

RHODES UNIVERSITY

Grahamstown • 6140 • South Africa

**AN OVERVIEW OF ENERGY MINERALS IN THE
SPRINGBOK FLATSBASIN, SOUTH AFRICA:
IMPLICATIONS FOR GEOCHEMICAL AND
GEOPHYSICAL EXPLORATION**

By

LEBOGANG LEDWABA

A dissertation submitted in partial fulfillment of the requirements for the degree of

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MSc Exploration Geology Programme
Geology Department
Rhodes University
P.O. Box 94
Grahamstown 6140
South Africa

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DECLARATION

I, Lebogang John Ledwaba, declare this dissertation to be my own work. It is submitted in fulfillment of the Degree of Master of Science at the University of Rhodes. It has not been submitted before for any degree or examination in any other University or tertiary institution.

Signature of the candidate: í í Lebogang Ledwabaí í í í í í í í í í í í í .

Date: í 01 December 2014í í

Dedicated to my late father Lesetja Daniel Ledwaba and my mother Khomotso Martha Ledwaba, thanks for the support and for funding my fees throughout the years. I am thankful for the advice and knowledge you provided me because without the loving parents like you I wouldn't be where I am today.

ABSTRACT

This study is informed by the rising demand for power needs in South Africa and aims at understanding the geophysical and geochemical characteristics of the energy minerals in the Springbok Flats Basin and relating them to the prevailing geological and structural setting for improved exploration targeting. The Springbok Flats Basin is part of the Karoo sediments and host to uranium, coal and coal bed methane (CBM) resources. The lithology sections in the basin indicate presence of basaltic lavas at the top, underlain by mudrocks, siltstones, sandstones, conglomerates and diamictite, with interbedded coal beds occasionally. The coals are uraniferous and shale bounded and of lower Beaufort age at 250 Ma.

The regional radiometric data identifies the regional extent of the Springbok Flats Basin as a basin with low total count values. This information is useful in exploration as it gives an idea of the limits of the area where to focus application for prospecting licenses. The reduced to pole of the total magnetic field, residuals and first vertical derivative maps clearly show the high magnetic susceptibility nature of the surrounding Bushveld rocks as compared to the low Karoo sediment susceptibility within the basin. There are distinct ring shaped picks within the basin possibly due to known Karoo dolerite sills in particular to the central south western part of the grid.

The regional geochemical mapping program is a cost-effective way of providing an overview of the relative abundance levels, regional trends and anomalous patterns in the underlying lithological units. Background values of elements in soils over different lithological units and the identification of anomalous values relative to these elements can easily be identified. The geochemical results show an excellent correlation between soil chemistry and underlying geological formations.

A few distinct gravity highs are clearly shown within the basin. Assuming the effect of the Letaba basalt to the gravity readings is uniform across the basin; these distinct anomalies could be due to Karoo dolerite sills as they coincide with areas of distinct high magnetic signature. A conceptual model was generated assuming that the Karoo sediments layering is uniform across the gravity profile but changes in the residual are due to an increased thickness of the sill supported by the gentle changes on the surface topography.

Satellite imagery has got its challenges especially in areas of vegetation but it does provide a very useful tool in exploration. A number of spectral analysis techniques and band ratios can be used to differentiate the areas underlain by the Letaba basalts, the Karoo sandstones/shale and Bushveld granites for mapping purposes. The priority focus will be on the shallower Karoo sediments because of the potential for cheaper mining.

Exploration targeting needs to be guided by observed geochemical and geophysical characteristics in order to prioritize areas taking into account the presence of Karoo intrusives such as the dolerite sills that tend to devolatilize the coal hence affecting the quality/rank. Structures and gravity signatures are very important in delineating areas with thick sediments that have a potential for CBM. The same understanding in targeting goes a long way in planning drill holes, resource modelling and pre-feasibility stages for mine planning.

A high resolution airborne geophysical survey is recommended over the basin to better resolve structures. Geophysical borehole logging is recommended to be part of the exploration drilling programs in the Springbok Flats Basin in order to define the in-situ geophysical characteristics. Geophysical logging is useful in particular for the uranium reserves that cannot be delineated from the surface due to deep intersection.

Keywords: *Coal, Uranium, Coal Bed Methane (CBM), Springbok Flats Basin, Karoo Basin, South Africa*

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

The major coal-bearing strata in Southern Africa occur in the Karoo sequence or its equivalent aged rocks. The Karoo Basin of Southern Africa is unique in Africa because it is the only basin which records a complete late carboniferous to Jurassic rock record and a change in paleo-climate from glacial to dry desert (Yao, 2013). The geophysics business unit has extended its services into analysing the mineral resource wealth using geophysical exploration in the Springbok flats basin which forms part of the Karoo Sequence. The work envisaged in this phase will involve application of geophysical techniques such as remote sensing, gravity and aeromagnetic surveys. The employment of geophysical services will relate specifically to unlocking the potential of coal, uraniumiferous coal and exploration of coal bed methane (CBM) in the Springbok Flats basin. Several studies have been concluded about the existence of mineral wealth in this basin, most notably coal reserves. The basin has been extensively drilled by the Council for Geoscience during the last century, for mineral exploration and groundwater purposes.

Remote sensing technique was used in this study in order to try analysing and interpreting the geological features without problems and challenges associated with field work. Images of Landsat 7 system collected in 2000 were used as part of the desktop study. Gravity data for the study area were collected by the Council for Geoscience. Even though the coverage is regional in nature, it still provides useful information with regards to the distribution of lithological units. Measurements were carried out with La Coste and Romberg gravimeters and elevations were determined using micro-barometers. Bouguer anomaly values were calculated assuming a mean density of 2670 kg/m^3 . The measurements were tied to the International Gravity Standardisation Net values and were referred to the gravity formula based on the 1980 geodetic reference system. The maximum error in the Bouguer anomaly value was estimated to be within 1 mgal.

The national airborne magnetic and radiometric survey for South Africa was conducted by the Council for Geoscience (CGS) between the years 1958 and 1997. The survey was flown in two primary sections of the Karoo survey, done between 1976 and 1982 and covering

almost half of the country; and the rest, which was surveyed by various contractors over a period of more than 30 years, starting in 1958 and ending in 1997. The magnetic data are complete while some of the radiometric data are missing. Our study area is covered by blocks 7/69, 10/71, 11/71, 12/71 and 15/73. Blocks 10/71, 11/71 and 12/71 are the blocks missing from the database (Figure 1). Since there is data missing for Th, U and K channels interpretation will be done on available data sets.

The amount of information that may be derived from airborne magnetic data is related to the line spacing and altitude of the measurements and the depth to source. Regional surveys flown with wide line spacing and at relatively high altitude will only provide information about large geological features. The magnetic data will be modelled to indicate the shape of lithological features in three-dimensions. Since gamma rays only penetrate rocks and soils to about 50 cm, this type of survey will only give information about the very shallow geology, lithologies and soils.

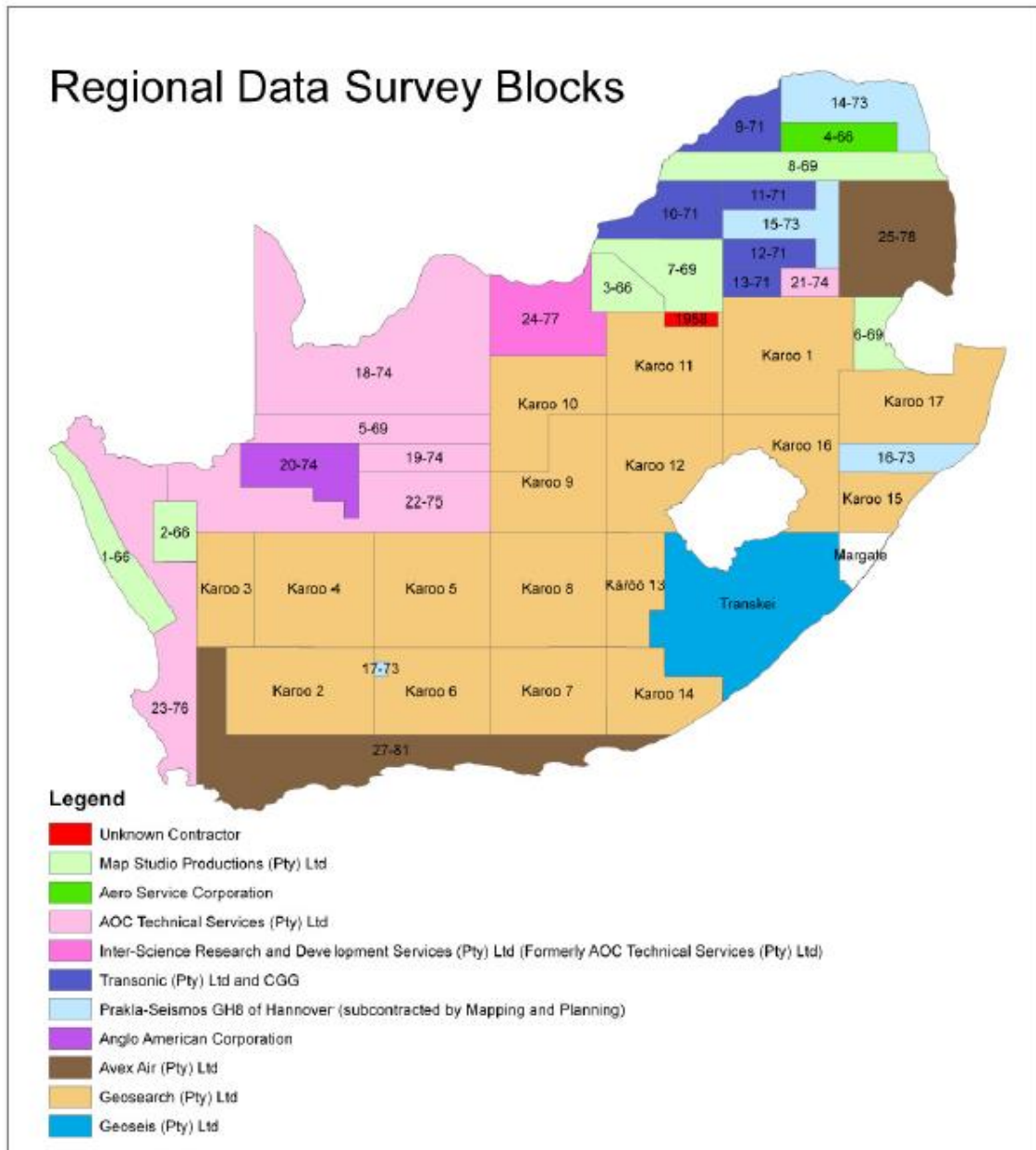


Figure 1: Aeromagnetic survey blocks with the various areas flown by different contractors shown in different colours (from Council for geoscience, 2014).

1.2. AIMS OF THE STUDY

This study aims at describing the geophysical characteristics of the energy minerals in the Springbok Flats Basin and relating them to the prevailing geological and structural setting for improved exploration targeting. The aim is to assist in the understanding of the occurrence of energy minerals occurring in the basin and preparedness for future exploitation.

1.3. LOCATION OF THE STUDY AREA

The Springbok Flats coalfield (Figure 2) occupies an area of approximately 160 km striking north-east to south-west and is 30 km wide. It is located within 28•00´ and 29•30´ east and 24•15´ and 25•30´ south. It constitutes an extensive tract of generally flat country extending from south of Bela-Bela north-eastwards to Zebediela Location. The topography of the Springbok flats is generally flat country and it is characterised by the absence over vast areas of trees and the scarcity of rock outcrops (Nel, 2012).

The Springbok Flats forms part of the Bushveld Basin and Physiographically it can be subdivided into four distinct areas, namely the Northern Springbok Flats, the Southern Springbok Flats, the Sand Bults and the Valley of the Nyl River (Wagner, 1927). The Northern and Southern Springbok Flats are separated by the Sand Bults and are characterized by their level nature, the absence over vast areas of trees and scrub, the paucity of rock outcrops, the almost entire lack of well-defined water courses and the peculiar black and red soils (Wagner, 1927).

The Northern Springbok Flats is bounded by the Zebediela Fault in the west-northwest. This fault is pre-Karoo in age and possibly still active, based on earthquake activity occasionally noticed in the area and in Modimole. The Elands River and the Pienaars River border the Southern Springbok Flats in the east and south respectively, resulting in topographical slopes towards these drainage systems. The Sand Bults occur as an elevated area along the strike of an anticlinal flexure that separates the Northern and Southern Springbok Flats (Nel, 2012). The Valley of the Nyl River is the most striking topographical feature of the Springbok Flats. The convergence of the Great Nyl and its main tributary the Little Nyl River occurs between Bela-Bela and Modimole (Nel, 2012).

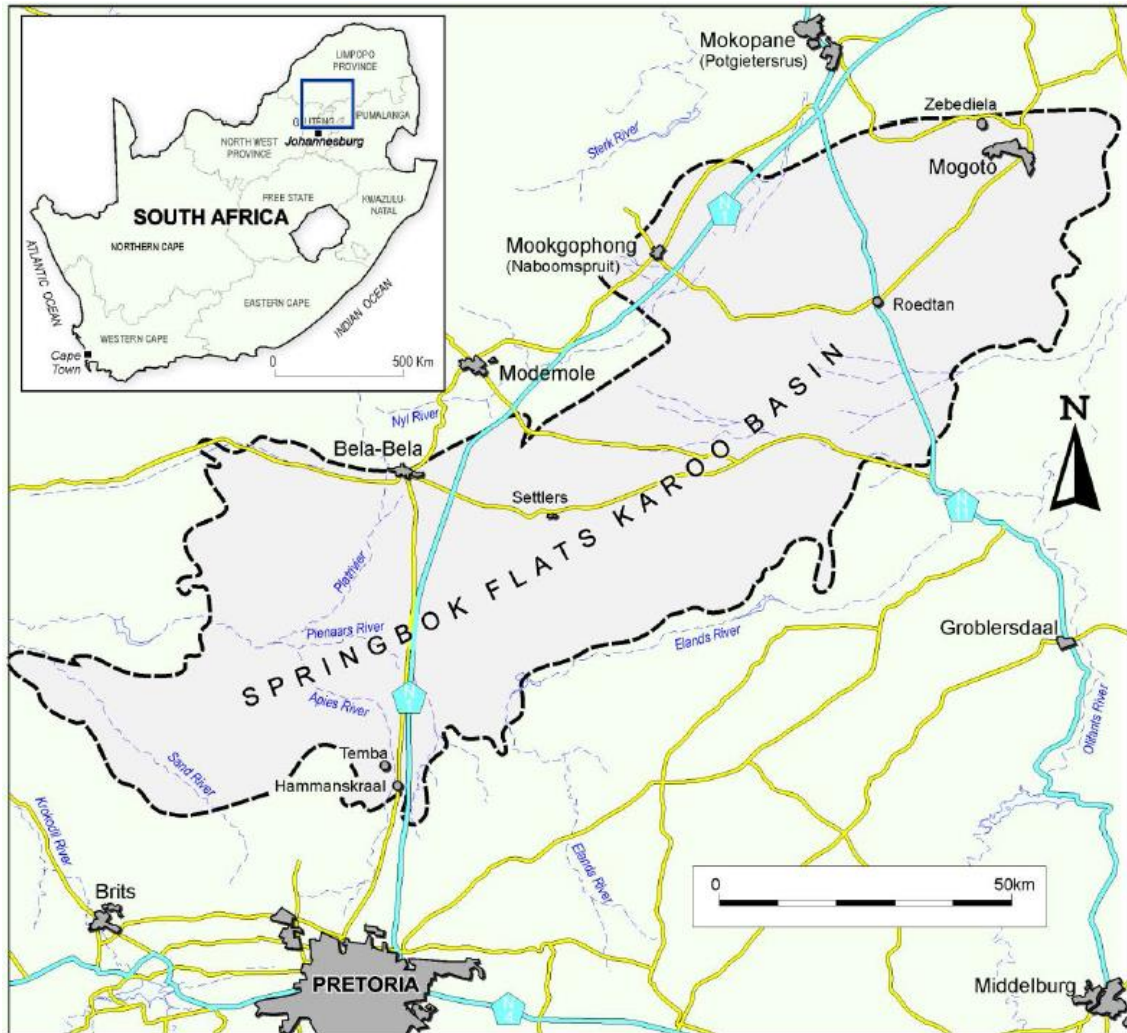


Figure 2: Locality map of the Springbok Flats Basin with respect to the major towns and national roads (modified from Nel, 2012).

1.4. ENERGY MINERAL POTENTIAL AND OCCURRENCE IN THE SPRINGBOK FLATS BASIN

The basin is a host to a number of energy mineral deposits that include uranium, coal and coal bed methane (CBM). The coal-bearing sequence is assigned to the Turfpan and Warmbad Formations (Roberts, 1992). The Turfpan Formation is comprised of high-ash coal (>30%) and is not of major economic significance. The overlying Warmbad Formation is the main target of economic interest and is up to 12 m thick. The Warmbad formation is correlated with the Volkrust Formation (Snyman, 1998). The sequence consists of interlaminated thin coal seams and mudstone.

The coals in the Springbok Flats are known to be highly uraniumiferous, containing 16061000 ppm uranium (Snyman, 1998). CBM is a fossil energy associated with nearly all coal beds where it results from the coal formation process as a by product. Adsorption of the methane gas occurs within the structure of the coal and is kept there by overburden and hydraulic pressure. Extraction of CBM is through pumping water out of the coal bed and thereby reducing the pressure and allowing the gas to escape to the surface. Ideally for CBM to form a considerable resource it would require thick sediments and the coal seams to be at depth.

1.5. MINING IN THE SPRINGBOK FLATS BASIN

The basin is of economic interest as it comprises appreciable coal and uranium deposits. There are some deposits of other mineable commodities within this basin. Several mines have operated since the 1900s and some new mines are still operational. Dimension stone: AG5 granite near Hammanskraal. About 8km south of Hammanskraal Police station, between the railway and the national road, rather primitive quarrying took place on the Bushveld red granite.

Molybdenum has been found in the Warmbaths tin field, fairly plentiful in patchy aggregates in pegmatites, particularly on Zwartkloof 470 KR and Witfontein 526 QC. The Rooiberg tin field covers some 180 km² about 60 km west of Warmbaths. It was first worked in prehistoric times; modern workings can be dated back from the first decade of this century and the field has been in continuous operation ever since.

Fluorite is mined at the Zwartkop Fluorspar mine, west of Warmbaths. Mining is carried out in open quarries the ore being transferred via an open pass to an underground haulage which runs through the base and length of the felsite ridge. But the mine has since been closed. Other fluorspar deposits have been mined around the basin, the Vischgat mine south of Naboomspruit and some small mines around Ruigtepoort and the Rooiberg area.

The presence of coal in the Springbok flats coal basin has been known from water boreholes since the beginning of the century. De Jager (1976) divided the coal field into a north-eastern portion with a slightly higher rank and southeastern portion with a lower rank. According to De Jager (1976) the coal has severely been devolatilized by the dolerite sill over about 30% of the total area of the coal field. A persistent coal seam with low-grade coal occurs within

the Turfpan formation. This coal has an ash content of between 30 and 83%, and can be excluded from resource estimations.

The major coal zone occurs in the Warmbad formation, which is correlated with the Volksrust formation (Snyman, 1998). The uranium mineralization is known to be associated with the occurrence of coal within the Warmbad Formation containing 16061000 ppm uranium (Snyman, 1998). The vast potential uranium resources have not been mined and it is proposed that it could be mined with the coal and be separated during the washing of the coal (Barker, 2012).

A diamondiferous kimberlite fissure and pipe system was discovered by De Beers on the farm Palmietgat 34 JR, approximately 15 km south southeast of Bela Bela. The dyke and pipe system is approximately 4 km long and includes six small pipes totalling about 4.8 ha (Nel, 2012). Three of these pipes were exploited by North American Mining Corporation (Pty) Ltd during 2005. An average of 16 cpht was recovered (Nel, 2012).

One of the most prominent gypsum deposits discovered so far is situated on the farms Klippan 555 KS and Uitzichtspunt 553 KS. The gypsum resources are estimated to be in the order of 500 000 t at an average grade of 20% gypsum. A similar sized deposit is known on the farm Klavervalley 616 KS (Nel, 2012). Dolomitic limestone deposits are situated near both the Immerpan and Zebediela railway stations. The actual resources of these deposits are unknown.

CHAPTER 2: GEO-TECTONIC SETTING

2.1. THE MAIN KAROO BASIN

The Karoo Basin of South Africa is unique in Africa because it is the only basin which records the complete late Carboniferous to Jurassic rock record and a change from glacial through temperature climatic to arid desert (Clarke et al., 2007). The Main Karoo Basin (Figure 3) is reported as approximately underlying 60% of the land surface of South Africa and as the largest sedimentary basin in South Africa. According to Viljoen et al. (2010) the basin covers approximately 700 000 sq. km and ranges in age from Late Carboniferous to Early Jurassic. The basin attains a total cumulative thickness of approximately 12 km in the south part and ranges in age from Late Carboniferous to Early Jurassic (Viljoen et al., 2010).

The Main Karoo Basin is largely underlain by a stable floor, comprising the Kaapvaal Craton in the north and the Namaqua-Natal Metamorphic Belt in the south, and is bound along its southern margin by a fold-thrust Cape Fold Belt (Nel, 2012). The main basin constitutes a retro-arc foreland basin (Dickinson, 1974) with maximum down warping along a linear belt (the Karoo Trough) situated along the southern edge of the basin, gradually shifting northward as the basin developed from the Late Carboniferous onwards by gradual subsidence of essentially cratonic crust (Figure 4). The Cape Fold Belt formed while sedimentation of at least the upper Karoo units was still in progress. This orogeny resulted in intense deformation of the Cape Supergroup and underlying basement, as well as the lower units of the Karoo Supergroup, along the southern basin edge.

The major lithostratigraphic units of the Karoo Supergroup crop out concentrically around the main basin (Figure 3). Lateral facies changes, particularly in the lower half of the succession, have given rise to intertonguing of formations in various parts of the basin. The Karoo basalt and dolerite intrusions constitute a major part of the stratigraphic section within the Karoo Basin.

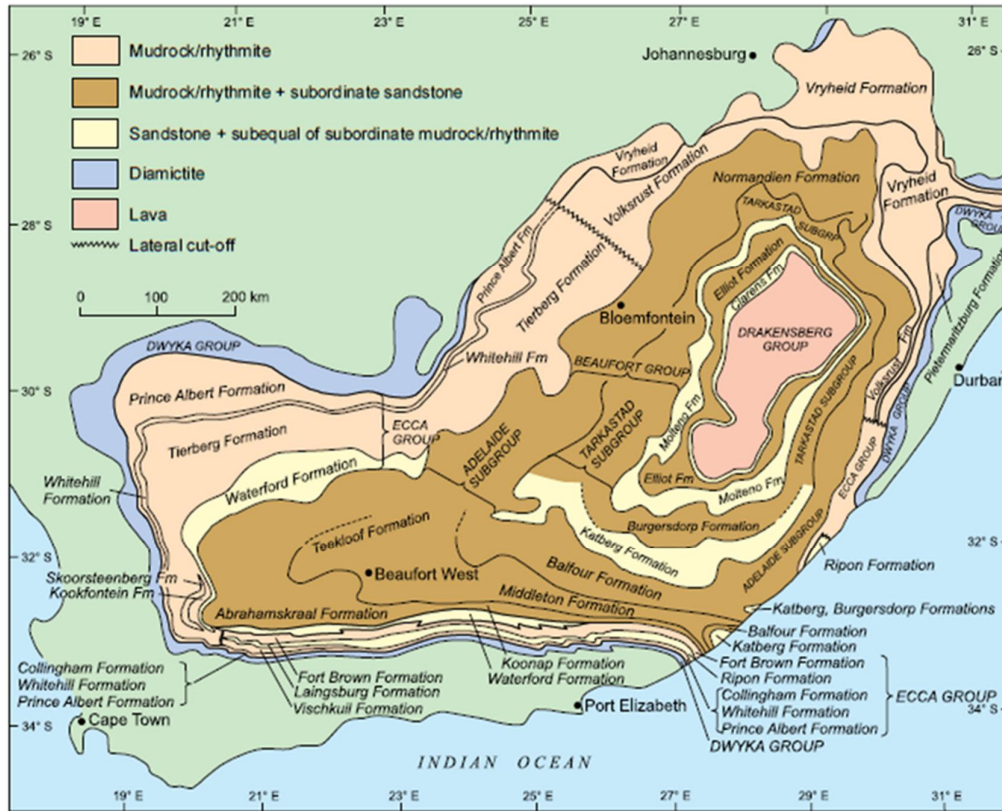


Figure 3: Geology map of the Main Karoo Basins showing the stratigraphy and the location of the Springbok Flats Basin (Viljoen et al., 2010).

