



THE GEOLOGY, PETROGRAPHY, GEOCHEMISTRY AND URANIUM ORE
MINERALOGY OF THE NAMIBPLAAS SHEETED LEUCOGRANITES.
DAMARAN OROGEN, NAMIBIA.

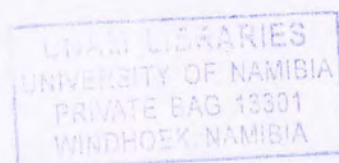
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ABSTRACT

This research study focused on the previously unknown uranium mineralisation hosted in garnet and magnetite bearing sheeted leucogranites (SLG's) / alaskites at Namibplaas. The various SLG's were distinguished and characterised by means of field, petrographic and geochemical studies into B, C and D-types based on the classification scheme of Nex and Kinnaird (1995) in the Goanikontes area. In addition, the stratigraphic positions of the SLG's were established.

The research techniques applied in the study included review of historical data, ground mapping, diamond drill core logging and sample preparation, thin section preparation, geochemical analyses and uranium ore mineralogical investigation.

At Namibplaas, the Damaran sequence is most complete; the B-types are least abundant and are localised to the Kuiseb Formation, the C-types are most abundant and intrude the whole stratigraphic sequence. The D-types are emplaced within the Karibib, Chuos, Rössing and Khan Formations and at the Khan-Rössing-Chuos-Karibib Formation boundaries. The B and C- types are post D₁- D₂ but pre D₃ deformation and are barren in uranium. D-types are post D₁- D₂- D₃ deformation, these are uranium enriched and cross-cut the B and C-types making them the youngest of the intrusives.

The sheeted leucogranites at both Goanikontes and at Namibplaas have undergone similar structural events. But there is however a difference in accessory mineralogy and U & Th geochemistry. The D-types at Namibplaas bear garnet and magnetite. The occurrence of these accessory minerals can be explained as a result of host stratigraphic – assimilation. Individual sheeted leucogranite types are discernable from each other by a number of major, trace and rare

earth element discrimination plots. Uranium and thorium and U/Th ratio distinguishes and characterises the Namibplaas sheeted leucogranites very well. The D-type contain the highest concentrations of uranium (22.5ppm to 1020ppm) with a U/Th ratio > 1 . The C-type sheeted leucogranites show the highest thorium concentrations (10ppm to 301ppm) with a U/Th ratio < 1 . The B-type sheeted leucogranites have lower concentrations of uranium (3ppm to 9ppm) and thorium (5ppm to 17.5ppm)

The late- to post- orogenic conformable and transgressive sheeted leucogranitic bodies range in composition from tonalite to syenogranite. The Namibplaas leucogranites are peraluminous to metaluminous indicating a highly evolved crustal source most probably the Abbabis basement gneisses. Partial melting of the Abbabis basement gneisses which was induced by M_2 resulted in the B and C-type leucogranites. Continued partial melting of the Abbabis basement gneisses during M_3 resulted into the more uranium enriched D-type leucogranites.

QEMSCAN investigation shows that uranium phases present in the D-type sheeted leucogranites are U-oxides as uraninite, U-Ti-oxides as betafite and Th(U)-silicates as uranothorite. The Namibplaas uranium project is typically a low grade high tonnage deposit with a resource in the measured category; 25 Mt at an average grade of 206 ppm U_3O_8 at a cut-off grade of 160 ppm. The project may not be economically viable under the current global uranium price; however, the project may become viable if the global uranium price doubles in the near future.

Further work which can be carried out at Namibplaas may include age dating of the leucogranites in order to establish the sequence of formation of the various leucogranites as well as fluid inclusion studies to determine the pressure and temperature regime, types and

compositions of the ore forming fluids, as well as more detailed structural studies to better constrain the various deformation phases of the Damaran Orogen in relation to uranium mineralisation.

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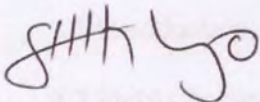
To my family, thank you Mom and Uncle John for your motivation and encouragement. To the Chuabiness (Muffin, Yola, Michi, Steven, Alex and Sackey); thank you for the support.

DECLARATIONS

I, Emmanuel Shilongo, declare hereby that this study is a true reflection of my own research, and that this work, or part thereof has not been submitted for a degree in any other institution of higher education.

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.....
[Emmanuel Shilongo]

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CHAPTER 1

INTRODUCTION

Uranium at Namibplaas is hosted within sheeted leucogranites, commonly known as 'alaskites', a name originally used by Spurr (1900) to describe light coloured alkali feldspar granites. The Namibplaas uranium prospect occurs 75 km southwest of Usakos and 7.5 km northeast of the Valencia uranium prospect (Figure 1.1). The two prospects together form what has been described as the Norasa Uranium Project (Forsys Metals, 2014), which consists of the Valencia (Mining License, ML 149) and Namibplaas (Exclusive Prospecting License, EPL 3638) uranium deposits.

Uranium at Namibplaas was discovered in the 1970's by Trekkopje Exploration and Mining Company, a wholly owned subsidiary of Gold Fields Mining and Development Ltd, who drilled 7 diamond drill holes on the property in the late 1970s and early 1980s, for a total of 1,665.9 meters (Forsys Metals, 2014). Airborne uranium anomaly maps, produced by the Namibian Geological Survey in 1997 indicated the presence of two prominent uranium anomalies on farm Namibplaas (Areas A and B in Figure 1.2), one in the Ababis basement and the other in Damaran meta-sediments (Forsys Metals, 2014). In 2008 Valencia Uranium (Pty) Ltd. commenced exploration at the Namibplaas deposit which is located in area B. A ground scintillometer survey confirmed the two anomalies and also revealed that the A anomaly is characterized by a high thorium and uranium (Th/U) ratio, whereas the B anomaly has a high U/Th ratio. The detailed ground radiometric survey in area B defined the initial drill target measuring 500m by 1,700m on surface (Figure 1.2) (Forsys Metals, 2014).



Figure 1.1 Location of the Namibplaas EPL 3638 and Valencia ML149 uranium prospects southeast of Usakos (Forsys Metals, 2014).

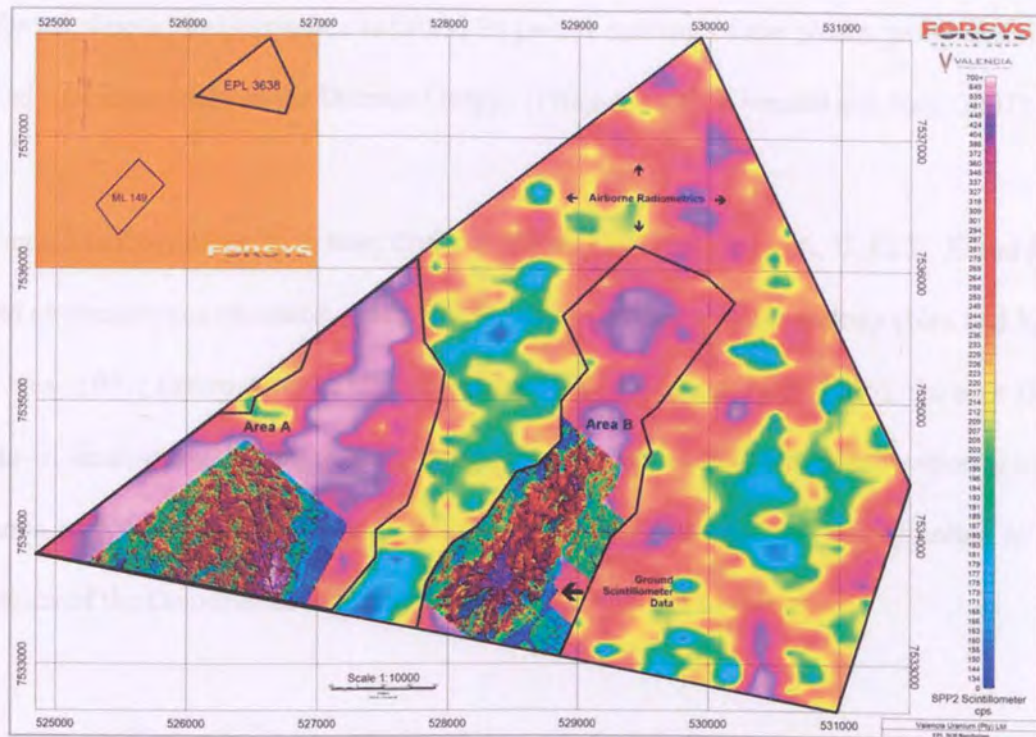


Figure 1.2 Map of Namibplaas (EPL 3638) showing the airborne radiometrics with Areas A and B delineated and superimposed SPP2 radiometric data (Laine & Shilongo, 2011).

By February 2014 Forsys Metals had determined the uranium reserves at Namibplaas to be 25 million tonnes (Mt) at a grade of 206 ppm U_3O_8 at a cut-off grade of 160 ppm compared to 152 (Mt) at 201 ppm U_3O_8 at a cut-off grade of 100 ppm at Valencia (Forsys Metals, 2014).

The uranium mineralisation at Namibplaas forms part of the Namibian uranium province within the Southern Central Zone (SCZ) of Miller (2008) which is characterized by the presence of sheeted leucogranites that intruded Neoproterozoic meta-sedimentary rocks (780 to 746 Ma) close to 2 Ga basement rocks and domes (Kinnaird and Nex, 2016). Ore minerals in the leucogranites include uraninite, betafite, uranophane, uranothorite, carnotite and niobates at currently operating mines of Rössing and Husab, as well as at prospects like Goanikontes and Valencia (Pirajno, 2009; Forsys Metals, 2014; Kinnaird and Nex, 2016). The origin of the

uraniferous sheeted leucogranites is linked to partial melting of the Nosib group and uranium-enriched basement rocks in the Damara Orogen (Pirajno, 1998; Kinnaird and Nex, 2007).

The sheeted leucogranites have been divided into six different types (A, B, C, D, E and F) based on field characteristics of colour, grain size, structural setting and mineralogy (Nex and Kinnaird, 1995; Nex, 1997; Freemantle, 2012). According to Kinnaird and Nex (2016), the post D₃ D and E types of leucogranites are the most prospective for uranium. This classification scheme has relevance at Namibplaas where the occurrence of B, C and D-type leucogranites in various formations of the Damaran stratigraphy have been recognized in this study.

The study area of this thesis (Figure 1.1) is referred to as the Namibplaas deposit or “Namibplaas” which is located within the Farm Namibplaas (Farm “93”, Usakos District, Erongo Region), in the Exclusive Prospecting License (EPL 3638) of Valencia Uranium (Pty) Ltd which covers a total surface area of 1,742 ha.

1.1 Statement of the problem.

In contrast to other sheeted leucogranites elsewhere in the Central Zone of the Damara Belt, uranium at Namibplaas is concentrated in sheeted leucogranites characterized by accessory garnet and magnetite. These accessory minerals are normally associated with barren sheeted leucogranites elsewhere in the Central Zone.

1.2 Objectives of the study.

The main objective of this study is to determine why uranium mineralisation at Namibplaas is associated with B and C-type sheeted leucogranites containing accessory minerals of garnet and magnetite which are typically barren elsewhere in the Central Zone of the Damara belt. Other

secondary objectives include establishing the type of uranium-phase minerals and the possible controls on uranium enrichment at Namibplaas in comparison to other sheeted leucogranites in the Central Zone of the Damara belt in relation to the local stratigraphy and the classification scheme originally proposed by Nex and Kinnaird (1995) based on field occurrence as well as mineralogical and geochemical characteristics of the sheeted leucogranites.

1.3 Methodology.

The study is based on quantitative research techniques over an area covering a total surface area of about 1,742 ha. The research methods involved; reviewing of historical data, mapping, geophysical surveying, rock sampling, core logging and core sampling, petrographical, geochemical and uranium ore mineralogical identification.

Review of historical data.

Diamond drill core from seven historic diamond boreholes drilled in the 1970's by Goldfields were re-logged. A ground radiometric map, a magnetic susceptibility map, and a geological map completed by Valencia Uranium (Pty) Ltd during 2008 were reviewed. Other data that has been reviewed include percussion cuttings and down the hole probing data from 17 percussion boreholes also completed by Valencia Uranium (Pty) Limited during the year 2009.

Mapping.

A radiometric survey at a grid of 5m by 5m was completed at Namibplaas in 2008 by Valencia Uranium (Pty) Ltd using handheld RS-120 Gamma – Ray Scintillometers. Detailed geological mapping was carried out along profiles varying between 600m to 900m, at a spacing of 50m, across the anomaly to describe the country rocks, the sheeted leucogranites, take structural measurements (joint sets, foliation, bedding and folding) and Gamma-ray scintillometer readings over outcrops.

Diamond drill core logging and Sample preparation.

Thirty-two diamond boreholes were logged: the logging involved describing the intact rock, differentiating and grouping the country rocks and sheeted leucogranites based on colour, and fabric. Drill core geological logging was followed by a radiometric survey. During the radiometric survey, SPP2 scintillometer readings were recorded every 10 cm of drill core recovered. The SPP2 scintillometer radiometric survey was supplemented by down-the-hole gamma logging.

After the diamond drill core logging process, selected drill core was marked and sawn into half drill core and sampled for thin section preparation, geochemical analysis and uranium ore mineral investigation. All samples were scrubbed to remove dust and saw cuttings. Figure 1.3 shows the location of diamond boreholes that have been logged and sampled and Figure 1.4 shows diamond drill core logging and sample preparation procedures. As for the sheeted leucogranites the number of samples from a particular sheeted leucogranites type was determined by its abundance. Due to confidentiality issues, no borehole log is presented in this Thesis. However, a cross section generated using logged boreholes is presented in Chapter 3, Figure 3.2.

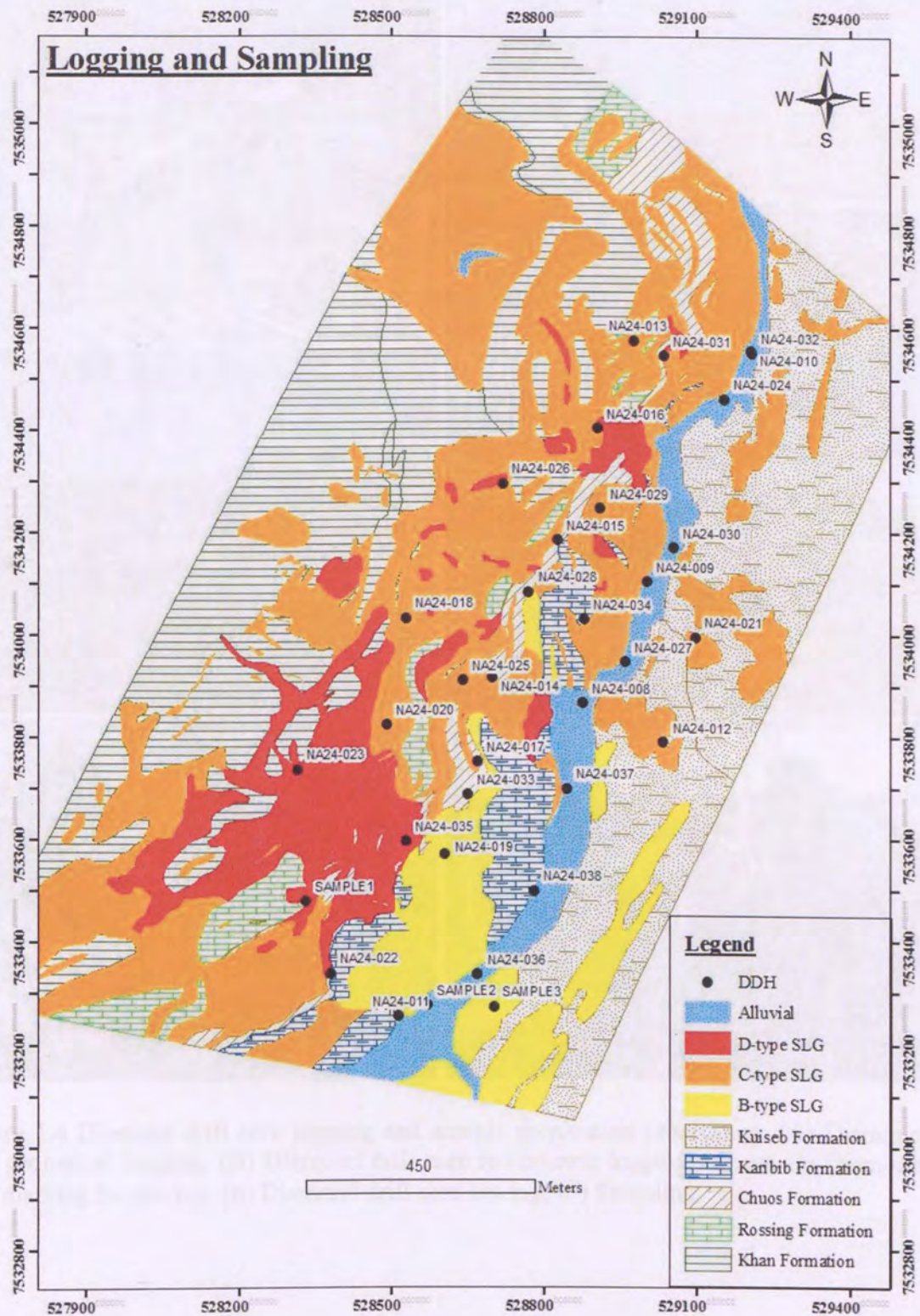


Figure 1.3 Location outcrop samples of diamond boreholes that have been logged (Geological map by Valencia Uranium (Pty) Ltd, 2008).

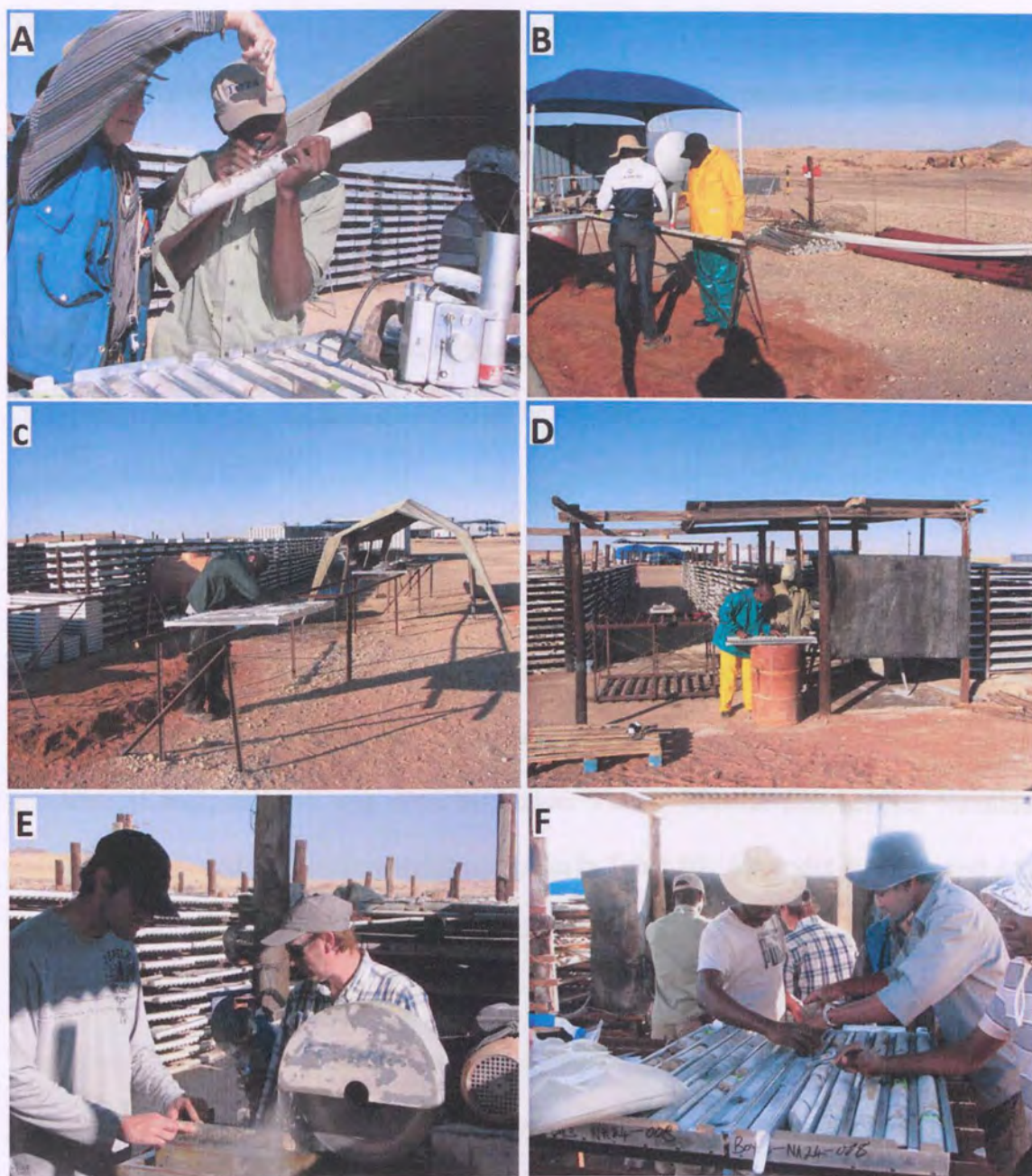


Figure 1.4 Diamond drill core logging and sample preparation procedures: (A) Diamond drill core geological logging; (B) Diamond drill core radiometric logging; (C and D) Diamond drill core marking for sawing; (E) Diamond drill core sawing; (F) Sampling.

Thin section preparation.

A total of fifty-two samples were selected and sent to the University of Namibia (UNAM) for thin section preparation, nineteen of these samples are from the country rocks and thirty-three are from the sheeted leucogranites. Sample localities are given in Table B1, Appendix B. A light transmitting microscope was used to study the thin sections and a microscope photographer was used to take thin section photographs with uncrossed polars and under crossed polars to illustrate the typical minerals and textures observed in the samples.

Geochemical analyses.

Forty-seven sheeted leucogranite samples were prepared for geochemical analyses. A major element analysis was undertaken on all the forty-seven samples. A trace element and rare earth elemental analysis was undertaken only on twenty-nine of the forty-seven samples. The geochemical analysis work was done by Bureau Veritas Mineral Laboratories Namibia. The sample localities and respective weights are given in Table B2, Appendix B. Units and detection limits of geochemical analyses results are presented in Table C3, C4 and C5 in the Appendix C.

The samples were sorted, dried and weighed. Sample weights varied from 0.4kg to 7kg. Primary preparation involved crushing the whole sample, which was split with a riffle splitter to obtain a sub-fraction which was pulverized in a vibrating disc pulveriser. The samples were digested with a mixture of acids including hydrofluoric, nitric, hydrochloric and perchloric acids. Although the acid digest liberates many elements some refractory oxides such as cassiterite, are not completely digested. In addition, barium occurs in the form of a sulphate at concentrations more than 4000

ppm may be reprecipitated after the digest, resulting in low Ba values. In addition, some sulphur losses may occur if the samples contain high levels of sulphide.

The elements As, Ag, Ba, Be, Bi, Cd, Cu, Co, Ga, Li, Mo, Pb, Sb, Se, Sn, W, Y, In, Cs, Re, Tl, Hf, Te, were determined by Inductively Coupled Plasma (ICP) Mass Spectrometry. Cr, Zn, Al, K, Na, P, S, V, Ca, Mn, Sc, Zr were determined by Inductively Coupled Plasma (ICP) Optical Emission Spectrometry. The samples were fused with Sodium Peroxide and subsequently the melt was dissolved in dilute Hydrochloric acid for analysis. Because of the high furnace temperatures, volatile elements are lost. This procedure is particularly efficient for determination of major element composition (including silica) in the samples as well as for the determination of refractory mineral species.

Ni, Sr, Ta, Nb, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Th, U, Rb were determined by Inductively Coupled Plasma (ICP) Mass Spectrometry, whereas Al_2O_3 , Fe_2O_3 , K_2O , MgO , CaO , MnO , P_2O_5 , SiO_2 , TiO_2 , Na_2O have been determined by X-Ray Fluorescence Spectrometry.

Uranium ore mineralogical investigation.

Five samples of sheeted leucogranite were prepared for uranium ore mineralogical investigation. This investigation was conducted by SGS South Africa (Pty) Ltd at the request of Valencia Uranium (Pty) Ltd, in order to incorporate the results of the uranium department in this thesis.

Each of the five uranium bearing leucogranite sample was stage crushed to 100% -1.7mm and subsequently milled to ~80% -850 μ m. Thereafter, the following geochemical and mineralogical analyses were conducted.

Head Assay and Chemistry: A split aliquot of each sample was analysed by XRF for major elements, U₃O₈ and ThO₂ and another split aliquot was analysed by ICP-OES for selected trace elements and for total S, sulphide S by LECO.

X-Ray Diffraction: A ~10g split aliquot of each sample was pulverized and the resultant powder analysed by means of X-Ray Diffraction (XRD) in order to identify the major minerals present in the sample. The XRD data was collected with the aid of Analytical X'Pert Pro Diffractometer (Co-radiation). Data interpretation was based on High Score analytical software and the PDF2 database.

Heavy Liquid Separation (HLS): Each sample was deslimed at 25 μ m. The +25 μ m fraction was separated by means of HLS, using TBE @ SG 2.96 into a Sinks and a Floats fraction. The slimes (-25 μ m), floats and sinks were analysed for their uranium and thorium content by XRF.

Trace Mineral Search and Modal Mineralogy: Two 90° cut polished sections were prepared from the head material of each sample (85% -850 μ m) and these were analysed by QEMSCAN Bulk Mineralogical Analysis (BMA) in order to obtain the quantitative mineralogical composition. QEMSCAN Trace Mineral Search (TMS) analyses were conducted on twenty polished sections, in order to quantitatively determine the uranium deportment of the samples.

CHAPTER 2

GEOLOGICAL BACKGROUND

2.1 Introduction.

The Damara Orogenic belt of Namibia belongs to the late-Precambrian, early-Paleozoic Pan-African thermal, tectono-thermal and orogenic belts that surrounds and dissects Africa (Miller, 1983) (Figure 2.1). The poly-deformed and polymetamorphic orogenic belt lies between the Kalahari and the Congo Cratons, and consists of two branches; the 400km-wide northeast trending intra-continental Damaran branch and the 150km wide north-south-trending coastal Kaoko belt (Miller, 1983). The southern end of the Kaoko belt extends out to sea in a southwesterly direction (Miller, 1983). The south-western end of the intracontinental Damara branch swings around to attain a north-north-easterly trend (Miller, 1983). This trend can be followed southwards until it swings inland again in the Gariep belt, the southern extension of the Damara Belt (Miller, 1983). The north-trending coastal Kaoko belt might be connected offshore with the Gariep and the Malmesbury fold belts (Figure 2.1), while the northeast trending branch may be connected beneath the younger cover of the Kalahari with the Zambezi and Mozambique belts (Porada, 1977).

The NE striking Damara Belt represents remnants of the continental collision zone between the Congo and Kalahari Cratons to the north and south, respectively (Ritter *et al.*, 2003) (Figure 2.2). It exhibits major changes of stratigraphic, structural and petrological evolution at distinct lineaments or shear zones oriented parallel to the suspected NE-strike of the suture zone (Ritter *et al.*, 2003).

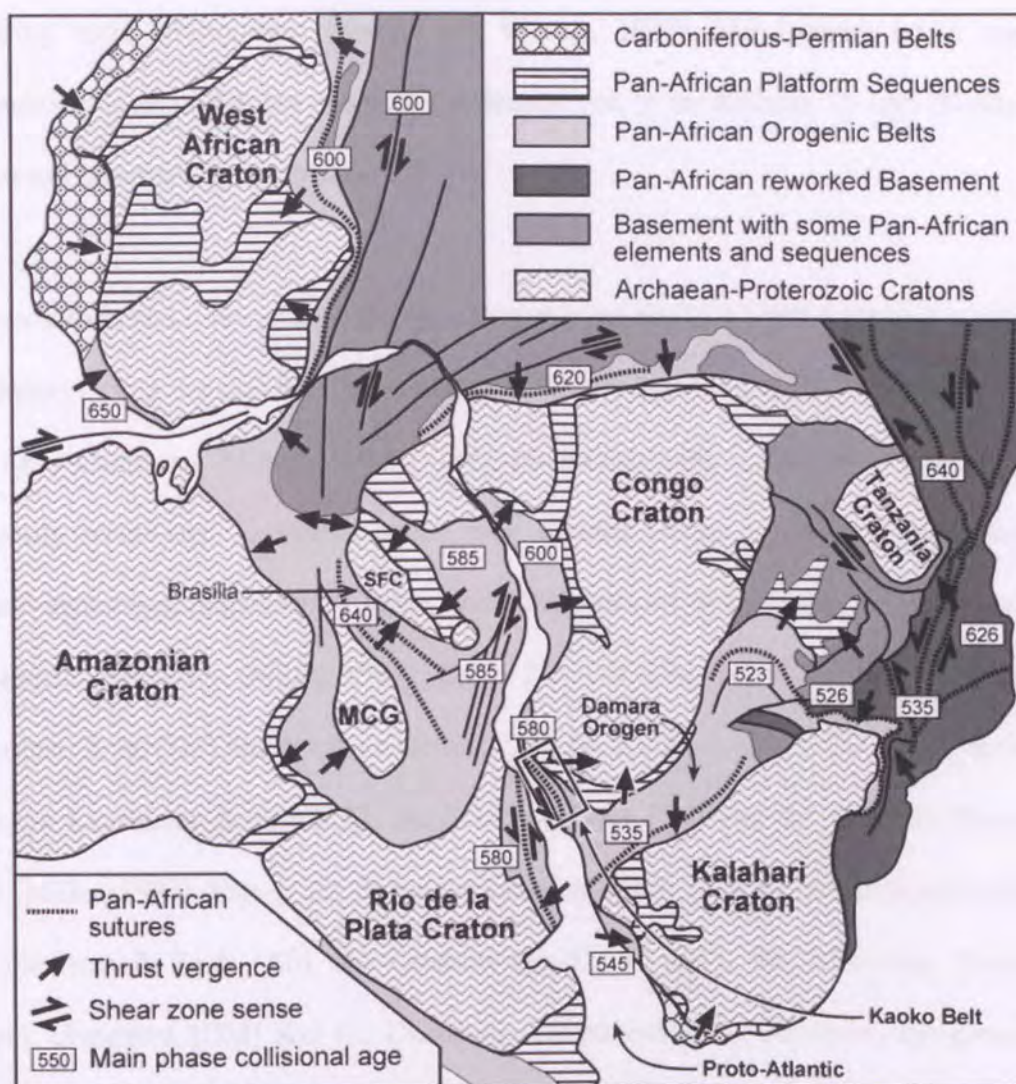


Figure 2.1 Thermal and tectono-thermal orogenic belts surrounding and dissecting Africa and South America. Source: <http://sp.lyellcollection.org> (2012).

The evolution of the Damara Orogen started with crustal extension and deposition of lacustrine to shallow marine rocks between 900 and 700 Ma, in fault-bounded rift basins (Ritter *et al.*, 2003). During subsequent passive margin evolution, the Damaran Sequence records a succession in at least one of the rift structures of what includes shallow marine clastics intercalated with abundant biogenic carbonates and volcanic rocks such as the Matchless amphibolite belt (Miller, 1983) as well as turbidic successions in the Ugab and Khomas Formations indicating a

subsiding basin environment (Porada and Witting, 1983). The Damara ocean reached its maximum width about 700 Ma ago with the deepest part in the Khomas Trough (Southern Zone + Omaruru Lineament Zone) (Miller, 1983).

Orogenesis followed a reversal of the spreading movements in a north-westward subduction of the Kalahari Craton beneath the Congo Craton at around 650 Ma and led to continental collision in the early Cambrian (Miller, 1983). During continental collision the older extensional faults were partly reactivated as thrusts which now separate zones of different stratigraphic and structural evolutions, metamorphic grade, and distribution of plutonic rocks, geochronology and aeromagnetic expression (Miller, 1983), Figure 2.2. The zones from the North to the South are the Northern Zone (NZ), the Northern Central Zone (nCZ), the Southern Central Zone (sCZ), the Okahandja Lineament Zone (OLZ), the Southern Zone (SZ) and the Southern Margin Zone (SMZ) (Miller, 1983). Figure 2.2 shows the location of the most prominent lineaments in plan view: the Autseib Fault (AF), the Otjohorong Thrust (OT), the Waterberg Thrust (WT), Omaruru Lineament (OM) and the Okahandja Lineament (OL). However, the geometry and interrelation of these lineaments at depth is unknown (Ritter *et al.*, 2003).

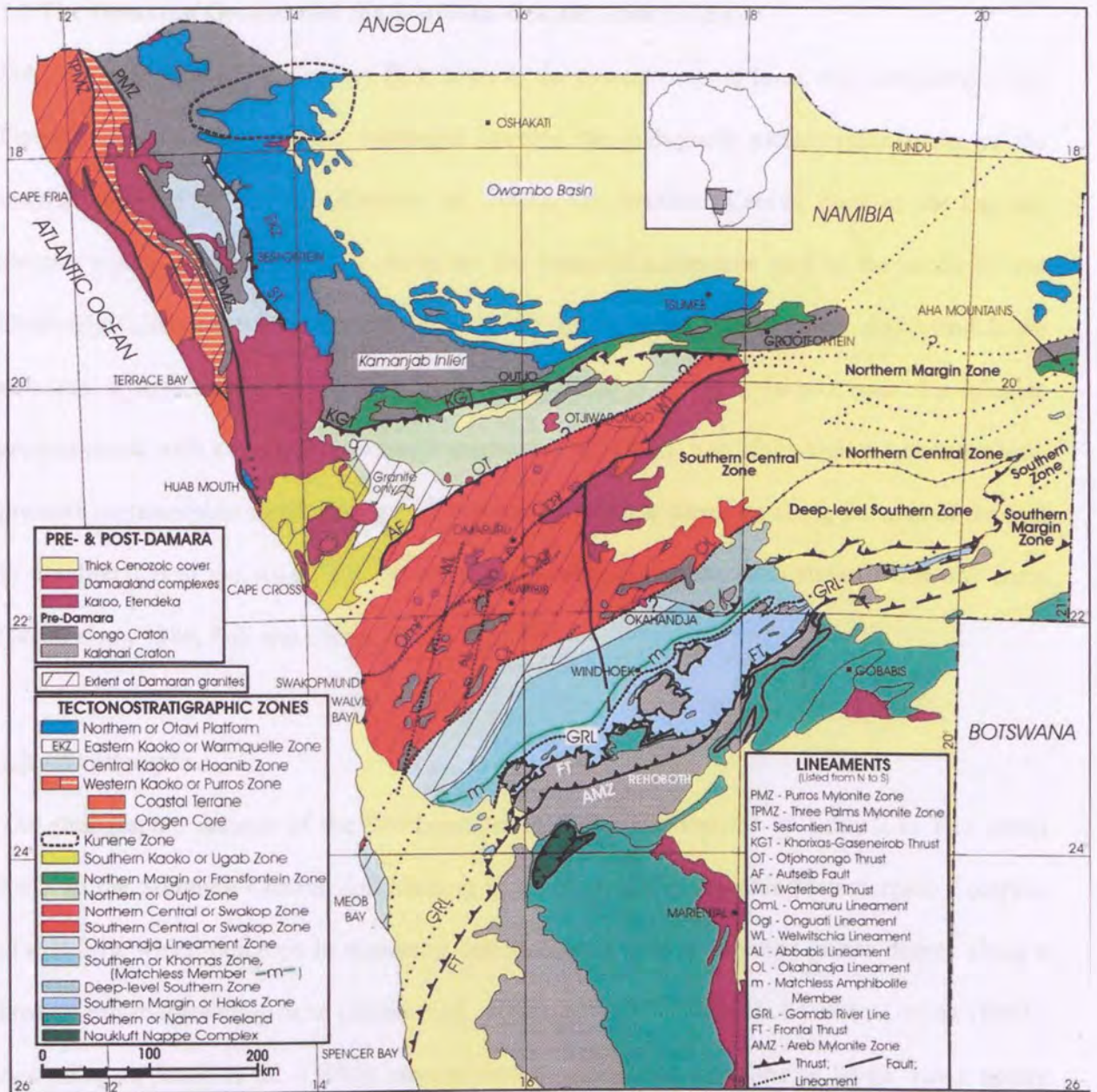


Figure 2.2 A simplified geological map of Namibia showing, pre- and post- Damara rocks, tectono-stratigraphic zones, lineaments and the Congo-Kalahari Cratons (Miller, 2008).

2.2 The Damaran Orogen and the Southern Central Zone (sCZ).

Subsequent erosion of the Damara Belt down to the present outcrop level was completed in the Permian when shallow marine sediments covered the high-grade metamorphic rocks of the internal zones of the orogen (Ritter *et al.*, 2003). The Southern Central Zone of the Damara Orogen which is bounded to the north by the Omaruru Lineament and to the south by the Okahandja Lineament is characterised by >300 granitoid intrusions and a dome and basin structural style (Kinnaird and Nex, 2007). It is considered to represent the root zone of a volcanic arc associated with a subduction zone (Stanistreet *et al.*, 1991). It exhibits high-temperature low-pressure metamorphism and the regional metamorphic grade increases along the axis of the belt in the direction of the Atlantic coast where a granulite facies has been attained near the coast (Jacob *et al.*, 1986; Poli and Oliver, 2001).

2.2.1 Stratigraphy.

The stratigraphic column of the Southern Central Zone is presented in Table 2.1. The oldest rocks in the Southern Central Zone belong to the Proterozoic Abbabis Metamorphic Complex (Table 2.1), which outcrops in numerous anticlinal structures as mantled gneiss domes along a broad north-east-trending zone (Jacob *et al.*, 1986), termed the Abbabis Swell by Gevers (1963). According to Jacob *et al.*, (1986); several authors agree that the Abbabis Swell was a gently sloping anticline during Damara times and strongly influenced sedimentation of the Damara sequence. The Damaran sequence overlays the Abbabis basement and comprises mainly of meta-sedimentary rocks which locally reaches a total thickness of 14km (Brandt, 1985). The Damaran sequence is subdivided into an early rift-fill sequence dominated by quartzites, meta-arkoses and calcsilicate rocks (Nosib Group) and later calcareous sediments consisting of alternating marble,

calcsilicate rock and schist (Swakop Group) reflecting deeper basin conditions (Brandt, 1985),
Table 2.1.

The basal Nosib Group is subdivided into the lower Etusis and upper Khan Formation, which generally have an interfingering relationship (Smith, 1965; Henry, 1992). Rocks of the Nosib Group are found in the cores of antiforms or enveloping the Abbabis basement domes (Brandt, 1985). The diversified rock types of the Swakop Group form the upper part of the Damara Sequence, and are subdivided into the Rössing, Chuos, Arandis, Karibib, Tinkas and Kuiseb Formations (Brandt, 1985). While the uppermost Kuiseb Formation is present throughout the area, the underlying Karibib and Arandis Formation occur only in the Central Zone (Brandt, 1985). The Tinkas Formation which interfingers with the Karibib Formation marbles is restricted to the immediate vicinity of the Okahandja Lineament and the basal Rössing and Chuos Formations are well exposed in the Southern Central Zone, south of the Omaruru Lineament (Brandt, 1985).

Table 2.1 Lithostratigraphy of the southern Central Zone (sCZ) (After Brandt 1987a and Wilkinson 1990).

