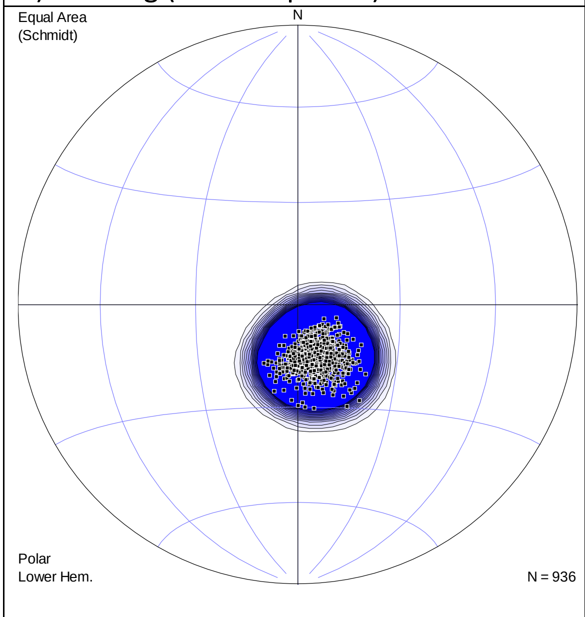
A) Fractures (Poles to planes)



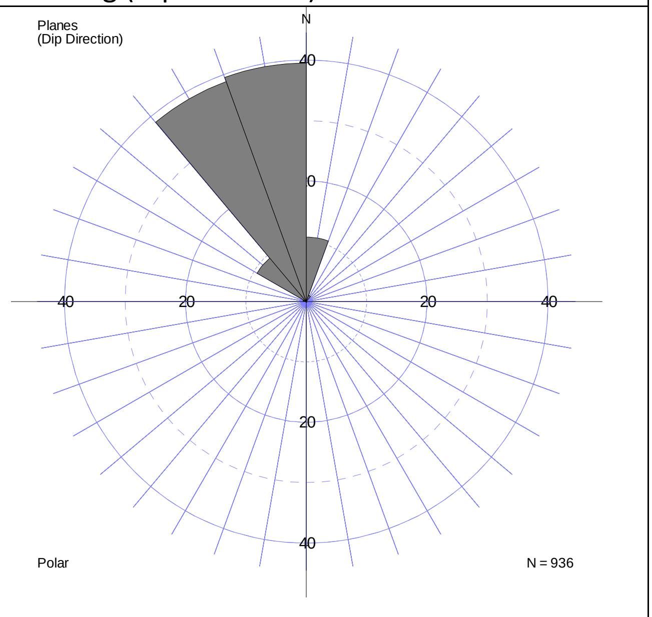
Fractures (Strike-direction)



B) Bedding (Poles to planes)



Bedding (Dip-Direction)



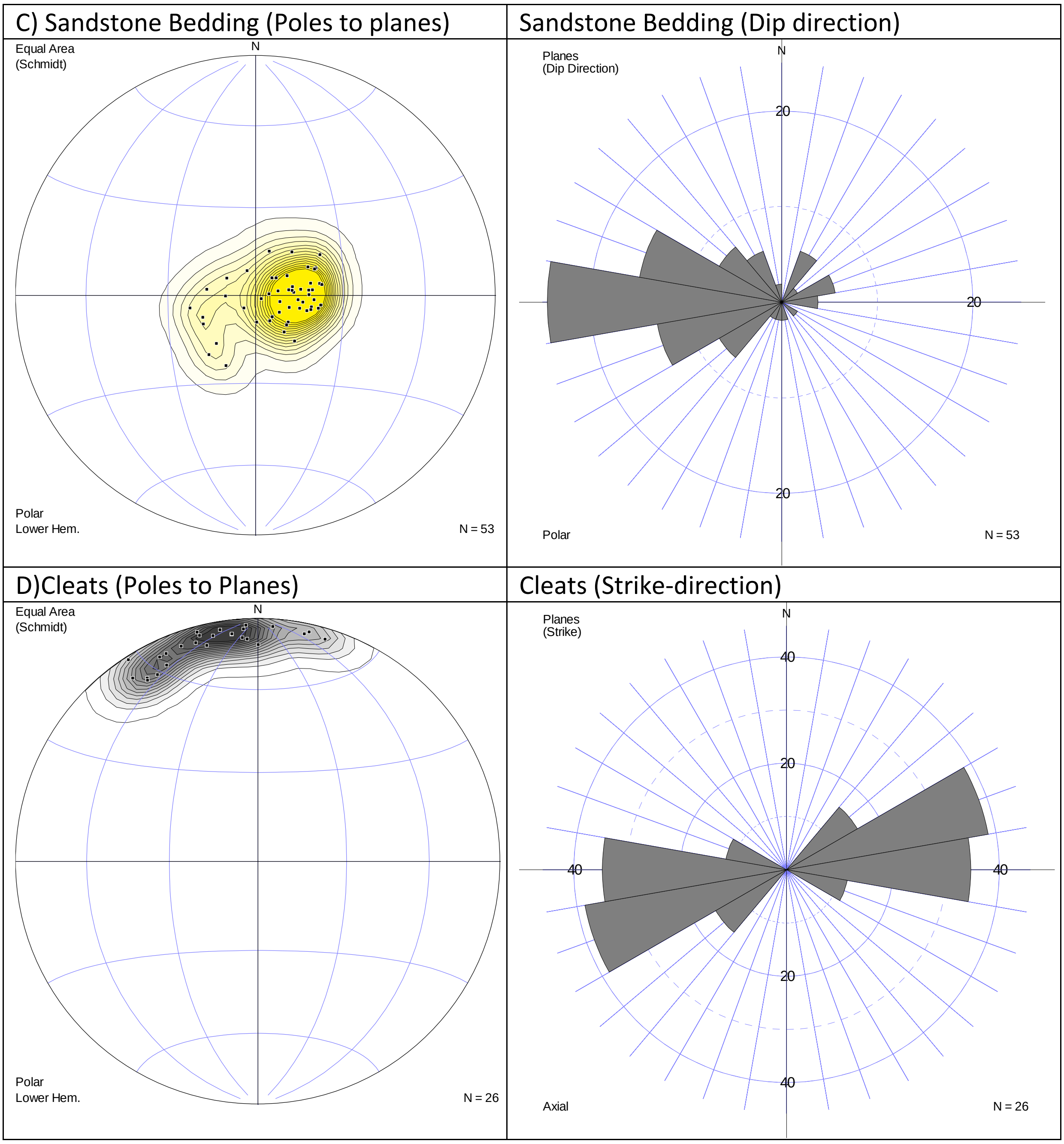


Figure 78 Mount Stuart ATV Measurements. A) Fractures B) Bedding (Strata) C) Sandstone cross-bedding D) Cleats

8.3. Drilling induced fractures

The drilling induced fractures measured in the ATV logs indicated below all strike approximately parallel to the regional ENE-WSW fault trend. This possibly reiterates the fact that any strain that builds up within the crust would preferentially be transferred into the structures of the underlying basement lithologies. This was the case in almost all the major tectonic events affecting the area from the formation of the Soutpansberg Group, formation of the Soutpansberg Karoo Basin and also the fragmentation of this basin during the split of Gondwana.

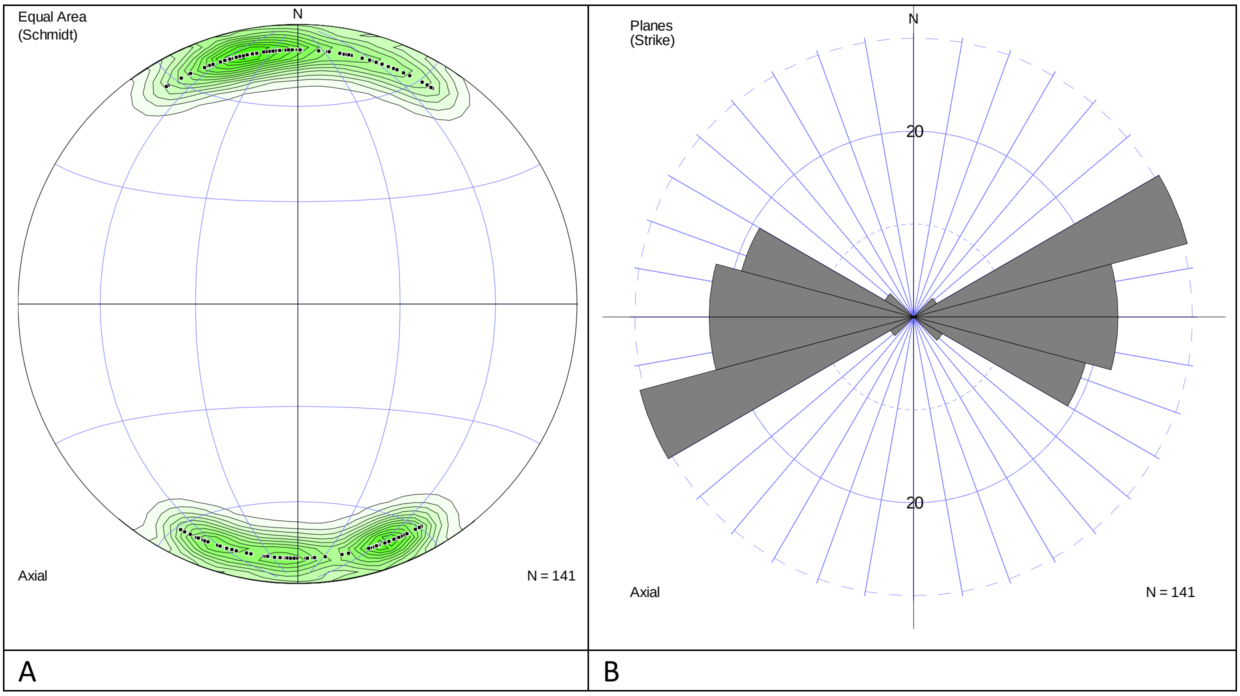


Figure 79: These images indicate the orientation of the drilling induced fractures. Image A is the poles to planes and image B represents the strike direction.