2.2. TECTONIC SETTING

The start of sedimentation of the Karoo Supergroup sequence across the Gondwana Supercontinent occurs in the Late Carboniferous at around 300Ma (Nel, 2012), following a major tectonic event along the southern boundary of the Supercontinent (Figure 5). Karoo sedimentation continued across Gondwana until the break-up of the Supercontinent in the mid Jurassic. Climate and tectonism impacted on the accumulation of sediments in the Karoo basins (Nel, 2012). Tectonic regimes during the Karoo time varied from dominant flexural tectonic in the south to extensional along the northern margin of Gondwana, respectively (Figure 5). The flexural tectonics experienced along the southern boundary resulted from subduction, accretion and mountain building along the Palaeo-Pacific margin of Gondwana. The extensional processes along the northern margin of Gondwana were caused by spreading tectonic regimes along the Tethyan margin of Gondwana (Catuneanu et al., 2005).

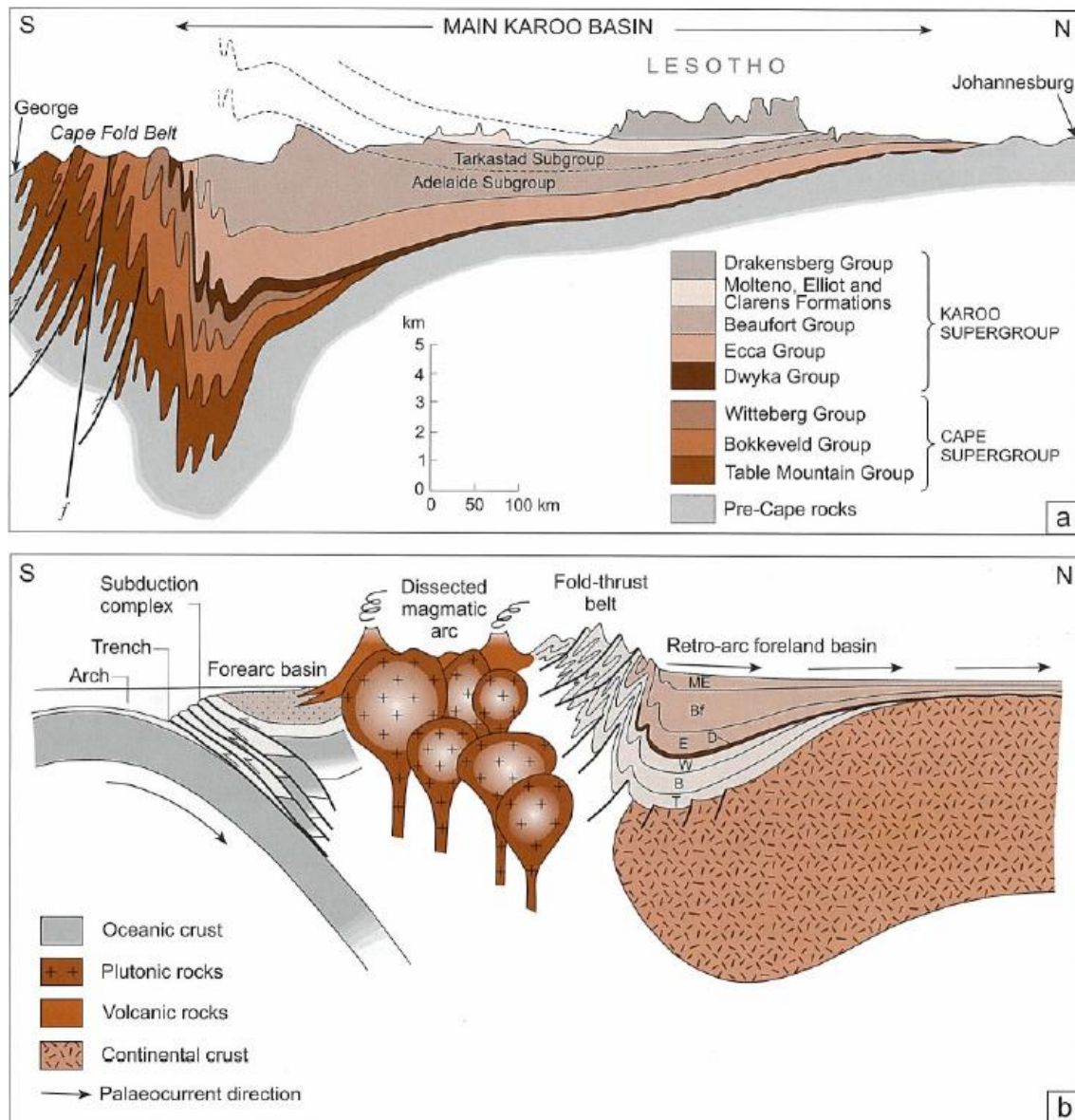


Figure 4: Schematic north-south section (a) across the Main Karoo Basin with envisaged plate tectonic setting of the basin during Late Triassic (b). (After Johnson et al., 2006).

Climate fluctuations also impacted on sedimentation indicating a shift from cold and semi-arid conditions during the Late Carboniferous to early Permian period, to warmer and eventually hot climates with fluctuating precipitation during the rest of Karoo times (Nel, 2012). It is not known to what extent the basins were physically connected prior to post Karoo erosion, thus the isolation of some of the present basins could be due to erosion that occurred in response to post Karoo crustal movements (Bordy, 2000).

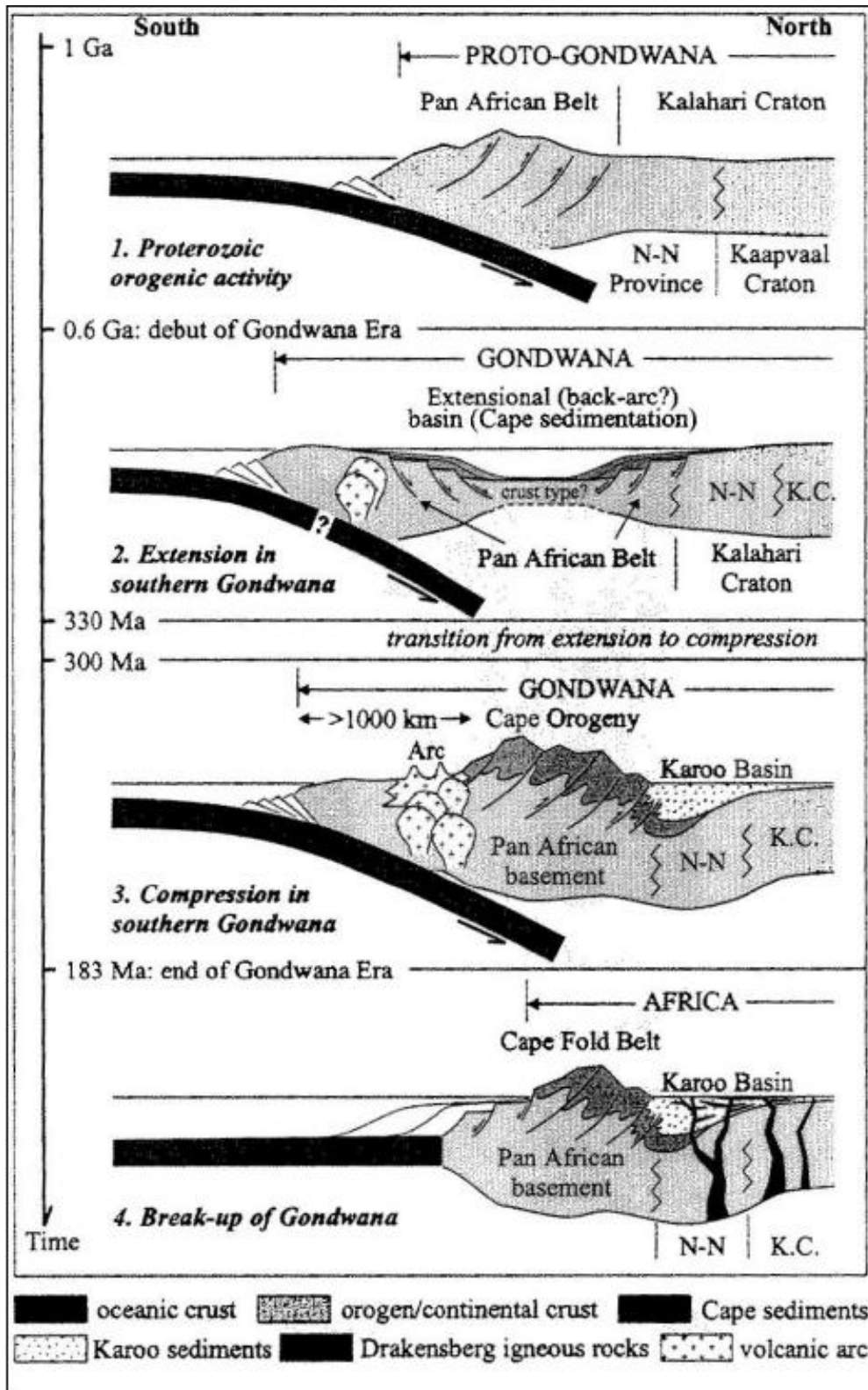


Figure 5: Crustal evolution of southern Africa. N-N = Namaqua-Natal; K.-C. = Kaapvaal Craton (Catuneanu *et al.*, 1998).

Despite different tectonic settings, the overall climatic overprinting in similar vertical lithological profiles is as follows:

- Karoo successions begin with diamictites and other glaciogenic rock types;
- Overlain by carbonaceous, coal bearing strata;
- Succeeded by both red and greenish strata (reflects a change from generally reducing to generally oxidizing conditions as a results of increasingly subaerial deposition);
- Capped by the aeolian sandstones (uppermost part) indicating arid climate;
- Sedimentation was terminated by intensive igneous activity (basalts and/or intrusive rocks).

2.3. REGIONAL STRATIGRAPHY

The lithostratigraphic units of the Karoo Supergroup depositional sequence is divided into several groups. In the main Karoo Basin of South Africa, the Karoo Supergroup consists of five groups namely: Dwyka, Ecca, Beaufort, Stormberg and Drakensberg (Figure 7). No major regional unconformities are known to exist in the basin, with possible exception of one at the base of the Molteno Formation.

Temperature reductions during the Mid-Carboniferous were the cause of a universal drop in sea level and the development of a widespread ice cover over the southern mountains that bordered with the palaeo-Pacific periphery. Together with this geological environment, a huge oceanic ice sheet covered the parts of the Basin that were within the polar circle (Johnson et al., 2006). The Dwyka Group was the first to be deposited and it happened mainly from a grounded ice sheet. With the commencement of somewhat warmer temperatures, some debris loosened from the ice gathered from a drifting ice shelf. Further rises in temperature resulted in the total disintegration of the ice sheet in the beginning of the Permian with glacial deposition limited to the valleys edging on the cratonic uplands.

With the disintegration of the ice sheet a major rise in sea level occurred regionally, which created the Ecca Group. The clay material of the Prince Albert and White-hill Formations was carried into the Basin. In the subduction zone to the south of the basin a volcanically active magmatic arc disrupted the deposition in the basin with ash layers. The consequent abrupt influx of coarser material from the magmatic arc led to the accumulation of sandy and silty submarine fans and basin plain turbidites of the Ripon, Laingsburg, Vischkuil and

Skoorsteenberg Formations (Figure 6, Johnson et al., 2006). The result of this was suspension settling of prodelta mud as the slope of this delta moved across the turbidite fans (Figure 6). The Tierberg Formation formed as a result of the deposition of mud in shallow water to the north of the Karoo trench. Following this, the rest of the Formations of the Ecca group were deposited. Details on the deposition can be found in Johnson et al. (2006).

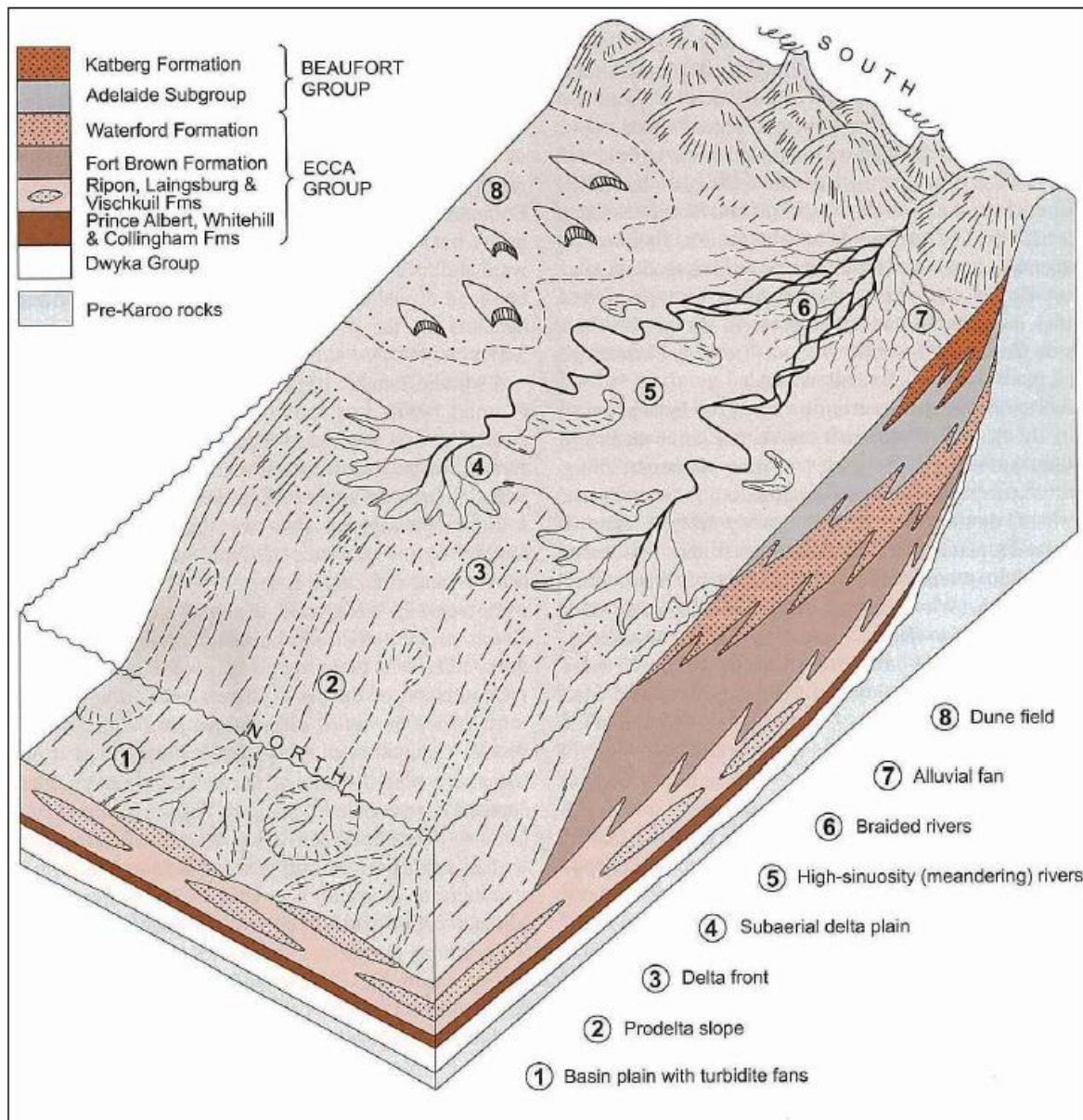


Figure 6: Depositional environments of the Karoo Supergroup (Johnson et al., 2006).

The Adelaide Subgroup of the Beaufort Group was deposited subaerially as upper delta-plain and fluvial mud and sand in the Late Permian (Figure 6). Due to the weathering of the

sediments origin, there was a source-ward change and the mixed load stream sediments were replaced by flood-basin and lake sediments in the western part of the Karoo basin. In the northeast of the basin, the Normandien Formation was deposited in a delta environment. The Katberg and Burgersdorp Formations were deposited during the beginning of the Triassic, followed by the Molteno Formation (Late Triassic), Elliot Formation (Late Triassic), Clarens Formation (Late Triassic ó Early Jurassic) and Drakensberg Group (Middle Jurassic). The Karoo Dolerites then intruded the Karoo Supergroup at 180-150 Ma ago (Johnson et al., 2006).

The Dwyka Group (Figure 7) is the lowermost stratigraphic unit of the Karoo Supergroup. The group is emplaced glaciated Precambrian bedrock surfaces to the north and unconformably overlies the Cape Supergroup to the south (Johnson et al., 2006). The lithology consists mainly of massive to stratified diamictite, conglomerate, sandstones, mudrock with stone facies and mudrock facies (Van Vuuren et al., 1998). The Ecca Group overlies the Dwyka Group and it is divided into three formations namely the Pietermaritzburg Formation, the Vryheid Formation and the Volksrust Formation. The Pietermaritzburg Formation is the lowermost unit of the Karoo Supergroup in the eastern part of the basin and generally overlies the Dwyka Group with a sharp contact. It comprises dark silty mudrock, which coarsen upwards, with heavily deformed sandy and silty beds appearing near the top (Johnson et al., 2006).

Johnson et al. (2006) described the contact between the Pietermaritzburg and Vryheid Formation as a strongly diachronous with sandstones successively higher up in the succession shaling out towards the south. The Vryheid Formation is a sequence of sandstone, shales, minor conglomerates and economically exploitable coal seams. The Vryheid Formation can be subdivided into a lower fluvial dominated deltaic interval, a middle fluvial interval and an upper fluvial dominated deltaic interval. These subdivisions correspond approximately to the lower sandstones, coal zones and upper sandstones (Johnson et.al, 2006).

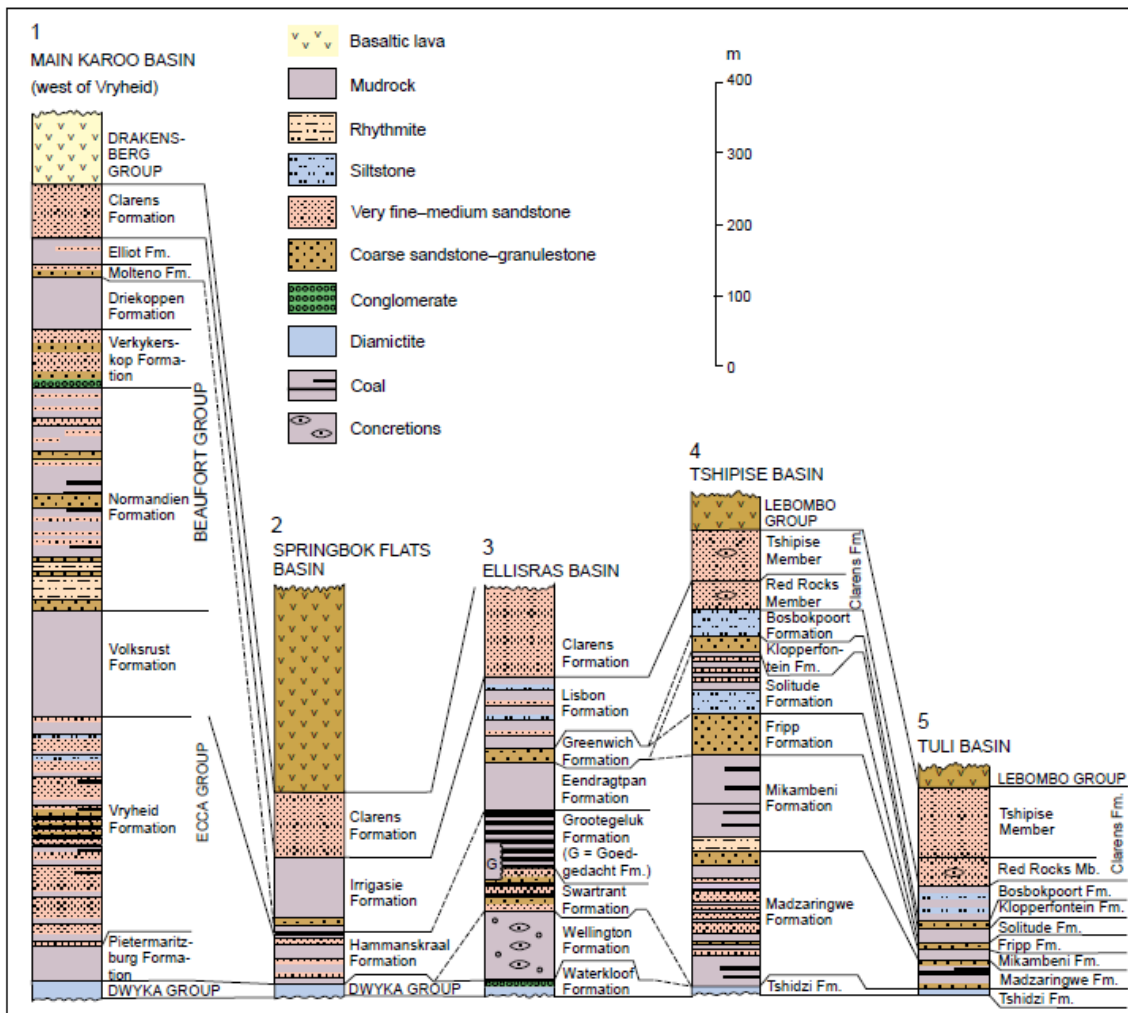


Figure 7: Stratigraphy and correlation of Karoo Supergroup strata of the main Karoo Basin and Springbok Flats, Ellisras, Tshipise and Tuli Basins (from Viljoen et al., 2010).

The Volksrust Formations is a predominately argillaceous unit which interfingers with the overlying Beaufort Group and underlying Vryheid Formation. The formation consists of grey to black silty shale with thin siltstone or sandstone lenses and beds. Thin phosphate beds, carbonate beds and concentrations are fairly common. The substantial thickness, fine grained lithology and great lateral extent of the formation suggest that it represents a transgressive sequence consisting largely of mud deposited from suspension (Johnson et al, 2006).

