

Geomechanical modeling as a tool for groundwater exploration of fractured rock aquifers in the Namaqualand region, South Africa

Report to the
Water Research Commission

by

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WRC Report No. 1117/1/06
ISBN No. 1-77005-397-2

January 2006

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SUMMARY

Groundwater-resource developments in hard-rock fractured aquifers are generally associated with conductive fractured zones characterised by high transmissivity. Identifying relatively highly productive borehole locations in these fractured-rock environments is an extremely difficult exercise as numerous dry wells are a demonstration of unsuccessful target selection.

A new procedure has been tested to evaluate the potential relationship between known groundwater abstraction locations in fractured-rock environments and geomechanically-modelled sites of high dilatancy. SMT is a computer-based method, relying on rock mechanic principles and stress-strain relationships, which seeks to transform strain data, in the form of a solid geology map, to stress data.

A modelling technique in which dilatancy (fracture permeability) in the crust is due to variations in mean stress allows for the wide variety of structural settings of fractured-rock localities, as these variations are a consequence of regional deviatoric stress acting on an inhomogeneous rock sequence, and a wide variety of potential sites of mean stress, dependent on variations in rock competency, and patterns of faults, fractures or shear zones. Thus a technique that measures variations in mean rock stress, such as SMT, has potential to generate viable dilatant sites, which could be exploration targets for fractured-rock aquifers.

In areas where the SMT method is applicable, a main advantage over previous lineament-analysis procedures is that once the tectonic history of a given area is determined, it is possible to predict which structural features, or combinations thereof, would likely be targeted for groundwater development. In this way, the siting of new boreholes can more effectively be facilitated, even in areas where no previous borehole information exists. The approach can be applied to other areas where a reasonable understanding of the most recent history of brittle tectonics exists. Through SMT and lineament analysis, therefore, the hydrogeologist can correlate the lineament directions with the various kinds of brittle structures known to be related to extension stresses.

The congruence of stress anomalies and known groundwater abstraction locations, as well as fracture density and fracture frequency in the study area demonstrates the usefulness of the technique as an additional data layer in groundwater exploration.

ACKNOWLEDGEMENTS

The authors of this report extend their gratitude to the Water Research Commission (WRC) for providing financial support to the project. In particular, the Project Steering Committee which consisted of the following persons:

Dr KC Pietersen	Water Research Commission
Mr R Domoney	University of the Western Cape
Mr CH de Beer	Council for Geoscience
Dr C Hartnady	Umvoto Africa
Mr E van Wyk	Department of Water Affairs and Forestry
Mr G van Dyk	Department of Water Affairs and Forestry
Mr KD Mbatha	Department of Water Affairs and Forestry

Two post-graduate students, Sean Davids and Anthony Fielies, both completed their respective M.Sc degrees on this WRC funded project. The research team acknowledge their contribution to the project.

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1 INTRODUCTION

1.1 BACKGROUND

Groundwater-resource developments in hard-rock fractured aquifers are generally associated with conductive fractured zones characterised by high transmissivity. Identifying relatively highly productive borehole locations in these fractured-rock environments is an extremely difficult exercise as numerous dry wells are a demonstration of unsuccessful target selection.

A new procedure has been developed to correlate known groundwater abstraction locations in fractured-rock environment with geomechanically-modelled sites of high dilatancy. The geomechanical technique is referred to as Stress Mapping Technology (SMT) and involves correlating the lineament features of a given area with the orientation of the primary stress fields and fractured structures associated with the recent tectonic history that affected the region of study.

SMT is a computer-based method, relying on rock mechanic principles and stress-strain relationships, which seeks to transform strain data, in the form of a solid (continuously traced) geology map, to stress data. A modelling technique in which dilatancy (fracture permeability) in the crust is due to variations in mean stress allows for the wide variety of structural settings of fractured-rock localities, as these variations are a consequence of regional deviatoric stress acting on an inhomogeneous rock sequence, and a wide variety of potential sites of mean stress, dependent on variations in rock competency, and patterns of faults, fractures or shear zones. Thus a technique that measures variations in mean rock stress, such as SMT, has potential to generate viable dilatant sites, which could be exploration targets for fractured-rock aquifers.

The main premises of the application of SMT in the exploration of groundwater-development/abstraction capacity of fractured zones are:

- the development of fractured rock is the result-structured deformation, which in turn is driven by tectonic stresses. SMT is a geomechanical technique developed to target structurally controlled dilatant (low stress) sites where fracture permeability occurs. Groundwater will accumulate in the fractured rock because of the rock mass permeability and the topographical setting of the low stress (dilatant) sites. Thus the authors argue that SMT can therefore be used as an additional tool and layer of information to explore and target fractured-rock aquifers.

- the most recent tectonic events in a given area had the most significant influence on the nature of the existing fracture network and subsequently on the regional groundwater flow characteristics.
- the brittle reactivation of older structures and generation of new ones during neotectonism (recent tectonic history).
- the negligible influence of rheology on the stress distribution in the upper crust.

By applying the SMT method in a series of test areas where fractured crystalline basement aquifers dominate, the research study endeavour to assess the technique's success in generating geomechanical anomalies within existing areas of known groundwater abstraction capacity. Furthermore, through the application of this technique, an integrated approach is shown to provide methodology for delineating fractured areas within rock environments that have high potential for groundwater-resource development by combining classical lineament analysis with a clear understanding of tectonic history of a given area.

1.2 OBJECTIVES

The aims of this study are:

- Predicting potential groundwater development locations by applying a geomechanical model and validating the model through hydrogeological investigations.
- Furnishing information to assist in the establishment of a groundwater monitoring network.
- Contributing to the quantification of groundwater in the region for community water supply purposes.

1.3 LOCATION OF STUDY AREA

The area is situated between latitude 17°00' - 18°30' and longitude 29°00' - 30°30' and includes the Buffels River catchment (F30) as well as parts of catchments F40 and F50 (Figure 1). Namaqualand consists of seven communal areas, namely the

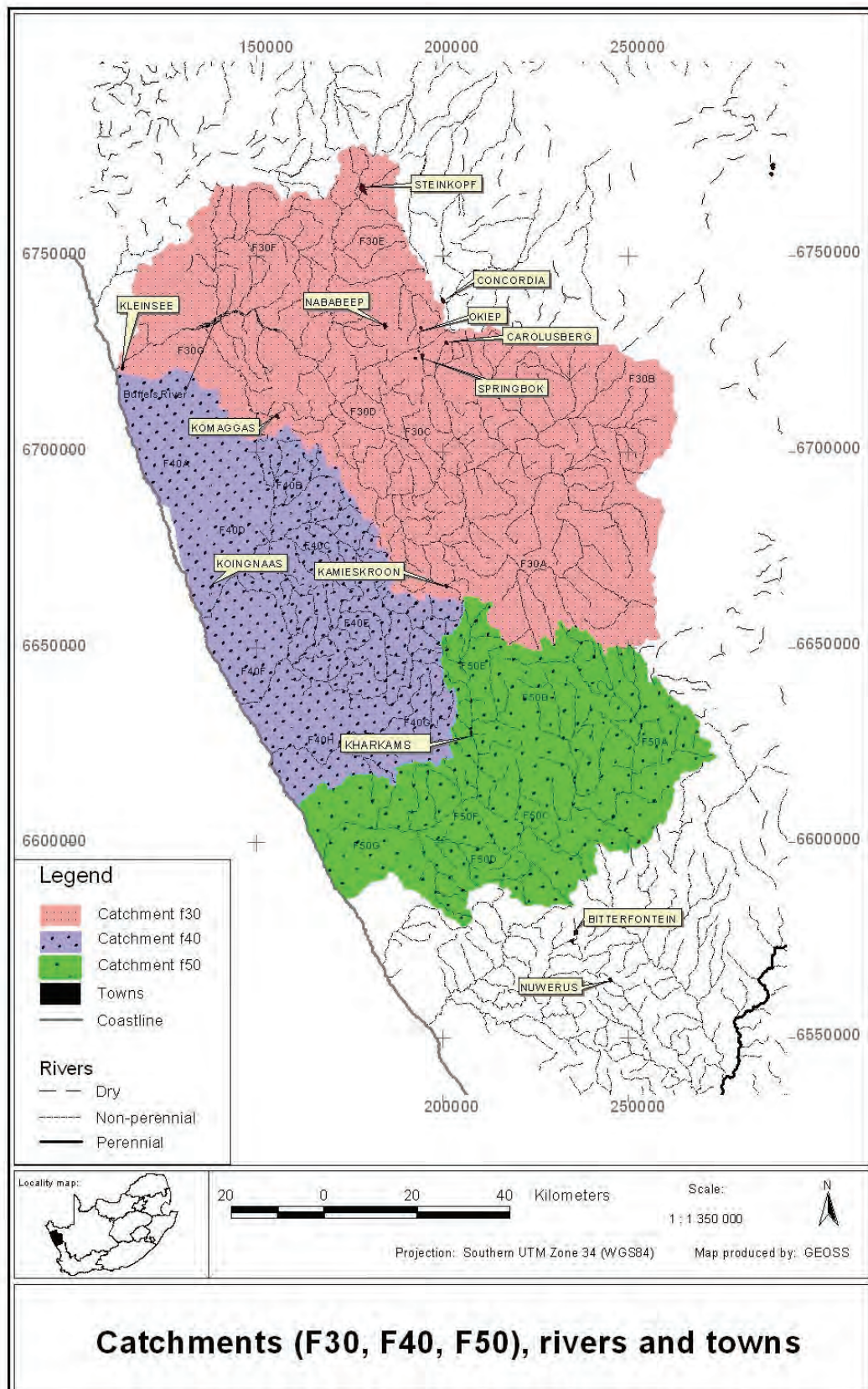


Figure 1: Geographic location map of the study area, showing the drainage patterns for the secondary drainage catchments F30, F40 and F50.

northern Richtersveld, southern Richtersveld, Steinkopf, Concordia, Komaggas, Pella and Leliefontein. Namakwa Water supplies surface water from the Orange River to the larger towns only, such as Springbok, Nababeep, Okiep and Kleinsee. State and privately owned farms also depend on groundwater for domestic and stock water supply.

The region can be classified as arid to semi-arid, with mountainous regions having higher rainfall than the arid lowland due to orographic effects. Rainfall occurs mostly during the winter months. Snow in the Kamiesberg Mountains is, however, not uncommon during the winter months. The average annual rainfall generally increases from west to east until it reaches the escarpment, and decreases towards the inland. The higher lying areas within the study area receive much higher rainfall than the surrounding lower lying areas and coastal plains.

1.4 SCOPE OF WORK

The focus of this study will be on the Namaqua province (in the Buffels River catchment), which form most of the crystalline basement in the Northern Cape and Southern Namibia. The study will form part of a research program focusing on “Sustainable Groundwater Management Utilization” in the semi-arid Northern Cape.

The development of a new method for assessing the validity of geomechanical modelling and the influence of neotectonics on the target selection and optimal location of productive boreholes in fractured media are the main results of the current work. The outcome of the new technique’s result must be correlated with the existing hydrological database to benchmark the usefulness of SMT as a data layer in a groundwater exploration programme.

2 METHODS AND MATERIALS

Forming part of the regional research program on “Sustainable Groundwater Management Utilization” in the semi-arid Northern Cape, this study involved the preparation and compilation of comprehensive data capturing exercise, involving remote sensing (*i.e.* Landsat TM 5 and 7), geophysical (*i.e.* aeromagnetic), geological (structural, lithological, geomorphological), and geohydrological data sets, as well as published geological maps and literature (see listing below). All digital data sets were georeferenced and projected to a UTM 34S projection using the WGS84 datum. The data base comprises the following captured data sets:

2.1 LITERATURE

An extensive literature research has been completed regarding the geology, tectono-metamorphic evolution and neotectonics of the Namaqualand region in the Northern Cape. This information forms the basis of the geological knowledge of the study area and assisted with the interpretation of remote sensing and geophysical data sets.

2.2 GEOLOGICAL MAPS

The area of interest is covered geologically by a published regional 1:250,000 geological maps, entitled “The tectonic units of parts of Namaqualand, Bushmanland and southern South-West Africa/Namibia” and compiled by Strydom *et al.* (1987) (Figure 2). The map was scanned at 300 dpi resolution and subsequently georeferenced and projected to the projection parameters mentioned above.

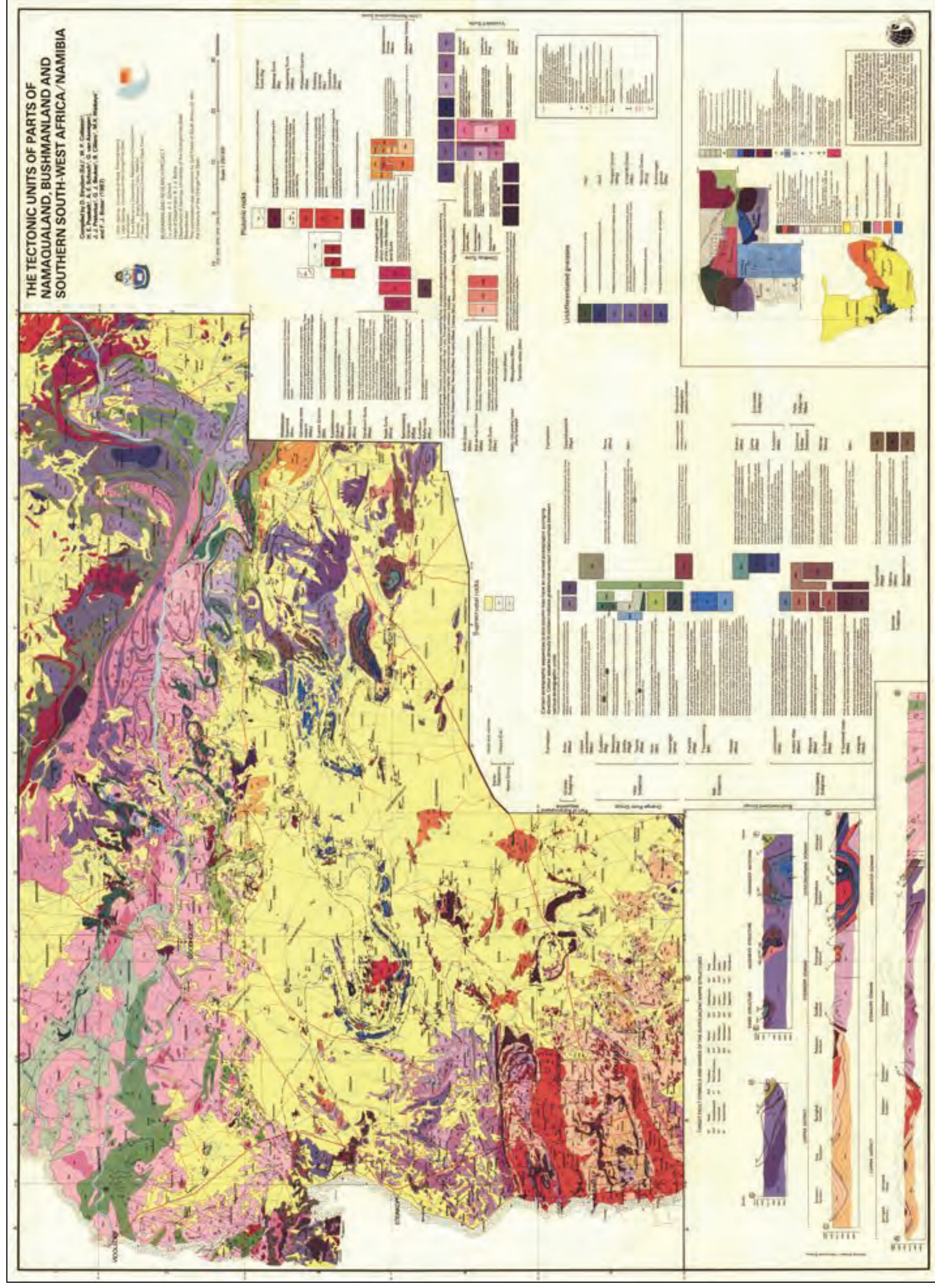


Figure 2: Geology map, showing the tectonic units of parts of Namaqualand, Bushmanland and southern Namibia (compiled by Strydom *et al.*, 1987).

2.3 LANDSAT TM IMAGERY

Landsat TM scenes 176/80 and 176/81 were georeferenced and projected to the above-specified projection parameters. A band combination of 741 was selected for highlighting structural features and differences between lithological units most effectively in a semi-arid terrain such as the Namaqualand region of the Northern Cape Province. Additional contrast enhancement was achieved by performing a principal component analysis (PCA) for all bands of both Landsat TM scenes, with the exception for the thermal band 6. Having selected only the first principal component (PC1) of both Landsat TM scenes, a high boost filter was applied to the both PC1s (Figure 3).

2.4 GEOPHYSICAL DATA

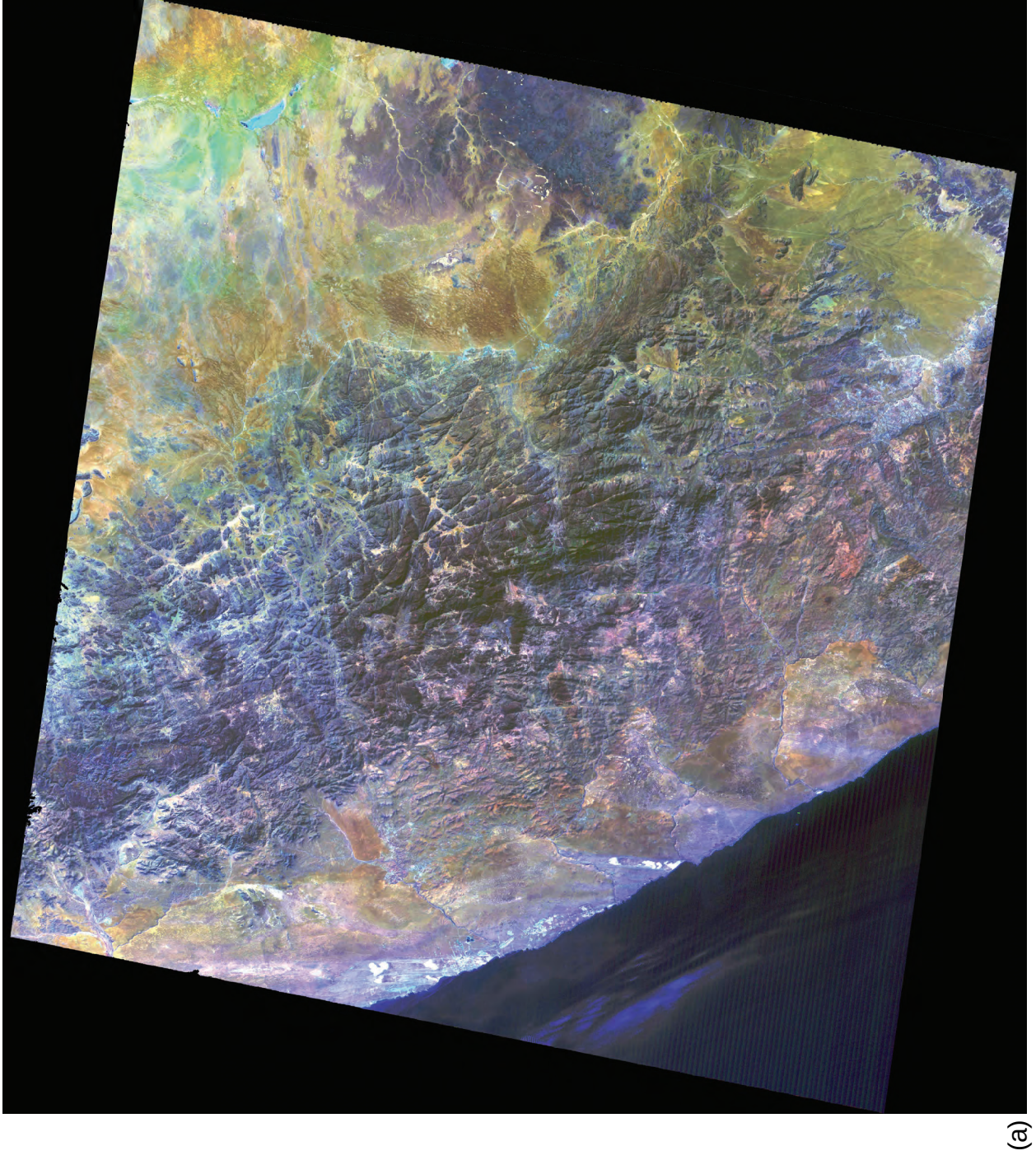
Regional aeromagnetic data, publicly available from the Council for Geoscience in Pretoria, were reprocessed and various contrast enhancement techniques performed. Total magnetic field and 1st vertical derivative images in colour and grey-scale were produced in the above-specified projection as hard copies and digital images at 1:100,000 scale (Figures 4 & 5).

2.5 AERIAL PHOTOGRAPHY

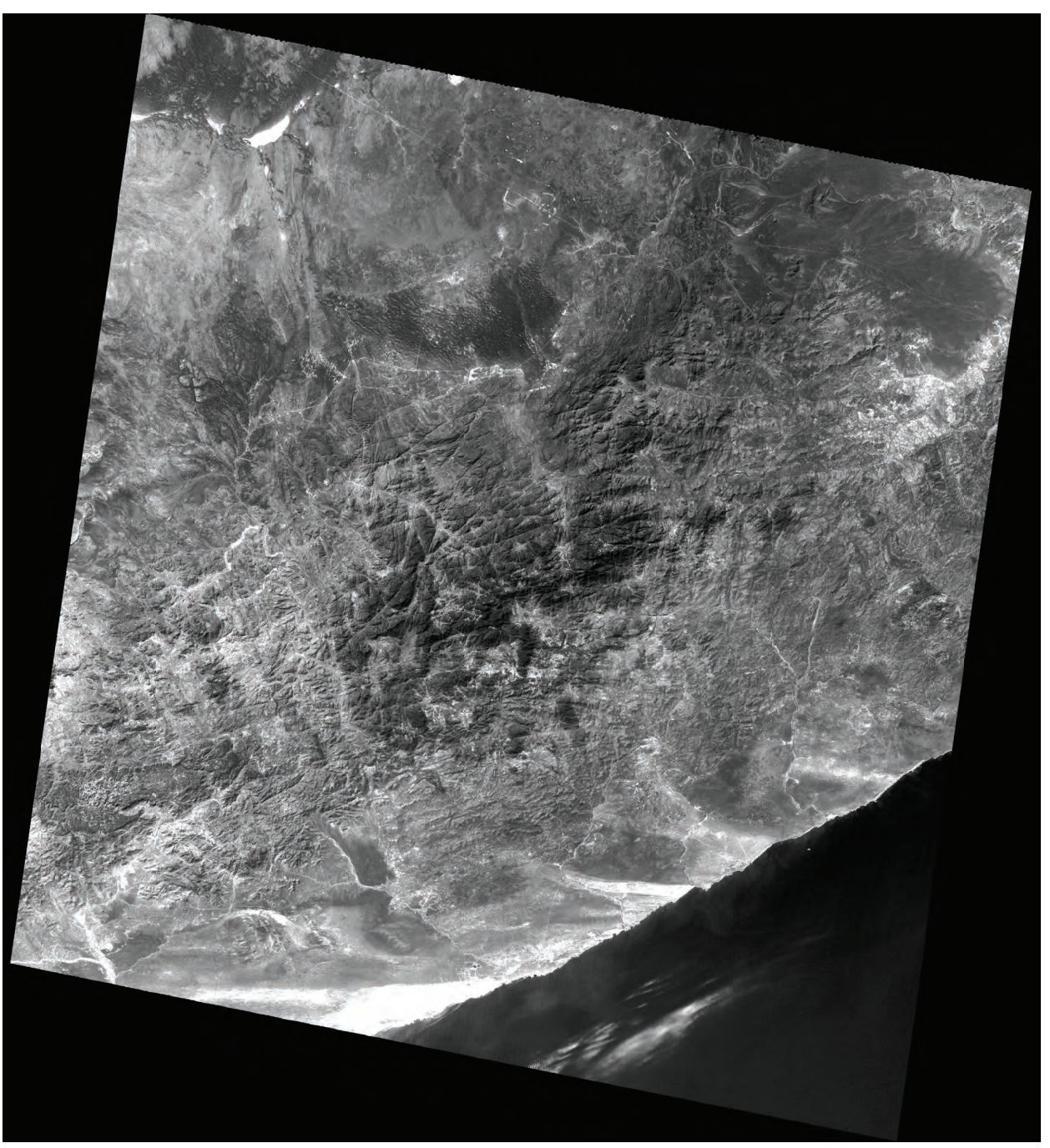
A total of 270 aerial photographs, covering the entire Okiep area, were scanned at 600 dpi resolution and resampled to 300 dpi in order to achieve file size reduction without the loss of image resolution. The scanned images were georeferenced and projected to the above-mentioned projection, and subsequently mosaicked to a single image (Figure 6).

2.6 TOPOGRAPHIC DATA

A total of 45 topographic sheets in 1:50,000 scale were scanned at 600 dpi and resampled to 300 dpi, covering 50% of the four 1:250,000 topographic sheets of Springbok, Pofadder, Garies and Loeribsfontein (Figure 7).



(a)



(b)

Figure 3: Landsat scene 176/80 processed to (a) RGB 741-band combination image and (b) to a first principal component (PC1) image with high boost filter applied for contrast enhancement.

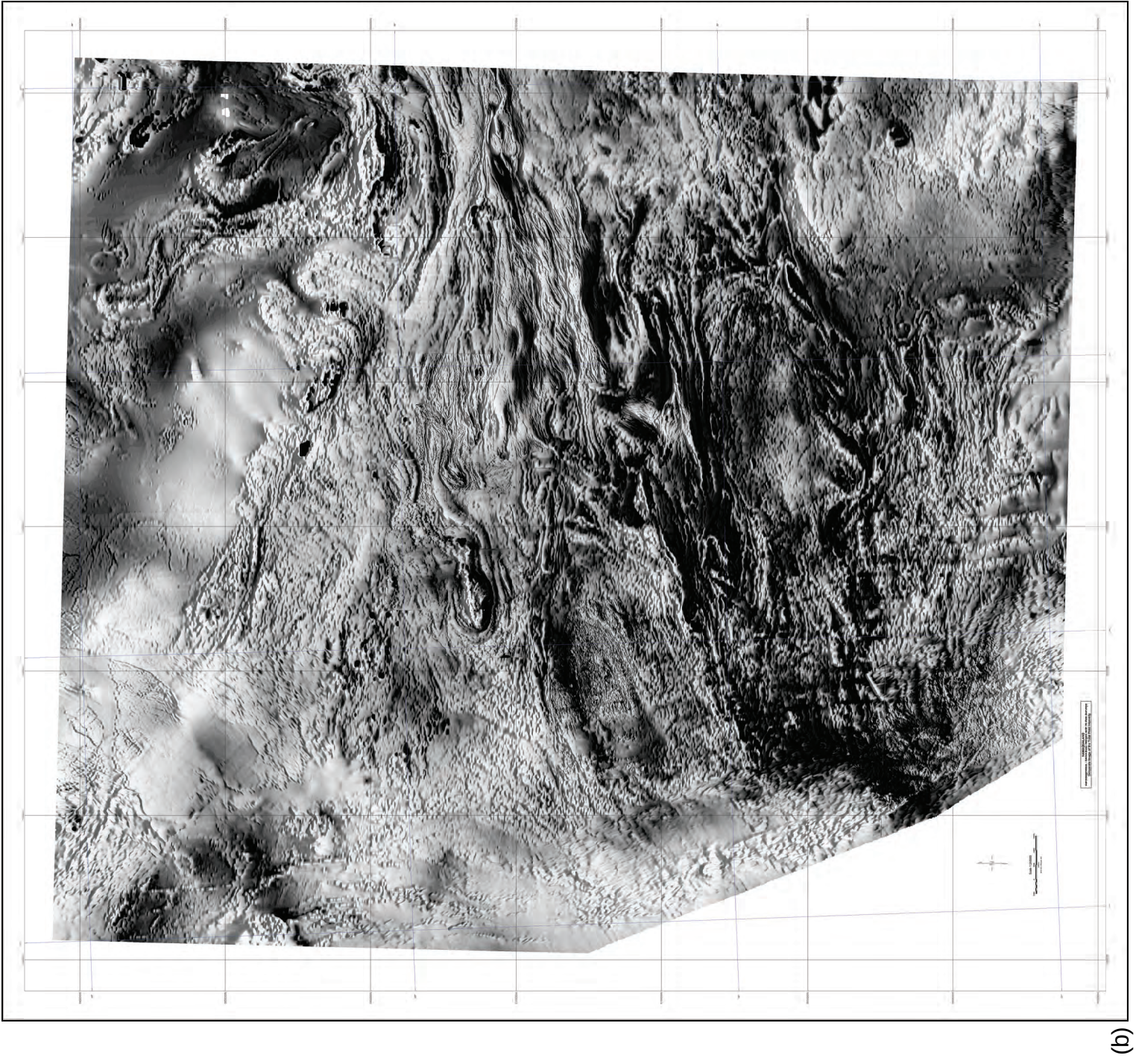
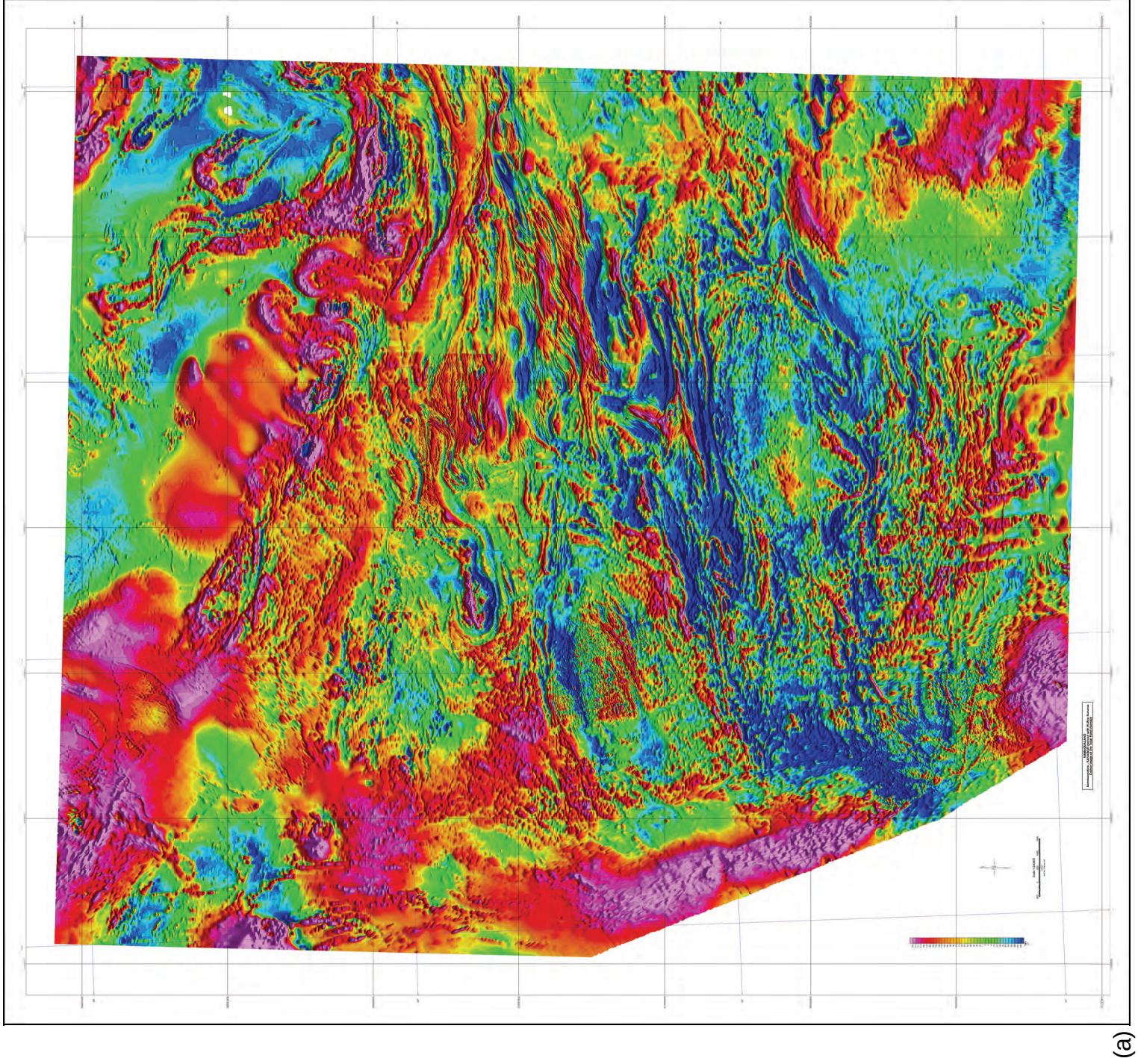


Figure 4: (a) Coloured and (b) grey-scale aeromagnetic total field images (200m grid line spacing and sun-shaded from 360/0°).