Group	Formation	Member/ informal unit	Lithology	Thickness
Swakop	Kuiseb		Biotite schist; minor arkosic quartzite, calcsilicate rock, marble	<3000m
	Tinkas		Schist, calcsilicate rock; marble, quartzite, amphibolite	1000m
	Karibib	Onguati	Impure marble, calcsilicate rock, schist	<150m
		Arises River	Pure marble	<200m
		Otjongeama	Impure marble with calcsilicate interlayers	<210m
	Arandis	Oberwasser	Biotite schist	<150m
		Okawayo	Marble with thin calcsilicate interlayers	<25m
Spes Bona		Calcsilicate rock, schist	<430m	
Karub		Marble with calcsilicate/schist interlayers	<60m	
Chuoss		Mixtite, pebble and boulder-bearing schist; minor quartzite, marble	<700m	
Unconformity				
	Rössing		Marble; minor quartzite, conglomerate, schist, gneiss, calcsilicate rock	<200m
Paraconformity				
Nosib	Khan		Calcsilicate rock; minor amphibole and biotite schist	<1100m
	Etusis	Rooikuisseb	Metarhyolite Feldparthic quartzite, meta-arkose, metaconglomerate, quartzofeldsparthic gneiss, sillimanite gneiss; minor biotite schist, marble, calcsilicate rock	<3500m
Major unconformity				
Abbabis metamorphic complex	Naob		Metavolcanic rocks Feldsparthic quartzite, marble, calcsilicate rock, schist, metabasite	ca. 1600m
	Tsawisis		Gneiss, meta-sedimentary rocks	
		Undifferentiated		Augen gneiss, biotite-sillimanite gneiss, amphibolite, migmatite Meta-sedimentary rocks, gneiss

2.2.2 Structure and metamorphism.

The Central Zone (CZ) is typified by regional amoeboid domes, sinuous synformal domains (Jacob *et al.*, 1986, Oliver and Kinnaird 1996, Miller 2008) and negative magnetic anomalies along the NNE-SSW Welwitschia Lineament of Corner (1982) (Figure 2.3). At least three major deformational phases (D_1 , D_2 , and D_3) occurred within the CZ; the second and third, together with a fourth are significant with regard to sheeted leucogranite timing and emplacement mechanisms (Anderson and Nash 1997). The earliest D_1 phase of deformation produced tight isoclinal folds while D_2 phase resulted in more open folds (Kinnaird and Nex, 2007). According to Smith (1965), D_1 and D_2 phases resulted in overturned and recumbent structures with axial planes trending roughly north-west south-east. Miller (2008) describes the F_2 folds being much larger than F_1 structures. Miller (2008) further describes the F_2 as tight to isoclinal, non-cylindrical and recumbent. The D_3 phase of deformation was responsible for the NE structural grain and for the formation of the NE-trending domes which now dominate the structure of the Southern Central Zone (Miller, 2008). According to Oliver (1994) the D_3 phase of deformation was focused at the basement/cover interface interpreted as a mid-crustal extensional detachment. A fourth deformational event (D_4) resulted in domes and structures having a north-northeasterly orientation (e.g. the Rössing Dome and the Welwitschia Lineament Zone) (Kinnaird and Nex, 2007).

The Central Zone is characterised by medium and high-grade metamorphism with common migmatitic phenomena (Sawyer, 1978). An early period of metamorphism, dated at 665 ± 34 Ma, predated widespread granite intrusion, produced migmatites, and accompanied the early D_1 and D_2 phases of deformation and a second period of metamorphism accompanied the third phase of

deformation (D₃). A late- to post-tectono thermal event accompanied the D₄ phase deformation, at approximately 470 Ma (Jacob *et al.*, 1986).

The D₄ phase was induced by voluminous magmatism which overprinted the D₃ extensional fabric at higher temperature granulite facies (Kinnaid and Nex, 2007). The syn-tectonic assemblage, plagioclase-alkali-feldspar-quartz-biotite-garnet-cordierite+-sillimanite is ubiquitous in cover gneisses of the Central Zone (Poli and Oliver, 2001). Metamorphic grade attained within the Central Zone is of medium pressure at upper amphibolite facies to higher temperature granulite facies (Kinnaid and Nex, 2007).

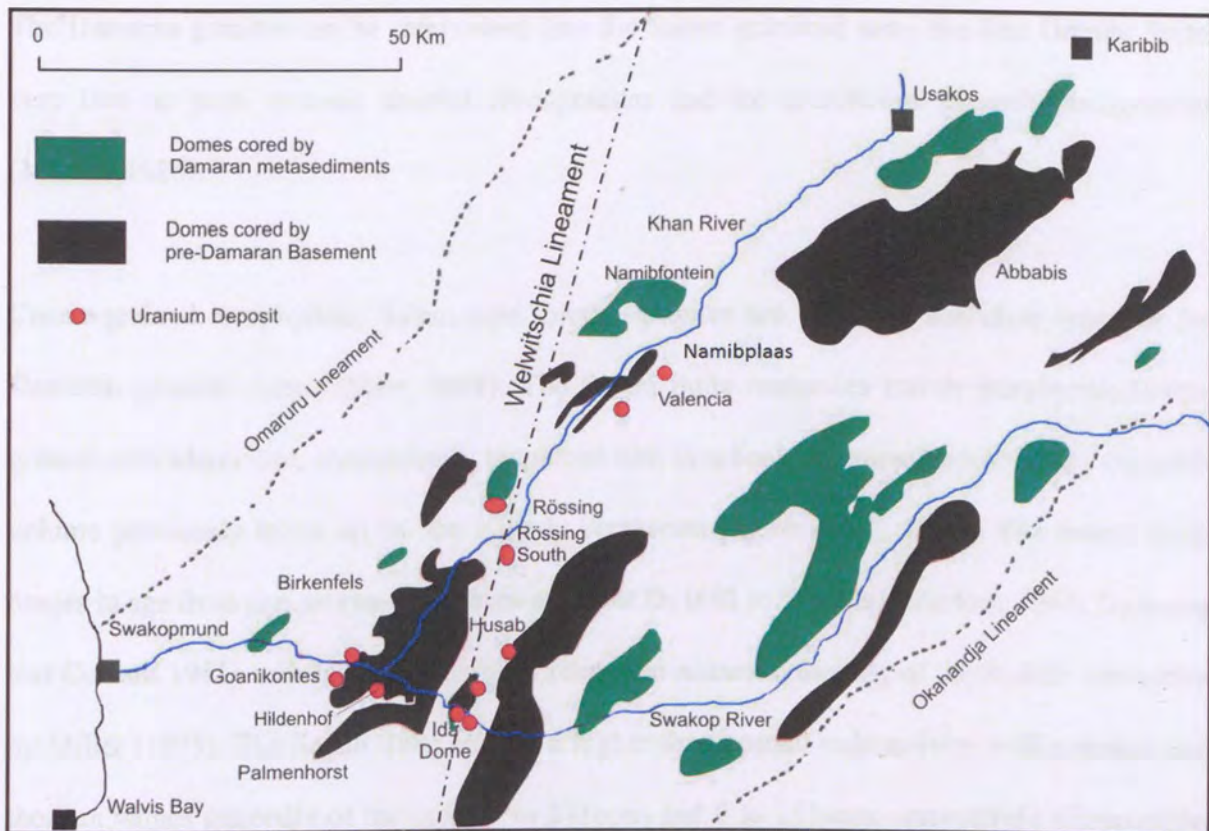


Figure 2.3 The various domes of the Central Zone and their associated primary uranium deposits. The Welwitschia Lineament is a regional magnetic trend produced by late kinematic movement which truncates and postdates D₃ structures. Source: Freemantle, 2016.

2.2.3 Damaran granite intrusives.

Damaran granitic and volcanic rocks were emplaced during five major episodes (Marlow 1983). The first relates to the early rifting phase at about 950Ma and is characterised by the emplacement of felsic volcanic rocks and volumetrically minor alkaline rocks (Miller 1983). The second episode took place between 650 and 540Ma and is characterised by the intrusion of calc-alkaline granitic rocks of I-type affinity (Miller 1983). The third episode of igneous activity is post-tectonic and occurred between 540 and 450Ma and is related to closure of the rifts and continental collision, resulting in a range of S-type granitic rocks (Miller 1983; Kinnaird and Nex 2007).

The Damaran granites can be categorised into the Salem granitoid suite, the Red Granite Suite, very late- to post- tectonic sheeted leucogranites and the uraniferous sheeted leucogranites (Marlow 1983).

Coarse-grained, porphyritic, Salem-type, biotite granites are the most abundant types in the Damaran plutonic suite (Miller, 2008). The Salem Suite comprises mainly porphyritic biotite granodiorite/adamellite, concordantly emplaced into synclinal structures and normally occupies volume previously taken up by the Kuiseb Formation (Jacob *et al.*, 1986). The Salem Suite ranges in age from pre- or syn- D₂ to syn- and post D₃ (601 to 554 Ma) (Marlow, 1983; Downing and Coward 1981) and its origin has been related to anatectic melting of the Kuiseb Formation by Miller (1973). The Salem Suite exhibit a higher than normal radioactivity with uranium and thorium values generally of the order 6 to 271ppm and 9 to 155ppm, respectively (Freemantle, 2016).

The Red Granite Suite consists of gneisses, gneissic granites, leucogranites and pegmatitic granites mostly found either below or at the level of the Etusis Formation with some members intruding to higher stratigraphic levels (Jacob *et al.*, 1986). The suite yields ages from late syn- to post- D₃ (542 to 508 Ma) (Miller, 2008)). Jacob *et al.*, (1986) suggest that the Red Granite Suite may represent partial resetting of basement ages as a result of Damaran metamorphism. The suite also exhibits higher than normal radioactivity with uranium and thorium values generally of the order of 2 to 20ppm and 10 to 50ppm respectively (Jacob *et al.*, 1986).

The very late- to post- D₃ sheeted leucogranites (+542 Ma) (Marlow, 1983) are a number of stocks and bosses of mesocratic granodiorite cross-cutting fold structures and deforming country rocks (Jacob *et al.*, 1986).

The volumetrically minor uraniferous sheeted leucogranites are limited to the Southern Central Zone. The late to post- D₃ (510 to 458 Ma) (Hawkesworth *et al.*, 1983) sheeted leucogranites are concentrated in the Khan and to a significantly lesser extent in the overlying Rössing and Chuos Formations (Miller, 2008). Some are present in the pre-Damara Abbabis basement and appear to have been derived *in situ* by partial melting of the basement gneisses (Miller, 2008). Berning (1986); Berning *et al.*, (1976); Marlow (1981); Hawkesworth and Marlow (1983) have suggested that the alaskites were derived from the Khan and Etusis Formations. However, model ages of the alaskites and the associated uranium indicate that both were derived from 2-Ga old crust, but since the Nosib rocks and the pre-Damara Abbabis have the same model ages it is not possible to determine whether the source was the Nosib or the pre-Damara Abbabis gneisses (Hawkesworth and Marlow, 1983).

2.2.4 The sheeted leucogranites.

The sheeted leucogranites are found only in the Southern Central Zone between the Okahandja and Omaruru lineaments (Figure 2.4) and are restricted to areas of highest metamorphic grade (Brandt, 1985). They are situated along the Abbabis Swell and are aligned with the magnetic Welwitchia Lineament and are also associated with the Red Granite-gneiss Suite (Brandt, 1985). They occur preferentially in and around anticlinal and dome structures and intrude into the Basement, the Nosib Groub and lower Swakop Group, mainly below prominent marbles of the Karibib Formation (Jacob *et al.*, 1986) (Figure 2.3).

The late-to-post-tectonic leucogranites are of particular importance for uranium mineralisation and for this reason they are distinguished from other leucogranite *sensu stricto* (Kinnaird and Nex, 2007). The leucogranite sheets occur as irregular, cross-cutting, anastomosing dykes and/or concordant bodies (Figure 2.4) and can reach more than 90m in thickness (Kinnaird and Nex, 2007). In one area an alaskite plug is 500m long and 200m across and containing mostly betafite as ore mineral (Pirajno 2009). Textures are variable, ranging from granophyric, aplitic to coarse-grained granitic to pegmatitic (Brandt, 1985).

According to Nex and Kinnaird (1995), there are six types of the late-to-post-tectonic leucogranites (A-F), Table 2.2. A, B and C types are early pre-D₃ while D, E and F types are post-D₃. The A, B, C and F types are barren, certainly not prospective for uranium (Kinnaird and Nex, 2007), whereas the type D has the highest U and Th concentrations, averaging 204 and 97.6ppm respectively (Kinnaird and Nex, 2007).

Table 2.2 Characteristic features of the Damaran sheeted leucogranites (Nex and Kinnaird 1995)

Types	Colour	Texture and Mineralogy
A	Pale pink to white	Irregular to boudinaged, folded by D3, weak S3 foliation at margins, occur in high-strain zones. They are homogeneous, saccharoidal and fine-grained.
B	White	Often boudinaged, inhomogeneous with a variable grain size from fine- to pegmatitic and form parallel sided tabular intrusions. Typically garnetiferous, infrequent abundant biotite and tourmaline
C	White to pink	Occasionally boudinaged, emplaced in F3 flexures. Medium to pegmatitic grain size, hyper solvus with interstitial clear quartz, magnetite, ilmenite and tourmaline
D	White	High grey or smoky quartz content, U-enriched and have a medium- to coarse-grain size. Have a granular texture, white feldspar with characteristic smoky quartz frequently visible. They frequently contain topaz that is absent from other types.
E	Variable	They are characterised by the presence of ubiquitous “oxidation haloes”, highly variable grain size and colour, may have a wide range in modal mineralogy within one sheet.
F	Red	Post-kinematic, have parallel sides and crosscut all preexisting structures. They have coarse-pegmatitic grain size. They contain large perthitic K-feldspars up to 30 cm in size, milky quartz, and interstitial biotite and they are almost albite free.

2.2.5 Uranium deposition.

The origin of the mineralisation is related to partial melting of Nosib Group and/or U-enriched basement rocks (Kinnaird and Nex, 2007). Primary uranium deposition was caused by uranyl-bearing fluids in contact with reducing layers containing methane, graphite and sulphides in the Khan and Rössing Formations (Kinnaird and Nex, 2007; Cuney and Kyser, 2008; Covino and Pretorius, 2013). According to Covino and Pretorius (2013), the marbles enhanced decarbonation reactions resulting in economically important uranium deposits in major F₂ and F₃ fold hinges. Kinnaird and Nex (2007) pointed out that there is evidence of sub-solidus hydrothermal overprints at Rössing, suggesting fluid flow and re-distribution of uranium in cracks and fractures both within the leucogranites and the country rocks in the form of secondary betauranophane.

The main uranium hosting primary minerals are uraninite, betafite and brannerite (Pirajno 2009). Secondary uranium minerals include uranophane, thorogummite, gummite, coffinite, autunite, monazite, torbenite, Rössingite, uranothallite, carnotite and some niobates (Pirajno 2009). These secondary minerals occur in the leucogranites and in cracks and fractures of the surrounding rocks and in quartz and carbonate veins (Pirajno 2009). Uraninite occurs as intragranular grains, up to 0.01 mm, in quartz and feldspar (Pirajno 2009). High uranium concentrations are associated with smoky quartz, a feature usually attributed to radiation damage (Kinnaird and Nex 2007).

Prospective areas for uranium deposits include sites of leucogranites, thickened reducing layers in contact with marble units around domes and fold hinges (Covino and Pretorius, 2013; Freemantle, 2016). A conceptual model of sheeted leucogranite (alaskite) emplacement and associated U mineralisation is given in figure 2.4.

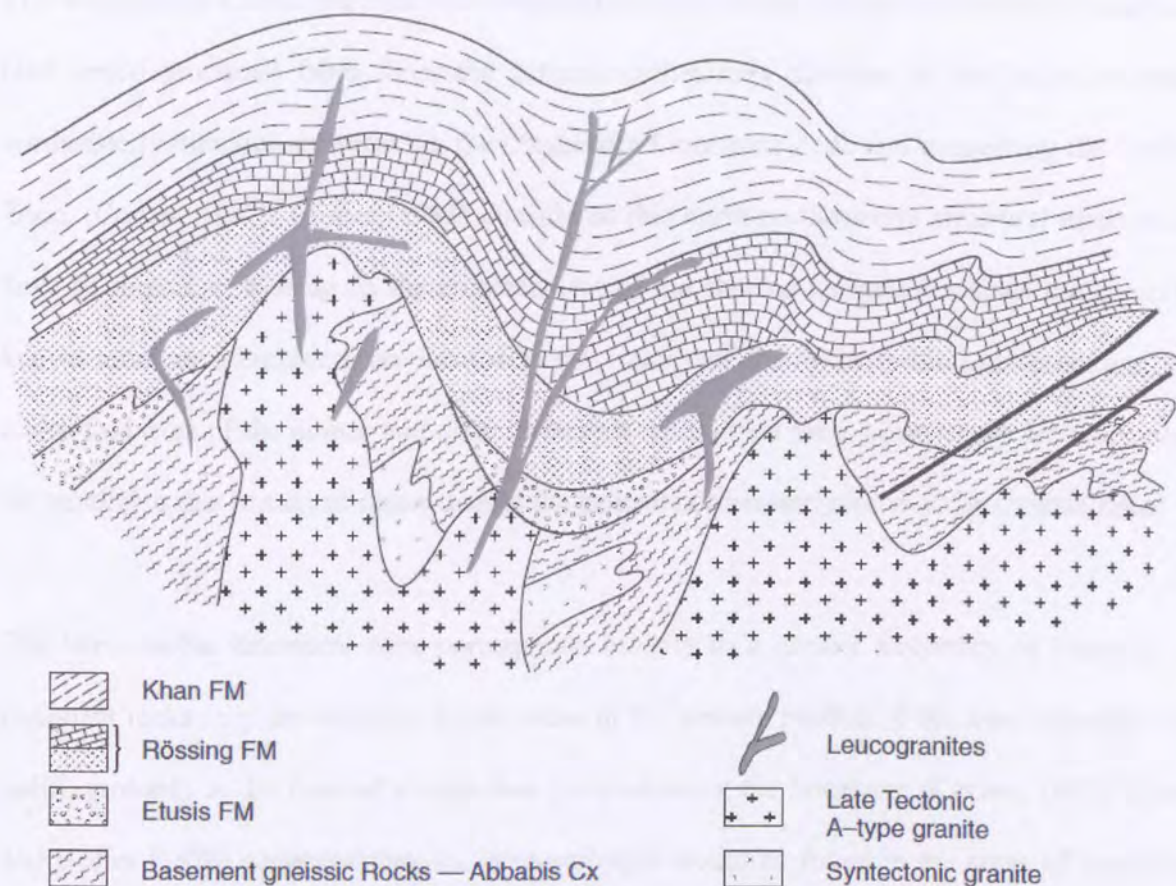


Figure 2.4 A Conceptual model of sheeted leucogranite (alaskite) emplacement and associated U mineralisation. Source: Pirajno 2009.

2.2.6 The Welwitschia lineament

A number of less intense phases of folding occurred after the D_3 phase of deformation and produced folds oriented in northeast and northwest directions (Roesener and Schreuder, 1994). Uraniferous sheeted leucogranites were emplaced post- D_3 and are associated with a north-northeast orientation, a direction which manifests itself in the prominent north-northeasterly trending magnetic Welwitschia Lineament, (Roesener and Schreuder, 1994).

The Welwitschia Lineament zone was identified from the abrupt change in direction of magnetic (and hence structural) fabric from the general northeasterly direction of the belt to a north-northeasterly direction overprinting the Okahandja Lineament Zone and transecting the Central Zone, (Corner, 1982). Corner (1982) considered this north-northeasterly structural direction to have an important bearing on the emplacement of the sheeted leucgranites since the currently known uranium occurrences are located in the vicinity of the Welwitschia Lineament and, the major fold axes of the domes and other structures with which these occurrences are associated, are parallel to this lineament rather than to the general northeasterly trend of the Central Zone.

The Welwitschia lineament zone corresponds broadly to a greater frequency of exposure of basement rocks (e.g. the Abbabis Swell) rocks in the western portion of the area indicating that uplift, probably in the form of a ridge has occurred along the lineament (Corner, 1982). Haack and Hoffer (1976) suggested that the youngest ages would be found in the areas of maximum uplift, which is consistent with Corner's proposal that uplift occurred along the Welwitschia Lineament resulting not only in lower stratigraphic levels, including basement rocks, becoming exposed but also in the emplacement of the young intrusive sheeted leucogranites/alaskites (Corner, 1982).

CHAPTER 3

GEOLOGY OF NAMIBPLAAS

3.1 Introduction.

The Namibplaas regional geological setting is part of a major syncline located east of the Khan River and west of the Khan berg, called the Kuiseb syncline. The 9km wide, NE-SW trending Kuiseb syncline which is underlain by the Karibib marbles and can be followed as far south as Husab, south of the Rössing mine. Apart from the Arandis and the Tinkas Formations which are not represented in the Namibplaas area, the Damaran stratigraphy comprises of the Etusis, Khan, Rössing, Chuos, Karibib and Kuiseb Formations. Numerous sheeted leucogranites intrude the stratigraphy (Figure 3.1).

The Etusis Formation described in this thesis was not observed during the ground mapping exercise but it was however recognized in the diamond drill cores. The detailed geological map of Namibplaas is presented in Figure 3.1 and the local stratigraphic column is given in Table 3.1.



Figure 3.1 Detailed Geology of Namibplaas showing the location of different formations and distribution of sheeted leucogranites intruded as B, C and D types in the region. (Geological map by Venter & van der Merwe (1991) & L. 2004).

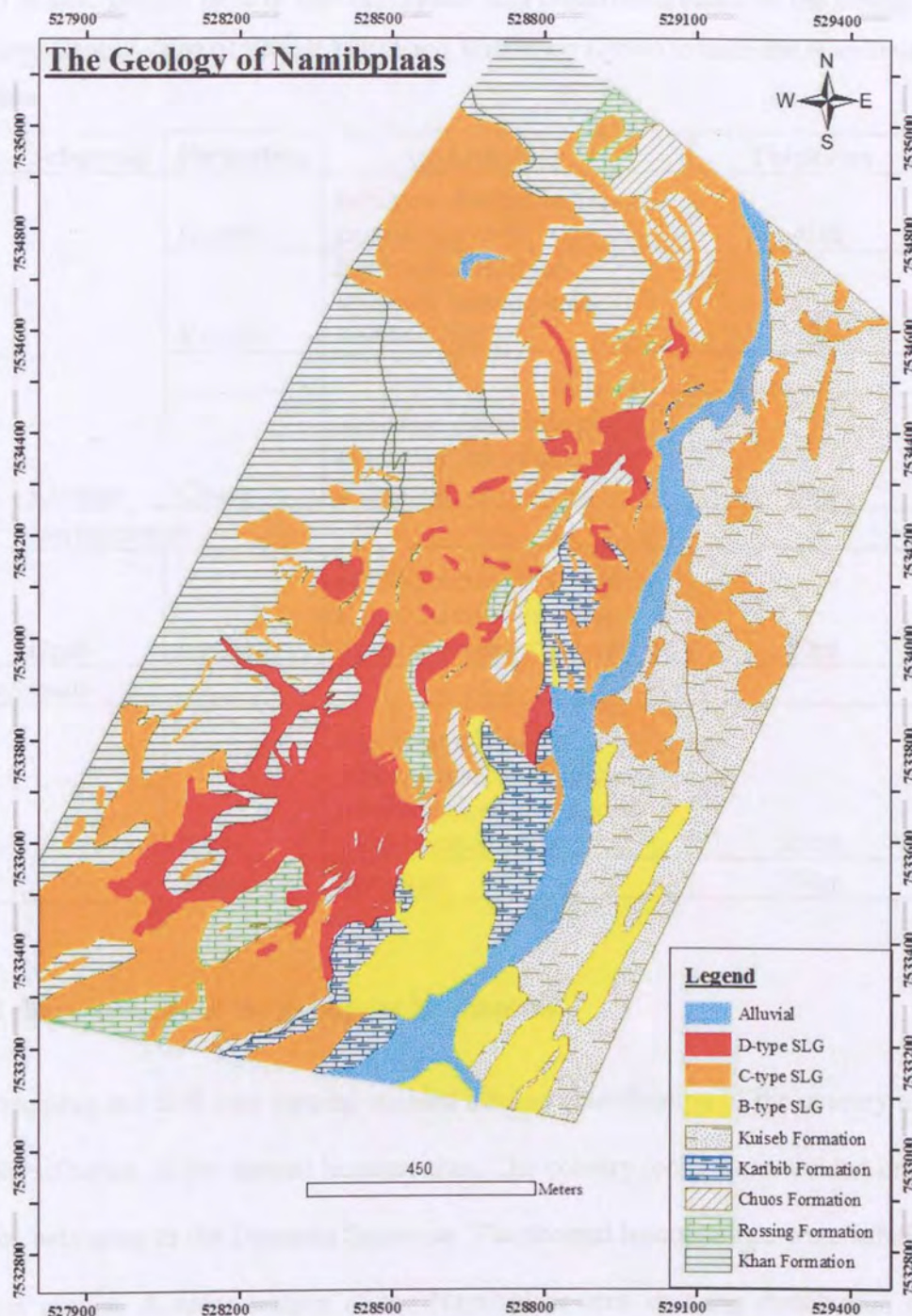


Figure 3.1 Detailed Geology of Namibplaas showing the location of different formations and distribution of sheeted leucogranites labelled as B, C and D types in the legend (Geological map by Valencia Uranium (Pty) Ltd, 2008).

Table 3.1 A stratigraphic table of the Namibplaas area constructed based on the stratigraphy of the Southern Central Zone of Brandt 1987a and Wilkinson (1990) to suite the Namibplaas observations.

Group	Subgroup	Formation	Lithology	Thickness
Swakop		Kuiseb	Schistose cordierite gneiss, calcsilicate rock.	>40m
		Karibib	Marble, calcsilicate, schistose biotite gneiss, biotite schist.	130m
			Schistose diamictite gneiss, diamictite schist/quartzitic diamictite, calcsilicate.	
	Khomas	Chuos		70m
	<i>Unconformity</i>			
	Ugab	Rössing	Marble, schistose cordierite schist, calcsilicate rock, quartzite, meta-conglomerate	50m
<i>Paraconformity</i>				
Nosib		Khan	Biotite-amphibolite schist/gneiss, meta-arkose, mottled calcsilicate gneiss, meta-conglomerate.	260m
		Etusis	Quartzite.	150m

3.2 Field characteristics of the geology of Namibplaas.

Ground mapping and drill core logging enabled a broad classification of the country rocks and a narrow classification of the sheeted leucogranites. The country rocks were divided into six main formations belonging to the Damaran Sequence. The sheeted leucogranites were subdivided into three main groups. A cross section of the Namibplaas area showing distribution of sheeted leucogranite types within stratigraphic units based on drill-hole data is given in Figure 3.2.



Figure 3.2 Cross section of the Namibplaas area showing distribution of sheeted leucogranite types within stratigraphic units based on drill-hole data. Scale 1cm = 15m.

3.2.1 The Namibplaas stratigraphy.

The lowermost Damaran unit present at Namibplaas is the Etusis Formation. Although not covered by the geological map, the Etusis quartzites occur northwest of the Namibplaas uranium described in this study. The Khan, Rössing, Chuos, Karibib and Kuiseb Formations are present throughout the map area. The Khan and the Kuiseb Formations border the anomaly along the general SW- NE strike of the country rocks with the Khan Formation forms the surface geological limit on the northwestern part of the radiometric anomaly and the Kuiseb Formation on the southeastern part of the anomaly. The Rössing, Chuos and Karibib Formations occur as elevated, sporadic, discontinuous folded outcrops along strike within the anomaly. Numerous leucogranite sheets intrude the whole metamorphic series.

Etusis Formation: The Etusis Formation is about 150m thick and is represented by magnetite and diopside-bearing quartzites. These quartzites show a highly recrystallised texture and are

well bedded, with magnetite layers along foresets in the cross-bedding. The quartzites are grey, fine- to medium-grained, and massive with white patches and bands of feldspar and quartz and disseminated green amphibole and black biotite (Figure 3.3).

Khan Formation: The Khan Formation is ~260m thick, is fine-grained and can be subdivided into a ferruginous banded foliated gneiss, a meta-arkose, a biotite banded foliated gneiss, and mottled calcsilicate gneiss. The Khan Gneisses are dark grey to green coloured. Gneissosity is also observed in a brown to yellow ferruginous schist and in a pink to buff-coloured meta-arkose with a distinctive sugary texture. Within the meta-arkose, magnetite layers occur along bedding planes. In the dark grey to green units and the ferruginous schist, magnetite occurs in a disseminated fashion. The banded ferruginous foliated gneiss is brown to yellow, fine-grained, foliated and banded with alternating layers of Fe-oxides (limonite and goethite). The biotite banded foliated gneiss is dark grey in drill core, fine-grained, thinly foliated and banded with alternating green biotite-diopside and white feldspar-quartz bands (≤ 1 mm), also thicker (0.5 cm wide) feldspar-quartz lenses and veins. The meta-arkose is pink to buff-coloured, medium-grained with magnetite layers along bedding planes, characterised by a sugary texture. The mottled calcsilicate gneiss is green, fine-grained, compositionally mottled with diopside and biotite, feldspar-quartz bands and disseminated magnetite (Figure 3.3).

Rössing Formation: The Rössing Formation is about 50m thick and is characterised by a banded impure marble, discontinuous along strike. This banded impure marble is associated with a quartzite, porphyroblastic schistose cordierite gneiss with varying amounts of cordierite (5-10%), a calcsilicate rock and a meta-conglomerate. The quartzite is white to grey, weathered to pink,

massive and fine-grained. The quartzite is sometimes cut by veins of sulphides. The schistose cordierite gneiss is grey, fine- to medium-grained, thinly foliated and banded with felsic bands of quartz, feldspar, cordierite and foliated black biotite. The calcsilicate is green and medium- to coarse-grained. The marble is white with grey bands, coarse-grained, and crystalline with disseminated spots of green tremolite and black opaques. Black opaques and tremolite within the Rössing marble makes a significant difference between the Rössing and the Karibib marble packages. Within the Formation, there are two marble bands separated by calcsilicate rocks (Figure 3.3).

Chuos Formation: Above the Rössing lies the Chuos schistose diamictite/ metamorphosed tillites (~70m thick) (Figure 3.1). The Chuos Formation is occasionally interbedded with calcsilicate bands, this unit is characterised by dropstones in a grey quartz-mica schistose to gneissic groundmass and magnetite layers. The dropstones are quartzo-feldspathic in composition and range in size from 20mm to 160mm. The Chuos Formation is unique as it shows a strong surface magnetic anomaly characterised by a violet colour (Figure 3.4) which correlates with either coarse-grained crystals of magnetite or narrow intervals of disseminated magnetite. The magnetite is observed during core logging and it is a good marker for down-the-hole magnetic-susceptibility logging and observations on drill core using a magnetic point. The Chuos Formation comprises of grey, fine-grained, thinly foliated to banded sometimes massive schistose gneiss with black biotite, white feldspar and quartz and red to brown garnet porphyroblasts in the more deformed units (Figure 3.3). The Chuos is very useful stratigraphic marker for diamond drill core logging.

Karibib Formation: The Karibib Formation (~130m thick) comprises of three main units; a marble, a calcsilicate rock and a dark grey biotite schist. The marble is grey, medium- to coarse-grained, almost pure marble. It occurs in several bands: at least seven packages of the marble alternating with calc silicate rock are observed. The biotite schist is fine-grained, thinly foliated and massive with black biotite, white feldspar and quartz. Just like the Chuos Formation, the Karibib schist bears coarse- to very coarse-grained porphyroblasts of garnet in the more deformed zones. The calcsilicate rock is tan to grey, fine-grained, massive cut by quartz-calcite veins and calcite-filled fractures (Figure 3.3). The Karibib Formation overlies the Chuos diamictite schist and the contact between the two is seen as a barrier underneath which mineralised sheeted leucogranite are observed (Figure 3.1).

Kuiseb Formation: The uppermost lithostratigraphic unit present at the deposit is represented by schistose cordierite augen gneisses. These are interbedded with meta-siltstone and calcsilicate bands. The grey augen gneiss weathers to brown, is medium- to coarse-grained, foliated and porphyroblastic, bearing cordierite with white bands of feldspar and quartz separated by foliated black biotite. Cordierite occurs as anhedral and fine-grained (≤ 0.5 to 1 mm) crystals with one good cleavage. Some poikilitic grains associated with plagioclase in deformed “augen” bands; whereas other grains are partly altered to sericite around grain margins and fractures, or completely replaced by sericite pseudomorphs (Figure 3.3). Right around the anomaly, the Kuiseb Formation shows a thickness of up to 70m. This is however not the true thickness of the Kuiseb as the Formation extends further to the east and south east for about 800m (Figure 3.1).

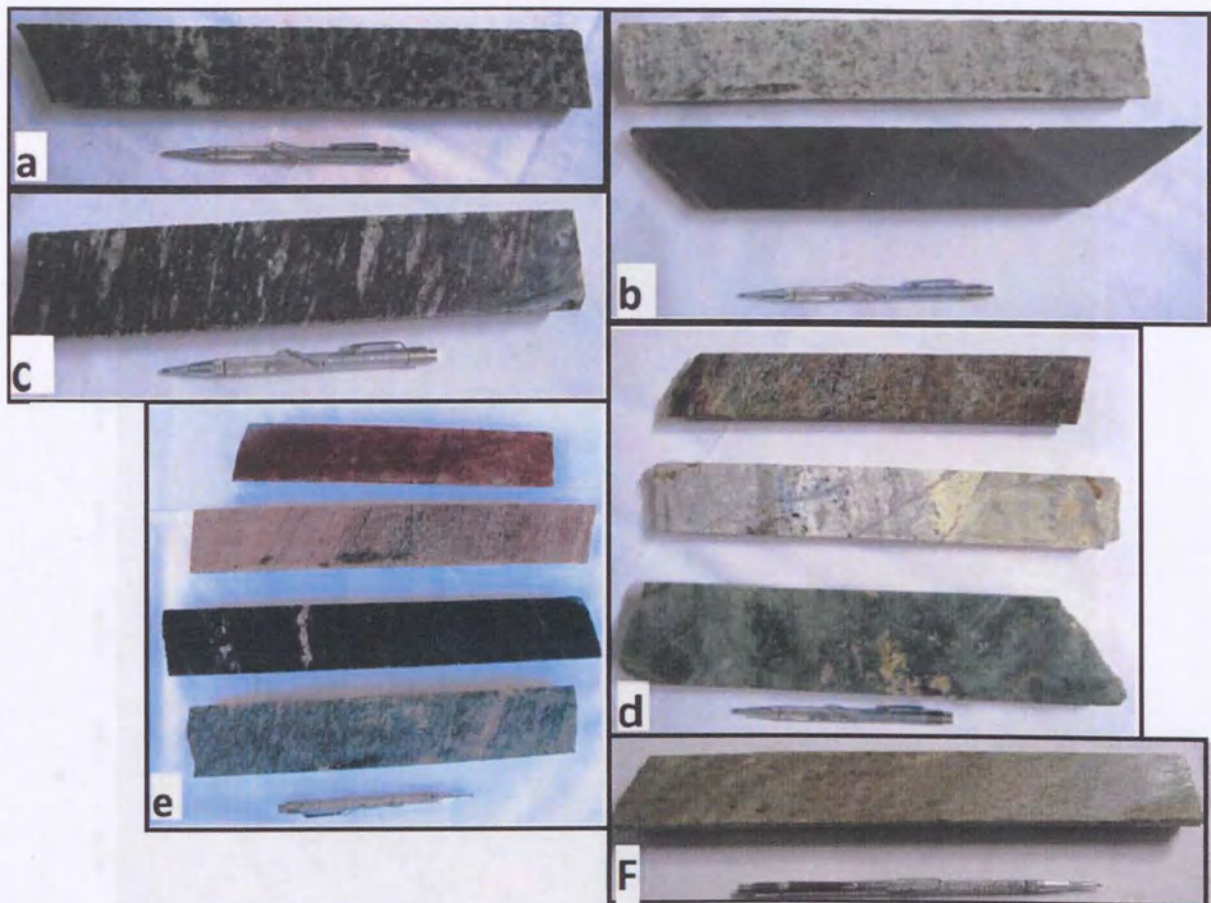


Figure 3.3 Namibplaas meta-sediments: (a) Kuiseb schistose cordierite gneiss (sampled from NA24-008), (b) Karibib; (top to bottom) marble and a biotite schist (all sampled from NA24-008), (c) Chuos diamictite (sampled from NA24-008), (d) Rössing; (top to bottom) Cordierite gneiss (sampled from NA24-012), marble (sampled from NA24-008) and a calcsilicate (sampled from NA24-013), (e) Khan Formation; (top to bottom) Ferruginous gneiss, meta-arkose, amphibolites-biotite gneiss and a calcsilicate gneiss (all sampled from NA24-008). (f) Etusis quartzite (sampled from NA24-013).

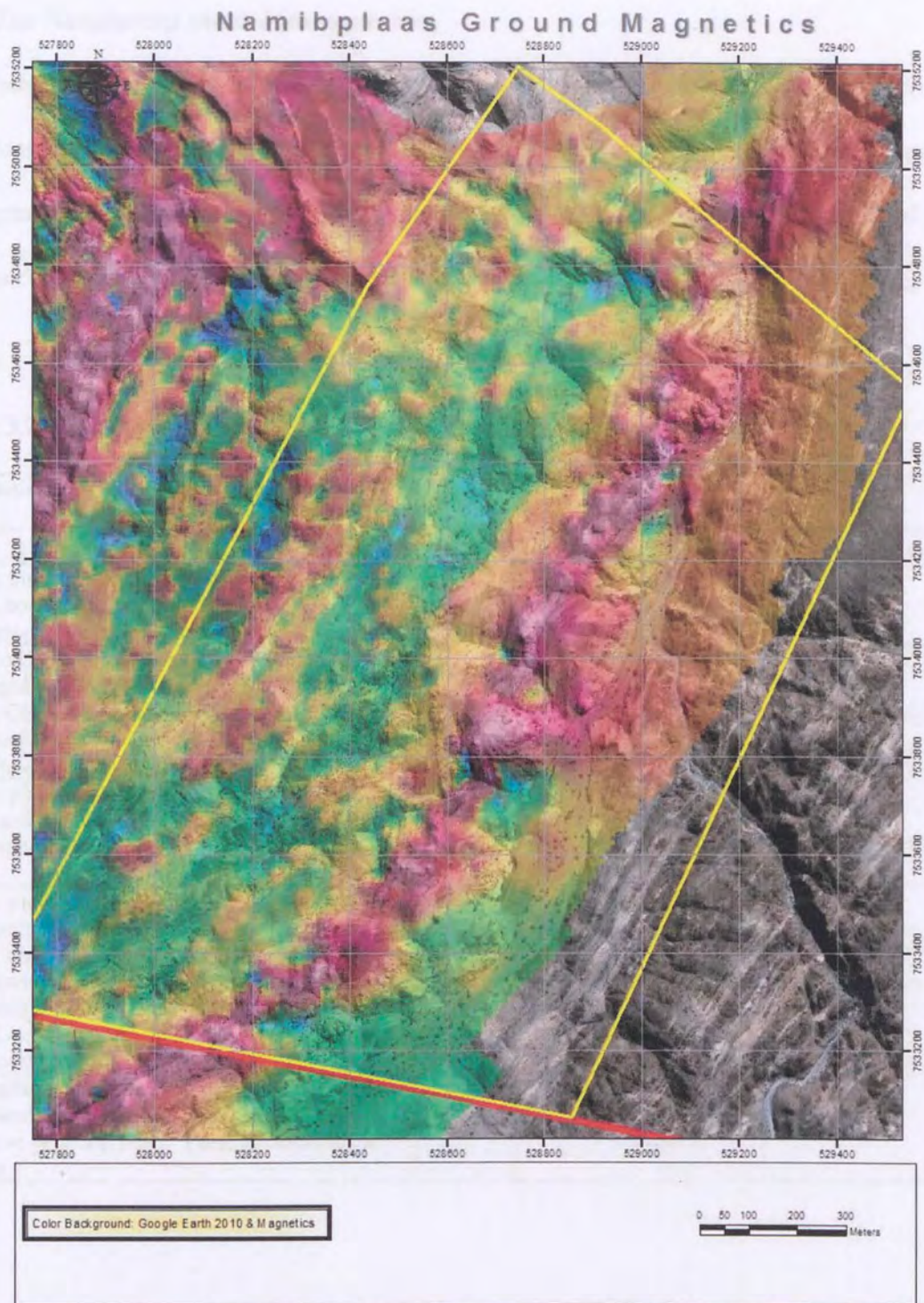


Figure 3.4 Mag Total field, Namibplaas deposit. The magnetic high is shown in the violet coloured area and the magnetic low is shown in the blue coloured area. The linear magnetic high exhibits a northeast orientation and is dominated by the Chuos diamictite (Valencia Uranium (Pty) Ltd, 2008).

3.2.2 The Namibplaas sheeted leucogranites.

The sheeted leucogranites have been examined in detail in the field and have been compared to the classification scheme by Nex and Kinnaird (1995) at Goanikontes. The Namibplaas leucogranites were subdivided into three main types. The classification scheme is based wholly on observable field characteristics of colour, grain size, texture and accessory mineralogy (Table 3.2).