The Beaufort Group (Figure 7) of the Karoo Supergroup overlies the Eccca Group (Van Vuuren et al., 1998) and covers the greatest surface within the Karoo Basin. The Beaufort Group records fluvial sedimentation by highly sinuous, suspension load streams, in a setting of increasing aridity and active subsidence (Johnson et al., 2006). The Beaufort Group is

overlain by the Stormberg Group. These group starts with a coarse sediment wedge of a braided river system, the Molteno Formation. It also comprises laterally continuous floodplain mudstones and associated fluvial sandstones, the Elliot Formation as well as Aeolian sandstones of the Clarens Formation (Van Vuuren et al., 1998). The Molteno Formation comprises alternating medium to coarse grained sandstones and grey mudstones, with secondary quartz overgrowth giving the sandstones a distinctive glittering appearance. The Elliot Formation comprises an alternating sequence of mudrock and subordinate fine to medium grained sandstones. The Clarens Formation is usually in the order of 100 m thick and generally contains a central zone representing true desert conditions dominated by an Aeolian dune environment. Minor basaltic lava flows interlayered with sandstone in the uppermost part of the Clarens Formation signal the commencement of magmatic activity that led to the termination of sedimentation in the Main Karoo Basin (Johnson et al., 2006).

The development of the Karoo Supergroup ended with the eruption of the basaltic lavas of the Drakensberg Group. The Drakensberg flood basalts originally covered much of southern Africa (Du Toit, 1954), but today are generally preserved in association with the various basins discussed in this paper. Their extrusion is related to the breakup of Gondwana. The 1370 m thick Drakensberg Group (Figure 7) reflects initial magmatic volcanism in the S and SE. This is followed by fissure-type eruptions building up thick sequences of evenly superposed flows associated with numerous dolerite dykes and sills, as well as diatremes and vents (Du Toit, 1954). Recent ages indicate that the entire Drakensberg Group was formed in a very short time interval (Marsh, 2002).

2.4. KAROO DOLERITE SUITE

The Jurassic dolerite dykes and sills were intruded into the sediments of the Karoo Supergroup during a period of extensive magmatic activity that took place over almost the entire Southern African subcontinent during one of the phases in the Gondwanaland break-up. They represent the roots and the feeder of the extrusive Drakensberg basalt that are dated at around 180 Ma (Duncan et al., 1997; Firch and Miller, 1984; Richardson, 1984) and represents one of the largest outpourings of flood basalt in the World. The total volume of the magma extruded on the Southern African Continent has been estimated at 10 million km³ (White, 1997). Large-scale erosion of the main Karoo Basin has revealed the deeper portions

of the intrusive system and a degree of tectonic complexity not encountered in the other major continental intrusive systems in the world.

The bulk of the intrusions is stratabound and concentrated in the Upper Ecca and Beaufort Sandstone. This means that the dolerite might have propagated laterally along strike, and not vertically. Chevallier and Woodford (1999) suggested that the magma source corresponds to a triple junction of three rift zones located east of East London. The dolerite sills and ring-complexes have the same geographic distribution than the dykes and are by far the most common tectonic style in the Karoo basin controlling the geomorphology of the landscape to a large extent. The inherent structural control in the intrusive event such as jointing associated with initial uplift just prior to the magmatic intrusions. The dolerite sills and dykes form a complex intrusive network that was probably acting as a shallow magma storage system (Chevallier and Woodford, 1999).

Van Zijl (2006) studied the mode of emplacement of the dolerites and their relation with the overlying basalts based on results from a resistivity study of the structure of the Karoo basin and augmented by an analysis of age and palaeomagnetic data. The author subdivided the dolerite intrusions into three zones. The different styles of intrusion from the bottom to the top were explained in terms of anisotropy, lithology and increasing upward bending stresses accompanied by a decrease in overburden thickness.

These intrusive dolerite suits represent the shallow feeder system to the flood basalts eruptions. They occur as interconnected network of dykes, sills and sheets which is why it is difficult to single out any particular intrusive or tectonic event. Most of the dykes in the Karoo do not show systematic orientation, but in the Main Karoo they generally form an interconnected plexus with sills. Local faulting and deformation is caused by these dolerite intrusions (Mtimkulu, 2009).

CHAPTER 3: EXPLORATION CASE STUDY: THE SPRINGBOK FLATS BASIN

3.1. THE SPRINGBOK FLATS BASIN

The Karoo Sequence of the Springbok Flats basin correlates moderately well with that of the main Karoo basin, with extremely poor outcrops which is why most information about the basin was obtained from borehole data. The large coal and uranium resources found in the basin make it a basin of economic interest. A cross section (Figure 8) taken across the basin from the southwest to the northeast through 12 boreholes (Johnson et al., 2006) indicated the varying depths of the Karoo Formations with a 125-150 m thick dolerite occurring predominantly to the southwest. The presence of the dolerite sill affected the quality of the coal by devolatilization as it sits directly below the coal. This led De Jager (1976) to classify the coals into high rank in the north-eastern section and low rank in the south western section.

Sand Bults and an east/west striking normal fault separates the south-western section and the north-eastern section, with both sections having black and red soils with a lack of well-defined water courses (Wagner, 1927). The Sand Bults occurs as an elevated area and they are characterized by the presence of pans. The north-eastern section has a maximum thickness of just more than 700m while the south-western section has a maximum thickness of about 100m (Viljoen et al., 2010). The sediments in the basin dip towards the center of the basin and northward towards the northern boundary fault, averaging a dip of 1 degree (Nel, 2012).

The north-eastern section is interrupted by the valley of the Nyl River even though the river doesn't influence it, with the Zebediela Fault bounding it west and northwestern side. De Jager (1976) said that the fault is pre-Karoo in age and it is possibly still active. The south-western section is bounded by the Elands River in the east and the Pienaars River in the south. The Valley of the Nyl River is the most striking topographic feature in the Springbok Flats. It attains its maximum width in areas where the Zebediela Fault depicts its maximum displacement and the geology of its floor rocks changes from Karoo strata to norites of the Bushveld towards the north (Nel, 2012).

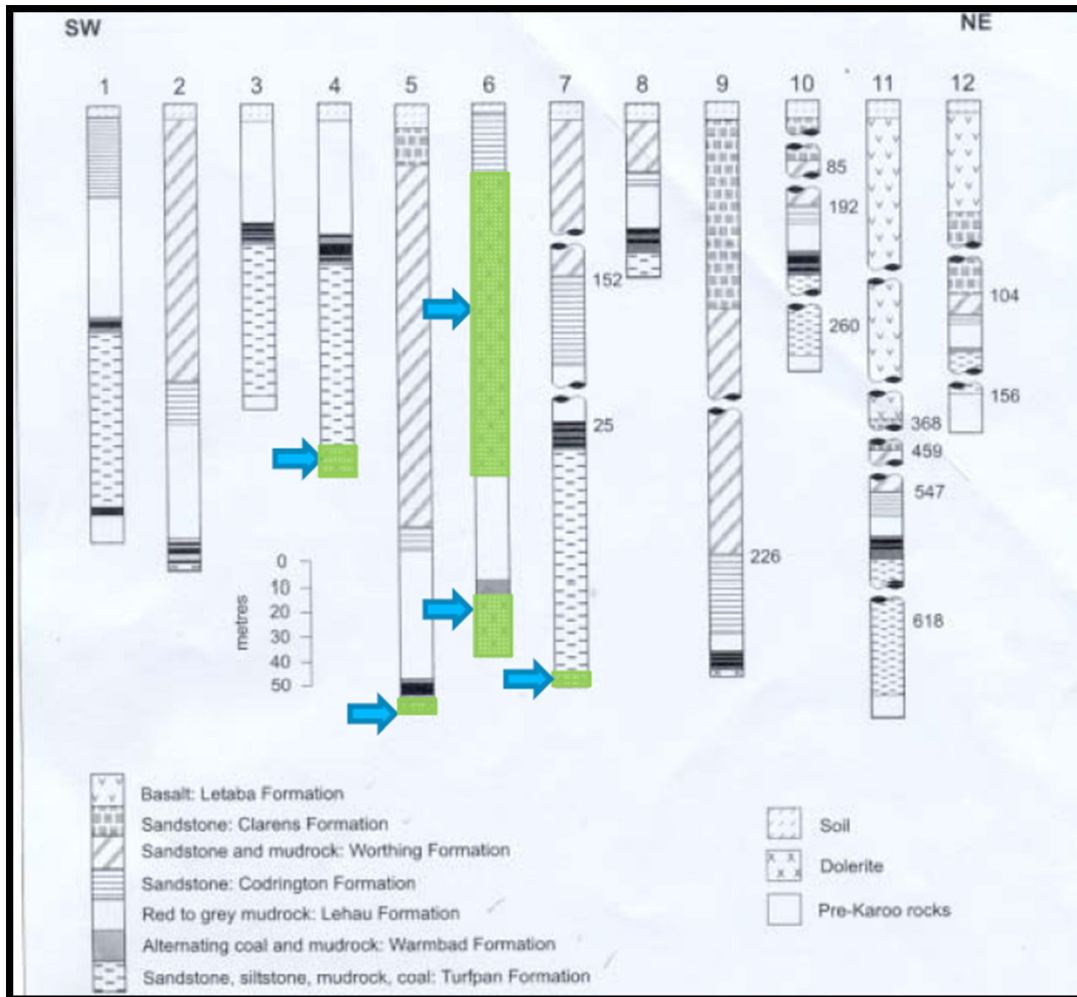


Figure 8: A borehole cross section from the southwest to the north east across the Springbok Flats Basin showing the relative location of a 125 m – 150 m thick Karoo dolerite sill (Modified from Johnson et al., 2006 by Myburgh, 2012).

3.2. STRUCTURE

The Springbok Flats Karoo Basin (Figure 9) is situated on the Kaapvaal Craton in a forebulge flexural province of the Main Karoo foreland system, and comprises two elongated NNE to SSW synclinal flexures separated by an anticlinal flexure with the same strike (Nel, 2012). The Roedtan Basin is the syncline flexure bordering the anticline flexure to the north and the Settlers-Tuinplaats Basin is the syncline flexure south of the anticline flexure. The northern limit of the Roedtan Basin is the Zebediela Fault and the Settlers-Tuinplaats Basin is bordered by the Droogekloof Fault, and both these faults forms part of the Thabazimbi-Murchison Lineament (Nel, 2012).

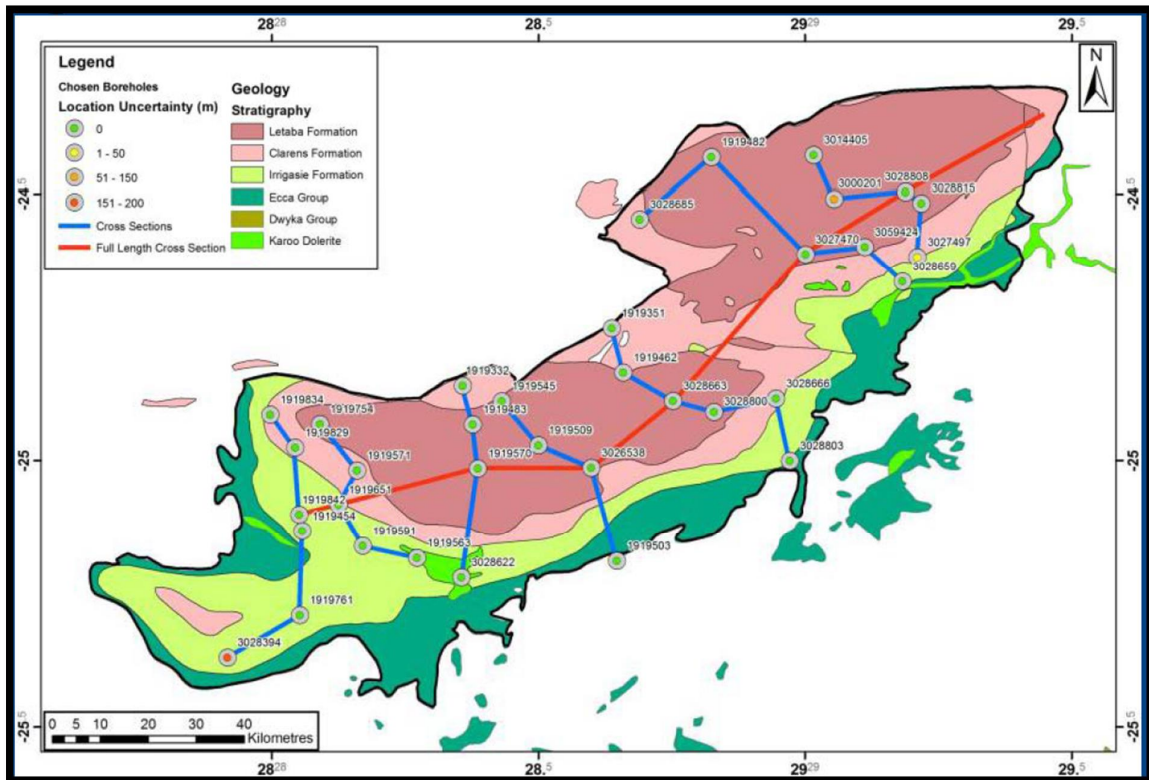


Figure 9: Geology map of the Springbok Flats Basin (from Myburgh, 2012).

According to Nel (2012), during the Late Carboniferous the forebulge was elevated above sea level supporting the formation of continental ice sheets (Figure 10). These elevated regions are referred to as the Cargonian Highlands that existed during the commencement of the Dwyka Group glaciation (Nel, 2012). The Springbok Flats Basin developed as a basin contained within these Cargonian Highlands (Figure 11). Reactivation of pre-Karoo faults after the deposition of the Karoo sediments in the Springbok Flats Basin resulted in the preservation of Karoo strata within existing geographical constraints. The Basin occurs as a geographical depression encompassed by elevated pre-Karoo rocks (Nel, 2012). The Basin possibly represents only a remnant of a Karoo Basin with a much larger aerial extent than the existing basin.

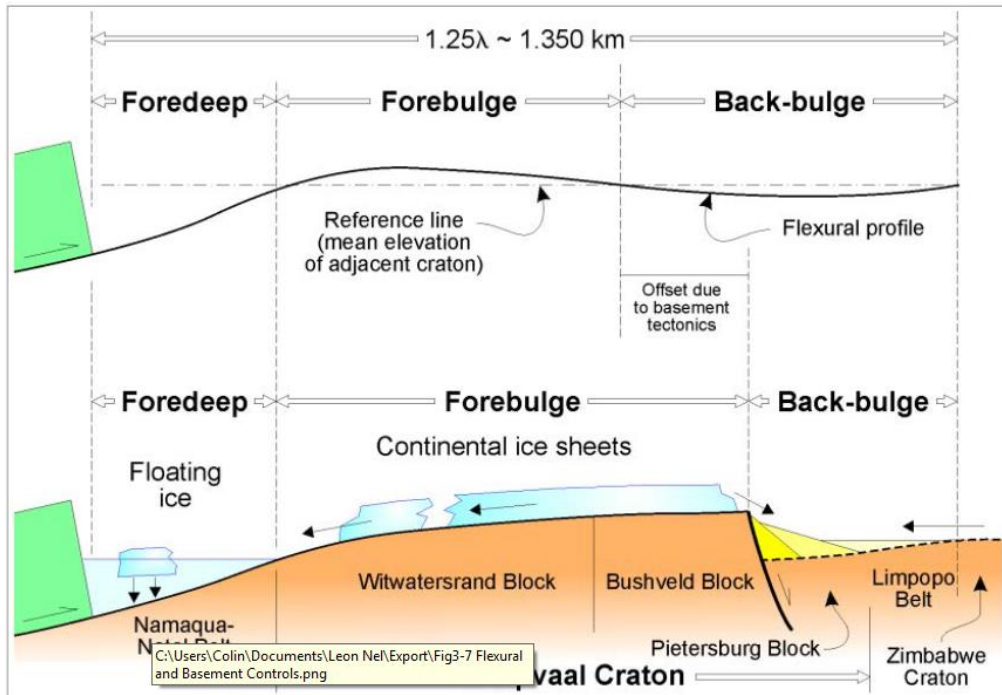


Figure 10: Flexural and basement controls on the distribution of late Carboniferous Dwyka glacial facies in the Karoo Basins (from Nel, 2012).

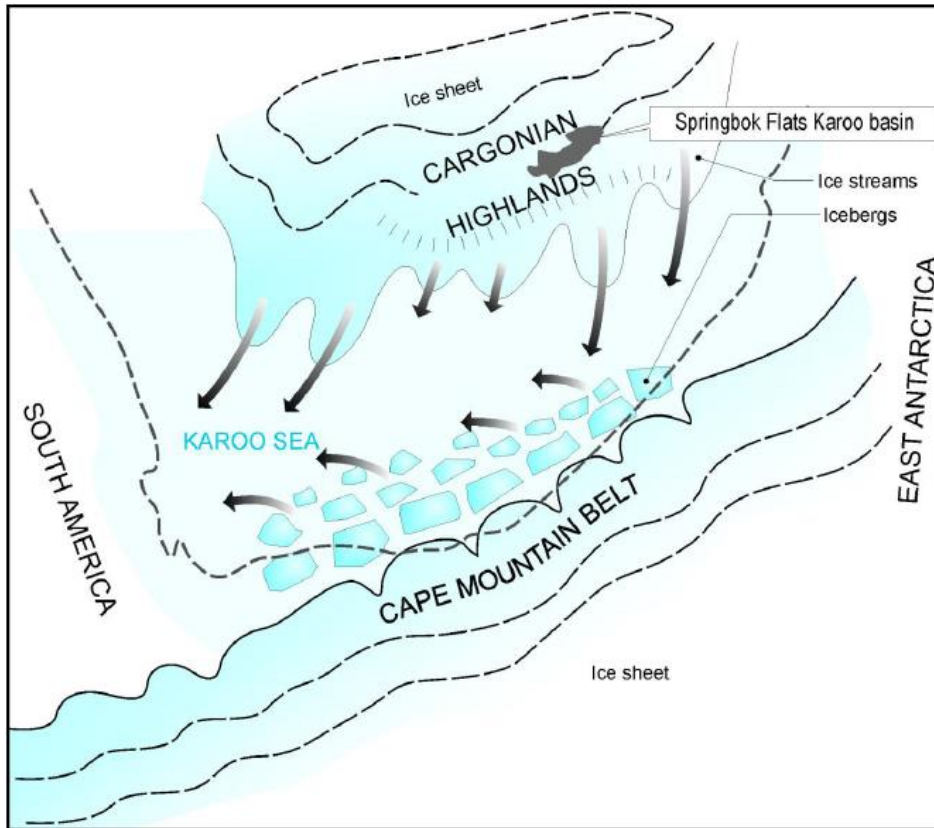


Figure 11: Cargonian Highlands and the Springbok Flats Basin (from Nel, 2012).

3.3. STRATIGRAPHY

The stratigraphic section in this basin includes the Dwyka Group, Ecca Group, Beaufort Group, Stormberg and the Drakensberg Groups (Table 1). The lithology sections indicate presence of basaltic lavas at the top, underlying mudrocks, siltstones, sandstones, conglomerates and diamictite, with interbedded coal beds occasionally. The coals are shale bounded and are of lower Beaufort age. Generally outcrop is very poor, most information were obtained from boreholes drilled by the Council for Geoscience formerly the Geological Survey (Visser and van Der Merve, 1959).

Table 1: A comparative lithostratigraphic representation of the Springbok Flats to the Main Karoo basin

Lithology	Main Karoo basin	Springbok Flats basin
Lava	Drakensburg group	Drakensburg group
Sandstone, mudstones.	Stormberg group	Irrigassie formation
Grey Mudstones, shale, coal	Beaufort Group	Irrigassie formation
Shale, siltstone and Carbonaceous mudstone.	Ecca group	Hammanskraal formation
Diamictites, Conglomerates, mudstones	Dwyka group	Wellington formation
		Waterberg formation

3.3.1. DWYKA GROUP

The Dwyka Group rest on top of the pre-Karoo floor, with rocks comprising of mudrock, diamictite and conglomerate with occasional coal seams. It is rare to find the Dwyka Group exceeding a few meters in thickness but can be up to 40m in local basement depressions (Mtimkulu, 2009). The presence of diamictites and conglomerates, apparent drop-stones and clasts up to boulder size, point strongly to glaciogenesis. The coal seams record warmer interludes when plant growth flourished and the rugged pre-Karoo terrain probably reflects glacial scour (Johnson et al., 2006).

3.3.2. ECCA GROUP

The Ecca Group is divided into the Lower Ecca, the Middle Ecca and the Upper Ecca. The Lower Ecca is about 72m thick with the Middle Ecca Group averaging a thickness of 4m in the south-western section and up to 61m in the north-eastern section (De Jager, 1976). The Middle Ecca consists of alterations of sandy shale and shaly cross-bedded sandstones. Over the entire basin the Upper Ecca is represented by a zone of carbonaceous shale containing coal seams and has a thickness of about 80 to 98m (Mtimkulu, 2009). Medium to coarse grained sandstones interbedded with shaly coal occur at the base of the sequence. The basal succession is overlain by a grey mudrock which coarsens upwards into fine to medium

grained sandstone (Johnson et al., 2006). The coal zone at the top of the formation is up to 12m thick and comprises of alternating carbonaceous mudrock and bright coal seams. The coal seams are indicative of a very humid climate (Johnson et al., 2006).

3.3.3. BEAUFORT GROUP

The Beaufort series attains a thickness of up to 75m in the north-eastern section, but at some places it is only few tens of centimeters thick because of the pre-Molteno stage erosion. In the south-western section it has a consistent thickness of about 60m (De Jager, 1976). This Irrigassie Formation consists of brownish-red mudstone with greenish mottling. Towards the base the colour changes to purple, with a thin zone of grey mudstone and shale directly overlie the coal zone. A variable thickness of sandstone is commonly present within the grey and purple mudrock. This unit comprises erosively based fining upward sequence in which coarse sandstone or even conglomerate grades upwards into siltstone (Johnson et al., 2006).

3.3.4. STORMBERG GROUP

The coarse feldspathic sandstones with occasional conglomerate, mudstones and silt stones of the Molteno stage of the Stormberg Group follows the Beaufort Group. In topographic low areas the beds of the Molteno reach a maximum thickness of about 100m (De Jager, 1976). The Molteno is followed by the red beds, which are up to 125m thick in the north-eastern section and up to 165m in the south-western section. The red beds are followed by the cave sandstone stage consisting of fine-grained light coloured textured sandstone which is up to 100m thick in the north-eastern section and up to 90m in the south-western section (De Jager, 1976).

3.3.5. DRAKENSBURG GROUP

The Karoo sediments in the Springbok Flats Basin are terminated by the Drakensburg lavas. The Drakensberg flood basalts originally covered much of southern Africa (Du Toit, 1954), but today are generally preserved in association with the various basins discussed in this paper. Their extrusion which began in the Late Triassic and continued until the early Cretaceous is related to the breakup of Gondwana. The 1370 m thick Drakensberg Group reflects initial magmatic volcanism in the S and SE (Marsh, 2002). This is followed by fissure-type eruptions building up thick sequences of evenly superposed flows associated

with numerous dolerite dykes and sills, as well as diatremes and vents (Du Toit, 1954). Recent ages indicate that the entire Drakensberg Group was formed in a very short time interval (Marsh, 2002).

3.4. GEOLOGY SURROUNDING THE SPRINGBOK FLATS BASIN

3.4.1. WOLKBERG GROUP

The Springbok Flats Basin is enclosed by rocks varying in age from approximately 1.9 Ga to 2.7 Ga years (Nel, 2012). The oldest stratigraphic unit in direct contact with the Karoo strata of the Springbok Flats Basin is sedimentary and volcanic rocks of the Wolkberg Group in the Roedtan Basin along the Zebediela Fault (Nel, 2012). The period of mechanical rifting around 2.65 Ma of the Kaapvaal Craton resulted in the deposition of the Wolkberg Group followed by thermal subsidence (Erikson et al., 2006).