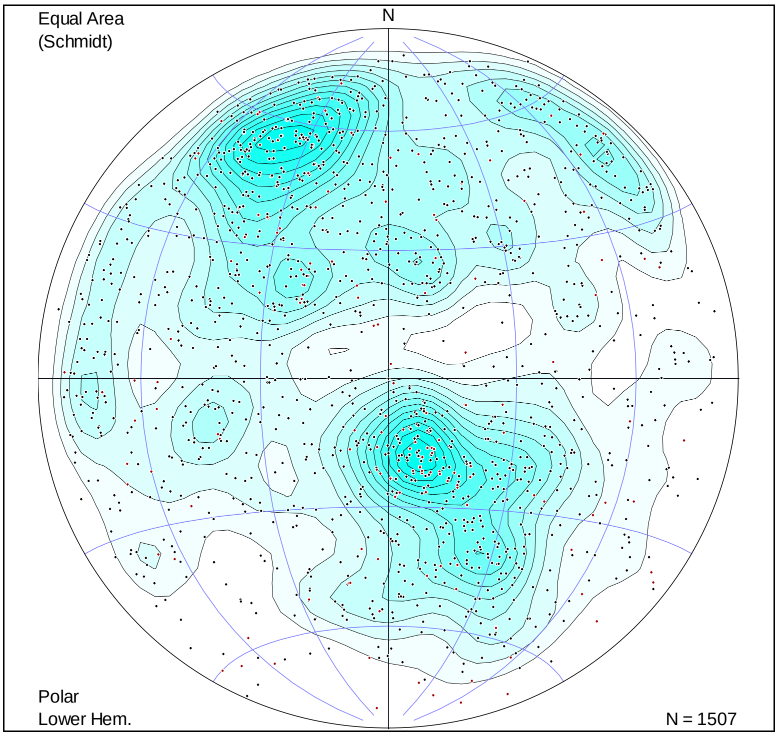
8.4. Discussion of measurements made from the ATV tool.

Overall the majority of the fractures measured in the boreholes logs reflect the main fault orientations that define the outline of the Tshipise Basin. The main set of ENE-WSW striking fractures are from the faults along which the normal faulting and formation of half grabens occurred. These fractures mostly dip to the SSE with a mean inclination of 65°. This set of fractures often has a conjugate pair that dips towards the NNW at a shallower inclination, normally at about 45°.

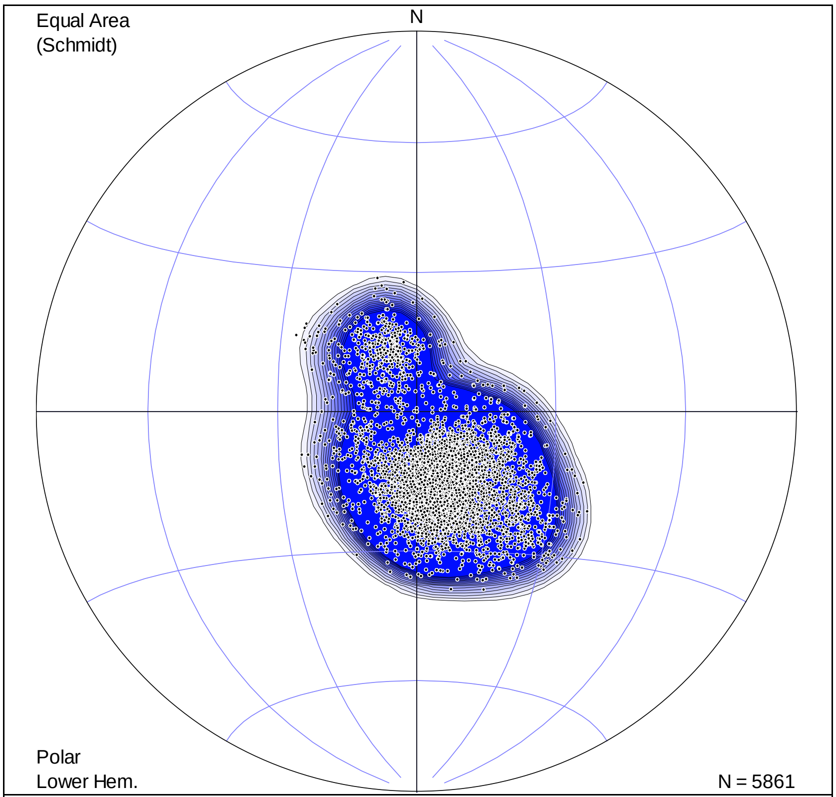
This conjugate set is often at a similar inclination, or slightly steeper, than that of the Karoo strata and the majority of large fractures observed lie within this fracture set (Fig 79). It is thought that this low angle (20°) set of fractures is either as a result of listric faulting that occurred during the half-graben formation or possibly from reverse movement on the already formed normal faults. The second most abundant set of fractures are orientated in a NW-SE direction dipping at a mean of 80° to the SW and this set of fractures does not have a conjugate set. The occurrence of this set of structures increases from west to east towards the Siloam Fault Zone and are seen mostly in the Makhado, Generaal and Chapudi East domains.

The bedding of the Karoo blocks dip predominantly to the NNW, between 12 and 19°,as a result of the extension that occurred along the major ENE-WSW trending faults which led to the formation of half grabens across the entire basin. A second cluster of points dip towards the SE and were noted in the Generaal and Telema and Gray sections and were as a result of possible folding and block rotation.

The cross-bedding measurements determined in the Fripp Formation display a wide range of orientations ranging from N to NW to W to SW with a mean transport direction towards the W (Fig 81).



A



B

Figure 80: A: Image showing all ATV structural measurements from the study area. B: Image showing all ATV bedding measurements made within the study area.

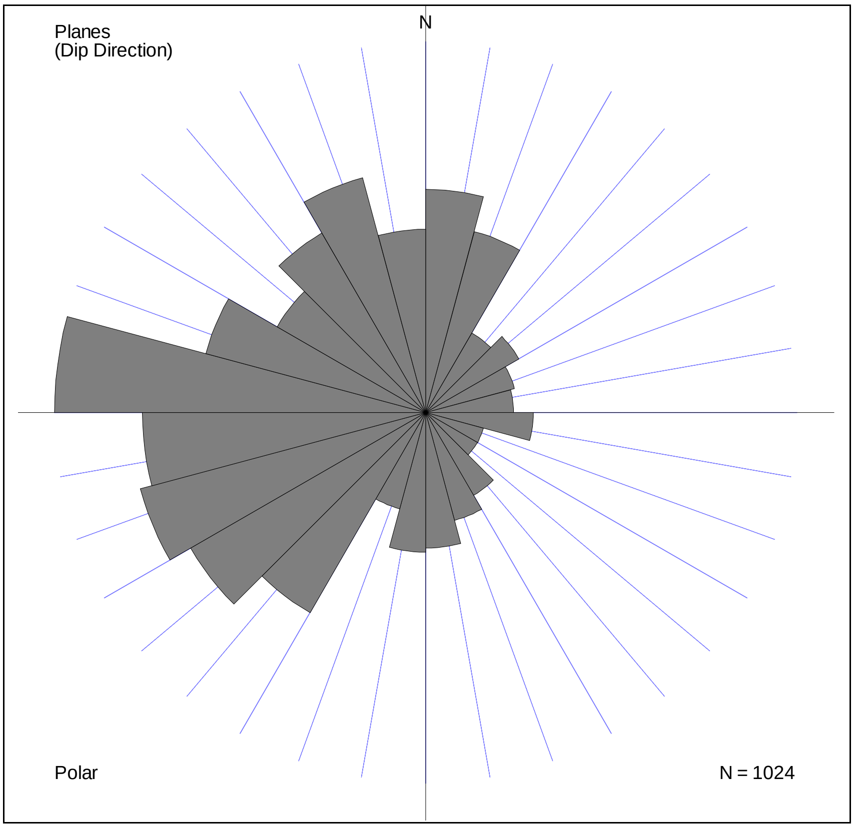


Figure 81: All palaeo-current measurements made within the sandstone of the Fripp Formation

9. Summary of the tectono-sedimentary development of the Tshipise Basin.

9.1. Pre-Karoo

- The Greater Soutpansberg Karoo Basin is underlain by the metamorphic rocks of the Limpopo Mobile Belt and the Proterozoic Soutpansberg Group. In the study area, the metamorphic provinces of the ENE-WSW trending Limpopo Mobile Belt are separated by a series of very large shear zones that have been intrinsic crustal weaknesses since their formation. Any regional strain caused from the neighbouring cratons would be released within these structures and they are also regarded to have played a significant role in the formation of the Proterozoic Soutpansberg Basin.
- During the Palaeozoic, subduction of the Palaeo-pacific plate underneath the Gondwana Plate led to the formation of the Cape Fold Belt. This orogenic loading led to the formation of a retroarc foreland system (Johnsonn and Beaumont 1995) where the Main Karoo Basin was deposited in the foredeep and forebulge of the system. The northern Karoo Basins (Springbok Flats, Waterberg, Tuli, Tshipise and Nuanetsi basins) are possibly related to the back-bulge of the flexural system, however the impact on subsidence from such a system is only considered to occur as far as 1350km from the orogenic front (Catuneanu 2004a). In the case of the Soutpansberg Karoo Basin, it is thought that the pre-existing faults and shear zones within the LMB might have been zones of strain release to form the Karoo depressions. However the tectonics north of the Main Karoo Basin is said to have changed to extension and it is thus possible that they formed during a combination of flexural and extensional tectonics.
- The palaeo-topography of the Tshipise Basin consisted of a number of ENE-WSW trending valleys created during the structuring of the Soutpansberg Group rocks and were most likely from movement that occurred along the structures of the Limpopo Mobile Belt. Several outliers of Wyllie's Poort Quartzite occur along the present outline of the Tshipise Fault and are considered to be up-faulted blocks that were brought to surface prior to Karoo times.

9.2. Syn-Karoo

- The Tshipise Karoo Basin, together with the two neighbouring Mopane and Nuanetsi basins, forms part of the larger Soutpansberg Karoo Basin. The main part of the Tshipise Basin occurs close to the junction of the two main, ENE-WSW and NW-SE, fault systems and comprise a series of long narrow Karoo-filled blocks orientated in the ENE-WSW direction (Van Eden et al., 1955). Most of these blocks are bounded to their north by faults along which the Karoo strata have been tilted and dip between 12 and 20° to the NW.
- The orientation and shape of these faults are all consistently parallel to the metamorphic foliation of the underlying LMB rocks (Fig.13 and 60). This suggests that the underlying basement structure played a major role in controlling the position and shape of these faults as well as the ultimate pattern of fragmentation of the Tshipise and Greater Soutpansberg Karoo basins.
- The extent of the original coal basin is not known, but the neighbouring Tuli Basin is considered to be genetically linked to the Tshipise Basin (Bordy, 2006). This, together with the presence of isolated occurrences of Lower Karoo units (Tshidzi and Madzaringwe formations) along the NW-SE Siloam Fault trend makes it likely that a Karoo aged depository once occupied a much larger area only to be dismembered and preserved within the blocks seen today.
- The isopach maps (Fig. 20) suggest that the pre-Karoo topography consisted of ENE-WSW trending valleys, parallel to the main Limpopo trend (Fig 82). The palaeo-drainage of the Tshidzi and Madzaringwe formations was from the E and NE to the WSW (Van Der Berg, 1980), similar drainage directions and patterns were determined for the Tuli Basin (Bordy, 2000) and the Ellisras Basin (Faure et al., 1996).
- The southernmost Makhado Block contained the thickest assemblage of lower Karoo sediments. This main valley was separated from the northern Generaal valley by a fault bounded ridge during the deposition of the lower Karoo. The main ENE-WSW valleys were possibly connected to some extent by smaller N-S palaeo-valleys which were a product of the pre-Karoo deformation. The 12° angular unconformity that exists between the Proterozoic Soutpansberg and the Karoo aged sediments further

confirms the presence of a large pre-Karoo tectonic event, although the timing of such an event is not known.