Table 3.2 Characteristic features of the sheeted leucogranitic rock types at Namibplaas.

SLG type	Colour, texture, structure and accessory mineralogy	Biotite	Tourmaline	Garnet	Magnetite	Age
		%	%	%	%	
B	White to pink, coarse-grained- to pegmatitic, foliated, boudinaged and folded, typically garnetiferous, bears biotite and traces of tourmaline.	1 to 3	<1	3 to 10	-	Post- F ₂ , Pre- F ₃
C-tour	White, coarse-grained to pegmatitic, foliated, boudinaged and folded, dominant within the Rössing-Chuos-Karibib zones, infrequent amounts of tourmaline, accessory biotite and traces of muscovite and garnet.	1 to 3	1 to 4	1 to 3	<5 (Occasional)	Post- F ₂ , Pre- F ₃
C-mag	White to pink, coarse-grained to pegmatitic, foliated and folded, occurs within the Khan, and bears magnetite, hematite, tourmaline and traces of chlorite.	<1	<1	-	1 to 2	Post- F ₂ , Pre- F ₃
D-bio	White to pink, homogeneous, coarse- to very coarse-grained equigranular with limited pegmatitic patches, smoky to black smoky quartz, bears biotite, garnet and beta-uranophane (coats of radioactive yellow product). Accessory magnetite occurs. Localised to the Rössing-Chuos- Karibib Formations.	1 to 5	<1	1 to 3	<5 (Occasional)	Post- F ₂ , F ₃
D-mag	Pink weathered to red brown, pegmatitic, smoky quartz, bears magnetite and hematite, coats of radioactive yellow product. These are localised to the Khan.	<1	<1	-	1 to 2	Post- F ₂ , F ₃

The sheeted leucogranites are characterised by a vein/sheet-like or anastomosing style of intrusion conformable and transgressive to country rock foliation (Figure 3.1). The B and C-types form narrow (~0.20m) to wide (~50m) sheeted intrusions, whereas the D-type

leucogranites are generally wide (10 to 50m) sheets. The B-type sheets can be followed along strike and open folds for up to 450m except in areas where they have been cross-cut by the D-type leucogranites. The C-type sheets which occur over the entire sequence can be followed along strike and open folds for over 900m except in areas where they have been cross-cut by the D-type leucogranites. D-type leucogranite sheets can be followed along strike for up to 500m.

B-type

The B-type leucogranites are white to pink, weathered to reddish brown (stains of iron oxides) and coarse-grained to pegmatitic (Figure 3.5). These are garnetiferous (3-10% of garnet) with accessory biotite (1-3%) and traces of tourmaline (<1%) and muscovite (<1%), (Figure 3.5). Garnets in these sheeted leucogranites are red to brown and coarse- to very coarse-grained. The B-type leucogranites show a weak foliation defined by biotite, they are boudinaged within the Kuiseb Formation and are folded together with the country rocks along open folds (Figure 3.5). These granites are continuous and almost regular; they intrude country rocks of the Kuiseb and Karibib Formations and at Karibib-Kuiseb Formation contact. Within the Kuiseb and Karibib Formations; the granites occur as narrow sheets (~0.20m) to wide sheets (~40m); they occur as wider intrusions (~50 wide) at the Karibib-Kuiseb Formation contact.

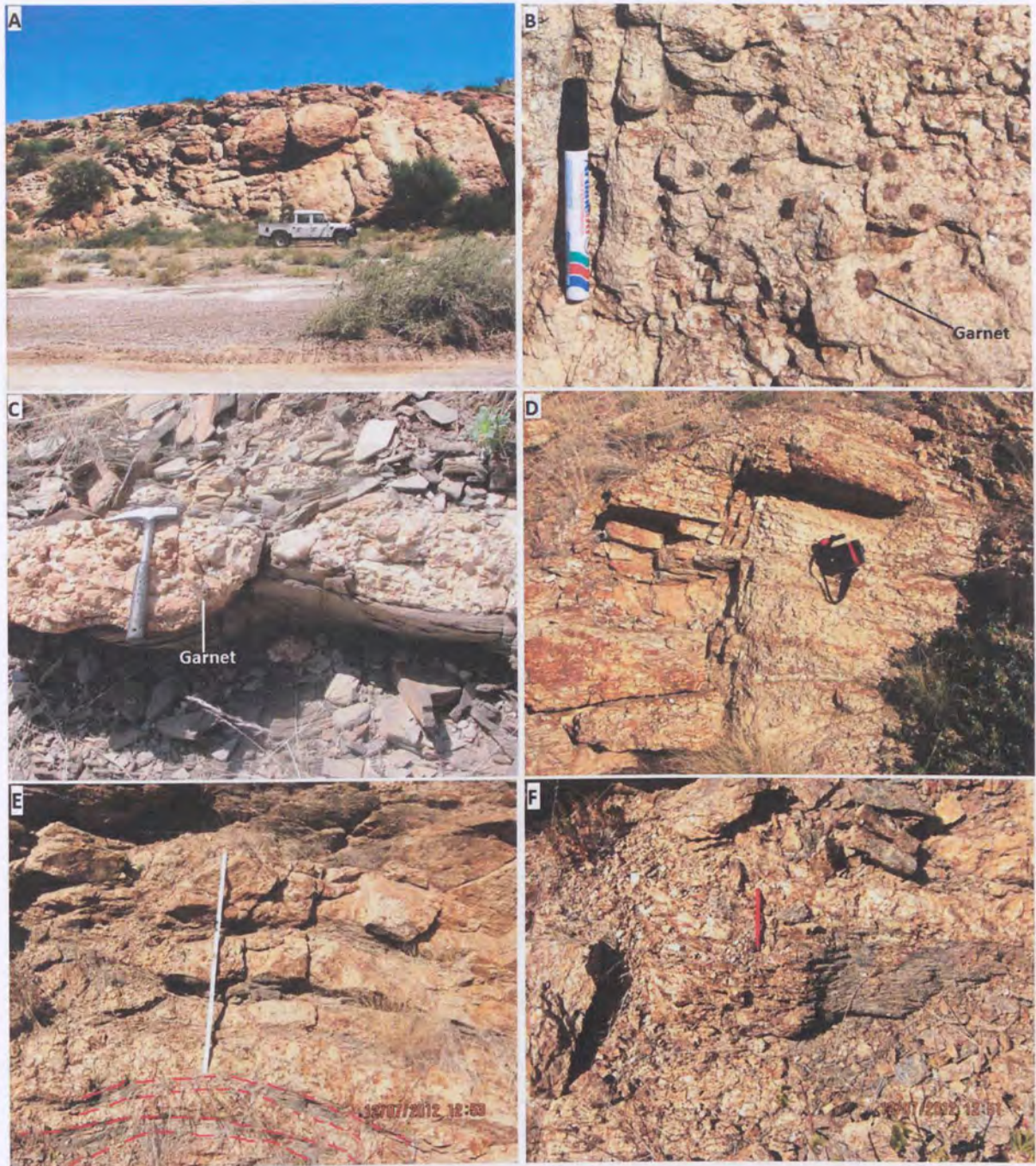


Figure 3.5 Namibplaas B-type sheeted leucogranites. (A) Concordant outcrop view; (B) garnet porphyroblast within the sheeted leucogranite; (C) Boudinages of the B-type within the Karibib schist; (D) Foliation within the B-type sheeted leucogranite; (E) B-type sheets folded together with the Kuiseb schist; (F) Foliation inheritance from the country rocks within the B-type leucogranites. GPS location of the field photos are given in Appendix A.

C-type

The C-type leucogranites are the most abundant at Namibplaas and they have a higher radioactivity (up to 780cps) than the B-type leucogranites. They occur as conformable and transgressive dykes (Figure 3.6) and are subdivided into two subtypes based on colour and accessory mineralogy.

C-tourmaline: The C-tourmaline types are coarse- to pegmatitic variation. These sheeted leucogranites bear nests of tourmaline (1-4%), biotite (1-3%) and muscovite (1%). Garnet (up to 3%) and magnetite (up to 5%) are occasionally observed within these sheeted leucogranites (Figure 3.6). These sheeted leucogranite types are boudinaged within the Kuiseb, the Karibib and Rössing meta-sediments and are folded together with the country rocks along open folds (Figure 3.6). These irregular continuous bodies intrude the country rocks; Kuiseb, Karibib, Chuos and Rössing Formations and the Rössing-Chuos-Karibib-Kuiseb Formation contacts. Within the Kuiseb, the granites occur as lenses of up to 0.20m, they occur as wider intrusions (~40m) at the Rössing-Chuos-Karibib-Kuiseb Formation contacts.

C-magnetite: These sheeted leucogranites are light pink to dark pink weathered to reddish brown. They are medium- to pegmatitic (Figure 3.6). Accessory minerals in these leucogranites consist of magnetite (2%), hematite (2%), biotite (<1%), chlorite (<1%) and traces of tourmaline (<1%), (Figure 3.6). The magnetite in these granites is coarse-grained and occurs within quartz or adjacent to the feldspars (Figure 3.6). These sheeted leucogranite types are folded together with the country rocks along open folds (Figure 3.6). These irregular continuous bodies are localised to the magnetite-bearing Khan Formation as narrow to wide intrusions (1m to ~30m).

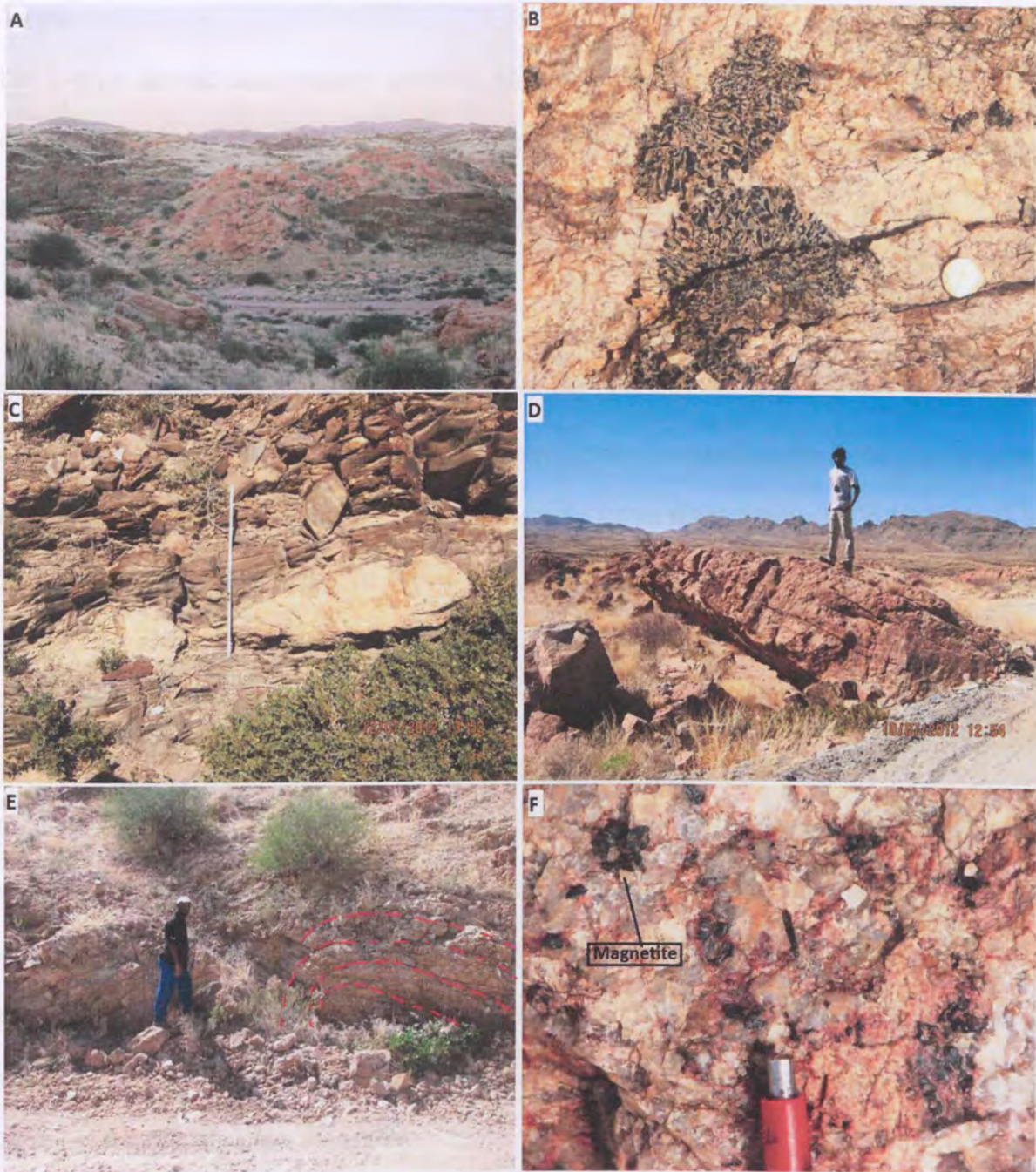


Figure 3.6 Namibplaas C-type sheeted leucogranites: (A) Outcrop view of the C-type tourmaline cross-cutting the Kuiseb Formation; (B) A nest of tourmaline within the C-type tourmaline; (C) boudinages of the C-type tourmaline within the Karibib Formation; (D) Concordant and sub-parallel C-type outcrop oriented $042/26^{\circ}\text{E}$, (E) C-type magnetite displaying open folding defined by foliation; (F) Coarse-grained magnetite hosted by the C-magnetite occurring within the quartz and adjacent to the feldspars. GPS location of the field photos are given in Appendix A.

D-type

The D-type sheeted leucogranites cross-cut C-type group and are very discontinuous along strike. They have a very high radioactivity (up to 7860cps) and are characterised by smoky quartz. Betauranophane occasionally form coats along fractures but is very rare. The D-type leucogranites are subdivided into two subtypes:

D-biotite: These are white to pink coarse- grained equigranular leucogranites occasionally weathered to reddish brown (Figure 3.7). Slightly smoky to black smoky quartz is observed within these sheeted leucogranites. Accessory minerals within these granites include biotite, (1 to 5%), garnet (up to 3%), magnetite (up to 5%), hematite (up to 7%) and traces of tourmaline (<1%). They are localised to the Karibib, Chuos, and Rössing Formations as well as at the Khan-Rössing-Chuos-Karibib Formation contacts.

D- magnetite: These sheeted leucogranites are pink coloured and often weathered to reddish-brown. They are coarse- to very coarse-grained and often pegmatitic. Slightly smoky to smoky quartz is observed within these granites. Accessory minerals within these sheeted leucogranites are magnetite (1 to 2%), hematite (7 to 15%), biotite (<1%), chlorite (<1%) and traces of tourmaline (<1%), (Figure 3.7). These discontinuous granites (3m to ~48m wide) are localised to the magnetite-bearing Khan Formation.

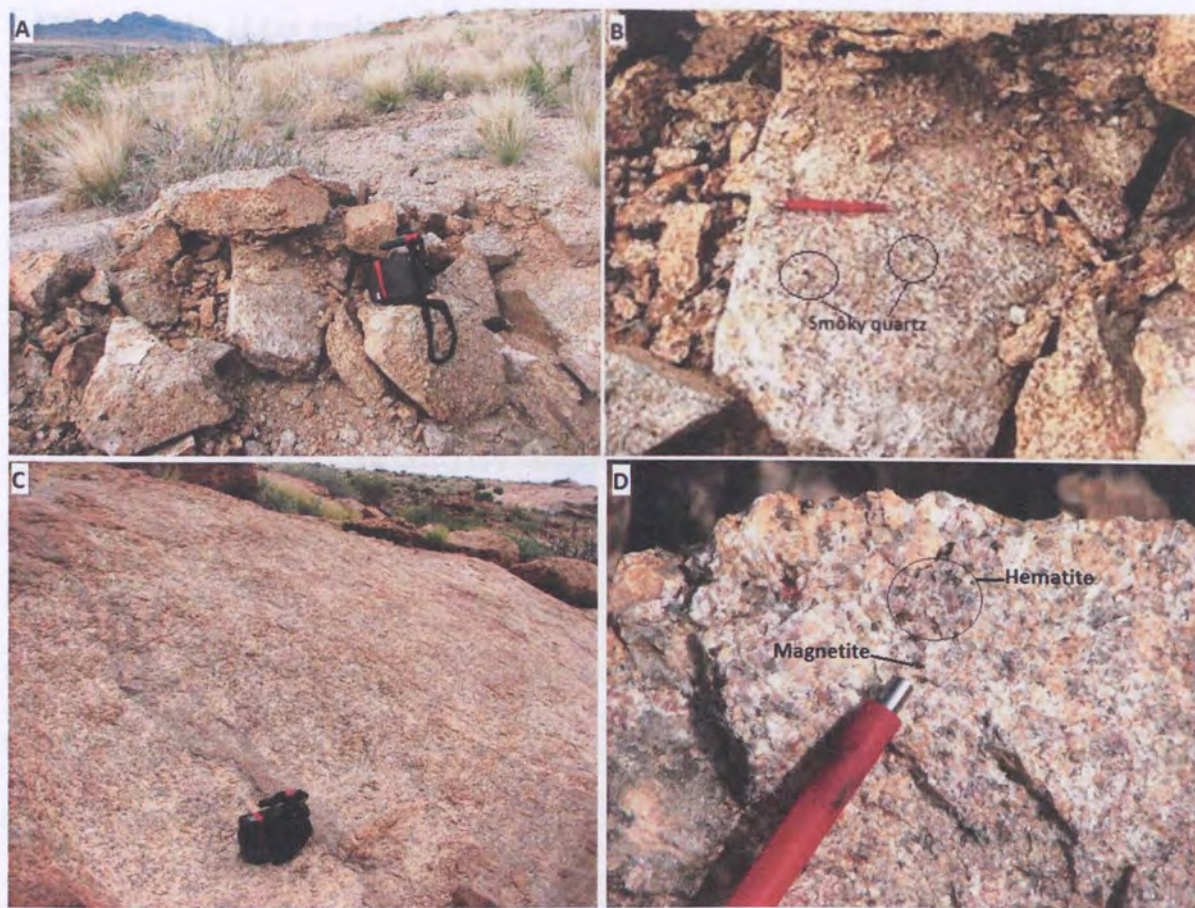


Figure 3.7 Namibplaas D-type sheeted leucogranites. (a) Outcrop view of the D-type biotite; (b) Characteristic smoky to black smoky quartz within the D-type biotite; (c) Outcrop view of the D-magnetite type; (d) Characteristic fine to very fine-grained magnetite and slightly smoky to smoky quartz with hematite (reddish discolourisation). GPS location of the field photos are given in Appendix A.

3.3 Petrography of the geology of Namibplaas.

Categorisation of the country rocks and the sheeted leucogranites by field observations was further supplemented by studies of thin sections under a light transmitting microscope to determine colour, texture, structure and type of minerals present. Fifty-two samples were selected for thin section preparation. Nineteen thin sections were prepared from country rock drill core samples. A total of thirty-three thin sections were prepared from sheeted leucogranites of which thirty-two were prepared from drill core samples and one from a hand specimen sample. Of the samples, four are from B type sheeted leucogranites, sixteen from C type sheeted leucogranites and thirteen from the D type sheeted leucogranites. Rock names given and metamorphic grades assigned to the rocks are based on the mineralogy and mineral textures observed. Thin section microphotographs taken with crossed and uncrossed polars are used to illustrate the typical mineral textures observed in the samples.

3.3.1 Petrography of the country rocks.

The nineteen samples consist mainly of cordierite gneiss/schist, biotite schist, calcsilicate, marble, biotite gneiss/schist and quartzite (Figure 3.8 to Figure 3.15). The results of the petrographic analyses are summarised in Table 3.3 with reference to mineralogy, mineral textures, rock type and formation unit. Modal proportions of the country rocks from thin section studies are presented in Table C1, Appendix C.

Table 3.3: Summary of the Namibpaas country rock petrographic analysis.

Samp no.	Mineralogy	Rock texture	Rock type	Formation	Metamorphic grade
KS01	Plagioclase, cordierite, biotite, microcline, quartz, opaques (pyrite, pyrrhotite); sericite, calcite	Medium-grained, banded, foliated and gneissic	Cordierite Gneiss	Kuiseb	Amphibolite facies
KrS02	Calcite, muscovite, quartz; opaques, sphene, plagioclase	Fine-grained, banded to foliated	Impure Marble	Karibib	Amphibolite facies
KrS03	Quartz, biotite, feldspar; muscovite, calcite, sericite, opaques, zircon	Foliated, fine-grained, schistose	Biotite Schist	Karibib	Amphibolite facies
ChS04	Quartz, biotite, plagioclase; garnet, tourmaline, calcite, muscovite, opaques, zircon	Foliated, fine-grained, schistose	Biotite Schist	Chuos	Amphibolite facies
ChS08	Plagioclase, cordierite, quartz, biotite, microcline, garnet, opaques (pyrite, pyrrhotite); sericite, calcite, zircon	Foliated, fine-grained, banded, schistose	Garnet-biotite Schist	Chuos	Amphibolite facies
RSc07	Plagioclase, biotite, microcline, cordierite, quartz, opaques (pyrite, pyrrhotite); sericite, muscovite, zircon	Fine- to medium-grained, banded, foliated and schistose	Cordierite Gneiss	Rössing	Amphibolite facies
RSc09	Plagioclase, cordierite, biotite, quartz, sericite; opaques, calcite, Fe-oxides	Foliated, fine-grained, banded, schistose	Cordierite-biotite Gneiss	Rössing	Amphibolite facies
RMb10	Calcite, tremolite; muscovite, opaques	Recrystallised, medium-grained, marble	Tremolite Marble	Rössing	Amphibolite facies
Khn11	Quartz, calcite, Fe-oxides; muscovite, sericite	Fine-grained, weathered and oxidised	Calcsilicate	Khan	Amphibolite facies
Calc12	Calcite, quartz, muscovite, opaques, feldspar, microcline, Fe-oxides	Fine-grained, slightly weathered, banded	Calcsilicate	Khan	Amphibolite facies
Calc13	Calcite, diopside, biotite, muscovite, sericite, sphene, quartz; apatite, opaques	Fine-grained, banded	Calcsilicate gneiss	Khan	Amphibolite facies
Khn14	Microcline, plagioclase, quartz, biotite, diopside, calcite; sericite, opaques, apatite, Fe-oxides	Foliated, fine-grained, schistose	Biotite Schist	Khan	Amphibolite facies

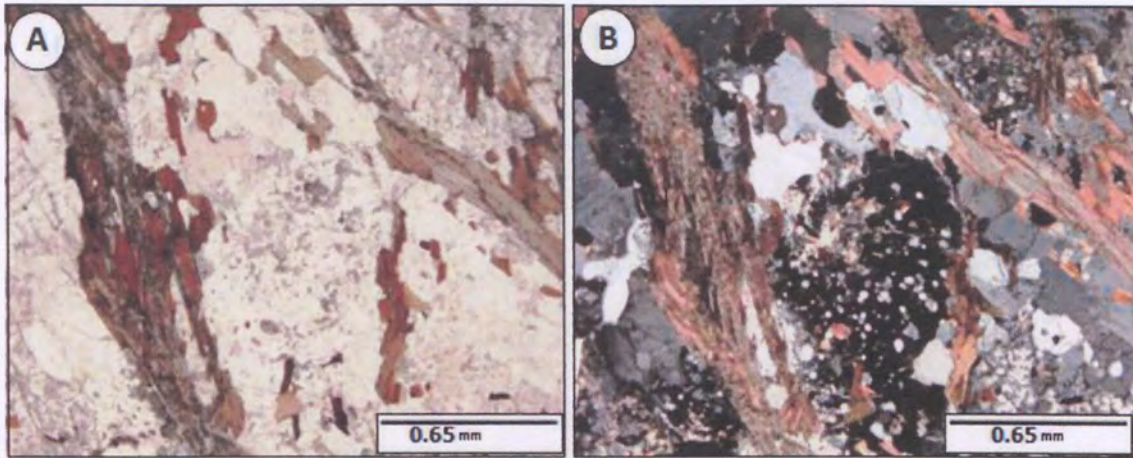


Figure 3.8 Sample No. KS01. Thin section (A) uncrossed polars, (B) crossed polars (**Kuisseb Schistose Cordierite Gneiss**): fine- to medium-grained texture of cordierite gneiss with foliated brown biotite enclosing feldspar, quartz and cordierite. GPS/drill-hole locations of the samples are given in Appendix B1.

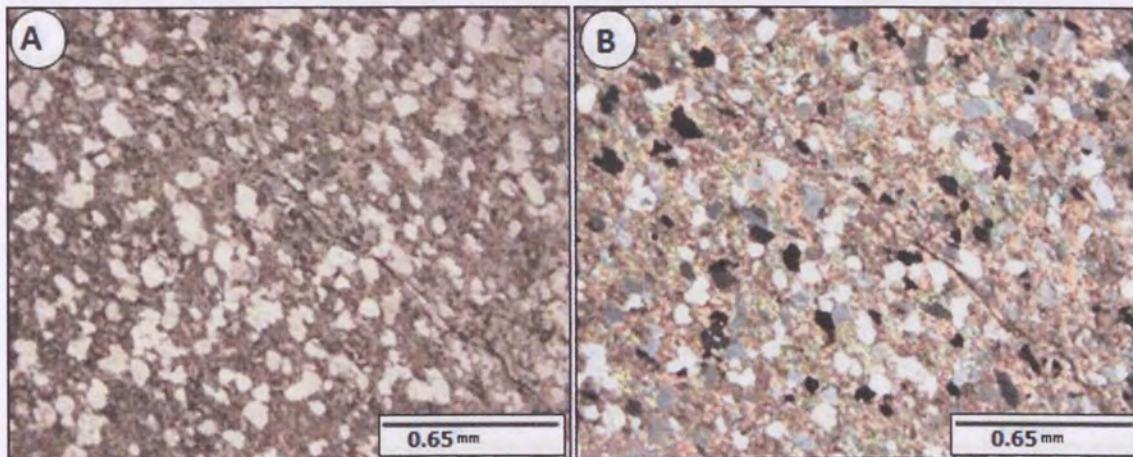


Figure 3.9 Sample No. KS02. Thin section (A) uncrossed polars, (B) crossed polars (**Karibib Impure Marble**): fine-grained texture of anhedral quartz (white) in a calcite matrix (pinkish-orange interference colours in (B) with disseminated muscovite flakes (blue-green interference colours in (B) cut by quartz and calcite veinlets. GPS / drill-hole location of the samples are given in Appendix B1.

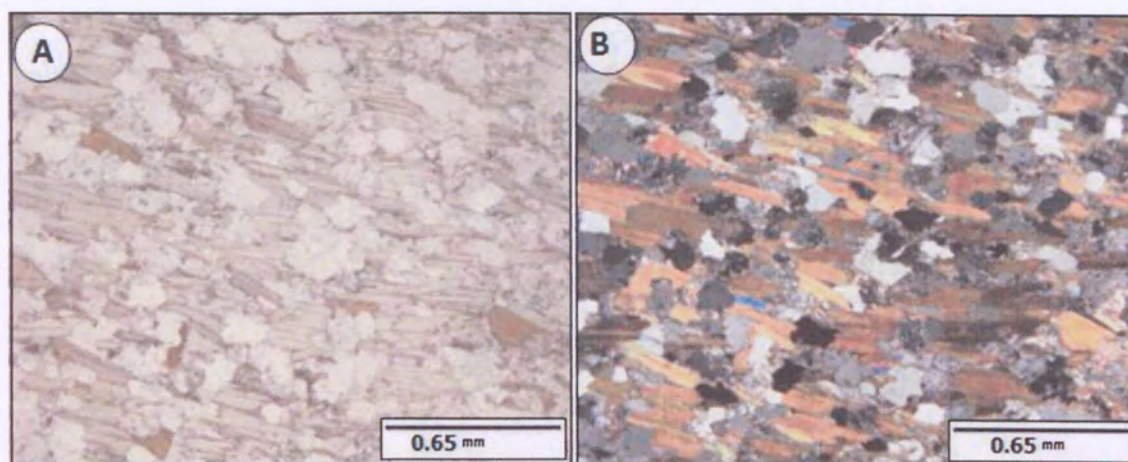


Figure 3.10 Sample No. KS03. Thin section (A) uncrossed polars, (B) crossed polars (**Karibib Biotite Schist**): fine- to medium-grained texture of anhedral quartz (white, clear) and foliated brown biotite with sericitised plagioclase. GPS/drill-hole locations of the samples are given in Appendix B1.

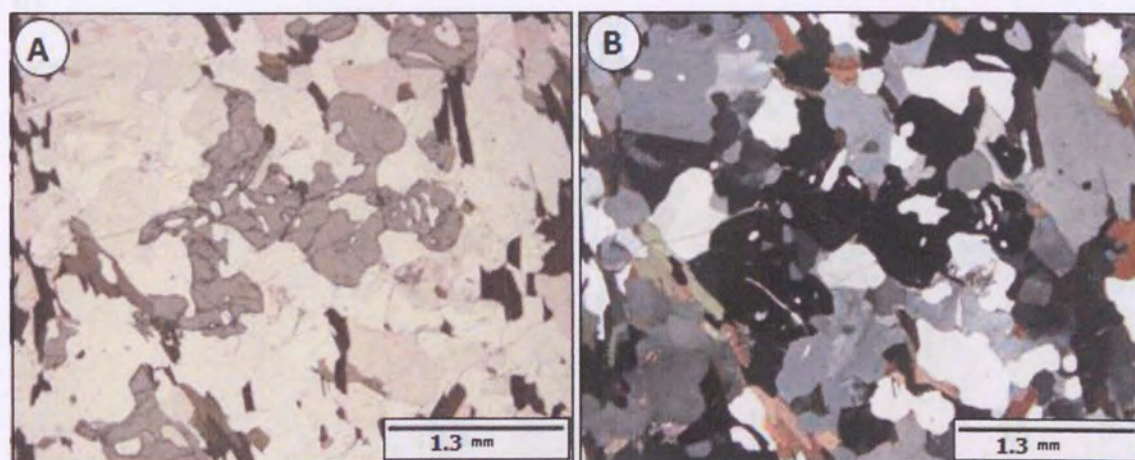


Figure 3.11 Sample No. ChS08. Thin section (A) uncrossed polars, (B) crossed polars (**Chuoes Garnet-Biotite Schist**): foliated brown biotite with associated fine- to medium-grained garnet (dark grey in A, isotropic (black) in B) and anhedral white feldspar, cordierite and quartz. GPS/drill-hole locations of the samples are given in Appendix B1.

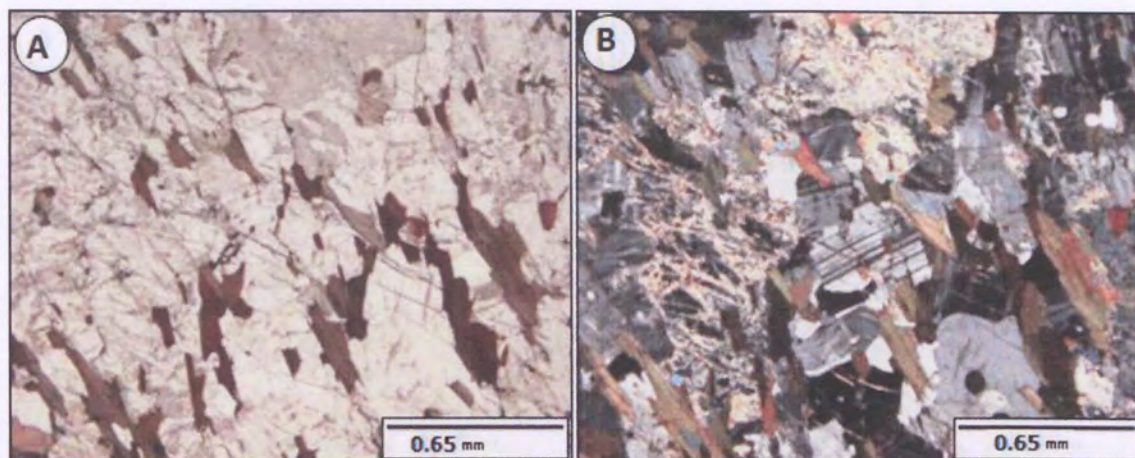


Figure 3.12 Sample No. RSc09. Thin Section (A) uncrossed polars, (B) crossed polars (**Rössing Schistose Cordierite Gneiss**): fine- to medium-grained texture of foliated brown biotite and plagioclase with associated cordierite and quartz as well as sericite (high birefringence in B) replacing feldspar and cordierite. GPS/drill-hole locations of the samples are given in Appendix B1.

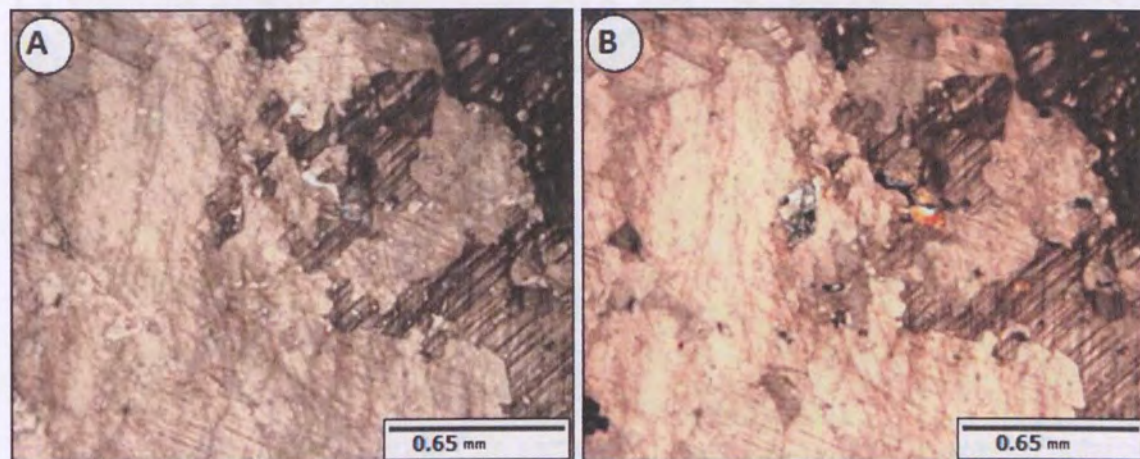


Figure 3.13 Sample No. RMb10. Thin section (A) uncrossed polars, (B) crossed polars (**Rössing Marble**): medium- to coarse-grained texture of recrystallised calcite with minor tremolite (yellow-orange interference colours). GPS/drill-hole locations of the samples are given in Appendix B1.

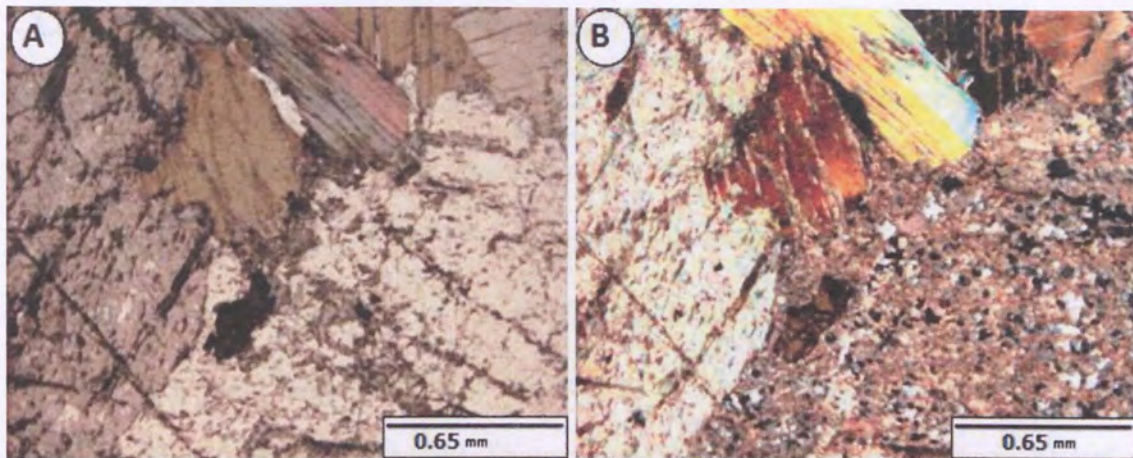


Figure 3.14 Sample No. Calc13. Thin Section (A) uncrossed polars, (B) crossed polars (**Khan Calcsilicate-Gneiss**): coarse-grained diopside (left) altered to sericite (high birefringence) and greenish-brown biotite (single cleavage) with fine-grained calcite and quartz (white) cut by epidote veins. GPS/drill-hole locations of the samples are given in Appendix B1.

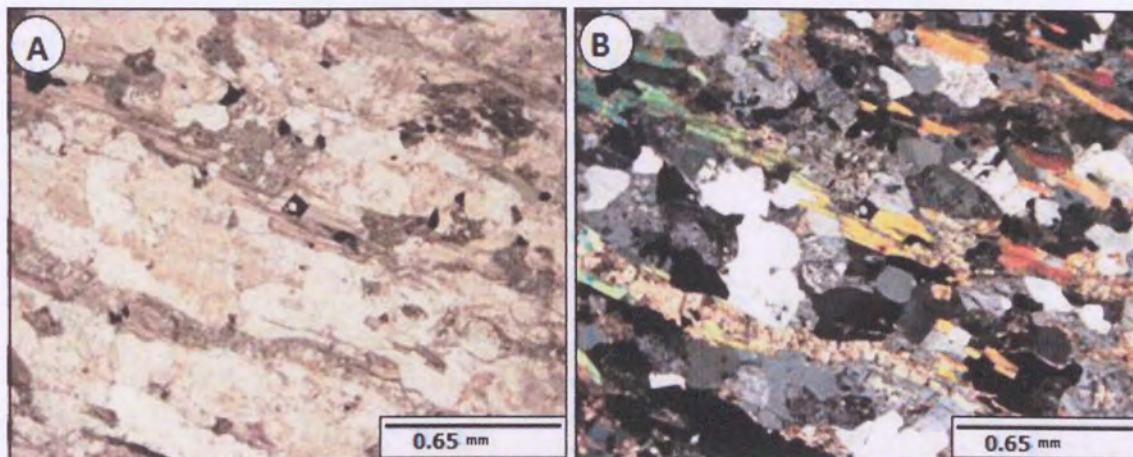


Figure 3.15 Sample No. Khn14. Thin section (A) uncrossed polars, (B) crossed polars (**Khan Biotite Schist**): fine- to medium-grained texture of foliated brown biotite with banded feldspar (twinned, sericite inclusions) and quartz (white, clear) with a foliation-parallel calcite vein (lower left, high birefringence). GPS/drill-hole locations of the samples are given in Appendix B1.

3.3.2 Petrography of the sheeted leucogranites

Modal proportions of the Namibplaas sheeted leucogranites were determined using a mineral visual estimation chart and they are plotted on the QAP tenary classification scheme of Streckeisen (1974), (Figure 3.16). Mineralogically, all sheeted leucogranites consist essentially of quartz, K-feldspar and plagioclase in varying proportions ranging from granodiorite to syenogranite in composition. Modal proportions of the sheeted leucogranites from thin sections are presented in Table C2 (appendix). Thin section sample numbers and the geochemical sample numbers to which this correlate is given in Table D1, Appendix D.