3.4.2. TRANSVAAL SUPERGROUP

According to Nel (2012) the sedimentary rocks of the Transvaal Supergroup were deposited on a large shallow continental shelf which was created when the Kaapvaal Craton subsided below sea level. Transgression then gave rise to the conglomerate, sandstone and mudstone deposits of the Black Reef Formation (McCarthy and Rubidge, 2005). As the Kaapvaal Craton continues to subside, shallow sea formed in which cyanobacteria thrived consuming carbon dioxide and causing the precipitation of calcium carbonate from sea water (McCarthy and Rubidge, 2005). According to Eriksson and Truswell (1974), the calcium carbonate deposits were later dolomitized to form the Malmani Subgroup. The Malmani Subgroup is subdivided into five formations based on the chert content, stromatolite morphology, intercalated shales and erosion surfaces (Erikson et al., 2006).

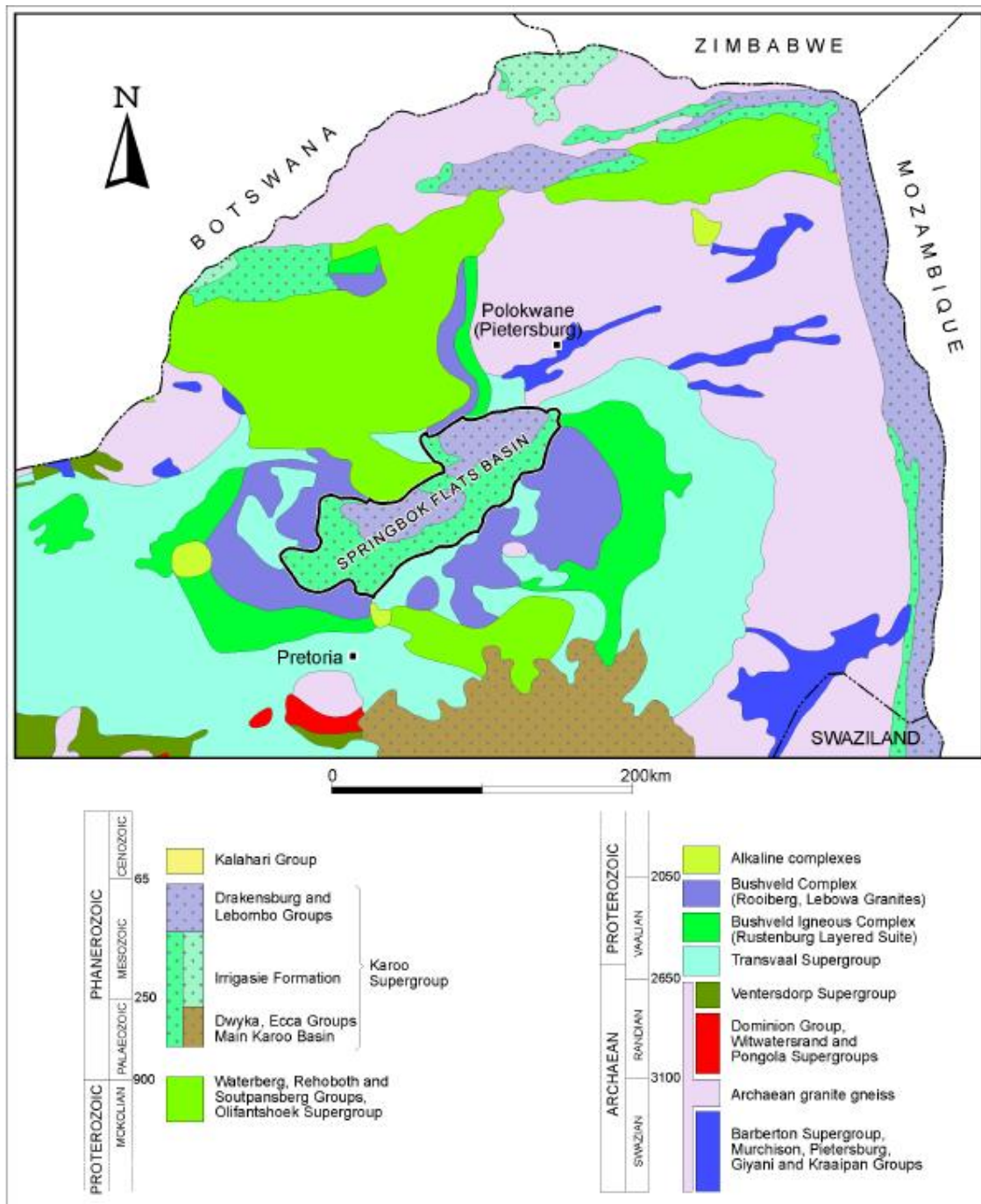


Figure 12: Regional surface geology surrounding the Springbok Flats Basin (from Nel, 2012).

A radical change in the depositional environment marked the commencement of the deposition of the Pretoria Group sediments (Eriksson et al., 2006). The Pretoria group comprises of mudrocks alternating with quartzitic sandstones, interbedded basaltic-andesitic lavas, subordinate conglomerates, diamictites and carbonate rocks which are have been subjected to low-grade metamorphism (Eriksson et al., 2006). The termination of shallow submerged continental shelf on which the Chueniespoort Group deposited resulted in the disappearance of the cyanobacteria (Eriksson and Truswell, 1974). A brief uplift in the Chueniespoort palaeo-environment resulted in the creation of a shallow marine environment (Nel, 2012). According to Eriksson et al. (2006) the deposition of the Transvaal Supergroup was terminated by the eruption of basaltic and rhyolitic lavas of the Rooiberg Group, and the volcanic Rooiberg Group overlies the Pretoria Group unconformably and is the upper most unit of the Transvaal Supergroup (Eriksson and Truswell, 1974).

3.4.3. BUSHVELD COMPLEX

The Transvaal Supergroup rocks in the Transvaal Basin were intruded by the approximately 2061 Ma Bushveld Complex (Eriksson et al., 2006). The lava sequence that erupted onto the sediments of the Transvaal Supergroup is known as the Rooiberg Group. This eruption event was followed by intrusive event of the Rustenburg Layered Suite, where magma intruded into the Rooiberg Group. The intrusive event was followed by the Lebowa Granite Suite, which intruded between the Rustenburg Layered Suite and the Rooiberg Group (Cawthorn et al., 2006). The Bushveld Complex also contains rocks of the Rasthoop Granophyre Suite occurring above and below the Lebowa Granite Suite (Cawthorn et al., 2006).

Below is a brief description of the major units found in the Bushveld Complex-:

- **Rooiberg Group**

Lavas and subordinate sedimentary rocks of the Rooiberg Group locally form the floor to the Bushveld Complex in the southeastern part of the basin, and elsewhere comprise the roof rocks to this major intrusion (Eriksson et al., 2006). The volcanic Rooiberg Group overlies the Pretoria Group unconformably and is the uppermost unit of the Transvaal supergroup (Eriksson et al., 2006). The bulk of the Rooiberg succession comprises generally siliceous volcanic rocks, with sandstone and shale intercalations present in places (Cawthorn et al., 2006). The Dullstroom Formation at the base is composed of mafic to intermediate volcanic rocks, ranging in composition from basalts to dacites (Buchanan, 2006). A thick sequence of

siliceous extrusive rocks in ascending order, the Damwal, Kwaggasnek and Schrikkloof formations overlies the Dullstroom Formation and apparently represents a continuation of the same magmatic activity (Buchanan, 2006).

- **Rustenburg Layered Suite**

The Rustenburg Layered Suite comprises rock types ranging from dunite, pyroxenite, norite, gabbro, anorthosite, magnetite- and apatite-rich diorite (Cawthorn et al., 2006). It demonstrates a complete differentiation sequence of a basaltic magma. The mafic rocks of the Rustenburg Layered Suite are the major source of South Africa's exploitable platinum group metals, as well as chromium and vanadium (Nel, 2012).

- **Rashoop Granophyre Suite**

The Granophyre rocks comprise a significant component of an acid phase of the Bushveld Complex (Cawthorn et al., 2006). These rocks can be classified into magmatic and metamorphic types. The magmatic rocks are characterised by well-developed micrographic intergrowths of quartz and alkali feldspar. In the metamorphic rocks the quartz-feldspar intergrowth are characteristically irregular and are interpreted to have formed by replacement of sediment minerals (Cawthorn et al., 2006). The granophyre occurs widespread in the Bushveld Complex and is chemically closely related to the Rooiberg Group, suggesting that the Rooiberg Group and Granophyre might have had the same magma source (Nel, 2012). However, these granophyres intruded sometime after the Rooiberg Group because they occur between the Rooiberg Group and the Rustenburg Layered Suite (Eales, 2001).

- **Lebowa Granite Suite**

According to Nel (2012) the emplacement of the Lebowa Granite Suite took place between 2.01 and 1.67 Ga, and it was the final stage of Bushveld magmatism. During this stage the Rooiberg Group was intruded by the Lebowa Granite Suite. The Lebowa Granite Suite can be subdivided into various granites but the four most abundant granites, namely the Nebo Granite, Bobbejaankop Granite, Klipkloof Granite and the Makhutso Granite (Cawthorn et al., 2006) will be discussed. The Nebo Granite is the main component of the acid phase of the Bushveld Complex. It is coarse in grain, pink to grey in colour, and consists of alkali feldspar, quartz with minor mafic minerals and accessory minerals (Cawthorn et al., 2006). The Bobbejaankop Granite is a medium to coarse grained red granite, consisting of altered

alkali feldspar with mafic minerals that are usually altered to chlorite. Biotite is the main mafic mineral found in these granites (Cawthorn et al., 2006).

The Klipkloof Granite usually occurs as irregular sills and dykes within the Nebo and the Bobbejaankop Granites, and it is medium to fine grained pink to grey granite with a low mafic mineral component (Nel, 2012). Makhutso Granite, the least abundant youngest of the Lebowa Granites is classified as medium grained grey coloured biotite-rich granite (Nel, 2012). The trace element chemistry and high mafic mineral content of the Makhutso granite resemble the Nebo Granites, with the Makhutso Granites not displaying continuous fractionation like other granites (Nel, 2012).

The granites of the Lebowa Granite Suite are characterised by differentiation and variations in mineralogy. Granites are generally classified into three types (Table 2) depending on their tectonic origin and chemical characteristics. These are:

- S - type,
- I - type
- A - type

The Bushveld Granites are classified by Cawthorn et al. (2006) as A - type granites. The A-type granites occur in anorogenic settings (Clemens et al., 1986). There are various mechanisms by which A-type granites might be produced as proposed by Fourie and Harris (2011) in terms of fractionation of magmas. The various granite types are classified (Table 2) in terms of tectonic environment of formation, chemical signature and typical minerals. The classification in Table 2 suggests that the Bushveld granites are enriched in iron and would contain iron-biotite, sodium pyroxene and would have sodium amphibole and fayalite as accessories in order to conform to A-type granite characteristics.

Table 2: Characteristics of S type, I-type and A-type granites (from Hunt, 2005).

Granite Type	Tectonic Environ	Chemical Signature	Typical Minerals	Accessory Minerals
S-Type	Orogenic	Metaluminous to strongly peraluminous, high $^{18}\text{O}/^{16}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$	Muscovite, cordierite, tourmaline	garnet,
I-Type	Orogenic	Metaluminous	Biotite, hornblende	
A-Type	Anorogenic / rift-related	Metaluminous to mildly peralkaline, Fe-enriched	Fe-biotite, Na-pyroxene, hedenbergite, titanite	Na-amphibole, fayalite,

3.4.4. WATERBERG GROUP

The Waterberg Group comprises the last of the major sedimentary accumulations to form on the Kaapvaal Craton during the Proterozoic (Nel, 2012). It rests unconformably on rocks of the Transvaal Supergroup, granites and mafic rocks of the Bushveld Complex, and Archean gneisses and granites of the Kaapvaal Craton (Barker et al., 2006). According to Callaghan et al. (1991), the basin evolved as a continental, fault-bounded basin in the northern part of the Kaapvaal Craton and Limpopo Belt as a result of rifting on the Kaapvaal Craton. Strike-slip movement along the ThabazimbióMurchison structural lineament and associated pull-apart structures acted as a depositional locus for the thick accumulation of Waterberg Group sedimentary rocks (Callaghan et al., 1991).

According to Nel (2012) the main basin consists of the northern Warmbath Basin and the southern Middelburg Basin. The Waterberg Group sediments in the basin are part of the northern boundary of the Settlers-Tuinplaats Basin along the Droogekloof Fault Zone (McCarthy and Rubidge, 2005). The Palala Fault, ThabazimbióMurchison structural lineament and the Sugarbush Fault were active during this rift period, resulting in the creation of asymmetrical troughs that today host the Warmbath Sub-Basin of the Waterberg Group (Nel, 2012).

3.4.5. ELANDSKRAAL VOLCANIC COMPLEX

The Elandskraal Volcanic Complex is a pre-Karoo volcanic complex situated in the proximity of Pienaarsriver and it is the largest complexes of the Pilanesburg Alkaline Province (Verwoerd, 2006). According to Nel (2012), the Pienaarsriver sub-province magma intruded along a NNW trending line referred to as the Franspoort line. The Complex forms part of the Pilanesburg Alkaline Province that intruded between 1.45 and 1.20 Ga ago (Nel, 2012). According to Verwoerd (2006) it forms part of the Pienaarsriver subprovince of the Pilanesburg Alkaline Province and it is completely covered by Karoo Supergroup mudstones and sandstones as well as dolerites. It is an eroded shield volcano that erupted onto a floor of Bushveld Complex granite (Frick and Walraven, 1985).

3.5. COAL FORMATION

Most of South African coal was formed about 300 million years ago, when much of the earth was covered by swamps. As plants and trees died, their remains sank to the bottom of the swampy areas, accumulating layer upon layer and eventually forming a damp, dense material called peat. Over long periods of time, the earth's surface and the climate changed. The seas and rivers caused deposition of sand, clay and other mineral matter which accumulated, burying the peat in the process. Sandstone and other sedimentary rocks were then formed, and the pressure caused by their weight squeezed water from the peat. Increasingly deeper burial and the heat associated with it gradually changed the material to coal. The formation of coal seams often depends on the crustal movements, which influence the coal seam thickness and control the splitting and thinning of the coal seam.

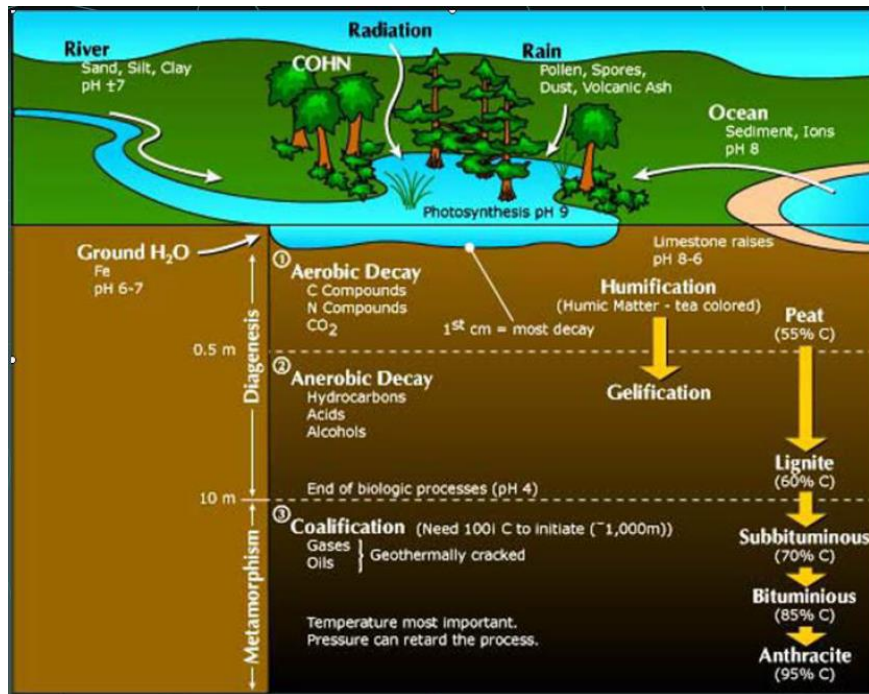


Figure 13: Illustration of Coal formation (MSc Coal course lecture notes, 2013).

3.6. MINERALOGY

Clays, quartz, carbonates and sulphides are the most common minerals in South African coal deposits. It was reported by Weeber (1996) that these clay minerals comprise 60-80% of the total mineral matters, with kaolinite and illite being the most common. Dolomite, calcite, siderite and ankerite are carbonate minerals common in coal deposits (Weeber, 1996). Coal of the Springbok Flats has high percentages of sulphur, averaging about 1% higher than the sulphur in the major coal field of the Main Karoo Basin (Nel, 2012). This constitutes a major environmental hazard especially when coal is combusted in power stations. The main difference between Springbok Flats Basin coal and the coal from other areas is that the Springbok Flats coal is more quartz rich, with lower feldspar and almost no mica or clay minerals (Viljoen et al., 2010).

The common sulphide mineral in the Springbok Flats Basin is Pyrite and small amounts of marcasite. It occurs as euhedral crystals, framboidal aggregates, as veins or on cleat surfaces (Nel, 2012). According to Ward (1984), pyrite probably represents the result of bacterial reduction of sulphate-rich peat waters during early diagenesis, with remobilization also likely under certain conditions. Siderite and calcite are carbonate minerals common in coals of the Springbok Flats Basin. According to Nel (2012) siderite occurs as spheroidal nodules within

the coal and was apparently formed by chemical precipitation during early diagenesis. It probably represents the interaction of iron with dissolved CO₂ in peat waters where sulphate concentrations were too low for pyrite formation. Calcite represents late stage accumulation in coals occurring as veins and on cleat surfaces (Ward, 1984).

Weeber (1996) mentioned that quartz often occurs as rounded to angular grains in clay-rich bands and that it may also occur as veins cross-cutting the coal structure. In the Springbok Flats Basin the fine cracks intersecting the coal are filled with a mixture of quartz, chamosite and calcite (Nel, 2012). Heavy minerals such as anatase, garnet, zircon, leucoxene, ilmenite, rutile, barite and tourmaline are also encountered in the basin. Coffinite is the only uranium mineral in the Springbok Flats Basin, and it is chemically associated with yttrium, calcium and phosphorus. It occurs in a wide variety of physical forms in carbonaceous shale and in massive vitrinitic and fusinitic coal (Nel, 2012). Pyrite is often closely associated with the coffinite.

3.7. MINERALIZATION

According to Nel (2012), uranium is leached from the chemically weathered source rock material, Bushveld Granites as uranyl ion ($[UO_2]^{2+}$) by bicarbonate rich water. Surface water and groundwater then transport the uranyl ions to the peat containing plant debris. The uranyl combines with humic-acid containing sediments, and they both become buried and the process of coalification starts. Local migration and enrichment of uranium takes place accompanied by the secondary mineralisation of uranium.

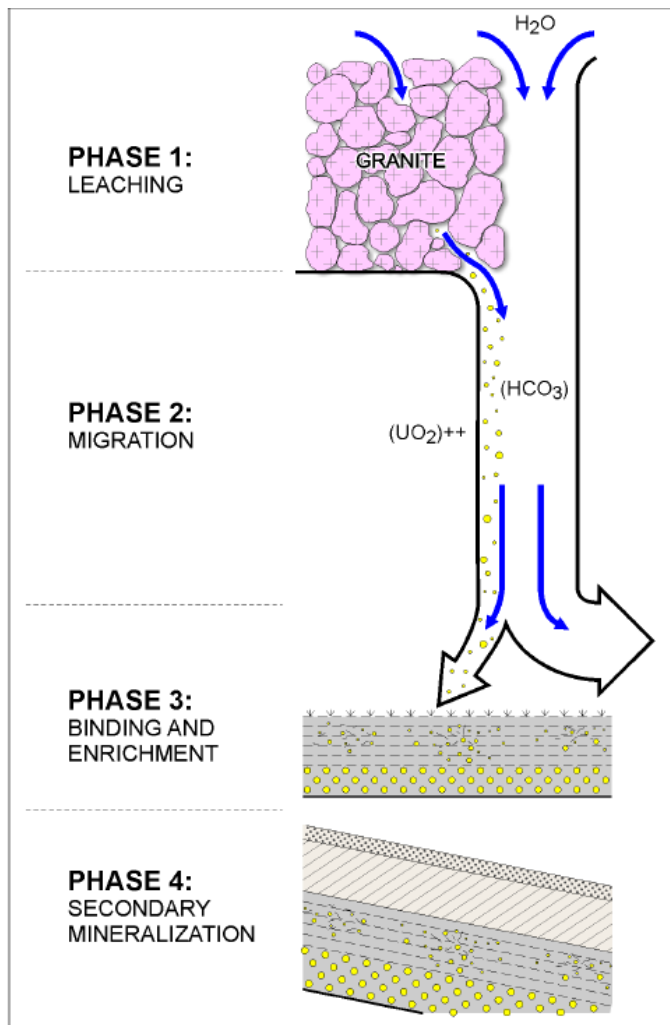


Figure 14: Schematic representation depicting the movement of uranium in the secondary environment and the enrichment in organic material (from Nel, 2012).

Uranyl ions had likely been transported in the adsorbed state on clay and other fine-grained particles, which precipitated in the form of microscopic sized uranium oxides, hydroxides or silicates in the shale matrix (Nel, 2012). Uranium occurs in coal and carbonaceous shale in the upper part of the coal zone which does not form part of the potentially mineable seam, and within the sandstones of the Late Permian Ecca Group in the Springbok Flats Basin of South Africa (Cole, 1998). This uranium mineralization in coal takes place in close proximity of the palaeo-topographical highs mainly where these highs comprise granites of the Lebowa Suite of the Bushveld Igneous Complex (Nel, 2012). The uranium mineralisation in coal is not uniformly distributed, but does occur in patches and tectonic zones of weakness in sedimentary rocks are favourable environments for its deposition (Cole, 1998). The origin of uranium mineralisation in the Springbok Flats Basin has not been investigated in detail.

3.8. ECONOMIC GEOLOGY

According to De Jager (1986) the Springbok Flats Basin coal is a vitric, bituminous coal that can be used as a low swelling coking coal and for power generation. The basin contains about 3,3 Gt of in situ resources (Table 3), of which 1,7 Gt is recoverable reserves (Viljoen et al., 2010). Considering the basin as a whole, the area of optimum coal formation is along the south-western, south and south-eastern margins of the basin (De Jager, 1976). According to Nel (2012) most of the coal resources in the Springbok Flats Basin will have to be exploited by underground mining methods since it is very deep. Since the basin is widely used for groundwater extraction, the coal in certain parts of the basin could contain large amounts of water (Viljoen et al., 2010).

According to Sandersen (1997) the Springbok Flats basin is made up of two coal zones, the lower coal zone which is equivalent to the Vryheid formation and a mudrock succession which is equivalent to the Waterberg main coal succession. The lower coal zone is patchily developed while the upper coal zone consists of bright coals interbedded with carbonaceous mudstones and is not present throughout the entire area (Sandersen, 1997). The Upper Middle Seam proved to be the most economically viable seam averaging 1.42 m in thickness (Nel, 2012).

Table 3: Distribution of coal resources and reserves in the different coalfields across South Africa (from Bredell, 1987).