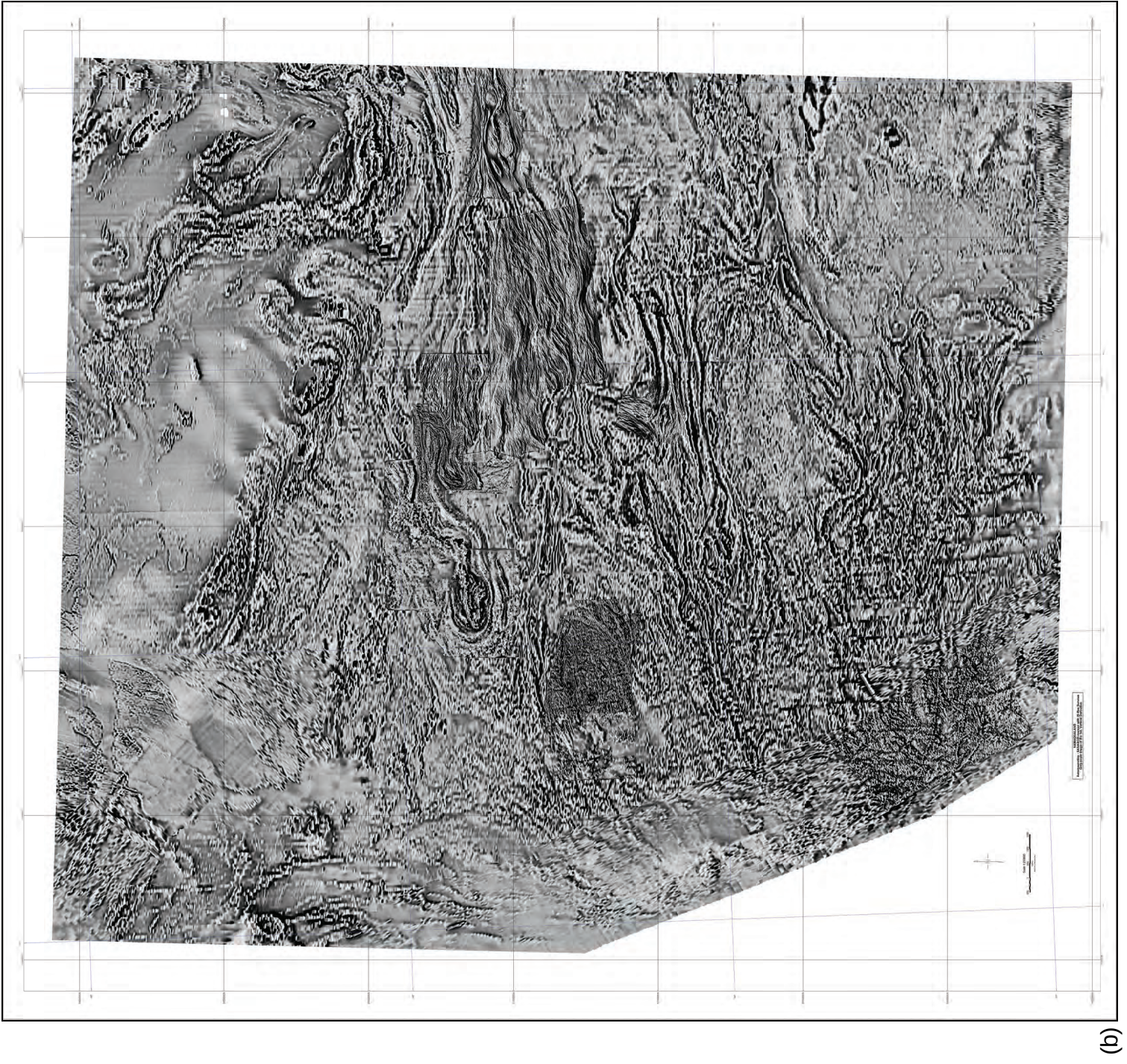
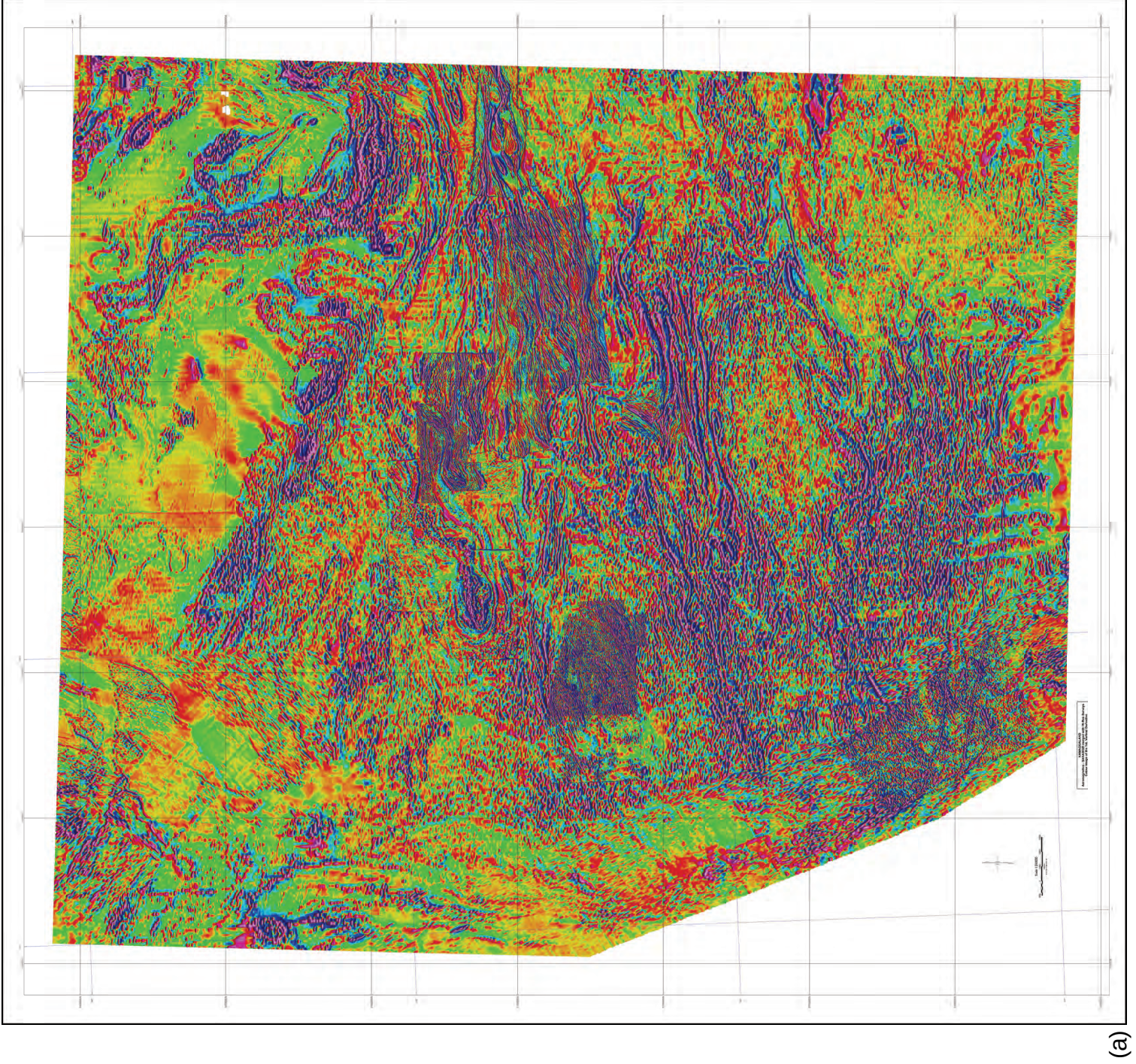


Figure 5: (a) Coloured and (b) grey-scale aeromagnetic first vertical derivate images (200m grid line spacing and sun-shaded from 360/0°).

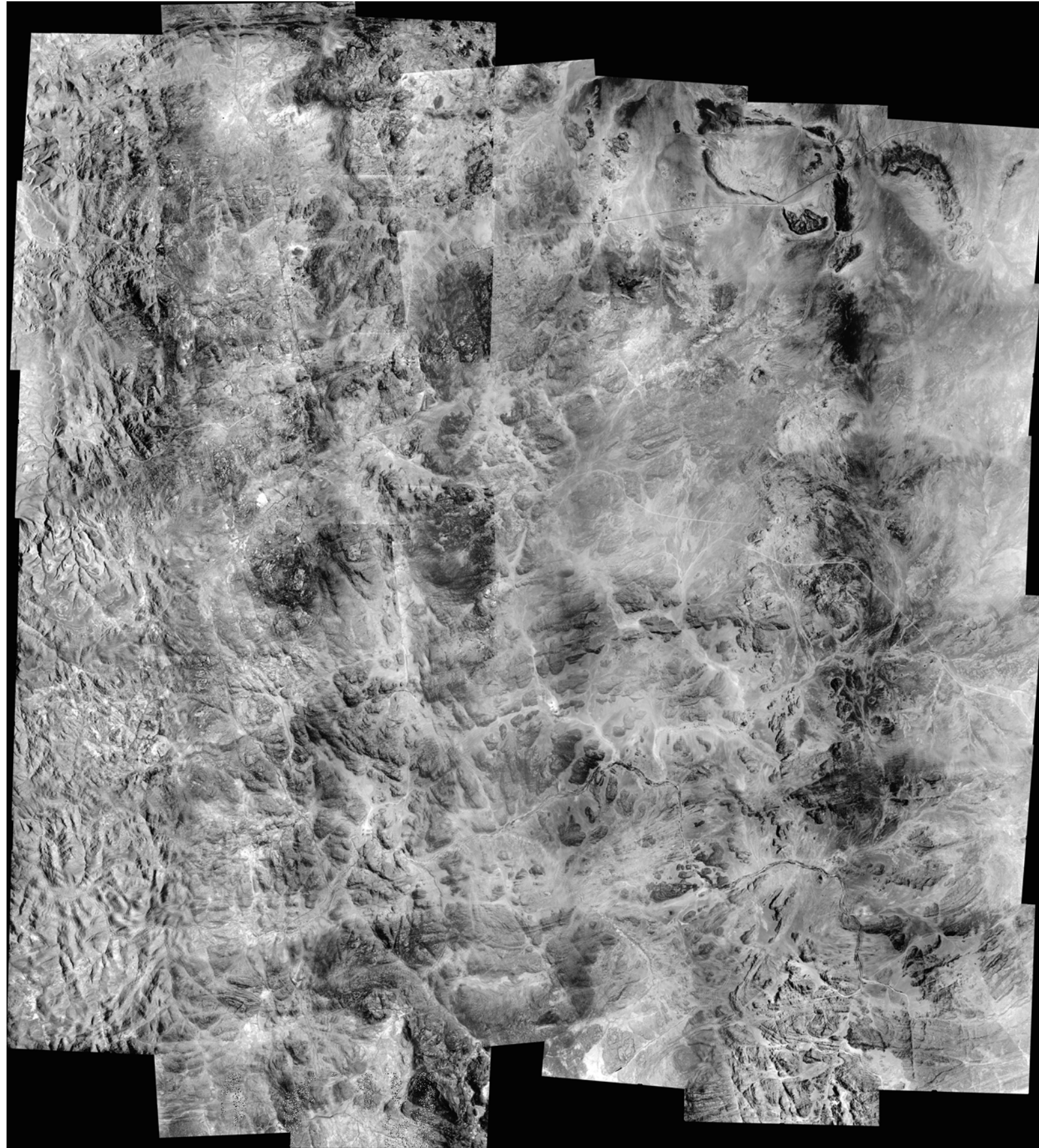


Figure 6: Aerial photographic mosaic.

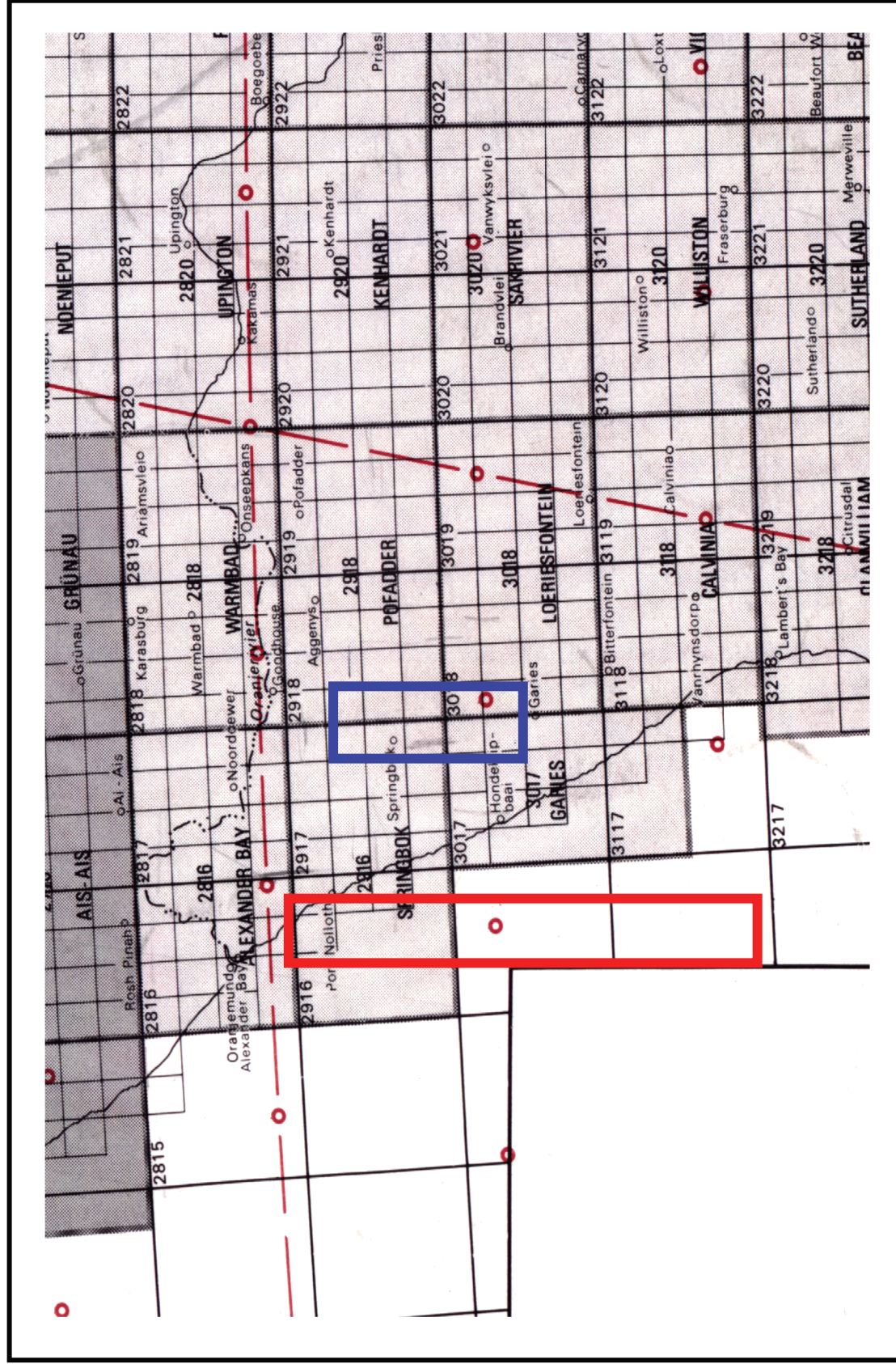


Figure 7: Layout plan for 1:250,000 and 1:50,000 scale topographic sheets over the Namaqualand region. Note: Wider study area (red outlined) and SMT study area (blue outlined) are covered by the 1:250,000 sheets Springbok, Pofadder, Garies and Loeriesfontein, and 45 topographic sheets in 1:50,000 scale.

2.7 PALAEO-LAND SURFACE DATA

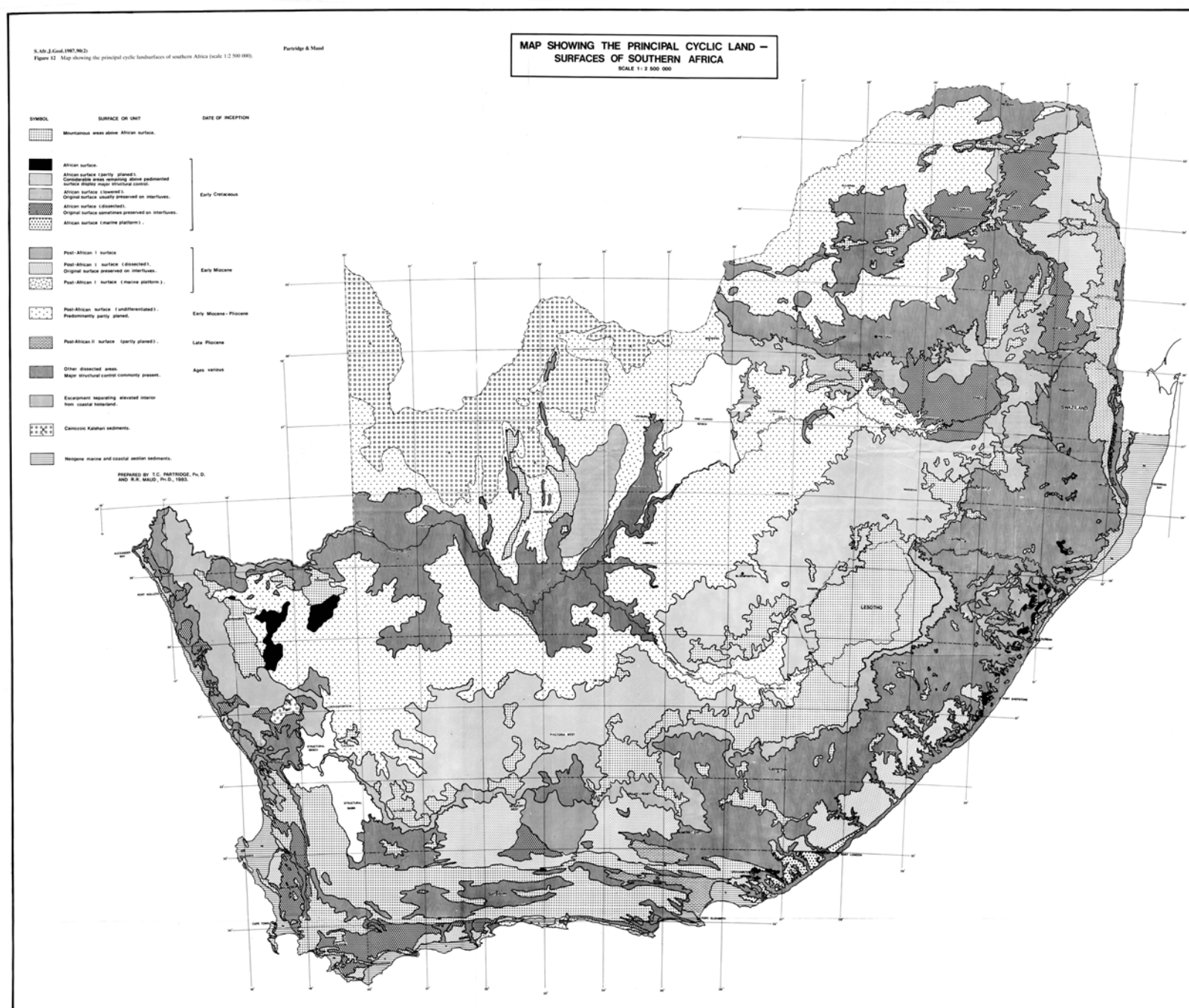
Information regarding the existence and nature of old land surfaces in the Namaqualand region were obtained from published literature. A published map entitled “Principle Cyclic Land Surfaces of Southern Africa” in 1:2,500,000 scale by Patridge & Maud, published in South African Journal of Geology, 90(2), 1987, was scanned at 300 dpi resolution, georeferenced and projected to the projection parameters mentioned above (Figure 8).

2.8 DIGITAL ELEVATION MODEL

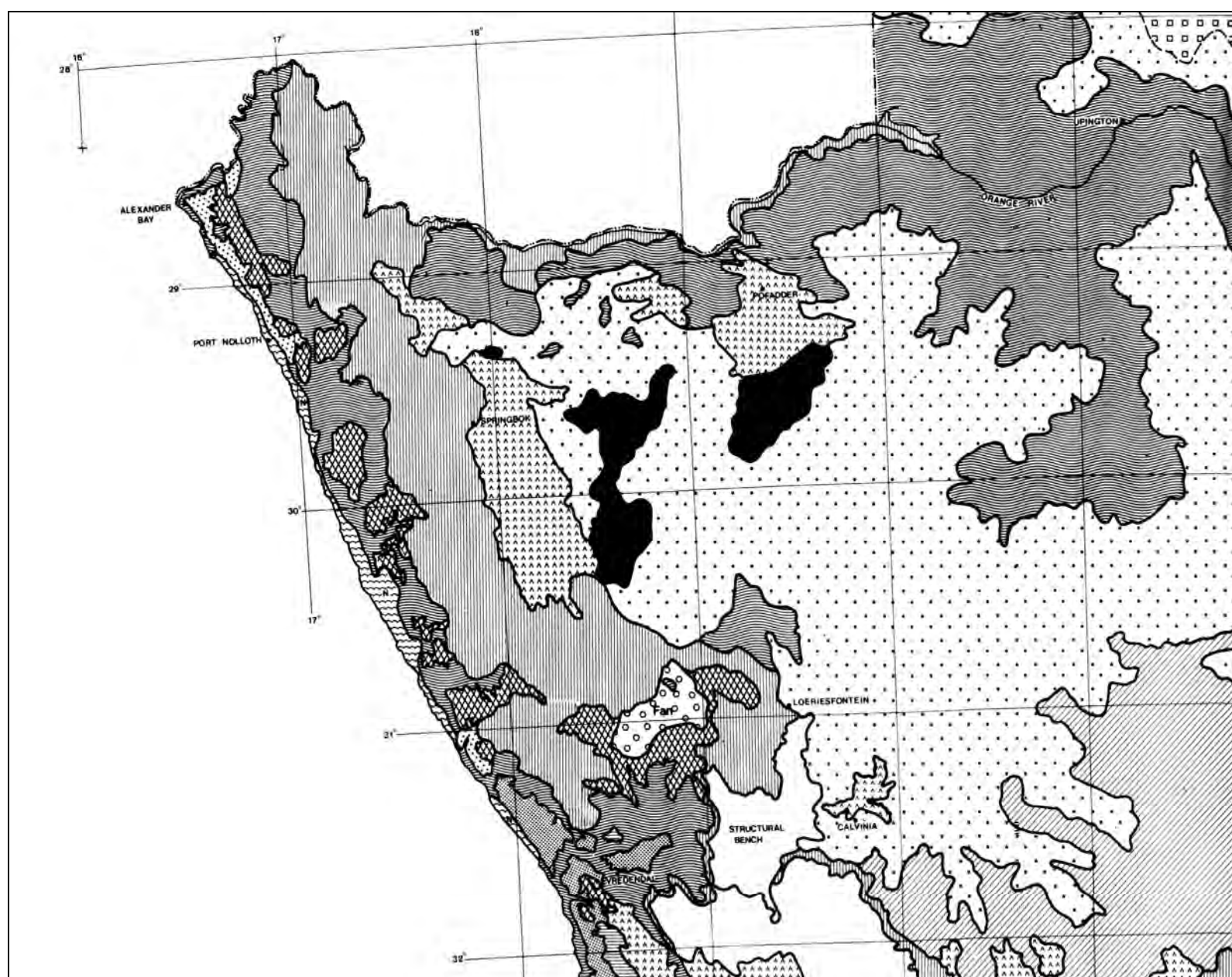
A digital elevation model had been purchased by the Earth Science Department of UWC from an outside consultant firm, but not been incorporated into the structural interpretation process so far due to late arrival of this data set (Figure 9).

2.9 FAR FIELD STRESS ORIENTATION AND AGE DATA

The nature, orientation and time of dominance of regional far field stress fields, induced into the lithosphere of the Namaqualand region since break-up of the Gondwana supercontinent (*i.e.* at ~180 Ma) until present time, was established from literature research, studying the relative age of different fracture/dyke pattern in the field and from remote sensing data, as well as from borehole break-out data and information regarding neotectonic/neoseismic activity (Figure 10).



(a)



(b)

Figure 8: (a) Palaeo-land surface map, showing the principal cyclic land surfaces of southern Africa (after Partridge & Maud, 1987); b) close-up view, showing the principal cyclic land surfaces in Namaqualand and Bushmanland regions.

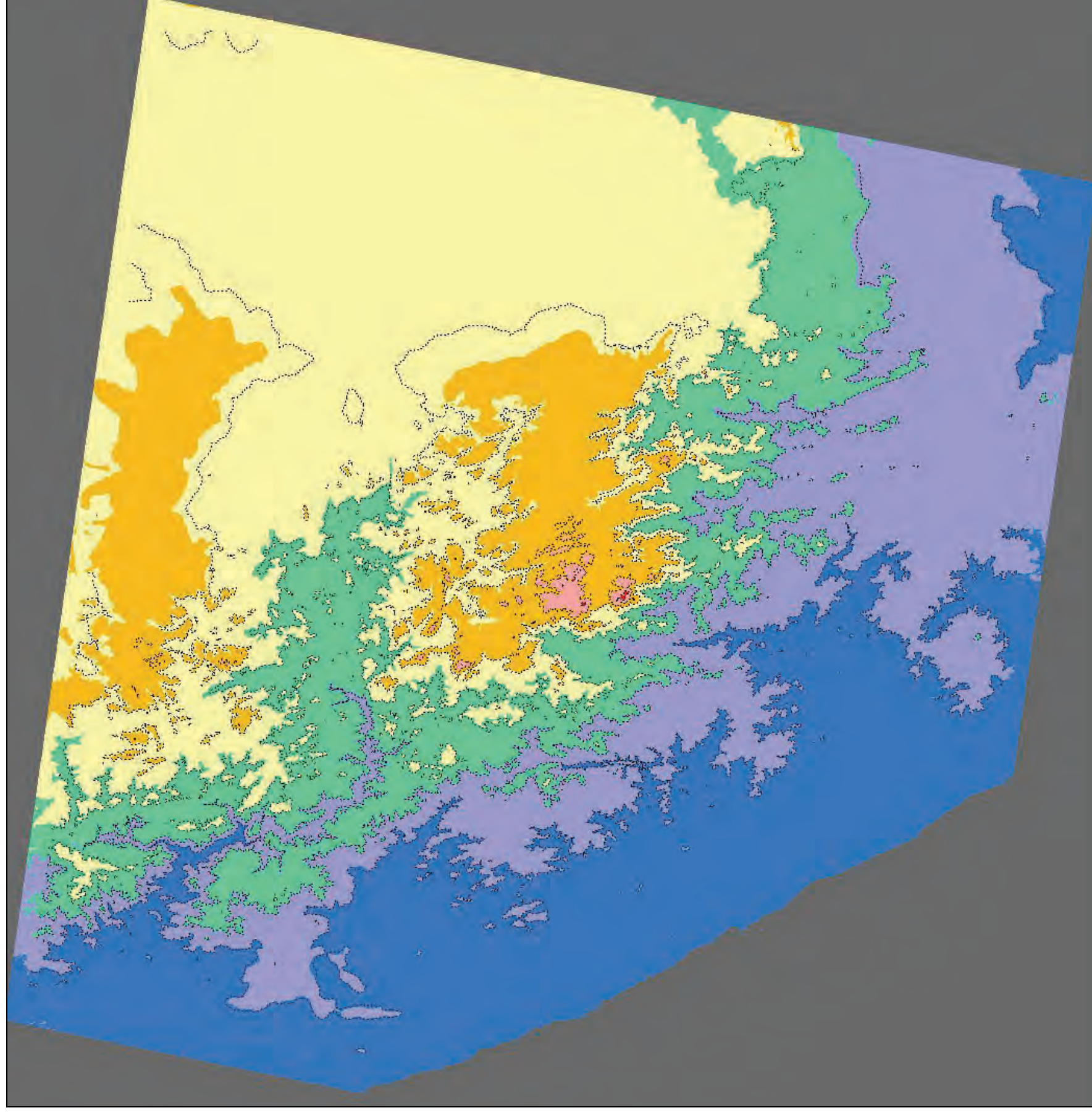


Figure 9: Contoured terrain model of the study area.

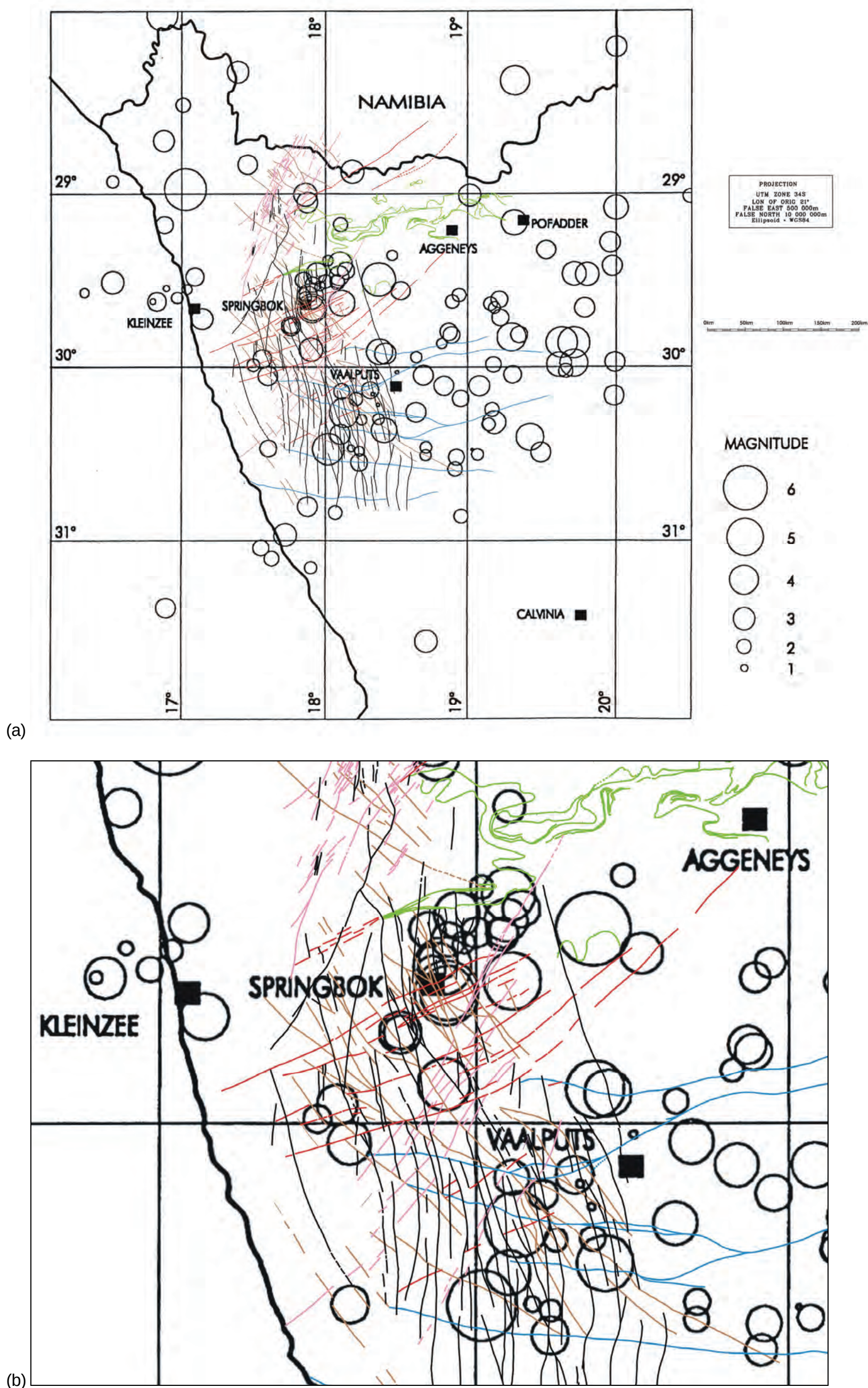


Figure 10: Neotectonic map, showing the location and magnitude of seismic epicentres (recorded during January-September 1996; courtesy of Council for Geoscience) in relation to major structural zones interpreted to have formed during the break-up phase of Gondwana and associated opening of the South Atlantic ocean, which were superimposed on a ductile structural grain (thrust zones (green) and strike-slip shear zones (blue)) acquired during the Mesoproterozoic Namaqua Orogeny.

3 GEOLOGICAL FRAMEWORK

3.1 REGIONAL SETTING

In their synthesis, Tankard *et al.* (1982) identified a distinct sequence of crustal evolutionary stages that incorporates the geological and tectonic events that have shaped the African subcontinent. The ancient geological evolution of southern Africa can be regarded as a sequence of accretion onto a stable Kaapvaal craton causing both extensional and compressional tectonic periods (Partridge & Maud, 2000). The formation of the Namaqua Province occurred between ~2000 Ma and 1000 Ma and resulted in the stabilisation of the Kalahari craton around ~1000 Ma.

The crystalline basement rocks of Namaqualand retained imprints of mostly the Proterozoic events, although much of the present landscape appears to have developed later, following the break-up of Gondwanaland in the Cretaceous.

3.2 LITHOSTRATIGRAPHY

The Northwestern Cape Region (i.e. Namaqualand) can be subdivided into three major geological provinces (Tankard *et al.*, 1982). These are the basement rocks of the Namaqua Province (further subdivided into three zones), the volcano-sedimentary rocks of the Gariep Complex (Visser, 1989) in the northwest, and a Phanerozoic cratonic cover (Table 1). The Namaqua Province (Table 1) comprises most of the crystalline basement in the northern Cape and southern Namibia (Tankard *et al.*, 1982).

In Namaqualand, the margins of the Namaqua Province are largely obscured by younger cover rocks of the Gariep, Nama and Karoo sequences, as well as with Cenozoic surficial sediments to the east and west. In the west and extreme north, rocks of the Namaqua Province and its correlatives are bordered by formations of the late Proterozoic Gariep Complex and in the east abut the Kaapvaal craton with marked structural discordance in both cases. In the south, rocks of the Nama Group, the Cape Supergroup and the lowermost units of the Karoo Supergroup cover the rocks of the Namaqua Province (Albat, 1984).

The Central Zone of the Namaqua Province, a complexly deformed heterogeneous group of gneisses and intrusions of medium to high grade metamorphism (Tankard

et al., 1982) covers most of the Namaqua Province comprising of an assemblage of metasedimentary, metavolcanic and intrusive rocks.

Table 1: Classification of major geological provinces (after Tankard *et al.*, 1982 and Visser, 1989).

Geological Province		Group	Age	Locality	OROGENIES & Subprovinces
Phanerozoic Cover Rocks		Sand, alluvium and calcrete	Late Phanerozoic (Cenozoic)	Along coast. Most of Western Bushmanland	
		Karoo Group 1. Prince Albert Fm 2. Dwyka Formation	Early Phanerozoic (Middle/Late Palaeozoic)	Southeastern corner of Namaqualand	
		Nama Group 1. Kuibis Formation 2. Schwarzrand Fm	Late Proterozoic (Late Namibian)	Isolated strip north of Springbok	
Gariep Province		Gariep Complex (6 Formations)	Late Proterozoic (Early/Middle Namibian)	Central and Western Richtersveld	PAN-AFRICAN Gariep Sub-province
Namaqua Province	Central Zone	Namaqua Metamorphic Complex/Province	Middle Proterozoic (Middle Mokolian)	Most of Namaqualand and parts of Bushmanland	NAMAQUAN Bushmanland & Gordonia Subprovinces
	Western Zone	Vioolsdrif Intrusive Suite	Middle Proterozoic (Early Mokolian)	Northeastern and Eastern Richtersveld Northern Namaqualand	EBURNIAN Richtersveld Subprovince
		Orange River Group	Middle Proterozoic (Early Mokolian)	Northeastern part of Richtersveld	
	Eastern Zone			Upington	

Cover rocks of the Nama group overlie the basement rocks to the north of the Buffels River catchment. The margins of the Namaqua Metamorphic Province are also obscured by younger cover rocks of the Gariep Complex to the northwest as

well as with Cenozoic surficial sediments to the east and west. In the south, rocks of the Nama Group, the Cape Supergroup and the lowermost units of the Karoo Supergroup cover the rocks of the Namaqua Metamorphic Province (Albat, 1984).