QAP diagram - Si oversaturated

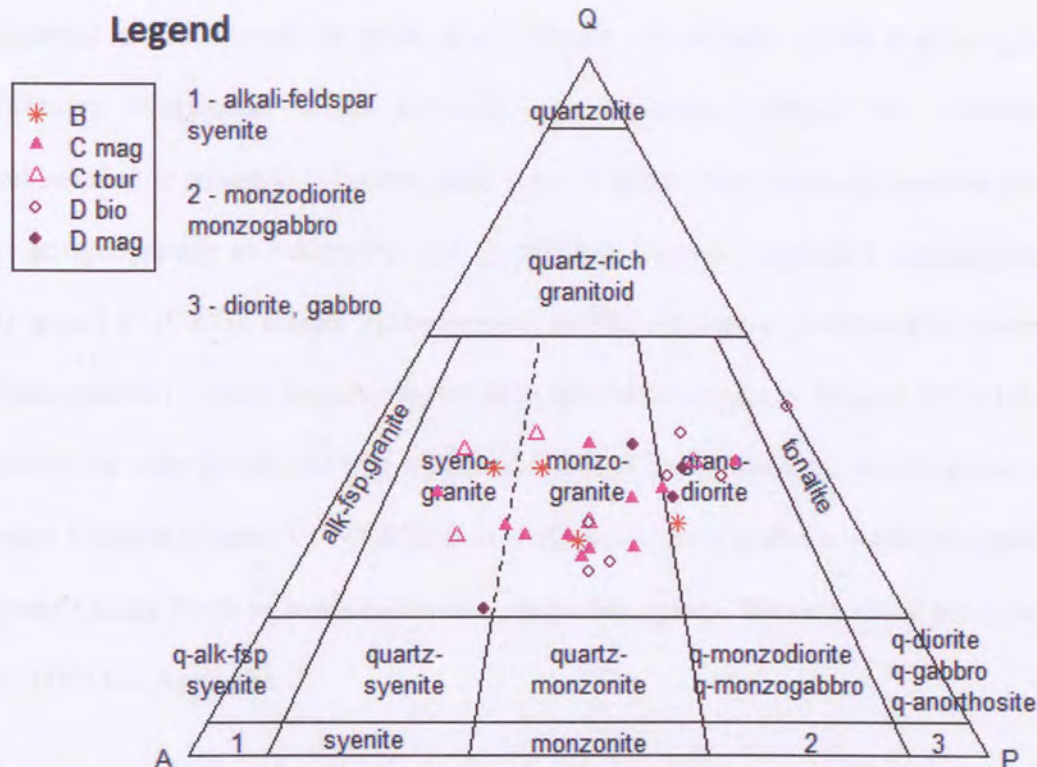


Figure 3.16 QAP (Streckeisen classification scheme, 1974) ternary plots of the Namibplaas sheeted leucogranites. The sheeted leucogranites range from tonalite to syenogranite in composition. For this and subsequent diagrams the following abbreviations are used in the legend, B: B-type sheeted leucogranites; C mag: C-magnetite type sheeted leucogranites; C tour: C-tourmaline type sheeted leucogranites; D bio: D-biotite type sheeted leucogranites; D mag: D-magnetite type sheeted leucogranites.

B-type

The relative proportions of the felsic minerals (quartz, alkali feldspar, and plagioclase) have been plotted on the QAP (Streckeisen classification scheme) ternary diagrams in Figure 3.16, which shows a variation in mineralogy from monzogranites to syenogranites.

Rock textures in thin section are inhomogeneous, coarse-grained, weakly foliated and porphyritic. Quartz is prominent ($>3.4\text{mm}$), forms anhedral to subeuhedral, disordered grains displaying strain extinction. Microcline is the dominant feldspar, it occurs as anhedral to euhedral grains ($>3\text{mm}$ in grain size) irregular, disordered grains displaying polysynthetic twinning. Plagioclase occurs sericitized in all sections (Figure 3.17 (A&B)) and forms subeuhedral to euhedral ($<3\text{mm}$ in grain size) irregular grains showing lamellae twinning. There is an intergrowth of microcline and plagioclase (perthite) observed forming anhedral grains (Figure 3.17 (C&D)). Garnet forms the phenocrysts, it occurs as prominent ($>3.6\text{mm}$) and as fine disseminated ($<1\text{mm}$) irregular grains with inclusions of quartz (Figure 3.17 (E&F)). Biotite is associated with garnet and iron oxide alteration; it forms euhedral brown grains and defines a weak foliation (Figure 3.17 (E&F)). Iron oxide occurs as alterations within the biotite and within veins. Calcite forms as inclusions within plagioclase grains. Mineral modal percentages are given in Table C2, Appendix C.

Some of the prominent garnets ($>3.6\text{mm}$) cross-cut biotite and muscovite grains (Figure 3.16 (E&F)); an indication that the micas must have been earlier than the garnet grains. This can be explained as a later event that might have happened as a result of post-tectonic growth, during which the country rocks supplied elements (aluminum phases) necessary for the growth of garnet within the sheeted leucogranites most probably induced by reactions between the granitic melts and the Kuiseb cordierite rocks during cooling. This is supported by sample locality (stratigraphic position) which indicates that the sheeted leucogranite is emplaced within the schistose cordierite gneiss of the Kuiseb Formation.

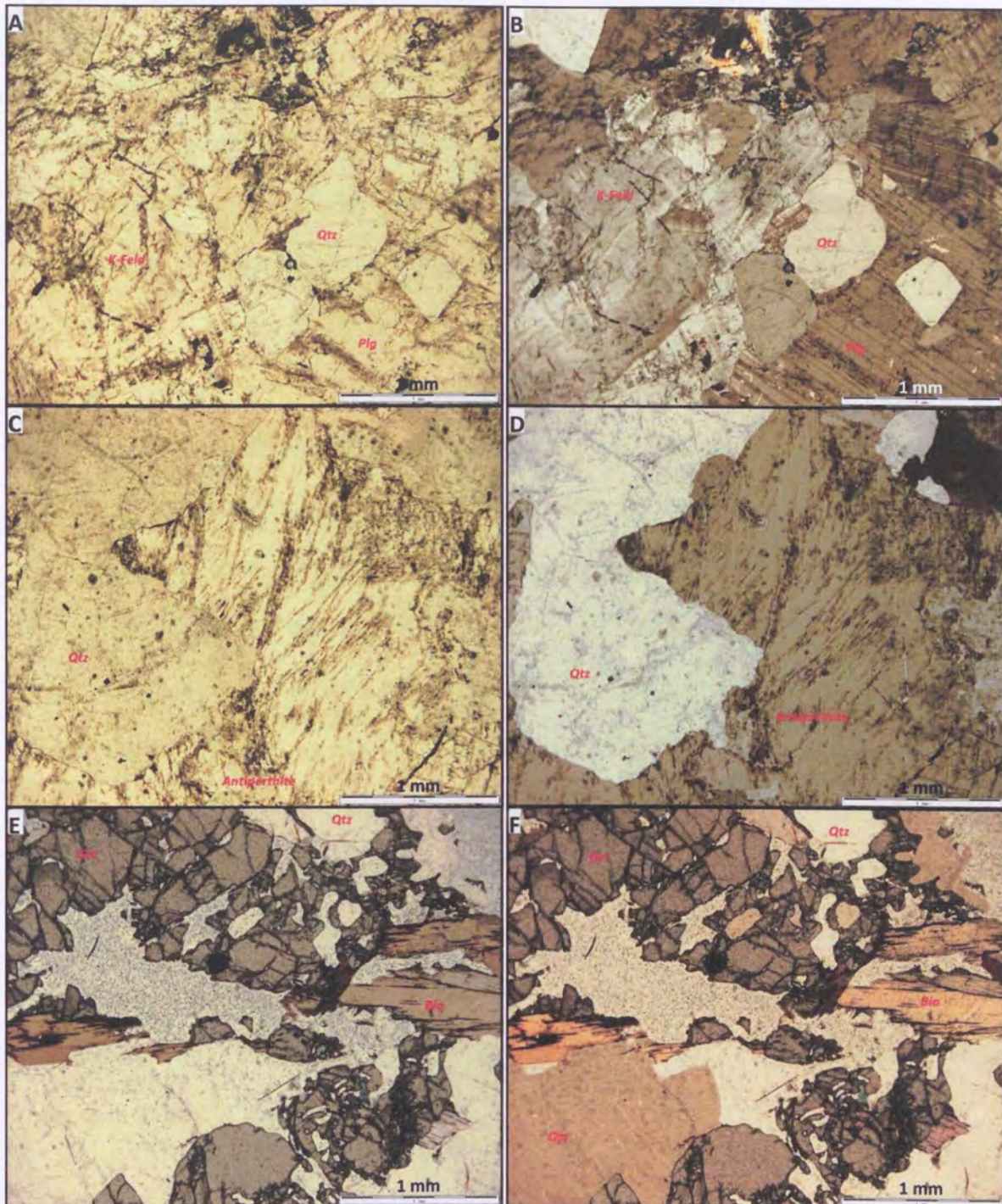


Figure 3.17 Namibplaas B-type sheeted leucogranites. Sample No. 13111. Thin Sections (A) uncrossed polars, (B) crossed polars: Inequigranular texture; medium- to coarse-grained. Thin Sections (C) uncrossed polars, (D) crossed polars: Perthite. Thin Sections (E) uncrossed polars, (F) crossed polars: A foliated porphyritic texture within the B type sheeted leucogranites and brown biotite being replaced by garnet. GPS/drill-hole locations of the samples are given in Appendix B1.

C-type

The C-type sheeted leucogranites are composed of quartz, alkali feldspar and plagioclase with microcline as the dominant feldspar (Table C 2, appendix). QAP plots of the C-type sheeted leucogranites show a mineralogical variation from granodiorite to syenogranite with the majority plotting within the monzogranite field (Figure 3.16).

C-tourmaline: Rock textures in the C-tourmaline type sheeted leucogranites are inhomogeneous, coarse- to very coarse-grained inequigranular (Figure 3.18). Quartz forms anhedral grains (1mm - >3.6mm in grain size) showing strain extinction. Microcline is the dominant feldspar; it occurs as anhedral to euhedral grains (>3.6mm in grain size) irregular, disordered grains displaying polysynthetic twinning. Plagioclase forms subeuhedral (<3mm in grain size) irregular grains showing lamellae twins with frequent inclusions of calcite. Perthite is observed in one of the sections forming anhedral grains (Figure 3.18 D). Accessory minerals are frequent within these sheeted leucogranites: Coarse anhedral to subeuhedral grains of tourmaline. Biotite is chloritised medium-grained and defines a weak foliation (Figure 3.18 B), muscovite is fine-grained, zircon is euhedral and fine-grained, iron oxide alterations occur around opaques and within veins, and garnet is anhedral and fine-grained. Veins filled with iron oxides cross - cut almost all main mineral grains within this sheeted leucogranite type (Figure 3.18 C). Mineral modal percentages are given in Table C2, Appendix.

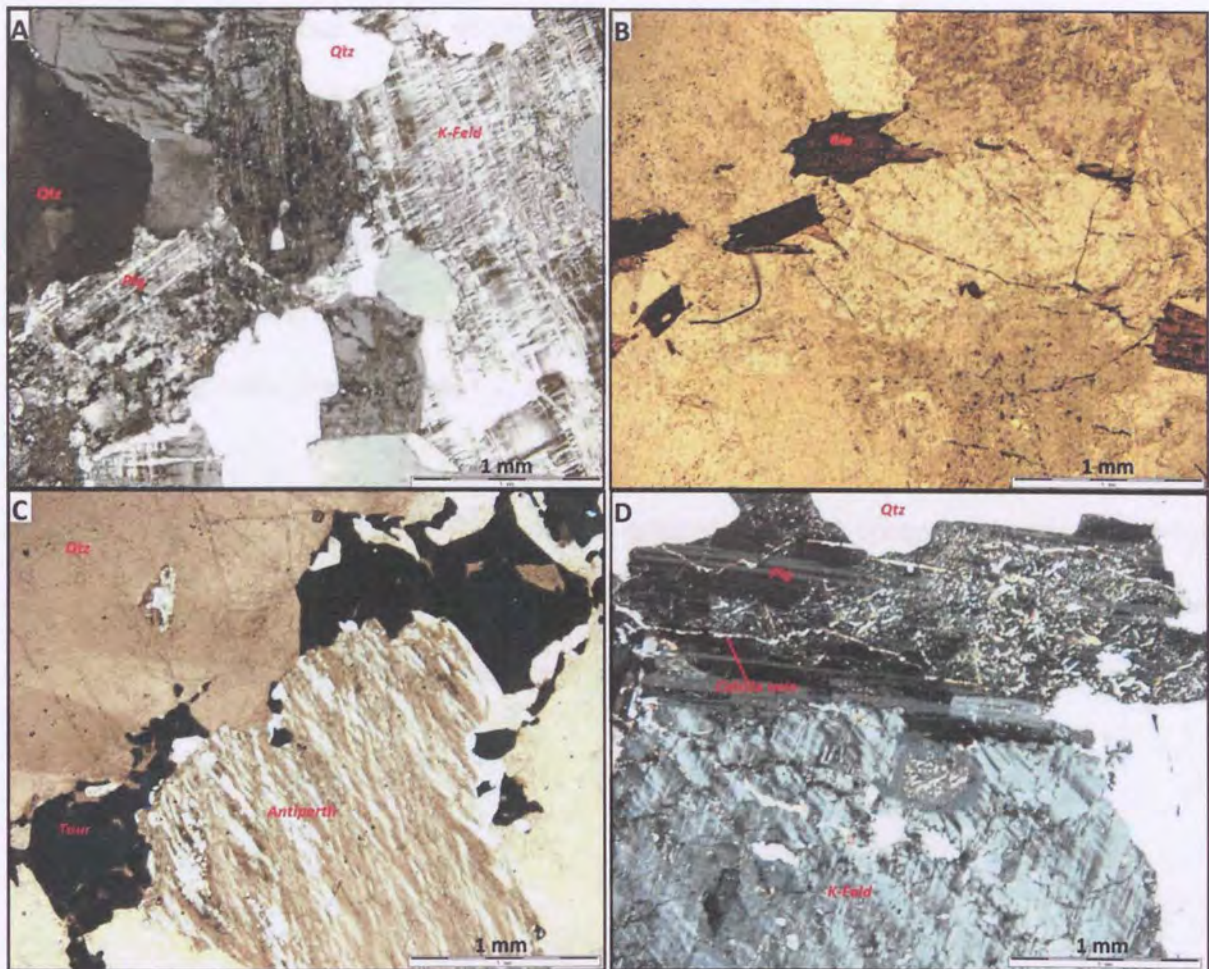


Figure 3.18 Namibplaas C-tourmaline type sheeted leucogranites. Thin section (A) crossed polars: A coarse- to very coarse-grained irregular texture (Sample No. 13106). Thin section (B) crossed polars: A weak foliation defined by biotite minerals (Sample No. 13116). (C) crossed polars: Tourmaline, Perthite and quartz displaying strain extinction (Sample No. 13120). Thin section (D) crossed polars: Sericite alteration within plagioclase (Sample No. 13117). GPS/drill-hole locations of the samples are given in Appendix B1.

C-magnetite: The C-magnetite type sheeted leucogranites vary from coarse- to very coarse-grained inequigranular and inhomogeneous in texture (Figure 3.19). Quartz (1mm->3.6mm in grain size) forms anhedral grains exhibiting strain extinction. Microcline is the dominant feldspar, forming anhedral grains (1.4mm to >3.6mm in grain size) with polysynthetic twinning. Plagioclase (>3.3mm in grain size) which is frequently disseminated with calcite forms anhedral to subeuhedral grains with albite twins. There is an intergrowth of microcline and plagioclase

It can be seen from Figure 3.18 (D) that fine-grained euhedral opaque magnetite cross-cut muscovite. This is evidence that the micas were earlier than “magnetite” and that magnetite occurrence within this sheeted leucogranites might have been a later event.

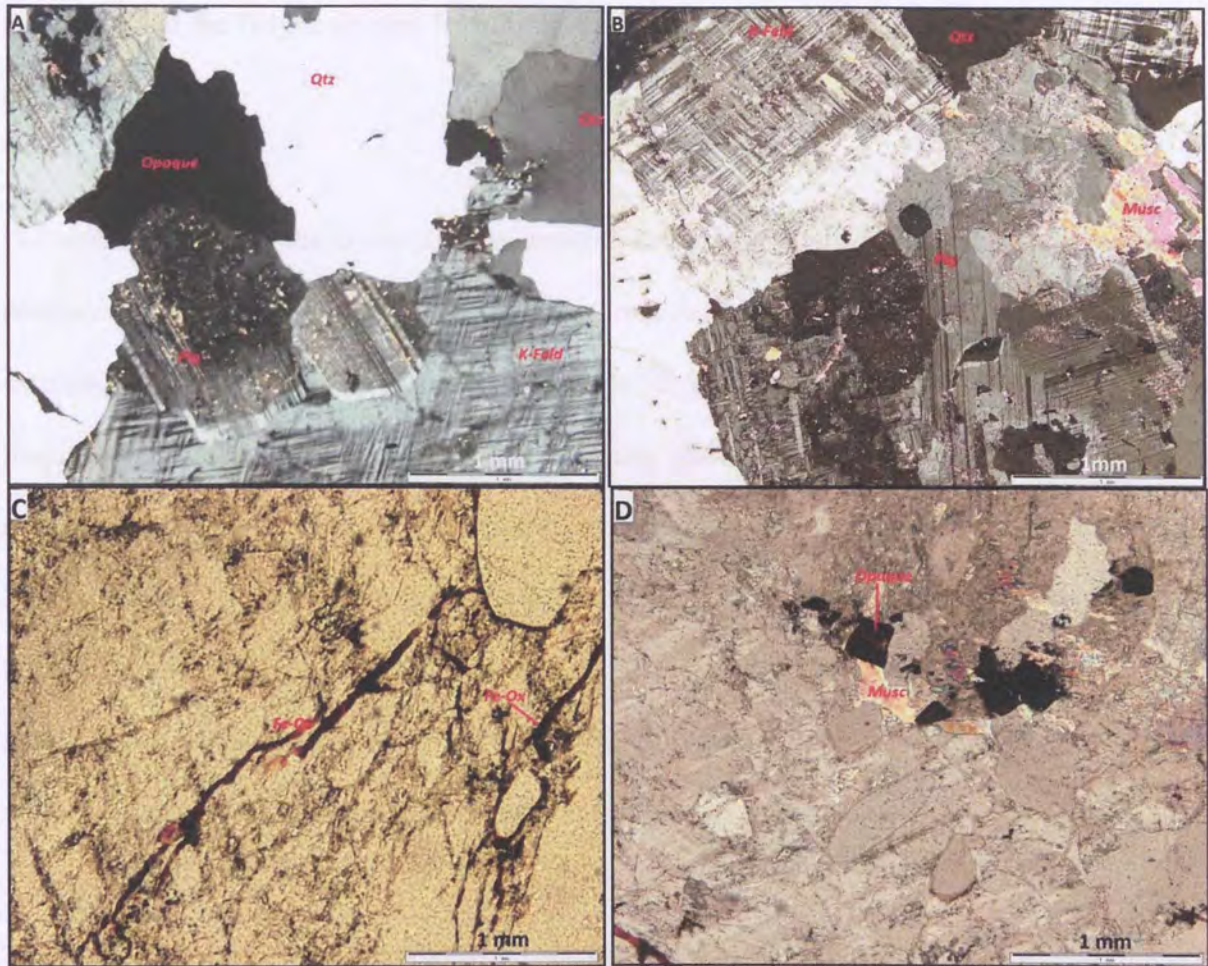


Figure 3.19 Namibplaas C-magnetite type sheeted leucogranites. Thin section (A) crossed polars: A coarse- to very coarse-grained equigranular, irregular texture (Sample No. 13108). Thin section (B) crossed polars: A coarse- to very coarse-grained equigranular, irregular texture (Sample No. 13115). Thin section (C) uncrossed polars: Veins filled with iron oxides cross cutting major minerals (Sample No. 13135). Thin section (D) uncrossed polars: Fine-grained magnetite cross cutting muscovite minerals. The fine-grained muscovite minerals show a weak foliation (Sample No. 13135). GPS/drill-hole locations of the samples are given in Appendix B1.

D-type

In some sections plagioclase and quartz are both dominant occurring in equal proportions (Table C2, Appendix C). Unlike the B and C type sheeted leucogranites; the D type is dominated by plagioclase feldspar. They are composed of quartz, alkali feldspar and plagioclase feldspar. Plots on the QAP diagram shows that mineralogically, the type D sheeted leucogranites vary from tonalite to monzogranites (Figure 3.16). These bear a wider spectrum of accessory minerals, an

indication that the D-type sheeted leucogranites have crystallised from highly evolved late stage melts.

D-biotite: Textures in the D-biotite type sheeted leucogranites vary from coarse equigranular to porphyritic (Figure 3.20). Quartz forms coarse (1mm to >3.6mm) anhedral grains showing strain extinction. Plagioclase occurs as coarse (1.8mm to >3.6mm) subeuhedral to euhedral grains with frequent calcite and sericite inclusions displaying albite twinning. Microcline forms coarse (>3.6mm) anhedral to euhedral grains showing polysynthetic twinning and sericite inclusions. Biotite forms chloritised coarse euhedral grains with iron oxide alterations and shows no foliation, muscovite and sericite occur as fine anhedral to euhedral grains, calcite occur as inclusions in plagioclase feldspar and in veins. Iron oxides occur in veins and as alterations within biotite and opaques. Mineral modal percentages are given in Table C2, Appendix.

There is a replacement texture observed in one of the sections; biotite minerals replacing rounded garnet grains (Figure 3.20 C). Magnetite forms coarse euhedral grains, cutting across main minerals and accessory grains. Zircon occurs as fine-grained inclusions within quartz grains (Figure 3.20 D). Veins filled with calcite cross-cutting almost all main mineral grains occur within this sheeted leucogranite type (Figure 3.20 B).

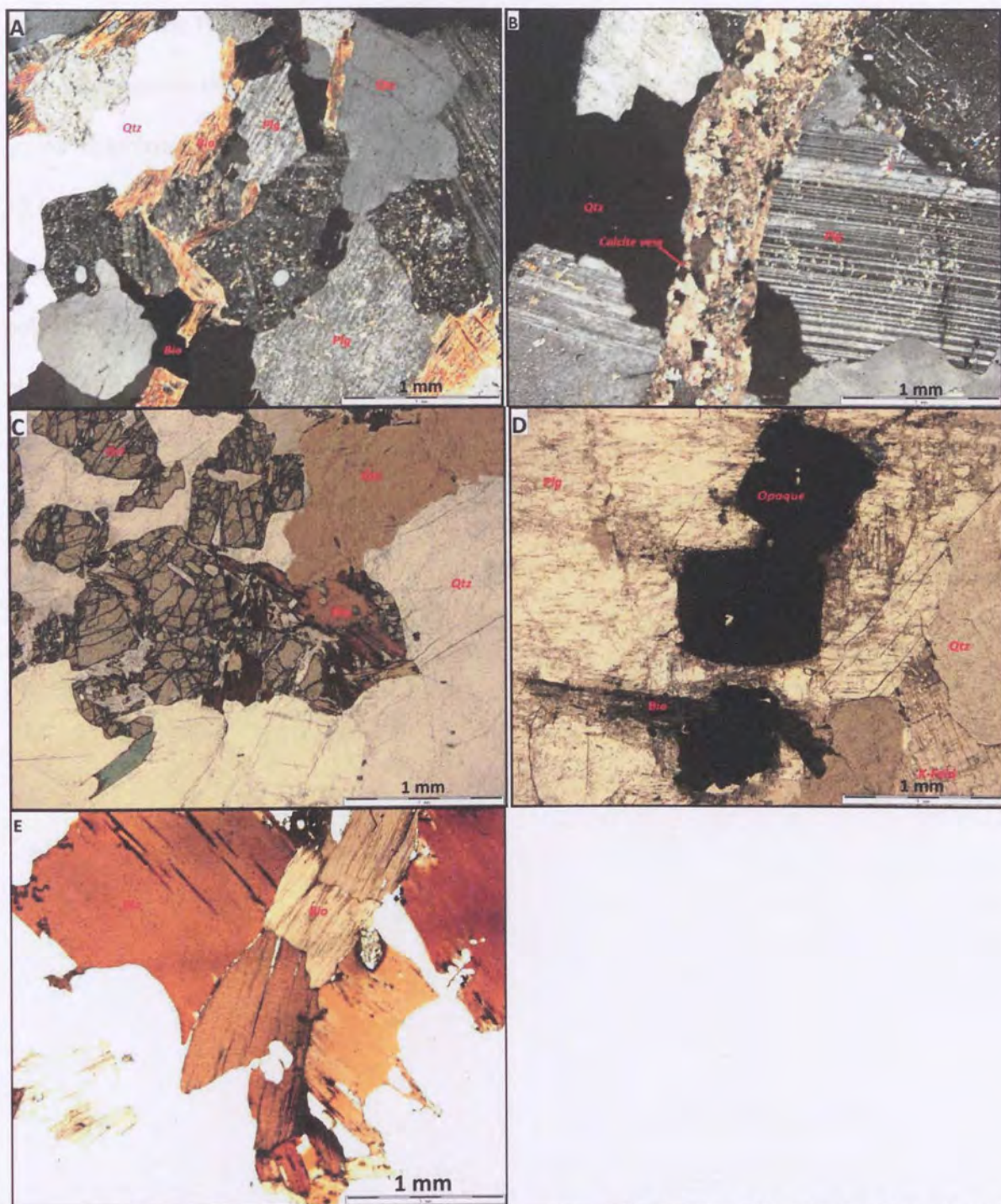


Figure 3.20 Namibplaas D-biotite type sheeted leucogranites. Thin Section (A) crossed polars: A coarse equigranular texture and a vein filled with calcite cross cutting all major minerals (Sample No. 13102). Thin Section (B) crossed polars: A coarse equigranular texture and a vein filled with calcite cross cutting all major minerals (Sample No. 13107). Thin section (C) crossed pollars: Garnet relation with biotite (Sample No. 13101). Thin section (D) uncrossed polars: Magnetite associated with chloritized biotite (Sample No. 13113). Thin section (E) uncrossed polars: Biotite relation within the D-biotite type, showing no preferred orientation (Sample No. 13112). GPS/drill-hole locations of the samples are given in Appendix B1.

D-magnetite: The D-magnetite type varies from coarse to very coarse-grained inequigranular and inhomogeneous in texture (Figure 3.21). Quartz (1.8mm to >3.6mm in grain size) forms anhedral grains exhibiting strain extinction. Plagioclase occurs as coarse to very coarse (1.8mm to >3.6mm) subeuhedral to euhedral grains with frequent sericite inclusions displaying albite twinning. Microcline forms very coarse (>3.6mm) anhedral to euhedral grains showing polysynthetic twinning and sericite inclusions. There is an intergrowth of microcline and plagioclase (perthite) observed in one of the sections forming anhedral grains. Accessory minerals are infrequent in this sheeted leucogranite type; magnetite occur as coarse-grained euhedral opaques with iron oxide alteration cross-cutting muscovite. Chlorite is medium-to coarse-grained with iron oxide alteration and biotite is coarse-grained with muscovite alteration. Veins filled with iron oxides are observed within the D-magnetite types. Mineral modal percentages are given in Table C2, Appendix.

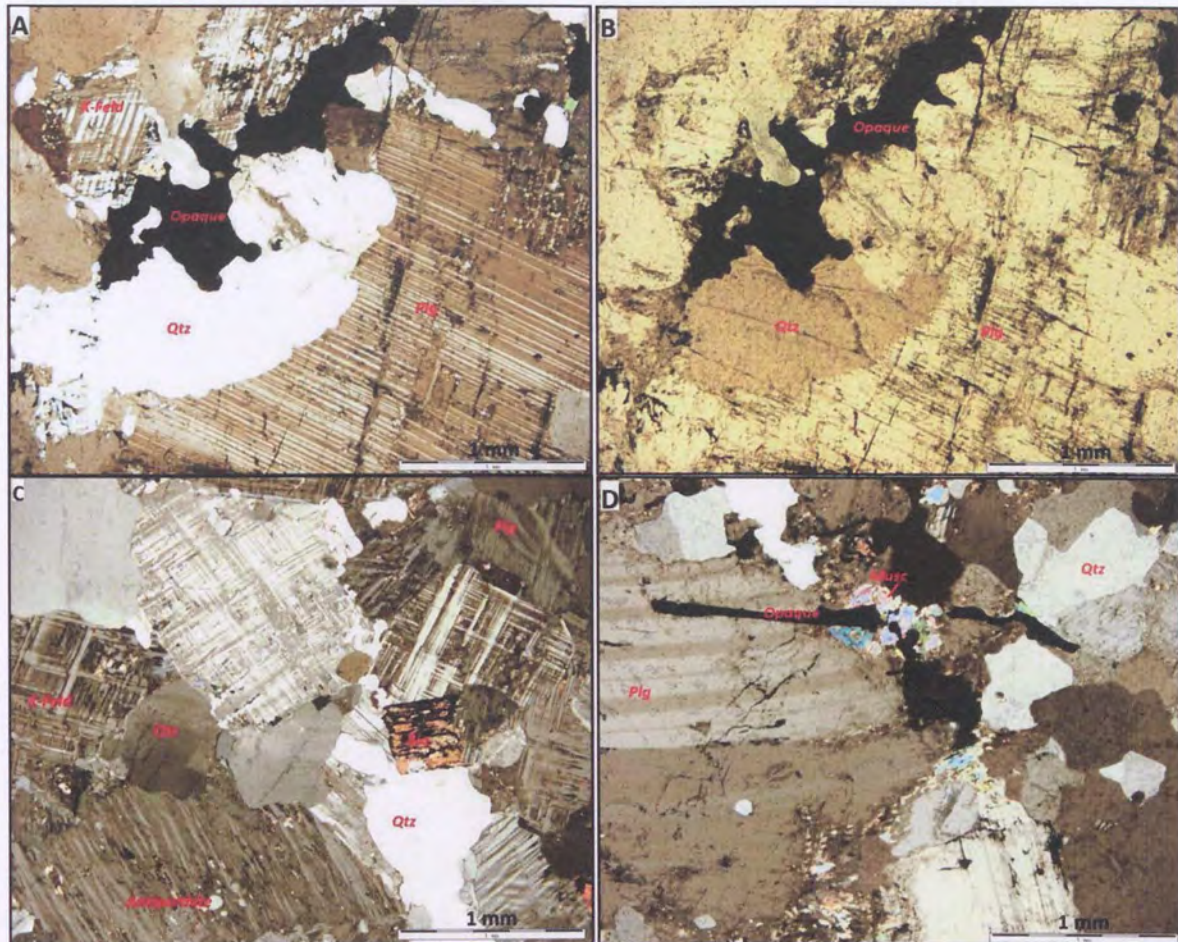


Figure 3.21 Namibplaas D-magnetite type sheeted leucogranites. Thin section (A) crossed polars (B) uncrossed polars: A coarse inequigranular texture (Sample No. 13153). Thin section (C) crossed polars: Section showing perthite, microcline (K-Feld), quartz and biotite (Sample No. 13150). Thin section (D) Magnetite associated with muscovite. Strain extinction is also observed within quartz grains (Sample No. 13152). GPS/drill-hole locations of the samples are given in Appendix B1.

3.4 Structure.

The Namibplaas main structural fabric is defined by preserved primary bedding (S_0) and a dominant foliation (S_1). The strong foliation is defined by biotite and quartz minerals that are parallel to lithological boundaries. The main structural fabric also comprises two lineation sets (L_1 and L_2) defined by cordierite porphyroblasts within the Kuiseb Formation. They lie in the

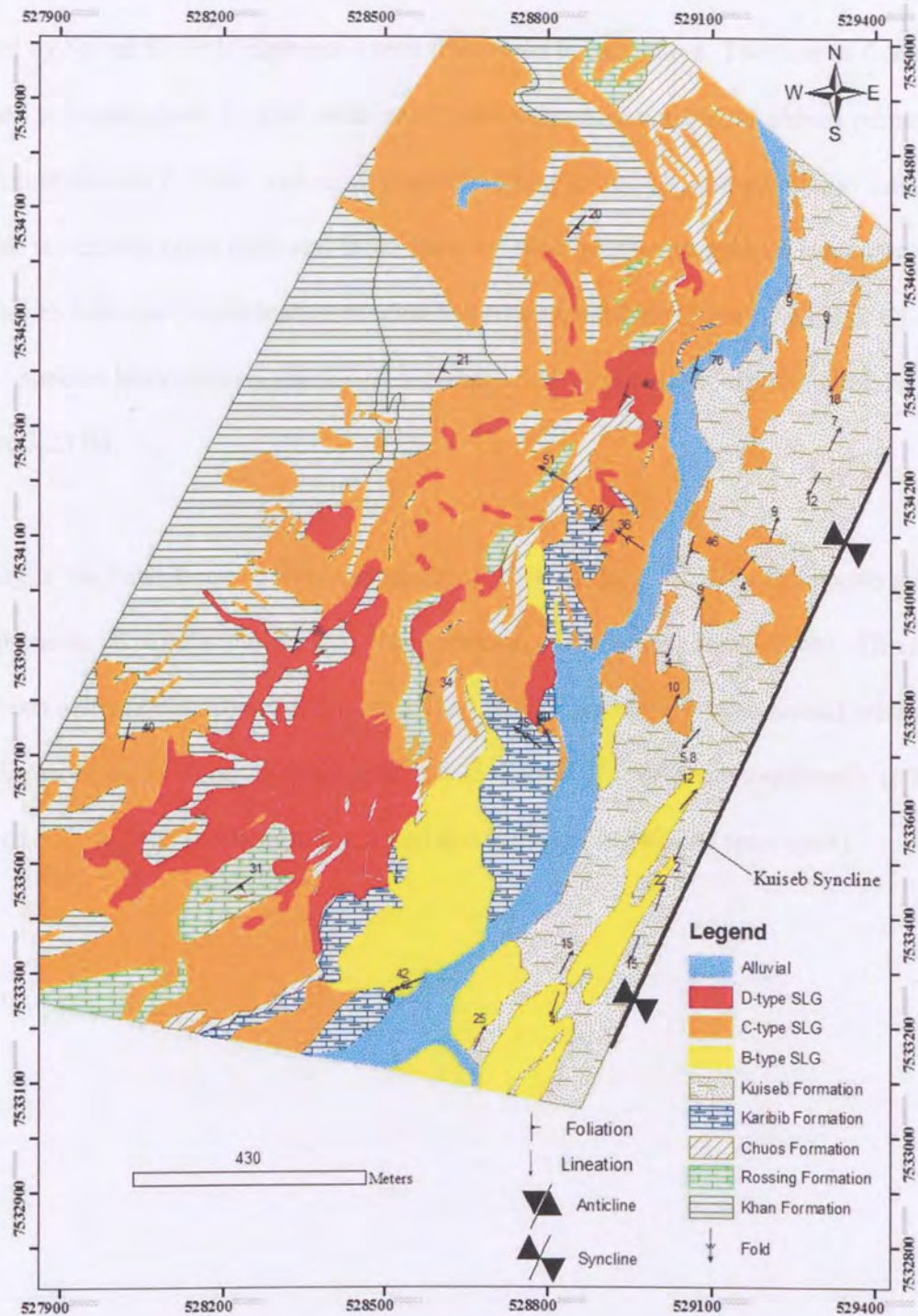


Figure 3.22 Geology of Namibplaas. Strike and dip symbols indicate foliation; arrows indicate plunge of lineation. The solid line shows the Kuiseb synform (Geological map by Valencia Uranium (Pty) Ltd, 2008).

Local folding is well developed in the Kuiseb, Karibib and Chuos Formations. This folding is defined by S_0 and S_1 . Fold tightness varies from open to recumbent. Two sets of folds have been mapped at Namibplaas; F_2 folds with axial planes trending northwest, almost perpendicular to foliation strike and F_3 folds with axial planes trending southwest, sub-parallel to foliation strike. F_2 folds are mainly open folds and these show no association with sheeted leucogranites (Figure 3.23 A). F_3 folds are a combination of open and recumbent folds (Figure 3.23 B & C). The B and C-type sheeted leucogranites are folded together with the country rocks along the F_3 open folds (Figure 3.23 B).

Jointing is the most frequent structure at Namibplaas (Figure 3.23 D). Conjugate joint sets are well pronounced within the sheeted leucogranites, marbles and meta-arkose. Three joint sets have been mapped out: The earlier joint set (J_1) is displaced by the later second joint set (J_2) and J_2 is displaced by J_3 . J_1 has a strike range of 033° to 060° (northeast-southwest), J_2 has a strike range of 300° to 340° (northwest-southeast) and J_3 strikes at 240 - 280 (east-west).

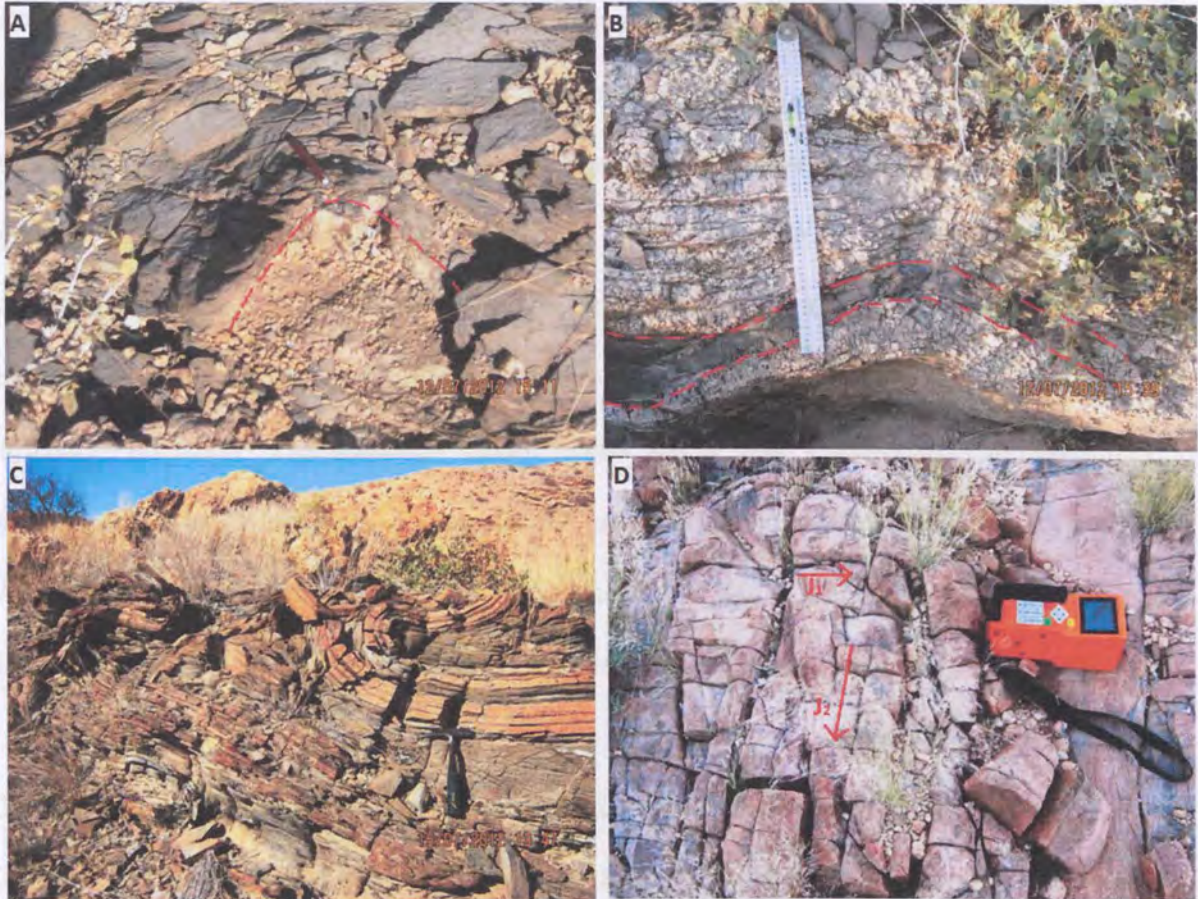


Figure 3.23 Namibplaas outcrops. (A) F_2 folding within the Karibib biotite schist; (B) F_3 open-folding within the Karibib biotite schist; C-tourmaline type sheeted leucogranite folded together with the Karibib biotite schist; (C) Recumbent folding within the Karibib biotite schist interchanging with calcsilicate rock. (D) Jointing within the Khan meta-arkose.

3.5 Metamorphism.

A series of metamorphic mineral assemblages are observed within the country rocks at Namibplaas (Table 3.3). The difference in metamorphic assemblages is owed to the difference in protolith type. All country rock formations have attained at least amphibolite facies.

Khan Formation: The schistose biotite-amphibole gneissic rocks of the Khan Formation are characterised by microcline-plagioclase-quartz-biotite-diopside-calcite mineral assemblage and a fine-grained foliated to banded rock texture.

Rössing Formation: The schistose cordierite gneiss has a plagioclase-cordierite-biotite-quartz-sericite mineral assemblage plus a fine-grained banded rock texture. The banded tremolite marble is characterised by the mineral assemblage Calcite-tremolite and a recrystallised medium-grained banded rock texture.