- Within the central and eastern area of the Makhado block the Tshidzi Formation displays a great variation in thicknesses over very short distances. These thickness variations correspond to the swath of post-Karoo faults within the Siloam Fault Zone, especially the N-S and NW-SE orientated structures. The post-Karoo reactivation of these faults formed a series of fault bounded Karoo blocks seen on the farm Castle Koppies (Fig. 62). These faults were most likely present prior to the deposition of the Karoo sediments, and differential movements along these faults created an undulating pre-Karoo palaeo-topography. The valleys created in between the fault bounded ridges could possibly have been further scoured by glaciers.
- The isopach map in Fig.23 of the main coal bearing Madzaringwe Formation shows that the overall basin shape was still similar to that of the Tshidzi Formation below it, though much of the undulating surface was filled up with sediment. The areas that showed thicker accumulations and a higher percentage of sandstone in the underlying Tshidzi Formation also show the same trends in this formation. The thickness of the unit decreases sharply towards the northern, Generaal, Jutland and Mopane blocks.
- Palaeo-current measurements in an Ecca time fluvial channel suggest that drainage occurred from the E and NE towards the WSW, parallel to the long axis of the basin.
- The Fripp Formation is stratigraphically and lithologically related to the Middle Unit of the northern neighbouring Tuli Basin (Bordy, 2006). The unit is considered to have been formed in response to tectonic uplift in the SE, creating a palaeo-topographic gradient from the SE towards the NW. In the eastern part of the basin the palaeo-current measurements indicate a unimodal transport direction towards the NW. Similar directions were also recorded in the northern most Mopane block as well as in the neighbouring Tuli Basin. Further west, in the Makhado and Generaal blocks, the transport directions become more variable and ultimately deviate towards the SW. At the western boundary of the Tshipise Basin, the transport directions are dominantly in a SW direction. This distinctive difference in transport direction is thought to be associated with the presence and of faults within

the Siloam Fault Zone. This change in transport direction is ascribed to the localised basin relief from differential movement of the individual blocks.

- The thickest accumulation of Fripp sandstones are within the eastern part of the Makhado Block, on the farm Fripp, where the unit reaches a thickness of more than 100m. Here the thickness of the Fripp Formation is almost 5 times greater in the compared to any of the northern blocks. The N-S valleys noticed in the underlying formations would have been expected to have been totally filled; however the fact that these patterns are still seen in the Triassic Fripp Formation suggests that these areas underwent enhanced subsidence in proximity to the faults.
- As the gradient became levelled off, the fluvial environment changed to a lower energy condition and ultimately created a meandering river system with wide flood plains as well as shallow lakes (Van Der Berg, 1980). During this time the purple, red and grey mudstone of the Solitude Formation was deposited.
- The coarse-grained Klopperfontein Formation is considered to be part of the basal sequence of the Bosbokpoort Formation possibly represents a similar, albeit smaller, tectonic reactivation event as was seen prior to the deposition of the Fripp Formation.
- The overlying redbed sequence of the Bosbokpoort Formation contains a series of upward fining sequence cycles believed to have been laid down in the semi-arid terrestrial environment, starved from major sediment and water inflow (Van Der Berg, 1980; Broadbent, 2005; Bordy, 2006). The unit is relatively thin (80-100m) considering it stretched over a timespan of approximately 30 Ma. It possibly represents a series of unconformity-bound sequences formed in response to tectonic uplift of the underlying units and the subsequent reworking and cannibalization of the underlying sediments (Broadbent, 2005). The Clarens Formation marks the final phase of sedimentation within the Karoo Supergroup (Fig 83).

9.3. Post-Karoo

- The Mwenezi Triple Junction marks the first essential phase of tectonism responsible for the ultimate fragmentation of the Gondwana Supercontinent at 167 Ma. The ENE-WSW trending Save-Limpopo Dyke Swarm was the first to evolve as a result of stretching and thinning of the crust in a NNW-SSE direction, which evolved into an ocean spreading centre that led to the separation of Africa and Antarctica (Jourdan, et al., 2005; Reeves, et al., 2016). It is believed that this extension led to the reactivation of the pre-existing, ENE-WSW trending, basement faults. The reactivation was translated into normal movement along the faults, which led to the formation of a series of half-grabens in which the Karoo strata were preserved (Fig Ö84). These half-grabens dip fairly constantly at about 12° towards the NNW (345°) throughout the entire basin. This is considered to be the main structural event of this area.
- The location of both the Okavango and Save-Limpopo dyke swarms are not only related to the Karoo Igneous Province but were in place even in Proterozoic times. They are both located on ancient crustal weaknesses that were once again exploited during the Karoo Igneous Province event (Le Gall et al., 2002, Watkeys, 2002, Jourdan et al., 2004). The Karoo Triple Junction initiated from an igneous center near Mwenezi (Cox, 1970; Watkeys & Sweeney, 1988) from which the igneous material was injected into the pre-existing crustal structures. The overall injection directions were initially sub-vertical near the igneous center, which changed to later lateral injection in a westerly direction, in the case of the ODS (Le Gall et al., 2002; Jourdan et al., 2007).
- The thermal effects of this event are thought to have increased the thermal gradient to levels normally associated shallow magma environments. The high thermal gradient and related hydrothermal fluid fluxing are thought to be main reason for the higher coal rank in this basin. The coal rank increases from the west to the east of the basin, however higher vitrinite reflectance patterns are localised around large faults and often confined to certain stratigraphic levels of enhanced hydrothermal fluxing.

- The majority of the ATV structural measurements made were parallel to the main ENE-WSW trending faults, mostly dipping between 45 and 70° to the SSE. A large amount of structures sub-parallel to the NNW dipping strata were measured and are thought to either be as a result of the fault becoming listric at depth or when reactivation and reverse movement/thrusting of these structures occurred.
- The NW-SE trending faults of the Siloam Fault Zone were also reactivated and led to block faulting within this fault zone. These faults displace the Letaba basalt but do not affect the E-W magnetic dykes associated with the later intrusion of the Okavango and Save-Limpopo dyke swarms.
- It was during this time that the Karoo sediments were intruded by the vast array of dolerite sills that, in most cases, vertically uplifted the overlying Karoo units. Overall there is an increase in the thickness of dolerite sills towards the eastern part of the basin, although the areas surrounding the Wildebeesthoek and Chapudi Blocks also contain a greater amount of dolerite compared to the surrounding areas.
- There are two main tectonic events that shaped the Tshipise Basin; the first is an event with a NE-SW directed principle horizontal stress (SHmax/ σ_1) related to the NW-SE regional extension, related to the initial split of Gondwana. This was the main tectonic event and also responsible for the down-faulting of the Karoo blocks into half-grabens. The second event has a NW/NNW-SE/SSE directed SHmax and is most likely related to a change in motion of the African and Antarctic plates after them separating. It is this event which led to the reactivation and inversion of the steeply dipping (40-60°) primary structures created during the first event to form high-angle reverse faults. This event is also thought to have led to localised folding of the Karoo strata focused around the Tshipise, Bosbokpoort and Voorbrug faults and Siloam Fault Zone.
- It was during this compressive event that led to up faulting of several large blocks, which occur in the region where the ENE-WSW and NW-SE structures intersect and the faults interconnect. The Generaal up-faulted block however, was in place prior to the Karoo deposition, and formed a dividing ridge that separated the southern (Makhado) and northern (Generaal) valleys; associated with these were smaller

scaled positive flower structures that occur along the Tshipise and Bosbokpoort faults.

- After rifting the area would probably have been relatively inactive tectonically apart from minor events.
- Very recent seismic activity has been recorded along the eastern part of the Bosbokpoort fault near the Zimbabwean border. This tectonic event occurred approximately 100 000 years ago and led the displacement of Quaternary sediments on either side of the fault to form a 10m high fault scarp which can still be seen today (T. Partridge pers. comm. 2008).
- A neotectonic stress orientated parallel to the main ENE-WSW orientated basement fabric reiterates the fact that any strain that builds up within the crust would preferentially be transmitted into the pre-existing basement structures. This seems to be the case in almost all the major tectonic events affecting this area from the formation of the Soutpansberg Group and Tshipise Basin as well as controlling the pattern of fragmentation of the latter during the split of Gondwana.

Age of event	Event	Evidence for event
2.7 Ga	Initial collision of the Kaapvaal and Zimbabwean cratons. Formation of the Kalahari Craton	High grade metamorphic rocks in the Limpopo Mobile belt.
1.9 Ga	Formation of Proterozoic Soutpansberg Group Basin	
1900-800Ma	Siloam Fault Movement	1500m normal displacement to the SW
	Pre-Karoo Left-lateral wrenching of the along the ESE-WSW Tshipise shear zone	NE-SW trending diabase dykes identified from the B3 aeromagnetic survey
800Ma-300Ma??	Formation of the Karoo palaeovalleys either by back bulge tectonism caused by Cape Fold Belt reactivating existing basement faults	12° unconformity between the Soutpansberg and Karoo sediments. Block faulting of pre-Karoo basement in Castel Koppies and East of Generaal
280-240Ma	Deposition of the Lower Karoo units (Fig 82)	
280-240Ma	Basin was under extension during the Lower Karoo time	NE-SW trending cleats in the coal measures.
230 Ma	Fripp Formation, active uplift in the SE part of the basin	Large bed thicknesses and trough cross bedding towards the NW, W and SW
230-200Ma	Tectonic movement along faults	
±184-178Ma	Karoo Igneous Province	Outpouring of Lavas
±182-180Ma	NNW-SSE extension as a result of the split of Gondwana. Rotation of the Karoo blocks along the ESE-WSW trending faults. (Fig 83)	Large scale extensional event, all blocks in the Soutpansberg Basin dip NNW. NE-SW directed SHmax.
181-178Ma	Intrusion of the ODS and SLDS	Dykes have not been rotated and thus post-date Basalt.
178-174Ma	Reactivation of N-S with simultaneous intrusion of negative, and some positively magnetised dykes. Related to final split of Gondwana or LDS	N-S structures from neighbouring blocks correlates and contain undisturbed N-S trending dykes of mostly negative polarity.
±167M	Right lateral transpressional wrenching along the main ENE-WSW fault system (Fig 85)	NW/NNW-SE/SSE directed SHmax. Forms pop-up structures along jogs in the Tshipise and Bosbokpoort faults. E-W folding of the Karoo sediments along the faults Reverse movement along existing normal faults (Juliana fault)
167Ma	Final separation of Gondwana	
30Ma	East African Rift	E-W extension
100 000	Normal faulting in the Bosbokpoort fault. As a result of the NE to SW compression, possibly from the East African Rift.	Displacement of quaternary sediment across the fault, presence of a fault scarp. NE-SW orientated DIF's