Proterozoic crystalline basement rocks of the Namaqua Metamorphic Province predominantly underlie the Buffels River catchment, as well as the surrounding catchments.

3.3 STRUCTURAL GEOLOGY

3.3.1 The Namaqua Geodynamics

The rocks of the Namaqualand Metamorphic Province underwent several phases of intensive folding (e.g. isoclinal folding) and shearing (thrusting), as well as brittle faulting and the intrusion of large-scale syntectonic granites (Visser, 1989). The interpretation of both vertical and lateral stratigraphic and structural relationships, as well as possible lateral correlatives, is thus extremely difficult. The high-grade metamorphism and multi-phase deformation undergone by these rocks, destroyed the normal stratigraphic criteria and produced generations of tight and isoclinal folding (Joubert, 1971; Jack, 1980) (Figure 11).

The Namaqua Province, in particular the Bushmanland Subprovince, has been subdivided into various terranes (Hartnady, 1985; van Aswegen, 1983) based on criteria such as metamorphic facies (Albat, 1984) and strain intensity. The study area can thus be subdivided into a number of domains:

- The Steinkopf domain (or Steinkopf terrain) comprises of medium to high-grade gneisses (Blignault *et al.*, 1983; van der Merwe & Botha, 1989; van der Merwe, 1995). The northern margin of this terrain is the Groothoek thrust zone and to the south the Ratelpoort shear zone bound the terrain. The intrusive Gladkop suite of rocks is dominant within this terrane (van Aswegen, 1983). The mid-crustal Steinkopf domain (van der Merwe, 1995) displays amphibolite-grade metamorphism (Blignault *et al.*, 1983).
- The high-grade metamorphic Okiep Copper District granulite facies (Blignault *et al.*, 1983; Thomas *et al.*, 1994; Gibson *et al.*, 1996) comprises of intrusive rocks belonging to Gladkop, Spektakel and Little Namaqualand suites. Rocks of the Spektakel and Little Namaqualand suites are the most abundant (Marais & Joubert, 1980), while the metasedimentary rocks (*i.e.* Khurisberg Subgroup) of the Okiep Group are associated with basin and

dome structures. The Koperberg suite of rocks is characterised by numerous small, irregular, dyke-like mafic bodies intruding along steep structures that are associated with tight antiforms (Clifford *et al.*, 1995, Gibson *et al.*, 1996; Watkeys, 1996; van Zwieten *et al.*, 1996). The Ratelpoort shear zone in the north and the Buffels River shear zone in the south bound the domain.

- The Kamieskroon high-grade granulite-facies south of the Buffels River shear zone. Further to the south, rocks of the Kamieskroon high-grade granulite terrain are thrust onto rocks of the Karkams low-grade granulite-facies.

The Proterozoic Namaqua mobile belt, including the Richtersveld Subprovince, was subjected to the 1000 – 1200 Ma Namaqua orogeny (Blignault *et al.*, 1983; Van der Merwe, 1995). The earliest episodes of deformation of the Namaqualand, when the rocks were plastically deformed, controlled the regional distribution of the lithological units and generated their generally east–west striking tectonic fabrics. During the succeeding stages of brittle deformation, the rocks were modified along zones of movement and resulted in the formation of a trough along the West Coast where later sedimentation took place. The rocks of the Namaqualand Metamorphic Province thus underwent several phases of intensive folding (such as isoclinal folding) as well as faulting and were intruded on a large scale by syntectonic granites (Visser, 1989). Researchers such as Albat (1984), Blignault *et al.*, (1983), Lipson (1978), Moore (1977) and Joubert (1971) recognised four deformation phases within the rocks of the Namaqua Metamorphic Complex. The interpretation of both vertical and lateral stratigraphic and structural relationships, as well as possible lateral correlatives, is extremely difficult. The high-grade metamorphism and multi-phase deformation undergone by these rocks, destroyed the normal stratigraphic criteria and produced generations of tight and isoclinal folding (Joubert, 1971; Jack, 1980). Uplift and erosion during the Cretaceous stripped off most of the cover rocks to expose the crystalline basement of the Namaqualand terrane (Joubert, 1971).

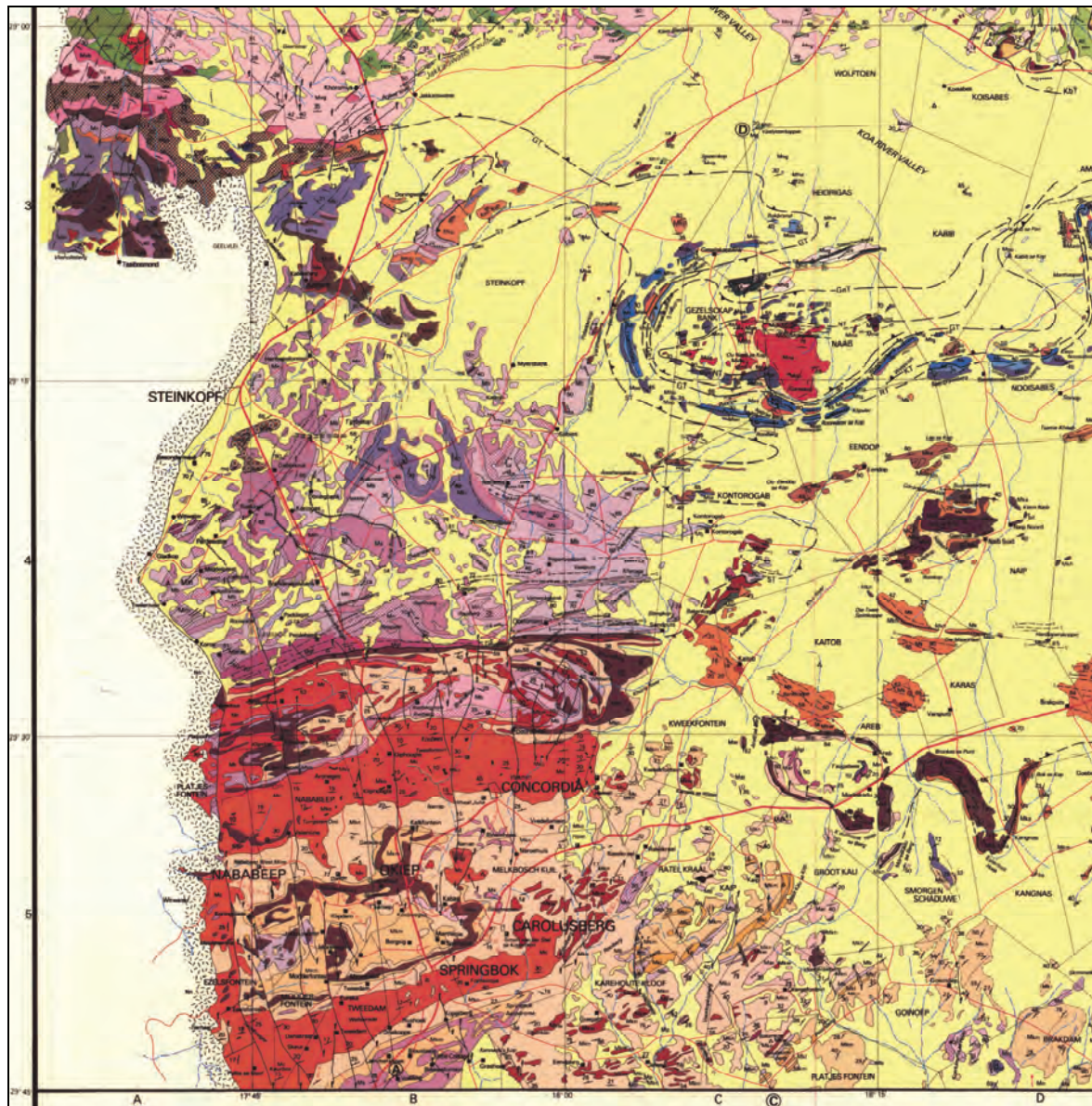


Figure 11: Geology map of study area (compiled by Strydom *et al.*, 1987).

3.3.2 Neoproterozoic Overprints

The differentiation of Neoproterozoic (Pan African) brittle fracture systems from the Neotectonic fracture system has not been attempted, as it is irrelevant within the context of the study objective. However, structural elements and deformation related to compression during Pan-African tectonism (forming the Gariep and Vanrhynsdorp fold-thrust belts) have not been conclusively identified within the study area.

3.3.3 Neotectonic activity and far field stress

Neotectonics, the study of young typically Neogene and Quaternary deformation, has been a long neglected discipline on its own and has its roots in seminal geomorphologic investigations (e.g. Du Toit, 1933; King, 1963; Partridge & Maud, 1987). In recent years, however, the distribution of in situ stress, seismicity and neotectonic activity across the subcontinent has attracted increasing attention and intense research (e.g. McCarthy *et al.*, 1993; Andreoli *et al.*, 1996; Brandt, 1998; Stacey & Wesseloo, 1998; Partridge & Maud, 2000; De Kock, 2000; Spönemann & Hagedorn, 2000; and references therein) especially as a result of major hydroelectric, nuclear engineering and mining projects. Such investigations have begun to identify a pattern of neotectonic history that was much more extensive than was ever imagined possible within a “stable” cratonic environment. Furthermore, a multidisciplinary set of data has emerged which allows today to develop and better constrain geodynamic models for the geologic evolution of the African subcontinent over its recent past, thus providing a framework for long-term seismic risk assessment in southern Africa.

The break-up of Gondwana since the Early-Jurassic (~205 Ma) is generally accepted as the last major tectonic episode to have affected southern Africa. Because of the continuation of the Gondwana fragmentation process during the Cretaceous and Cenozoic until present time, the beginning of the neotectonic period in South Africa has never been formally established. In the past, the term neotectonics has been used to imply a generic Cenozoic (especially Quaternary) crustal deformation (*cf.* Hartnady, 1985; Andreoli *et al.*, 1990; Ransome & De Wit, 1992; Ransome *et al.*, 1993) and Andreoli *et al.* (1996) proposed neotectonic activity in South Africa to have been initiated in the Miocene (~25 Ma). Nowadays, the beginning of neotectonic activity in southern Africa is envisaged to have started with the beginning of the Oligocene at ~35 Ma which coincides with the African continent to have become stationary over the so-called African Superplume (*cf.* Burke, 1996).

The behaviour of the African Plate has changed during the Oligocene at ~35-30 Ma and many, if not all of the phenomena that have characterised Africa over the past ~35-30 Ma have been induced by the cessation of plate motion (*i.e.* a reduction to below a velocity of ~10 mm/year). Significant erosional and depositional changes on the African Plate over the past ~35-30 Ma have been dominated by responses to changes in topography induced by the action of a single or numerous underlying plume(s) (Burke, 1996).

In recent years, intense research regarding neotectonic activity in Southern Africa has revealed that there is a striking match between the tectonic fabric of the southeast Atlantic and southwest Indian Ocean and the tectonic fabric of

the African subcontinent (e.g. Andreoli *et al.*, 1989, 1990, 1993, 1994, 1995, 1996). It is evident that a number of major oceanic transform faults or fracture zones, e.g. the Cape/False Bay, Falkland-Agulhas, Trans-Indian/Ceres-Prince Edward and Mozambique-Madagascar fracture zones, continue into on-shelf and on-shore joints/faults of the South African continent (Figures 12 & 13).

In addition, neotectonic activity in Southern Africa has been analysed in terms of known stress fields and it is clear today, that the African plate south of the equator appears divided in two zones of compressive stress orientation: one zone of predominant NNE-directed trends which corresponds to the East African Rift system, and a second zone in southern and southwestern Africa, but including the southwest Indian Ocean, characterized by NW-WNW trends (Zoback *et al.*, 1989, Zoback, 1992; Andreoli *et al.*, 1996) (Figures 13 & 14).

In South Africa, the boundary between these two zones coincides with the apparent southern termination of the Rift System in southern Mozambique, near Richards Bay, and in the Northern Transvaal. Most of South Africa, Namibia and the ocean floor between the Bredasdorp Basin and the Southwest Indian ridge is dominated by this pervasive, NW-WNW-trending, horizontal compressive stress field of deep-seated, until recently undetermined origin for which the term Wegener Stress Anomaly (WSA) was proposed (Andreoli *et al.*, 1996) (Figures 14). The WSA appears to have existed already in the Jurassic, before the break-up of Gondwana, which is indicated by the orientation of major Jurassic dyke swarms in South America, South Africa and in Botswana, and persisted during the south Atlantic break-up phase in the Cretaceous (indicated by WNW-trending Cretaceous kimberlite dykes in Lesotho) until today. Offshore fault zones caused by the WSA include the WNW-trending, so-called Ceres-Prince Edward and Trans Indian Fractures Zones in the southwest Indian Ocean (Figures 12, 13 & 14). Short periods of waning during the Late Cretaceous caused the stress field to be dominated by NE-directed ridge push, which led to strike-slip along the Falkland-Agulhas Fracture Zone and the formation of the Cape-Tzaneen Fracture Zone, the on-shore continuation within the South African continent of the False Bay Fracture Zone (Andreoli *et al.*, 1996) (Figures 12 & 13).

Pavoni's (1997) proposed model of bicellular, whole-mantle convection and associated global geotectonic and geophysical bipolarity explains both, the orientation and the deep-seated, until now undetermined origin of the WSA. According to this model, two torus-like convection cells, the Pacific cell and the African cell, with ascending flow in the mantle underneath the central Pacific and African plates respectively, and converging and descending flow beneath Indonesia and Central America, are responsible for the formation of two large-scale zones of both, lithospheric divergence (marked by growth of the Pacific

and African plates from two spreading centres) and convergence (marked by the belt of young folded mountains) since the Mid-Jurassic.

The effects of large-scale mantle convection beneath the African plate is nowadays believed to be responsible for the tectono-magmatic and geomorphological development of southern Africa since the beginning of the break-up and dispersal process of the Gondwana supercontinent at ~205 Ma, which continues until present time and is responsible for neoseismicity and neotectonic activity, controlling the neomorphological development of the southern African landscape. The current in situ stress field present in southern Africa is the result of a complex interplay between mantle convection and lithospheric basal drag, thermally induced continental uplift and ridge-push forces.

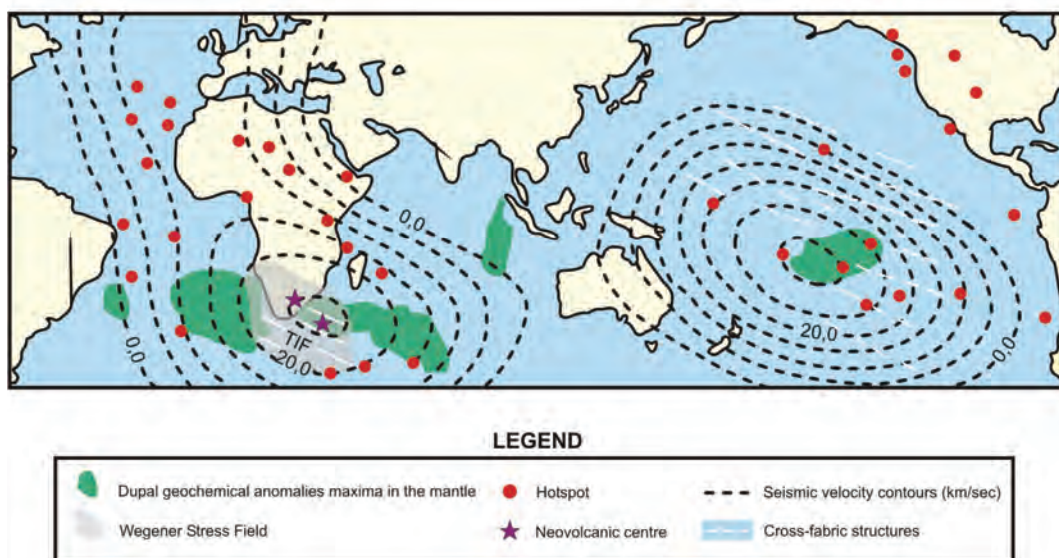
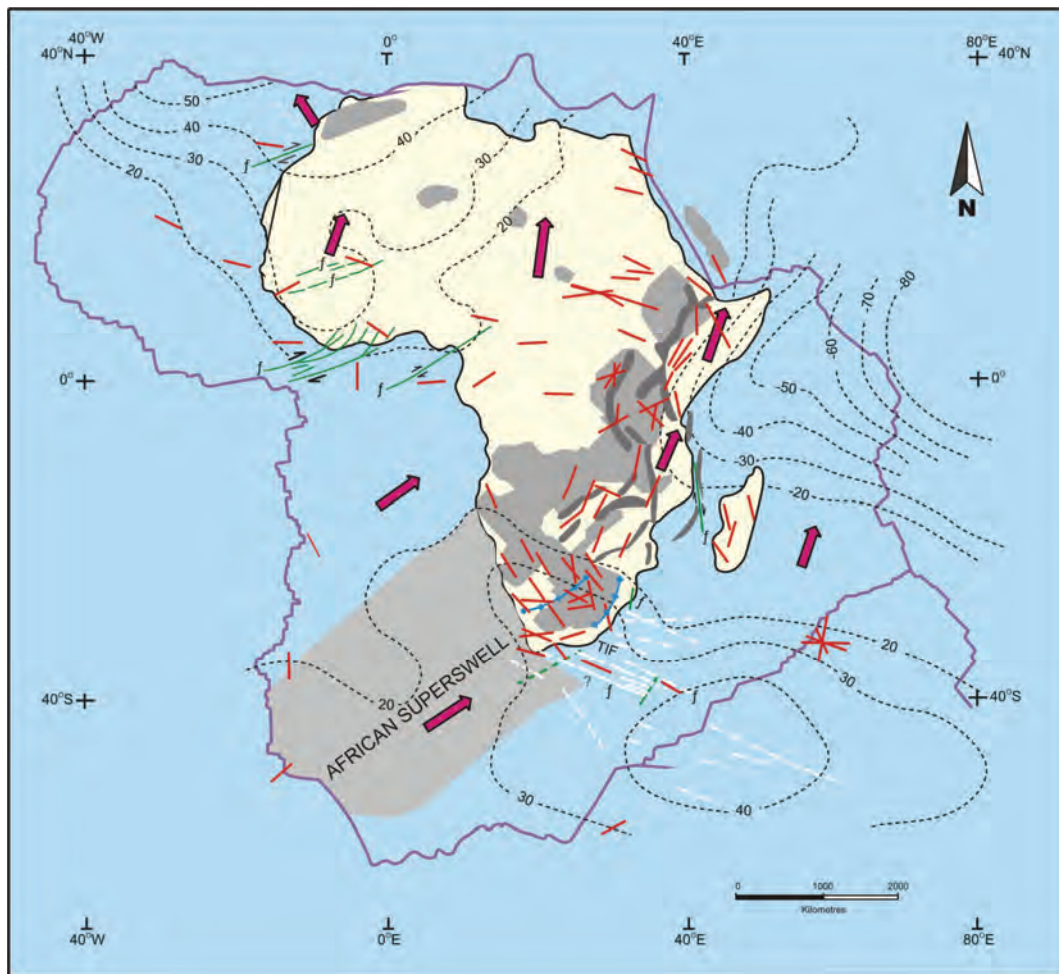


Figure 12: Stress map of the African plate (after Andreoli *et al.*, 1996; and references therein). **Note:** Thick bars = H_{max} ; stippled = regions with average elevation higher than 1000m; heavy stippled = East African Rift; light stippled = African Superswell; ---- f = major Mesozoic and Cenozoic faults; TIF = Trans-Indian Fabric; arrows = absolute velocity trajectories; light contours relate to long-wavelength undulations in the African geoid.

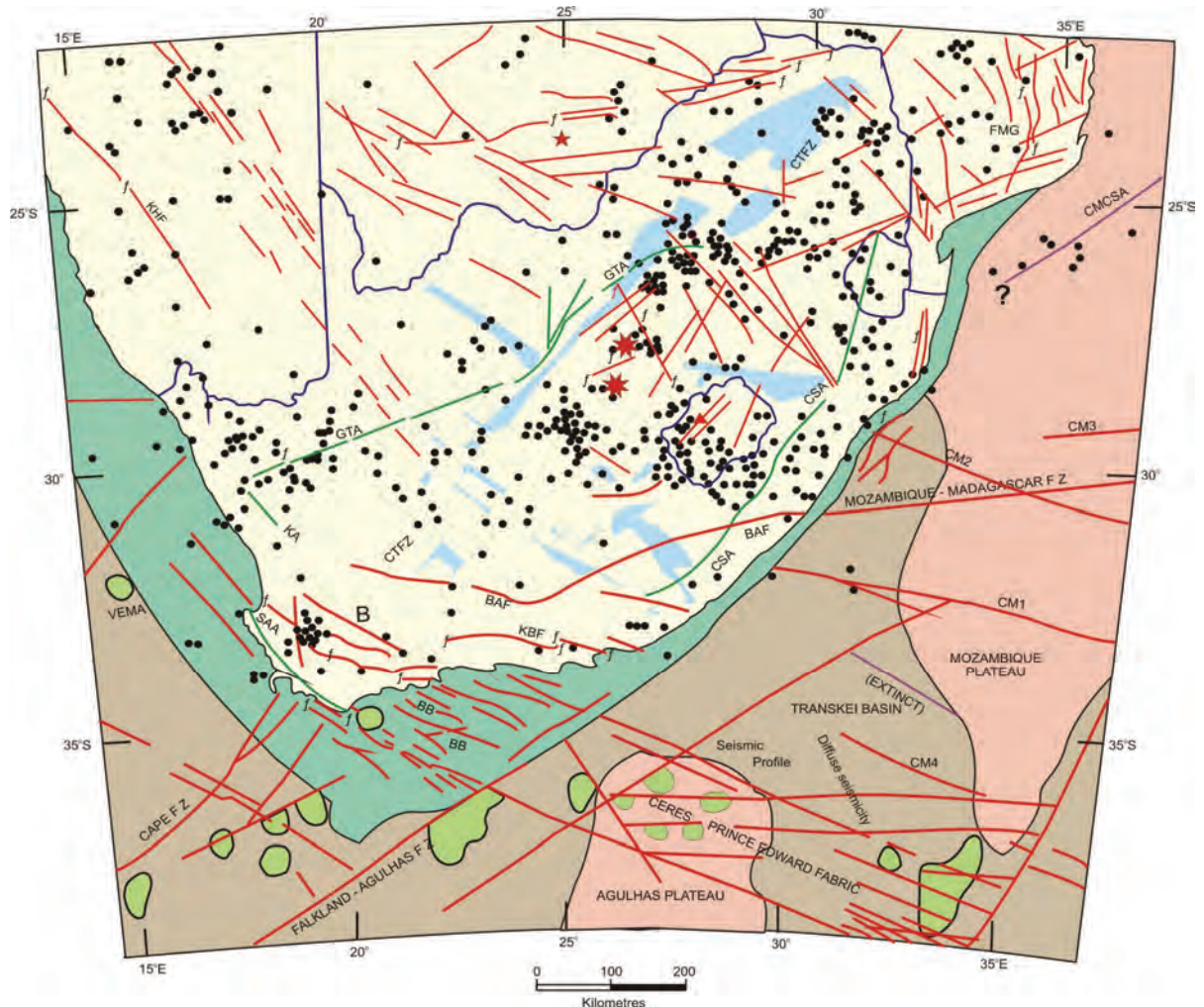


Figure 13: Seismic epicentres in relation to the post-Karoo tectonic framework of South Africa and nearby regions (after Andreoli *et al.*, 1996; and references therein). Note: blank=continental crust; crosses = continental crust invaded by oceanic basalt; stippled = oceanic basalt crust; straws = offshore volcanic domains; shaded = lineament belts; ET = eastern Transvaal; GA = Gauteng; KN = KwaZulu Natal; NT = northern Transvaal; KFB = Koega-Baviaanskloof Fault; FMG = Funhalouro-Mazenga Graben; KHF = Kuiseb-Hebron Fault; CTFZ = Cape-Tzaneen Fracture Zone; BB = Bredasdorp Basin; lines with opposing daggers = uplift axes; SAA = Saldanha-Agulhas Axis; KA = Kamiesberge Axis; GTA = Griqualand-Transvaal Axis; CSA = Ciskei-Swaziland Axis; BAF = Beattie Anomaly Fracture; CMCSA = Central Mozambique Channel Seismic Axis; barbed line = spreading/extinct axis; f-f = neotectonic faults active since the Miocene; dashed lines = lineaments/possible neotectonic faults; lines with single dagger = Cenozoic geomorphological gradients with daggers on downslope; open stars=localities affected by catastrophic Pleistocene (?) earthquakes; open triangle = proposed neovolcanic centre of Lesotho.

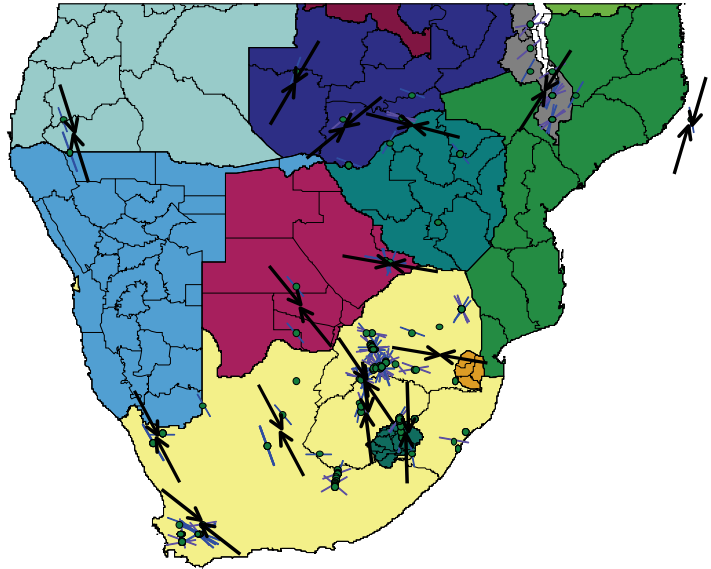


Figure 14: Neotectonic stress orientation map for southern Africa (Stacey & Wesseloo, 1998).

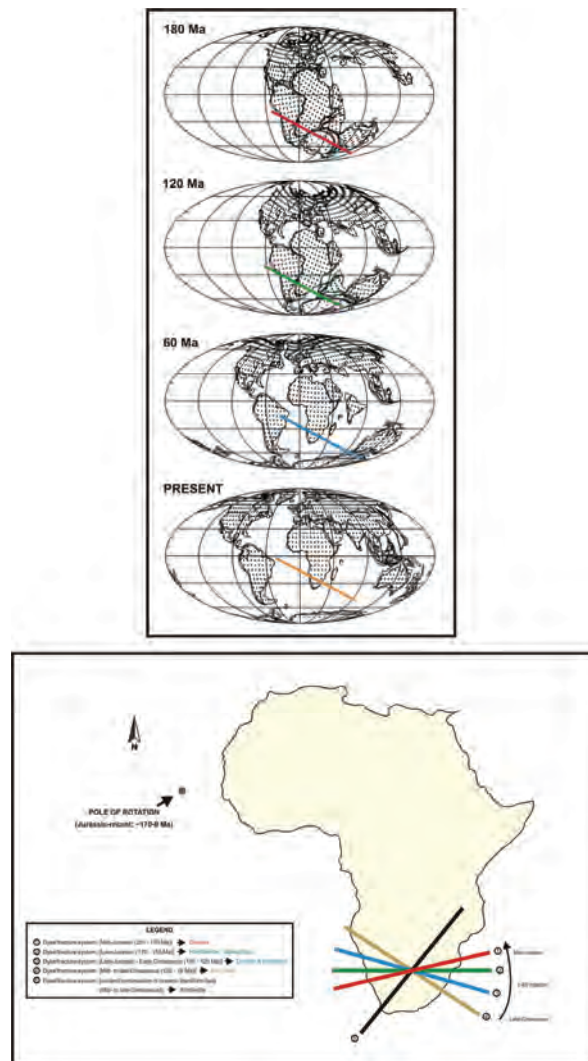


Figure 15: Proposed sequential development of extensional fracture zones and associated emplacement of dyke intrusions across the southern African continent in response to Gondwana supercontinent break-up and dispersal tectonics at ~200-80 Ma.

4 HYDROGEOLOGICAL SETTING

4.1 PHYSIOGRAPHY OF THE STUDY AREA

The Namaqualand area is classified by three physiographic regions according to topography, altitude and landforms. These regions are the higher lying Bushmanland Plateau to the east, the Namaqualand highlands (which is the escarpment zone), and the lower lying coastal area to the west (Visser, 1989). This study will focus on the Buffels River catchment (F30), although data from the adjacent catchments will be used to define clearly the boundaries between the catchments (Figure 1).

4.1.1 Climate

The study area falls in the arid, hot (BWh), tropical desert climatic region of South Africa, according to the Koeppen classification. The climate of the study area is determined by altitude, topography, and distance from the sea. Climatological data for the study area (*i.e.* precipitation, evaporation and temperature data) was received from the South African Weather Bureau, Computing Centre for Water Research (CCWR) and extracted from WR90 (Midgley *et al.*, 1994).

4.1.2 Precipitation

The region can be classified as arid to semi-arid, with mountainous regions having higher rainfall than the arid lowland due to orographic effects. Rainfall occurs mostly during the winter months. Snow in the Kamiesberg Mountains is, however, not uncommon during the summer months. Climatological data (Midgley *et al.*, 1994) for the various sub-catchments are shown in Table 2. The quaternary catchment scale data best represent the prevailing precipitation. However, due to the strong orographic effects, precipitation at higher altitudes can be considerably higher than that determined for the quaternary catchment scale data. Average monthly rainfall data for the three topographic zones are shown in Figure 16a.

The average annual rainfall generally increases from west to east until it reaches the escarpment, and decreases towards the inland. The higher lying areas within the study area receive much higher rainfall than the surrounding lower lying areas

and coastal plains (Figure 16b). Figure 16c indicates how the precipitation increases from the sea to the inland areas (that is, from west to east), with the topography also changing from coastal to mountainous regions in the same direction. The rain gauge station (Dabeep) situated on the Bushmanland plateau shows a different climatic regime (Figure 16a).

Table 2: Climatological data for the various catchments that comprise the study area (from Midgley *et al.*, 1994).

F30				
Catchment	Gross area (km ²)	MAE (mm)	MAP (mm)	MAE/MAP
F30A	1954	2200	162	14
F30B	1462	2200	107	21
F30C	1655	2200	184	12
F30D	976	2200	162	14
F30E	1260	2200	153	14
F30F	1469	2200	112	19
F30G	980	2200	102	22
F30	9756	2200	143	15
F40				
F40A	984	1900	118	16
F40B	404	1900	130	15
F40C	608	1900	173	11
F40D	741	1900	123	16
F40E	1065	1900	186	10
F40F	682	1900	118	16
F40G	348	1900	168	11
F40H	514	1900	109	17
F40	5346	1900	140	14
F50				
F50A	1303	1900	179	11
F50B	603	1900	208	9
F50C	439	1900	159	12
F50D	687	1900	112	17
F50E	487	1900	246	8
F50F	575	1900	133	14
F50G	775	1900	96	20
F50	4869	1900	159	12

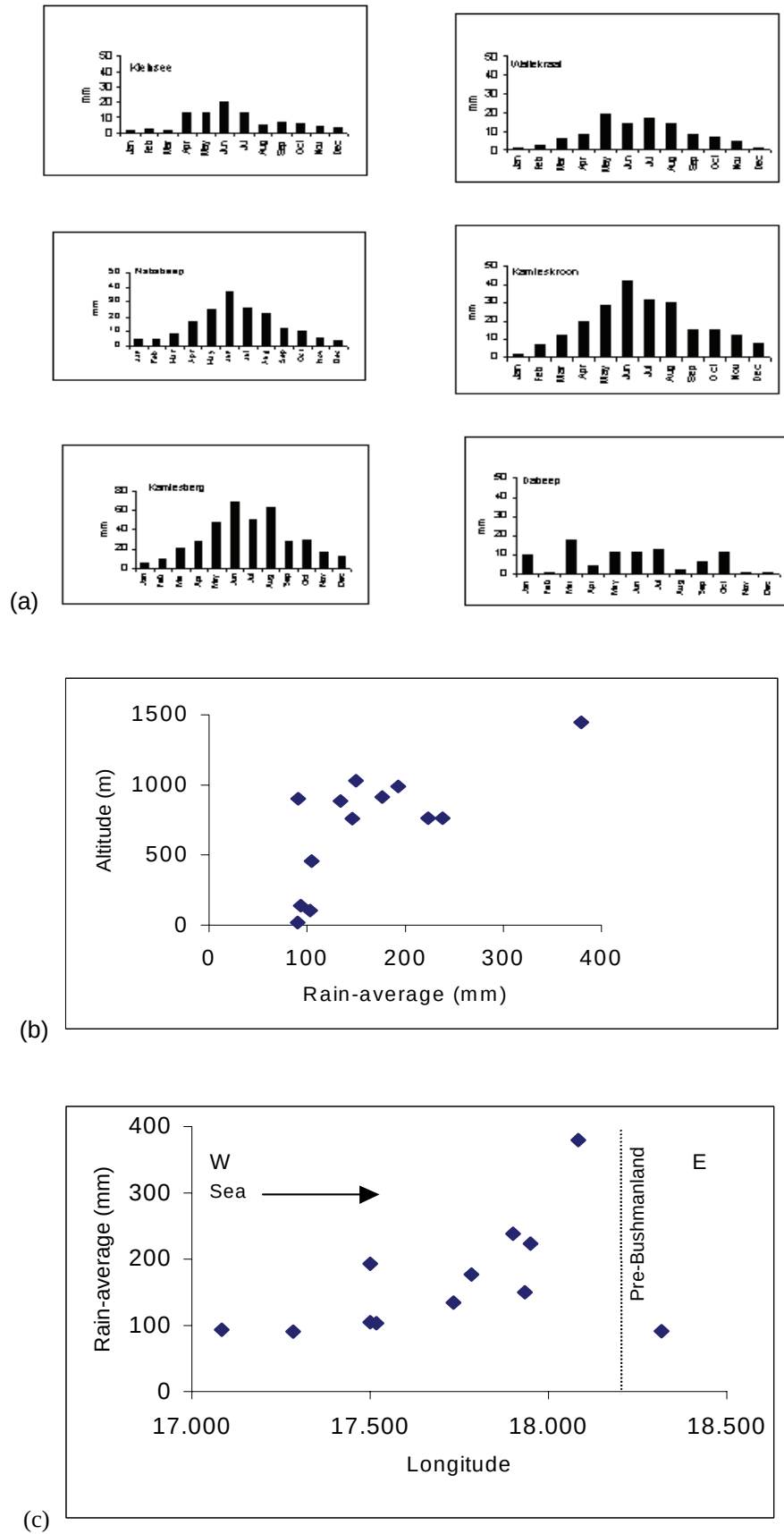


Figure 16: (a) Average monthly rainfall for six rainfall stations. (b) Relationship between mean annual rainfall and altitude. (c) Influence of distance from sea and topography on mean annual rainfall.