Chuosi Formation: The schistose diamictite schist has a plagioclase-cordierite-quartz-biotite-microcline-garnet mineral assemblage and a fine-grained foliated rock texture,

Karibib Formation: The schistose biotite gneiss has a plagioclase-quartz-biotite-microcline-garnet mineral assemblage and a schistose fine-grained foliated rock texture.

Kuiseb Formation: The schistose cordierite gneiss has a plagioclase-cordierite-quartz-biotite-microcline mineral assemblage and a medium-grained banded, foliated and gneissic rock texture.

3.6 Timing of the sheeted leucogranites emplacement and their age relationship.

The sheeted leucogranites are emplaced along foliation (S_1) as conformable and transgressive bodies. The sheeted leucogranites however do not show any association or relation to the F_2 folding a possibility that the B and C-type sheeted leucogranites were emplaced after the F_2 folding event.

The B and C-type sheeted leucogranites are boudinaged within the meta-sediments and folded together with the country rocks along F_3 folds. This illustrates that the B and C-type leucogranites are pre F_3 . The D-type leucogranites have not been boudinaged within or folded together with the meta-sediments; this means that the D-type leucogranites were most likely emplaced post- F_2 , F_3 . Quartz within the D-type leucogranites however show strain extinction

under thin section (Figure 3.20 & Figure 3.21), indicating that the sheeted leucogranites have been deformed. This deformation might have been induced by a later folding event (F₄).

The D-type sheeted leucogranites cross-cut the B and C-type leucogranites (Figure 3.24 D&E) making them the youngest of the intrusives. The B and C-type leucogranites seem not to show a cross-cutting relationship.

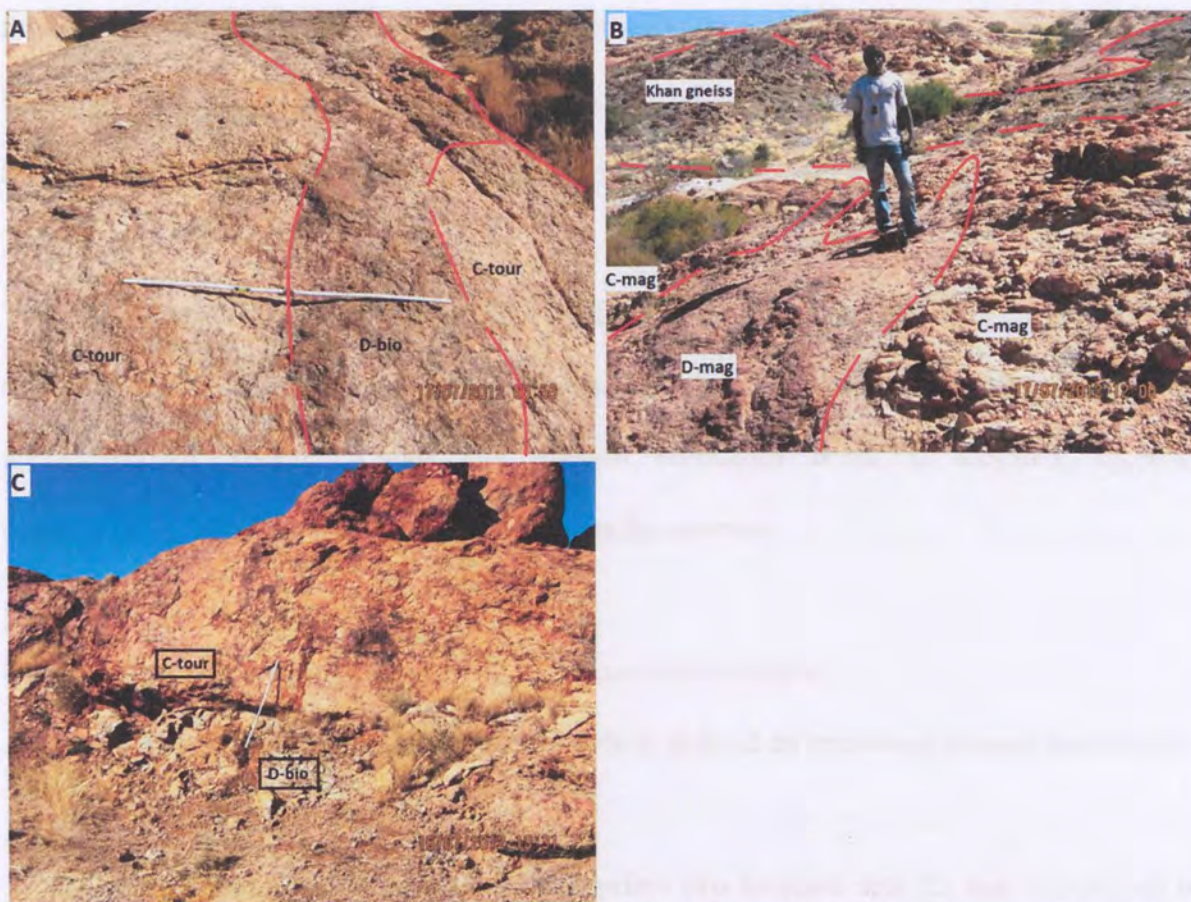


Figure 3.24 Namibplaas outcrops. (A) D-bio and C-tour type sheeted leucogranite cross-cutting relationship, the C-tourmaline has a northeast to southwest strike; (B) D-mag cross-cutting the C-mag type sheeted leucogranite with a northwest-southeast strike (picture taken facing northwest); (C) A concordant/sub parallel emplacement between a D-biotite and a C-tourmaline type sheeted leucogranite.

3.7 Summary of the geology of Namibplaas.

At Namibplaas; the Damaran stratigraphy comprises substantially attenuated representatives of Khan, Rössing, Chuos, Karibib and Kuiseb Formations. The Khan Formation is the lowermost Damaran unit and outcrops mainly as meta-arkose, biotite-amphibole gneisses and calcsilicate gneisses that occur to the northwest of the Namibplaas uranium anomaly. White banded marbles, calcsilicate rocks, schistose cordierite gneisses and pure quartzites are representative of the Rössing Formation. The Chuos Formation is dominantly schistose to gneissic diamictites, the Karibib Formation comprises schistose biotite gneiss and the uppermost Damaran Kuiseb Formation is predominantly schistose cordierite gneiss.

The Khan Formation forms the surface geological limit on the northwestern part of the radiometric anomaly and the Kuiseb Formation on the southeastern part. The highly metamorphosed Rössing, Chuos and Karibib Formations occur as elevated, sporadic, discontinuous folded outcrops along strike within the anomaly.

Structural analysis at Namibplaas revealed five consistent features.

- i) The Namibplaas main structural fabric is defined by preserved primary bedding (S_0) and a dominant foliation (S_1).
- ii) The main structural fabric also comprises two lineation sets (L_1 and L_2) defined by cordierite porphyroblasts within the Kuiseb Formation. They lie in the foliation plane (S_1) and have a sub-parallel alignment to S_1 .

- iii) Folding is defined by S_0 and S_1 . Fold tightness varies from open to recumbent. Two trend sets of folding have been mapped out at Namibplaas; folds (F_1) with axial planes trending southwest, almost perpendicular to foliation strike and folds (F_2) with axial planes trending northeast, sub-parallel to foliation strike.
- iv) Folds (F_2) with axial planes trending southwest, almost perpendicular to foliation strike.
- v) Folds (F_3) with axial planes trending northeast, sub-parallel to foliation strike.

Metamorphism of the Namibplaas meta-sedimentary rocks reached amphibolite facies grade of metamorphism associated with two phases of folding (F_2 , F_3).

Numerous sheeted leucogranites (sheeted leucogranites) intrude the whole metamorphic series. The sheeted leucogranites are coarse- to pegmatitic in texture and are characterised by a vein/sheet-like or anastomosing style of intrusion conformable and transgressive to country rock foliation (S_1). The syn- to post- deformation sheeted leucogranites range in composition from tonalite to syenogranite and have been subdivided into three main types; B, C and D. The pegmatitic B-type sheeted leucogranites are boudinaged, foliated and folded together with the country rocks along open folds of the F_3 structural evolution. They are characterised by infrequent garnet where the leucogranite is emplaced within garnet-bearing country rocks. The C-type sheeted leucogranites have a pegmatitic rock texture. These are boudinaged, foliated and folded together with the country rocks along open folds of the F_3 event. These are characterised by tourmaline nests and coarse-grained magnetite where the leucogranite is emplaced within magnetite-bearing country rocks. D-type sheeted leucogranites have a coarse equigranular to

pegmatitic rock texture and these are characterised by smoky to black smoky quartz. The D-type leucogranites bear accessory garnet and magnetite where the leucogranite is emplaced within garnet- or magnetite-bearing country rocks. Accessory garnet and magnetite within the D-type sheeted leucogranites is a result of post-tectonic growth, host rock assimilation and incorporation of the two accessory phases. B and C-type sheeted leucogranites are pre- F_3 and the D-type sheeted leucogranites are post F_3 . A Cross-cutting relationship indicates that the D-type leucogranites are the youngest of the intrusives.

Table 3.4 Summary of the Namibplaas sheeted leucogranite geology.

Type	Age	Structure	Texture	Diagnostic mineralogy
B	Post- F_2 , Pre- F_3	Foliation, Boudinage, Open folding, Jointing	Coarse-grained to pegmatitic	Garnet
C-tour	Post- F_2 , Pre- F_3	Foliation, Boudinage, Open folding, Jointing	Coarse-grained to pegmatitic	Tourmaline
C-mag	Post- F_2 , Pre- F_3	Foliation, Open folding, Jointing	Coarse-grained to pegmatitic	Magnetite
D-bio	Post- F_2 , F_3	Jointing	Coarse-grained equigranular to pegmatitic	Smoky quartz, Garnet, Magnetite.
D-mag	Post- F_2 , F_3	Jointing	Coarse-grained to pegmatitic	Smoky quartz, Magnetite, Hematite

CHAPTER 4

GEOCHEMISTRY OF THE NAMIBPLAAS SHEETED LEUCOGRANITES

4.1 Introduction.

Geochemical analyses were undertaken in order to further characterise the Namibplaas sheeted leucogranites based on major elements, trace elements and rare earth elements and also to evaluate the igneous processes that led to their formation.

Geochemical analyses were conducted by Bureau Veritas Mineral Laboratories Namibia. The sample preparation and analytical methods are given in Chapter 1 under the methodology section.

4.2 Major element geochemistry.

The major elements of the analysed sheeted leucogranites are presented in Table C3 (Appendix C) and a summary of this data is given in Table 4.1. The sheeted leucogranites are extreme leucocratic rocks which are high in silica (67.8 to 79.1) and low in CaO (0.11 to 1.71%) as well as MgO (0.01 to 0.9%). The Namibplaas sheeted leucogranites show a high K₂O and Na₂O content as compared to CaO (Table C2, Appendix). The high K₂O + Na₂O > CaO in these sheeted leucogranites suggests that they are alkaline.

Table 4.1 Average major element data for the Namibplaas sheeted leucogranites. The single value represents an average in concentration from respective samples and the dual set of values represent the range in concentration from lowest to highest. The “n” row is the number of samples.

	Units	Detection limit	B	C tour	C mag	D bio	D mag
n			4	9	13	13	13
SiO ₂	%	0.01	75.52 73.64-77.01	74.53 71.57-79.07	75.5 73.21-78.33	74.39 67.80-78.93	75.14 71.20-77.70
Al ₂ O ₃	%	0.01	13.54 13.02-13.91	14.15 12.01-16.30	13.35 11.69-14.47	13.46 11.05-15.90	13.73 11.80-16.00
Fe ₂ O ₃	%	0.01	1.41 1.32-1.57	1.33 0.47-3.19	1.3 0.61-3.72	1.42 0.58-2.87	0.88 0.44-1.80
MgO	%	0.01	0.07 0.02-0.12	0.29 0.03-0.90	0.09 0.01-0.30	0.36 0.08-0.88	0.12 0.01-0.22
MnO	%	0.01	0.12 0.08-0.17	0.02 0.01-0.04	0.02 0.01-0.04	0.04 0.01-0.13	0.02 0.01-0.06
CaO	%	0.01	0.59 0.52-0.67	0.68 0.11-1.48	1.05 0.45-1.71	0.96 0.15-1.61	0.87 0.54-1.03
Na ₂ O	%	0.01	2.68 2.39-3.31	3.18 2.31-4.83	3.06 1.55-4.28	3.06 1.68-4.32	3.6 2.87-4.11
K ₂ O	%	0.01	5.20 4.83-6.10	5.83 4.38-8.19	5.08 2.68-7.90	5.20 3.39-7.15	5.56 4.22-7.37
P ₂ O ₅	%	0.01	0.14 0.07-0.19	0.10 0.04-0.15	0.05 0.02-0.15	0.08 0.03-0.20	0.02 0.01-0.04
TiO ₂	%	0.01	0.01 0-0.03	0.12 0-0.29	0.05 0.01-0.31	0.13 0.05-0.36	0.07 0.03-0.11

The Aluminum Saturation Index of Shand (1943) plotted as A/NK ($\text{Al}_2\text{O}_3/\text{Na}_2\text{O}+\text{K}_2\text{O}$) against A/CNK ($\text{Al}_2\text{O}_3/\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O}$) shows that the B and the C-type sheeted leucogranites are peraluminous. The D-type sheeted leucogranites are peraluminous to metaluminous (Figure 4.1). Peraluminous granites are generated by partial melting of meta-sedimentary rocks in the continental crust (Chappell and White 1974; Miller 1985). The geotectonic classification diagram of Batchelor and Bowden (1985) classifies most of the granites as sync-collision to late-orogenic intrusions (Figure 4.2). Some of the earlier sheeted leucogranites (B & C-type leucogranites) plot as post- orogenic suggesting effects of later hydrothermal alterations during

the D₃ and D₄ events. Similarly, some of the late- orogenic D-type leucogranites plot as syn-orogenic, probably due to the later D₄ orogenic event.

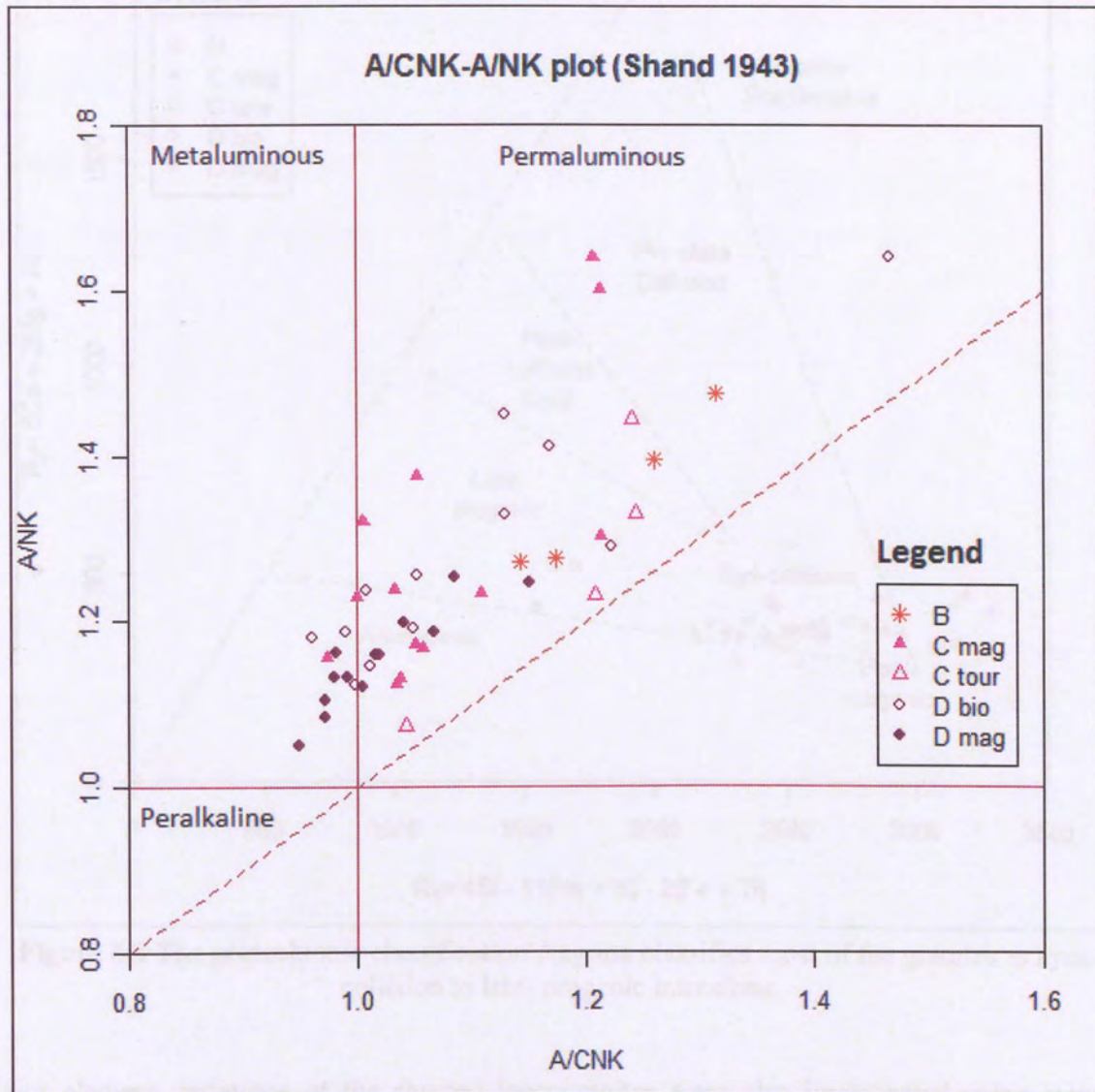


Figure 4.1 A/CNK-A/NK plot showing that the granites are of a peraluminous to a metaluminous nature.

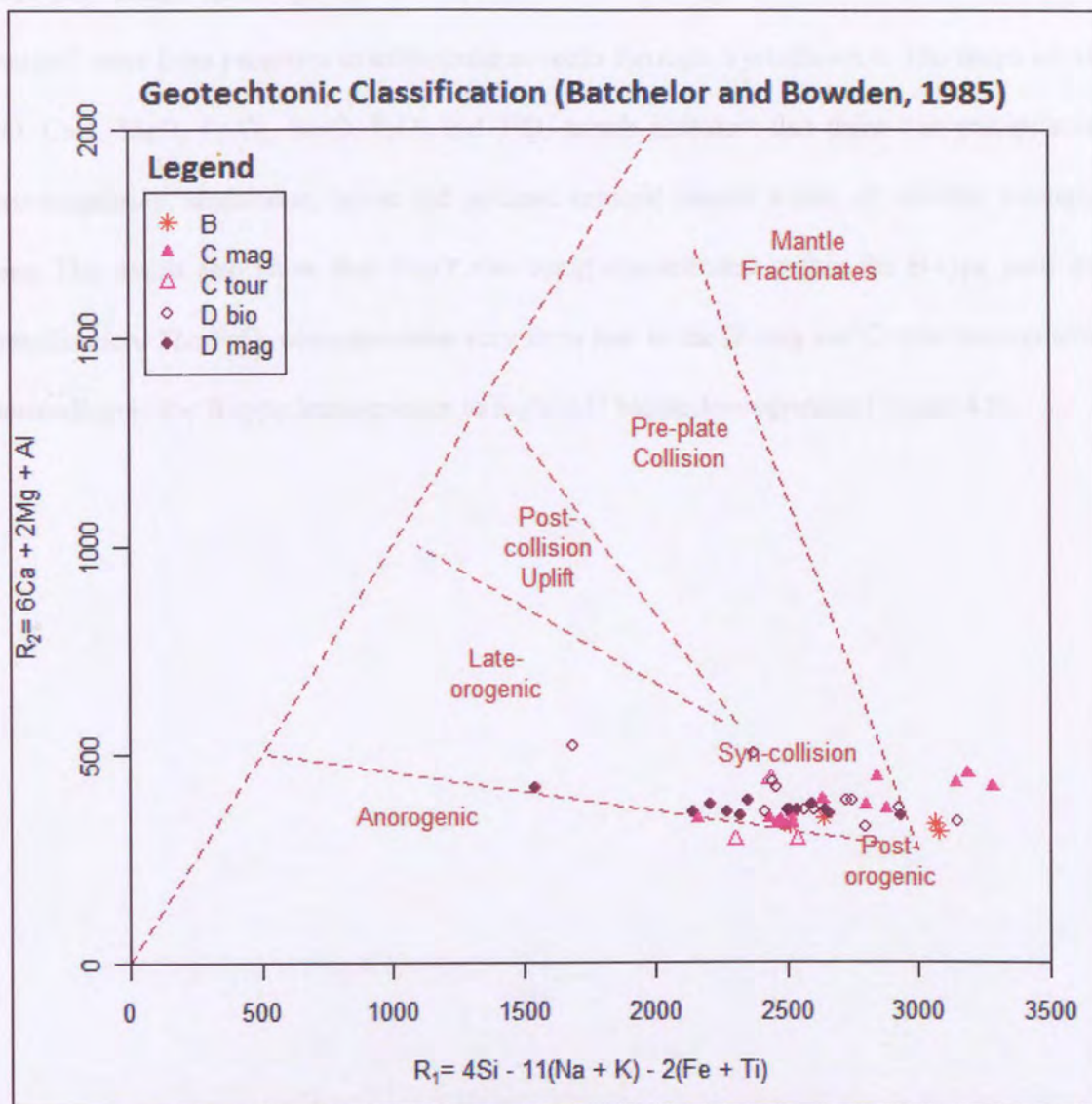


Figure 4.2 The geotectonic classification diagram classifies most of the granites as syn-collision to late-orogenic intrusions.

Major element variations of the sheeted leucogranites were also investigated using standard Harker (1909) diagrams (Figure 4.3 to Figure 4.11). From the Harker plots; the sheeted leucogranites show a general decrease in Al_2O_3 , K_2O , CaO , MgO , Fe_2O_3 , MnO , P_2O_5 and TiO_2 for all sheeted leucogranite types. A general increase in Na_2O with increasing SiO_2 is observed within the C and D types (Figure 4.4). The B-types have a decrease in Na_2O with increasing

SiO₂. The nature of the geochemical trends shows a magmatic evolution within individual granitoid types from primitive to differentiated rocks through crystallisation. The shape of Al₂O₃, K₂O, CaO, MgO, Fe₂O₃, MnO, P₂O₅ and TiO₂ trends indicates that there was precipitation of ferro-magnesian, aluminous, calcic and potassic mineral phases within all sheeted leucogranite types. The trends also show that Na₂O was being concentrated within the B-type melt during crystallisation. The FeO₂ concentrations vary from low in the D mag and C-type leucogranites to intermediate in the B-type leucogranites to high in D biotite leucogranites (Figure 4.8).



Figure 4.8: Variation of FeO₂ concentrations (wt%) versus a parameter (X-axis) for different leucogranite types (D mag, C-type, B-type, D biotite).

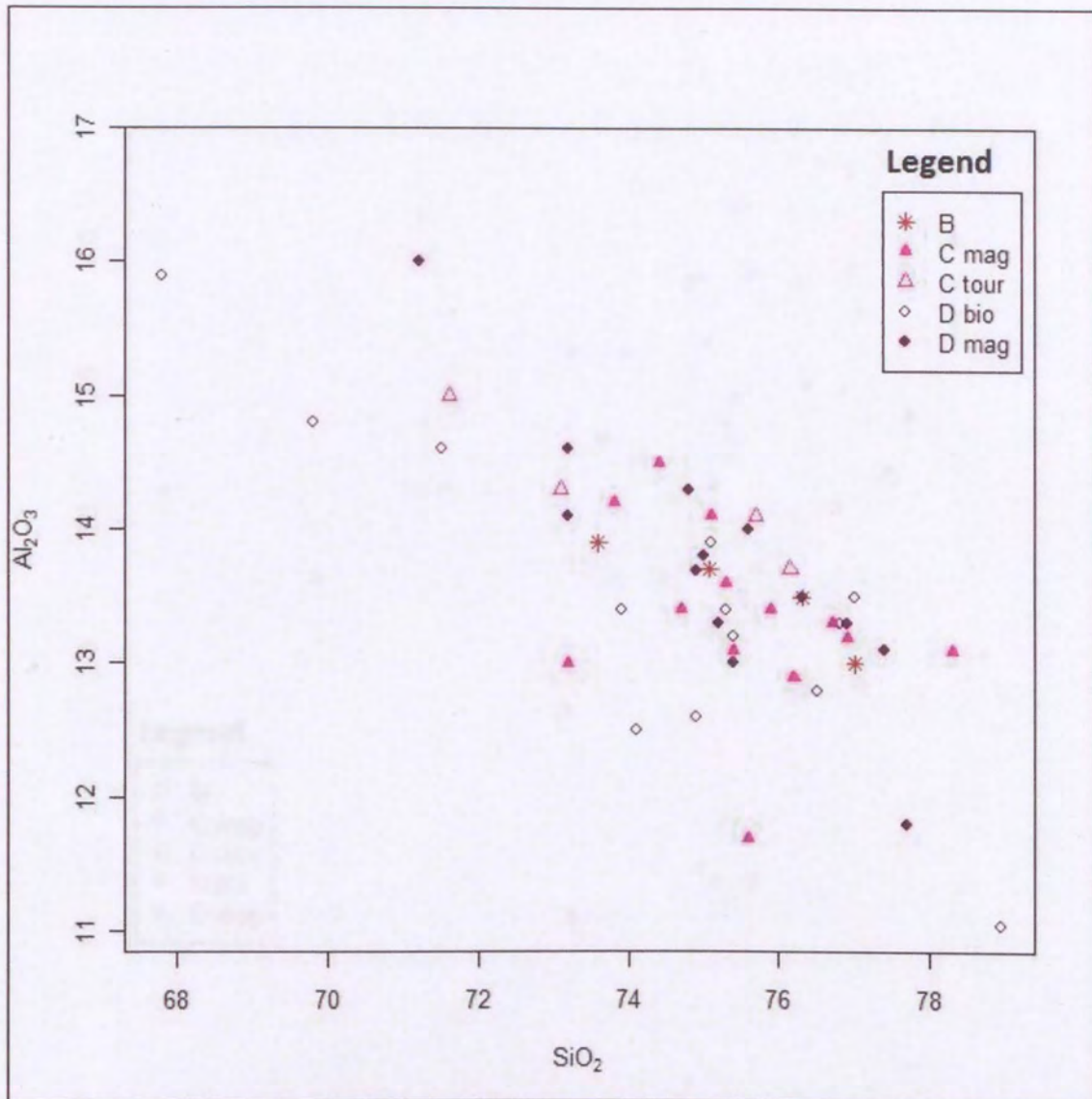


Figure 4.3 Harker plot illustrating Al_2O_3 vs SiO_2 .

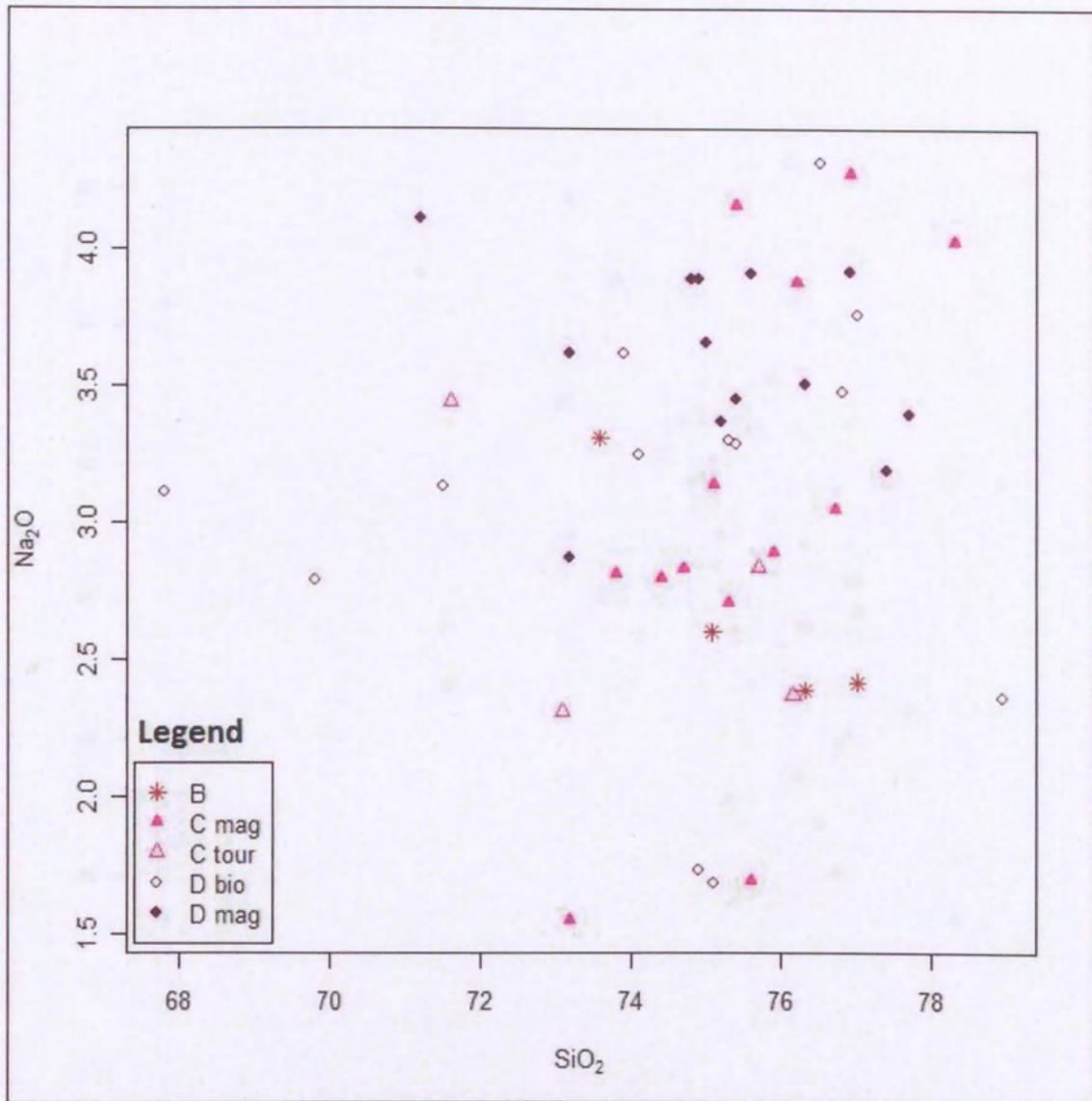


Figure 4.4 Harker plot illustrating Na_2O vs SiO_2 .

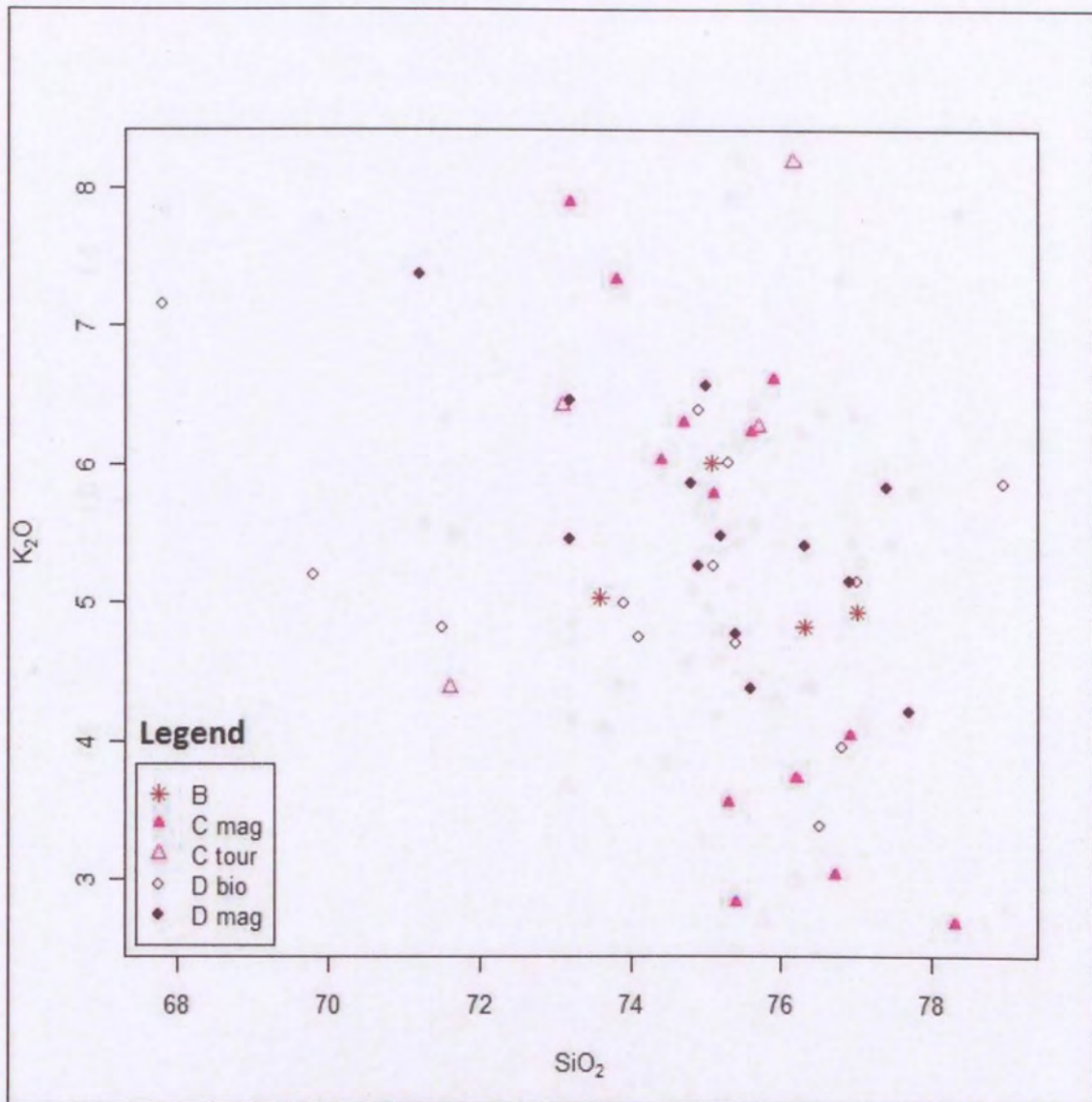


Figure 4.5 Harker plot illustrating K_2O vs SiO_2 .

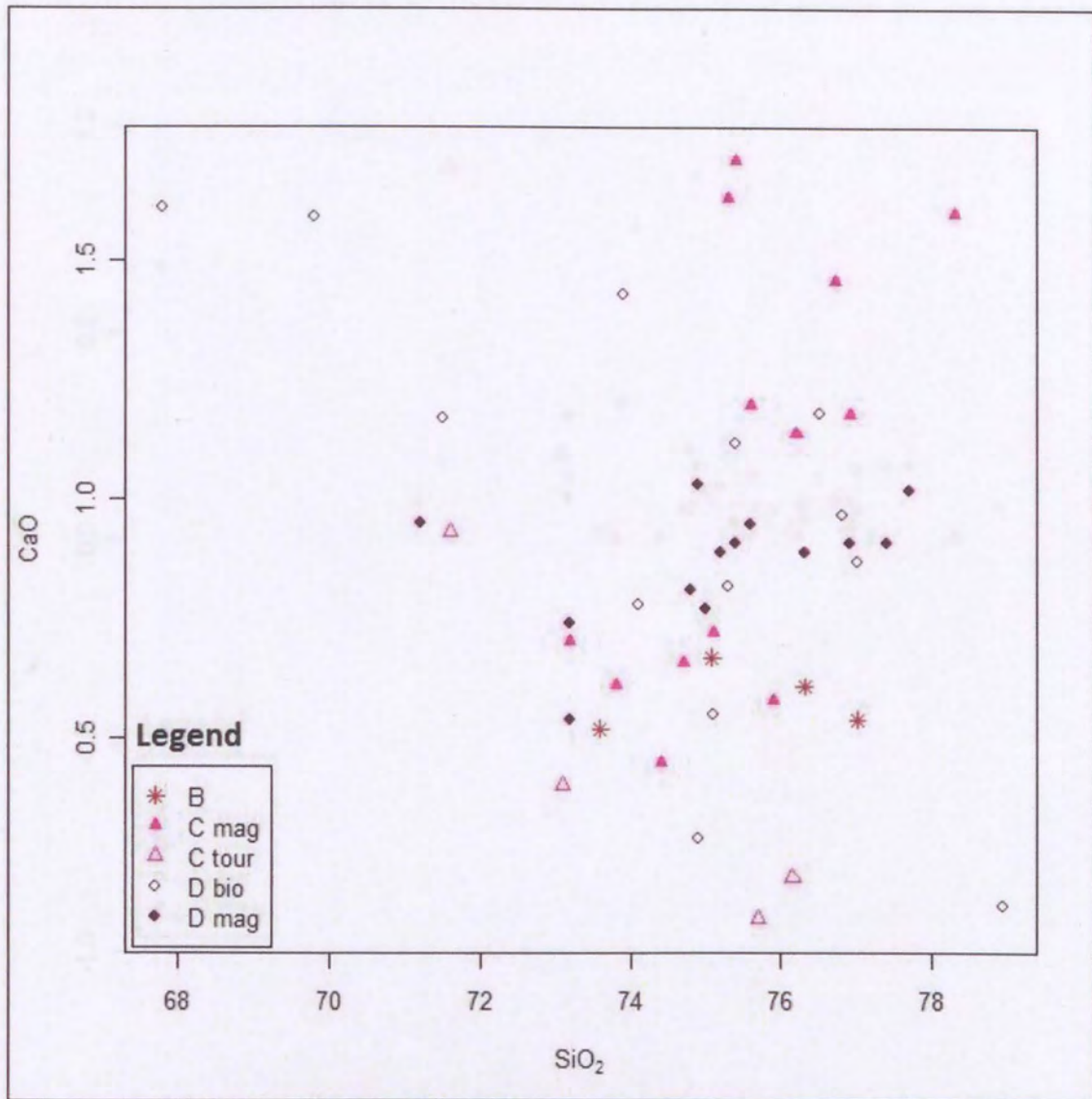


Figure 4.6 Harker plot illustrating CaO vs SiO₂.

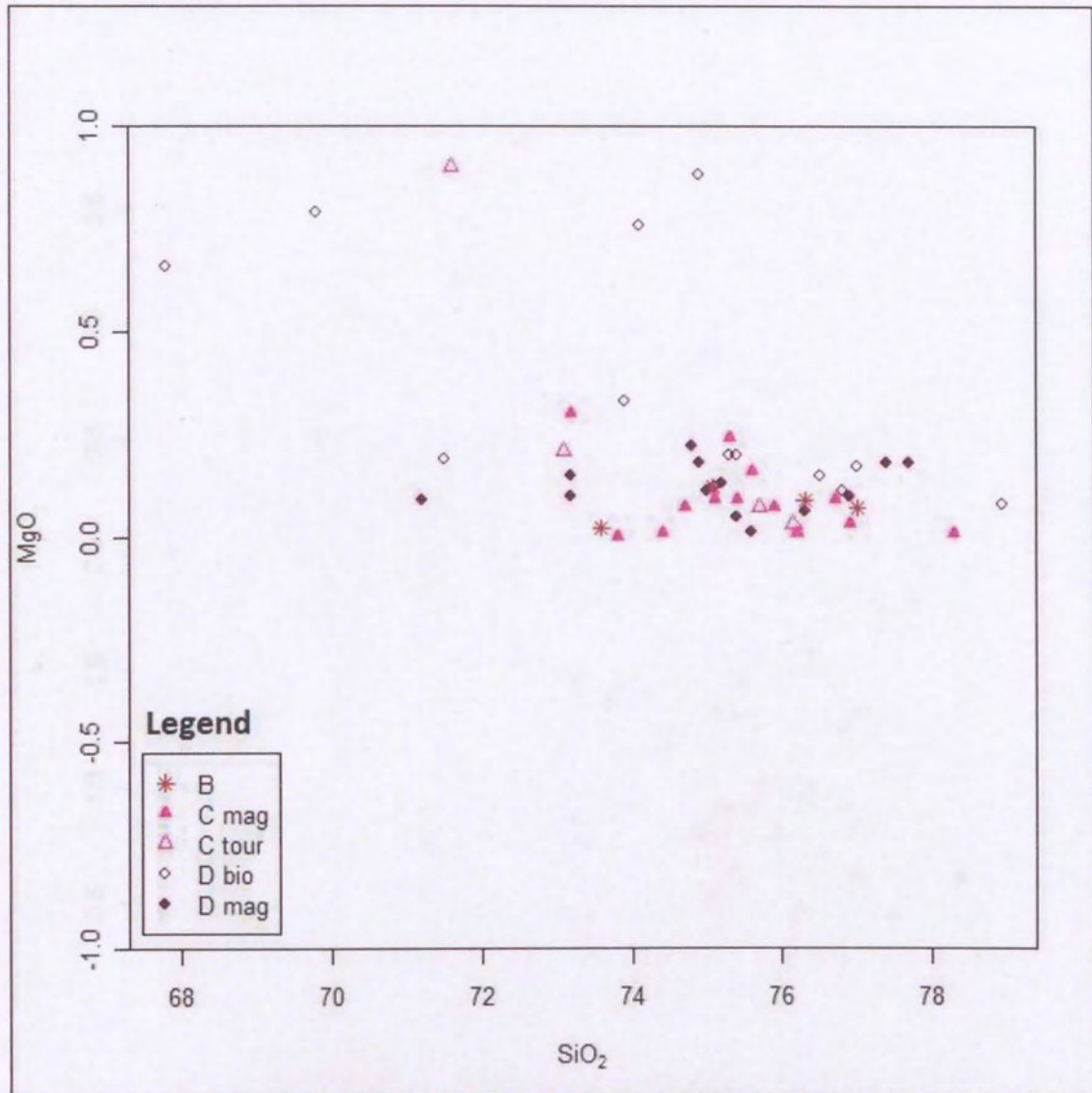


Figure 4.7 Harker plot illustrating MgO vs SiO₂.