Table 2: Chronological sequence of tectonic events of the study area

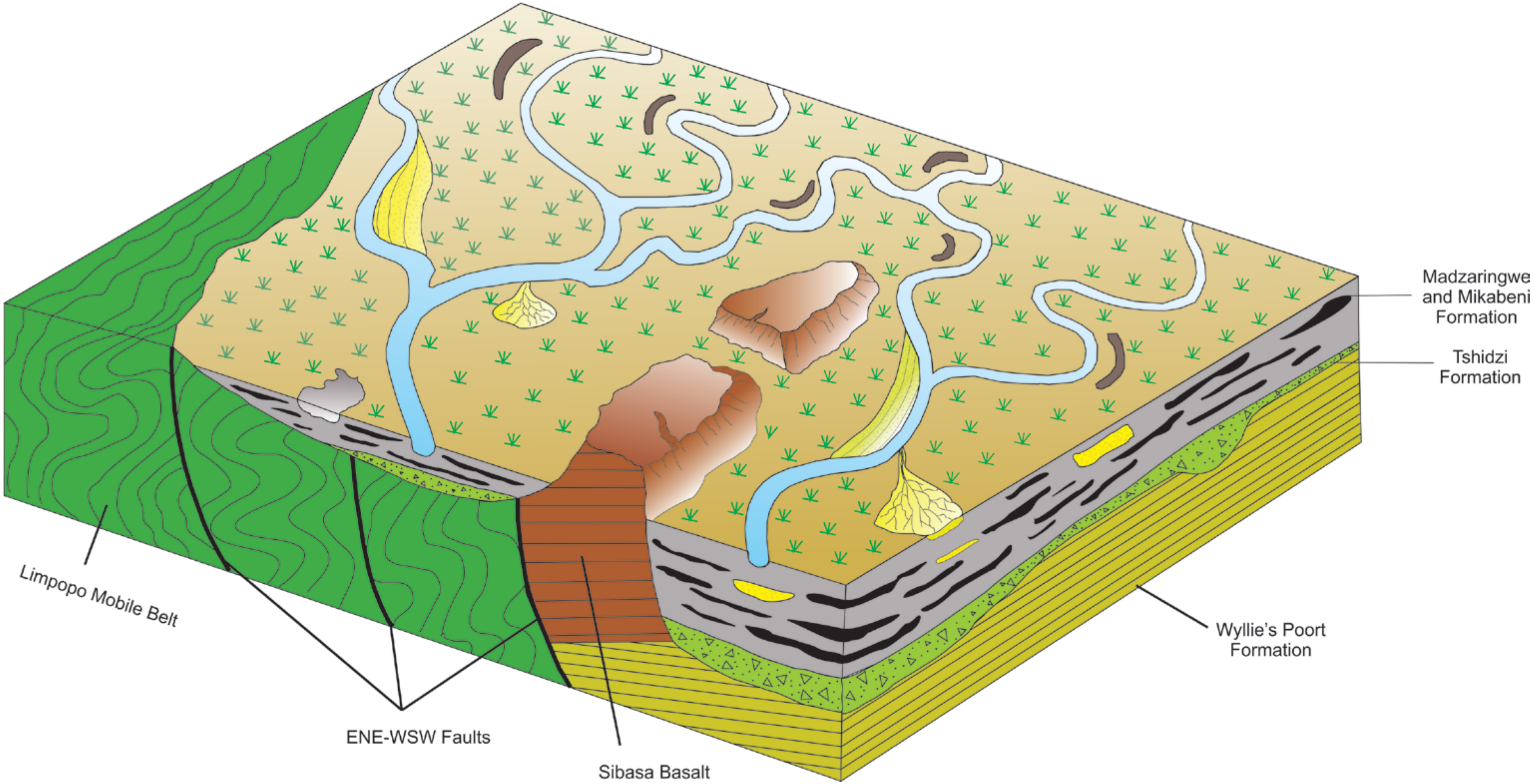


Figure 82: Deposition of the Madzaringwe Formation within the Tshipise Basin.

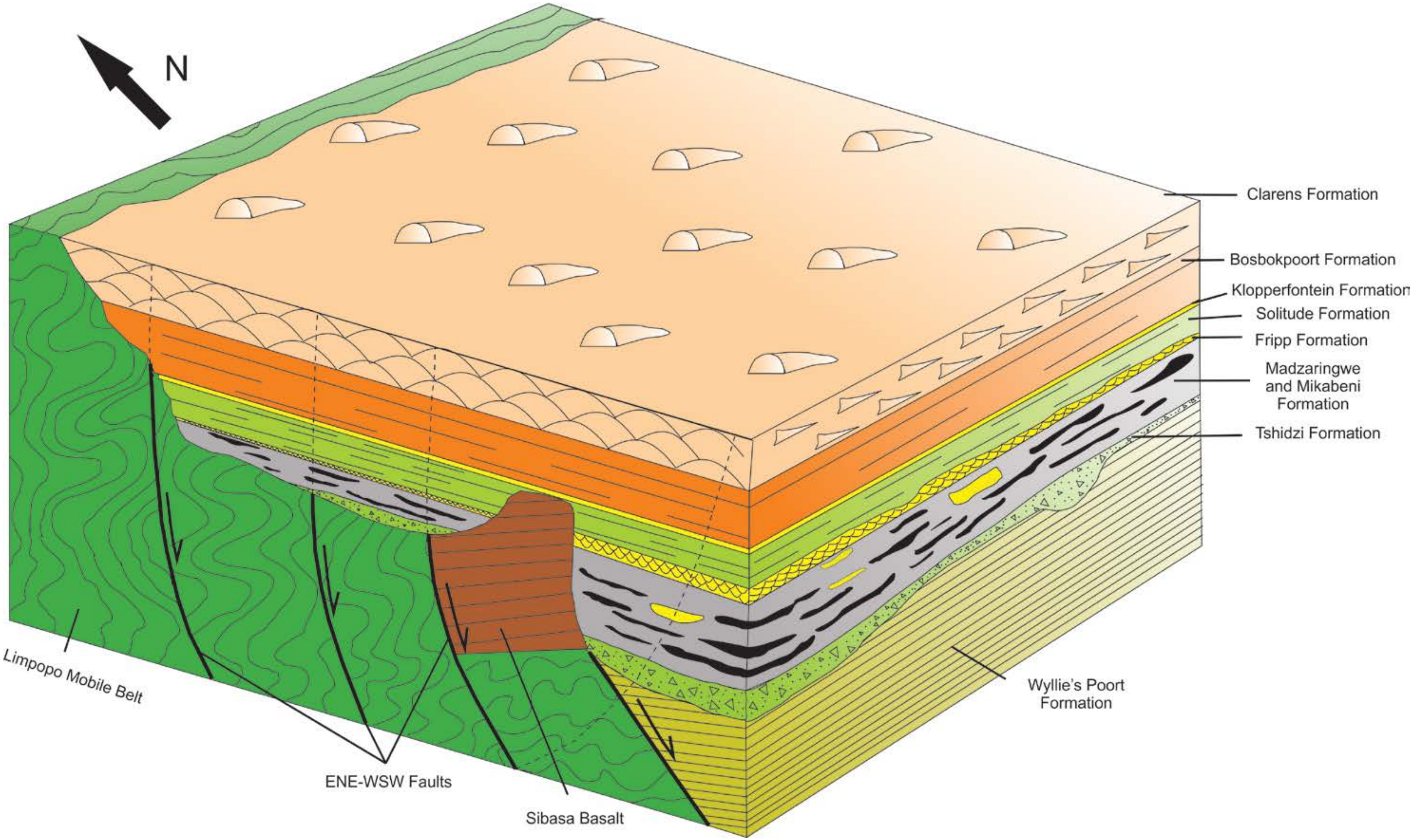


Figure 83: The full Karoo sequence present in the Tshipise Basin.

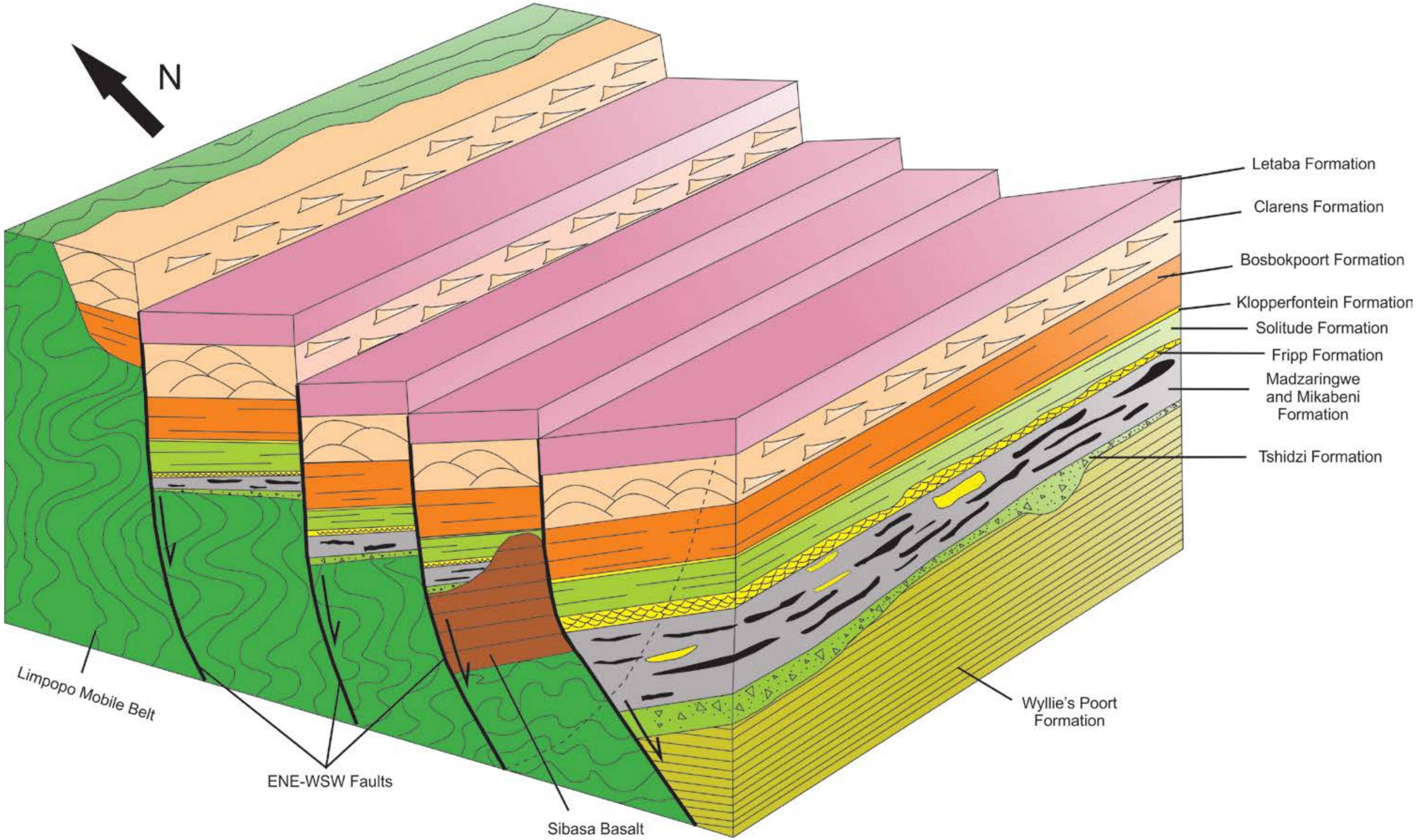


Figure 84: Extension perpendicular to the underlying basement structures leading to normal fault and rotation of Karoo sediments.