4.1.2.1 Potential Evapotranspiration

Potential evapotranspiration can be as much as from 12 to 15 times the precipitation. In some areas, this factor is as high as 22 times the precipitation. This high evaporation to precipitation ratio means that salts will easily form on the surface, as well as in the subsurface. Campbell *et al.* (1992) found that actual evaporation occurred to a depth of 91cm in the alluvium. Van der Sommen & Geirnaert (1988) found that in areas of dense vegetation and shallow water levels, the actual evapotranspiration is much higher than in areas of sparse vegetation and where deeper water levels occur.

Three evaporation stations (Table 3) have S-pan and A-pan MAE (mm) data (Midgley *et al.*, 1994).

Table 3: Evaporation data from S-pan and A-pan experiments at selected stations in Namaqualand.

Gauge No.	Station name	S-pan	A-pan	Years
F3E001	Okiep		3193	1957-1979
F3E003	Grootmis	1939	2260	1964-1979
F4E001	Hondeklipbaai		1823	1964-1979

Controversy exists over the validity of pan evaporation measurements, since wind, temperature effects and humidity can vary considerably in micro-environments and for different surface types. However, the data obtained from pan measurements can be used for baseline considerations. Evaporation is at its maximum during the summer months, and much lower during the winter months when rainfall is at its highest (Figure 17).

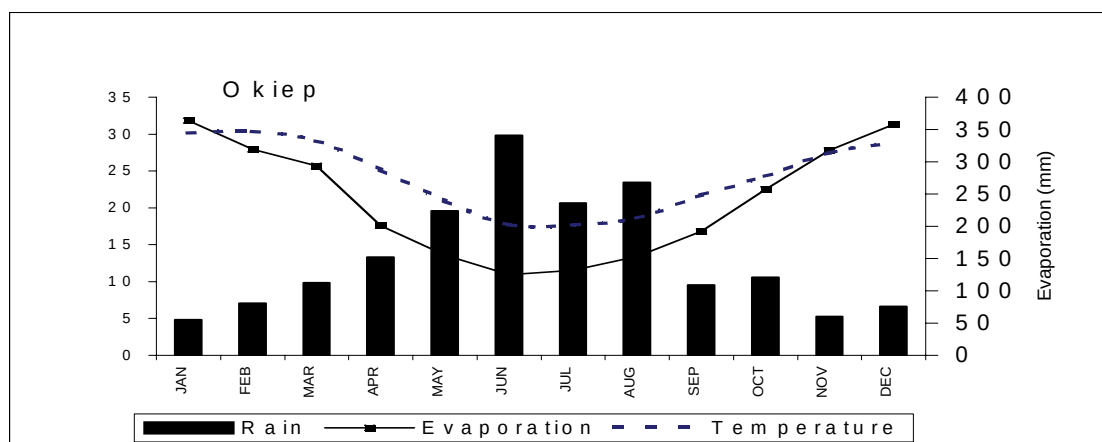


Figure 17: Average monthly evaporation for the Okiep area, and the relationship that exists between temperature and rainfall.

4.1.2.2 Temperature

Large variations between the maximum and minimum temperatures, as well as daily and seasonal temperatures exist for the region. Table 4 shows typical temperature variations over the three topographic regions of the study area. The average monthly temperatures for Springbok are shown in Figure 18.

Table 4: Temperature variations over the three topographic regions.

	Summer temperature (in °C)		Winter temperature (in °C)	
	Max.	Min.	Max.	Min.
Lowveld	20	13	15	8
Escarpment Zone	30	17	16	8
Highveld	34	17	18	5

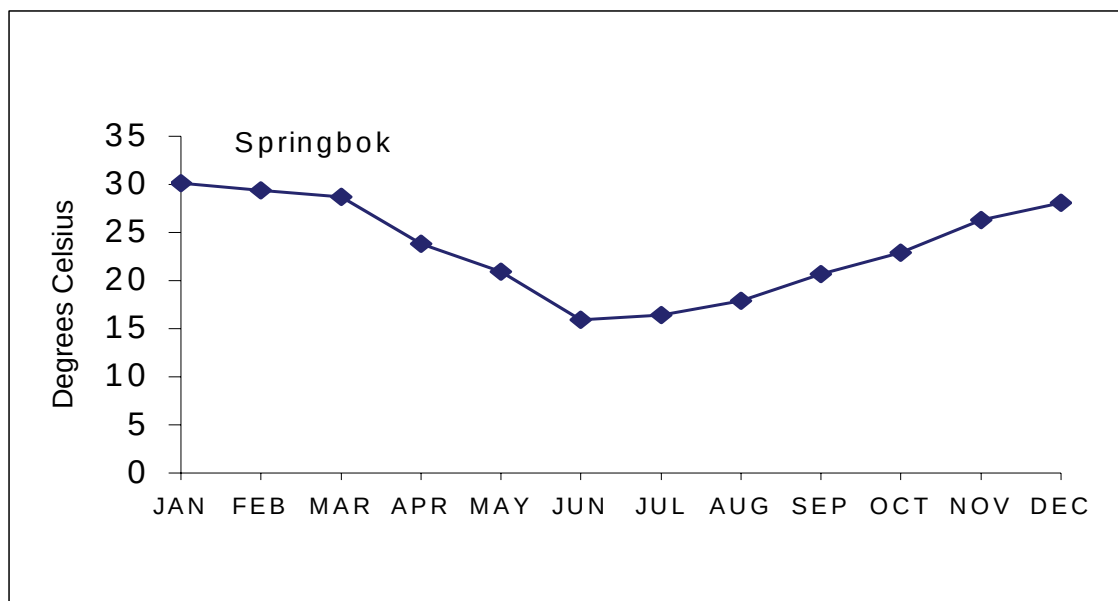


Figure 18: Average monthly temperatures for Springbok.

4.1.3 Vegetation

The vegetation is characterised by the Nama karoo biome, which is dominated by a mixture of grasses and low shrubs (Low and Rebelo, 1996). Most of the shrubs are classified as drought deciduous and tend to develop deep root systems.

In alluvial plains and riparian zones, vegetation is dependent on groundwater. Plant species such as *Prosopis* (moderately drought tolerant, facultative phreatophytes) form extensive thickets that indicate the availability of groundwater (Low and Rebelo, 1996). *Acacia karoo* (riparian shrubs and trees) is found in the alluvium of the Buffels River.

Acocks (1954) recognised four different vegetation types in the area:

- Succulent Karoo in the low-lying Sandveld area;
- Namaqualand Broken Veld in the lower mountain areas;
- Mountain Renosterveld in the Kamiesberg mountains;
- False succulent Karoo on the eastern Kamiesberg mountain range.

Succulents, semi-succulents and grasses are prominent in the Sandveld area (*i.e.* the lower lying coastal plains). The Namaqualand Broken Veld, characterised by succulents, semi-succulents and herbs, is generally found on the dome-shaped hills. The Mountain Renoster Veld is unique to the Kamiesberg Mountain range, whereas the False Succulent Karoo vegetation is found towards the east (*i.e.* in the Gamoep to Platbakkies area).

4.2 GEOMORPHOLOGICAL DEVELOPMENT AND CLIMATE CHANGE

4.2.1 Introduction

The macro-scale geomorphological evolution of southern Africa is the result of an Archaean geological history as well as changing climatic conditions, massive fluvial erosion, associated with the evolution of major drainage networks, and the formation of elevated interior plateaus during the late Mesozoic (*i.e.* the Cretaceous period) and Cenozoic eras (Partridge and Maud, 2000).

Three physiographic regions, viz. the western Coastal Lowveld (or Western plateau slopes), the Great Escarpment zone (or Namaqua Highlands) and the extensive Highveld (or Bushmanland Plateau), can be distinguished in the Northern Cape region (Visser, 1989).

The Buffels River catchment (*i.e.* secondary drainage catchment F30) is confined mainly to the Great Escarpment zone (Figure 19). This zone is characterised by relatively high local relief (Gilchrist *et al.*, 1994). The Great Escarpment of southern Africa is a prominent geomorphic feature along the edge of the southern part of the African continent. The Great Escarpment, which is approximately parallel to the coastline, separates the elevated interior plateau of the subcontinent

from the coastal plain lowland (Moon and Dardis, 1988) and trends roughly parallel to the coast at distances between 50 km and 300 km.

The topographic cross sections (Figures 20 & 21) through the Buffels River catchment have been computed from a Digital Elevation Model (DEM) available at the USGS on the Internet. The sections are orientated N-S and W-E. The W-E cross sections (Figure 21) show less variation than the N-S sections, since the Escarpment zone between the Coastal Lowveld and Bushmanland Highveld is primarily a N-S feature. These sections also show the Coastal Lowveld as a gently dipping coastal plain dissected by some river courses. In the western part of the Escarpment zone, the meta-sediments of the Nama age are prominent and resist erosion, thus forming a plateau.

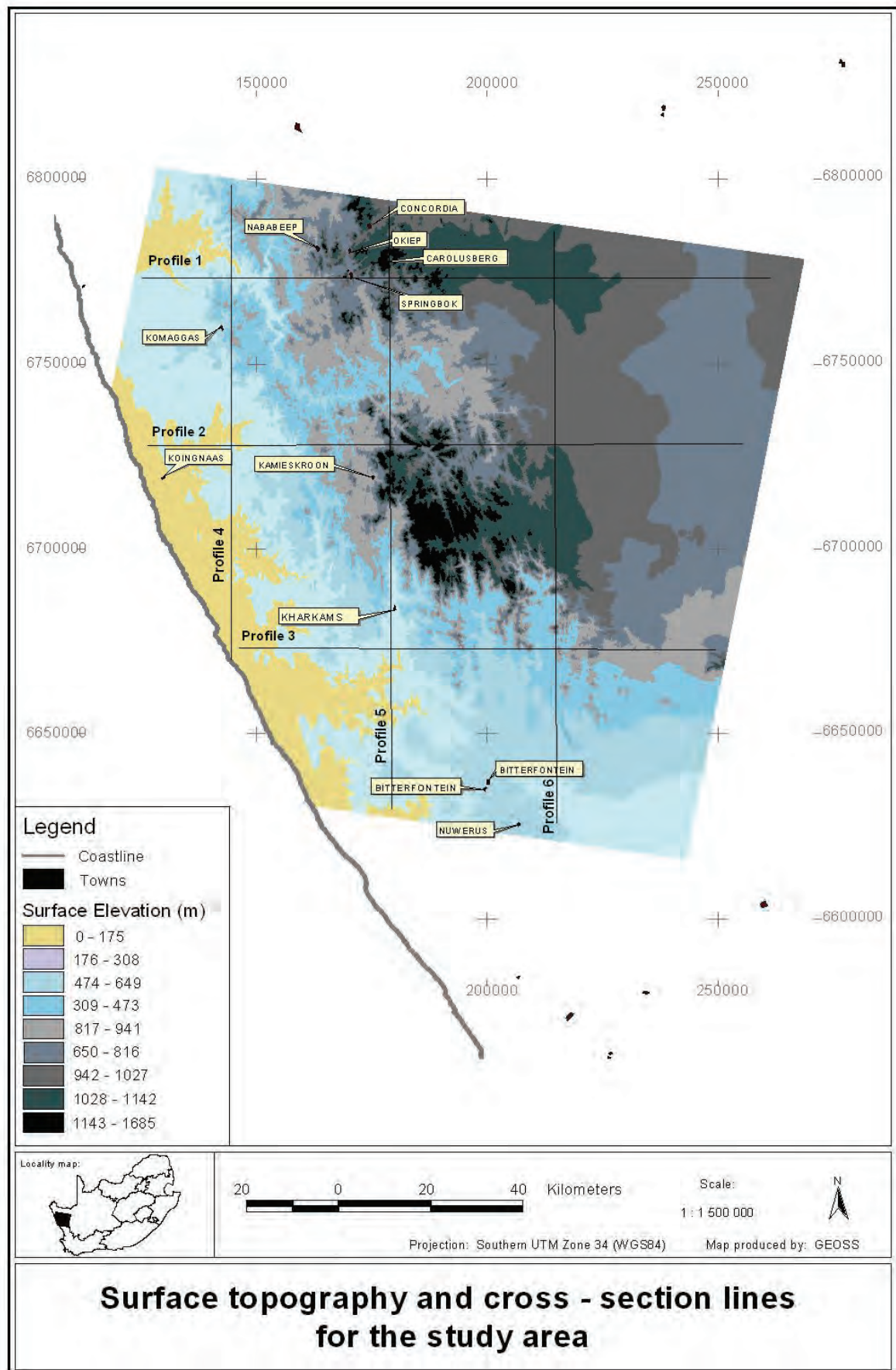


Figure 19: Surface topography and lines for the N-S and W-E cross-sections.

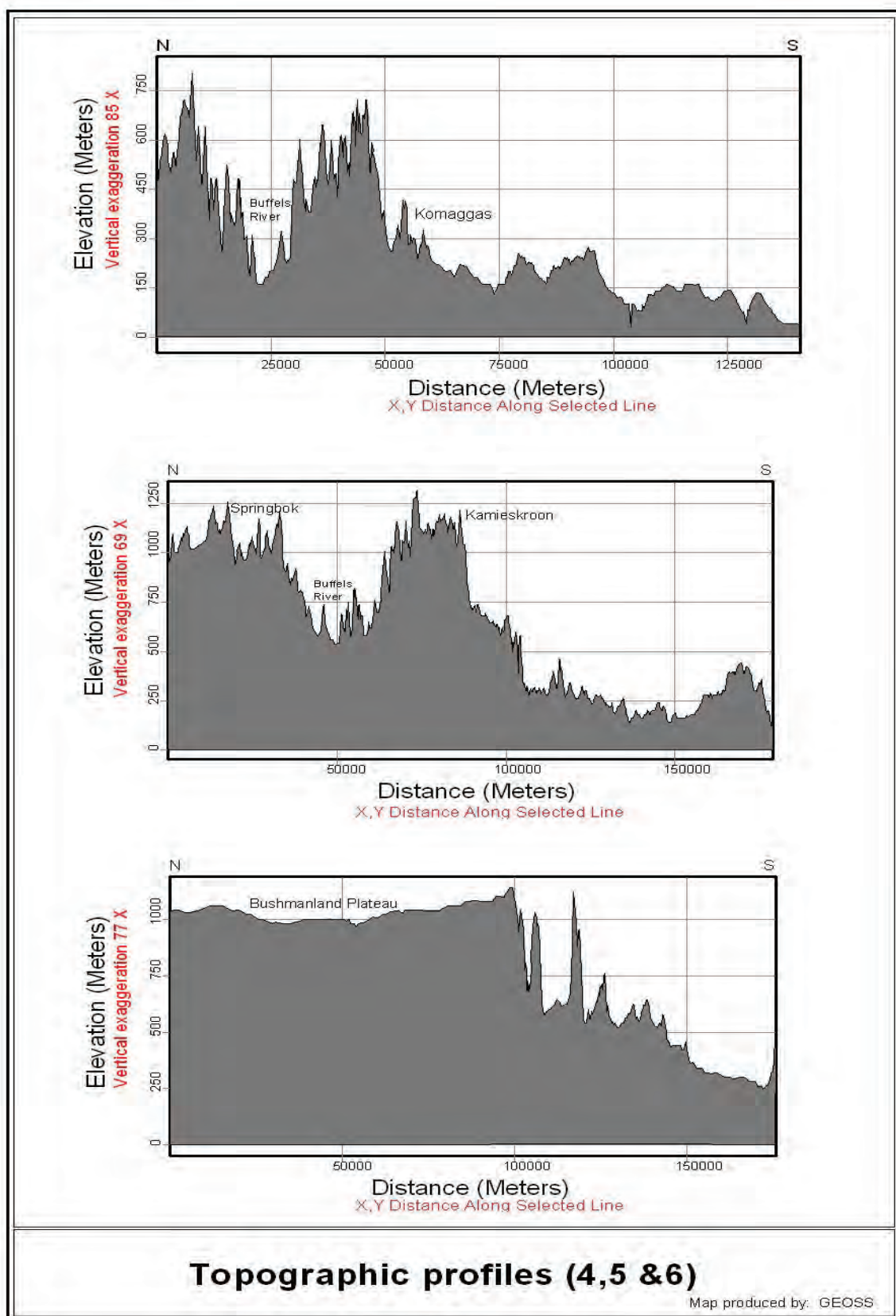


Figure 20: N-S cross-sections. The locations of the cross-sections are given on a topographic map prepared from a DEM.

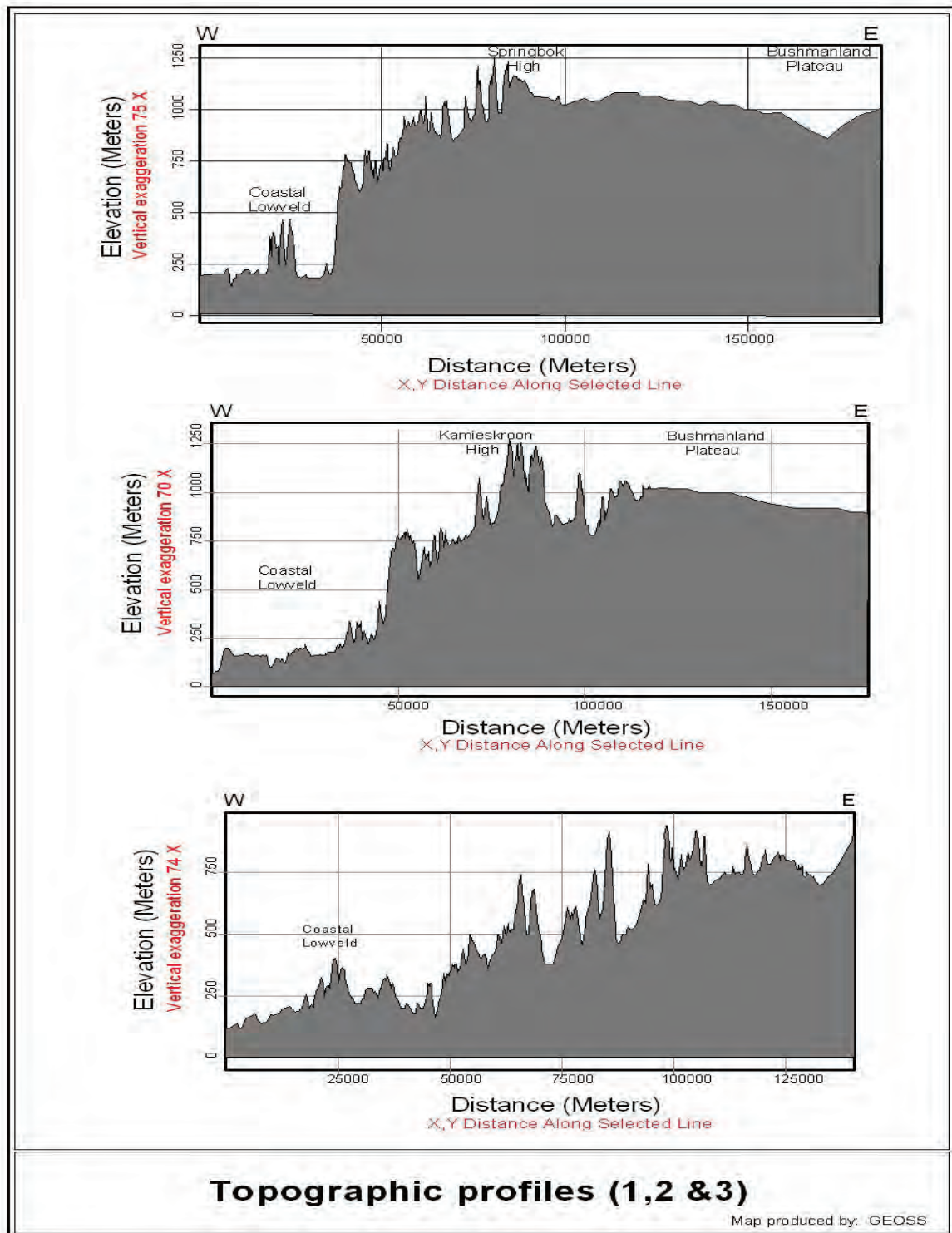


Figure 21: E-W cross-sections. The locations of the cross-sections are given on a topographic map prepared from a DEM.

4.2.2 Prominent geomorphological features

Bornhardts (Twidale, 1976, 1982, 1988; Ollier, 1984; Rice, 1988; Bridges, 1990) are the most prominent geomorphological features of the escarpment zone. Bornhardts are inselbergs or 'Island Mountains' with rounded dome-shaped forms usually prominent in the granitic and gneissic rocks of Namaqualand. The shapes of the bornhardts are determined by the orthogonal fracture systems and by the upward-arching sheeting planes. The orthogonal fracture systems developed either during emplacement or during subsequent tectonic events affecting the crystalline rocks. Bornhardts can be massifs or juxtaposed groups of domes arranged in an ordered pattern due to the structural control on its development. The Kamiesberg mountain range is a complex massif of large, predominantly dome-shaped bornhardts developed on major fracture systems with various orientations. The bornhardts are separated by valleys and narrow plains formed by pronounced weathering and erosion of the fracture zones. Deep subsurface weathering is essential for bornhardt development.

Several hypotheses have been proposed to explain the development of bornhardts (Twidale, 1976, 1982, 1988; Ollier, 1984; Rice, 1988; Bridges, 1990). The most likely hypothesis for the development of bornhardts in Namaqualand is the variations in the spacing of fractures (*i.e.* fracture density) from hills to plains. Fractures are preferred pathways for the infiltration of water and more densely fractured materials are more prone to weathering processes than massive, dense material.

The Namaqualand rocks were subjected to tectonic forces that resulted in folds, thrust and shear zones, and faults with the associated joint systems. The more transmissive and especially larger fault zones have been weathered and eroded more intensely to form the valleys that separate the massive domes. Within the weathered sections, core stones of fresh granite are present in a matrix of weathered rock derived from in-situ weathering of the host rock. Ordered groups of bornhardts are particularly evident in the mountainous regions. The variation in fracture density is probably due to recurring stresses resulting in rhomboidal shaped fracture patterns and the propagation of secondary fractures. Such recurrent stresses resulted in bornhardts as massive, compressionally stressed core zones (such as the compressive core zones of anticlines) in a matrix of highly weathered fractured rock. On a regional scale, the massive and stressed core zones (*i.e.* massive domes) can be regarded as enormous core-stones within and surrounded by a matrix of weathered rock expressed as the fault-controlled valleys and narrow plains.

The hypothesis that bornhardts are composed of massive, compressional core zones accounts both for:

- The observed paucity of open fractures in bornhardt masses;
- The association of bornhardts and sheet structures. The development of sheet structures can be attributed to both erosional off-loading and compressional stresses.

The landscape for crystalline terrains can be attributed to two stages of development (Twidale, 1982):

1. Differential subsurface weathering (*i.e.* moisture controlled weathering) exploiting varying rock composition and texture as well as variations in the fracture density. Differential subsurface weathering results in a highly irregular weathering front (or lower limit of significant weathering). Moisture is responsible for both the chemical alteration (which occurs when there are reactions between water and rock) and physical disintegration of the crystalline rocks. Humid to subhumid palaeo-climates are responsible for ancient differential subsurface weathering.
2. Subsequent erosion and exposure of the more resistant rocks (*i.e.* the bornhardts). The massive bornhardts are thus protrusions of the dynamic weathering front (which is the exposed parts of the lower limit of significant weathering) upward into the regolith or overlying weathered material. Fluvial erosion is primarily responsible for erosion and the exposure of the bornhardts.

4.2.3 The African, Post- African I and Post- African II erosion surfaces

The morphology of southern Africa is to a great extent controlled by the underlying geology, predominantly consisting of granitic to gneissic bedrock and by the processes affecting it. Most of southern Africa is characterized by a mature landscape with different erosion surfaces separated by prominent geomorphic scarps. These erosion surfaces resulted from successive phases of erosion, initiated by continental uplift, at various times since the fragmentation of Gondwana. Preservation of the erosion surfaces of varying ages occurs by pediplanation, in which back wearing predominates (King, 1951). Both back-wearing and down-wearing had, according to Moon and Dardis (1988), contributed to the presence of the erosional surfaces in the present African landscape.

Numerous erosion surfaces have been recognized on the African landscape. According to Moon and Dardis (1988) and Partridge & Maud (1987), conflicting interpretations arose due to problems associated with correlating surfaces across the Great Escarpment, the ambiguity of the results from dating the surfaces, and

to the structural control (such as lithology, stratigraphy, tectonics, etc.) of the landscape development. Partridge & Maud (1987, 1998, 2000) have re-interpreted the macro-scale denudation history of the subcontinent and provided a complete literature summary on this topic.

The surfaces identified by Partridge & Maud (1987) conform to King's terminology (King, 1967), but do not imply agreement with King's denudation history. The oldest and most widespread is the Gondwana surface (Jurassic) and African surface (mid-Cretaceous) followed by the Post-African surface inland of the Great Escarpment. Seaward of the Great Escarpment, two surfaces of Post-African age have been recognized, referred to as Post-African I (Miocene) usually present as dissected tablelands, and a younger Post-African II (Late Tertiary) surface expressed as recent incisions of coastal gorges.

4.2.3.1 The mid- to late-Cretaceous African erosion surface

Rifting, separating Africa from South America and associated with pre-existing Pan-African orogenic belts, occurred between 129 Ma and 121 Ma in the west (Partridge & Maud, 2000). Uplift along the rift shoulders resulted in a major marginal escarpment (this is the current Great Escarpment) that was driven inland by erosion during the early Cretaceous.

The Cretaceous period was characterised by warm, humid tropical climatic conditions (Tyson & Partridge, 2000) resulting in accelerated weathering and fluvial erosion due to dense well-integrated drainage networks (Partridge & Maud, 2000). Vast erosional surfaces of late Cretaceous age were formed above and below the Great Escarpment (Partridge & Maud, 2000), and correctly termed much earlier as the African surface by King & King (1959). The warm and humid tropical climate of the Cretaceous period also resulted in the development of deep, kaolinised weathering mantles especially on susceptible lithologies (such as crystalline rocks containing thermodynamically unstable aluminosilicate minerals). Towards the end of the Mesozoic (*i.e.* upper/late Cretaceous), the African surface was characterized by kaolinised profiles to depths of 50 m or more beneath silcrete duricrusts (Partridge & Maud, 1987, 2000; Tyson & Partridge, 2000; Moon & Dardis, 1988).

Late Cretaceous and early Palaeocene pedocrete cappings (*i.e.* duricrusts) protected the African surface, and its deeply kaolinised saprolite, from erosion processes in many localities (Partridge and Maud, 2000). The pedocrete cappings, comprising predominantly of silcrete and calcrete in the western and central parts of the southern African subcontinent, formed in response to the onset of drier climates towards the end of the Cretaceous period (Partridge & Maud, 2000; Tyson & Partridge, 2000). The Cretaceous-Tertiary boundary (the K-T boundary) is

characterised by significant cooling and aridification in southern Africa that is linked to major changes in atmospheric chemistry (Tyson & Partridge, 2000).

The African erosional phase was of long duration (>100 million years) and erosion proceeded to different base levels between the interior plateau and seaward of the Great Escarpment. Planation within the African cycle, according to Partridge (1988), was complete before the end of the Cretaceous, while massive duricrust formation ended by the early Palaeocene. Huge thicknesses of material were removed during this period.

The African landscape was not subjected to significant regional tectonism during the Palaeogene (Partridge & Maud, 2000). In addition, arid conditions persisted into the early Eocene in the western parts of the African subcontinent while more humid conditions prevailed in the east (Tyson & Partridge, 2000). Both factors contributed to slow landscape development during the Palaeogene (Partridge & Maud, 2000).

4.2.3.2 The Miocene post-African I erosion surface

Moderate but asymmetrical early Miocene crustal uplift along several axes caused the westward tilting of the subcontinent and resulted in a slight steepening of the courses of westward flowing rivers (Partridge & Maud, 1987, 2000; King & King, 1959). The early Miocene crustal uplift and subsequent erosion resulted in the mid-Miocene Post-African I erosion surface (Partridge and Maud, 1987) dated at ages ranging between 12 Ma to 19 Ma (Pickford *et al.*, 1996). Early Miocene uplift is associated with limited incision of drainage channels of up to 100 m to 200 m below the African surface (Partridge & Maud, 2000; Pickford *et al.*, 1996). The Post-African I landscape development phase involved the removal of the deeply weathered mantles underlying the African surface (Partridge & Maud, 2000). In areas (*i.e.* western parts of southern Africa) subjected to minimal Miocene uplift, scattered residuals or reduced thicknesses of the weathered mantles remained. The Post-African I surface dominates the southern African landscape (Partridge & Maud, 2000).

The late Oligocene and early Miocene epochs are characterised by a period of global oceanic warming regionally influencing atmospheric circulation patterns (Tyson & Partridge, 2000). As a result, rain producing weather systems penetrated the arid western (*i.e.* Bushmanland and Gordonia) parts of southern Africa resulting in a sub-tropical wet climate and a well-integrated drainage system (Tyson & Partridge, 2000). The wet interval of the early Miocene was brought to an end with the onset of cold upwelling in the Benguela current system on the west coast. The global effects of cooling and drying, especially during the Eocene and mid-Miocene, have greatly impacted on the southern African environments with the onset of true

coastal desert conditions (at approximately 15 Ma) along the west coast of southern Africa (Partridge & Maud, 2000; Tyson & Partridge, 2000).

The advent of warmer and more humid conditions during the early Pliocene resulted in a rejuvenation of major drainage systems in the semi-arid western interior.

Massive and significantly asymmetrical late Pliocene uplift interrupted the Post-African I erosion phase and accentuated the westward tilting of the subcontinent. The results of the late Pliocene uplift in the western parts of southern Africa include; (a) further increases in the gradients of westward-flowing rivers with renewed incision within river valleys, and (b) renewed movement along the Griqualand-Transvaal axis (Tyson & Partridge, 2000). The large-scale regional uplifts, within the south-eastern and eastern hinterland of the subcontinent, induced major influences on the regional climatic conditions. The east-west precipitation gradient is thus a result of the existence of contrasting current regimes along the east and west coasts as well as the enhanced regional uplift in the eastern parts of the African subcontinent. Late Pliocene uplift resulted, according to Partridge & Maud (2000) in a steepening of the east-west climatic gradient with the establishment or re-establishment of desert conditions in the western part of the African subcontinent. Furthermore, the initiation of the various phases of uplift coincided with the onset of an interval of global cooling at approximately 2.8 Ma (Tyson & Partridge, 2000). This resulted in the aridification of large tracts of sub-Saharan Africa with the development of extensive but discontinuous dune systems (such as the mega Kalahari) extending into the Northern Cape Province of South Africa.

4.3 SOIL PROFILE FOR THE ESCARPMENT ZONE (NAMAQUALAND REGION)

The physical and chemical characteristics of the complex soil zone for the Namaqualand region influence the chemical character of the recharging waters.

Ellis (1988) described a mountainous physiographic region (*i.e.* the Escarpment zone) of predominantly high relief and a soil zone dominated by rock fragments. The Escarpment zone incorporates the secondary drainage catchment F30 that constitutes the study area.

Lithosols, comprising of imperfectly weathered rock or rock fragments (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991), with high lime content (as CaCO_3 and $\text{Ca}(\text{OH})_2$) dominate (Ellis, 1988)). Calcrete horizons (*i.e.* calcareous crusts), cemented by calcium carbonate and/or calcium-magnesium carbonates, occur generally within the region. As a result, the influence of carbonate mineral dissolution on the groundwater compositions is important.

Soil horizons, comprising A-, B- and E-horizons (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991), are usually shallow but differ over short distances due to the complex geomorphology of the region and the spatial differences in rainfall intensity (Ellis, 1988). Aca as well as A, E and B2 soil horizons were described for the schists and phyllites of the Gariep sub-group and granitic sequences respectively.

A-horizons are described as mineral horizons with a darker colour due to the accumulation of humified organic matter which is associated with the mineral fraction (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991). Ellis (1988) referred to orthic A-horizons, predominantly with sandy textures. An orthic A-horizon does not show an organic or humic character (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991) and these A-horizons are usually well drained topsoil horizons.

In the higher rainfall areas, lime is absent with E-horizons present (Ellis, 1988). An E-horizon is a structureless mineral horizon characterised by resistant minerals (e.g. quartz) due to the removal of colloidal matter in the form of iron oxides, silicate clay and organic matter (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991). Redox reactions can also result in the removal of iron oxides and organic matter from this horizon.

Ellis (1988) furthermore described lithocutanic B2-mineral horizons. The lithocutanic B-subsoil horizons are described as heterogeneous zones comprising soil material (without traces of parent rock) interspersed with parent rock (or saprolite) in differing stages of weathering (van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991). In addition, the B-horizon is characterised by silicate clay, oxides of iron, aluminium and manganese, organic matter as well as lime (Acworth, 1987; van der Walt & van Rooyen, 1990; Driessen & Dudal, 1991; Soil Classification Working Group, 1991). The silicate clay, oxides of iron, aluminium and manganese, organic matter as well as lime can concentrate in a specific horizon through the processes of illuviation (i.e. removal in solution or in suspension and subsequent deposition), residual accumulation (i.e. in-situ disintegration) and alteration (i.e. total obliteration of parent material). The products of the weathering processes involving aluminosilicate minerals are evident in the B2-horizon.

4.4 CATCHMENT AREAS AND SURFACE DRAINAGE SYSTEMS

Non-perennial rivers drain the catchments (Figures 22 and 23a & b). The drainage patterns are well developed and are often controlled by geologic structures. In areas where the sediment cover is sparse or absent, the fault patterns are reflected in the drainage patterns, which include the Buffels River.