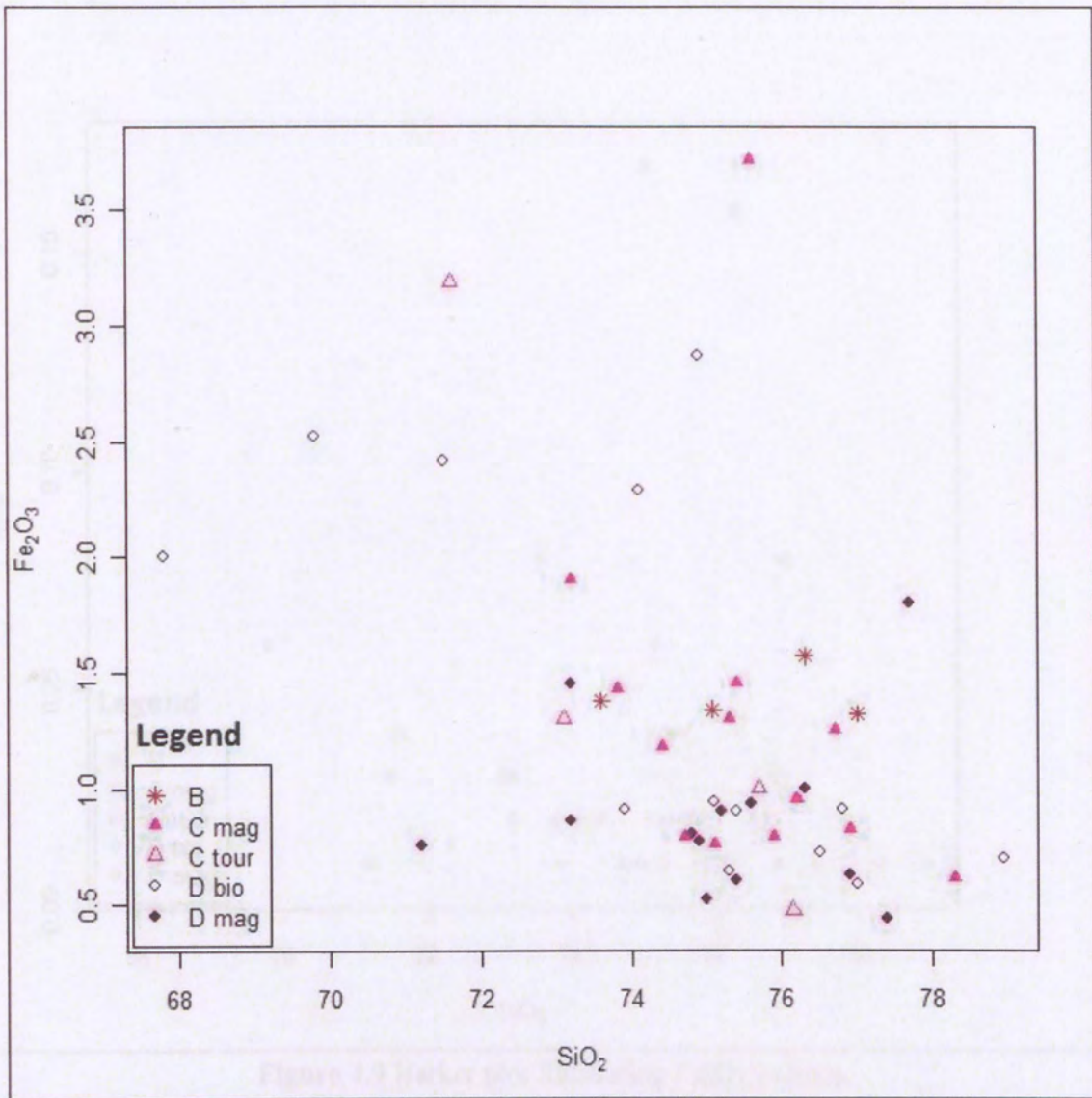


Figure 4.8 Harker plot illustrating Fe_2O_3 vs SiO_2 .

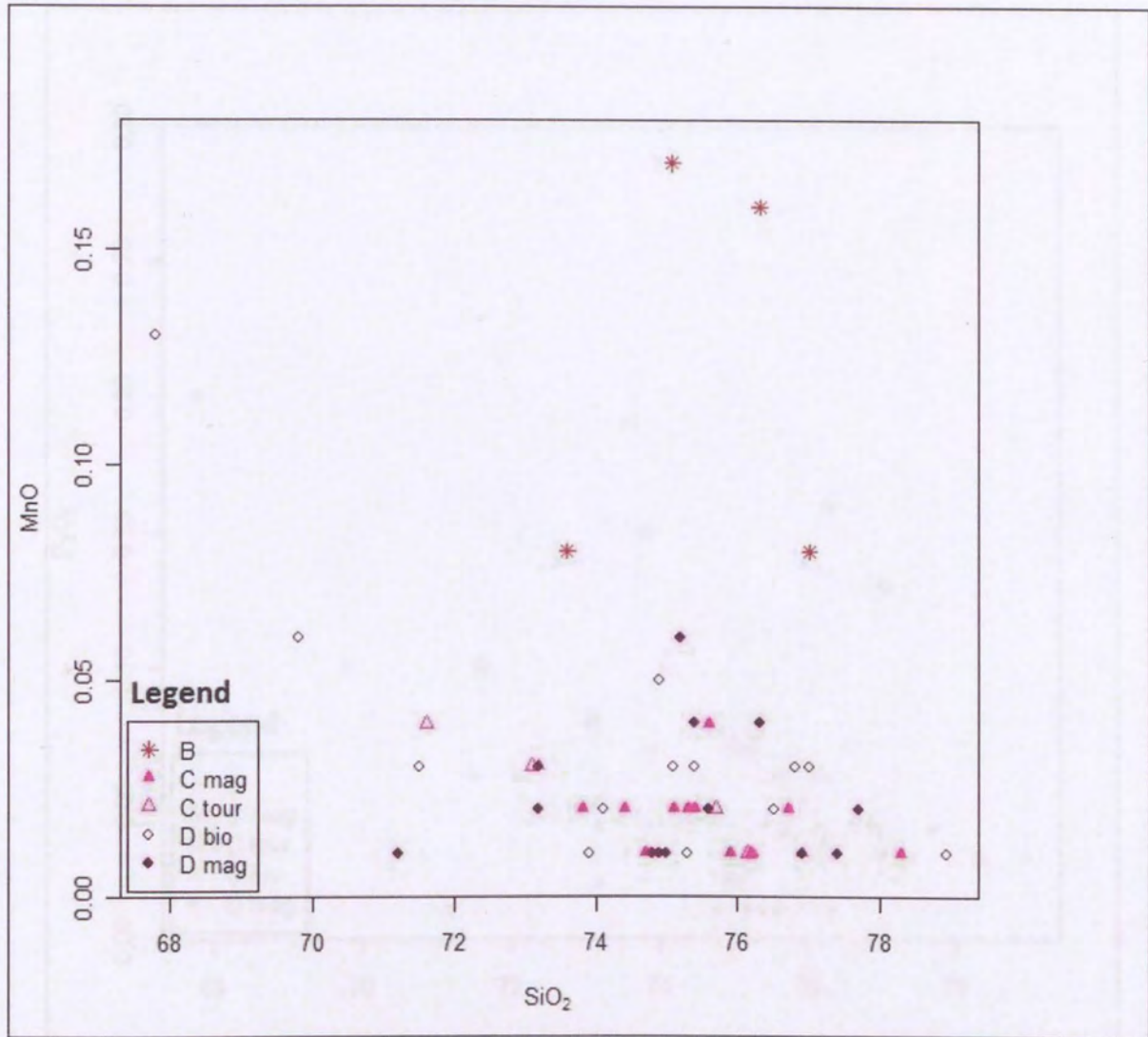


Figure 4.9 Harker plot illustrating Fe_2O_3 vs SiO_2 .

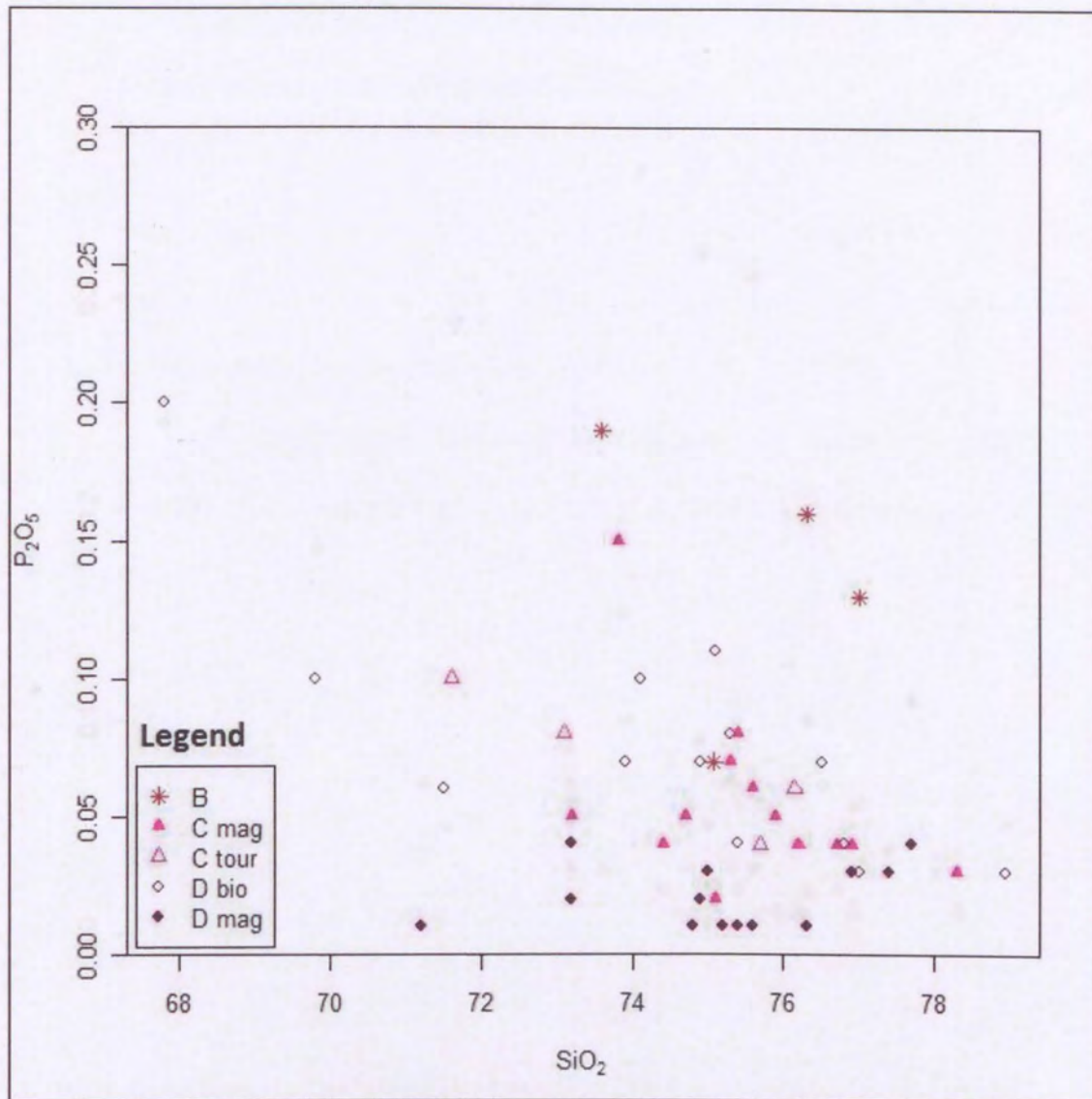


Figure 4.10 Harker plot illustrating P_2O_5 vs SiO_2 .

Major elements reflect the mineralogy of the rock and for this reason they have the potential to differentiate the various mineral leucogranite types. Choosing a plot of P_2O_5 vs SiO_2 as a discriminant (Figure 4.12 to Figure 4.15).

B-type leucogranites are characterized by low concentrations of TiO_2 and increased to high concentrations of P_2O_5 , F_2O_3 , HfO_2 , W_2O_5 , CaO and Na_2O (Figure 4.12 to Figure 4.15).

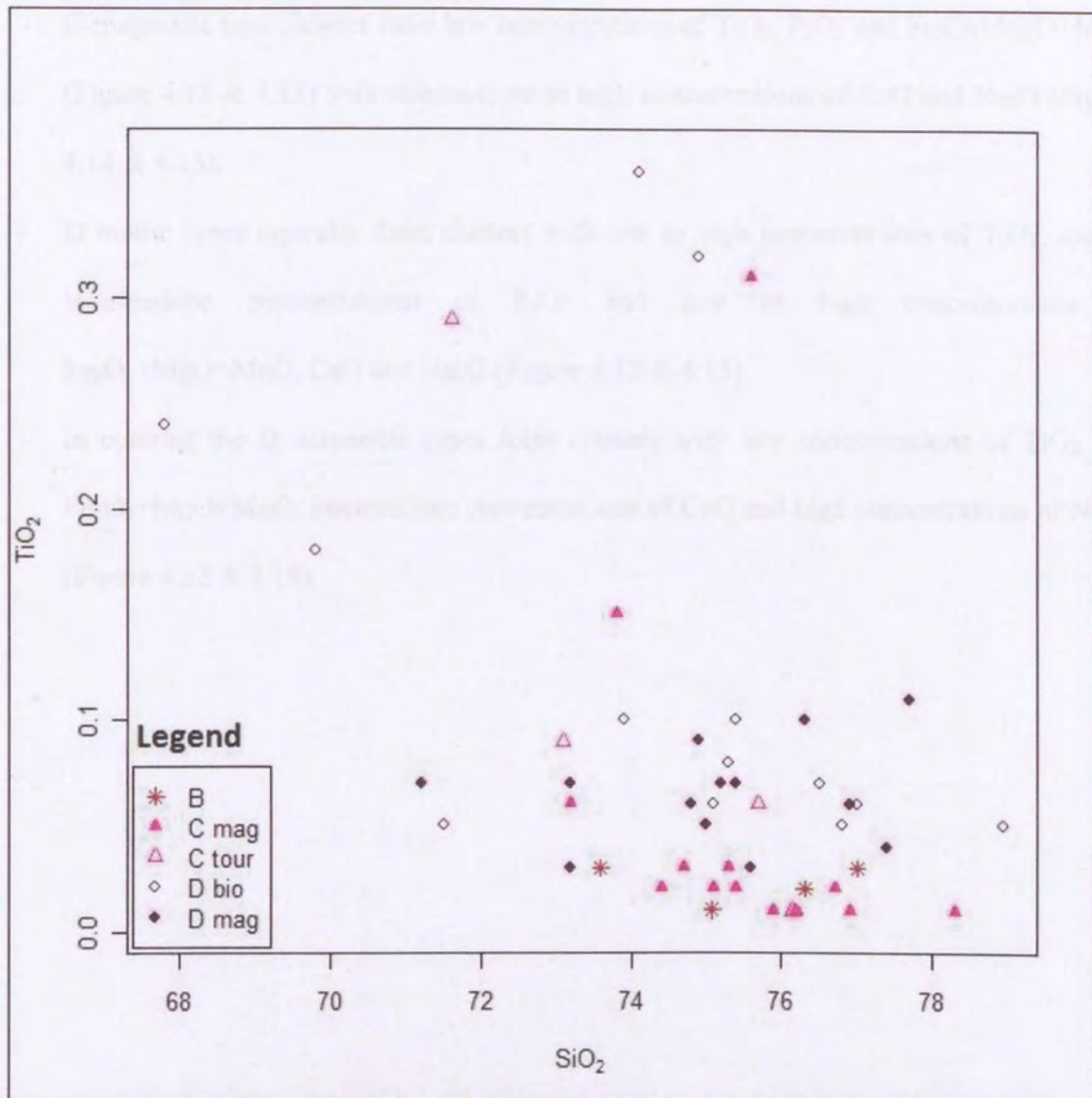


Figure 4.11 Harker plot illustrating TiO₂ vs SiO₂.

Major elements reflect the mineralogy of the rock and for this reason they have the potential to differentiate the various sheeted leucogranite types. Clustering is observed within the sheeted leucogranite types using TiO₂ as a discriminator (Figure 4.12 to Figure 4.15):

- B-type clusters are characterised by low concentrations of TiO₂ and intermediate to high concentrations of P₂O₅, Fe₂O₃+MgO+MnO, CaO and Na₂O (Figure 4.12 to Figure 4.15).

- C-magnetite type clusters have low concentrations of TiO_2 , P_2O_5 and $\text{Fe}_2\text{O}_3+\text{MgO}+\text{MnO}$ (Figure 4.12 & 4.13) with intermediate to high concentrations of CaO and Na_2O (Figure 4.14 & 4.15).
- D biotite types typically form clusters with low to high concentrations of TiO_2 , low to intermediate concentrations of P_2O_5 and low to high concentrations of $\text{Fe}_2\text{O}_3+\text{MgO}+\text{MnO}$, CaO and Na_2O (Figure 4.12 & 4.15).
- In contrast the D magnetite types form clusters with low concentrations of TiO_2 and $\text{Fe}_2\text{O}_3+\text{MgO}+\text{MnO}$, intermediate concentrations of CaO and high concentrations of Na_2O (Figure 4.12 & 4.15).

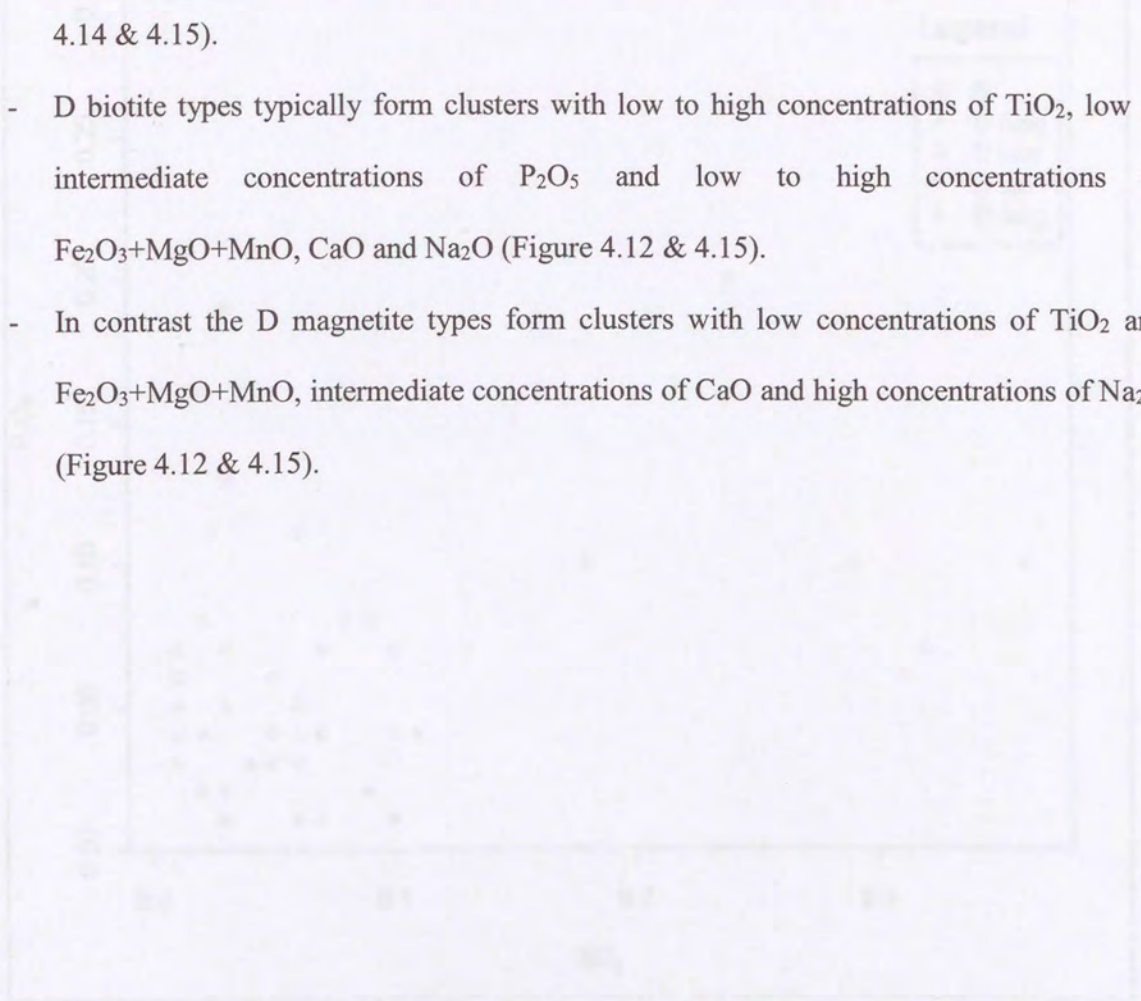


Figure 4.12: Biotite magnetite clusters (see Table 4.1 for details).

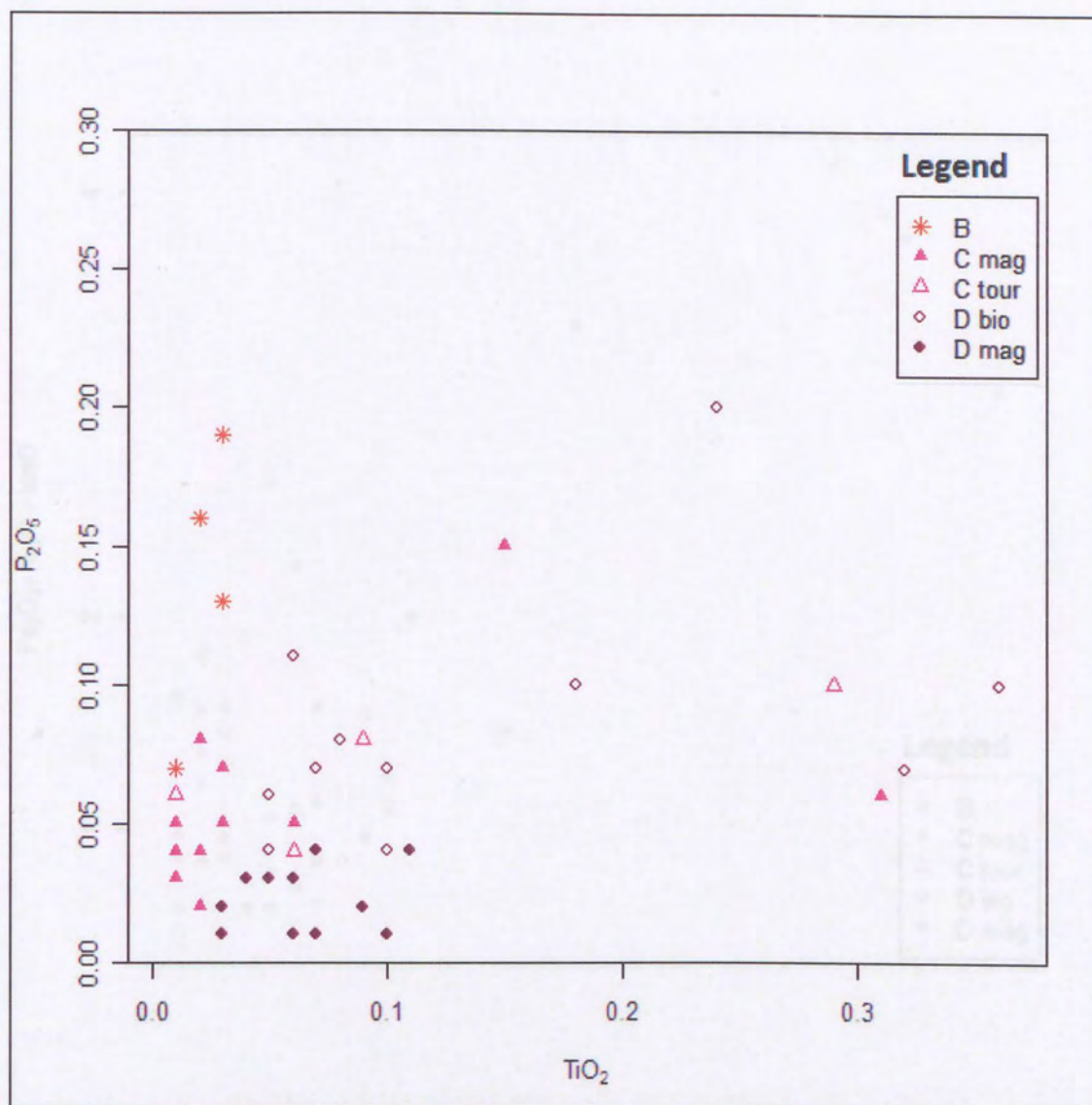


Figure 4.12 Binary major element plot TiO_2 Vs P_2O_5 .

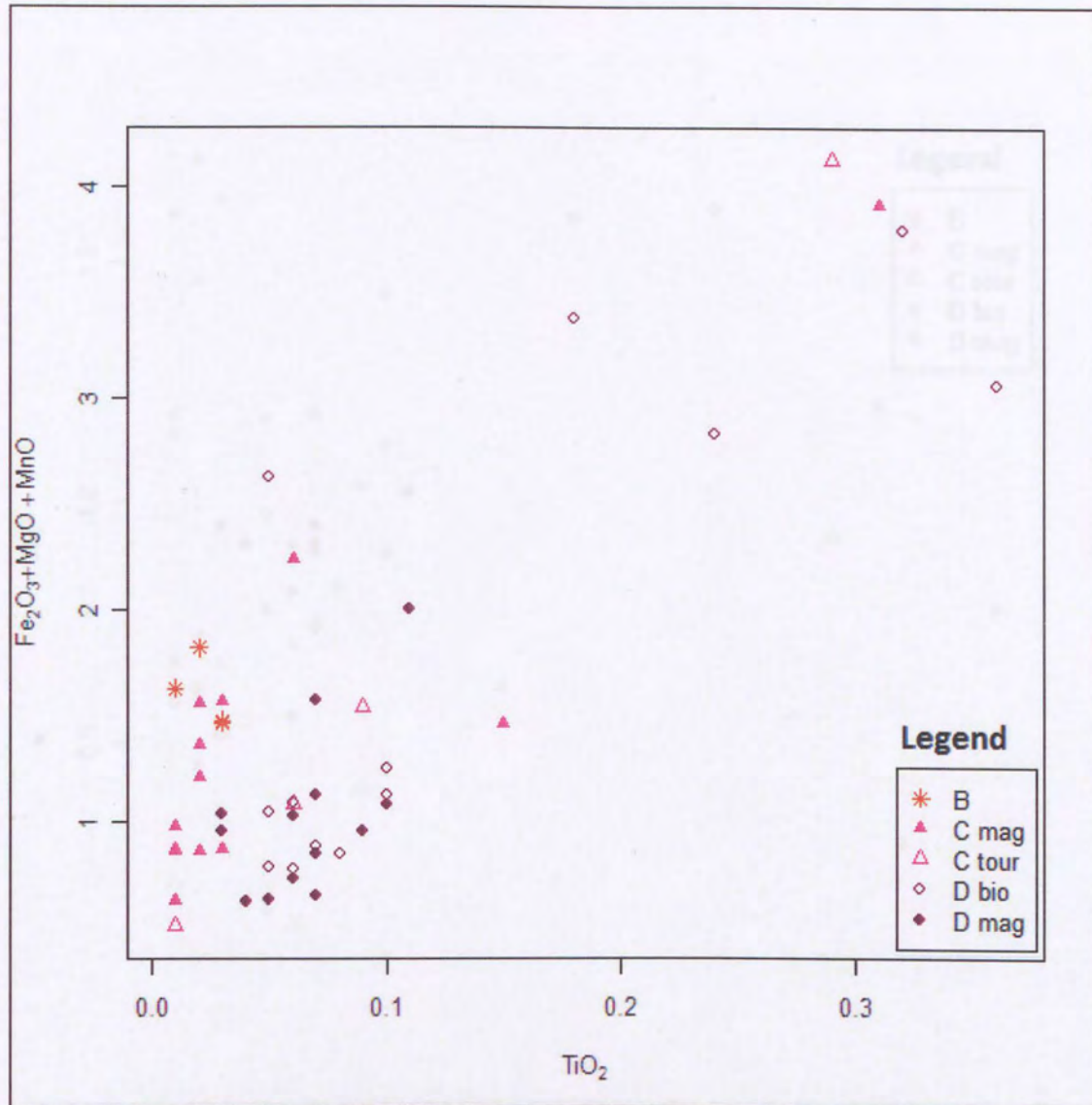


Figure 4.13 Binary major element plot of TiO_2 Vs $\text{Fe}_2\text{O}_3 + \text{MgO} + \text{MnO}$.

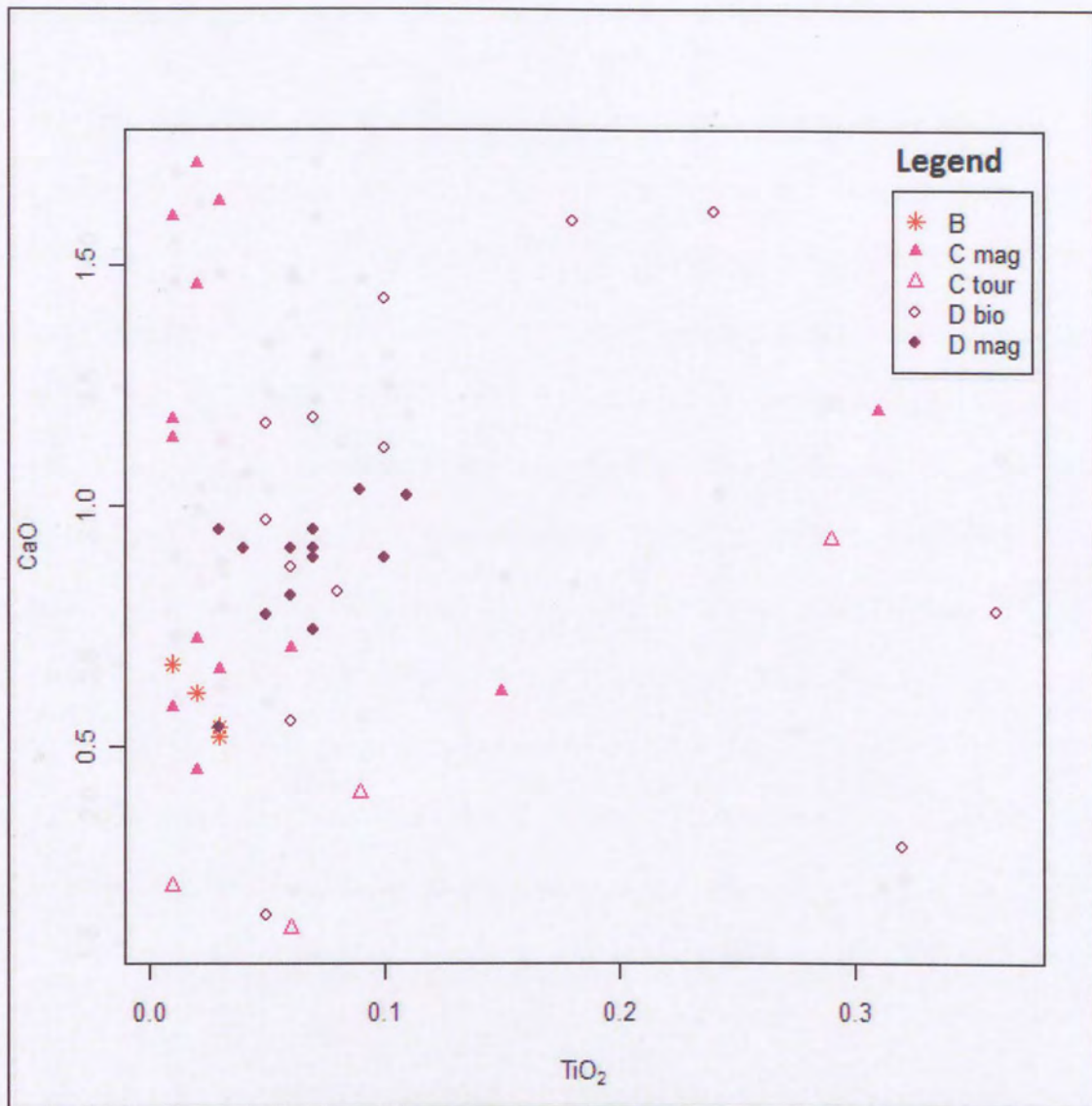


Figure 4.14 Binary major element plot of TiO₂ Vs CaO.

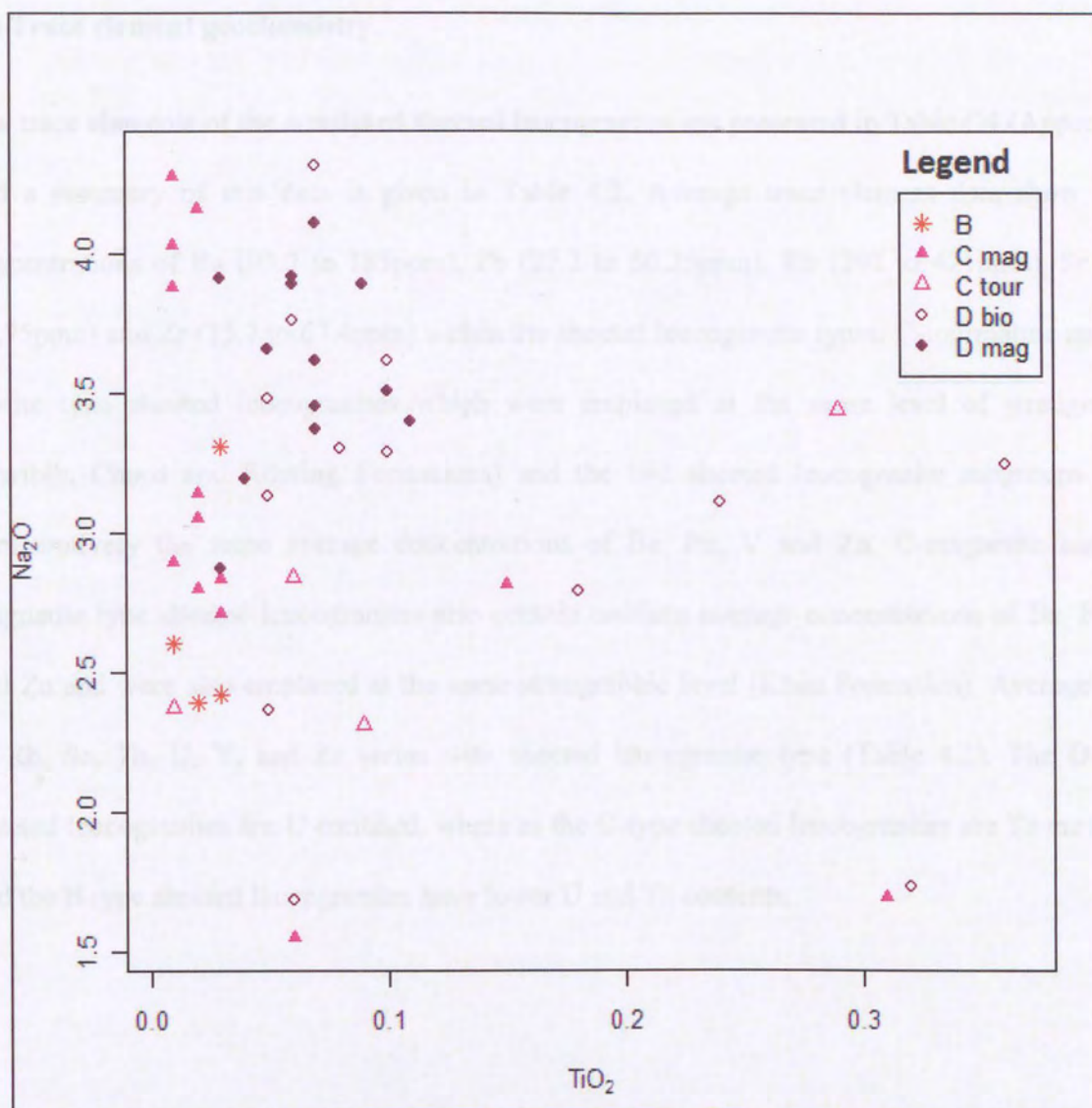


Figure 4.15 Binary Major element plot of TiO_2 Vs Na_2O .

4.3 Trace element geochemistry.

The trace elements of the analysed sheeted leucogranites are presented in Table C4 (Appendix) and a summary of this data is given in Table 4.2. Average trace element data show high concentrations of Ba (93.7 to 185ppm), Pb (27.2 to 50.25ppm), Rb (297 to 421ppm), Sr (30-46.75ppm) and Zr (25.7 to 67.4ppm) within the sheeted leucogranite types. C-tourmaline and D-biotite type sheeted leucogranites which were emplaced at the same level of stratigraphy (Karibib, Chuos and Rössing Formations) and the two sheeted leucogranite subgroups bear comparatively the same average concentrations of Ba, Pb, V and Zn. C-magnetite and D-magnetite type sheeted leucogranites also contain uniform average concentrations of Ba, Pb, V and Zn and were also emplaced at the same stratigraphic level (Khan Formation). Average data of Rb, Sc, Th, U, Y, and Zr varies with sheeted leucogranite type (Table 4.2). The D-type sheeted leucogranites are U enriched, where as the C-type sheeted leucogranites are Th enriched and the B type sheeted leucogranites have lower U and Th contents.

Table 4.2 Average trace element data for the Namibplaas sheeted leucogranites. The single value represents an average in concentration from respective samples and the dual set of values represent the range in concentration from lowest to highest. The “n” row is the number of samples.