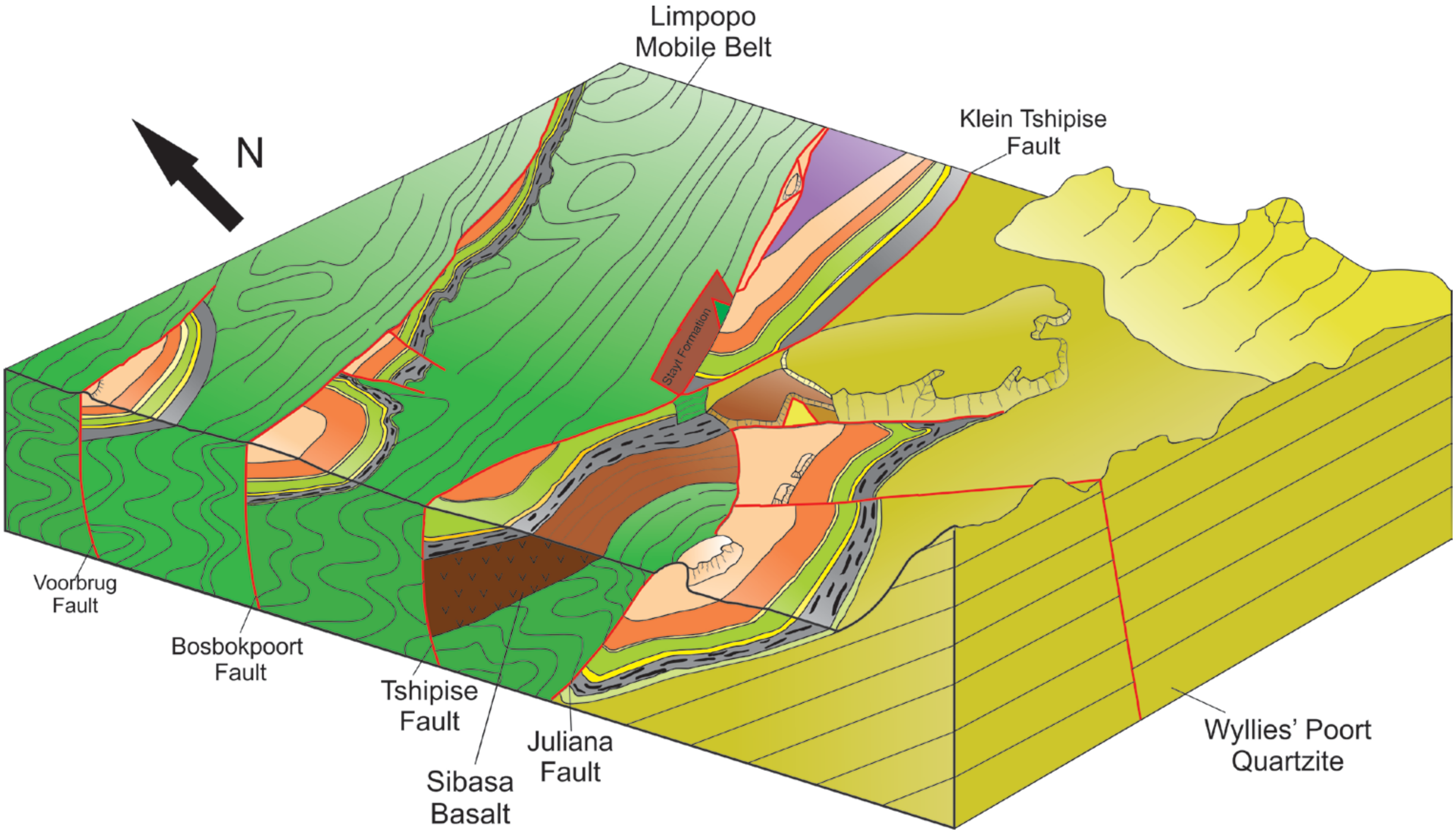


Figure 85: Current outline of the different blocks of the Tshipise Basin.

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Appendix A

1. Aeromagnetic Surveys

Aeromagnetic surveys are widely used for the production of geological maps and are commonly used for mineral and petroleum exploration. As the aircraft flies, the magnetometer measures and records the total intensity of the magnetic field, which is a combination of the desired magnetic field generated in the earth's crust as well as small variations (i.e. diurnal effect, solar wind and magnetic field of the of the aircraft). By subtracting these effects, the resultant aeromagnetic map can display the spatial distribution and relative abundance of magnetic minerals (most commonly magnetite) in the upper levels of the earth's crust (Reeves, 2005). These magnetic minerals are commonly found in igneous rocks where the external magnetising field is induced into the material; this is referred to induced magnetisation. These magnetic properties can only exist at temperatures below the Curie point which is found to be between 550 to 600 °C. The magnetic minerals will tend to align themselves to the direction of the geomagnetic field during the time at which the temperature of the rocks passes below the Curie point; this is referred to as remnant magnetisation.

The remnant magnetisation can be destroyed or overwritten if the rock mass is subjected to metamorphism or intruded by igneous bodies where temperatures exceed the Curie point. The geomagnetic field is not constant and can vary drastically over short time periods (few thousand years) allowing igneous bodies to exhibit varying magnetic orientations. This can also be useful in determining age differences in rocks and possibly determine rough emplacement sequences of volcanic flows or igneous intrusions.

- Reduction to the Pole (RTP)

  This transform generates a total field data set whose magnetic anomaly signatures correspond with a -90º inclination of the magnetization of the prospect area. This simplifies the magnetic map by rendering anomaly waveforms independent of strike direction and by generating positive, symmetrical anomalies over vertically magnetic sources like dykes. RTP thus allows for a better characterisation and separation of sub-vertical dykes and that of the sub-horizontal sills.

- Vertical/Horizontal Gradient Data (VG/HG)

  Vertical and horizontal gradient data sets accentuate shallow magnetic sources at the expense of regional and deeper magnetic responses and allow for the recognition of low amplitude, short wavelength magnetic anomalies in areas of significant magnetic relief. Such features are often linear structures such as dykes and the resultant anomalies are narrower than their total field equivalents. This transform was used in determining the width of steeply dipping dykes as well as determining their dip.

- Analytical signal

  This total magnetic gradient parameter is the scalar sum of the vertical and horizontal gradients of the total magnetic field and produces a positive bell-shaped anomaly over the magnetic source irrespective of its geological dip or remnant magnetisation. This data is useful for mapping strike trace of long magnetic sources or the center of plug-like sources.

2 Wireline Geophysics.

In modern coal exploration it has become common practise to log each completed borehole geophysically to a certain extent in order to obtain accurate depth measurements of lithological contacts as well as to provide petrophysical measurements of the target horizons. Soon after the drilling has been completed, the borehole is logged geophysically in order to take measurements of the borehole sidewall before it becomes damaged through sidewall collapse. These measurements are made by a geophysical sonde lowered down into the borehole via a cable being fed from a winch at surface, normally mounted on a truck or bakkie.

2.1 Density Measurements

Coal has low apparent densities ranging between 1.2 and 1.8 g/cm^3 whereas the more consolidated strata such as mudstone and sandstone have densities generally greater than 2 g/cm^3. This characteristic means that it has become one of the most used and possibly the singularly most important log in modern coal exploration. This log provides a continuous density record down of the formation sidewall and is used to alongside the coal core samples to distinguish relative coal quality and determine the depth of lithological contacts. The density measurement is conducted by bombarding the formation with a radioactive source, normally Caesium-137, and then measuring the resulting gamma ray count after the effects of Compton scattering and photoelectric absorption (Rider, 2008). The resultant log produces a continuous depth vs. density curve down the borehole with a resolution of approximately 5 -15cm.

2.2 Gamma Measurements

Gamma Ray logging is a method used of measuring naturally occurring gamma radiation and this tool is normally incorporated into the density tool and measurements are made concurrently. Only three elements, together with their decay states, have the potential to emit natural radiation from rock, these are Potassium, Thorium-series and the Uranium-series. In sedimentary rocks potassium is dominant emitter and is mostly contained within the clay minerals. Mudstones predominantly contain clay and emit high gamma readings whereas sandstones would give off low gamma responses. The study area contains thick layers of dolerite which produce virtually no gamma responses at all. Sedimentary cycles can be observed from variations in gamma values with depth; upward fining cycles show an increase in gamma counts with depth whereas upward-coarsening cycles display the opposite.

2.3 Acoustic Televiewer Logs (ATV)

The acoustic televiewer (ATV) logs are used mainly for assessing the structural geological aspects of a borehole by producing an orientated image of almost photographic quality of the borehole sidewall. Prior to recent developments in acoustic scanner imaging, the determination of the orientation of tectonic structures, stress and strain states and sedimentary fabrics was only possible via the retrieval of orientated core (Titheridge, 2010), however since its advent, orientated measurements of the structures can easily be made from the resultant log image.

The tool contains a rapidly rotating transducer which emits short bursts of acoustic waves into the borehole wall. These bursts produce reflections whose amplitude and travel time are measured and recorded at surface to produce a continual high resolution image of the borehole sidewall. From the image accurate, unambiguous measurements of the orientation and dip can be made for any planar feature that intersects the borehole such as joints, faults and cleats (Firth, 2003). Additionally to this, stress field orientations of the rock mass can also be made from borehole breakouts and drilling induced fractures. The borehole image tool produces "unwrapped" 2D image of the borehole sidewall. This image is orientated to magnetic north and displays the azimuth of the boreholes from 0° (left) to 360° (right), i.e. from north back to north. Variations of the amplitude and travel times of the rock mass in the borehole sidewall are highlighted by variations in image colour intensities. Competent rocks display high amplitude (light colour) colours while structures such as joints and faults are displayed as darker coloured features. These image logs are always displayed alongside the density, gamma and caliper logs to make interpreting lithological characteristics more discernible.

The structures in the ATV images were all interpreted and "picked" in a software package (Wellcad). During the picking process it is advised that the actual core be used to validate the presence of certain structures, especially sandstone bedding. However in this case all the cores were discarded after they were logged and sampled; and the author had to rely solely on his own discretion for the classification of structures. It needs to be stated that although the core could not be used in the interpretation process the results obtained from the ATV images on their own are still of high quality and for the purpose of this study, are sound.