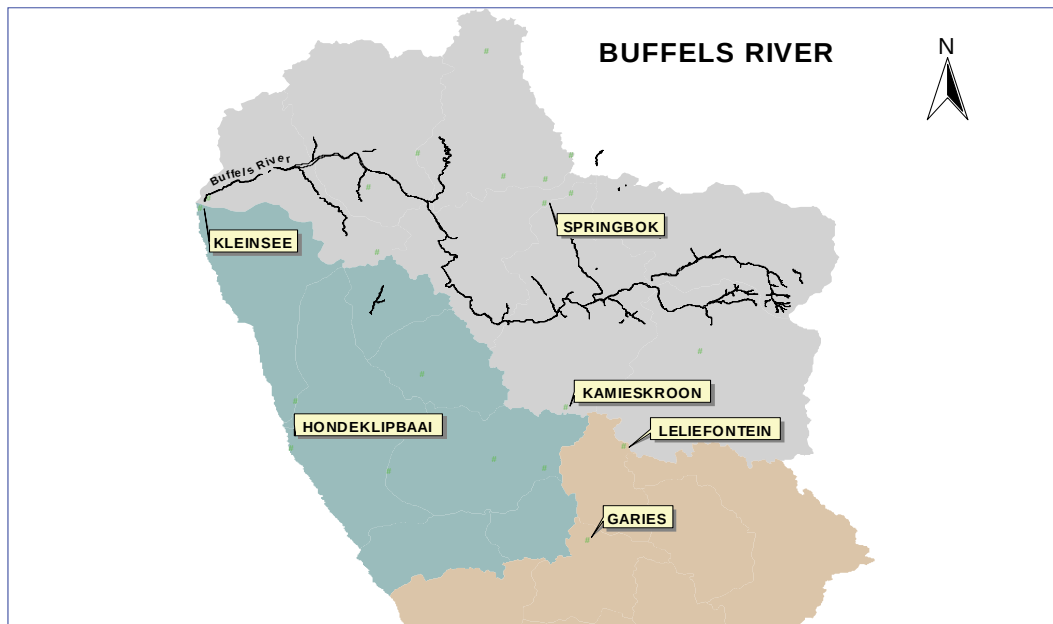


Figure 22: The course of the Buffels River in secondary drainage catchment F30.

Two effects are particularly important to the geomorphic development of rifted margins (Gilchrist & Summerfield, 1994). Firstly, during the first phase of formation of the passive margin, extension within the rift zone causes subsidence and the formation of sedimentary basins that lower the base level of fluvial systems draining into the rift. Secondly, extension can cause significant surface uplift immediately adjacent to and landward of the newly formed sedimentary basins, thereby generating a rift flank uplift that can deflect the existing drainage systems. The result of these mechanisms can be the re-orientation of the existing drainage system into two major fluvial systems. The exterior catchment drains directly into the rift and in the interior catchment the drainage systems are deflected away from the rift toward the continental interior. Such re-orientation would not occur if rates of fluvial incision exceed surface uplift rates. The deflected drainage patterns on young-rifted margins suggest, however, that re-orientation commonly occurs (Gilchrist & Summerfield, 1994).

The “synrift” drainage pattern drains the rift flanks through short, steep rivers that are aligned perpendicular to the rift. The tectonically induced fall in the base level promotes rapid incision and catchment growth by the retreat of headwaters, rejuvenating the landscape into a high relief.

As rivers incise the exterior catchment, the water divide retreats toward the continental interior. This pattern of drainage growth leads to increased competition between neighbouring river systems, and the more aggressive back-wearing/incising systems capture the upland regions of adjacent catchments. Large catchments develop and grow headward most rapidly with the possibility of capturing the deflected drainage of the continental interior.

Lithology and climate exert additional controls on the evolution. The intrinsic strength of the rocks, secondary structures such as joints and faults, and the degree of weathering will determine the erodibility of back-wearing velocity.

The Buffels River has a length of about 250 km and finds its main source in the Kamiesberg Mountains, peaking 1371 m above sea level, and with an annual average precipitation of 305 mm. The catchment is further fed by the western part of the Bushmanland plateau at an elevation at 900 m, which gets an annual precipitation of 102 mm. The catchment is also fed by the Springbok highlands at an elevation of approximately 1100 m and with an average rainfall of 178 mm per year (Marais, 1975). On the average, the Buffels River flows once every three years, only for short periods and only after heavy rainstorms (estimated to be at least 60 mm of rain per day). Close to the source, near Kamieskroon, the river flows inland to the east, away from the Escarpment edge representing the water divide. Around Pedroskloof the rivers follow the directions indicated by the rectangular fault pattern. After Goraap, the river flows to the North in the direction of Rooifontein. After Tweefontein the river flows westward through the depression between the Springbok High and the Kamiesberg High where the Escarpment is transected. The depressions are probably partly lithologically controlled. Hereafter, the river continues in a north-westerly direction before it enters the Lowveld near the Spektakelpas.

The terraces of the Buffels River and the Orange River have been extensively mined for diamonds, which have been transported by these rivers away from the kimberlite intrusions in the central part of South Africa. The evolution of the drainage system has therefore been the subject of several studies. These try to reveal the source areas of the sediments in the rivers in order to predict where diamondiferous deposits might be located.

The evolution of the Buffels River catchment corresponds to a great extent to the generalised model for the drainage development of southwest Africa as presented by Gilchrist *et al.* (1994). Within the Buffels River catchment the earlier interior and exterior (sub-) catchments can still be recognised. The edge of the Escarpment is still the water divide over the largest part of the area, except where crossed by the Buffels River.

The sub-catchments of the Buffels River have been split into two groups separated by the water divide that is formed by the Escarpment edge transected only by the Buffels River itself. The exterior sub-catchments are located west of the Escarpment edge while the interior sub-catchments are east of the Escarpment edge. The three most extensive sub-catchments are those of the Brak River on the interior side and of the Stry River and Schaap River on the exterior side.

The drainage system of the Buffels River catchment shows a large variation in drainage characteristics, such as the channel width and depth, the sediment thickness, the drainage density and the development of river terraces. The development of the drainage pattern can be described and the variation explained by the model proposed by Gilchrist *et al.* (1994). The influence of the underlying geology on the drainage characteristics is significant.

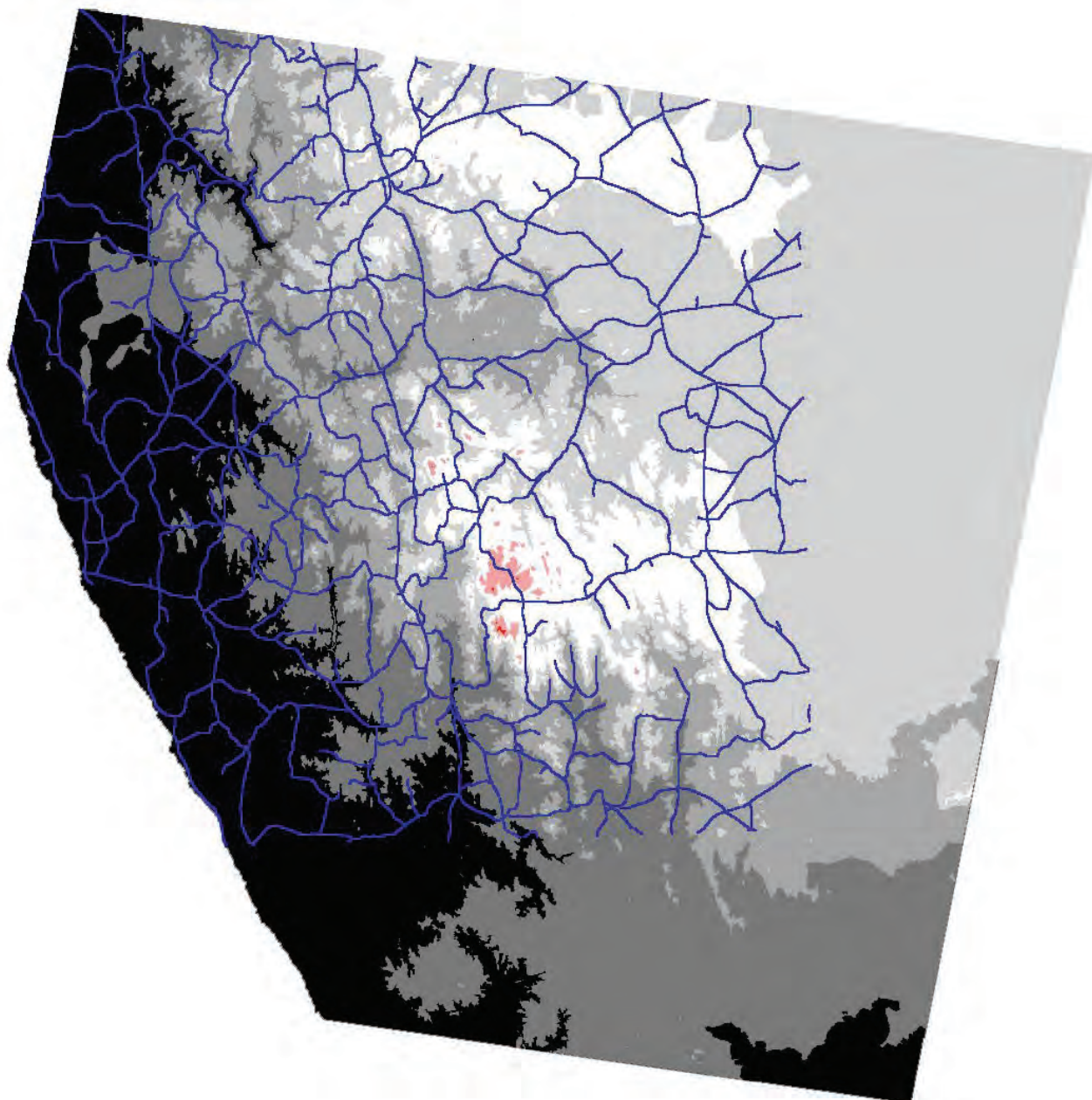
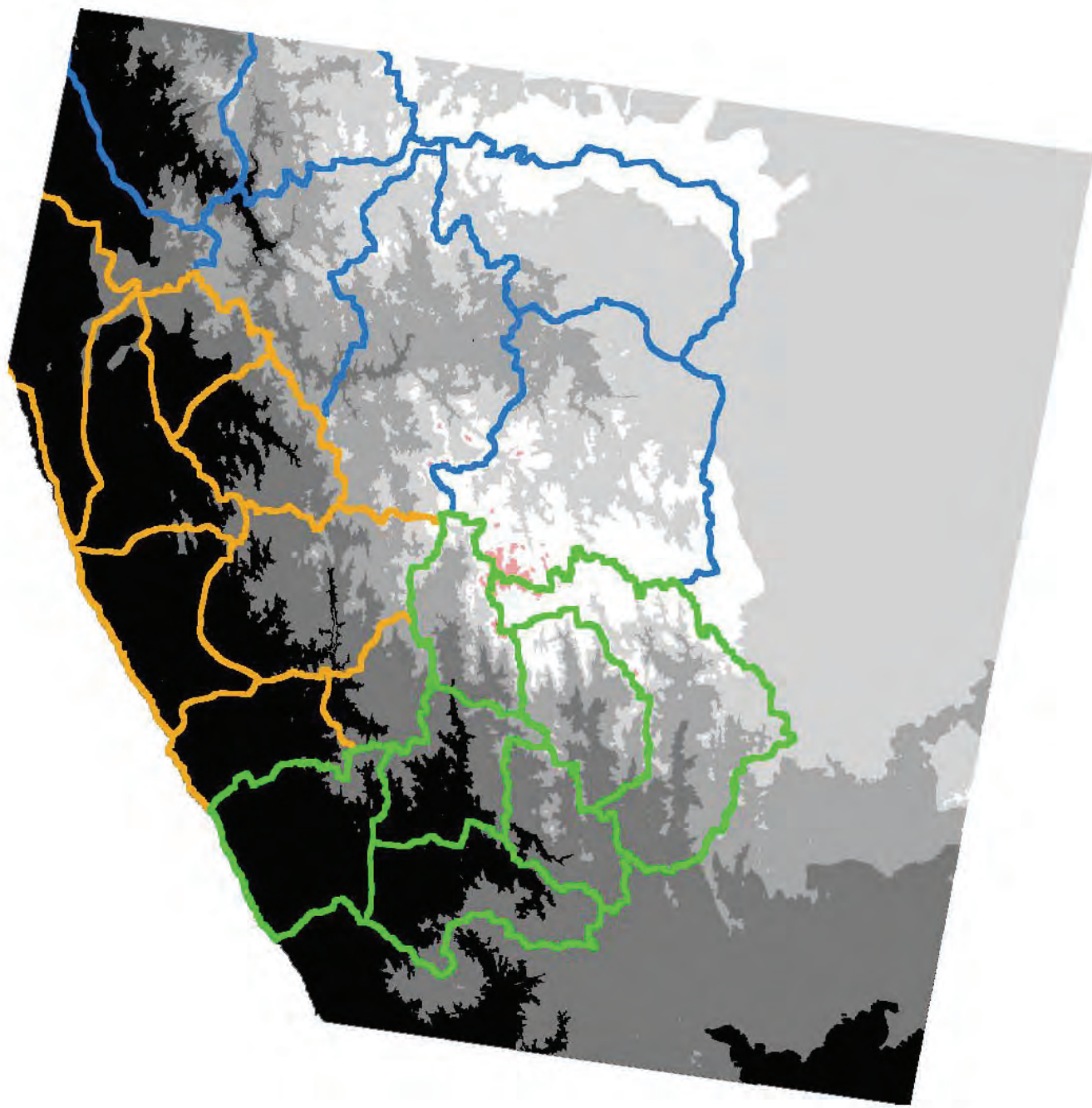


Figure 23: (a) Buffels River catchment area; (b) Surface drainage map.

5 AQUIFER SYSTEMS

5.1 ATTRIBUTES

On a regional scale the aquifer system in Namaqualand can be classified as a fractured crystalline basement aquifer but on a local scale two aquifer systems exist (viz. a weathered zone or regolith aquifer underlain by a fractured crystalline aquifer). The fractured aquifers generally have a low storability but where fractures systems exist, a much higher transmissivity exists. The thickness and character of these composite aquifers changes spatially particularly in relation to the petrographic composition of the respective rocks, their type of tectonic deformations (faulting) and type of weathering, to the morphological and climatic conditions (Gustafson & Krásný, 1993).

Groundwater flow and storage in these aquifers are inherently complex, partly as a result of the heterogeneity associated with the mechanical discontinuity resulting from the presence of fractures. The depth of the weathering extends to 54-60 m below the surface for both the metasediments and the gneissic rocks (Titus *et al.*, 2000). Differential weathering occurs throughout the rock mass and is also observed on fracture/joint planes. Weathering and fracturing decreases with depth, to a depth at which the cost of drilling outweighs the chance of significantly increasing the yield of the borehole (according to current understanding). The average depth of the boreholes in the area is 60m to 80 m but the economics and the capacity of the drilling rigs probably determines this depth. In the Nebo granites, better yields were obtained on structures at greater depths than was proposed by others (Botha *et al.*, 2000).

5.2 FLOW MECHANISMS

Groundwater flow in Namaqualand is a function of complex topographic and hydrogeologic environments with multiple flow systems (Titus, 2003). Natural groundwater flow, mostly topographically controlled, can be subdivided into local, intermediate and regional flow regimes (Ah, 1963). In deeper basins the following was observed regarding groundwater flow (Toth, 1999):

1. The hydraulically continuous nature of the rock framework, which facilitates large-scale cross formational flow systems;

2. Time lags in the adjustment of flow patterns to changing boundary conditions, ranging on the time spectrum from the human to the geological scales; and
3. The multiplicity of possible flow-inducing energy sources.

Two fundamental causes are responsible for groundwater's geological agency, namely (Toth, 1999):

1. Interaction between water and its ambient environment, and
2. Systematised and hierarchical flow paths.

Local relief in Namaqualand is associated with prominent ridges (i.e. domes) and structurally controlled valleys. As a result, localised, shallow circulating groundwater flow systems are dominant in near surface environments.

Local flow paths are characteristically short. Intermediate flow paths are longer and deeper than local flow and can underlie several local flow regimes. Regional flow regimes theoretically extend from regional recharge areas to distant discharge areas, such as major rivers or may be represented by higher salinity structurally controlled artesian springs.

Delineating groundwater flow patterns for the basement aquifer system in Namaqualand was difficult to construct due to the paucity of boreholes, borehole position and spatial distribution of the boreholes. Most of the boreholes are topographically located within structurally controlled valleys. Only in a few instances were structural features targeted at higher elevations. A shallow circulating and relatively young groundwater system is recognised, together with an older, deeper and slower circulating groundwater system (Titus, 2003). The groundwater chemistry for these flow systems is a result of varying flow-path length (residence time) and thus water-rock interaction reactions. Flow towards the major, approximately, north-south striking structurally controlled valleys from the higher lying adjacent domes are dominant. On a regional scale, groundwater flow from topographic highs to lows occurs along major fractures as a function of the natural hydraulic gradients. Often, the lowest part within the Buffels River catchment is the Buffels River itself and flow may then be directed to these zones thus recharging the alluvial aquifers.

5.3 RECHARGE AND STORAGE

The mechanisms that are responsible for the varied water qualities are spatially variable and preferential recharge patterns, water-rock interaction, residence times/salinisation and the infiltration of evaporated surface waters and/or the leaching of previously evaporated salts (Titus, 2003). The saturation states of the groundwater compositions, with regard to mineral phases, are a result of:

- The groundwater compositions can be a function of a combination of factors including the active weathering of aluminosilicate minerals with older more saline water;
- The groundwater compositions becoming increasingly supersaturated with increasing salinity;
- The dilute and aggressive waters, together with relatively dynamic flow systems (related to significant head differences) contribute to the weathering processes;
- A reduction in the weathering capacity, with regard to the mineral phases, of the higher salinity groundwater is related to the groundwater being saturated with certain major ions due to the residence time and/or mixing with an older, more saline groundwater.

Based on the above considerations, the following conceptual model of groundwater development in the Buffels River catchment is proposed based on (Titus, 2003):

1. The spatial and vertical variation in groundwater chemistry;
2. The numerous lineaments, at all scales. The presence and varying intensity of horizontal joints in all lithologies. These observations are supported by a wealth of data on Proterozoic deformation phases (*i.e.* thrusting and folding) but limited geological data on Cenozoic faulting (*i.e.* the major faults targeted for groundwater exploration); and
3. The structural control on minor drainage systems visible on GIS topographic data.

Shallow circulating and relatively young groundwater systems are recognised together with older, deeper and slower circulating groundwater systems (Titus,

2003). The groundwater chemistry in these fractured crystalline rocks thus seems to be dependant on the position of the sampling point within either shallow, fast circulating (i.e. active) or deeper, slower circulating flow systems. Johnston (1982) came to a similar conclusion to explain the variable groundwater chemistry in crystalline rocks. The deeper circulating, higher salinity ground waters probably experience insignificant recharge under present climatic conditions. The fracture patterns in most of the lithologies are well developed with relatively active groundwater flow systems. The broad range of orientations for these fracture systems may indicate that most of the fractures are connected with complex groundwater flow paths. Kay (1987) also concluded that well developed fracture networks with active groundwater flow systems occur in granitic rocks. The general movement of groundwater for these semi-confined aquifer systems will be a function of head differences associated with topography. Groundwater flow from topographic highs occurs along major fractures as a function of the naturally high vertical hydraulic gradients in these regions. Groundwater circulating deeper and slower are associated with a reduction of the hydraulic gradients and hydraulic conductivity with depth (Titus, 2003).

5.4 A REVIEW OF BASEMENT AQUIFERS

5.4.1 Introduction

Basement aquifers (*i.e.* usually fractured, Precambrian crystalline rocks) are found extensively in sub-Saharan Africa. Basement aquifers are developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin that are mainly of Precambrian age (Wright, 1992).

Studies on basement aquifers around the world have predominantly focused on the development of groundwater resources in thick regolith (*i.e.* weathered overburden) with dominant intergranular flow in tropical to sub-tropical regions (*i.e.* Western and Southern Africa, South America, Norway and Sweden) compared to dominant fissure flow in temperate and higher latitude regions. The weathered overburden is usually the main groundwater storage compartment, although boreholes may be developed in the underlying fractured bedrock (Lloyd, 1999; Chilton & Foster, 1995; Gustafson & Krásný, 1994; Rebouças, 1993; Olofsson, 1993; Wright & Burgess, 1992; Commonwealth Science Council (CSC) Technical Paper (TP) 273, 1990; Acworth, 1987).

Rebouças (1993) reviewed the groundwater bearing properties of Precambrian basement rocks in both South America and Western Africa. Most of the Precambrian crystalline rocks in South America (*i.e.* 90%) are located within the humid to sub-humid tropical regions of Brazil with an average annual rainfall of between 1000mm and 3000mm, resulting in densely developed drainage systems. The Precambrian rocks of Western Africa are subjected to dry, tropical climatic conditions with less than 40% of the total surface area of Western Africa receiving an average annual rainfall varying between 500mm and 2000mm.

The hydrogeological characteristics of the weathered crystalline rock derive from and are related to long-term, tectonically controlled geomorphic processes (Taylor & Howard, 2000). However, rainfall continues to drive the geomorphic processes, in particular deep weathering and stripping, acting on deeply weathered basement rocks.

5.4.2 The Weathered Overburden

Past weathering and erosion processes have resulted in the formation of a regolith, a zone of alteration products, normally more than 10m thick and overlain by residual soil (Taylor & Howard, 2000; Chilton & Foster, 1995; Gustafson & Krásný, 1994; Acworth, 1987). The regolith is a result of the infiltrating and acidic rainfall reacting with the host minerals, followed by leaching of the more soluble and mobile elements (or compounds) with contemporary as well as subsequent re-precipitation of the less mobile elements or compounds (*i.e.* the formation of Al/Fe oxides and kaolinite as examples). The saprolite (Figure 24) is characterized by massive accumulations of secondary clay minerals (especially kaolinite) with both primary minerals as well as intermediate weathering products. The hydrogeologic properties of the regolith, including the rate and depth of weathering, are influenced by bedrock type, by the presence of Fe-Mg minerals and by the density of structural features such as fracture zones and dykes.

According to Rebouças (1993), crystalline rocks with deeply weathered overburden (from 10 to 100m thick) comprise 70% to 90% of the Precambrian basement regions in both South America and Western Africa (Figure 25). The weathered overburden in certain parts of Brazil may, however, be more than 200m thick in regions subjected to neotectonic uplift and an annual rainfall varying between 2000mm and 3000mm. The average thickness is estimated at approximately 42m. The thickness of the weathered mantle for Western Africa (*i.e.* Senegal, Ivory Coast, Ghana, Niger and Zaire) varies from 10m to 175m, with an average thickness of 30m influences the weathering process and thus the development of the weathered overburden (Rebouças, 1993; Gustafson & Krásný, 1994).

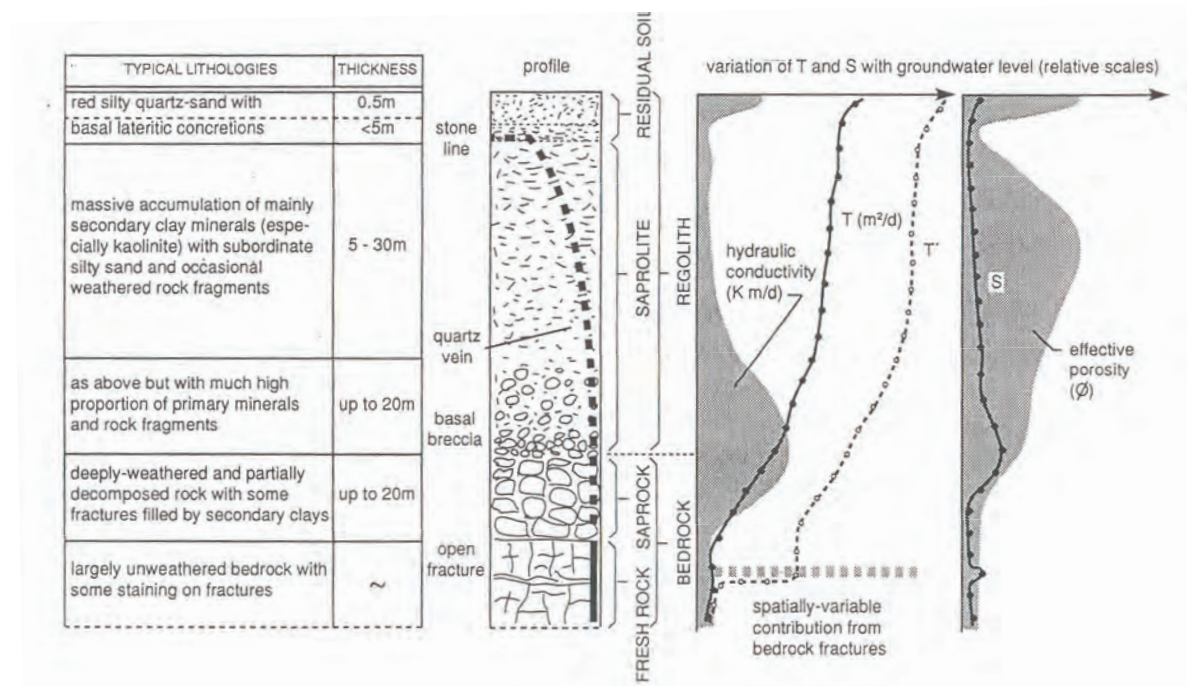


Figure 24: Typical weathered profile for Precambrian basement rocks (after Chilton & Foster, 1995; see also Taylor & Howard, 2000).

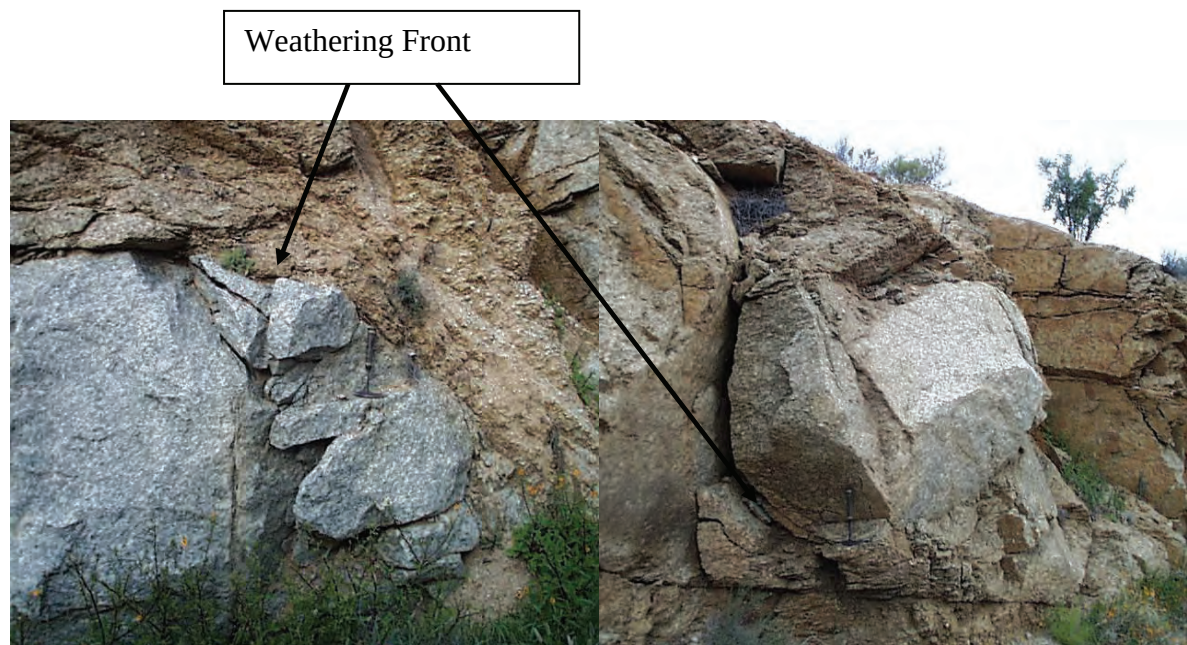


Figure 25: The weathering front and the resultant in-situ clayey products exposed in a road cut. Visible weathering around an ellipsoidal core block, and a 3D view parallel to the long-axis of an ellipsoidal core block, bounded by a vertical fracture to the left and a shear at the bottom of an ellipsoidal core block (left photograph).

Basement aquifers in arid regions are characterized by relatively thin saturated regolith generally present above deeper groundwater levels (Chilton & Foster,

1995). The deeper groundwater levels and thin saturated regolith thickness in arid regions necessitates the drilling of deep boreholes to intercept structural features and contact zones at depth within the unweathered bedrock.

The in-situ weathered products can be observed around relatively fresh core blocks within road cuts in Namaqualand (Figure 25). The weathering front on these predominantly ellipsoidal core blocks is easily observed. The shape of the weathering front may be related to the tectonic history of the region resulting in orthogonal fracture sets. Weathering can also be seen along fracture zones internal to these relatively fresh core blocks. The extent of weathering is assumed to be much deeper within the structurally controlled, open valleys characteristic of the lower lying regions of Namaqualand (Titus, 2003).

A general weathered profile (Figure 26) for crystalline basement rocks in Southern Africa is based on studies conducted by McFarlane (1987). Detailed studies have been conducted on the textural and mineralogical content as well as the hydrologic properties (the permeability and porosity) of the various zones within the weathered profile. Their studies concluded that the regolith is the main aquifer system and can attain a thickness of more than 80m. Furthermore, local groundwater flow systems dominate with the water level seldom exceeding the depth of 15m below surface. However, the basement aquifer for the Namaqualand region corresponds more favourably with the saprolite to saprock transition zone underlain by fresh bedrock with various fracture systems (Titus, 2003).

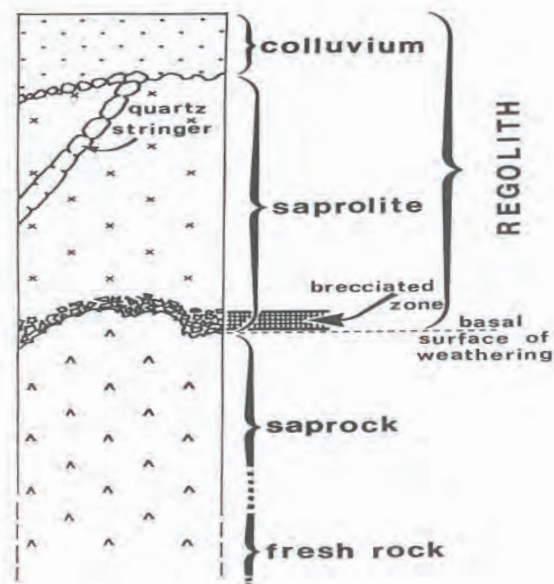


Figure 26: A generalised weathered profile for crystalline basement rocks in southern Africa (McFarlane, 1987).

An initial attempt to characterise the weathering profiles, based on limited data from the Komaggas reserve, was made for the crystalline aquifers in Namaqualand

(Titus, 2003). Detailed studies on the textural and mineralogical content as well as the hydrologic properties of the weathered overburden in Namaqualand are required. The data represented is based on information gained from borehole logs:

- The depth of weathering (to different scales) in the Komaggas Rural Reserve is present to depths of 54m to 60m below surface for both the metasediments of the Subgroup Khurisberg and for the granitic/gneissic rocks. In a few cases the depth of weathering, especially for the metasediments of the Subgroup Khurisberg, can extend to depths of 70m to 80m below surface or even deeper.
- Intense weathering of in-situ material can occur to depths of 40m to 49m below surface for both the metasediments of the Subgroup Khurisberg as well as for the granitic/gneissic rocks. In a few localities, associated with the metasediments of the Subgroup Khurisberg, intensely weathered, *in situ* material can occur to depths greater than 80m below the surface.
- Degrees of weathering for different, as well as similar, rock types occur together with localised weathering on fracture systems, especially on the joint systems. Combinations of differential weathering of rock types together with localised weathering on fracture systems also occur. Fracture systems (e.g. joint systems, fault zones and fracturing associated with vein quartz) seem to be conduits for preferred flow, especially for the granitic/gneissic rocks.
- A scree cover or talus, with approximate thicknesses varying between 1m and 16m, occurs in valleys. The talus comprises both clay and coarse-grained quartzitic material. The quartzitic material probably remained after leaching by groundwater.
- Where inter-layering of especially schist and quartzite layers or pseudo-layering based on degrees of weathering of the Subgroup Khurisberg occurs, groundwater is intersected over vertical zones in boreholes. Exceptions to the above do occur, where inter-layering between schist and quartzite layers, or pseudo-layering, generate single groundwater strikes. Single groundwater strikes are common in granitic/gneissic rocks. Furthermore, fractures (especially joints) with an iron-oxide coating on the fracture walls occur frequently in both the schist and quartzite. According to Toens *et al.* (1995), groundwater strikes are usually associated with small, isolated brecciated zones both in the schist and quartzites as well as with brecciated vein quartz.

5.4.3 Groundwater Development

Groundwater, developed in weathered and/or fractured basement rocks, is generally regarded as a 'local' resource for individual domestic needs, particularly in rural regions. The basal part of the regolith, which is the approximate base of the saprolite and the top of the weathered saprock (*i.e.* the weathered bedrock), has sufficient permeability to support successful boreholes for small-scale village water supply (Chilton & Foster, 1995). Rebouças (1993) supported the latter statement and referred to the most productive zone for groundwater development corresponding to the lowest zone of the weathered profile and top of the fractured bedrock.

Furthermore, a thick saturated regolith is essential (especially in humid regions) for adequate aquifer storage and available drawdown (Taylor & Howard, 2000; Chilton & Foster, 1995; Acworth, 1987). The average yield from a production borehole in weathered basement aquifers is normally less than 1 l/s (Chilton & Foster, 1995). The average yield for wells and boreholes located in fractured and/or weathered rocks is 16m³/h for Brazil compared to an average yield of 3m³/h for certain countries in Western Africa (Rebouças, 1993). The groundwater usually has a low total dissolved solid load (TDS) of less than 100 mg/l. Groundwater, within the lowermost unweathered basement rocks, is stored in interconnected systems of fractures, joints and fissures associated with regional tectonism (Rebouças, 1993). The yield from these unweathered basement aquifers, located in humid and sub-humid tropical climatic sub-regions, vary between 1m³/h and 20m³/h with a TDS of less than 100mg/l (Rebouças, 1993).