Coalfield	In situ resources (Gt)	Recoverable reserves (Gt)
Witbank	16.24	12.45
Highveld	16.97	10.96
Ermelo	7.52	4.70
Utrecht	1.09	0.66
Klip River	1.21	0.66
Vryheid	0.36	0.22
South Rand	3.03	0.72
Vereeniging - Sasolburg	4.73	2.21
Free State	8.85	4.87
Nongoma/Somkele	0.24	0.11
Kangwane	0.48	0.17
Springbok Flats	3.27	1.72
Ellisras	55.52	15.49
Mopane/Tshipise/Pafuri	1.45	0.28
Tuli	0.24	0.11
Total	121.218	55.333

According to De Jager (1986) analyses conducted on the coals showed the following:

South Western Sector:

- In situ (raw) coal = 2 500 Mt < 22 MJ (30-55% Ash)
- Washed at 1,65 = 1 250 Mt 25,5MJ (22-30% Ash)

North Eastern Sector:

- In situ (raw) coal = 4 000 Mt < 22 MJ (30-55% Ash)
- Washed at 1,65 = 2 000 Mt 26 MJ (22-30% Ash)

According to De Jager (1986) the South-western side coal has a moisture content of up to 6% and volatile of 28% or higher, thus making it a low quality, low rank coal. The North-western side coal is a high rank coal with moisture content between 2 and 3 % and a swelling index of five and a half (De Jager, 1976). These coalfields are a potential source for coalbed methane because of the tectonic structures related to the pre-Karoo structures encountered in the basin, the depth of burial, high vitrinite content and the rank of the coal seams (Nel, 2012). The coal fields can also be a good geological storage potential for carbon dioxide (Viljoen et al., 2010), suitable for power generation through conventional stations (De Jager, 1986) and can be used for the production of hydrocarbons because of their high vitrinite content (De Jager, 1976).

Table 4: Estimated remaining recoverable reserves as at the end of 2000 (after South African Coal Statistics and Marketing Manual, 2001).

Coalfield	Recoverable reserves (Gt) in 1987	ROM Production (Mt) until - 2000	Remaining (Gt) in 2000
Witbank	12.45	2,320.23	10.13
Highveld	10.96	972.49	9.98
Ermelo	4.70	101.11	4.60
Utrecht	0.66	64.47	0.60
Klip River	0.66	85.26	0.58
Vryheid	0.22	81.80	0.14
South Rand	0.72	22.03	0.70
Vereeniging - Sasolburg	2.21	334.91	1.88
Free State	4.87	0.22	4.87
Nongoma/Somkele	0.11	15.18	0.10
Kangwane	0.17	0.96	0.17
Springbok Flats	1.72	0.00	1.72
Ellisras	15.49	384.00	15.11
Mopane/Tshipise/Pafuri	0.28	6.11	0.27
Tuli	0.11	0.00	0.11
Total	55.33	4,388.77	50.94

The coal zone in total contains about 77 072 tonnes of uranium, which is more than double the identified resources of the Karoo Uranium Province in the Main Karoo Basin (Viljoen et al., 2012). According to Cole (1998), the uranium mineralization is concentrated in the upper part of the coal zone over a vertical interval of 1 m in the vicinity of bedrock in the form of Bushveld Complex granite on the close proximity of the palaeotopographic highs. This upper coal layer does not form part of the potentially mineable seams, with the presence of more than one coal seam located away from the palaeotopographic highs (De Jager, 1998). The coal zones in the central and north-eastern part of the basin are the only significantly mineralized zones with several ore bodies containing between 0.16 and 1 kg U/t (Cole, 1998). According to Cole (1998) the uranium is disseminated throughout the coal and carbonaceous shale, with uranium phases having grain sizes of less than 20 microns.

CHAPTER 4: EXPLORATION TECHNIQUES

4.1. REMOTE SENSING

Remote sensing mapping provides an opportunity to analyse and interpret the geological features without the problems that are associated with the field work: high cost, remoteness, lack of infrastructure, environmental sensitivity, and short mapping season. A remote sensing map is an estimate of geological features of an area. Igneous and sedimentary rocks could impact the petroleum system in the Springbok Flats basin. The presence of sills, dykes and faults are usually considered as either harmful to preservation of oil and gas or useful for indication of existence of oil and gas. In general, igneous rocks are perceived as detrimental to the petroleum system. The high temperature associated with them will cause the organic matter in potential source rocks to be destroyed.

ASTER images were used for this study. Before using the satellite images for analysis, it is required to pre-process them to correct for any errors that are associated with the satellite sensors, atmospheric errors and converting the digital numbers to reflectance. In this study, colour composite and band ratio techniques are utilized based on the study area's geological features and spectral reflectance properties of different rocks. Before applying remote sensing techniques, it is important to examine the general spectral reflectance of geological features. Remote Sensing was chosen because it is the most appropriate cost effective method for mapping the geological feature on the Springbok Fields Basin. However, in this project the scope of research has been narrowed down to the eastern part of the study area. This study was also faced with a few limitations that were associated with the datasets. One of these limitations was in regards to ASTER satellite images, the six bands in the short wave infrared (SWIR). Aster images were acquired in 2000 which meant that the ASTER SWIR was missing from the data because the SWIR detectors stopped functioning during this period. This study was limited to work with only ASTER satellite thermal bands (TIR) and visible and near infrared (VNIR) on the parts of the study area that SWIR bands were not available.

4.2. GEOCHEMICAL SURVEY

The Council for Geoscience undertook the task of producing regional geochemical maps of South Africa to complement the existing geochemical information. The aim of the survey was to create a geochemical database and to determine the baseline for different lithological units.

The geochemical information obtained is very useful in identifying exploration targets for a wide range of commodities. It can also be used to test exploration models and to initiate geological research. A helicopter was used to collect first-order stream sediments or representative soil samples. The sample density used whereby soils and first-order stream sediments are sampled was 1 sample per square kilometre. In areas of poor drainage, where first-order streams are not developed at the required density or where they are not accessible, a representative soil sample is taken avoiding roads, pans and cultivated areas where possible (Lombard et al., 1999).

Samples of approximately 5 kg each were taken from the top 25 cm of the soil profile avoiding rocks and organic matter where possible. Approximately 300-400 samples were collected daily due to the fact that a helicopter was used. Samples were dry sieved to extract the -75 micron fraction, pressed into powder briquettes and analysed for 24 chemical elements (TiO₂, MnO, Fe₂O₃T, Sc, V, Cr, Co Ni, Cu, Zn, As, Rb, Sr, Y, Zr, Nb, Mo, Sn, Sb, Ba, W, Pb, Th, U) on a Simultaneous X-Ray Spectrometer. The remainder of the sieved sample was retained for future use. Orientation studies suggested that most of the elements analysed for are concentrated above the detection limit for the analytic technique used. A well constrained global positioning system was used for navigation and this also ensures the accurate recording of sample positions (Lombard et al., 1999). Chemical mapping program is a cost-effective way of providing an overview of the relative abundance levels, regional trends and anomalous patterns in the underlying lithological units (Lombard et al., 1999). It also allows detailed geochemical characterisation of different lithological units. The results show an excellent correlation between soil chemistry and underlying geological formations. Background values of elements in soils are determined over different lithological units for the identification of anomalous values relative to these.

4.3. GEOPHYSICAL SURVEYS

Geophysics involves applying the principles of physics to the Earth. The interior of the Earth is investigated by taking surface measurements that are influenced by the internal distribution of physical properties. Geophysical methods can be applied at a range of scales, from investigations of whole Earth structure, to exploration of a localised region of the upper crust. Geophysical surveying is naturally prone to ambiguities and uncertainties, but provides a relatively rapid and cost-effective method of deriving aerielly distributed information on

subsurface geology. If it is properly applied, it can optimise exploration programmes by maximising the rate of ground coverage and minimising drilling requirements. There is a broad division between geophysical surveying methods that make use of natural fields and those that require the input of artificially generated energy. Generally, natural field methods can provide information on earth properties to significantly greater depths and are simpler to carry out than artificial source methods. Artificial methods are capable of producing a more detailed and better resolved picture of subsurface geology. In this study we used only natural field methods, namely Gravity, Magnetic and Radiometric methods. The parameters measured using these methods are density, magnetic susceptibility and remanence, and natural radioactivity respectively. From these parameters or geophysical observations we can extract geological information such as lithologies, structures, hydrothermal alteration and weathering (Yao, 2013).

4.3.1. GRAVITY SURVEY

The gravity method is a non-destructive geophysical technique that measures differences in the earth's gravitational field at specific locations. These differences arise from differences in rock densities. The success of the gravity method depends on the different earth materials having different bulk densities that produce variations in the measured gravitational field. The idea is to search for anomalous masses by assessing the depth and shape of them. The anomalies result from lateral variations in the density of subsurface materials and the distance of the bodies from the measuring equipment. The gravity data were collected over the whole of South Africa by the Council for Geoscience. The gravity stations were mainly located along roads resulting in a measurement roughly every 13 km²

Gravity measurements were conducted with Scintrex CG5 gravimeter gravimeters and elevations were determined by micro-barometers. Bouguer anomalous values were calculated assuming a mean density of 2670 kg/m³ (Stettler et al., 1999). The measurements were tied to the International Gravity Standardisation Net values and were referred to the gravity formula based on the 1967 geodetic reference system. According to Stettler et al. (1999), a maximum error in a regional Bouguer anomaly value is calculated by combining an inaccuracy of ~ 2m (~4 gravity units) in the barometrically determined elevation with a maximum error in the observed gravity of 2 mgal and a positional error of 150m in a north south direction (1 mgal).

This worst case error amounts to about 7 mgal. The data set was gridded using a minimum curvature algorithm with a grid cell size of 1 km. The gravimeter was calibrated to correspond with the known differences in absolute gravitational acceleration between the Pretoria and Mowbray (Cape Town) stations. This is in accordance with the International Gravity Standardization Net (IGSNØ71) as described by Morelli et al. (1974) and was referred to the gravity formula based on the 1967 Geodetic Reference System (Moritz, 1968). Calibration factors have been determined for the gravimeters used.

4.3.2. MAGNETICS AND RADIOMETRIC SURVEY

Magnetics is a branch of geophysics that studies the influence of magnetic materials in the subsurface on the observed magnetic field of the Earth. The aim of a magnetic survey is to investigate subsurface geology on the basis of anomalies in the Earth's magnetic field resulting from the magnetic properties of underlying rocks. Although most rock-forming minerals are effectively non-magnetic, certain rock types contain sufficient magnetic minerals to produce significant magnetic anomalies. The technique is widely employed and the speed of operation of airborne surveys makes the method very attractive in exploration. Magnetic surveys are conducted by recording the Earth's magnetic field at specified locations along traverses which are approximately perpendicular to the geological strike of the magnetic features. The magnetic field readings have to be corrected for diurnal variations in the earth's field which are due to fluctuations in the ionosphere driven by solar activity. These diurnal variations are monitored by a separate magnetometer placed at a fixed point known as a base station during magnetic surveys. The base station readings are then used to compensate for the diurnal variations observed by the roving magnetometer.

The radiometric method measures the quantities of the three naturally occurring radioactive elements namely Uranium (U), Potassium (K) and Thorium (Th) within the top < 50 cm of overlying material. Gamma rays are attenuated over a short distance which is why the method only provides information about the first meter below the surface. The decay in the atoms is influenced by the size of the nucleus and the ratio of protons to neutrons (Minty, 1997). Uranium (U) occurs naturally as radioisotopes ^{238}U and ^{235}U . The ^{235}U isotope forms only 0.72% of naturally occurring U resources and the gamma ray energies are too low to be diagnosed in the airborne gamma-ray spectrometry. Thorium (Th), occurring as radioisotope ^{232}Th , gives rise to the decay series that terminates in the stable isotope ^{208}Pb . Potassium,

which is the weakest source of radiation, is measured as a percentage, but it is abundant enough to be an equal contributor to Thorium and Uranium in the natural radiation flux (Minty, 1997). The alpha particles cannot be detected in radiometric surveying, while the Beta particles can only be detected in ground surveys and the gamma rays can be detected in airborne surveys. In general, the activity in sedimentary rocks and metamorphosed sediments is higher than in igneous and other metamorphic types, with the exception of potassium-rich granites (Telford et al., 1976). Although there is no fixed rule regarding the amount of radioactivity a given rock may have, because of potassium decay, shales, clays and marbles are generally several times more radioactive than clean sands, sandstones, limestones and dolomites. Once the radiometric dataset is collected it gets corrected for altitude, background and cosmic radiation and individual channels are corrected for Compton scattering (Minty, 1997).

An airborne geophysical survey collecting magnetic and radiometric data over the study area was undertaken by the Council for Geoscience in April 2006. The airborne data survey specifications are (Ledwaba et al., 2009):

- Survey flying height: 150 m
- Line spacing: 1 km
- Flight Line direction: East óWest
- Tie line spacing: 10 km
- Tie line direction: Perpendicular to the flight line direction
- Flight Speed: 240 km/hour
- Data Recorded: Total field magnetic, radiometric data

CHAPTER 5: RESULTS AND INTERPRETATION

5.1. REMOTE SENSING

5.1.1. SPECTRAL CHARACTERISTICS

Before applying image enhancement techniques, it is important to examine the spectral reflectance of the target features and their surrounding materials. The spectral reflectance of the same type of rocks could vary at different areas. Generally the reflectance spectrum of a rock depends on its mineral composition, weathering minerals and vegetation covers. The particle size could also impact the reflectance properties of a rock as generally the reflectance increases with decrease of particle size. Therefore, it is important to use the spectral reflectance characteristics of these rocks as only a reference and employ different image enhancement techniques for geological analysis. The study area is mostly composed of shale, sandstone, and igneous rocks (basalt and gabbro).

5.1.1.1. FALSE COLOUR COMPOSITION

False colour composite, displays a colour image which is suitable for geological analysis. Three bands are required to assign to fundamental colours Red (R), Green (G), and Blue (B). The best band combinations are those that delineate the desired geological features. There are eighty-four possible band combination types from the nine VNIR and SWIR of ASTER bands, and ten possible band combinations from the TIR ASTER bands. To determine the most suitable colour composite for overall geological mapping of the study area, statistical techniques such as correlation coefficient (CC, Tables 5, 6) were employed to determine the most suitable colour composite.

The VNIR and SWIR ASTER bands of 1, 8, 2, 5, 6, and 3 have relatively low correlation coefficients. Consequently, band combination of RGB 862, 832 and 621 were evaluated for their ability to discriminate geological features of the study area. The granite rocks in colour composite RGB 621 (Figure 15) is clearly visible as Blue colour. Colour composite RGB 862 (Figure 16) well highlights different geological features (sandstone is highlighted in light grey and granites are highlighted as brown and dark blue). Colour composite RGB 832 does not create a good colour contrast between different geological features. The ASTER colour composite RGB 421 highlights the igneous rocks and delineates different geological features better than colour composite ASTER band image RGB 321.

Table 5: Correlation matrix of VNIR and SWIR ASTER bands (from Council for Geoscience, 2014).

Correlation	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9
Band 1	1								
Band 2	0.987	1							
Band 3	0.978	0.985	1						
Band 4	0.785	0.747	0.797	1					
Band 5	0.780	0.743	0.786	0.992	1				
Band 6	0.778	0.743	0.787	0.992	0.997	1			
Band 7	0.786	0.753	0.794	0.990	0.995	0.995	1		
Band 8	0.772	0.739	0.779	0.987	0.994	0.993	0.996	1	
Band 9	0.781	0.746	0.785	0.986	0.994	0.992	0.995	0.995	1

Table 6: Correlation matrix of ASTER TIR bands (from Council for Geoscience, 2014).

Correlation	Band 10	Band 11	Band 12	Band 13	Band 14
Band 10	1				
Band 11	0.999	1			
Band 12	0.999	0.99	1		
Band 13	0.999	0.999	0.999	1	
Band 14	0.994	0.999	0.993	0.9943	1

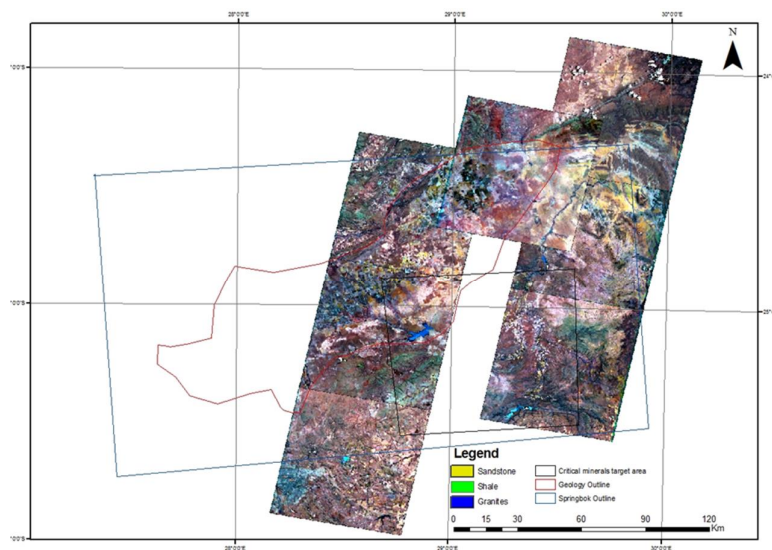


Figure 15: Colour composite image of RGB 621 (from Council for Geoscience, 2014).

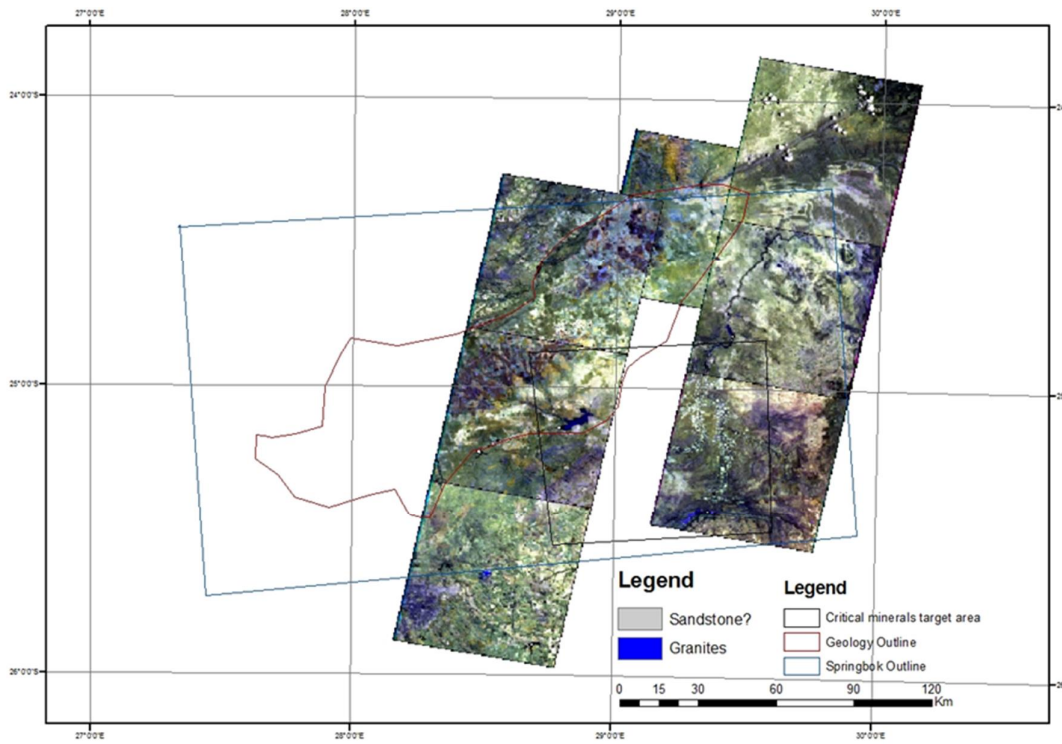


Figure 16: Colour composite image of RGB 862 (from Council for Geoscience, 2014).

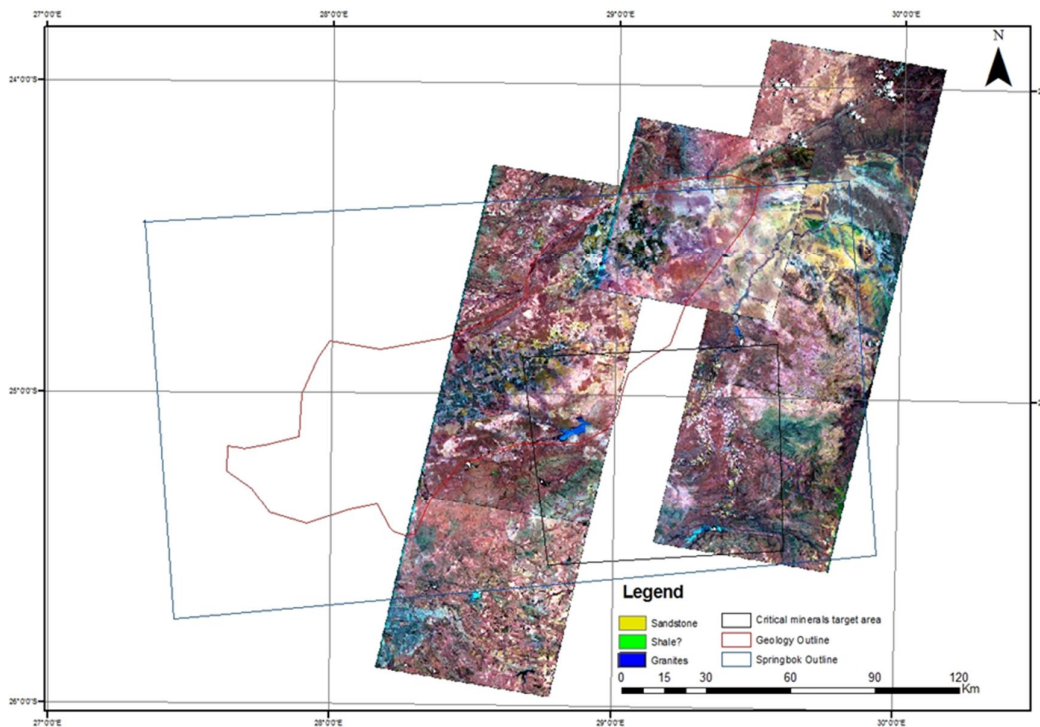


Figure 17: Colour composite image of RGB 421 (from Council for Geoscience, 2014).

5.1.2. BAND RATIOS

The band ratio technique divides pixel values of one band with another band, to emphasize differences in the spectral reflectance of materials. It is useful for reducing the effect of illumination direct from the sun, topographic slope and shadows. The bands to be rationed are determined based on the reflectance and absorption properties of the desired geological features. This method creates a greater contrast between the units, which will mitigate the feature of recognition. This technique has been widely used in mineral exploration. To determine the best band ratio for delineating a geological feature, it is important to select bands in which the target geological feature has high value or vice versa, relative to their surrounding features. However, it is almost impossible to achieve this aim, especially in low spectral resolution satellite images, because of the spectral reflectance correlation of other minerals. Therefore, it is important to examine different possible band ratios.

Based on the experimentation with different colour composite and colour composite statistical techniques used earlier in this study, it has been inferred that the major geological features (outcrops) of the study area have high reflectance in band 2 (0.630-0.690 m) and band 4 of ASTER. To better highlight these outcrops, difference normalized index (DNI) has been developed using ASTER bands 4 and 2,

$$\text{DNI} = (\text{b4} - \text{b2}) / (\text{b4} + \text{b2})$$

The ASTER normalized index has been used as one of the fundamental colours. Also band ratio 2/1 was used for highlighting the iron oxide bearing rocks.

The proposed grey scale (Figure 18) and colour composite (Figure 19) band ratio image produced from combination of 6/8:4/8:12/13 as Red:Green:Blue (R:G:B) was also used and it was very useful for detecting basalt rocks in the study area. Ninomiya et al. (2005) proposed several mineralogical indices Mafic Index (MI) for detecting silicate rocks with ASTER-TIR data. This mineralogical index provides one unified approach for lithological mapping in arid and semi-arid regions of the earth. The mafic index was applied on the current study area is expressed as:

$$\text{Mafic index} = \text{b12}/\text{b13}$$

MI is expected to be high for mafic and ultramafic rocks and low for felsic rocks.