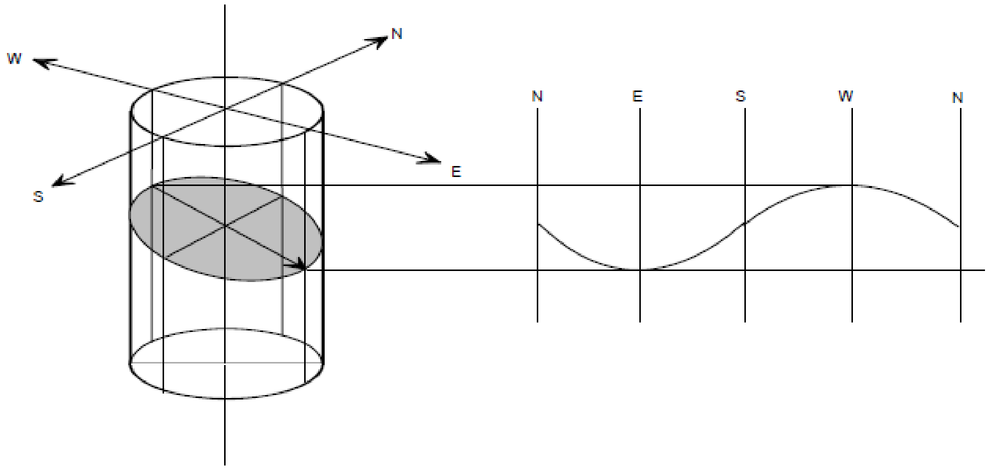


Figure 86 Representation of the resultant sine wave that forms from an inclined plane intersecting borehole sidewall when view in an unwrapped ATV image.

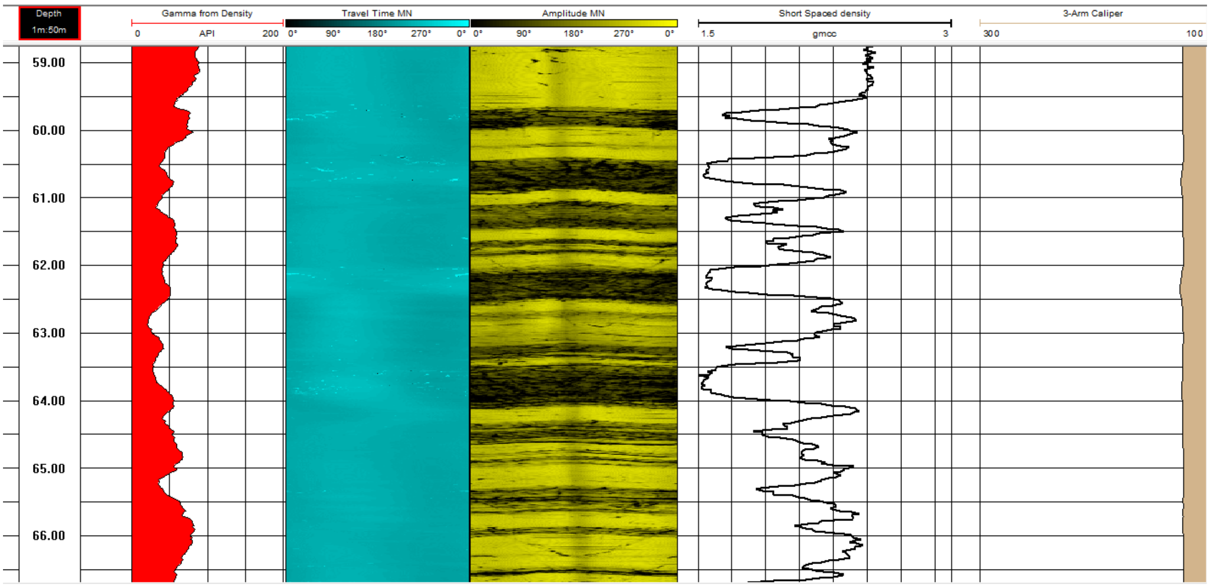


Figure 87: An example of a wireline log; this log contains from the left; a gamma log (red), travel time log (turquoise), amplitude log (yellow and black), density (black line) and a caliper log (brown line).

2.3.1 Natural Fractures

The term fracture is a general term for any non-sedimentary, mechanical failure pertaining to structures naturally formed and preserved by regional or local tectonic forces. These include structures like joints, quartz veins and faults.

The intersection of these inclined planes with a vertical borehole is represented by sine wave in an unwrapped image. The amplitude of the wave represents the dip-angle of the structure while its orientation with respect to magnetic north is defined by the amplitude

(Firth, 2003). Naturally occurring fractures will always be represented by a full sine curve and during the picking process it is important to distinguish these from non-natural, drilling induced structures. The software creates a perfect sine wave which is placed onto the orientated image and if the wave does not fit it cannot be considered to have formed naturally. Once a number of structures have been picked the software allows the user to correct these structures from magnetic to true north and all the azimuth and dip values can be exported to be used in stereographic software, in this case Spheristat 3.0 was used for the structural analyses.

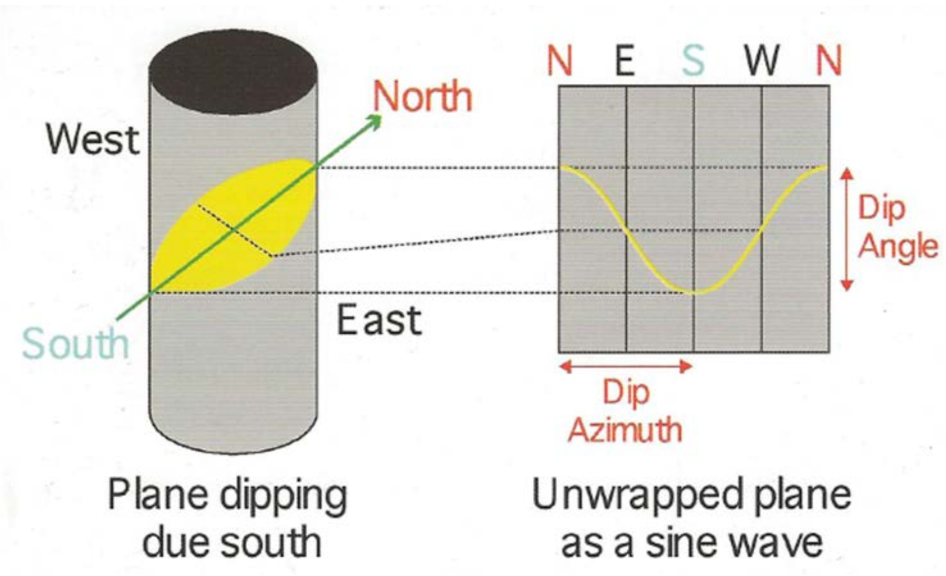


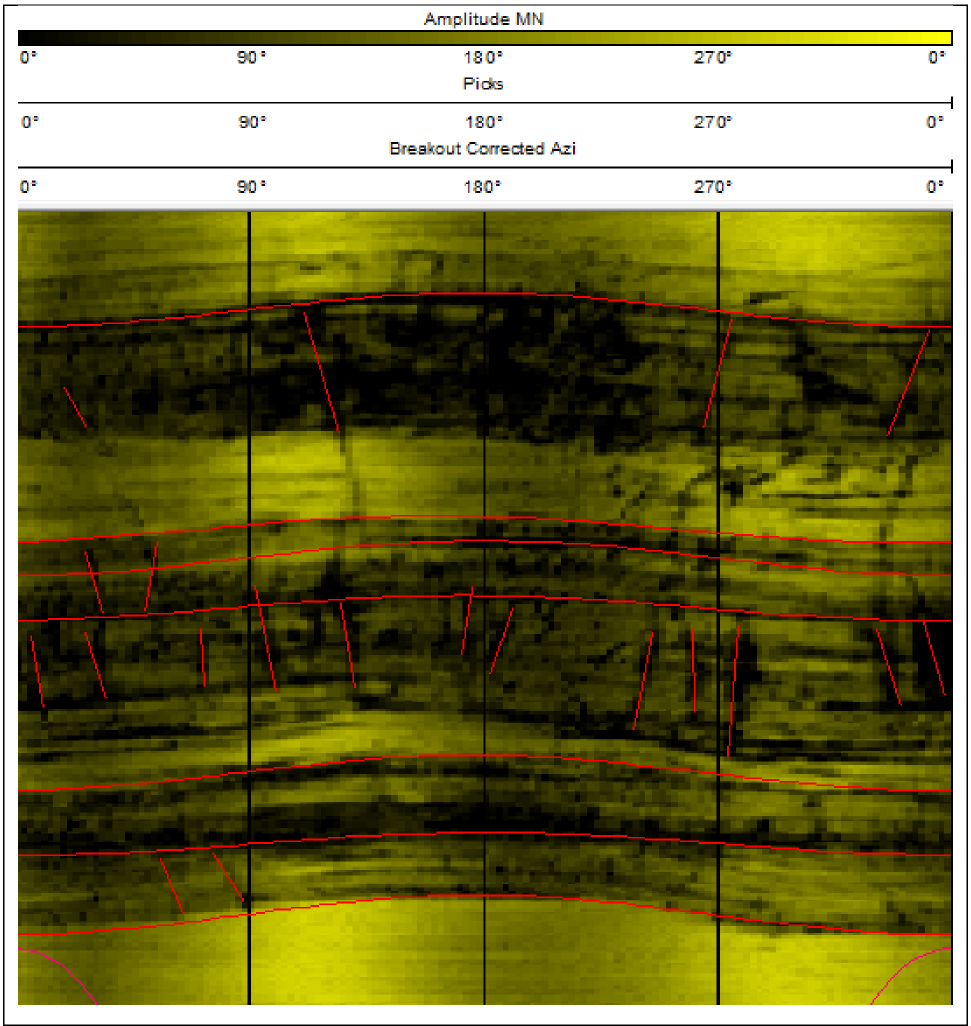
Figure 88 Real and unwrapped schematics of a dipping plane (Firth, 2003)

Faults can be measured from the images if displacement within the beds can be observed, however it is best to interpret the ATV logs alongside the borehole core in order to inspect and describe the nature of each structure picked.