More intensive development of the groundwater resources is possible at locations where favourable lithology, structural features and weathering coincide to form zones of higher transmissivity (Chilton & Foster, 1995; Sami *et al.*, 2002). The infiltration of water from soil to rock is strongly heterogeneous and requires permeable soils, or permeable horizons (*i.e.* 'infiltration routes'), as well as 'open' and interconnected fracture systems in the bedrock (Olofsson, 1993). Hydraulic continuity must exist between groundwater reservoir(s) in the overlying soil horizons (or weathered overburden) and the underlying bedrock. The fracture zones act as conduits for deeper flows from groundwater reservoirs located in upper permeable soils or the weathered overburden. Olofsson (1993) reported on a number of studies that indicate a direct correlation between the tectonic conditions (*i.e.* the nature of fracturing) in the superficial or upper bedrock, and drainage of the overburden. He also noted that the capacities of wells drilled into bedrock increased rapidly with the increasing thickness of the weathered overburden that represents large, highly conductive groundwater reservoirs.

However, fractured crystalline rocks are characterized, according to Gustafson & Krásný (1994), by extreme heterogeneity in their hydraulic properties. The hydraulic conductivity can vary, within the same rock mass, by orders of magnitude and over short distances. The weathering (*i.e.* dissolution of minerals) and leaching processes tend to increase the porosity, permeability and specific yield, while the deposition of clay minerals (as products of the weathering processes) can cause a reduction in these hydrogeologic properties (Chilton & Foster, 1995; Acworth, 1987). Gustafson & Krásný (1994) thus referred to hydraulic conductors within fractured crystalline rocks, rather than aquifers, to describe the storage and flow of groundwater in these rocks. The term aquifer implies that the groundwater reservoir is related to the formation rather than the structures within it. Structural features such as fractures and fissures, in crystalline rock, are described as hydraulic conductors while zones of intense fracturing are described as compound conductors.

Infiltration for the fractured crystalline rocks in Namaqualand occurs along the vertical to sub-vertical fractures, with lateral flow predominantly along horizontal to sub-horizontal fractures (Figure 27) fractured crystalline rocks in Namaqualand are characterized by extreme heterogeneity in their hydraulic properties with poor connectivity between fractures. Water is stored and transmitted in these fractures and fissures, which serve as hydraulic conductors, through a relatively impermeable matrix (Titus, 2003).



Figure 27: Water flowing from regularly spaced horizontal joint planes. The surface planes of the vertical joints are clearly visible.

The natural chemical quality of groundwater from basement aquifers in tropical regions of Africa is considered to be of acceptable quality (Chilton & Foster, 1995). The groundwater for igneous and metamorphic rocks within temperate climatic zones is characterized by low TDS values varying between 100mg/l to 300mg/l and by bicarbonate and calcium as the dominant ions. In humid equatorial regions of Africa, groundwater of the bicarbonate type dominates and TDS values of up to 1g/l are possible. With increasing latitude from the equatorial zone in Africa, both southward and northward, the TDS content increases and the anion composition of the groundwater changes from bicarbonate to sulphate, and even chloride dominated groundwater with varying cation content (Gustafson & Krásný, 1994). The TDS content within desert (or arid to semi-arid) regions commonly exceed 2000mg/l and can increase up to 10g/l, while the groundwater chemistry is dominated by chloride and sodium (Gustafson & Krásný, 1994). Thus, in contrast to the acceptable yield and quantity for basement aquifers located in humid and sub-humid tropical climatic sub-regions, the yield and quality for basement aquifers located in wet-dry and dry tropical climatic sub regions have generally been poor (Rebouças, 1993).

The structural control on the surface drainage systems, in semi-arid regions, is evident in their alignment along fracture systems that are associated with the underlying bedrock. Recharge to the underlying fractured and unweathered bedrock, for basement aquifers located in humid and sub humid tropical climatic sub regions, is associated with the high storability of the weathered overburden. The main source of recharge, in wet-dry and dry tropical climatic sub regions, is the drainage systems that are aligned along fracture systems. Groundwater in both humid and temperate regions is traditionally considered in terms of groundwater quality problems, such as pollution, and for geotechnical and engineering problems, such as dewatering for mining and civil engineering purposes. In semi-arid regions, however, groundwater commonly represents the sole rural water supply and is often subjected to detailed hydrogeological investigations.

5.5 BASEMENT AQUIFERS IN NAMAQUALAND

5.5.1 Introduction

Previous studies on basement aquifers in South Africa have predominantly focused either on projects related to water supply for various rural communities (Toens *et al.*, 1991, 1993, 1994, 1995, 1996; Esterhuyse, 1987, 1990, 1991) throughout the Buffels River catchment (*i.e.* secondary drainage catchment F30) or on very comprehensive and detailed studies related to the storage of nuclear waste (Andersen, 1986; Andreoli *et al.*, 1986; de Beer & Blume, 1986; Levin *et al.*, 1986; Verhagen & Levin, 1986). The aquifer systems identified in Namaqualand included the lowermost parts of the weathered overburden (*i.e.* regolith) and the relatively weathered and fractured underlying bedrock (*i.e.* the saprock and fresh rock). Primary aquifers are strongly seasonal and are limited to alluvial deposits, especially along the Buffels River. The groundwater possesses a dominant sodium-chloride (Na-Cl) character and can broadly be characterised as relatively saline, especially when development occurs in the lower lying structurally controlled valleys (Titus, 2003). Relatively lower salinity groundwater is limited to the mountainous regions of the secondary drainage catchment F30. Average yields for Namaqualand vary approximately between 0.2 to 2 l/s (Toens *et al.*, 1996).

5.5.2 Groundwater Chemistry

The groundwater for Namaqualand is generally very similar in character with a dominant NaCl signature throughout the recorded EC ranges. The Na⁺ and Cl⁻ dominated groundwater for Namaqualand can be described as end-point waters.

The groundwater tends to react with both the primary mineral phases and the reactive weathering products (*i.e.* crystallized aluminum oxide and hydroxide phases) or at least with an intermediate, meta-stable phase (*i.e.* amorphous aluminum oxide and hydroxide phases). Molar ratios indicate, however, that the incongruent weathering processes of various aluminosilicate minerals cannot alone account for the groundwater compositions (Titus, 2003).

The groundwater is generally over-saturated with regard to quartz and under-saturated with respect to amorphous silica. As a result, quartz and amorphous silica do not exert an important influence on the level of silica in groundwater. The level of dissolved silica, as silicic acid (H₄SiO₄), for the groundwater of

Namaqualand is controlled by the weathering of aluminosilicate minerals with a high silica content indicating the active degradation of silicate minerals.

The groundwater compositions are most likely to be in equilibrium or near-equilibrium with both kaolinite and Na-montmorillonite as weathering products. The even higher salinity groundwater compositions may be in equilibrium or near-equilibrium with Na-montmorillonite as a weathering product. This may again indicate longer residence periods and sluggish flow conditions for the more brackish, slower circulating and relatively older groundwater systems (Titus, 2003). However, the slow reaction kinetics of silicate minerals (including clay minerals) can result in uncertainties about the stability of the weathering products.

5.5.3 Geometry and Extent of Aquifer System

The aquifer systems in Namaqualand are confined to both narrow and open valleys associated with fault zones occurring throughout the area. These fault-controlled valleys are especially prominent in the mountainous escarpment zone and are the traditional targets for the development of groundwater resources.

Laterally extensive, linear and structurally controlled valley system are the usual target for groundwater development within the Escarpment zone. The formation of the valleys is associated with the tectonic history and geomorphic development (*i.e.* bornhardt development) of the region. Deep and differential subsurface weathering results in a highly irregular weathering front (or lower limit of significant weathering). The warm and humid tropical climate of the Cretaceous period resulted in the development of deep, kaolinised weathering mantles, to depths of 50m or more, especially on crystalline rocks containing thermodynamically unstable alumino-silicate minerals. Late Cretaceous and early Palaeocene pedocrete cappings (*i.e.* duricrusts) protected the African surface, and its deeply kaolinised saprolite, from erosion processes in many localities. Early Miocene crustal uplift and subsequent erosion, associated with limited incision of drainage channels of up to 100 m to 200 m below the African surface, resulted in the mid-Miocene Post-African I erosion surface. The Post-African I landscape development phase thus involved the removal of the deeply weathered mantles underlying the African surface (Partridge & Maud, 2000). In areas (*i.e.* western parts of southern Africa) subjected to minimal Miocene uplift, scattered residuals or reduced thicknesses' of the weathered mantles remained. Visual inspection of the exposed weathered overburden and a description of selected borehole logs for the Namaqualand region showed a highly variable bedrock zone with mainly the saprock and top part of the underlying fractured rock (Titus, 2003).

The aquifer system proposed (Figure 28) is a linear system associated with the structurally controlled valleys. The aquifer system may be laterally extensive depending on the nature of the fault systems. A micro-fissured model with predominantly fissure flow was adopted for the fractured, crystalline rocks of Namaqualand. Infiltration of water occurs along vertical to sub-vertical fractures with lateral flow along horizontal to sub-horizontal fracture systems. The water chemistry varies considerably among closely spaced fracture systems. The model displays a dominant vertical flow system (*i.e.* an infiltration phase) driven by local relief and an intermediate flow system driven by gradients along these laterally extensive valley systems.

In summary, the proposed geometry for the aquifer system can be described as laterally extensive, linear, structurally controlled valley systems (Titus, 2003). Wide, open valleys may result from the intersection of different sets of fracture systems. The saprock and top part of the underlying fractured rock (*i.e.* the bedrock) constitute the main aquifer system (Figure 29). The saprolite to saprock transition zone with associated higher yielding boreholes may be preserved in isolated locations.

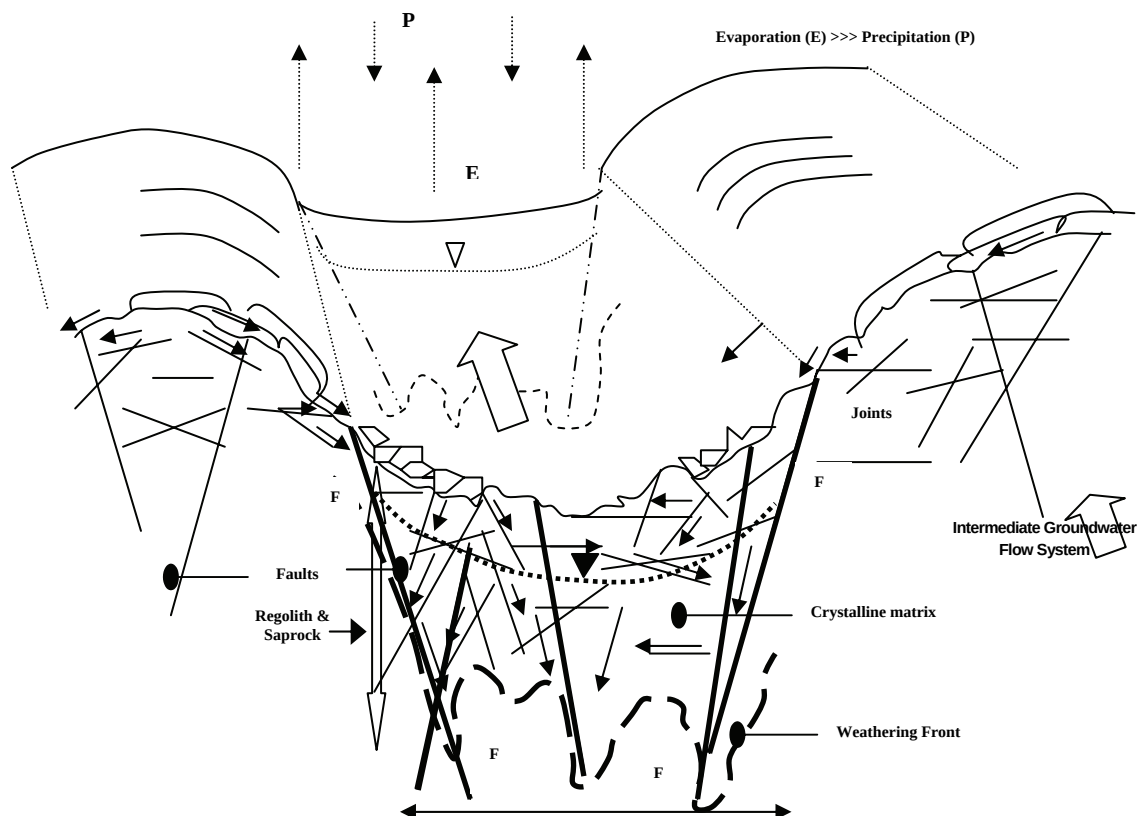


Figure 28: Proposed aquifer geometry and local to intermediate flow regimes for a typical structurally controlled valley within secondary drainage catchment F30 (Titus, 2003).

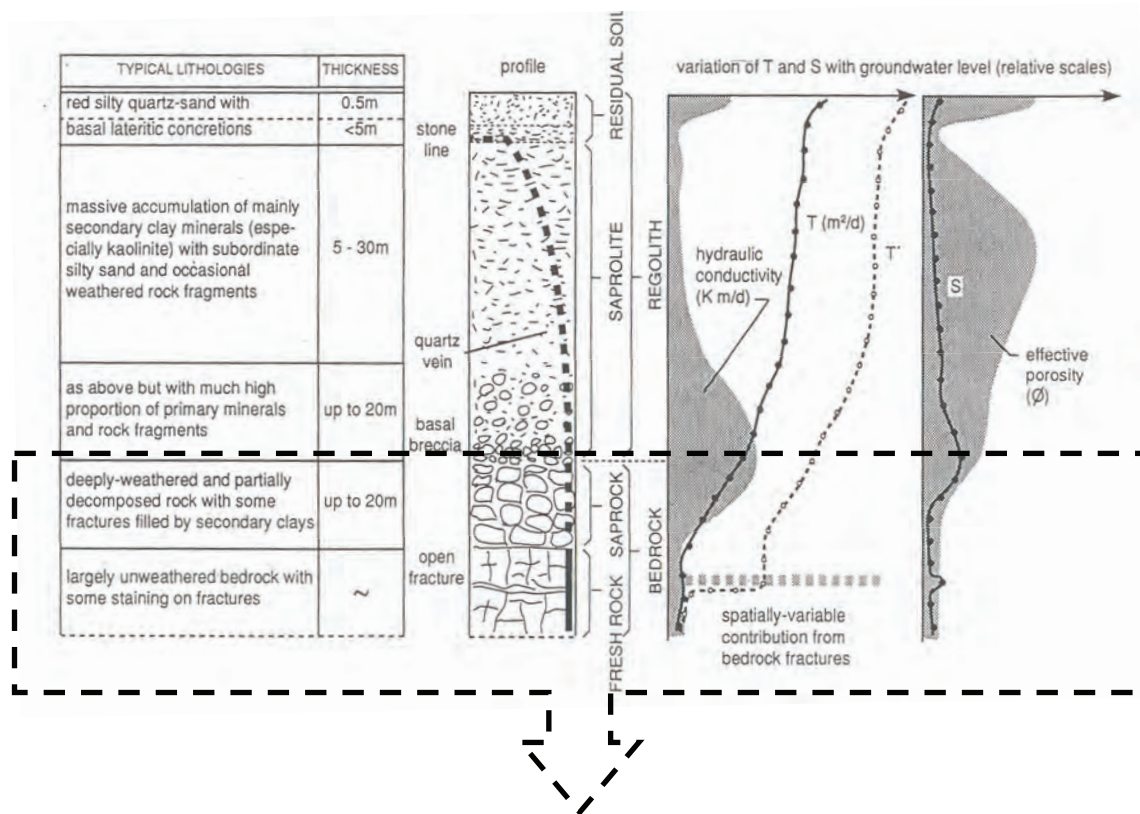


Figure 29: The bedrock (*i.e.* saprock to fractured rock) basement aquifer system of Namaqualand (Titus, 2003).

5.5.4 Groundwater Borehole Information

The existing borehole localities and yield data for the study area compiled by DWAF and the Hydrogeological Department of the University of the Western Cape are illustrated in Figure 30. The yield data have been contoured using the SURFER software package enhancing in particular the high yielding boreholes.

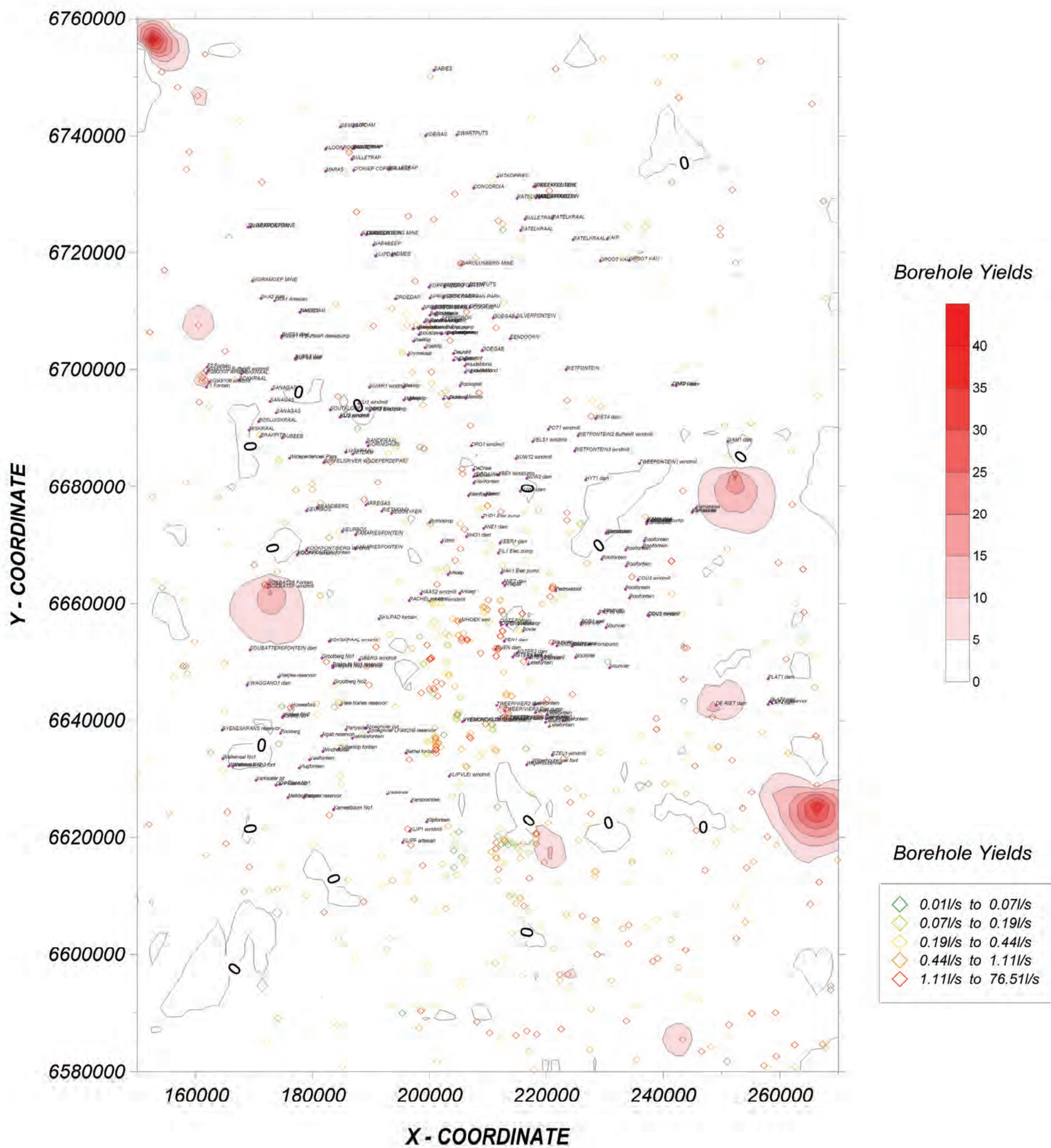


Figure 30: Borehole distribution map. Note: Purple circle = borehole investigated by Earth Science Department of UWC; Diamond = DWAF borehole.

6 STRESS MAPPING TECHNOLOGY

6.1 INTRODUCTION

Stress Mapping TechnologyTM (SMT) is a commercial software package and proprietary method developed by Terra Sancta, Perth, Western Australia, which introduces geomechanics into regional exploration for mineral deposits, oil and gas deposits, and groundwater.

This new technology is cheaper and faster than conventional prospecting techniques and provides targets by identifying areas that experienced, or are currently experiencing minimal stress (*i.e.* maximum dilation and structural permeability). These areas would be expected to be the main conduits and storage sites for hydrothermal ore forming fluids, oil and gas, as well as groundwater.

In general, the basic nature of all hydrothermal ore deposits revolves around the focusing of migrating fluids into dilatant structures, *i.e.* sites of low mean stress. These low mean-stress areas within the Earth's crust are commonly associated with brittle failure in areas of structural complexity. It is now widely accepted that such structures have a controlling factor on the loci of hydrothermal mineralisation (Hodgson, 1989; Vearncombe *et al.*, 1989; Vearncombe, 1998).

Typically, mineralisation occurs in discrete segments of individual structures and within the mineral deposits some parts of the host structures are better mineralised than others. Epigenetic mineral deposits are related, in general, to structurally focused fluid flow during active deformation (Hodgson, 1989). Hronsky *et al.* (1990) and Ridley (1993) reviewed the common structural controls on localization of mineralisation and ore shoots:

1. the intersection of host structure with a particular lithological unit (*e.g.* banded iron-formation-hosted gold deposits);
2. intersection of two syn-mineralisation structures;
3. dilatant sites such as dilational jogs, releasing bends, tension gashes, Riedel shears, divergent bends in faults or en échelon fault segmentation;
4. in competent layers that have undergone layer normal compression, *i.e.* in boudin necks,

5. in competent layers that have undergone layer parallel compression, *i.e.* in saddle reefs,
6. flexures in the host structure with axes oblique to, and commonly at a high angle to, the movement direction;
7. low pressure sites (pressure shadows) around rigid bodies adjacent to granite mass; and
8. zones that plunge subparallel to the stretching lineation but in which the specific controls on their location are unclear.

If only one control applies to mineralisation, it may be possible to predict the location of the next mineralized zone in a particular area or structure. However, commonly several controls interact, and the complex three-dimensional geometry of the controlling structures makes interpretation very difficult. In addition to geometry, competency contrasts and rheological properties of the host lithologies may have a significant influence. Therefore, even a purely kinematic approach to structural interpretation of a geological map is commonly based more on the interpreter's intuition than true geometrical relationships (Holyland & Ojala, 1997). Potentially the feature in common to all sites of hydrothermal ore is fluid focussing into sites of low mean stress during mineralization (Ridley, 1993).

The orientation of palaeo-stresses can be determined from these structures and other strain markers within the crust. Combined with an understanding of rheological variations of the rock types within a specified area, this knowledge may locate potential areas of low stress, and hence viable exploration targets of hydrothermal mineralisation.

The applicability of SMT to groundwater flow and storage in fractured aquifers has not been demonstrated as yet. It is the current objective of this study to illustrate the relationship of the technique to groundwater modelling, *i.e.* to determine fracture permeability in the continental crust and boundary conditions for groundwater flow.

6.2 DEFINITIONS – MECHANICS OF DEFORMATION

The following section attempts to clarify some of the basic structural geology principles on which forward palaeo-stress modelling is based on.

6.2.1 Stress

One of the fundamental criteria behind stress-modelling is the three principle stresses which form the basis of mechanical deformation within the Earth's crust. Stress can be defined as the result of force (F) applied per unit area (A) or ($S = F/A$). A principle stress can be defined as the corresponding stress which acts perpendicular to a surface when the shear stress acting on that surface is equal to zero (Price & Cosgrove, 1990). This shear stress can be caused by thermal and/or gravitational activated movements within the Earth's crust resulting in stress fields, which in turn give rise to a spectrum of structures of which fracture development is one phenomena.

6.2.2 Stress/Strain Relationships

One manifestation of strain within rocks can be defined as the physical response of stress in rocks. The amount of strain is a direct result of the physical properties (rheology) of the rock that is undergoing deformation. The complex behaviour that the rock exhibits as a result of stress yields complicated rheological stress-strain relationships that the structural geologist observes in deformed terrains, and can be explained by a few simple concepts, such as elasticity, viscous and plastic behaviour.

6.2.2.1 *Elasticity*

When a material is subjected to a stress of a particular magnitude, it responds by deforming. If the stress of load is removed and the deformation instantaneously reverses with completely recovery, the material is said to be perfectly elastic.

This theory of elasticity resolves around four simplifying assumptions: that the material is a) homogenous; b) isotropic; c) the elastic strains are infinitesimal and d) the material has a linear stress-strain relationship. Most rock types depart from this ideal, but provided a suitable scale is chosen for the task in hand, many of them can be considered homogenous and isotropic. It has been found that geological materials on the whole do not have a linear stress-strain relationship. However, the deviation from these linear relationships is small enough that a single value for Young's Modulus^a (E) can be applied to most rock types (Price & Cosgrove, 1990).

6.2.2.2 Viscosity

Under many geologic conditions, a crystalline solid can behave in a similar manner to a “stiff” liquid (i.e. putty). This property is defined as viscosity (η) and can be determined from:

$$\text{shear stress} = \eta \times \text{rate of strain}$$

Behaviour of mantle rheology under a load can be used as an example of a viscous liquid over an extended period of time, particularly with respect to isostatic readjustments of the lithosphere to the loading caused, for example, by sedimentary basins (Beaumont, 1981) or ice cover (McQueen & Lambeck; 1989, Lambeck, 1990).

6.2.2.3 Plasticity

Viscosity is applied to rocks to simulate behaviour as that of a liquid. In contrast, plasticity relates to behaviour of rocks as a solid. Plastic deformation begins when a critical yield-strength of a material is reached. Theoretically from that moment on, unlimited plastic flow should be able to occur. In natural materials, perfectly rigid behaviour is uncommon. Instead there is an initial elastic response prior to plastic flow. Materials that show this type of response are termed viscoelastic materials. More commonly, however, is that after the initial yield-stress is reached and the first increment of plastic strain occurs, a further increase in stress is necessary for increasing plastic deformation to occur. The strain hardening that necessitates this increase in stress is explained in Section 6.2.2.4. Figure 31 shows the relationship between stress and strain for a) a rigid “perfectly” plastic body; b) an elastic-plastic body; and c) an elastic-plastic body that has undergone strain-hardening.

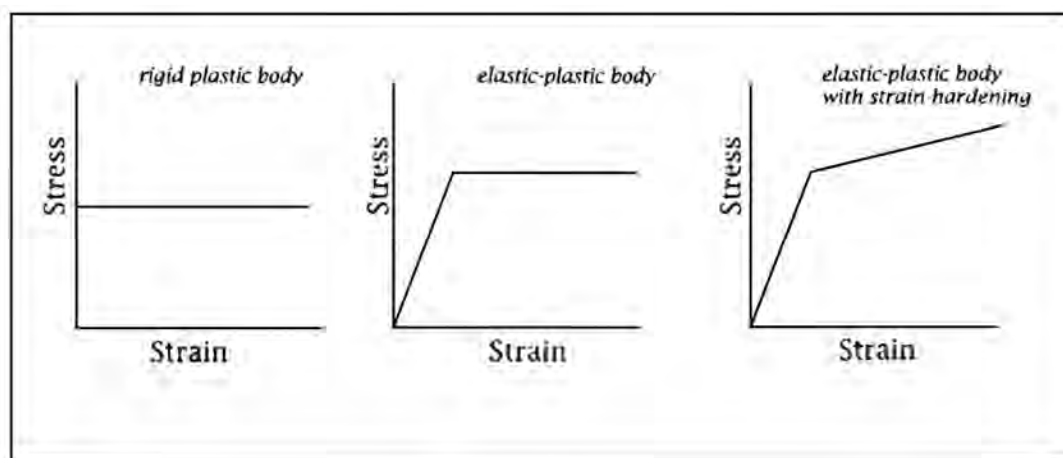


Figure 31: Stress-strain relationships of differing elastic-plastic material (adapted from Price & Cosgrove, 1990).

6.2.2.3.1 Strain-hardening/Strain-softening

Simplistically, a rock buried deep within the Earth's crust is surrounded by confined stresses and therefore is unable to fracture. Consequently, the shear strain in this scenario is then taken up by the crystal lattice of the rock, where *dislocation creep* is the primary deformation mechanism. Dislocation creep occurs as a result of inhomogeneities present along the crystal boundaries which allow movements at the atomic scale. As these crystal lattice adjustments occur, differing temperatures allow either *strain-hardening* or *strain-softening*. Strain-hardening occurs at relatively low temperatures where deformation utilises the most readily available dislocations first and, as these are used up, an increase in stress is required in order to allow plastic deformation to continue. Conversely, when the rock exists at higher temperatures, the increase in atomic mobility allows creep to continue, this process would occur, for example in the mantle.

6.2.3 Brittle/Ductile Deformation

Deformation can be loosely categorised into brittle and ductile failure. The development of faults and fractures are generally described as a result of brittle failure, albeit with some exceptions such as the development of mylonitic zones.

Brittle or ductile deformation occurs when the elastic limit of a material or rock is reached as a result of an applied stress. The material can then respond in either a brittle or ductile manner. Certain external conditions also constrain the manner in that the material will deform: at high strain rates and low temperatures, the response will be one of brittle deformation, whereas ductile deformation will predominate under high temperature and low strain rate conditions. It should be noted, however, here that neither deformation mechanism is entirely divorced from one another since these processes are dynamic (for instance, during progressive deformation and changing tectonic conditions).

6.2.3.1 Brittle Failure

The theories on brittle failures that are most applicable to rocks, and the Earth's crust, are the *Navier-Coulomb criterion* and the *Griffith theory*.

The *Navier-Coulomb criterion* of brittle shear can be expressed by:

$$\tau = C_0 + \sigma_n \mu$$

Where τ and σ_n are the shear and normal stresses respectively acting on a potential failure plane. It has been recognised that prior to the development of a fracture plane, cohesion (C_o) must be overcome. In order for that fracture plane to slide, so must the coefficient of friction (μ) be also overcome. Differences noted by Griffith (1925), between theoretical and observed tensile strength values were a result of intense local stress concentrations at the tip of microscopic flaws. The result was the development of the *Griffith theory*, which revolves around the inter-atomic bond-strength of the material. Griffith (1925) assumed that these flaws were elliptical with a large eccentricity. He demonstrated that when a material is subjected to a tensile stress (σ_1), the maximum tensile tip stress becomes large enough to equal the atomic bonding strength of the material, therefore permitting flaw propagation.

To briefly summarise, one can state that the *Navier-Coulomb criterion* sufficiently describes failure in the compressive region whilst the *Griffith theory* adequately expresses extensional regions.

6.2.4 Youngs' Modulus (E)

Young's Modulus is the constant (E) that defines the relationship between stress (S) and strain (e), which can be expressed as:

$$S/e = E$$

Since strain is dimensionless, E must have the same dimensions as S, which is measured in MPa.

6.2.5 Poisson's Ratio (ν)

When a stress is applied to a cube of rock in the z direction, the amount of shortening experienced by the cube is defined as the strain. However, in addition to the strain in the z direction, the applied stress also causes a lateral expansion in the x and y directions. It is this ratio of deformation that is termed Poisson's Ratio and is given below as:

$$\frac{\text{extension normal to the applied stress}}{\text{extension parallel to the applied stress}}$$

6.2.6 Bulk Modulus (Compressibility) (κ)

The compressibility or bulk modulus is the measure of the ratio of the change in volume of an elastic solid to the change in hydrostatic pressure. It can be defined as:

$$\kappa = \frac{dV}{dP}$$

where V is the volume and P is the hydrostatic pressure. The porous bulk moduli represent the fluid compressibility, which forms an integral part of the model.

6.3 METHODOLOGY

6.3.1 Overview

Fluid focussing into sites of low rock stress (dilatancies) can be modelled by stress-mapping (Holyland 1990a, b; Holyland *et al.*, 1993). This technique calculates spatial variations in mean or minimum stress using a solid geology map as a basis for providing constraints on rock geometry and rheology, and an estimate of regional stress directions as input. Thus, SMT can be regarded as a geomechanical approach using two- and three-dimensional computer simulations to attempt to predict the locations of dilational sites, which result from deformation of a complex rock and fracture geometry. Thus, stress mapping requires:

1. An interpreted, accurate geological map, which is greatly facilitated by the integration of aeromagnetic data. Gravimetric and radiometric data, LANDSAT images, air photos and published geological maps are additional and essential datasets particularly in poorly exposed terrains. Geological map data are converted to a crack and block model, representing the solid geology interpretation, which provides continuous lithological and structural information. The study area is treated as a mosaic of polygonal blocks (rock units) and cracks (faults and shear zones), where cracks must form a continuous network such that polygonal blocks bounded by these cracks form a complete tessellated array over the whole area to be modelled. The model is then converted into simple .DXF files and the SMT-software is used to apply compressive stress to the model in various directions. When external stress is applied to this system, the blocks are juggled and internally deform until equilibrium is attained. This juggling and internal deformation results in areas of lower stress (*i.e.* dilation zones), which

would represent favoured areas for mineralisation and therefore targets in exploration. The stress data generated by SMT is then gridded, contoured and displayed as a simple 8-bit grey or colour raster.

2. Production of a stress map requires estimates of the magnitudes and orientations of the far-field horizontal stresses.
3. Rock deformation properties including strength and moduli, and fault deformation properties of friction and stiffness are required for the modelling.

Modelling is by a state-of-the-art, two-dimensional distinct element code (UDEC program) and the method has three distinguishing features which make it well suited for discontinuum modelling (Holyland, 1990a, b):

1. The method is simulated as an assemblage of blocks, which interact through corner and edge contacts.
2. Discontinuities are regarded as boundary interactions between these blocks; discontinuity (fault) behaviour is prescribed for these interactions.
3. The method utilises an explicit time stepping (dynamic) algorithm, which allows large displacements and rotations, and general non-linear constitutive behaviour for both the matrix and discontinuities.

Modelling can be done at any scale and in addition to minimum, maximum and mean stresses, total displacement and fault displacements are computed. The total displacement is the amount of movement experienced by the rock blocks, and their movement directions.

6.3.2 Detailed Description of Methodology

6.3.2.1 *Discontinuity Classification – Faults and Fractures*

Faults and/or fractures within an area can be incorporated into a tessellated array. Two classes of faults can be defined: major faults and minor faults (or fractures), referred to as strike faults and cross faults, respectively. Lithological boundaries are constructed as cracks in the geological input map. Because, in nature, minor faults tend to die out within lithologies, “tie lines” are used in the program to mimic this scenario and to complete the aerial network of continuous fracture necessary for analysis.