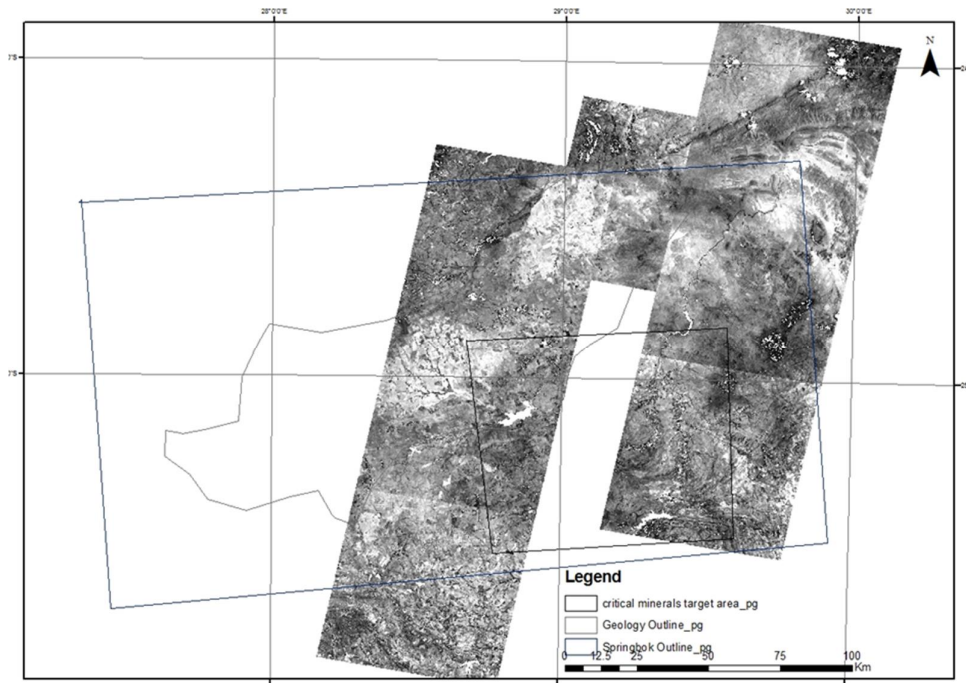


Figure 18: Gray-scale image of mafic Index (MI). Mafic and ultramafic rocks, mainly basalt rocks as white whereas felsic rocks as dark colour (from Council for Geoscience, 2014).

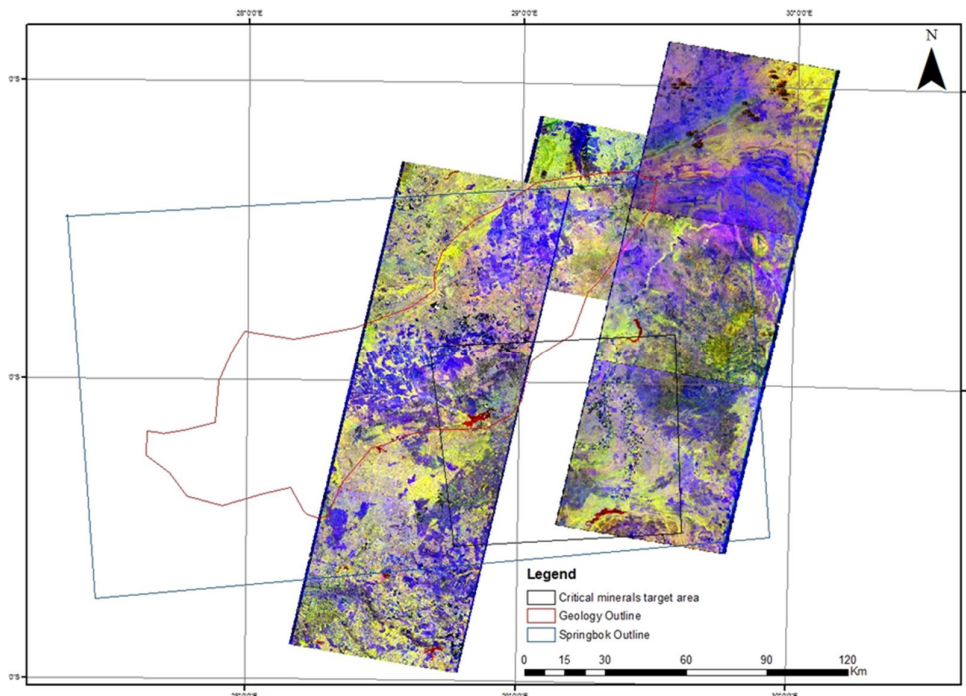


Figure 19: False colour band ratio combination 6/8:4/8:12/13 for R:G:B ASTER data. The basalt appears purple and for the Springbok Flats area it represents the Letaba Basalt (from Council for Geoscience, 2014).

5.2. GEOCHEMISTRY

The definition of a geochemical anomaly related to mineralization implies more than just unusually high or low values of the content of an element in a sample media. Many geochemical anomalies are unrelated to mineralization. The following interpretation was done based on the crustal abundance of the chemical elements.

Table 7: A Table showing the calibration range of elements, precision of in-house monitor and the summary statistics of the complete data set (after Wolfaardt & Van Rooyen, 2001).

TABLE 1: Calibration concentration range of elements in reference materials that were used and the calculated determination limits (DL)			TABLE 2: Precision of in-house monitor Element n = 110							TABLE 3: Summary statistics on the complete data set (n = 22 256) for sheet 2428 Nylistroom							
Element	Range (ppm)	DL (ppm)	Element	Mean	Std Dev.	Minimum	Maximum	Range	Precision	Element	Mean	Std Dev.	Minimum	Maximum	Mean + (2 x StdD)	Range	Crustal Abundance
Sc	1-55	1	Sc	202	4	195	219	18	4	Sc	16	9	<DL	126	35	126	22
TiO ₂	0,2-3,77%	100	TiO ₂	6,43	0,03	6,34	6,49	0,15	1	TiO ₂	0,91	0,41	0,10	10,45	2	10,35	0,57
V	9-526	5	V	2.000	13	1.953	2.023	70	1	V	74	71	<DL	2.179	216	2.179	135
Cr	10-2.900	4	Cr	1.822	7	1.802	1.837	35	1	Cr	242	1.057	<DL	82.115	2.356	82.115	100
MnO	0,01-0,32%	100	MnO	1,39	0,07	1,25	1,45	0,2	10	MnO	0,12	0,21	0,01	9,99	1	9,98	0,09
Fe ₂ O ₃ T	1,40-18,76	100	Fe ₂ O ₃ T	14,23	0,2	13,9	14,56	0,66	3	Fe ₂ O ₃ T	5,51	3,33	<DL	30,62	12	30,62	5,63
Co	11-210	10	Co	1.002	16	970	1.024	54	3	Co	20	58	<DL	887	135	887	25
Ni	10-2.380	10	Ni	1.036	2	1.030	1.043	13	0,4	Ni	52	107	<DL	5.202	267	5.202	75
Cu	19-1.230	9	Cu	562	2	558	567	9	0,7	Cu	37	44	<DL	2.470	125	2.470	55
Zn	10-680	3	Zn	516	6	508	526	18	2	Zn	48	55	<DL	5.643	158	5.643	70
As	18-412	10	As	165	3	156	172	16	4	As	16	17	<DL	845	49	845	1,8
Rb	9-860	1	Rb	569	2	563	572	9	1	Rb	114	72	<DL	870	258	870	90
Sr	25-1.100	1	Sr	337	0,78	335	339	4	0,5	Sr	68	68	<DL	1.362	205	1.362	375
Y	5-718	1	Y	146	0,65	144	147	3	1	Y	42	35	<DL	624	112	624	33
Zr	22-1.210	1	Zr	831	1,5	828	835	7	0,4	Zr	836	639	<DL	7.070	2.114	7.070	165
Nb	10-960	5	Nb	161	0,5	161	162	1	0,6	Nb	23	11	<DL	180	44	180	20
Sn	3-370	2	Sn	9	1,3	5	12	7	29	Sn***	<2	13	<DL	986	27	986	2
Sb	10-2.000	5	Sb	13	4,7	3	23	20	72	Sb*	21	112	<DL	2.594	244	2.594	0,2
Ba	114-2.400	10	Ba	1.069	14	1.029	1.104	75	3	Ba	456	324	<DL	3.246	1.105	3.246	425
W	24-490	4	W	18	3	12	24	12	33	W	9	6	<DL	366	22	366	1,5
Pb	11-636	4	Pb	1.435	10	1.408	1.456	48	1	Pb	13	21	<DL	657	54	657	12,5
Th	17-1.000	4	Th	71	1	69	74	5	3	Th	20	12	<DL	163	43	163	9,6
U	9-650	2	U	14	1	11	17	6	14	U**	<2	3	<DL	39	7	39	2,7

NOTES (TABLE 3): * Variable briquette thickness results in an "Infinite Thickness" analytical error. Map intervals were set to > 15 (Sn) and > 40 (Sb) respectively. ** Calculated MEAN less than determination limit. Mean + 2 StdD is an approximate value. DL - Determination Limit

The scattered As anomalies are found in the Black Reef Formation. Figure 20 shows the regional soil geochemistry of As with values ranging between 0.5 to 32.5 ppm. The high As values are associated with the known fluorite, molybdenum, REEs and gold mineralization (Wolfaardt & Van Rooyen, 2001). The iron formation and the Penge formation are outlined by high concentrations of Sc, Fe₂O₃T, MnO and Co. The Co concentrations on the Penge Formation are anomalous because of the Fe₂O₃T interference resulting from the analytical technique used (Wolfaardt & Van Rooyen, 2001). Dolomite of the Deutschland Formation shows anomalous MnO values. The Malmani Subgroup dolomite contains high concentrations of MnO and As. Moderate to low Th values outline Magaliesburg formation.

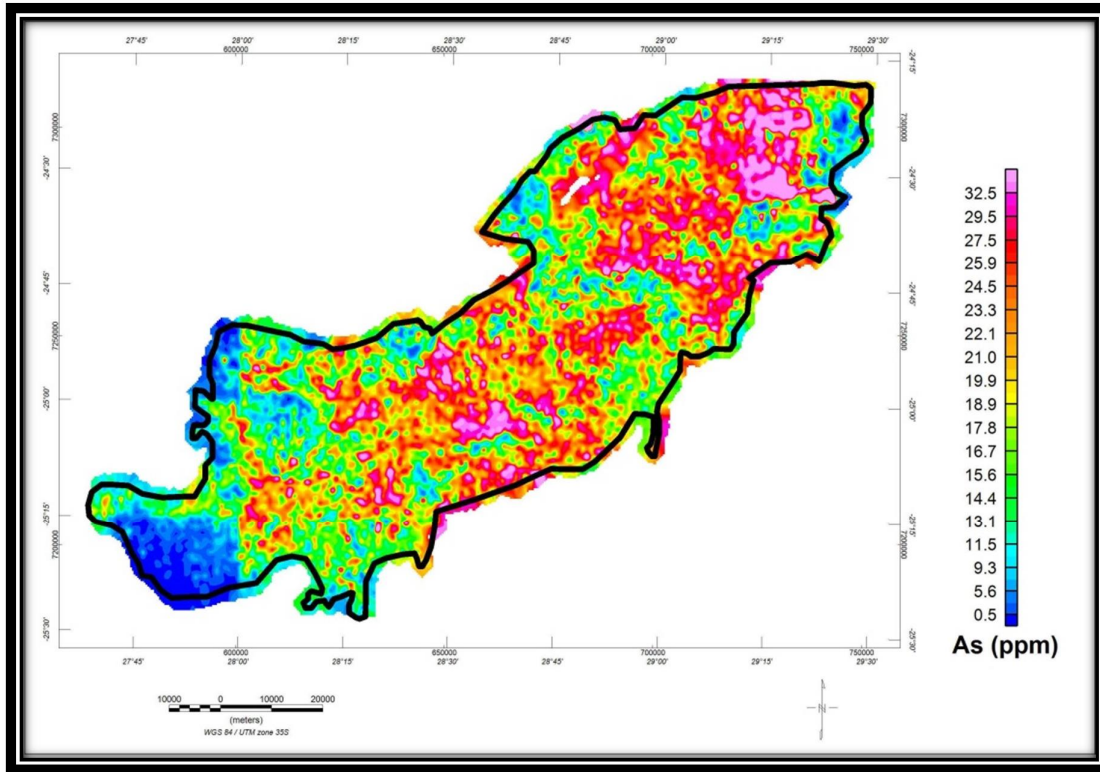


Figure 20: Regional Arsenic soil geochemical map of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

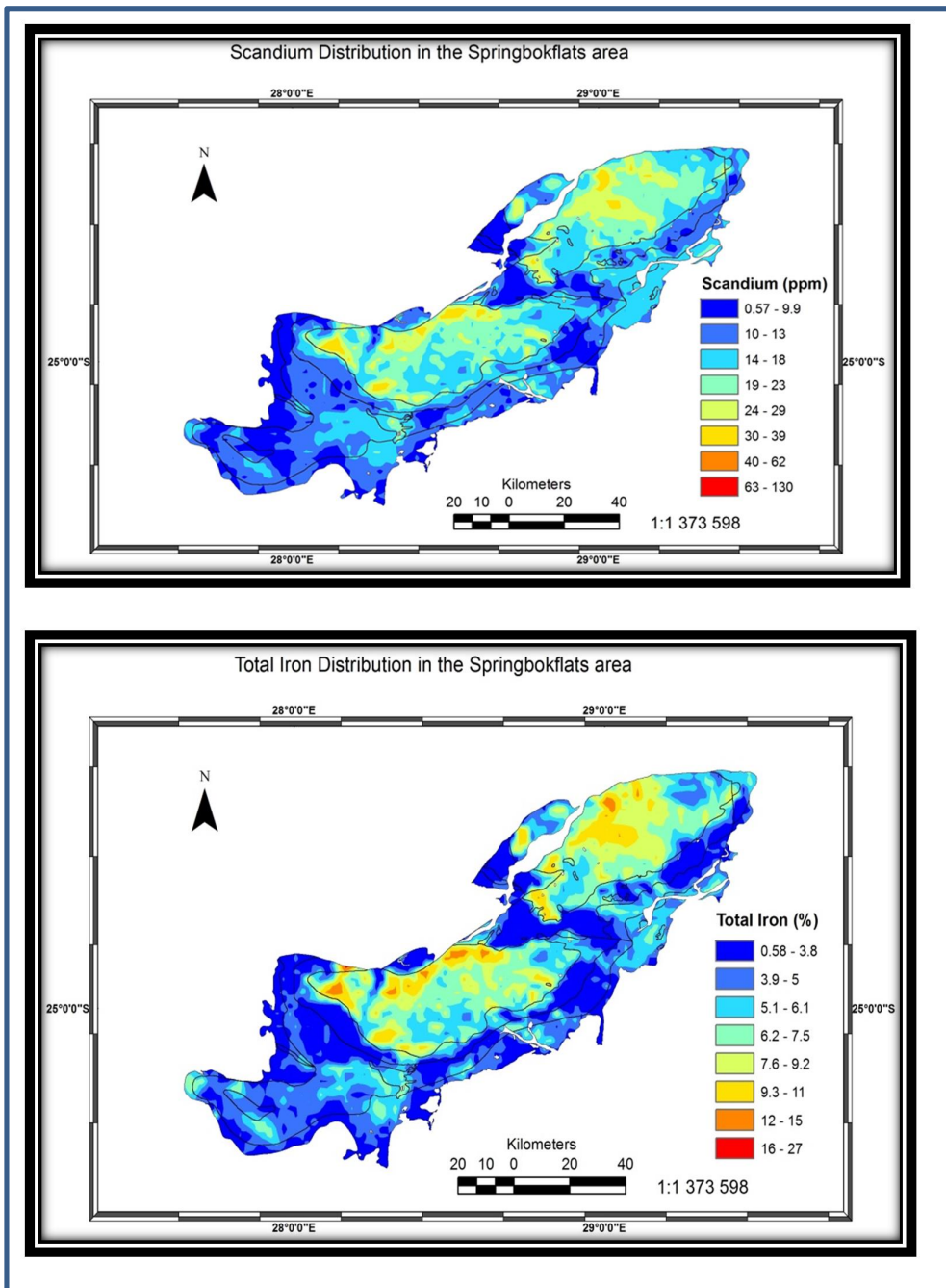


Figure 21: Regional Scandium and Iron soil geochemical maps of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

The Rashop Granophyre shows anomalies for Y, Zr, Nb, Sn, W, Pb and Th. In the Waterberg group the alma formation is mainly recognised by Zr, whereas the Aasvoelkop formation has low background values Sc, Fe₂O₃T, Ba, Nb, Zn, TiO₂, V and Th (Wolfaardt & Van Rooyen, 2001). High anomalous values of Th and U delineate the Lebowa Granite Suite of the

Bushveld Complex. Dolerite sills and diabase dykes are delineated by anomalies of Sc, TiO₂, V, Fe and Cu, while Sr is anomalous in the dolerite only (Wolfaardt & Van Rooyen, 2001).

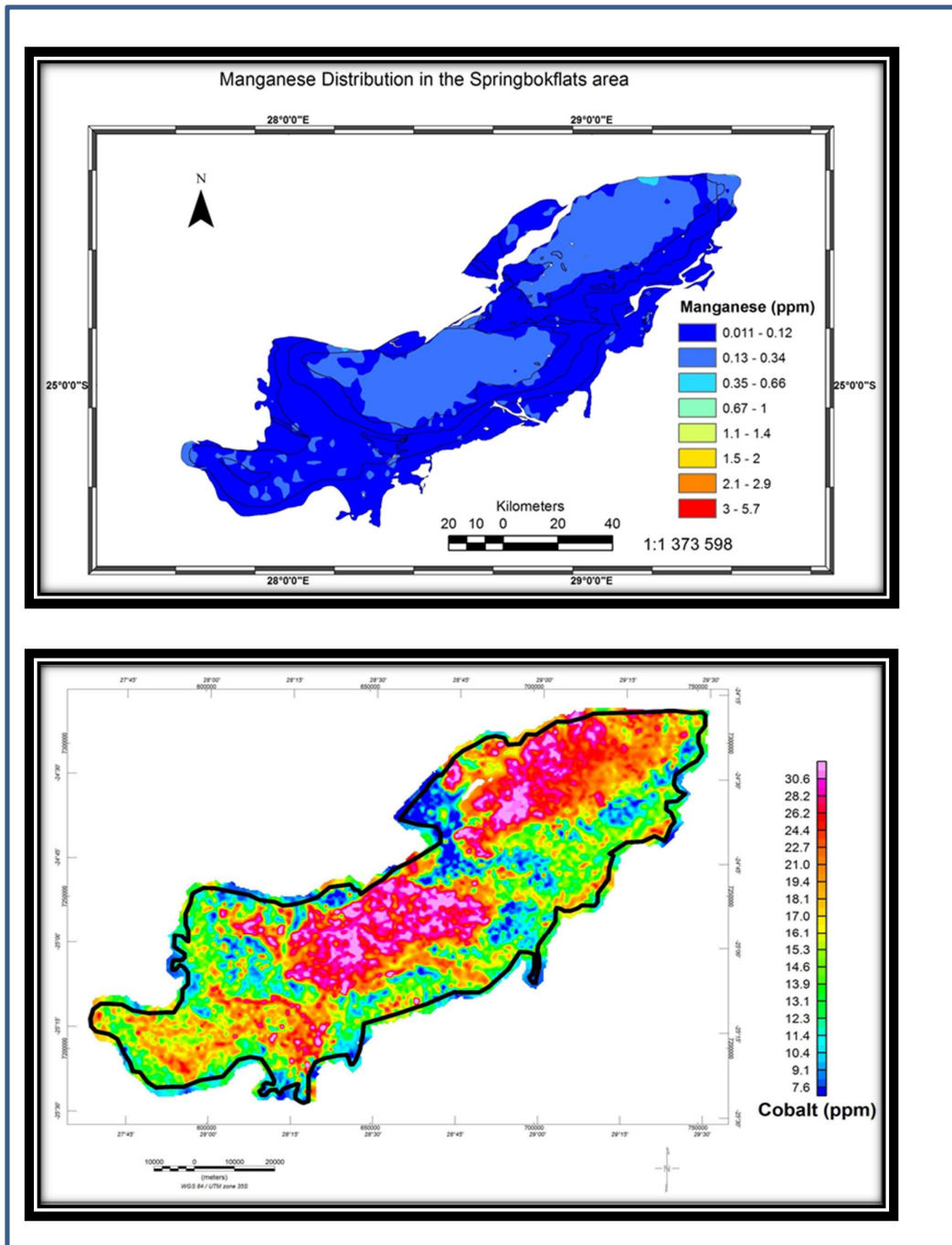


Figure 22: Regional Manganese and Cobalt soil geochemical maps of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

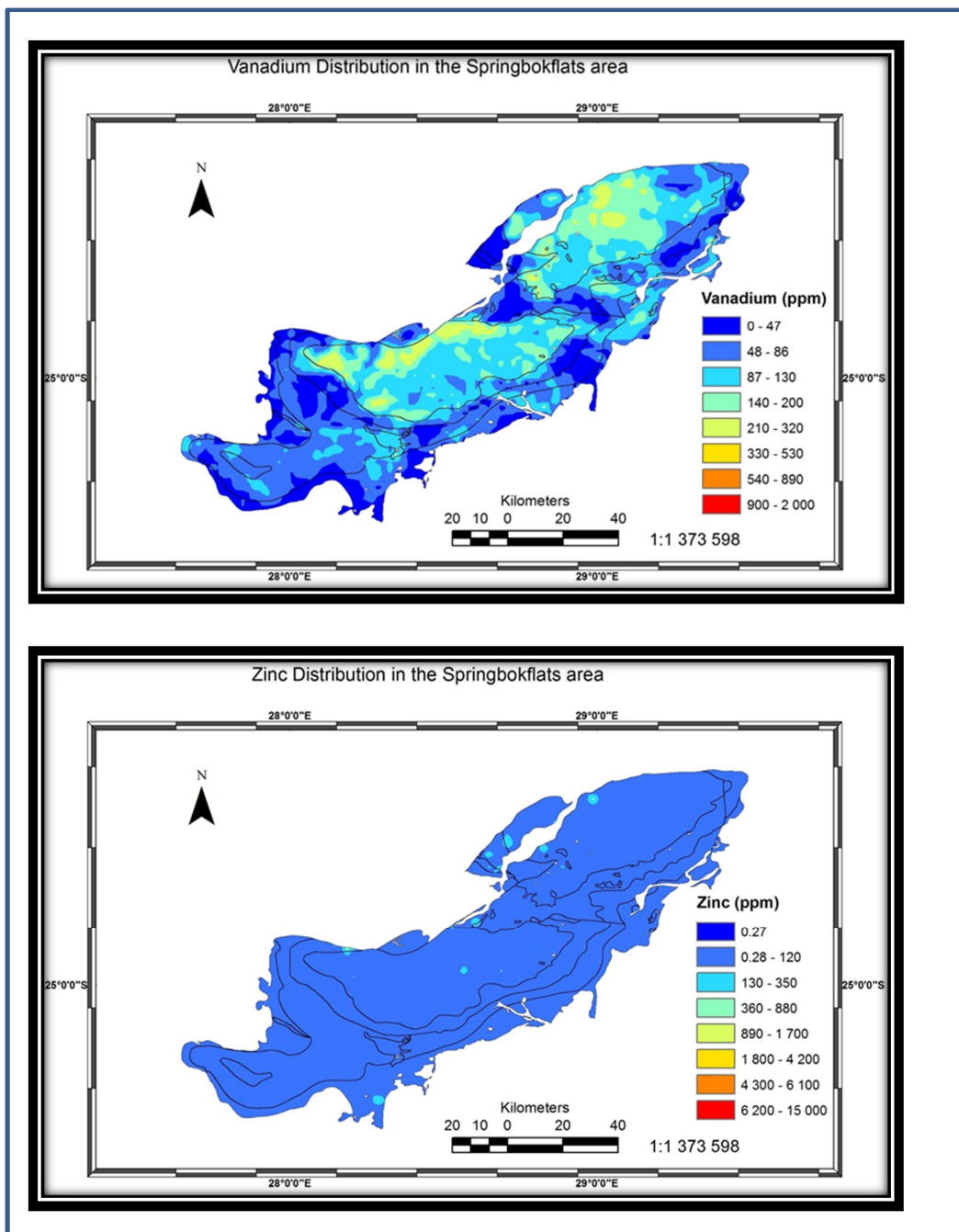


Figure 23: Regional Vanadium and Zinc soil geochemical maps of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

The Ecca group is moderately anomalous in Sc, V and Fe_2O_3T . The high anomalous concentrations of Zr delineate the Clarens formation. Zr is normally present in detrital xenotime, titanite, ilmenite in soils and clays (Levinson, 1974). Zr is also present as a minor constituent in xenotime, titanite and ilmenite (Levinson, 1974). The Zr values ranges from 253 to 1424 ppm (Figure 24).