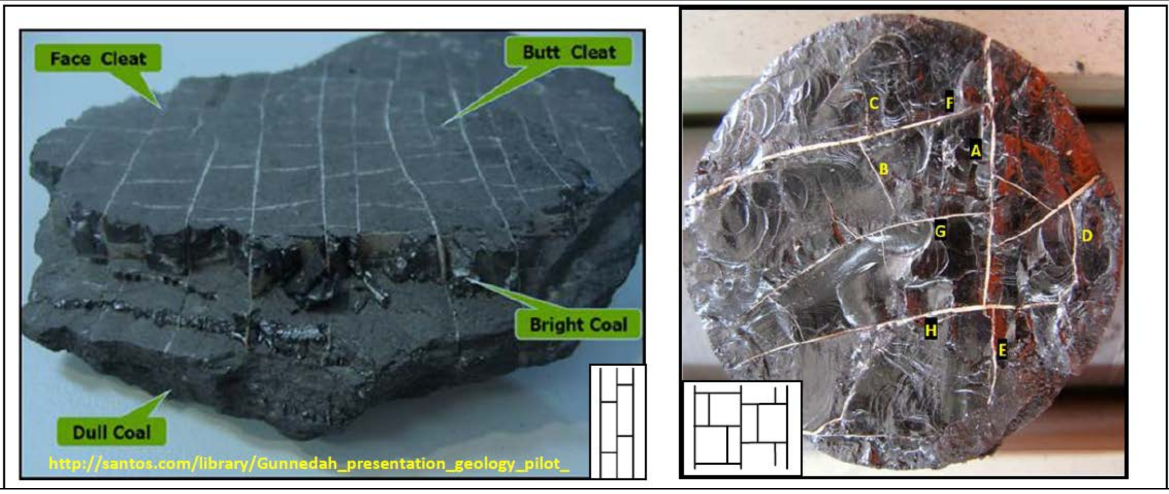
2.4 Coal Cleats

Cleats are natural occurring opening-mode (tensile), sub-vertical joints in coal beds which are typically orientated perpendicular to the coal bedding even where beds are folded (Laubach, et al., 1998). They develop during the early coalification process with loss in moisture and volatiles and generally develop parallel to the maximum horizontal stress. Although there are some cases where the σ1 has remained the same since early coalification in general the relationship of the face cleat orientation and current stress tensors departs during time as a result of regional changes in stress directions.

In many cases cleating is confined to layers composed of a certain maceral type conducive to fracturing. In the case of the Tshipise Basin, coal beds are composed of 90% vitrinite, assuring the majority of the coal beds are well cleated. Generally they are arranged in sub-parallel sets that have uniform regional trends, yet they can show abrupt lateral and vertical shifts in strike when in close proximity to large faults or reactivation by slip on pre-existing cleats. They usually occur in two sets that are, mutually perpendicular and also perpendicular to bedding. The abutting nature between the cleats generally show that through-going cleats, referred to face cleats, form first. Cleats that end at intersections with through-going cleats formed later and are referred to as butt cleats.



A



B

Figure: 89: A: An image of the coal cleats measured in borehole 643MS001, the cleats are inclined as a result of the northward dipping strata. B: Image showing a well cleated coal, face and butt cleats (Laubach, et al., 1998).

Cleats without any observable offset allows us to relate cleat orientation to past stress fields. Cleats normally propagate along a plane of zero shear stress, specifically the plane perpendicular to the least compressive principal stress making such fractures indicators of past stress orientation, where cleats are aligned to the maximum horizontal stress at the time of their formation (Laubach, et al., 1998).

In the endeavour to determine the tectonic history of the basin this information is very useful to determine the strain tensor in the rock-mass during the coalification process.

2.4.1 In-Situ Stress Field measurements

The in-situ stress condition is naturally present within the earth's crust and is normally caused by horizontal strain being applied to the rock mass, mostly by the local geological and structural environment. These measurements made can be used to determine the principal horizon stress present within the subsurface rock mass.

As a drill bit penetrates the virgin rock mass a series drilling induced fractures and failures can develop which is entirely a function of the local in-situ stress field. Care needs to be taken when picking these structures as not to confuse them with naturally occurring fractures which were formed by structural events and not related to the current in-situ stress field.

2.4.1.1 Borehole Breakout

Breakout of the borehole sidewall often results when an imbalance of the horizontal stress, σ2 and σ3, exists in the rock mass. Stress is transferred laterally around the circumference of the borehole wall and meets in the two compressive quadrants. If the rock is too weak or brittle, breakout (caving) of the sidewall will occur within both of the two compressive quadrants. Breakout occurs 180° apart in the sidewall and normally only for short intervals, it is important to compare multiple breakout pair occurrences within a borehole to support the assumption that it is indeed breakout. Once it is confirmed, these orientations can be used to reliably determine the orientation the maximum horizontal stress, usually normal to that of the breakout direction (Chatfield, 2014). Breakout might not exist or be limited to just a few short sections in the log; in general breakout does not form readily in coal but might be present in arenaceous or argillaceous units in the stratigraphy.

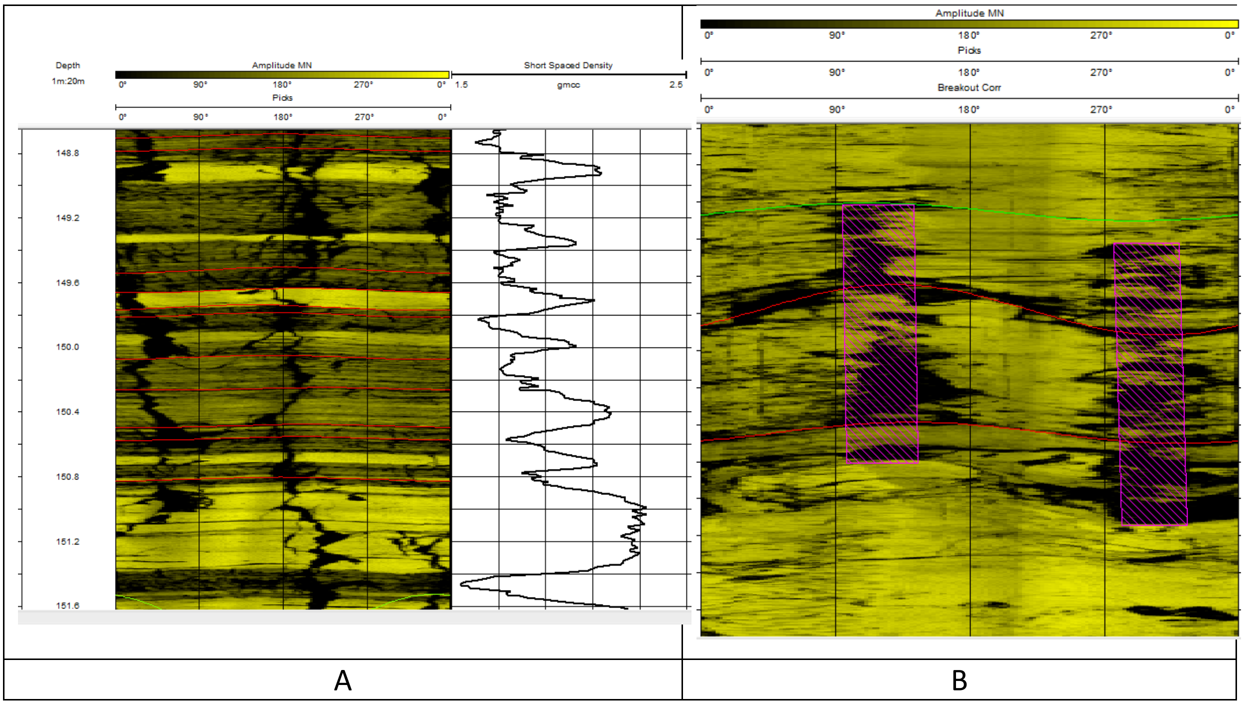


Figure 90: A: drilling induced cnterline fractures formed within the tensile quadrant of th borehole 689MS13. B: Borehole breakout within the compressive quadrant of borehole 649MS001.

2.4.1.2 Drilling Induced Fractures

Drilling Induced Fractures (DIF's) are, as the name suggests, not natural structures but are produced during the drilling process. These are nearly vertical, asymmetrical fractures that occur in the tensile quadrants, 90°to that of breakout and are orientated parallel to the principle horizontal stress (SHmax).

Pre-drilling tensile fractures develop ahead of the drill bit and are more often associated with shallow coal exploration boreholes. These fractures occur especially in bright, vitrainous coal seams (Chatfield, 2014) associated with the Soutpansberg Coalfield. When interpreting these structures, care should be taken not to mistake crumbling tensile fractures for breakout, as in fig 91 below.

Post-Drilling hydraulic tensile fractures are common drilling induced phenomenon although is less prevalent in the shallow coal exploration boreholes. They form by pressurized drilling fluid, normally as a result of depth and rapid lowering of the drill string, whereby the hydraulic pressure exploit existing weaknesses (cleats etc.) in the borehole sidewall.

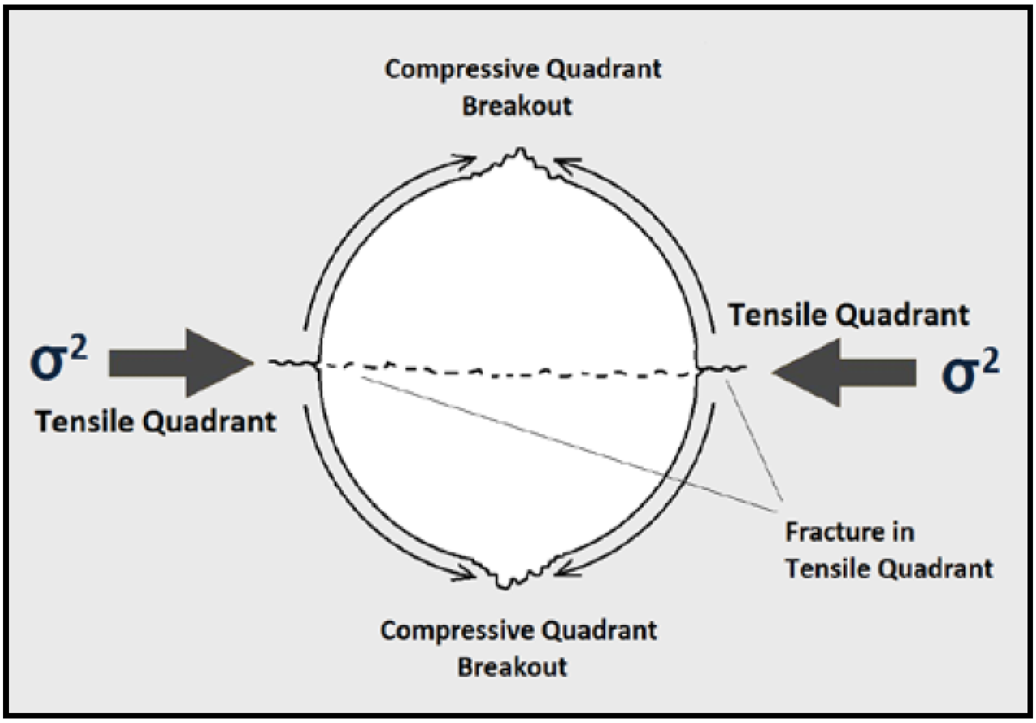


Figure 91: The formation of tensile fractures and breakout in their respective quadrants within a normal faulting regime (Chatfield, 2014).