6.3.2.2 Scaling

An important factor in the construction of a palaeo-stress map is the scale at which the geological input map is produced. The SMT software only has the ability to produce stress maps at the 1:50 000 scale, therefore if the area of interest is on a different scale, the .DXF files, representing the geological input map, need to be converted to 1:50 000. This conversion factor is applied again in reverse, when the stress map has been produced, reinstating the correct scale prior to contouring the corresponding stress map. The SMT program which is designed to implement this conversion is *Meanstrs.bas*.

6.3.2.3 Output Files

The output geological map generated in CAD programs like AutoCad™ or Bentley MicroStation consists of four graphical files (in .DXF format):

1. a “crack file” containing all “cracks” - that is the major and minor faults, as well as the geological boundaries.
2. a “block file” containing 4 point polygons that define the different rock blocks.
3. a “strike-fault” file containing all the major or strike faults.
4. a “cross fault” file containing all the minor or cross faults.

6.3.2.4 Far Field Stresses

Interpretation of palaeo-stress orientations is not simple. This is highlighted by the compilation of the World Stress Map (WSM). On a global scale, the World Stress Map collates the orientation of present-day stresses within the lithosphere that result from a variety of forces acting on and within the tectonic plates (Tapponier *et al.*, 1986; Zoback *et al.*, 1989; Zoback, 1992; Zoback & Burke, 1993). It is believed that these stresses primarily emanate from tectonic plate interactions at their boundaries and that these stresses control the intraplate stresses and, in turn, local stress fields.

Within individual tectonic plates, local mapping the present-day stress-field has demonstrated that “inboard” (within plate) effects of plate boundary deformation

are experienced thousands of kilometres away from the originating stress at the plate boundary. Information of such far-field stresses is valuable in interpreting past geologic deformation and palaeo-stress fields (Zoback & Burke, 1993). This type of stress data may aid us in understanding the apparent “weakness” of major continental transform faults. This kind of information is of particular value in unravelling the tectonism of areas along major intracratonic suture zones/terrane boundaries (particularly during their early evolution), of which faults like the San Andreas Fault may be used a present-day analogy.

Recently, Marshak & van der Pluijm (1997) recognised that continental interiors, previously thought to be rigid and undeformable, can act as sensitive recorders of tectonic activity at plate boundaries.

Orogenic stresses of the order of megapascals, at plate margins within the North American plate have been found to transmit over distances up to 2000 km. The implication of this, in light of intraplate fault reactivation is, that the orientation of the fault zone relative to the plate margin is the controlling factor in intraplate stress release, and not necessarily its orientation to the far-field stresses (Pluijm *et al.*, 1997).

With these gross influences in mind, it is not surprising that local stress field orientation of a specified area can be difficult to ascertain. However, possibly in a manner similar to a fractal, smaller structures often appear to mimic the larger ones, allowing one to apply a similar local stress-field to that of the intraplate stress. This is supported by the remarkable uniformity that midplate or intraplate stress field displays in the upper brittle part of the lithosphere (despite the complex vertical and horizontal tectonic structure and fabric of the earth’s crust), often over very broad regions, 20-200 times the approximately 10-25 km thickness of the upper brittle lithosphere (Zoback & Burke, 1993). Using the general knowledge, local stress orientations along smaller features might be predictable. Such an approach is described below.

As part of stress mapping modelling, far field stresses are applied to the geological input map in an appropriate orientation usually deduced from regional geological features such as late dyke swarms or fold axes orientations. An area that has experienced several episodes of tectonic activity, for examples numerous discrete deformational periods, with successive stress fields oriented in varying directions, must be analysed in different “time-slices”. “Time-slices” display only the structures that either pre-existed and/or formed during the time that the specific far field stress regime was active. In complex terrains, the orientation of the far field stresses often cannot be accurately determined.

To resolve this, one can apply a far field stress orientation interpreted to enhance potential low stress areas. This method allows maps of differing far field stress

orientations to be created and used as a comparative tool in aiding interpretation of the far field stresses producing the structures observed in the area of interest.

This application of SMT can be used detrimentally if the geological history is not fully reasoned out. However, at the same time, if utilised with a comprehensive knowledge of the geology and an awareness of the erroneous interpretation that could arise from these stress maps, it has the potential to be an important exploration and interpretive tool. This highlights the iterative process between modelling and knowledge of the terrain.

6.3.2.5 SMT Conversions

The UDEC environment can imitate geological environments conducive to gold and base metal deposits. This option is termed UDECGOLD. UDECGOLD is further subdivided into Epithermal, Archean Brittle, Archean Brittle/Ductile, Archean Ductile and Proterozoic Sedimentary options (Table 5). Each of the five gold options has different input parameters for the behaviour of the block materials and crack types. The main function of the UDECGOLD option is to define these parameters in the UDEC input file.

To use the UDEC rock mechanics code, data files need to be converted from .DXF into a readable format. The SMT software developed to do this is essentially a loose collection of stand-alone programs in Basic and FORTRAN. The following suite of programs is used:

- a) **Crackpro.bas:** This line of code defines the geometry of the blocks in terms of their bounding cracks in UDEC. It extracts the line segments from the .DXF files and writes a text file with one line segment on each line that defines the coordinates of the crack.
- b) **Blockpro.bas:** This extracts the four noded polygons from the .DXF block file. The polygons cover a centre point to which the rheological properties are assigned according to the dominant rock type.
- c) **Modicrak.bas:** This conversion extracts the line segments for the strike and cross fault files. The output file is the co-ordinates of each line segment.
- d) **Polygons.exe:** This program generates long thin polygons around each fault and assigns a numerical nomenclature to each one depending on whether it is a strike or cross fault.

Table 5: Interactive screen of the UDECGOLD module.

UDECGOLD		
Type of UDEC Run	Epithermal	1 []
	Archean Brittle	2 []
	Archean Brittle/Ductile	3 [X]
	Archean Ductile	4 []
	Proterozoic Sedimentary	5 []
Type of Compression	North-South Compression	D [X]
	East-West Compression	E []
File Names	Crackfile Name	F [insert file name]
	Blockfile Name	G [insert file name]
	UDEC Input Filename	H [insert file name]
Block co-ordinates of map	x1 y1 (clockwise)	J [] []
	x2 y2	K [] []
	x3 y3	L [] []
	x4 y4	M [] []
Minimum/Maximum	max x /max y	N []
	min x /min y	O []
	Mat Number	P this is the default material number for the most common lithology
	make input fule quit	I Q

The output from the file conversions *blockpro.bas*, *modicrak.bas* and *polygons.exe* on the faults are concatenated using DOS copy to produce a “block” file. This contains the string of polygon co-ordinates followed by the rheological parameters assigned to each lithological polygon and the polygon that define the cracks.

In addition to this block file, there is the crack file and these two files now contain the UDEC commands of the geometry and material types of the stress mapping model. The subsequent steps involve inserting these files into the UDECGOLD module. This is done interactively as the example below shows:

In the UDEC environment (Table 5), only two stress orientation options are available, *i.e.* N-S and E-W. Under many geological conditions, the stress orientation is rarely exactly north-south or east-west. In order to stress the model in the correct orientation, the model has to be rotated while the digital data is still in .DXF format. After the stress map has been produced, the model must be rotated back to the original position before contouring. *Rotmean.bas* is the relevant rotation program designed for SMT.

6.3.2.6 UDEC – Rock Mechanics Code

The 2-dimensional rock mechanics code, forming the crux of the computer modelling used in SMT is the Universal Distinct Element Code (UDEC) developed by Itasca Consulting of Minneapolis, USA. The formulation of the code is based on the *Indirect Boundary Element Method* of Banerjee & Butterfield (1981). It can be described as a distinct element method, which is a recognised discontinuum modelling approach for simulating the behaviour of jointed rock masses (Holyland, 1990a). UDEC is a form of finite Element Analysis (FEA) in which variable spacing and orientation of the boundaries between geometric elements are defined (Figure 32).

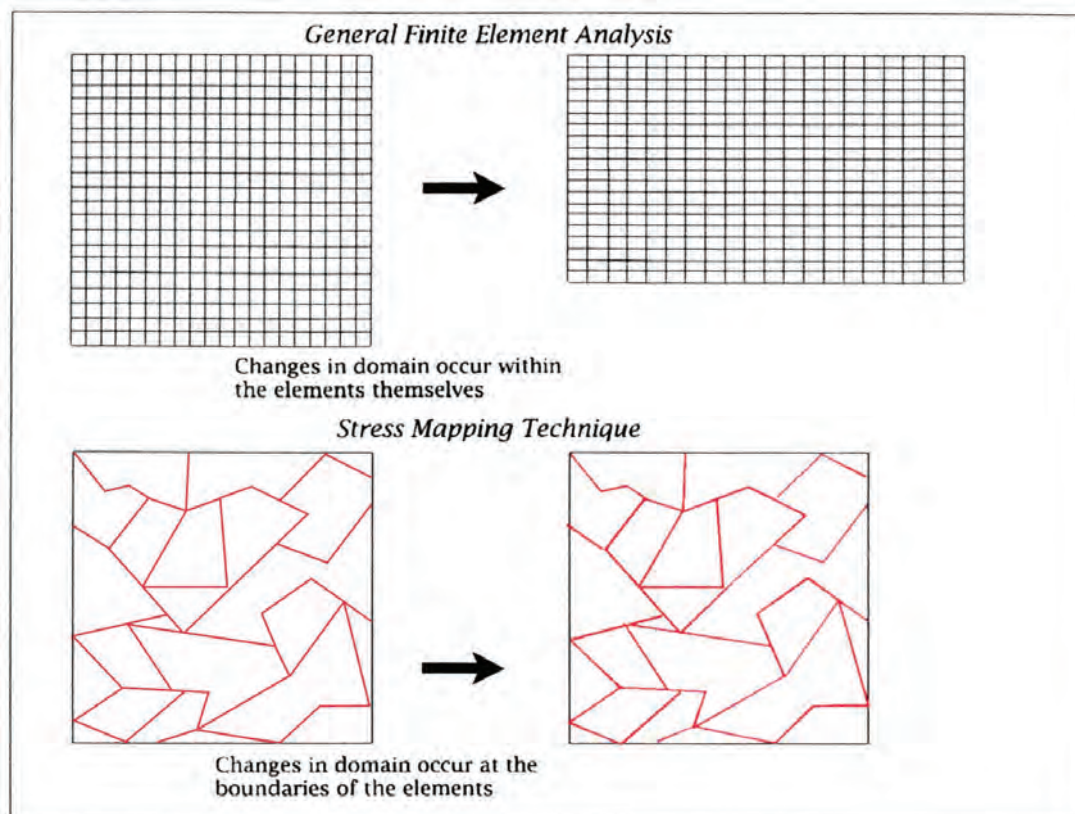


Figure 32: Graphic representation of the differences between Finite Element Analysis and Boundary Element Method, used by SMT.

Vearncombe & Holyland (1995) describe three distinguishing features that characterise the code modified for the use in SMT; these are:

- a) The assemblage of blocks in a domain interact through corner and edge contacts;
- b) The discontinuities are regarded as boundary interactions between the blocks, with fault behaviour prescribed for these interactions;
- c) The algorithm that is utilised in the program is explicit, iterative and dynamic allowing large displacements, rotations and a general non-linear constitutive behaviour of the matrix and discontinuities.

An integral part of the development of the SMT software entails the specification of numerical values of tables that can be loosely classified as the rock deformation and fault deformation properties for different rock and fracture types (Table 6). Table 7 exhibits a typical set of numerical values for the variables shown in Table 6.

Table 6: The relationship between the different variables that comprise the rock deformation and fault deformation criteria used in SMT.

<i>Rock Deformation</i>		<i>Fault Deformation</i>	
<i>Bulk Rock Moduli</i>		<i>Stiffness</i>	
Young's Modulus	Poisson's Ratio	Normal	Shear
<i>Strength</i>			
Compressive	Tensile	Compressive	Tensile
<i>Cohesion</i>			
<i>Friction Angle</i>			
<i>Principle Stresses σ_1 σ_2 σ_3</i>			

Table 7: Typical values of granitoids and sediments used in the computer modelling of a Stress Map (P. Holyland, pers. comm., 1997).

<i>Material Type</i>	<i>Granitoid</i>	<i>Sedimentary Rock</i>	<i>Lithological Contact</i>
Young's Modulus (MPa)	50 000	25 000	-
Poisson's Ratio	0.25	0.2	-
Normal Stiffness (MPa)	-	-	5
Shear Stiffness (MPa)	-	-	0.0001
Tensile Strength (MPa)	4	3	0
Compressive Strength	30	20	0
Cohesion (MPa)	6	4	0
Friction Angle (°)	20	20	10
σ_1 (MPa)	100	100	100
σ_2 (MPa)	80	80	80
σ_3 (MPa)	50	50	50

6.3.2.7 Stress Cycles, Gridding & Contouring the Stress Map

Stress cycles form the integral part in the production of a palaeo-stress map, mimicking the compression of the proposed far-field stresses. The following section describes how these cycles are employed.

Once the stress simulation has been selected in the UDECGOLD module, one can then start UDEC and call up the input file. The model is stressed under the desired stress orientation for one cycle of compression to automatically check for any, either graphical (incomplete polygons) or material definitions. Providing no errors exist, one can then subject the model to any number of stress cycles. Terra Sancta, who developed the software, typically applies 500 cycles for a “normal compression” and 1000 cycles for a “prolonged compression”.

Once the cycles are completed, the file created from this procedure is saved in a UDEC format. This UDEC file has a *.STRS file extension. Following this, any rescaling or rotation of the output file to its original size and position is then executed.

To grid and contour the data, using software such as SURFER for Windows by Golden Software, the output file must now be converted to a file with a *.DAT extension. This is achieved using the *Meanstrs.bas* program.

Once the file is readable by SURFER, one can contour the high and low stress areas. Overlaying this contoured stress map with the geology of the area facilitates correlation and interpretation of the low and high stress zones with the pre-existing geologic structures and any known mineralisation sites.

6.3.3 Potential Errors and Limitations of SMT

Numerous published SMT-studies performed in Australia (e.g. Holyland, 1990a, b, c, d; Holyland *et al.*, 1993; Holyland & Ojala, 1997), as well as within the Kaapvaal Craton (Vearncombe & Holyland, 1995) are, to date, highly encouraging. However, in spite of the success, the restrictions of the technique which are implicit in the assumptions involved, should not be ignored. Arguably, the most severe limiting assumption of two-dimensional stress modelling is that the plane of a map does not accurately reflect the stress pattern in an area with complex three-dimensional geometry (Holyland *et al.*, 1993). In many Archaean terrains this may not be a critical restriction, since the vast majority of the observed craton-scale structures are upright and the majority of gold deposits are hosted in steep structures, although significant exceptions do occur (Libby *et al.*, 1990; Hronsky *et al.*, 1990; Campbell & Pitfield, 1994; Groves *et al.*, 1995). The accuracy of the

three-dimensional geological interpretation becomes especially important in deposit-scale modelling where the extent of interest of the vertical dimension is similar to horizontal dimensions.

Other assumptions include the physical and mechanical parameters of lithological units, the interpretation of limited outcrop geology to the hard-rock map, and the polygon construction for the stress analysis. Thus, stress mapping is, like other structural techniques, dependent on the quality of the mapping and interpretation.

Because in palaeo-stress mapping one qualitatively relates stress and strain across an area using geometric analysis, this is essentially a “kinematic” technique. However, errors may arise when analysing only the kinematics of structures. Additionally, the analysis assumes specific rock mechanical properties which are only approximates and thus also subject to error. Specifically, these include variations in rheology which, in turn, may effect the local fault interaction. Fault dilatancy will also vary with crustal depth (Sibson *et al.*, 1975). The modelling also assumes homogenous behaviour on the scale of the polygons (rock volume units) as defined in the geometric analysis.

However, this can be solved by equating rock mechanics to a kinematic analysis such as palaeo-stress mapping, and thus the stress/strain relationship is then quantitatively related. As a result, rheological-induced errors (or unknowns) do not manifest themselves.

7 APPLICATION OF SMT TECHNIQUE

7.1 STRUCTURAL INTERPRETATION

A regional structural interpretation at 1:100,000 scale of the available Landsat TM scenes and aerial photographs, in conjunction with available geological maps, was performed prior to a first field visit as a desktop study. The interpretation was performed jointly on screen and on hard copies printed at 1:100,000 scale. The final interpretation map (Figure 34) was composed in Bentley MicroStation SE in .dgn file format, using the projection parameters mentioned above.

7.2 FIELD VISIT VALIDATION

In order to be able to ground-truth some of the interpreted structural elements a field trip was undertaken to the study area with the following objectives in mind:

- To ground truth the structural interpretation, which was, until then, based solely on processed remote and geophysical data sets, as well as published geoscientific information.
- To establish the relative age, orientation and geometry of different fracture/joint sets, their kinematics and associated fault rock types, as well as any age relationship between these fractures/joints and magmatic units that have variably intruded along them.
- To verify and identify the existence, nature and geohydrological importance of palaeo-land surfaces.
- To study the relationship between geology (in particular structure and lithology) with morphology, topography and vegetation.

Ground-truthing of certain areas within the study area confirmed and refined the structural interpretation (Figure 33) carried out as a desktop study prior to the field visit. Figures 34a-c show some representative ductile and brittle structural discontinuities, being the products of compressive Namaqua and extensional Gondwana break-up tectonics respectively.



Figure 33: Representative images of brittle faults and fractures/joints interpreted to have formed as new structural discontinuities, or by reactivation of pre-existing fault/shear zones in response to continent-wide crustal extension during the break-up phase of the supercontinent Gondwana in the Mesozoic at ~200-120 Ma. (a) N-S striking, subvertical, brittle faults; (b) E-W striking, Mesoproterozoic Ratelpoort shear zone showing evidence for minor extensional reactivation under brittle conditions; (c) N-S striking, brittle fractures/joints traversing ductile, E-W striking fabrics developed during the Mesoproterozoic Namaqua Orogeny.

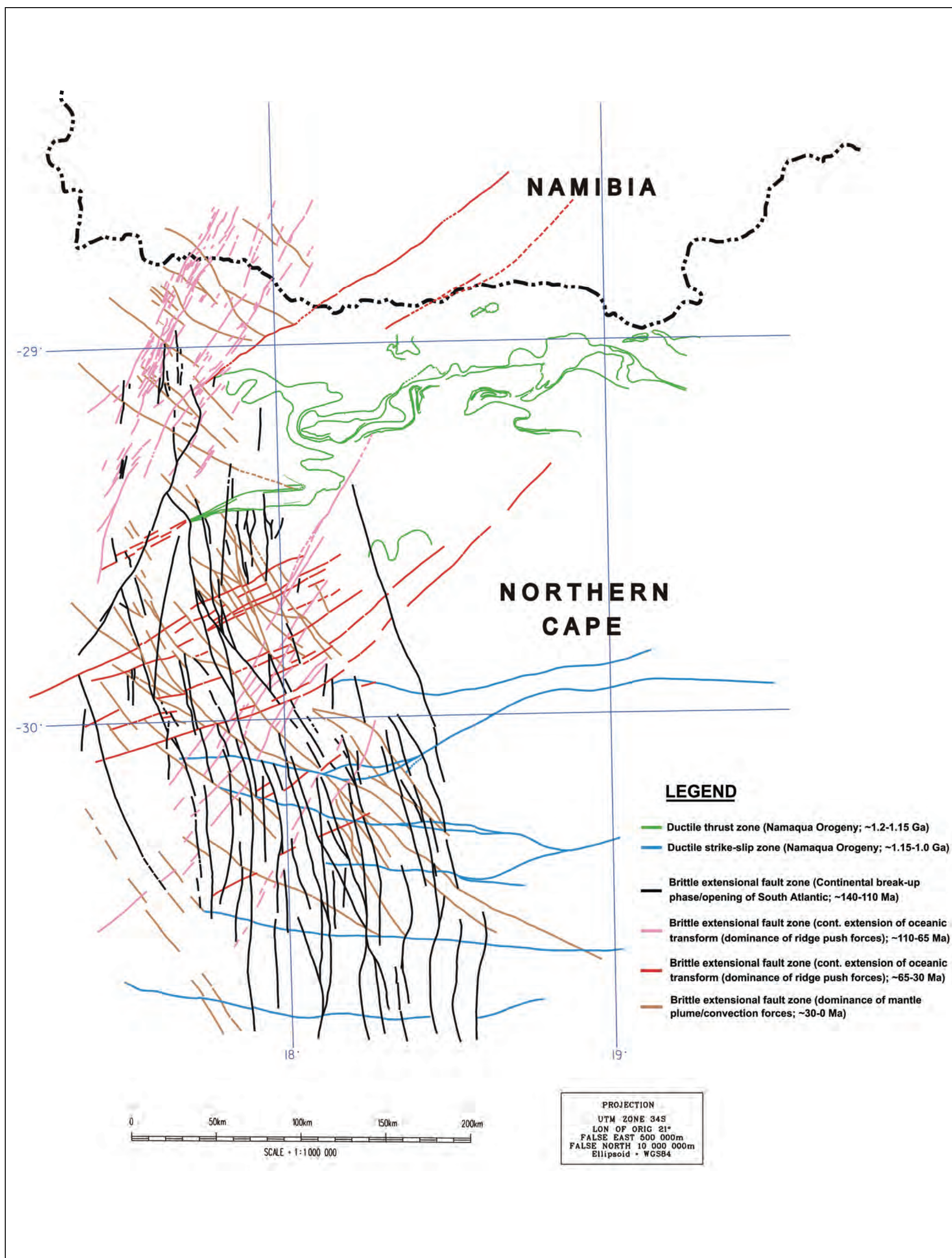


Figure 34: Regional structural interpretation of the study area.

7.3 SMT PROCEDURE AND RESULTS

Following below is the flow chart diagram for the SMT study outlining the different data processing steps (Figure 35), solid geology input map (Figure 36), and resultant contoured stress output map (Figure 37) generated. Figure 38 illustrates the regional contoured SMT output map (Figure 37) with sun-shading applied from the southwest, in order to highlight the general elongation direction of the mean low-stress anomalies, coinciding in general with known northwest-southeast striking fault/fracture zones. The SMT output maps are overlain by the structural input map and borehole yield data.

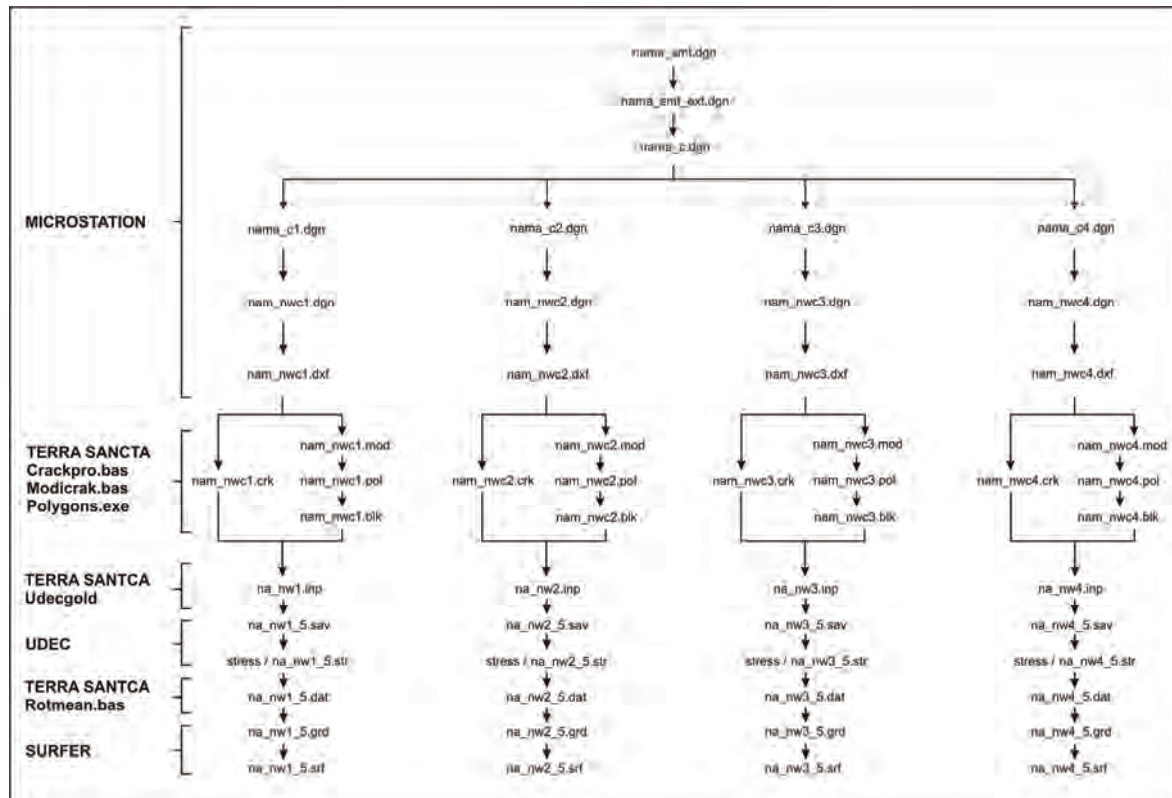


Figure 35: Flow Chart diagram for SMT study.

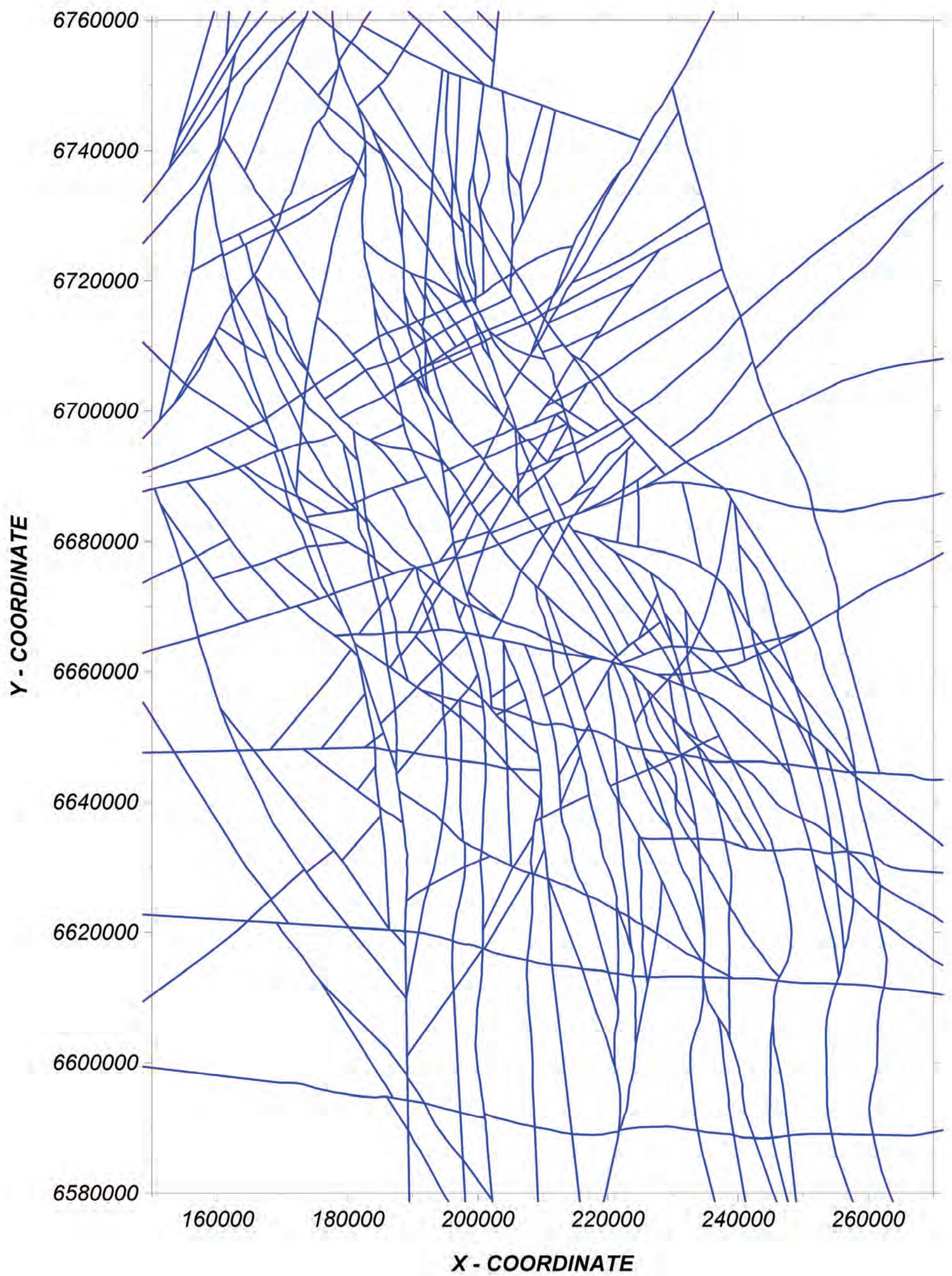


Figure 36: Solid geology input map for SMT.

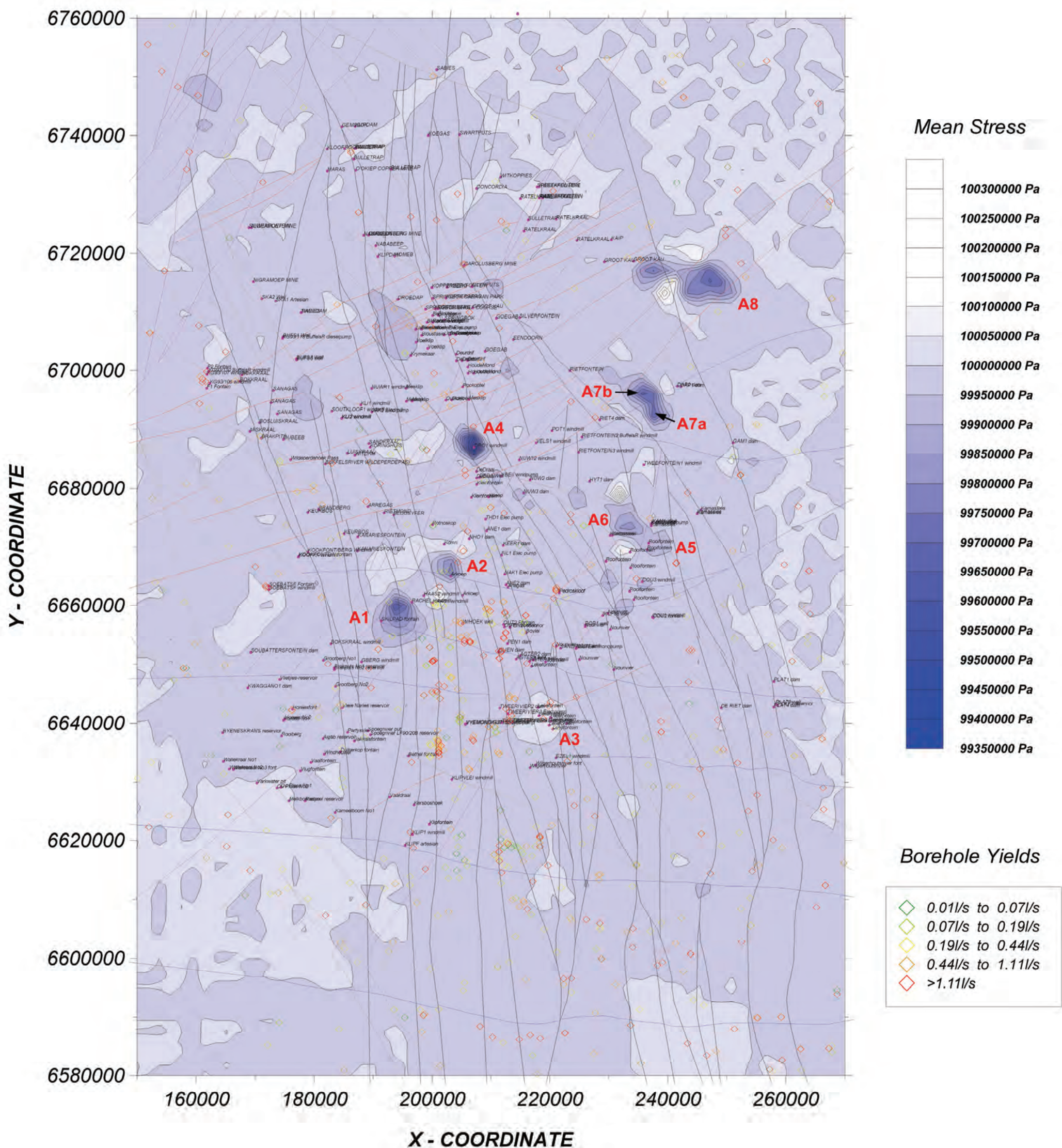


Figure 37: Regional SMT output map, showing mean high and low stress areas in relation to borehole yields and interpreted structures.