	Units	Detection limit	B	C tour	C mag	D bio	D mag
n			4	5	13	12	13
Ba (ppm)	ppm	3	185	151.6	112	143.2	93.7
			50-320	95-200	20-350	75-271	19-180
Ga (ppm)	ppm	1	15.5	16.96	17	16.96	20.5
			12-20	14-19	12-20	14.2-20	18.6-22
Nb (ppm)	ppm	1	6.75	14	14	13	21.7
			1-15	5-25	1-60	10-20	10-30
Ni (ppm)	ppm	1	8.25	8.2	4.54	6.4	6.7
			5-12	1-20	1-12	1-15	5-10
Pb (ppm)	ppm	3	50.25	46.2	27.2	45.8	35.7
			47-56	35-66	14-46	42-52	32-40
Rb (ppm)	ppm	2	277	421	297	305	420
			221-352	254-573	130-567	253-390	374-484
Sc (ppm)	ppm	1	9.25	3.4	2.42	3.6	1.67
			12-Jul	1-7.5	0.5-8	2-6.5	0.5-2.5
Sr (ppm)	ppm	2	46.75	38.8	36.4	44.2	30
			25-81	35-43	24-63	29-68	14-55
Th (ppm)	ppm	1	8.5	40	32.6	66.8	38
			5-17.5	10-94	7-54.5	21-176	25-52
U (ppm)	ppm	1	7.38	19.6	15.8	169.5	131.5
			3-9	6-54	4-41	22.5-271	63.5-200
V (ppm)	ppm	1	2	19.6	9.77	16.8	8
			1-4	6-52	1-28	8-32	4-10
Y (ppm)	ppm	2	29.5	17.54	8.02	10.52	13.4
			17-41	5-49.9	2-29	8.7-13	10.5-16
Zn (ppm)	ppm	1	14.75	26	12.4	25.2	18.3
			5-24	1-62	2-44	1-60	6-28
Zr (ppm)	ppm	4	33.25	32.2	45.1	67.4	25.7
			18-57	15-44	8-78	26-94	21-33

Immobile elements distinguish the sheeted leucogranites quite well although there are some overlaps within the sheeted leucogranite types. Using U, Y, U+Th, Ga, Th and Zr as discriminators (Figure 4.16 to Figure 4.18):

- The B-type clusters form; low concentrations of U, U+Th & V, low to intermediate concentrations of Zr and intermediate to high concentrations of Y & Sc (Figure 4.16 to 4.18).
- The C-type clusters form; low to intermediate concentrations of U, Y, U+Th, V, Sc & Zr (Figure 4.16 to 4.18).
- The D-type clusters form; low to intermediate concentrations of Y, V & Sc and high concentrations of U & U+Th (Figure 4.16 to 4.18).



Figure 4.16: Scatter plot of U (ppm) vs Y (ppm) for sheeted leucogranites. The plot shows distinct clusters for different leucogranite types. The clusters are: B-type (low U, low Y), C-type (intermediate U, intermediate Y), D-type (high U, high Y), and E-type (high U, high Y).

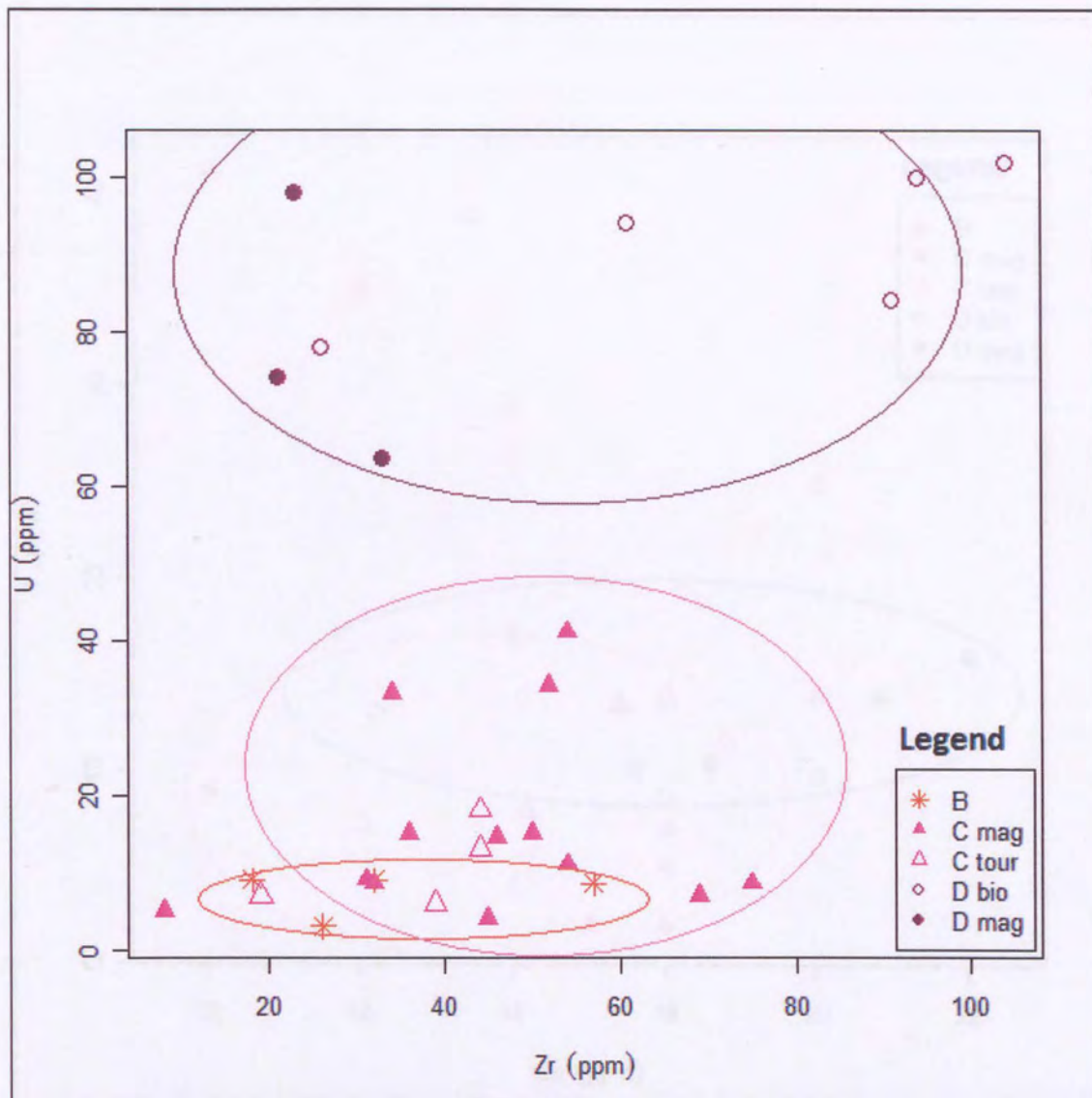


Figure 4.16 Binary immobile element plot of Zr vs U. The plot show cluster concentrations of different sheeted leucogranite types. The circular to elipsoidal shapes show clusters of the different sheeted leucogranite types.

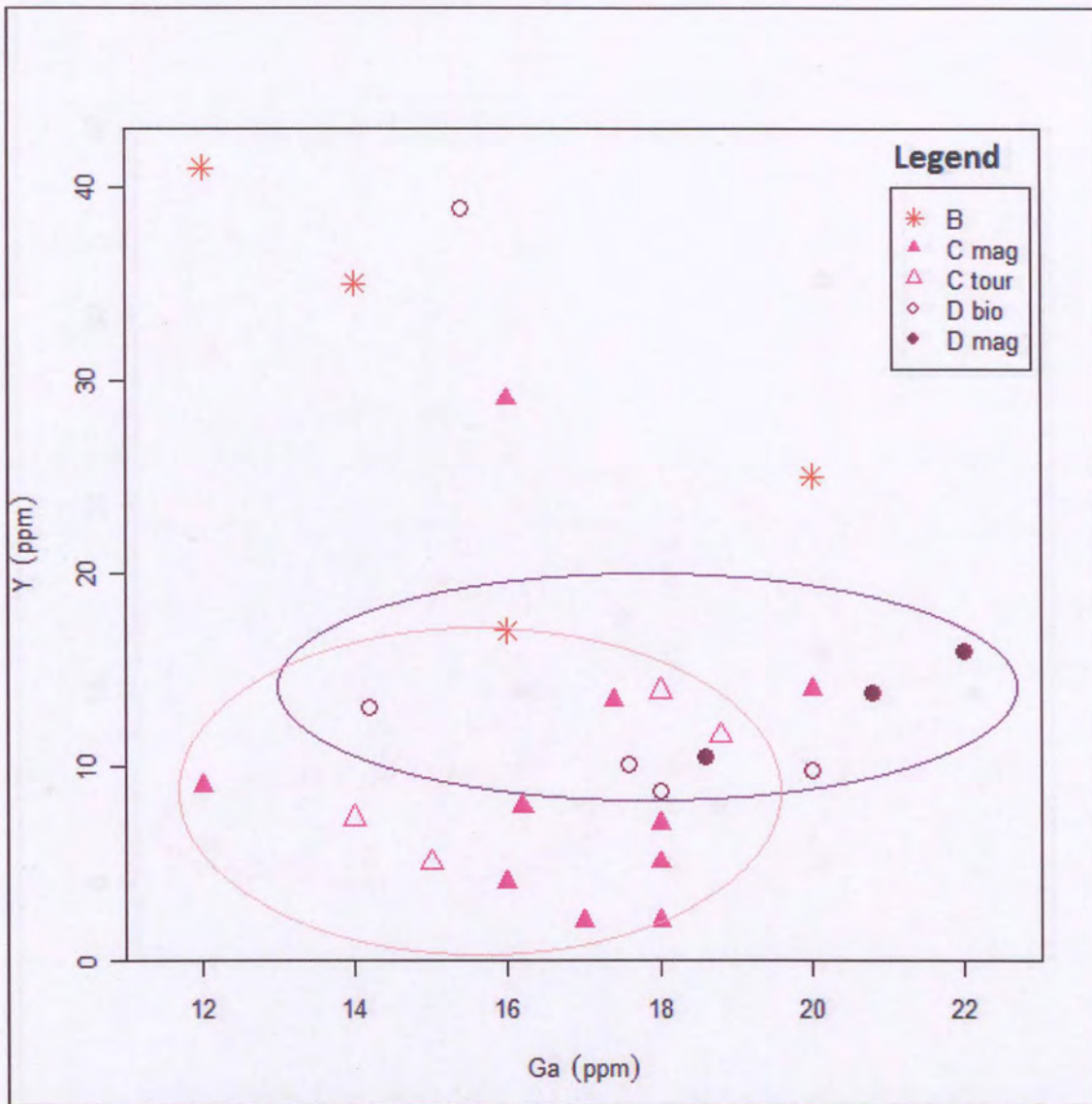


Figure 4.17 Binary immobile element plot of Ga vs Y. The plot show cluster concentrations of different sheeted leucogranite types. The circular to elipsoidal shapes show clusters of the different sheeted leucogranite types.

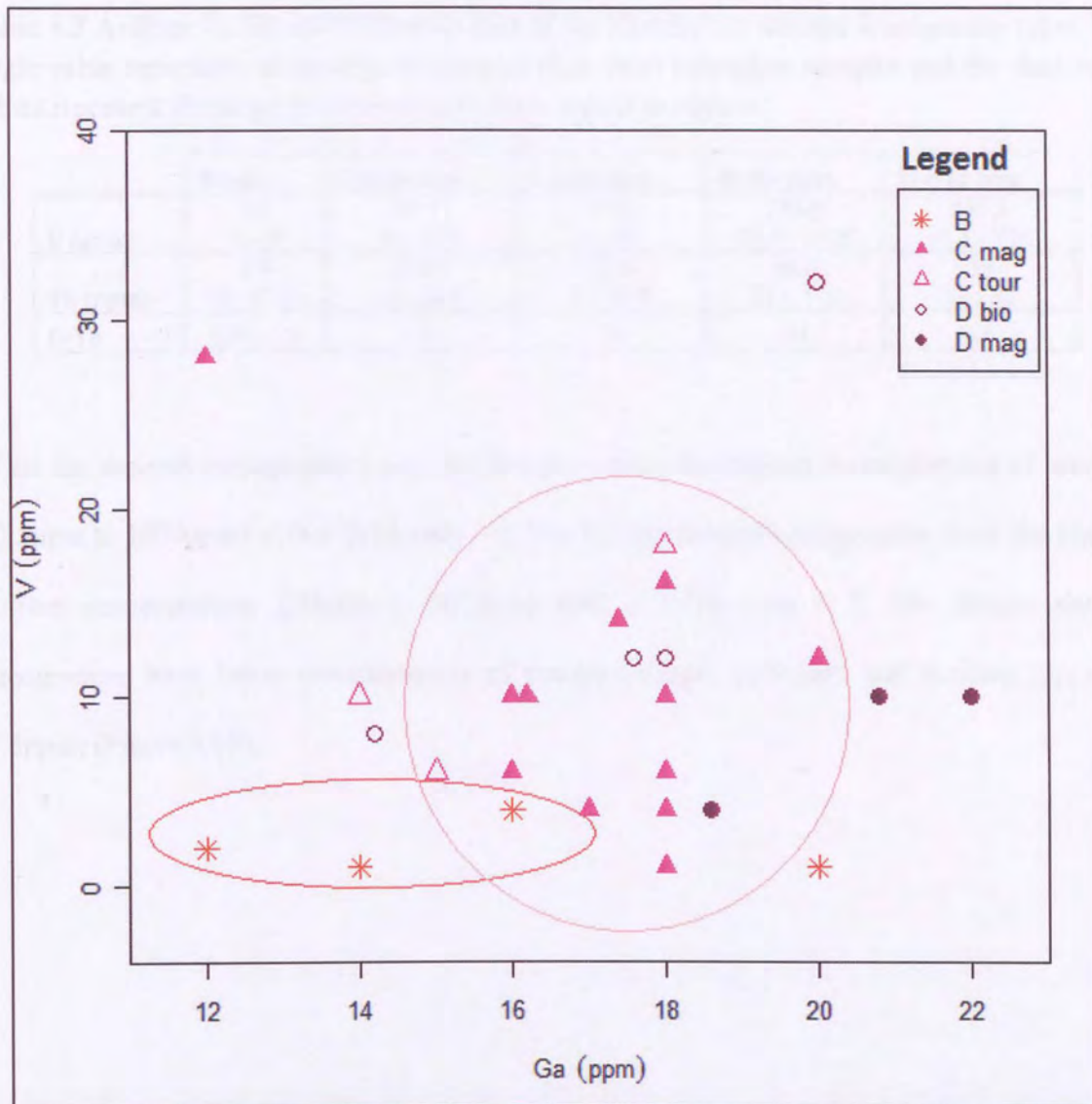


Figure 4.18 Binary immobile element plot of Ga vs V. The plot show cluster concentrations of different sheeted leucogranite types. The circular to elipsoidal shapes show clusters of the different sheeted leucogranite types.

U, Th and U/Th ratio distinguishes and characterises the sheeted leucogranites very well. The D-type sheeted leucogranites have a U/Th ratio greater than one, the C-type sheeted leucogranites have a U/Th ratio less than one and the U/Th ratio of the B-type leucogranites vary (0.6 – 1.8) (Table 4.3).

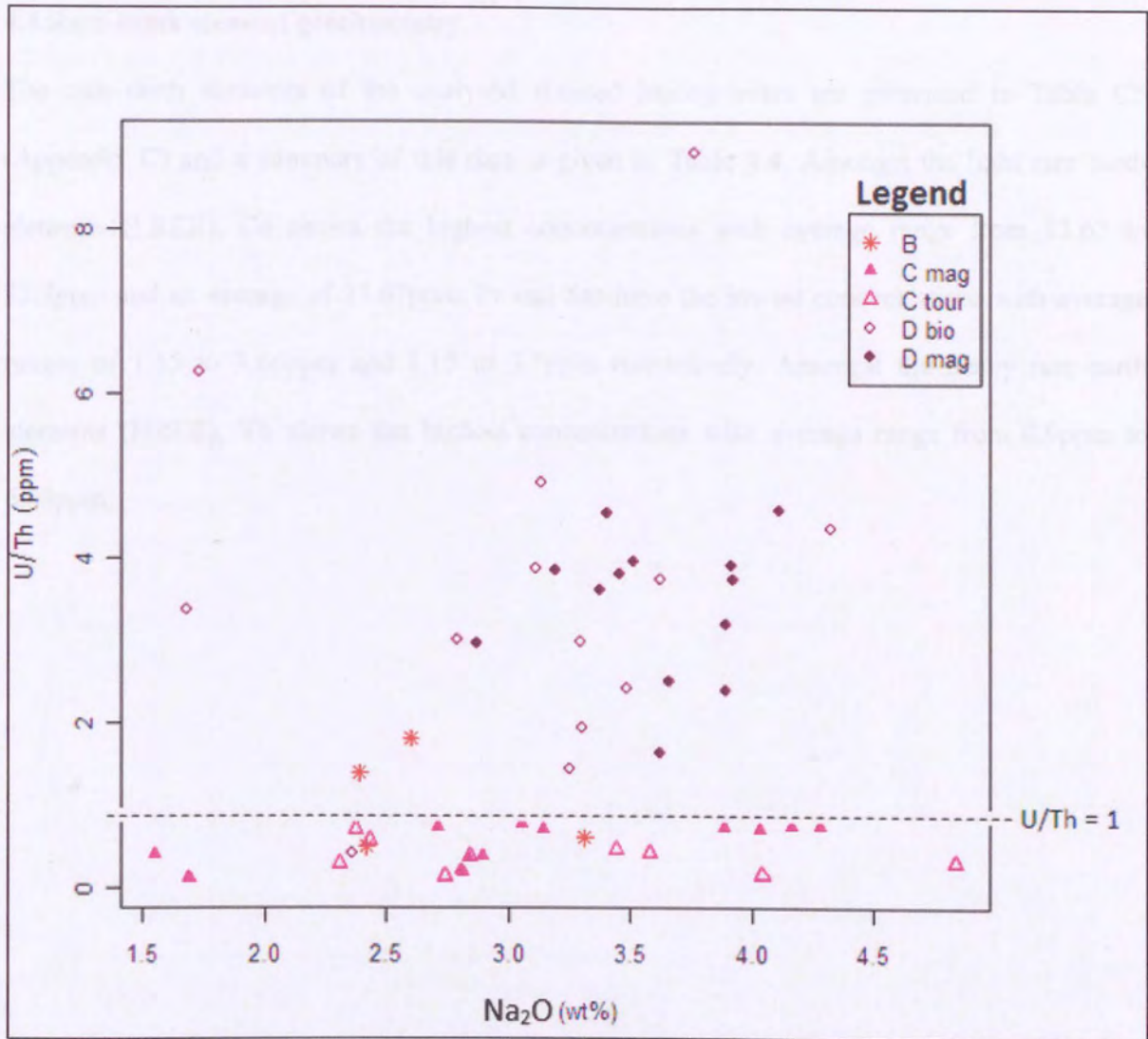
Table 4.3 Average U, Th and U/Th ratio data of the Namibplaas sheeted leucogranite types. The single value represents an average in concentration from respective samples and the dual set of values represent the range in concentration from lowest to highest.

	B type	C-tour type	C-mag type	D-bio type	D-mag type
U (ppm)	7.4 3 – 9	36.7 6 – 127	15.8 4 – 41	234.9 22.5 – 1020	131.5 63.5 – 200
Th (ppm)	8.5 5 – 17.5	115.1 10 – 301	32.6 7 – 54.5	66.8 21 – 176	38 25 – 52
U/Th	0.6 – 1.8	<1	<1	>1	>1

Of all the sheeted leucogranite types, the D-type contain the highest concentrations of uranium (22.5ppm to 1020ppm) with a U/Th ratio > 1 . The C-type sheeted leucogranites show the highest thorium concentrations (10ppm to 301ppm) with a U/Th ratio < 1 . The B-type sheeted leucogranites have lower concentrations of uranium (3ppm to 9ppm) and thorium (5ppm to 17.5ppm) (Figure 4.19).



Figure 4.19: The relationship between Th and U concentrations in the sheeted leucogranites. The D-type leucogranites plot at high U and low Th, the C-type leucogranites plot at low U and high Th, and the B-type leucogranites plot at low U and low Th.



4.4 Rare earth element geochemistry.

The rare earth elements of the analysed sheeted leucogranites are presented in Table C5 (Appendix C) and a summary of this data is given in Table 4.4. Amongst the light rare earth elements (LREE), Ce shows the highest concentrations with average range from 13.63 to 33.7ppm and an average of 23.67ppm. Pr and Sm have the lowest concentrations with average ranges of 1.55 to 3.66ppm and 1.15 to 3.7ppm respectively. Amongst the heavy rare earth elements (HREE), Yb shows the highest concentrations with average range from 0.9ppm to 6.63ppm.

Table 4.4 Average REE data for the Namibplaas sheeted leucogranites. The dual set of values represent the range in concentration from lowest to highest. The "n" row is the number of samples.

	Units	Detection limit	B	C tour	C mag	D bio	D mag
n			4	5	13	5	3
La (ppm)	ppm	0.1	7.75	18.1	9.58	18.3	14.83
			4.5-12.5	8.5-31	2.5-30.5	4.5-29.5	5.5-27
Ce (ppm)	ppm	0.1	13.63	33.7	15.73	31.9	24.5
			9-24	15.5-55	3-52	7-49	8.5-44
Pr (ppm)	ppm	0.05	1.55	3.64	1.56	3.66	2.33
			1-2.8	1.2-6	0-5.5	0.8-5	1-4
Nd (ppm)	ppm	0.1	5.38	11.3	5	11.7	7.8
			4-9.5	4-19.5	0-15	3.5-17	2.5-13.5
Sm (ppm)	ppm	0.1	1.5	3.7	1.15	3.4	2.3
			0.5-3	0.5-6	0-4	1-4.5	2-3
Eu (ppm)	ppm	0.05	0.23	0.1	0.12	0.3	0.13
			0-0.8	0-0.5	0-0.4	0-1	0-0.4
Gd (ppm)	ppm	0.1	0.5	3.8	0.5	2.8	1.3
			0-2	0-8	0-3	0-4	0-2
Tb (ppm)	ppm	0.1	0.4	0.64	0.06	0.24	0.13
			0.2-0.8	0-1.5	0-0.6	0-1	0-0.4
Dy (ppm)	ppm	0.1	3.63	5.3	1.38	3.6	2.5
			2.5-5.5	1-9	0-4	1.5-6.5	1.5-3.5
Ho (ppm)	ppm	0.1	1	1.44	0.17	1.08	0.53
			0.6-1.4	0.2-3	0-0.8	0.4-2	0-1
Er (ppm)	ppm	0.1	3.63	4.1	0.96	3.1	1.83
			2-4.5	0-8.5	0-3	1.5-6	1-2.5
Tm (ppm)	ppm	0.05	0.8	0.6	0.08	0.28	0.13
			0.4-1	0-2	0-0.8	0-1	0-0.4
Yb (ppm)	ppm	0.1	6.63	5.1	0.92	3.7	2.5
			3-8	0.5-13	0-5	1.5-8	2-3
Lu (ppm)	ppm	0.1	1.15	0.6	0.12	0.24	0.13
			0.4-1.6	0-2	0-1	0-1	0-0.4

The REE plots of the granitoids have wing shaped patterns with both negative and positive europium (Eu) anomalies within the B and C types and a negative Eu anomaly within the D-type leucogranites (Figure 4.20 to 4.24).

The B-type leucogranites are characterised by similar concentrations of LREE (19.5ppm to 51.8ppm) and HREE plots (8.9ppm to 24.7ppm), Figure 4.20. Eu shows both negative and positive anomalies indicating the existence of a trivalent and a tetravalent Eu state. The trivalent Eu relates to the substitution of Ca by Eu during crystallisation of plagioclase thus depleting residual magmas of europium relative to the other REE's. The tetravalent Eu state relates to oxidation of Eu^{3+} to Eu^{4+} within the magmatic fluids resulting in higher concentrations of Eu^{4+} relative to other REE's.

Figure 4.20 REE patterns of the Na-saturated B-type leucogranites (sample 11605) showing both negative and positive Eu anomalies.

The C leucogranites have similar concentrations of LREE (19.5ppm to 51.8ppm) with both positive and negative Eu anomalies (Figure 4.21). However, the HREE show a wider range of concentrations (2.9ppm to 47ppm) with the lowest values in sample 11605 and highest values in sample 11607. This indicates different magmatic fluids with relatively low, intermediate and high HREE during the formation of the C-type leucogranites (Figure 4.21).

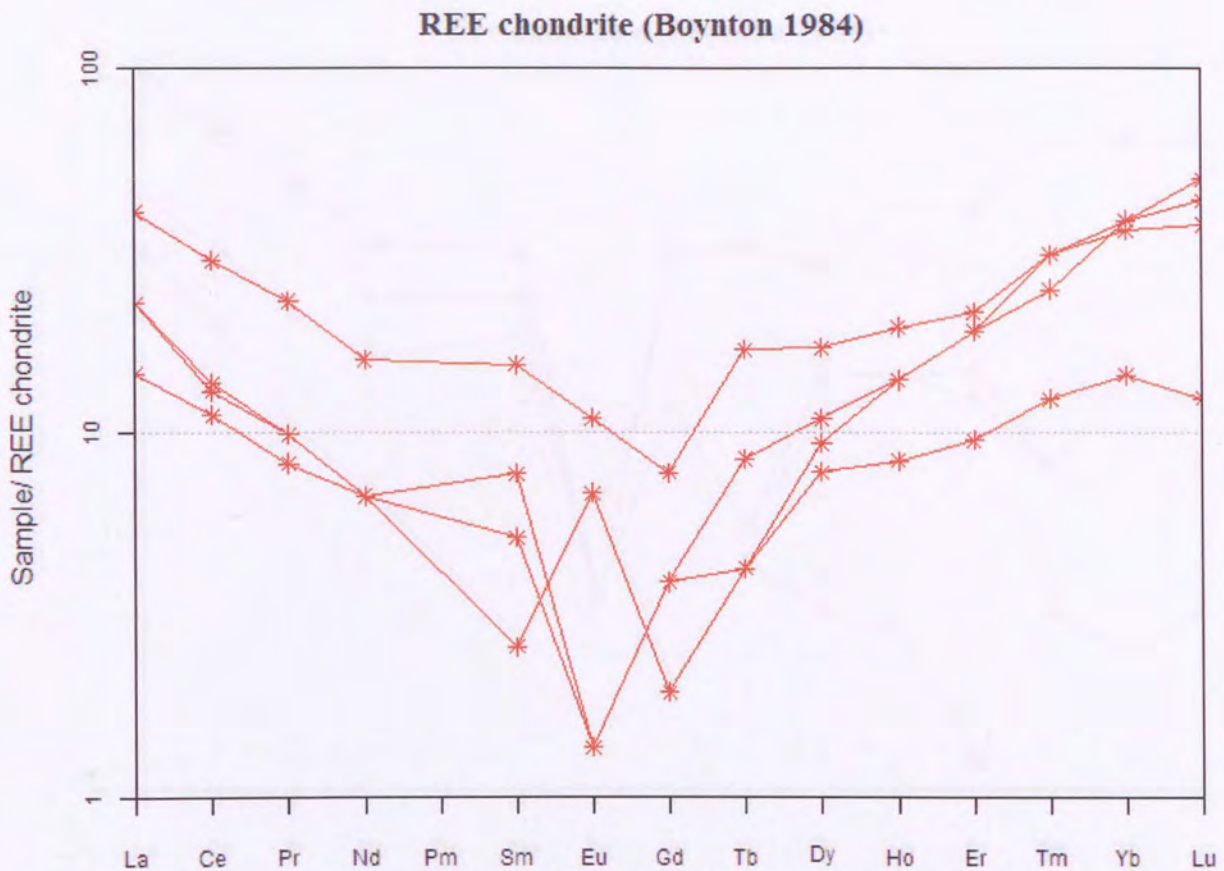


Figure 4.20 REE chondrite-normalised plots of the Namibplaas B-type sheeted leucogranites normalised to Boynton (1984); the sheeted leucogranites have both negative and positive Eu anomalies.

The C tourmaline types show similar concentrations of LREE (46.5ppm to 114.5ppm) with both positive and negative Eu anomalies (Figure 4.21). However, the HREE show a wider range of concentrations (2.4ppm to 47ppm) with the lowest values in sample 13124 and highest values in sample 13665. This indicates different magmatic fluids with relatively low, intermediate and high HREE during the formation of the C-tourmaline sheeted leucogranites.

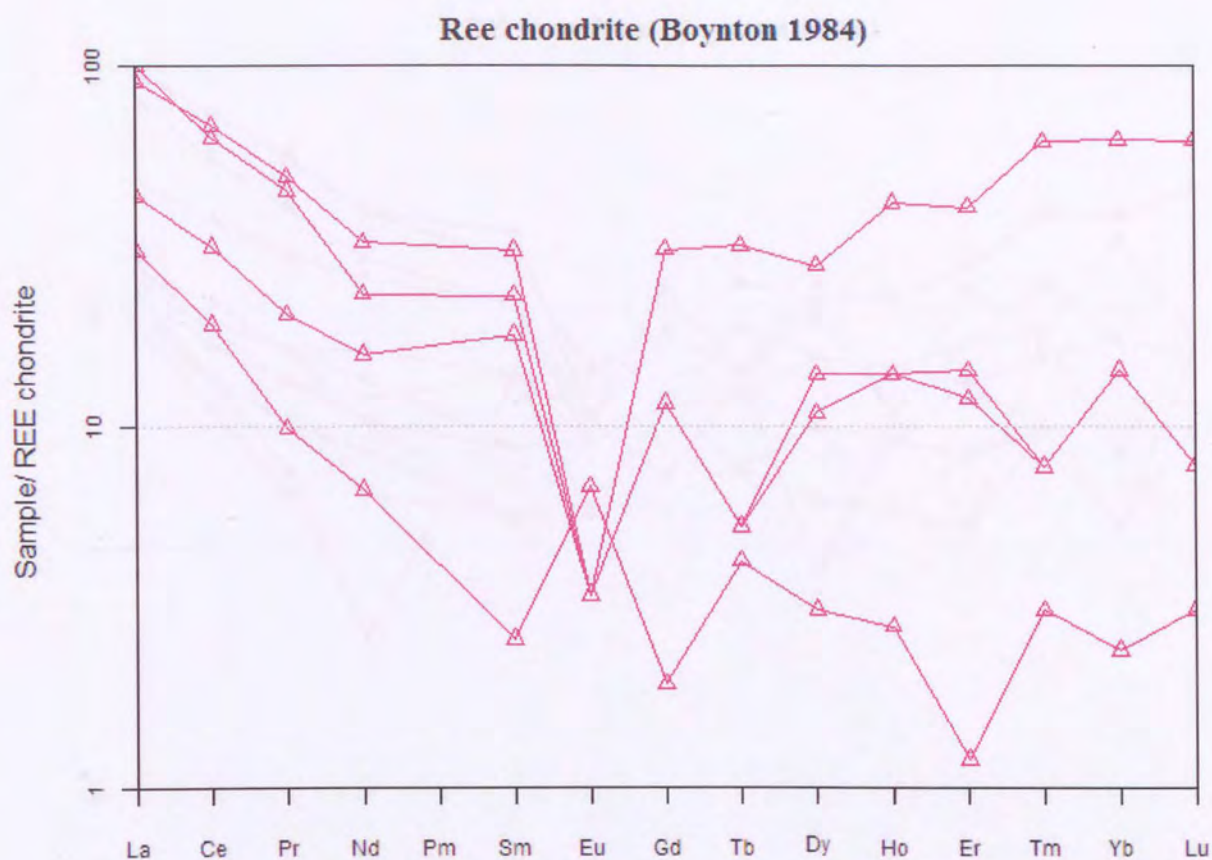


Figure 4.21 REE chondrite-normalised plots of the Namibplaas C tourmaline-type sheeted leucogranites normalised to Boynton (1984) for REE Chondrite; the sheeted leucogranites have both negative and positive Eu anomalies.

C-magnetite types show a set of relatively high and low concentrations of LREE (7.2ppm to 104.5ppm), Figure 4.22. This indicates different phases of high and low LREE magmatic fluids during the formation of the C-magnetite type. The HREE shows a moderate range in concentrations (0ppm to 17.1ppm) within the C-magnetite types.

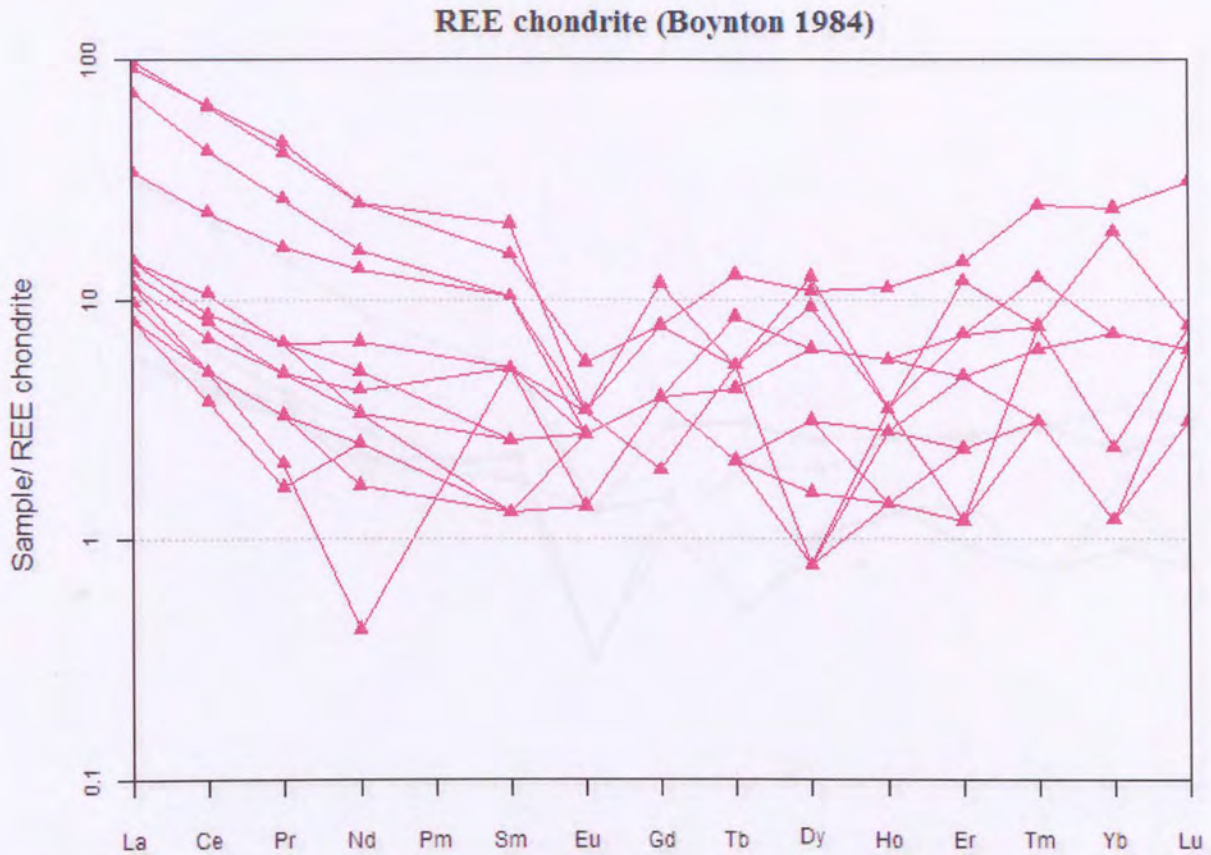


Figure 4.22 REE chondrite-normalised plots of the Namibplaas C magnetite-type sheeted leucogranites normalised to Boynton (1984) for REE Chondrite; the sheeted leucogranites have a negative Eu anomaly.

Both the D-biotite and D-magnetite types are characterised by a relatively higher concentration of LREE (16.8ppm to 104ppm) and a relatively lower concentration of HREE (12ppm to 28.5ppm) with a negative Eu anomaly (Figure 4.23 & 4.24). The range in REE values is relatively lower compared to the other sheeted leucogranite types. This indicates that the D-type leucogranites formed during one distinct event.

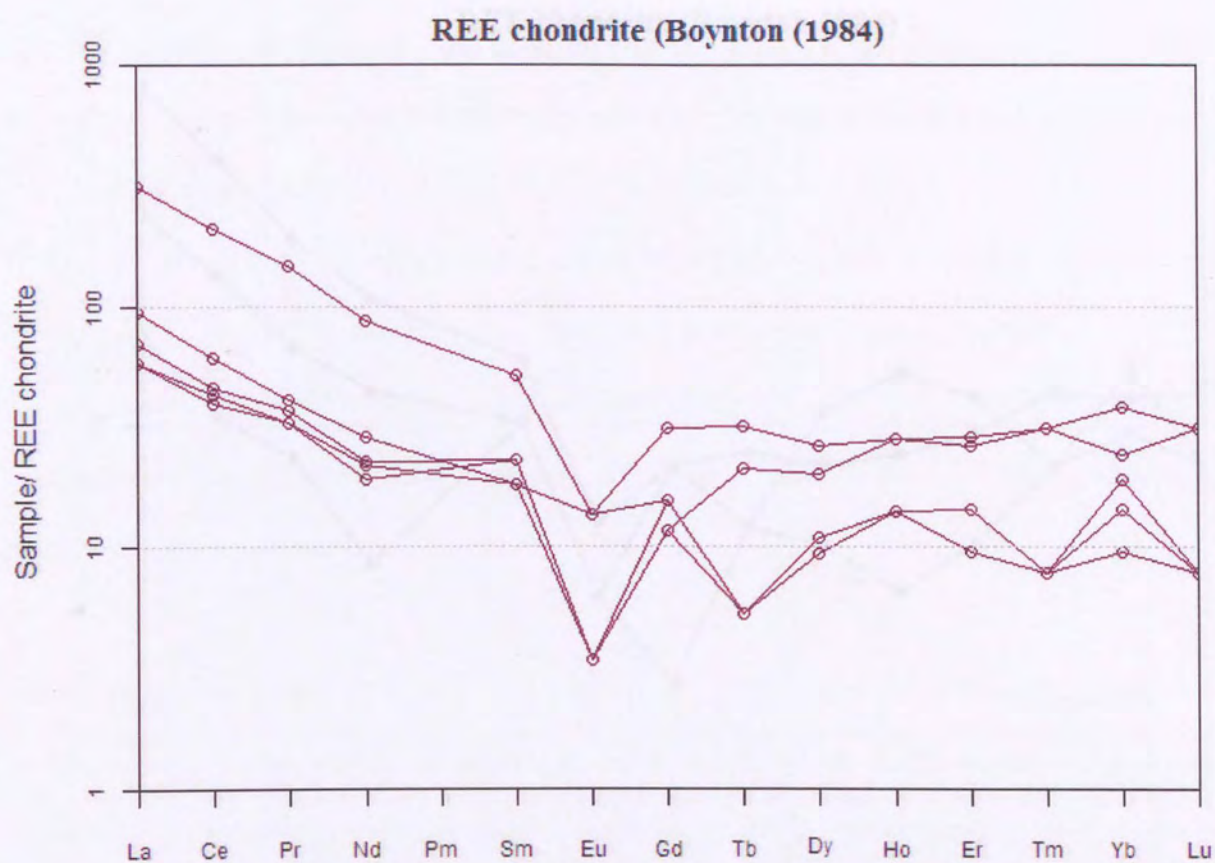


Figure 4.23 REE chondrite-normalised plots of the Namibplaas D biotite-type sheeted leucogranites normalised to Boynton (1984) for REE Chondrite; the sheeted leucogranites have a negative Eu anomaly.