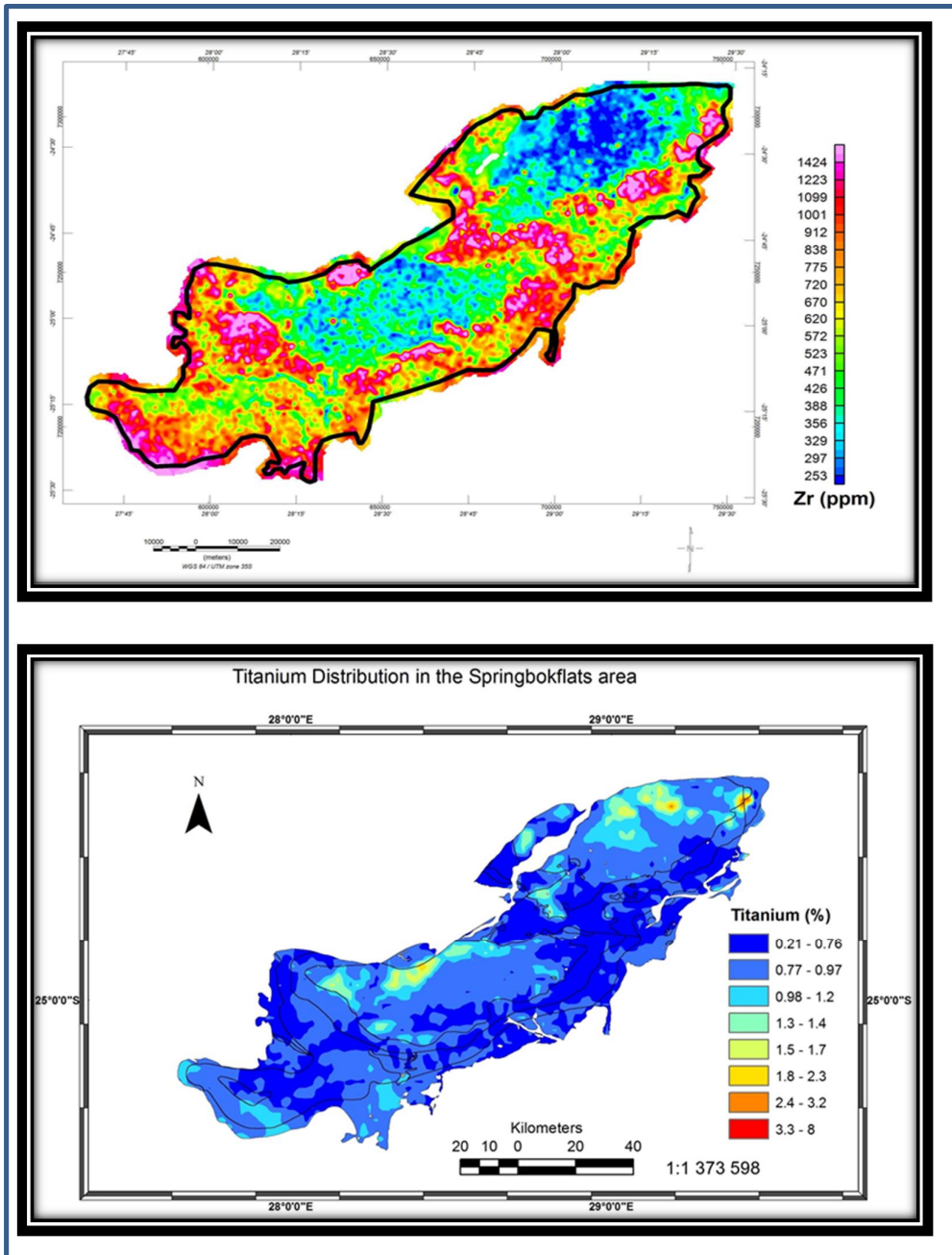


Figure 24: Regional Zirconium and Titanium soil geochemical maps of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

High concentrations of Sc, TiO_2 , V, Fe_2O_3 and Cu delineate the basalts of the Letaba Subgroup. The basalts of the Letaba Subgroup have moderate concentrations of MnO, Co and Ni. High Zn content are due to action of ground water moving through the halos associated with Zn-Pb deposits scattered around the surrounding area (Wolfaardt & Van Rooyen, 2001).

Zn occurs in clays and organic matter, and maybe found in some phosphate fertilizer. Since a lot of farming happens around the area, the Zn anomalies might be false anomalies caused by the fertilizers. The Zn values range from 0.27 to 15 000 ppm with the area dominated by low Zn values (Figure 23). V is a widely dispersed (Figure 23), relatively abundant element occurring in clays and thus it's a good indicator of its own deposits (Wolfaardt & Van Rooyen, 2001).

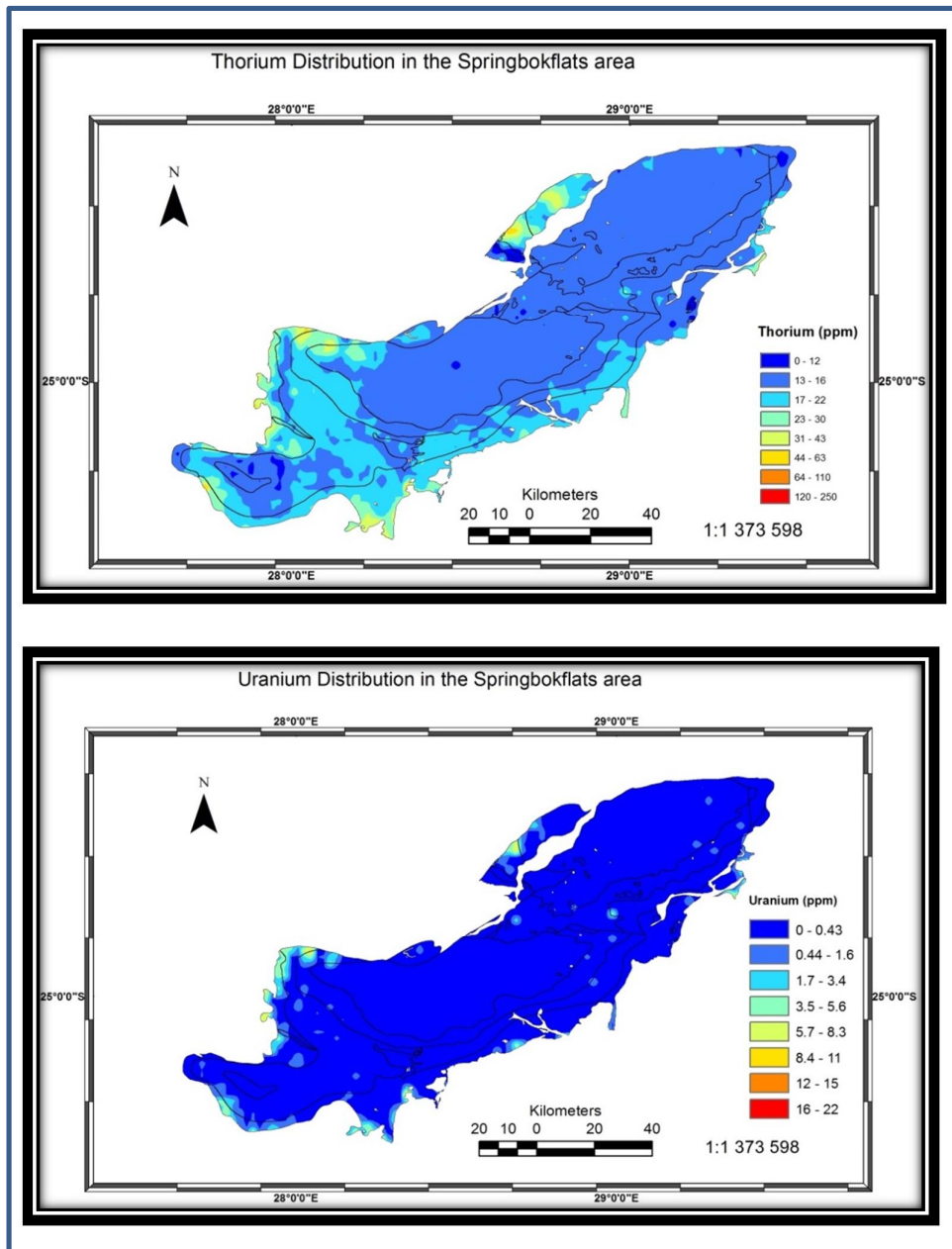


Figure 25: Regional Thorium and Uranium soil geochemical maps of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

The thorium values ranges from 0 to 250 ppm (Figure 25), and the high concentrations of thorium could be due to specific ore-related minerals such as REE-bearing phosphates. Fluorite, molybdenum, tin and REEs occur in association with high thorium values ranging from 40 to 420 ppm. The high values of thorium can be used as an exploration target for REEs and fluorspar mineralization. Uranium values ranges from 0 and 22 ppm (Figure 25). Generally the uranium values are very low, and its highest values are found on the boundary of the Springbok Flats Basin proving the fact that the uranium in the basin was leached from the Bushveld granites. They have very high uranium values ranging from approximately 8 to 65 ppm, which makes most authors question why the Uranium in the Springbok Flats Basin is low if it came from the Bushveld granites.

The strontium values ranges between 23.5 to 95.9 ppm (Figure 27) with high anomalous values dominating the north eastern section of the Springbok Flats Basin. The high Sr values are not related to any type of mineralization or known mineral occurrences in the study area. The trace metals Cu, Fe, Mn and Zn are all concentrated in formation waters but their mode of concentration remains ambiguous. The Cu values ranges from 2.7 to 3400 ppm (Figure 26) and they are scattered throughout the south-western section and the north-eastern section. Since high Cu concentrations delineate dykes and sills, the Cu anomalies in the Springbok Flats Basin might be due to ground water moving through the halos from the nearby Pb-Zn-Cu deposits (Wolfaardt & Van Rooyen, 2001).

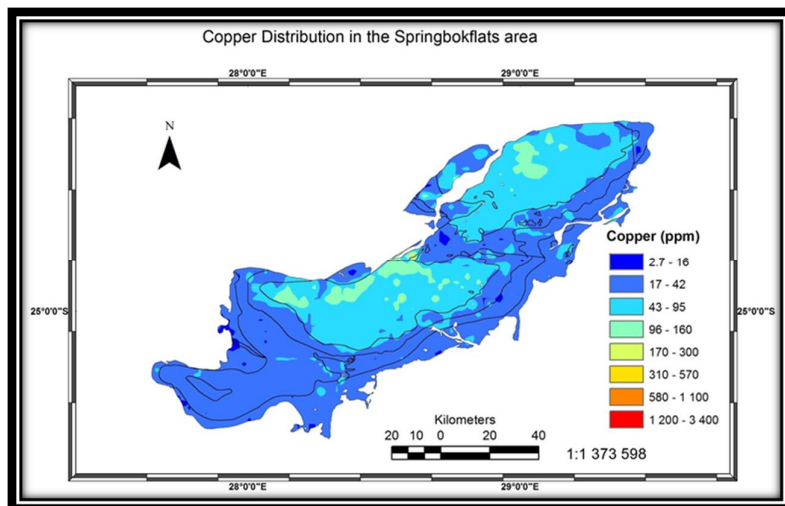


Figure 26: Regional Copper soil geochemical map of the Springbok Flats Basin (Data from Council for Geoscience, 2014).

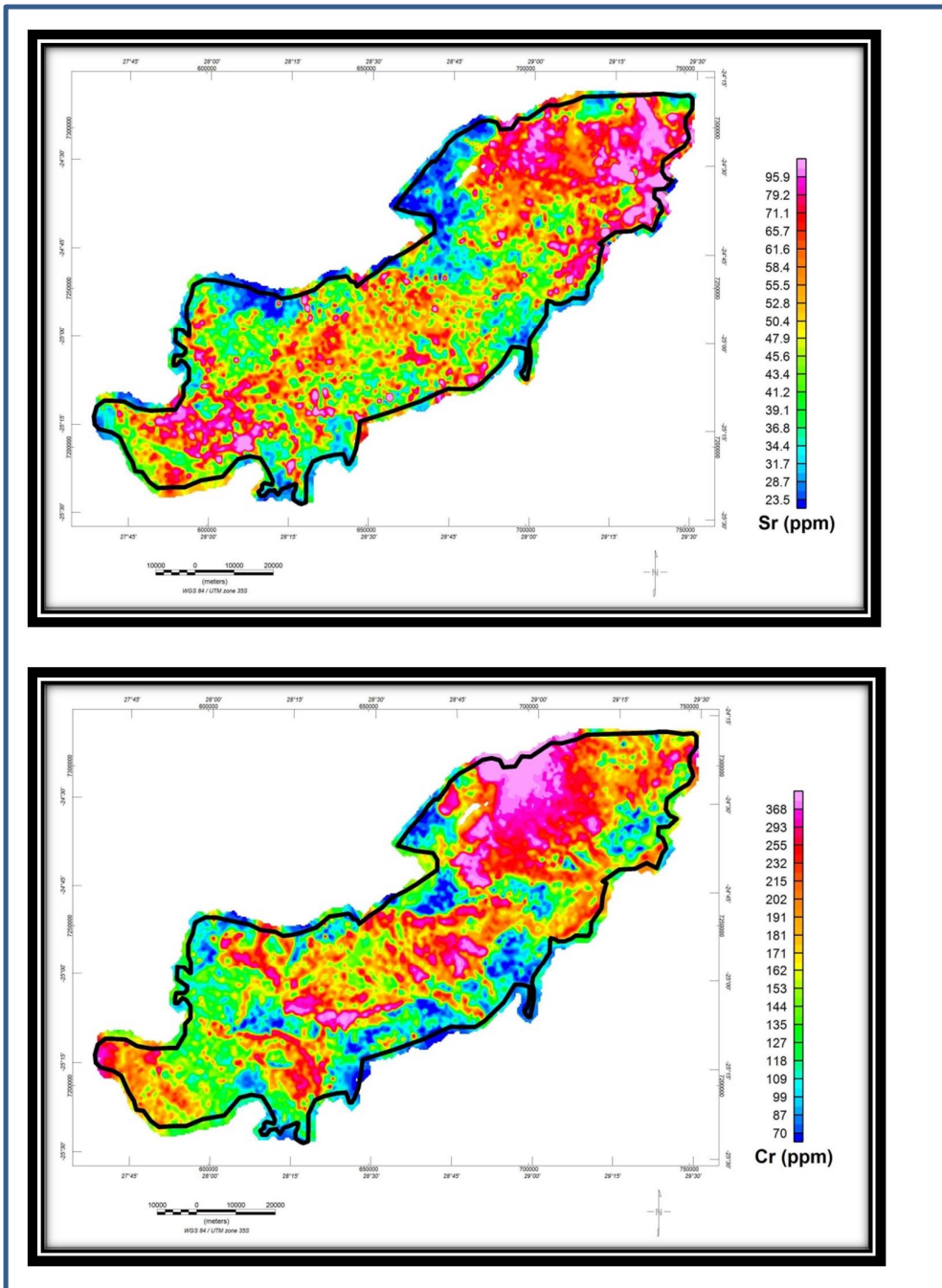


Figure 27: Regional Strontium and Chromium soil geochemical maps of the Springbok Flats Basin (from Council for Geoscience, 2014).

5.3. GEOPHYSICS

5.3.1 RADIOMETRICS

The regional radiometric data (Figure 28) identifies the regional extent of the Springbok Flats Basin as low total count zone. This information is useful in exploration as it gives an idea of limits of the area to which to focus application for prospecting licences. Considering that at a tectonic scale the Springbok Flats Basin is almost entirely bounded by rocks of the Bushveld complex.

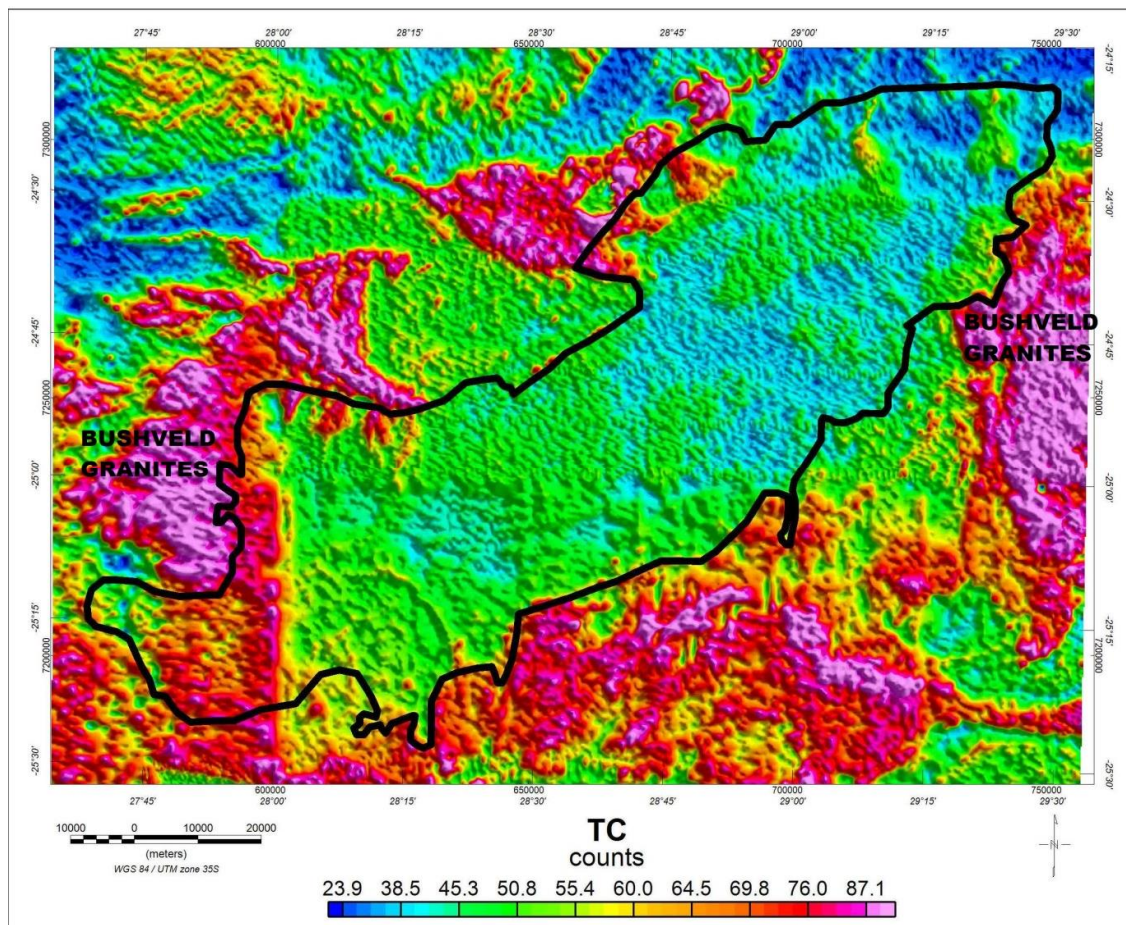


Figure 28: The regional radiometric Total Count map showing the extent of the Springbok Flats Basin. The map shows very low Total Counts values for the study area as compared to the surrounding Bushveld Granites (from Council for Geoscience, 2014).

The fact that the basin is generally surrounded by rocks of the acid phase of the Bushveld Complex makes the radiometric method suitable for identifying the contacts between rocks of the Bushveld Complex and the sediments in the basin. This is because the acid phase granites of the Bushveld complex are highly radioactive to the extent that they are believed by some authors to be the source of the uranium being observed alongside the shaly coal in the basin. The U in the basin is sitting at variable and deep depths that are difficult to detect using the radiometric method which only detects the upper 40 cm of the top soil and hence the data cannot be used for targeting in this kind of a geological setting. The data are only useful in the identification of the extent of the basin as discussed earlier. The airborne radiometric data show linear artefact to the south western portion of the grid and this is not to be taken as related to geology because it is most likely a processing/levelling induced.

5.3.2 MAGNETICS

The regional total magnetic field intensity map is shown in Figure 30. The derivative products of the total magnetic intensity namely the reduction to the magnetic pole (RTP) and the first vertical derivative (FVD) are shown in Figure 29 and Figure 31 respectively. The derived maps are meant to enhance the effect non regional features at that particular scale of observation, e.g. lineaments. The RTP, residuals and FVD maps clearly define the high magnetic susceptibility nature of the surrounding Bushveld rocks as compared to the low Karoo sediment susceptibility within the basin. There are distinct ring shaped picks within the basin possibly due to known Karoo dolerite sills in particular to the central south western part of the grid. The RTP (Figure 29) and the FVD (Figure 31) show scattered high frequency magnetic medium intensity anomalies covering the entire Springbok Basin. These scattered high frequency magnetic anomalies could be due to iron rich soils indicative of the presence of shallow and weathered basaltic lavas attributed to the Letaba Basalts overlying the Karoo sediments of the Clarens Formation.

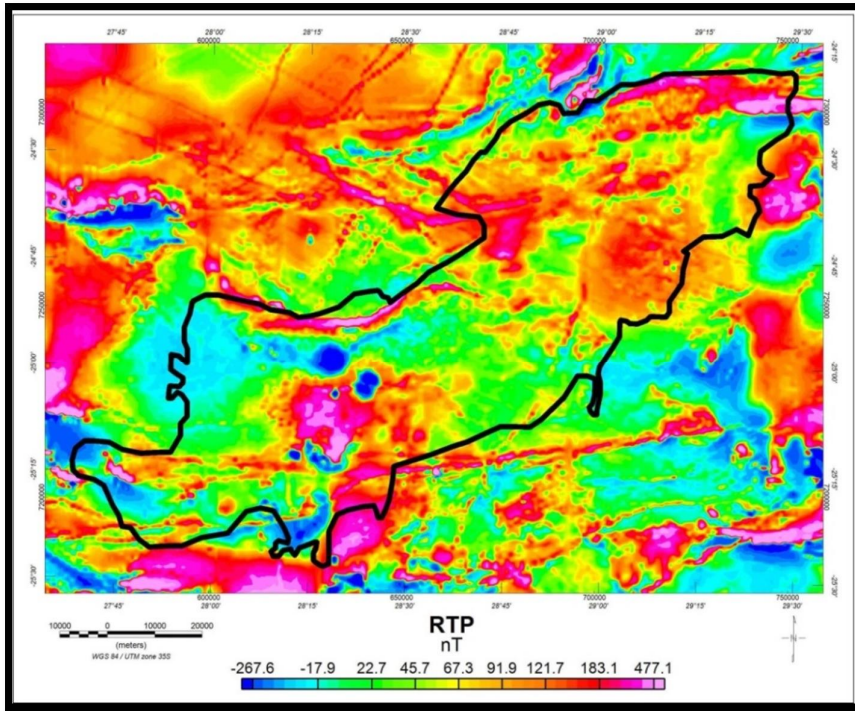


Figure 29: The Reduced to Pole (RTP) map of the Springbok Flats and surroundings (from Council for Geoscience, 2014).