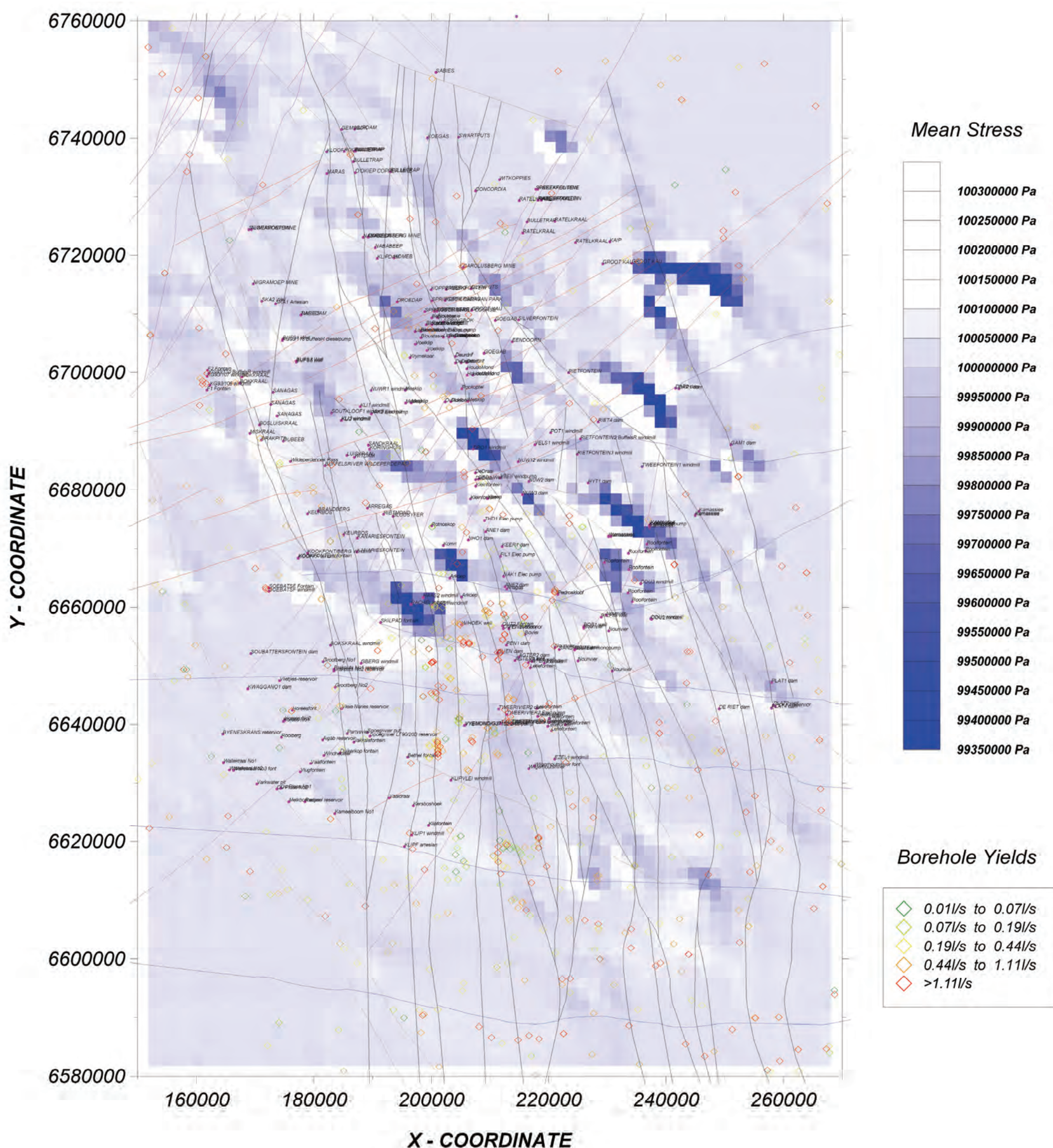


Figure 38: Regional SMT output map (shaded from the southwest), showing mean high- and low-stress areas in relation to borehole yields and interpreted structures. Note the elongation direction of the mean low-stress anomalies coinciding in general with known northwest-southeast striking fault/fracture zones.

8 DISCUSSION

Following the geomechanical modelling exercise and generation of a number of prominent SMT anomalies, a field trip was undertaken to verify these anomalies by investigating their geological (structural and lithological) and hydrogeological setting, as well as by studying the morphology, topographic and vegetation characterising these anomalous areas.

8.1 STRUCTURAL SETTING OF SMT ANOMALIES

Within the overall study area boreholes are without exception located near or on lineaments observable from aerial photographs, Landsat images or magnetic lineaments.

Typically the SMT anomalies like Skilpadfontein (A1 & A2), Rooifontein (A5) and DRO (A4) (Figure 37) are associated with high fracture frequency and fracture intersection density (Figures 39 - 41). The SMT method considers fracture aperture as the most important factor in controlling hydraulic conductivity in basement aquifers. As a result of the mode of propagation, fractures generated by and extension mechanism tend to have wider apertures than those created through a shear mechanism. By means of SMT and lineament analysis and knowledge of the tectonic evolution of the study area, the direction of extension fractures can be highlighted by low stress anomalies and thus recognised within the lineament cluster.

Results of the SMT analysis for the study area have revealed a strong correlation between known borehole positions and the proximity, as well as the alignment of these boreholes to two prominent fault/fracture zone systems. In addition to the well-known coastal-subparallel, NNW-SSE striking system of brittle fault/fracture zones, related to the Gondwana continental break-up phase and historically proven to be associated with productive boreholes, another important set of NNE-SSW striking fault/fracture zones has been identified by the SMT study. The latter set represents continental continuations of oceanic transform faults, which developed also during the Gondwana fragmentation/dispersal phase and formed penecontemporaneously with the NNW-SSE striking fault/fracture zones. They are oriented subparallel to the direction of present-day neotectonic crustal extension and undergo currently neotectonic reactivation/seismicity. Both fracture systems in general, and specifically at, or in close proximity to their intersection areas, represent the highest dilational zones within this Namaqualand coastal rift system and therefore the most prospective sites for well field development.

8.2 HYDROGEOLOGICAL SETTING OF SMT ANOMALIES

In general, the borehole yields from the study area are quite low, ranging from 0,01l/s to >1,11l/s, with a very few ranging above 1l/s. The boreholes were drilled both in crystalline basement, meta-sediments and metavolcanics. Borehole depths range from 20m to 200m, most fall within the 30m to 100m interval. The borehole yield data have traditionally been analysed relative to the lineament proximity, lithology, topographic setting and overburden characteristics, in order to determine the influence that these factors have on groundwater development potential. In the current study these factors are assessed along with geomechanical modelling assuming the influence of recent tectonic activity on groundwater storage and flow.

The congruence of major fault controlled structural basins (topographic depressions) and thick alluvial overburden is favourable for productive aquifers, as well as alluvial systems. The Skilpadfontein (A1), Leliefontein (A3), DRO (A4), Rooifontein (A5), Kamassies (A6), and Rietfontein (A7b) SMT anomalies fall within this category (Figures 37, 38 & 42-46).

The Skilpadfontein (A1) and Leliefontein (A3) anomalies represent geographically higher lying areas with preferentially higher recharge. These areas are characterised by adequate groundwater resources of higher quality developed with a shallow fractured aquifer system.

The Arkoep (A2) and DRO (A4) anomalies represent lower lying areas with lower recharge. These anomalous areas are characterised by poor groundwater quality due to longer residence times and relatively deeper flow paths within the weathered and fractured aquifer systems. The SMT study has indicated that the anomalous areas have adequate transmissivity due to high fracture permeability/frequency and relatively greater present-day crustal dilation.

The Rooifontein (A5) and Kamassies (A6) anomalous areas are located in close proximity to the Buffelsriver system. In these low recharge areas the groundwater is developed within the shallow alluvial system of the Orange River. During the dry season the deep water levels within the alluvium is sustained through influx of groundwater along both fault/fracture systems mentioned above that either cross-cut or run parallel to and thereby controlling the position of the Buffelsriver River valley.

The Rietfontein SMT anomaly (A7) is positioned at the intersection of a prominent ~E-W striking Namaqua age shear zone with NNW-trending brittle fault/fracture zones. The area is underlain by ~5 m of Tertiary-Recent organic-rich black soils overlying ~7 m of Cretaceous alluvial sediments (red and white sands, capped by a thin (~3-5 cm) layer of kieselgur and thin (~10-15 cm) calcrete layer) and crystalline

Namaquan basement. The area represents the lowest lying area in the region, where discharge of groundwater occurs. This periodically flooded area is characterised by the appearance of groundwater near/at surface responsible for lush vegetation and the formation of swamps (“Rietfontein Oasis”).

8.3 RELATIONSHIP BETWEEN LOW-STRESS DISTRIBUTION AND GROUNDWATER FLOW PATH

The preferential dilational trend indicated by the shaded gradient of the SMT map shows a strong directional trend along a NNW-SSE strike direction (Figure 38). This mirrors the trend of the major Gondwana rift faults. It is therefore concluded that the rift faults are the conduits of the regional circulating flow path of the groundwater in Namaqualand. Validation for this assumption is the inflow of better quality water along the north-south striking fault at the Dabeeb (A7a) and Rietfontein (A7b) anomalies. The older east-west striking Namaqua-age shear zones are ductile structural discontinuities, which are oriented approximately normal to the prevailing neotectonic *in-situ* stress field and hence represent in general relatively closed structural zones. These shear zones have theoretically not contributed to higher permeability/transmissivity in the crust with resultant limited groundwater development potential.

8.4 GROUNDWATER QUANTITY AND QUALITY ASSESSMENT IN RELATION TO SMT ANOMALIES

A correlation exists between the intensity of the low stress anomalies and specific localities within the regional Namaqualand fractured aquifer system that should be targeted for further groundwater development. The reliability of the correlation relies on adequate borehole information.

The groundwater quantity and quality of an anomalous area is dependent on the hydrogeological setting of the boreholes and the age and orientation of the fault structures which determines its crustal permeability/transmissivity in relation to the current *in-situ* stress field.

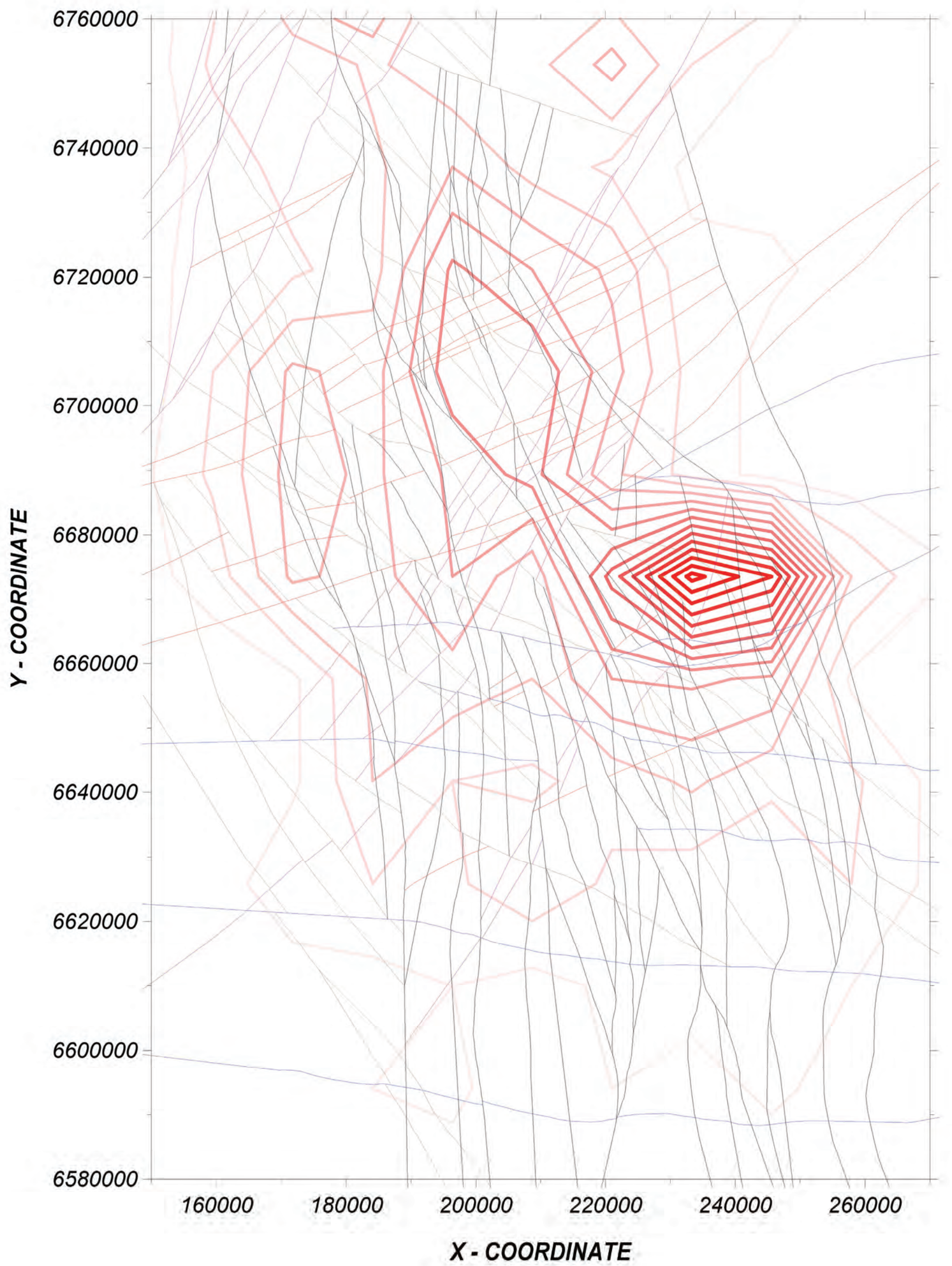


Figure 39: Fracture frequency map.

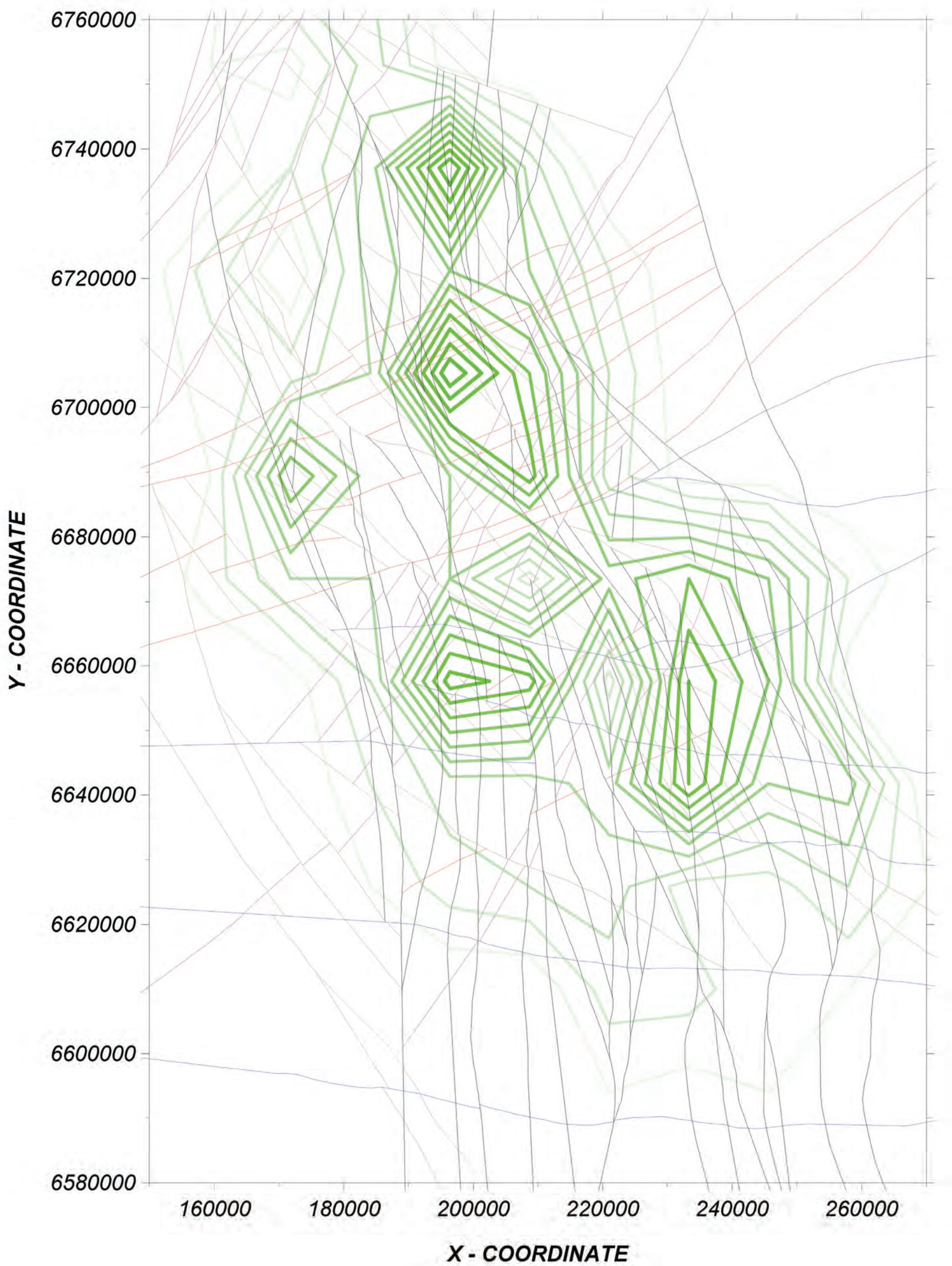


Figure 40: Fracture intersection density map.

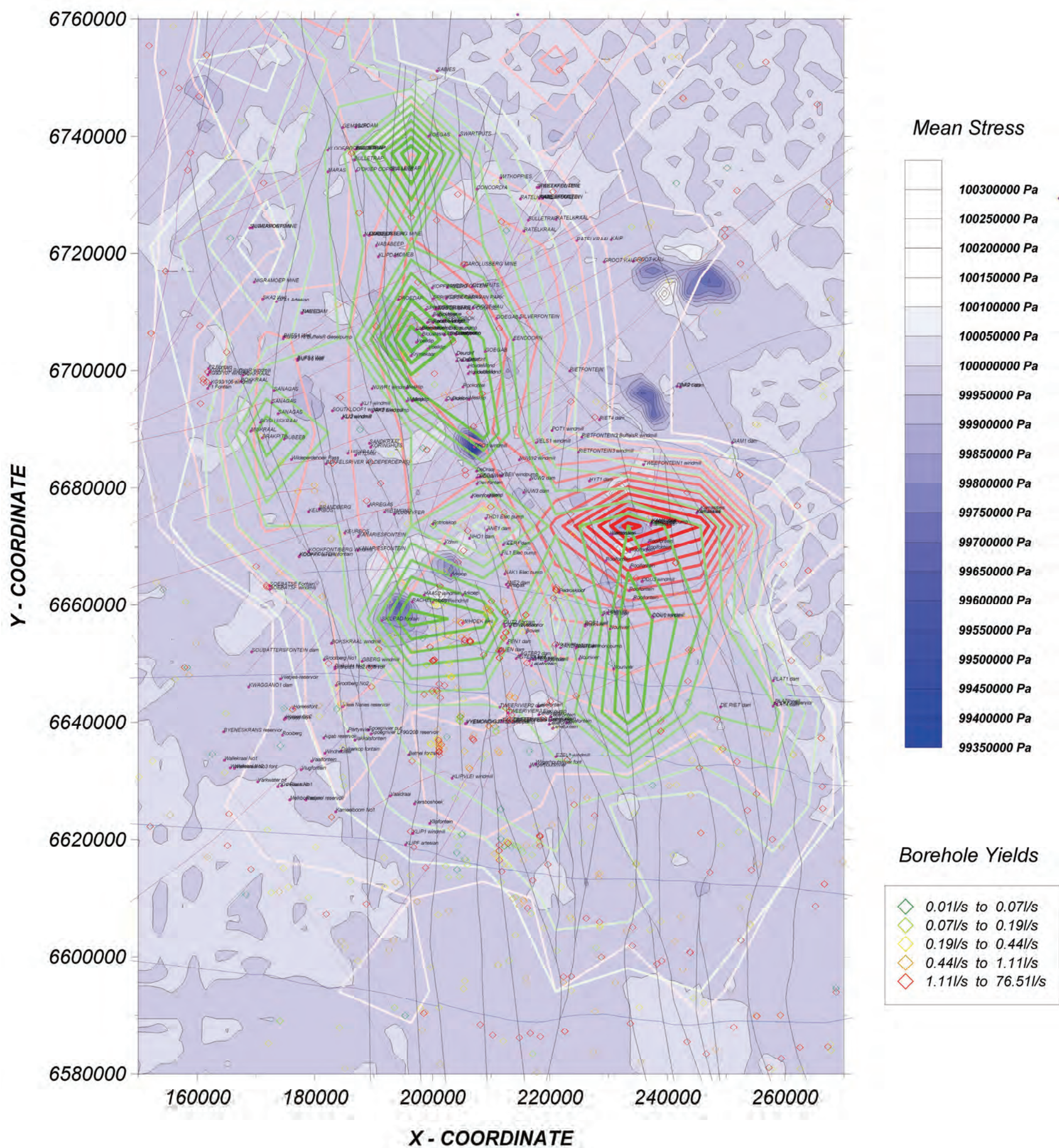


Figure 41: Comparative summary map showing fracture intersection density and fracture frequency, in relation to SMT generated mean high- and low-stress anomalies, borehole yields and interpreted structures.



Figure 42: Skilpadfontein (A1) and Skilpadfontein Spring (A2) SMT anomalies. (a) South-westwards view along the Voëlfontein se Kloof valley. Photograph is taken at the site of the Skilpadfontein (A1) SMT anomaly (cf. Fig. 37). The anomaly is situated topographically on top of a plateau forming the boundary between the catchment areas F30 (part of Buffelsriver Catchment) and F40 (Coastal Catchment area), and structurally within the intersection area of a NNW- and NE-trending fracture zone, the latter giving rise to the development of the Voëlfontein se Kloof valley. (b-e) Skilpadfontein Spring (A2) SMT anomaly, which is situated in the Voëlfontein se Kloof valley to the northeast of the Skilpadfontein (A1) SMT anomaly along the same NE-trending fracture zone, and where the latter is intersected by NNW-trending fracture zones. Numerous shallow boreholes (5-30 m in depth) and windmill pumps aligned along the fault-controlled valley have confirmed a fairly sustainable water table, characterised by yields of 1l/s, but a fairly high salinity (just under upper limit of 230 mS/m). (e) A system of NE- and NNW-trending, brittle fractures are developed as subsidiary structures adjacent to the major fracture zones in granitoid gneisses.

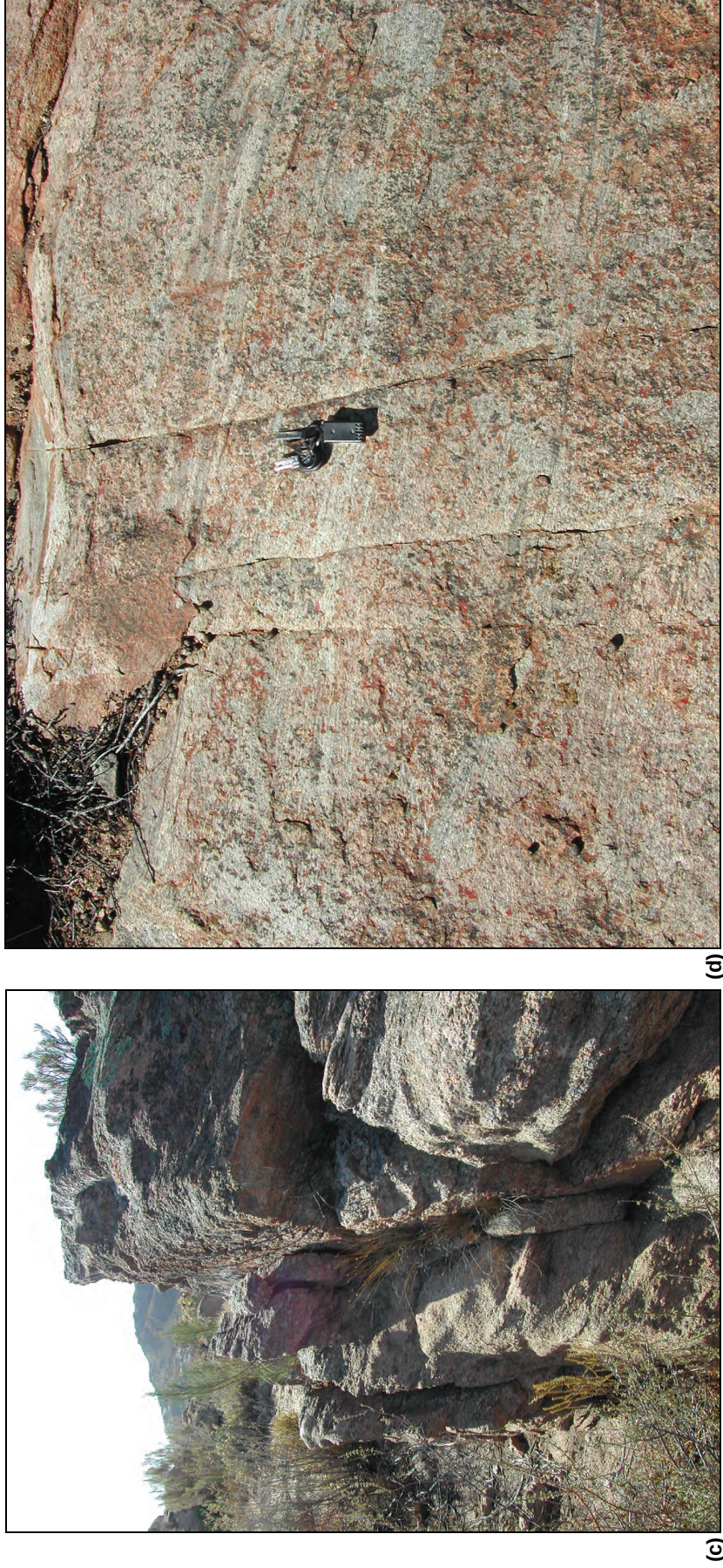
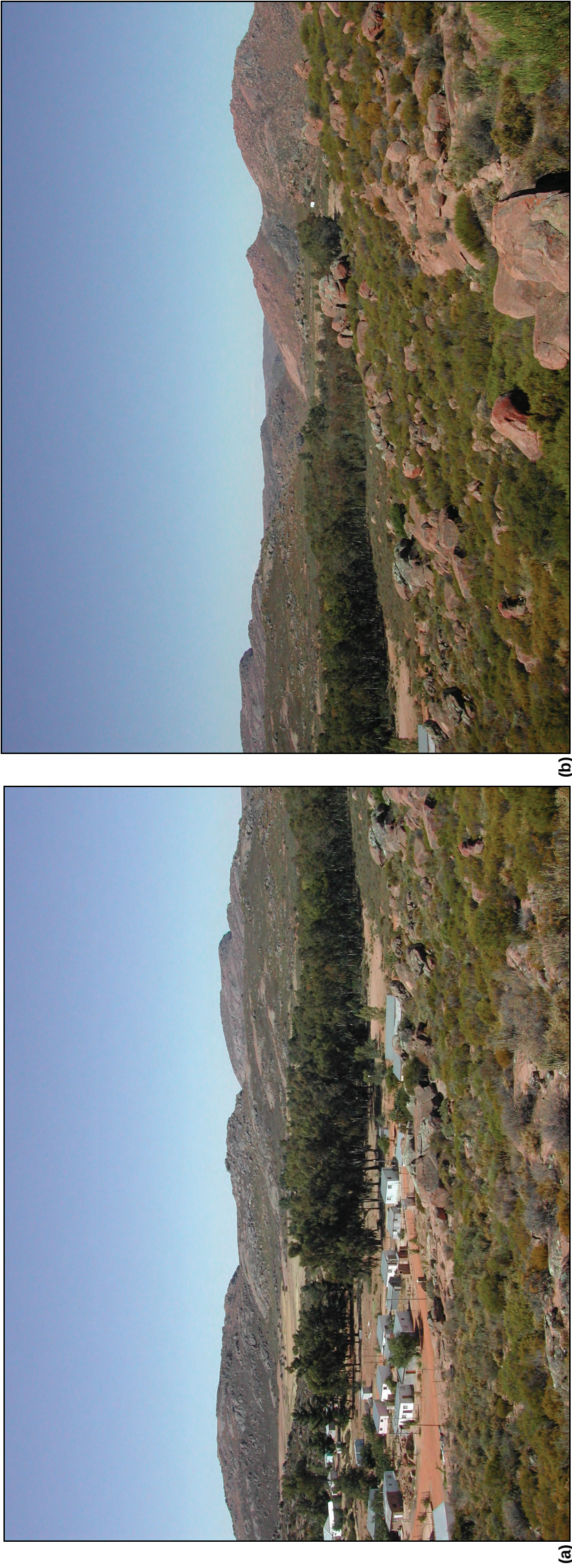
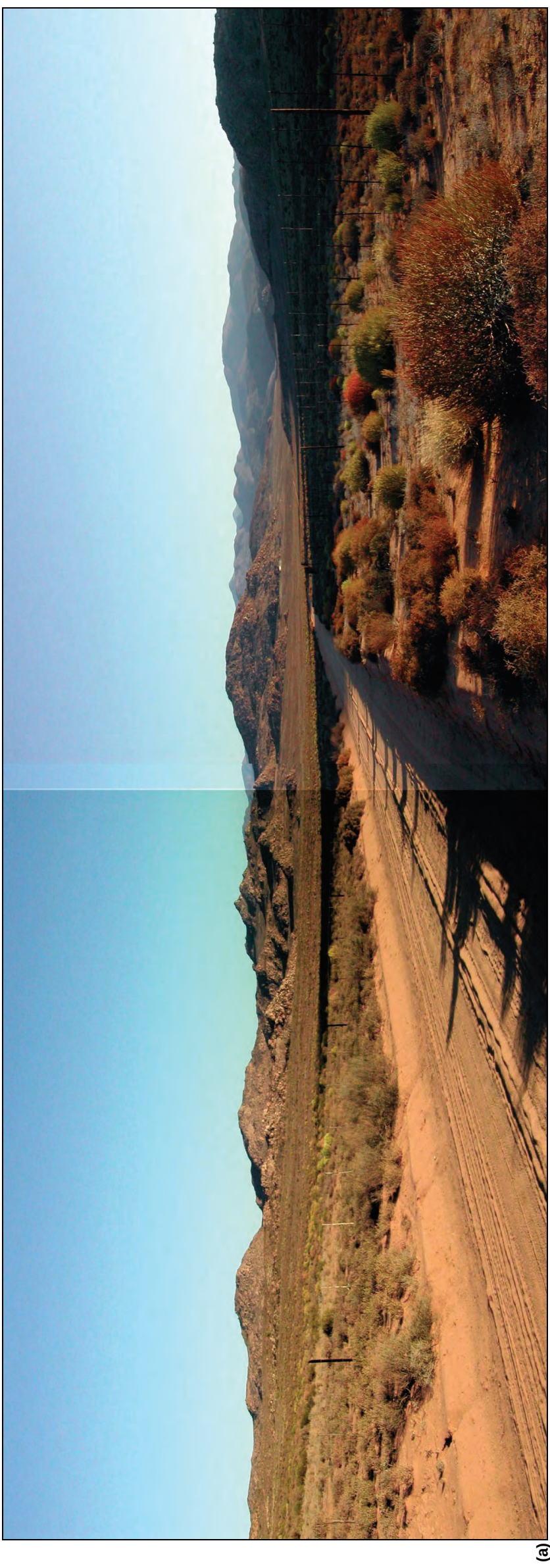


Figure 43: Leliefontein SMT anomaly (A3). (a & b) The anomaly is topographically characterised by a trough-like depression, with its centre situated approximately 500-700 m east of the village Leliefontein. The area is known for its anomalously high groundwater production, giving rise to lush vegetation within the depression. Within the area of the SMT anomaly several structural zones of different strike orientation intersect and are responsible for a high fracture frequency and fracture intersection density, i.e. ductile sheared and brittle reactivated E-W striking contacts between sheet-like granites of the Spectacle Suite (red-brownish) and darker paragneiss enclaves (b) representing large Namaqua-age S-verging thrust/strike-slip zones, and NE- and N-trending brittle fracture/fault zones (c & d), forming subsidiary and major valleys respectively.



(a)



(b)



(c)

Figure 44: DRO SMT anomaly (A4). (a) This prominent and circular shaped SMT anomaly coincides spatially and in shape with a circular depression/valley situated on a high plateau, and is situated structurally between two prominent NNW-trending brittle fracture/fault zones and crosscut by several NE-trending fracture/fault zones (cf. Figs. 37). (b & c) Two boreholes (one positioned near the centre of the circular valley) are providing sustainable groundwater resources to a farm in this depression.



Figure 45: Rooifontein anomaly SMT (A5). This anomaly is situated in the Buffelsriver valley in an area of high fracture frequency caused by intersecting NNW- and NE-trending fracture/fault zones. Numerous boreholes drilled to 80 m in average into bed rock are characterised by low yields, however a single shallow borehole (b), drilled to a depth of ~10m down to the interface between bed rock and overlying alluvium, is the sole major water supplier for domestic purposes of the Rooifontein settlement.



Figure 46: Rietfontein SMT anomaly (A7). This anomaly is positioned at the intersection of a prominent ~E-W striking Namaqua age shear zone with NNW-trending brittle fault/fracture zones. The area is underlain by ~5 m of Tertiary-Recent organic-rich black soils overlying ~7 m of Cretaceous alluvial sediments (red and white sands, capped by a thin (~3-5 cm) layer of kieselgur and thin (~10-15 cm) calcrete layer) and crystalline Namaquan basement. The area represents the lowest lying area in the region, where discharge of groundwater occurs. This periodically flooded area is characterised by the appearance of groundwater near/at surface vegetation and the formation of swamps ("Rietfontein Oasis"). Highly saline (300-350 mS/m) brackish groundwater is confined to the alluvium, whereas good quality water circulates along the NNW-trending fault/fracture zones within the crystalline basement down to depths of 60-70 metres.

9 CONCLUSIONS

Numerical modelling of rock-mass deformation is not an exact science and there will always be parameters of the rock-mass that are not understood. In other words, rock mechanic models are 'data-limited' and there is seldom enough data to simulate the rock-mass behaviour unambiguously (Starfield & Cundall, 1988). However, published results of numerous two-and three-dimensional SMT studies of structurally controlled gold and base-metal mineralisation indicate, that SMT is a quantitative and objective method of producing exploration targets from geological map data derived from interpretation of remote sensing and geophysical image data.

Lineament analysis has been applied in the past to relate structural features to the occurrence of groundwater resources in hard-rock environments. By including a detailed understanding of the tectonic history of a given area, particularly the most recent tectonic events, along with careful lineament tracing the procedure can provide predictive information for groundwater development.

The objective of the SMT project is to understand the mechanics and influence of brittle structures on the circulation and storage of groundwater in fractured rocks affected by neotectonic activity. It is concluded that the prevailing stress fields related to these recent tectonic events, which in the study area are Cenozoic and, to a great degree, Quaternary in age, have a definite control on the opening or closing of the old and young fracture systems. For both neo-formed and reactivated fractures, the dilation depends mostly on the orientation of the fracture surface in relation to the principal stresses of a given tectonic event, because this orientation controls the mode of propagation of the fracture (either extension or shear). Brittle deformation generates shear fractures that remain under compression and are not transmissive, and more permeable extension structures that tend to be associated with wide-aperture fractures. The recognition of these extension features would be valuable for groundwater development.

In areas where the SMT method is applicable, a main advantage over previous lineament-analysis procedures is that once the tectonic history of a given area is determined, it is possible to predict which structural features would likely yield the highest capacity boreholes. In this way, the siting of new boreholes can more effectively be facilitated, even in areas where no previous borehole information exists. The approach can be applied to other areas where a reasonable understanding of the most recent history of brittle tectonics exists. Through SMT and lineament analysis, therefore, the geohydrologist can correlate the lineament directions with the various kinds of brittle structures known to be related to extension stresses.

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