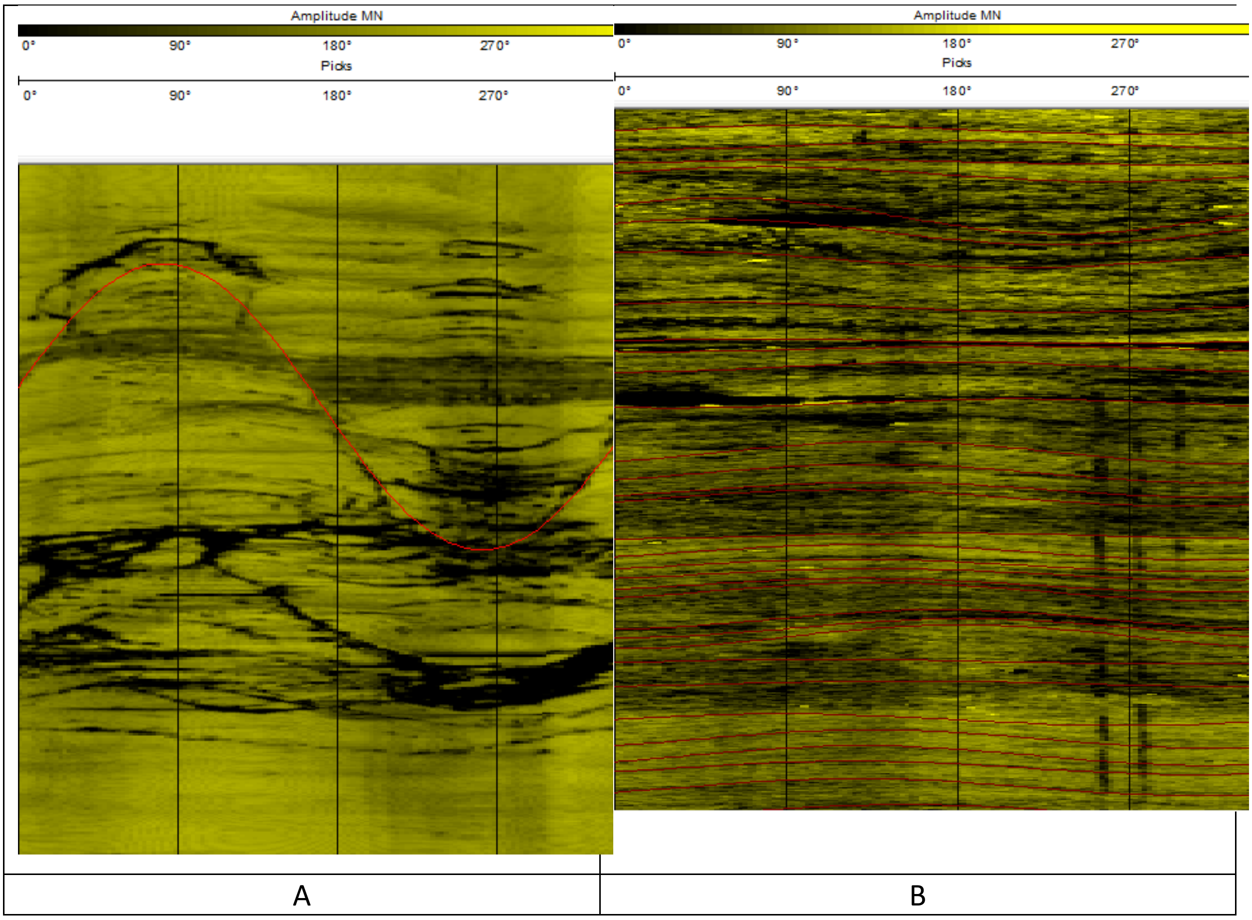


Figure 92: A: Small scale normal fault displacing the coal and mudstone bedding. B: Fripp sandstone bedding measured in borehole 689MS012

In general, near vertical fractures develop in the tensile quadrant which is referred to as centreline fractures. A perfect dissecting fracture of this kind is most likely to occur where the borehole is vertically aligned with a principle stress directions and where there is a significant imbalance between horizontal stresses. This is a reliable indicator of the orientation of the principle horizontal (σ_2) stress acting on the rock mass. Centreline fractures often are often not consistent in their orientation and care needs to be taken in delineating them; however the alignment remains fairly constant with true centreline fractures always 180° apart.

Curvi-planar induced tensile fractures, also known as petal fractures, enter coal core at a relatively low angle and steepen towards the center of the core where they become planar to near planar. In certain instances petal fractures only penetrate about a third of the core diameter and commonly terminate before becoming vertical.

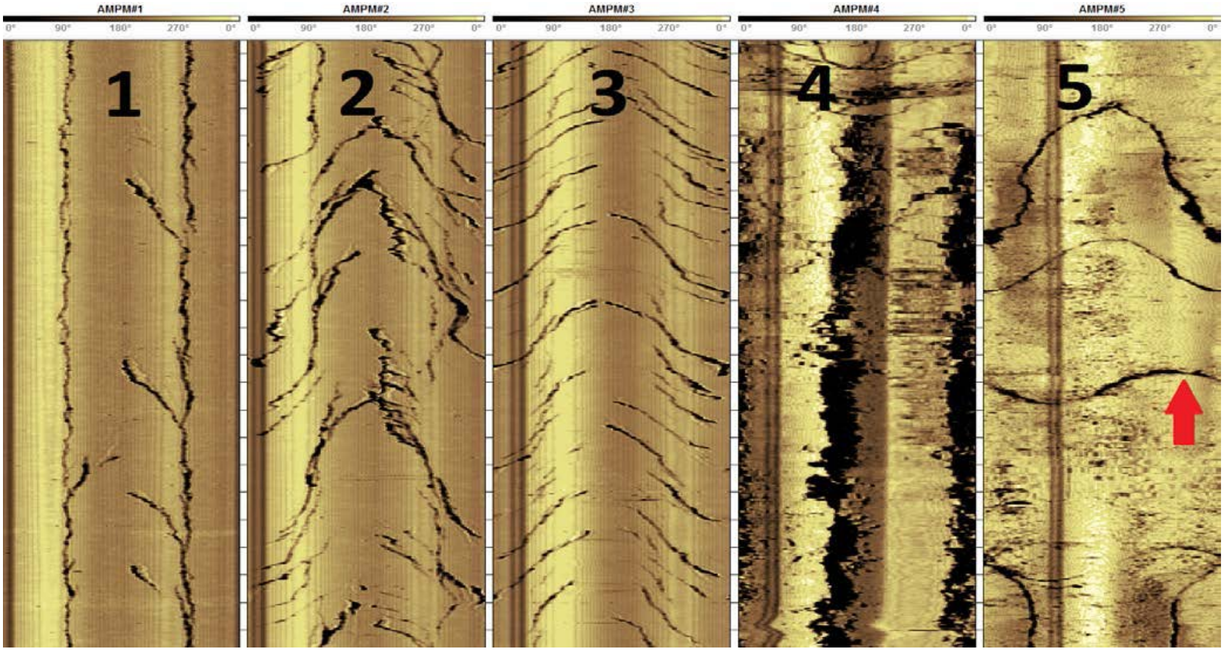


Figure 93: This image illustrates some of the drilling induced fractures types. Image 1 shows a centreline fracture with poorly-developed petal fractures emanating from the one compressive quadrant. Image 2 show petal fractures with no centreline developed. Image 3 shows en-echelon fractures. Image 4 shows breakout. Image 5 is the only image that shows an natural fracture (red arrow) (Lacazette, 2001).

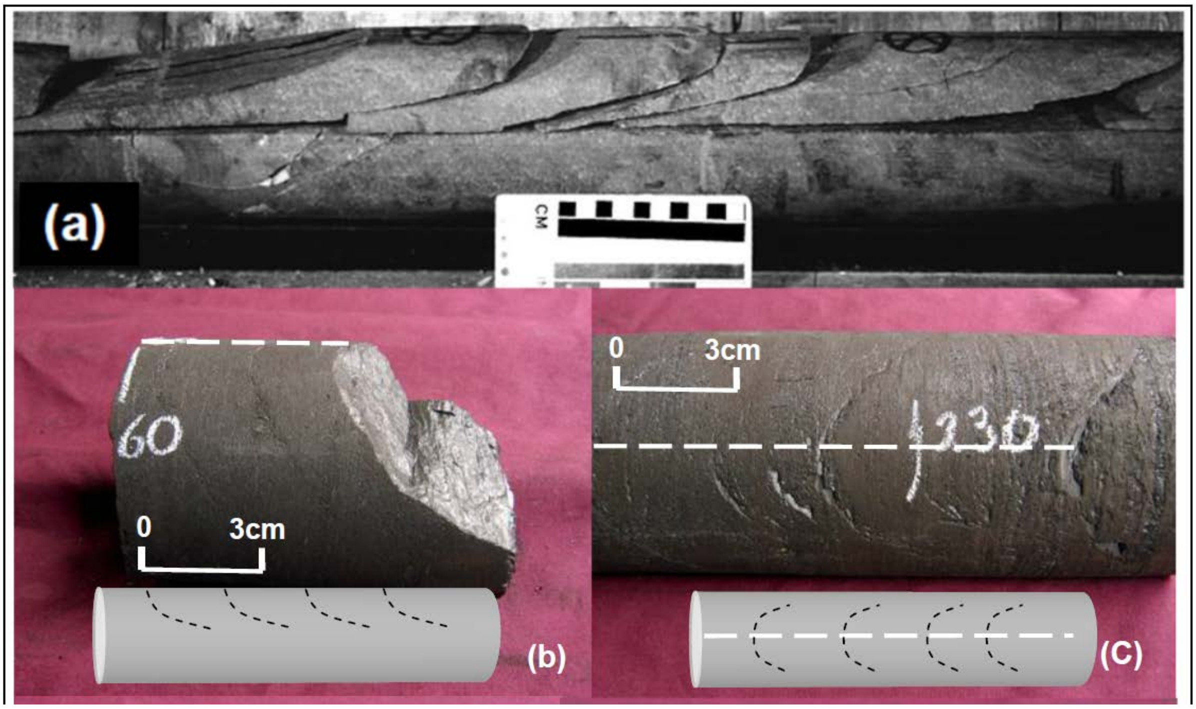


Figure 94: Image (a) shows core samples with centreline fractures that give way to petals. Image (b) and (c) illustrate

2.4.1.3 Sandstone Cross-Bedding (Fig.91 A)

Cross-bedding of a sandstone unit is measured similarly to structural features, as the bedding plane also represents a sinusoidal wave when unwrapped in 2 dimensions. Large numbers of bedding measurements can be made in the sandstone units, however it is advised to have the borehole core on hand confirm whether the structures measure are indeed cross-bedding. Relative grain sizes of the arenaceous units can also be noticed can be used in conjunction with gamma measurements to display sedimentary cycles. A number of boreholes in the study area intersected the Fripp Formation located just above the coal measures and were logged by the ATV tool.