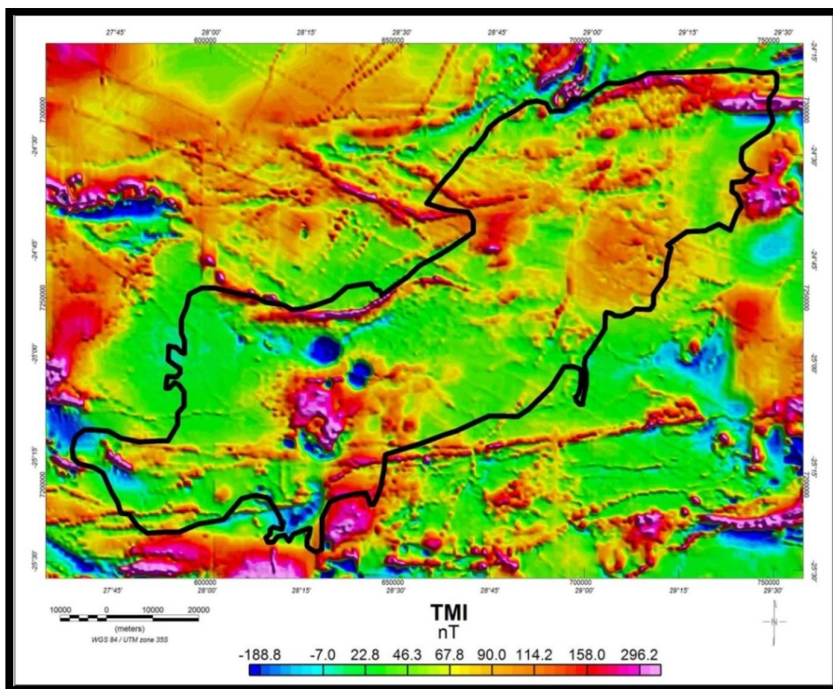


Figure 30: The Total Magnetic Field of the Springbok Flats and surrounding area (from Council for Geoscience, 2014).

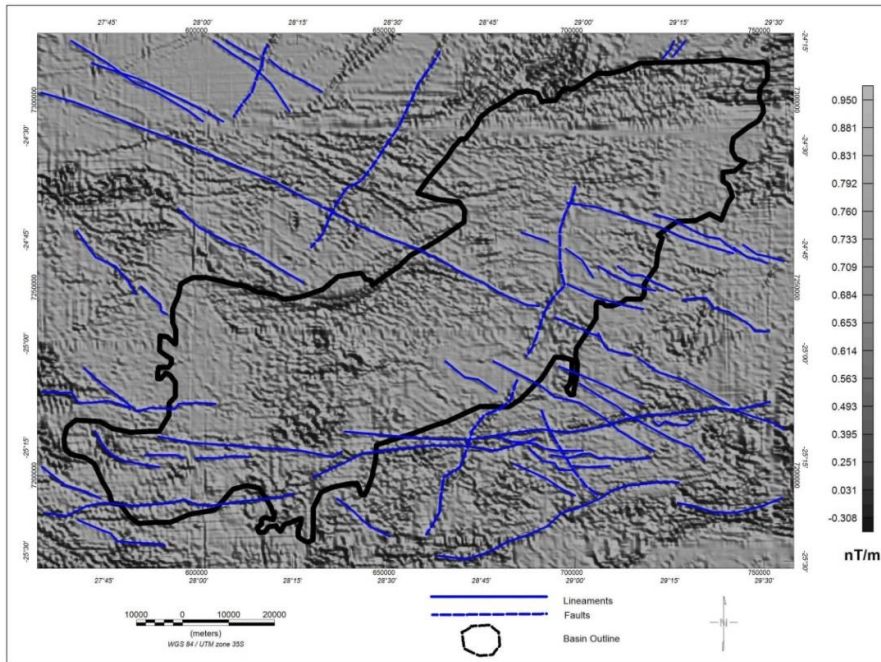


Figure 31: First Vertical Derivative map of the Springbok Flats and the surrounding areas (from Council for Geoscience, 2014).

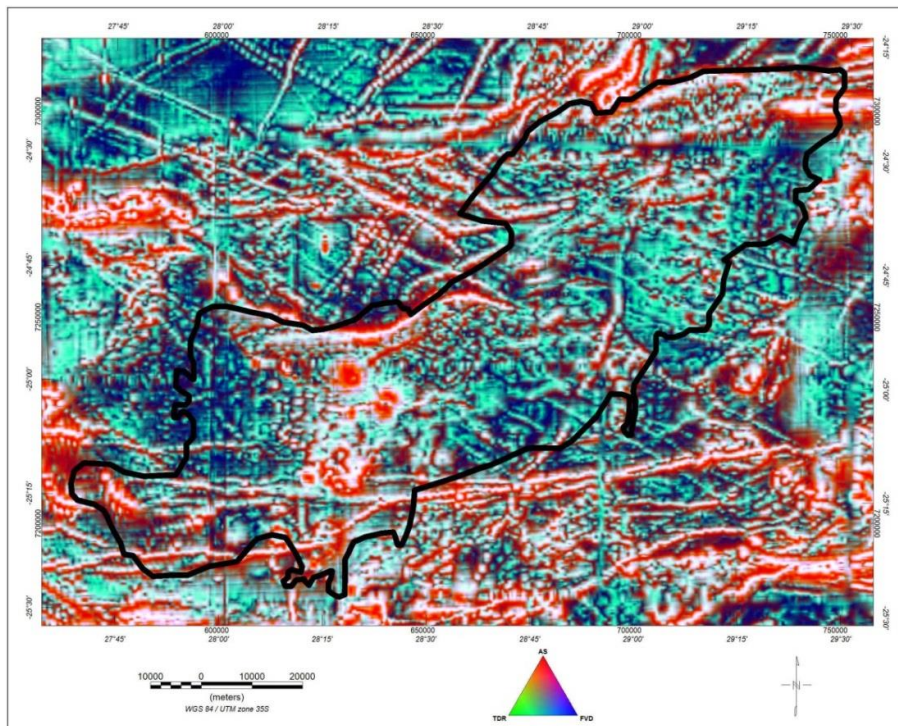


Figure 32: A ternary composite image of the Analytic Signal (red), Tilt derivative (green) and the Vertical derivative (blue) of the residual magnetic field of the Springbok Flats and surrounding areas (from Council for Geoscience, 2014).

A ternary image (Figure 32) comprising of derivatives of the residual magnetic field namely the analytic signal, tilt derivative and the vertical derivative was generated. This was to try and verify whether the edges of the distinct high magnetic anomaly in the central south west portion of the magnetic grids believed to be Karoo dolerite sills. The results indicate concentric high amplitude magnetic anomalies supporting that they could be due to sills.

5.3.3. GRAVITY

5.3.3.1. REGIONAL RESIDUAL GRAVITY

The residual of the national Bouguer grid anomaly was calculated to enhance non regional features. The resulting residual map (Figure 33) shows that the Springbok Flats Basin is a generally a low density region as compared to the surrounding Bushveld rocks. This is due to the fact that sediments are generally of low density as compared to igneous rocks. The density of the Karoo sediments generally vary from 2.55 kg/m³ to 2.87 kg/m³ (<http://196.33.85.22/arcgis/geophysics/geophysics.htm>) whereas for igneous Letaba Formation basalt it is about 2.76 kg/m³ whereas for the Karoo volcanic suite the range is from 2.81 kg/m³ to 3.13 kg/m³ (<http://196.33.85.22/arcgis/geophysics/geophysics.htm>).

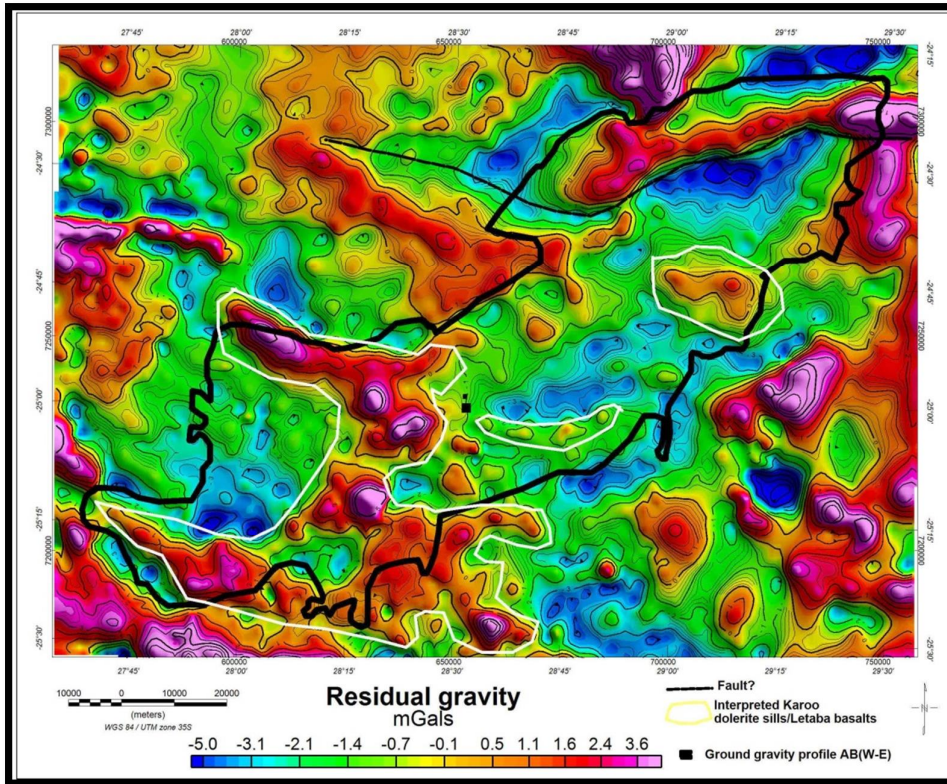


Figure 33: Residual Bouguer gravity map of the Springbok Flats and surrounding areas. Also shown is the location of the ground gravity profile AB (from Council for Geoscience, 2014).

A few distinct gravity highs are clearly shown within the basin. Assuming the effect of the Letaba Formation basalt to the gravity readings is uniform across the basin; these distinct anomalies could be due to Karoo dolerite sills as they coincide with areas of distinct high magnetic signature. Contrary to the magnetic field the residual Bouguer shows a large sheet-like ring shaped high density body to the central south western part of the basin, suggesting that the interpreted sill possibly covers a large area. This is very possible as it has been observed in a number of drill holes (Myburgh, 2012) within the area of approximate extent. Towards the north-eastern part of the residual gravity map within the basin is reduced intensity gravity anomaly. The reduced intensity possibly indicates a deeper depth of burial for the interpreted sill.

CHAPTER 6: DISCUSSION

Image analysis techniques can be used to better interpret the geological features and their mineralogy. The color composite technique is a fast and easy technique for highlighting different geological features. Mineralization associated with sedimentary sandstone deposits in the Springbok Flats Basin can be targeted by delineating silica rich outcrops using the Aster color composite ratios. Mineral occurrence data (Figure 35) and the soil geochemical data don't full correspond but few mineral occurrences fall under the target area and these are areas where high geochemical values are present. T1, T2, T3 and T7 are such areas and they can be further explored to confirm if they are potential of mineralization. High values of Scandium, Iron, Vanadium, Titanium and Copper correspond with the magnetic anomalies on the south-western section and at some few parts on the north-eastern section (T1, T2, and T4). The Cobalt anomaly corresponds with target 4 (T4) and target 2 (T2), while Strontium corresponds with target 1 (T1) and Cr with target 2 (T2). Manganese scavenges cobalt thus the T4 and T2 targets might be false anomaly created by the presence of manganese in the area. Some of the other high geochemical values as well might not be because of mineralization but further exploration work will need to be done to confirm this.

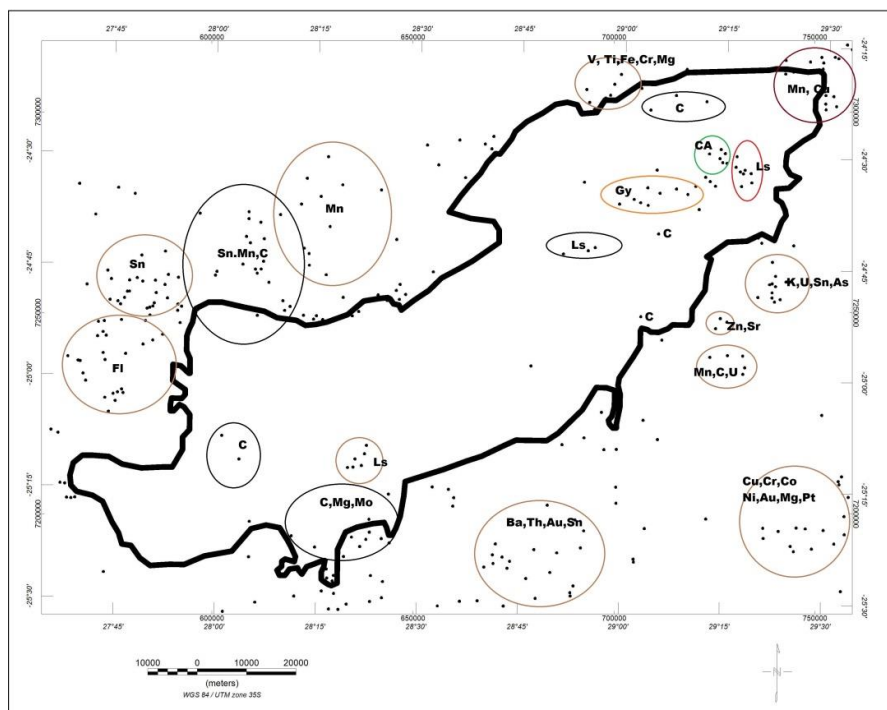


Figure 34: Mineral occurrence map of the Springbok Flats Basin and the surrounding area (from Council for Geoscience, 2014).

The regional magnetic map of the Springbok Flats Basin shows that the basin is dominated by low to very low magnetic values. These low magnetic field values might be due to the fact that the magnetic susceptibility of dolerites and lava are of the same magnitude, thus making it difficult to distinguish between lavas and dolerites. This is why on the northeastern section the high anomalous dolerite sills are clearly visible on the gravity map. The two circular magnetic anomaly lows (Figure 36) at target 5 (T5) may be due to Kimberlite pipes under the Karoo which have not yet erupted to surface.

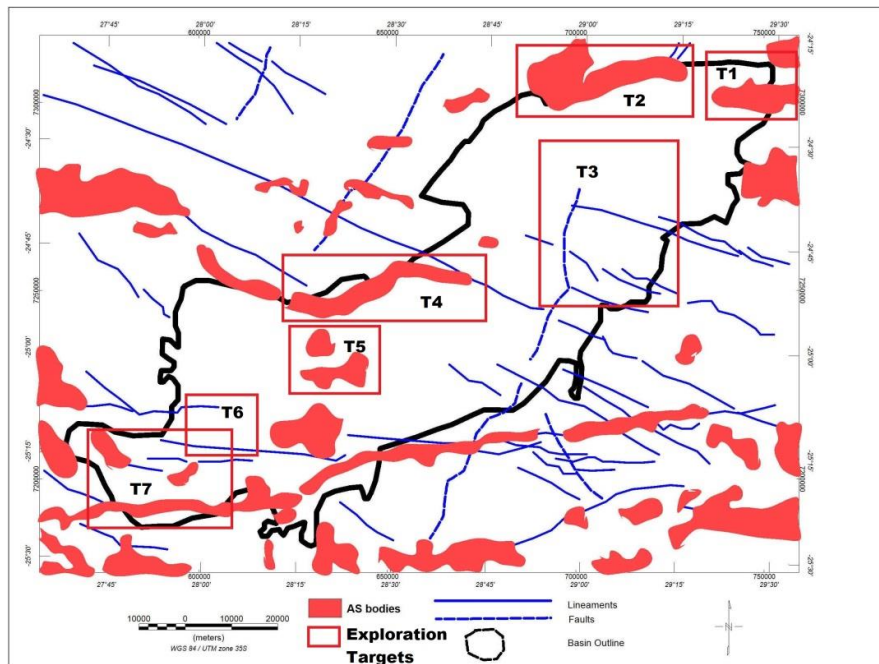


Figure 35: Target generation map derived from the magnetic and the geochemical data sets in the Springbok Flats Basin (from Council for Geoscience, 2014).

Since the gravity survey can be used to identify trapping sites or basin outlines, target 3 (T3), target 6 (T6) and target 7 (T7) (Figure 36) can be used to explore for oil shell, coalbed methane gas and coal depending on the tectonic history. The relationship between lineaments and oil shell occurrences is difficult to assess due to the low resolution of the data set. But we know from literature that in areas where the sills intruded in close proximity to the coal, total devolatilisation of the coal occurs. Sills also act as hydrocarbon reservoirs, either as seals or as fractured reservoirs themselves. Dykes may only contribute to the formation of coalbed methane and oil shell reservoirs. Reservoirs formation may then be encouraged at sill-faults or sill-dyke contacts provided the dykes/faults have low permeability. The fact that the coal is

situated very deep and that it has high vitrinite content makes it suitable for gas exploration, especially on the northeastern section (T6 and T7).

All in the entire Springbok Flats basin can be explored for coal, coalbed methane, oil, uranium, gypsum, limestone and kimberlites. Coal resources were estimated to be 1700 Mt (De Jager, 1976; Myburg, 2012; Jeffrey, 2005) and uranium resources were estimated to be 77 072 metric tons (Jeffrey, 2005). Other commodities such as limestone etc. have not been estimated because not enough exploration was done in the basin. Coetzee (1961) estimated the gypsum resources to be approximately 500 00 tons with an average grade of 20% gypsum.

Geologically it is known that the tectonic events associated with the assembly of the Kaapvaal Craton impacted directly on the development and sedimentation associated with the Karoo Supergroup in Southern Africa. The Springbok Flats Basin basin comprises two elongated NNE to SSW synclinal flexures separated by an anticlinal flexure with the same strike. The synclinal flexure bordering the anticlinal flexure to the north is referred to as the Roedtan Basin, which is bordered by the Zebediela Fault to the north (Nel, 2012). The synclinal flexure that developed south of the anticlinal flexure is defined as the Settlers-Tuinplaats Basin and is bordered by the Droogekloof Fault to the north. Both these faults forms part of the Thabazimbi-Murchison Lineament tectonic regime (Visser and Van der Merwe, 1959).

These tectonic zones of weakness caused by the Thabazimbi-Murchison Lineament constitute favourable environments for deposition of uranium and Kimberlites. High concentrations of uranium in the basin occur in close proximity of the palaeo-topographical highs especially where these highs comprise granites of the Lebowa Suite of the Bushveld Igneous Complex (Nel, 2012). The development of coal in the basin might have been limited by the pre-Karoo topography in areas adjacent to the topographic highs. Local fracturing due to post-Karoo faulting in the basin can be an ideal place for coal bed methane exploration, especially since the coal is situated at depth.

The position of the dolerite sills can be accurately determined in areas where the Clarens and the Elliot Formations of the Stormberg group outcrops. The position of the dolerite in areas where the Drakensberg Group outcrops cannot be accurately determined because both the dolerite and lava have the same magnetic susceptibilities. The soil profile in the basin comprises of black and reddish brown turf, with sandy soils restricted to the anticlinal flexure that separates the Roedtan Basin and the Settlers-Tuinplaats Basin. The black turf soils are indicative of deep weathering and poor drainage conditions; hosting both calcrete and gypsum deposits (Nel, 2012). The concentration and accumulation of gypsum in these poorly drained black turf soils might have been enhanced by the weathering of pyrite occurring in the underlying lavas.

CHAPTER 7: TARGETING CRITERIA IN THE SPRINGBOK FLATS BASIN

Based on the overview and the analysis of the geochemical, geophysical and satellite imagery for the basin an exploration targeting criteria is described:

1. Radiometric data provide the simplest method for delineating the extent of the basin, which is a guide as to the limits of acidic phase granites.
2. The basin is reported to be faulted and faulting results in downthrows of various magnitudes especially when grabens and horsts are being formed. This eventually affects the depth at which intersection of the uraniferous coals is expected for drilling and feasibility studies.
3. A further study of the lineaments to determine the normal faults is essential for targeting for CBM. Ideally the downthrown sediments have a more favourable chance of forming and trapping a better CBM resource. However there is a chance that the gas may escape through the fault structure to the surface so it is important to understand the fault mechanisms.
4. Identification of lineaments is an important part of the advanced exploration and prefeasibility stage of mining as structures have to be input in the resource estimation models and the mine plans.
5. Intrusions such as Karoo dolerite dykes and sills devolatilize the coal thereby lowering the rank of the coals for beneficiation purposes. Therefore identification of potential intrusions that affect the quality of the coal should be prioritized during localized targeting. The gravity data identify high density bodies that coincide with magnetic high anomalies and these could be linked to the Karoo intrusives that could devolatilize the coal and evaporate CBM.
6. The gravity data may be used to develop conceptual models for exploration purposes so as to identify the areas where the sediments are thicker to improve the targeting and drill hole planning.
7. Satellite imagery has got its challenges especially in areas of vegetation but it does provide a very useful tool in exploration. A number of spectral analysis techniques and band ratios can be used to differentiate the areas underlain by the Letaba basalts, the Karoo

sandstones/shale and Bushveld granites for mapping purposes. The priority focus will be on the shallower Karoo sediments because of the potential for cheaper mining.

8. A combined analysis of the datasets may shed light into the little understood genesis of the uranium in the Springbok Flats basin.

9. Coupled to the above geophysical logging using the following needs to be performed on drill holes drilled within the basin.

10. The geochemical mapping data provide an overview of the relative abundance levels, regional trends and anomalous patterns in the underlying lithological units.

11. The geochemical data can be used to identify the crustal abundance of elements and their anomalous values in soils.

12. The geochemical results show an excellent correlation between soil chemistry and underlying geological formations.

CHAPTER 8: CONCLUSIONS

The basin is faulted and faulting zones are at various depths where intersection of the uraniferous coals is expected for drilling and feasibility investigations. It is important to study the lineaments for determination of the normal faults to target CBM with the downthrown sediments, which provide a more favourable chance of forming and trapping a better CBM resource. Intrusions such as Karoo dolerite dykes and sills devolatilize the coal, lowering the coal ranks for beneficiation, therefore, it is prioritized to identify intrusions for localized targeting.

The gravity data coincide with magnetic high anomalies, which suggest that they are linked to the Karoo intrusives, where are the places to devolatilize the coal and evaporate CBM. Identification of lineaments in the Springbok Flats Basin is important to conduct advanced exploration in prefeasibility stage as structures have to be input in the resource estimation models and the mine plans.

A conceptual model of the sedimentation was generated based on ground measured gravity data. The satellite imagery has gotten its challenges especially in areas of vegetation but it does provide a very useful tool in the basin exploration, in particular, for identification of lithologies. Intense studies of geophysical data shed light into the little understood genesis of the uranium in the Springbok Flats basin. A high resolution geophysical survey is suggested to be carried out over the basin for a better resolution of structures. Geophysical borehole logging is considered to be part of drilling programs in the Springbok Flats Basin.

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