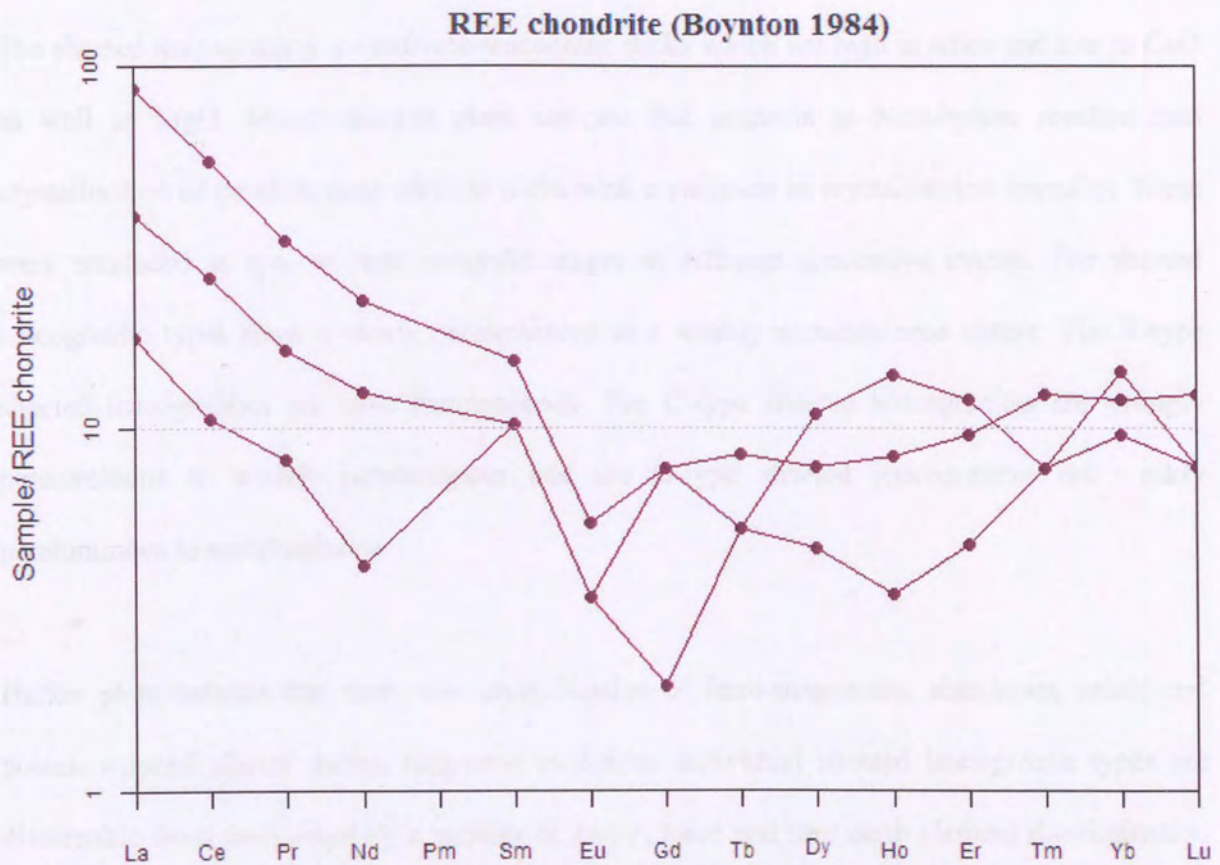


Figure 4.24 REE chondrite-normalised plots of the Namibplaas D magnetite-type sheeted leucogranites normalised to Boynton (1984) for REE Chondrite; the sheeted leucogranites have a negative Eu anomaly.

4.5 Summary of the geochemistry of the Namibplaas sheeted leucogranites.

The sheeted leucogranites are extreme leucocratic rocks which are high in silica and low in CaO as well as MgO. Major element plots indicate that anatexis at Namibplaas resulted into crystallisation of peraluminous alkaline melts with a variation in crystallisation intensity. These were emplaced at syn- to post- orogenic stages at different successive events. The sheeted leucogranite types show a strong peraluminous to a weakly metaluminous nature. The B-type sheeted leucogranites are most peraluminous. The C-type sheeted leucogranites are strongly peraluminous to weakly peraluminous and the D-type sheeted leucogranites are weakly peraluminous to metaluminous.

Harker plots indicate that there was crystallisation of ferro-magnesian, aluminous, calcic and potassic mineral phases during magmatic evolution. Individual sheeted leucogranite types are discernable from each other by a number of major, trace and rare earth element discrimination plots. Uranium and thorium and U/Th ratio distinguishes and characterises the sheeted leucogranites very well. The D-type contain the highest concentrations of uranium (22.5ppm to 1020ppm) with a U/Th ratio > 1 . The C-type sheeted leucogranites show the highest thorium concentrations (10ppm to 301ppm) with a U/Th ratio < 1 . The B-type sheeted leucogranites have lower concentrations of uranium (3ppm to 9ppm) and thorium (5ppm to 17.5ppm)

REE chondrite-normalised plots indicate that the B-type leucogranites crystallized from a single magma batch that have undergone an oxidation stage. The C-type leucogranites resulted from at

least two different magma batches that have also undergone oxidation stages and the D-type leucogranites formed from one magma batch.

LEUCOGRANITES

5.1 Introduction

This chapter focuses on the relationships and evolutionary development of the different leucogranite types, the origin of leucogranites within the D-type leucogranites and the structural control on the D-type leucogranites including structural evolution.

A ground magnetic survey was conducted over the leucogranite area during 2006 by Valencia University (Fig. 1.1). The survey was carried out at a 100 m by 100 m grid spacing using portable 30 mH Gaussmeter/Flux Sensor/compass and the ground magnetic images given in Figure 5.2. The aeromagnetic readings given in Table 5.1 for the different structural leucogranite types were compared with the data using the aeromagnetic images in Figure 5.2 and the results are given in Table 5.2.

The aeromagnetic data were collected by SGE North Africa (Fig. 1.1) at the request of Valencia University (Fig. 1.1) on the samples. The sample preparation and analytical methods are given in Chapter 1 under the 'methodology' section. Both the aeromagnetic and ground magnetic data are incorporated into the data with permission of Valencia University (Fig. 1.1).

5.2 Field characteristics of leucogranite rocks

Grains per second (GPS) as measured by the magnetometer are related to the total field intensity within the rock, provided principally by the cores of magnetite, hematite and goethite. Table 5.1

CHAPTER 5

URANIUM MINERALISATION OF THE NAMIBPLAAS SHEETED

LEUCOGRANITES

5.1 Introduction.

This chapter focuses on the radiometrics and uranium geochemistry of the different sheeted leucogranite types, the uranium ore mineralogy within the D-type sheeted leucogranites and the stratigraphic control on the D-type sheeted leucogranites including uranium enrichment.

A ground radiometric survey was conducted over the Namibplaas area during 2008 by Valencia Uranium (Pty) Ltd. The survey was carried out at a 5m by 5m grid spacing using portable handheld Gamma – Ray Scintillometers and the ground radiometric image is given in Figure 5.2. The scintillometer readings given in Table 5.1 for the different sheeted leucogranite types were determined by the author using the same portable handheld Gamma – Ray Scintillometer.

The uranium ore mineral identification was conducted by SGS South Africa (Pty) Ltd at the request of Valencia Uranium (Pty) Ltd on five samples. The sample preparation and analytical methods are given in Chapter 1 under the methodology section. Both the radiometric and uranium mineral data are incorporated into the thesis with permission of Valencia Uranium (Pty) Ltd.

5.2 Field characteristics of uranium mineralisation.

Counts per second (c/s) as measured by the scintillometer are related to the total radioactivity within the rock provided principally by the decay of uranium, thorium and potassium. Since the

values of potassium as determined by whole rock XRF analysis are similar for all the granitoids, then the observed variation in c/s is likely to be caused by the varying amounts of U and Th within the granitoids. Ground scintillometer readings show that the different types of sheeted leucogranites have a localised range of radioactivity. The instrument used is a handheld RS-120 Gamma – Ray Scintillometer.

A summary of scintillometer radiometric readings of the various sheeted leucogranites measured over outcrop are presented in Table 5.1. Figure 5.2 shows the ground radiometric anomaly (Spp2 Scintillometer) of the Namibplaas study area. It can be seen from Figure 5.2 that the Spp2 anomaly has a north-northeast strike, an orientation similar to the orientation of structures associated to uranium deposits e.g. Valencia and Rössing.

Table 5.1 Summary of ground radiometric readings from the ground radiometric survey (n) is the number of readings. The instrument used was a RS-120 Gamma – Ray Scintillometer handheld.

sheeted leucogranite Type	cps (scintillometer)			
	(n)	Min	Max	Average
B	78	220	470	308
C-tourmaline	119	220	780	443
C-magnetite	95	170	750	392
D-biotite	88	480	7860	1194
D-magnetite	60	520	6420	1032

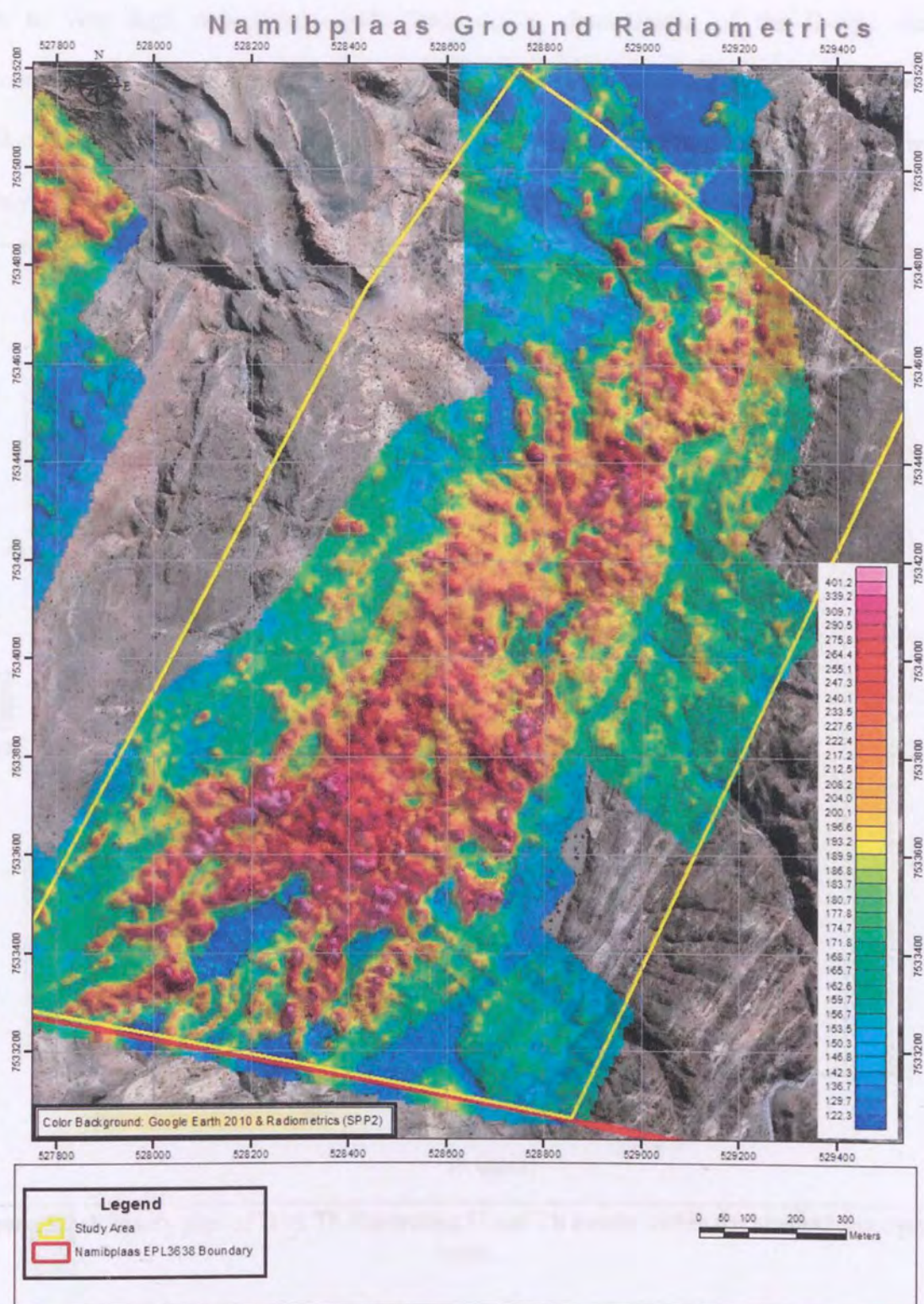


Figure 5.1 Ground radiometrics (Spp2 Scintillometer) of Namibplaas overlain on a landsat image (Valencia Uranium (Pty) Ltd, 2008).

High to very high radioactivity (480-7860 c/s) is characteristic of the D-type sheeted leucogranites. Rock textures vary from coarse equigranular to pegmatitic. They are weakly peraluminous to metaluminous, and coarse-grained pegmatitic with U/Th ratio >1 and composed mainly of microcline smoky quartz and albite. Figure 5.1 shows a binary plot of U vs Th

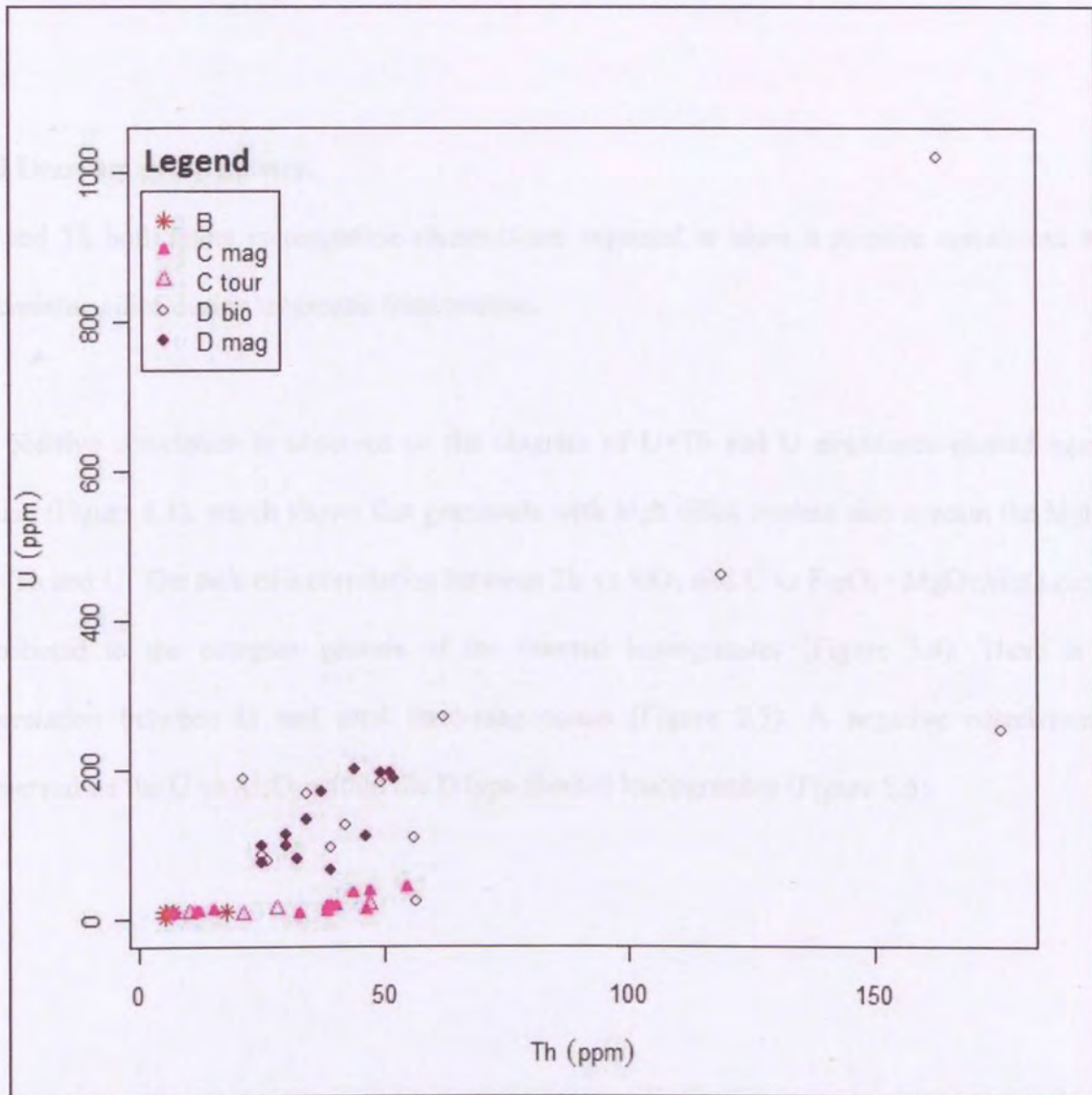


Figure 5.2 A binary plot of U vs Th illustrating U and Th trends within the sheeted leucogranite types.

In contrast, the C-type leucogranites are peraluminous to weakly peraluminous and pegmatitic with a U/Th ratio <1 and composed mainly of microcline, clear quartz, and albite.

Compared to the D- and C-type leucogranites, the B-type leucogranites are peraluminous and pegmatitic with a U/Th ratio varying from <1 to >1 and composed mainly of microcline, clear quartz, and albite.

5.3 Uranium geochemistry.

U and Th both being incompatible elements are expected to show a positive correlation with increasing silica during magmatic fractionation.

A positive correlation is observed on the diagram of U+Th and U abundance plotted against silica (Figure 5.3), which shows that granitoids with high silica content also contain the highest U+Th and U. The lack of a correlation between Th vs SiO_2 and U vs $\text{Fe}_2\text{O}_3 + \text{MgO} + \text{MnO}$ can be attributed to the complex genesis of the sheeted leucogranites (Figure 5.4). There is no correlation between U and total ferro-magnesian (Figure 5.5). A negative correlation is observed on the U vs Al_2O_3 within the D type sheeted leucogranites (Figure 5.6).

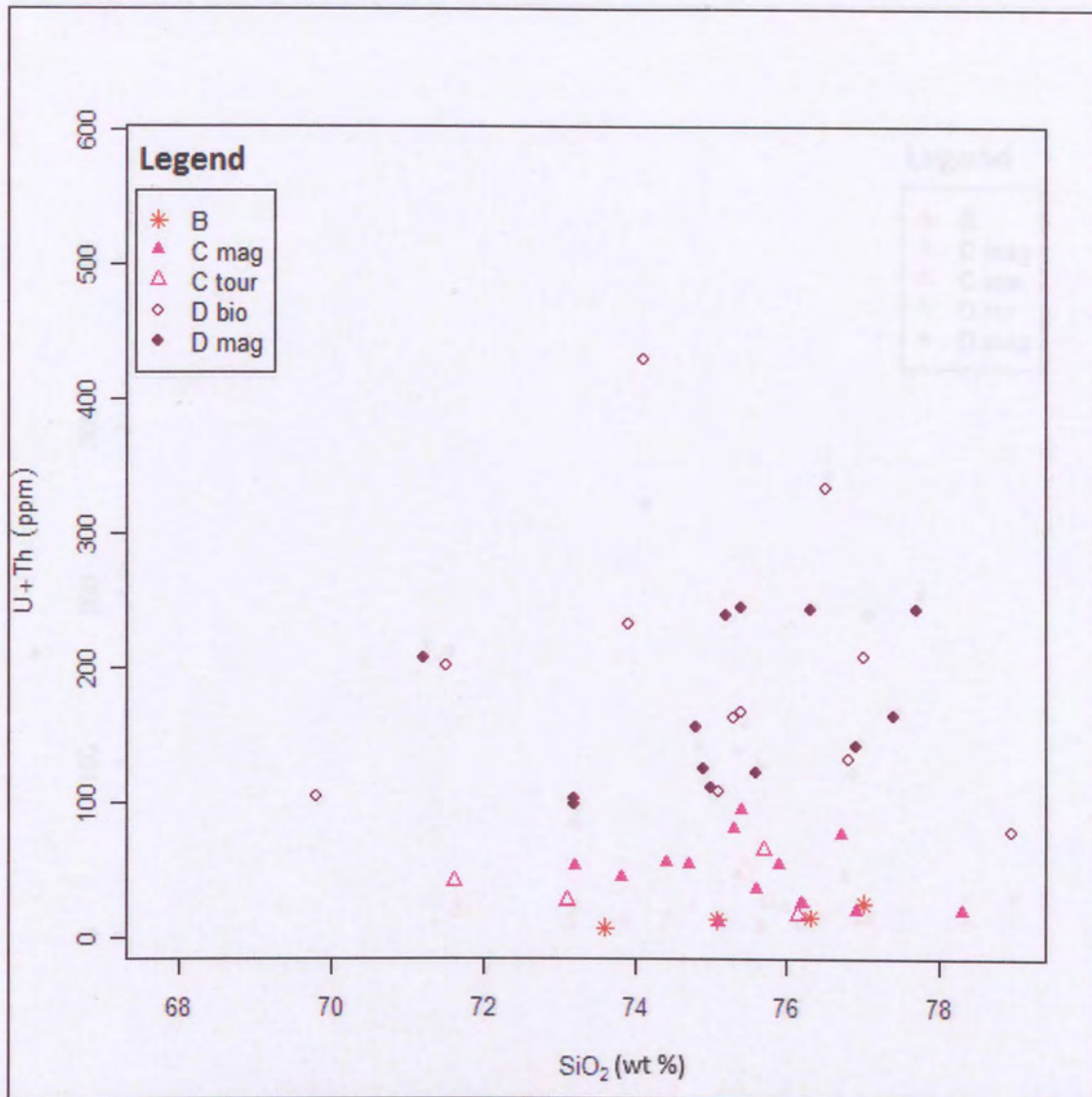


Figure 5.3 Binary plot of SiO₂ vs U+Th.

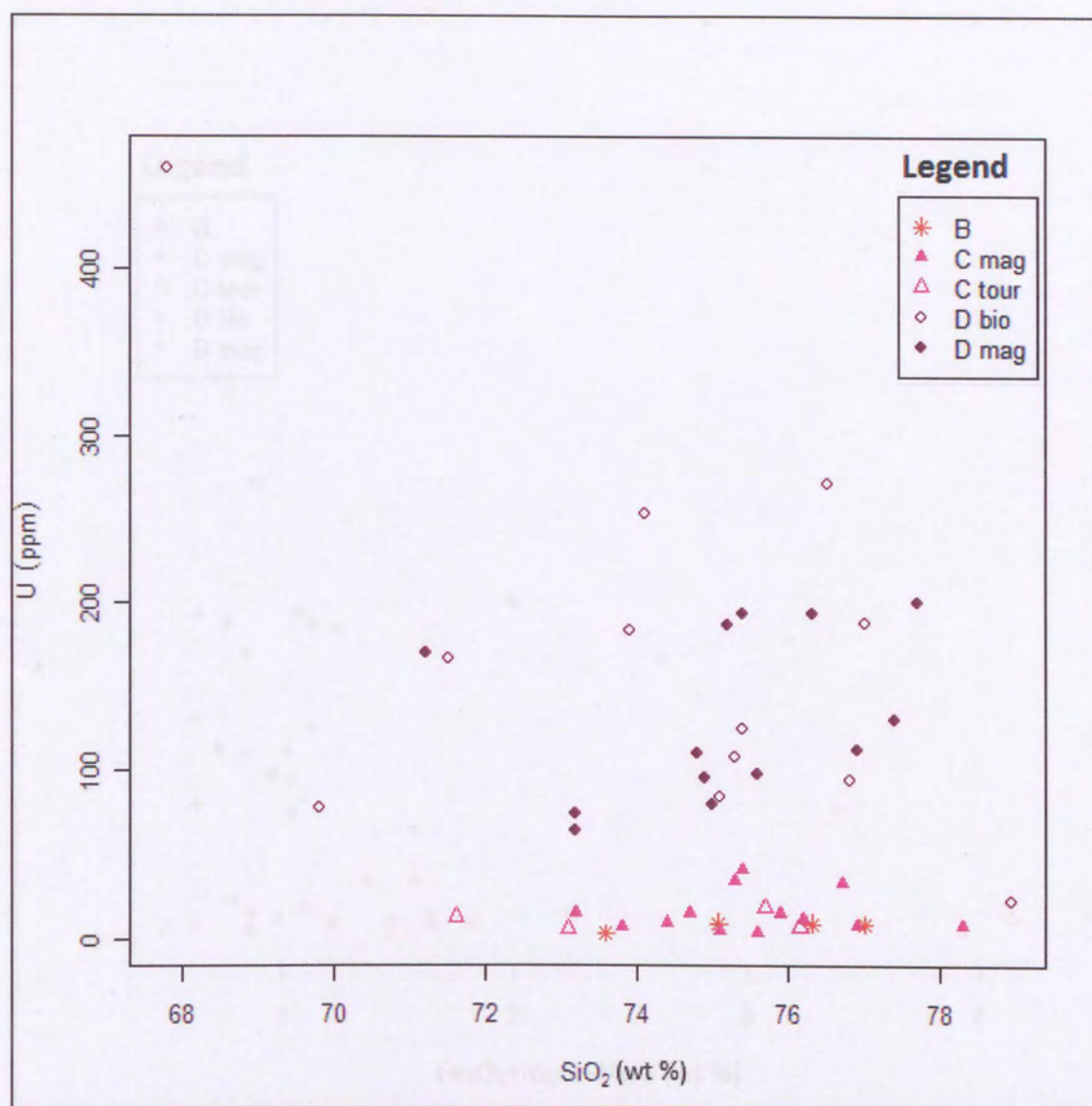


Figure 5.4 Binary plot of SiO_2 vs U.

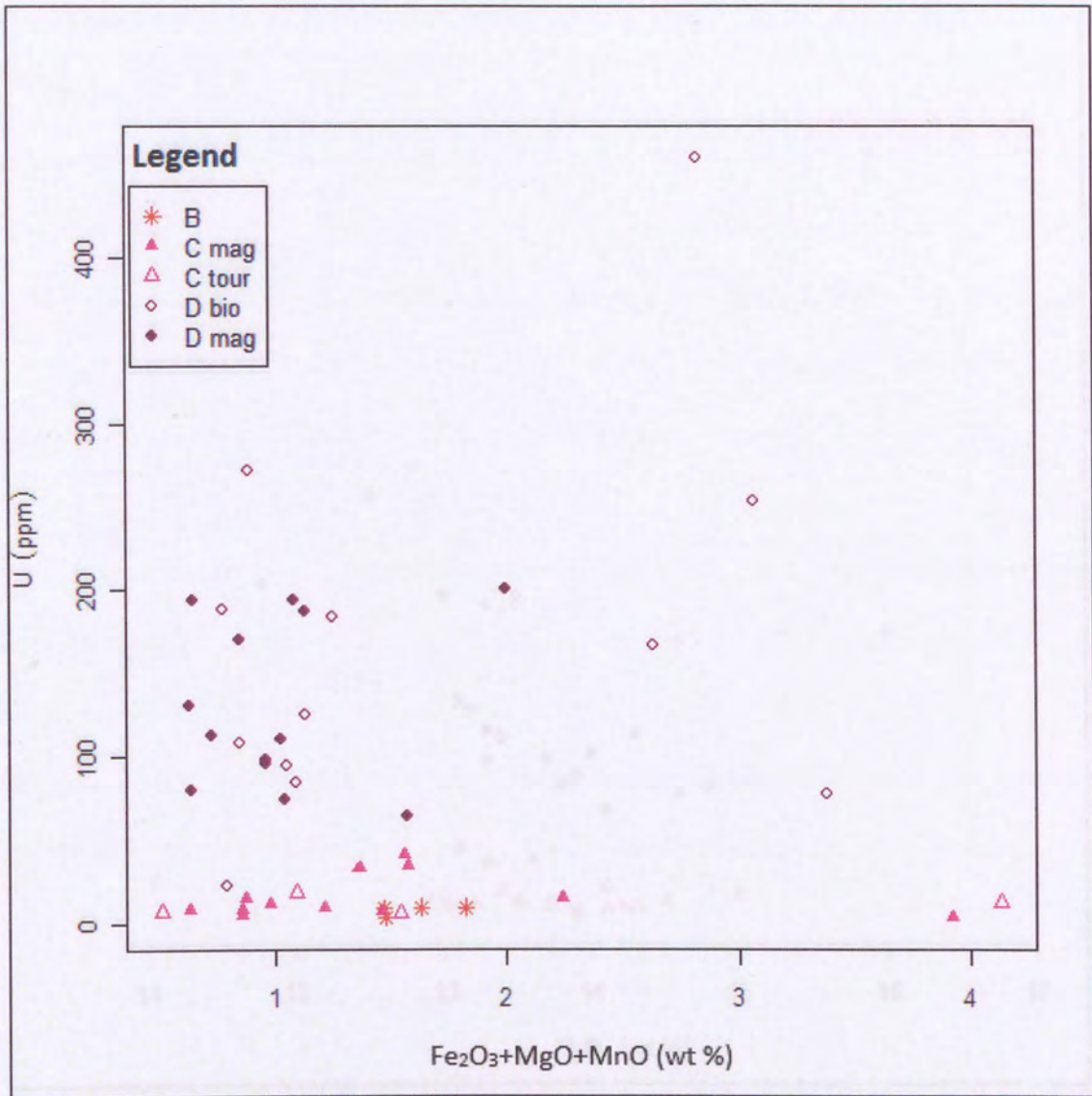


Figure 5.5 Binary plot of Fe₂O₃+ MgO+MnO vs U.

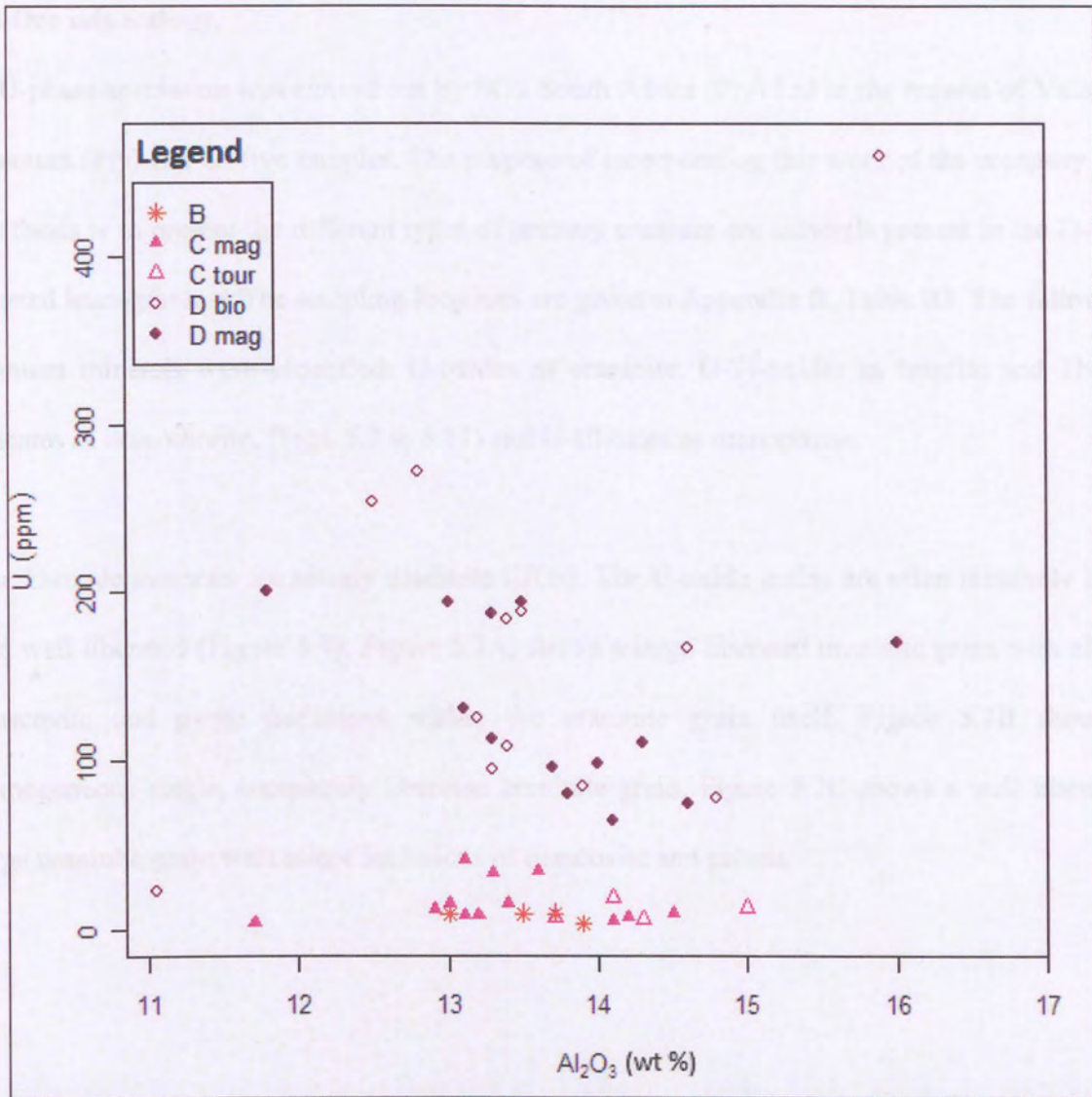


Figure 5.6 Binary plot of Al_2O_3 vs U.

5.4 Ore mineralogy.

A U-phase speciation was carried out by SGS South Africa (Pty) Ltd at the request of Valencia Uranium (Pty) Ltd on five samples. The purpose of incorporating this work of the company into the thesis is to present the different types of primary uranium ore minerals present in the D-type sheeted leucogranites. The sampling localities are given in Appendix B, Table B3. The following uranium minerals were identified: U-oxides as uraninite, U-Ti-oxides as betafite and Th(U)-silicates as uranothorite, (Figs. 5.7 to 5.11) and U-silicates as uranophane.

The U-oxide minerals are mainly uraninite (UO_2). The U-oxide grains are often relatively large and well liberated (Figure 5.7). Figure 5.7A, shows a large liberated uraninite grain with albite, muscovite and pyrite inclusions within the uraninite grain itself. Figure 5.7B shows a homogeneous single, completely liberated uraninite grain. Figure 5.7C shows a well liberated, large uraninite grain with minor inclusions of muscovite and galena.

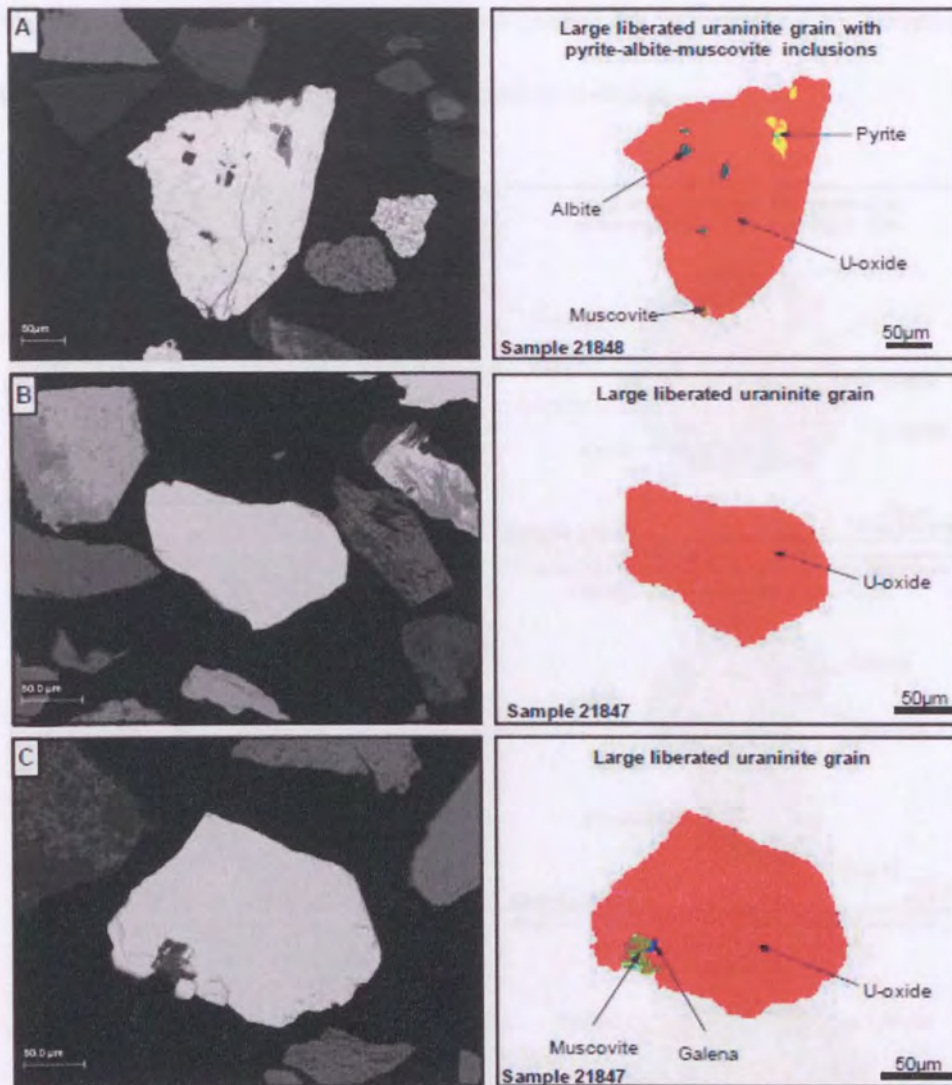


Figure 5.7 Examples of typical U-phase containing particles observed in the Namibplaas uranium ore samples. The images on the left are Scanning Electron Backscattered Electron (SEM-BSE) images and the images on the right are QEMSCAN particle maps. (A) Sample number 21848 (B) Sample number 21847 (C) Sample number 21847 (SGS South Africa, 2011).

Figure 5.8A shows a completely locked uraninite grain contained within a radiation rim of albite with minor amounts of chlorite, k-feldspar, pyrite, calcite and iron-oxide. Figure 5.8B shows two completely locked uraninite grains showing an intergrowth of their respective radiation rims. These rims consist of albite and chlorite with minor calcite, pyrite and iron-oxide. Figure 5.8C

shows a slightly liberated uraninite grain almost completely surrounded by a radiation rim of muscovite and albite with minor chlorite, pyrite and iron-oxide.

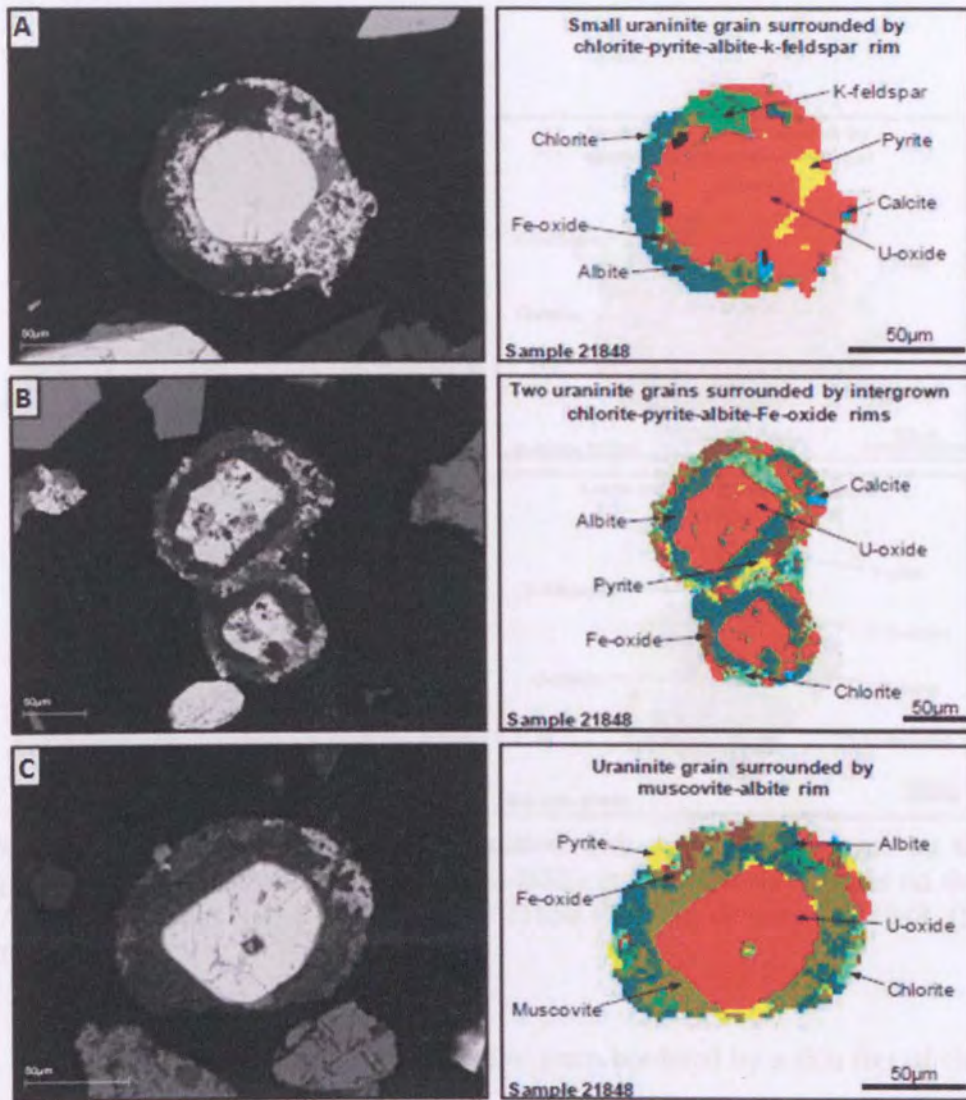


Figure 5.8 Examples of large uraninite grains with large radiation rims. The images on the left are Scanning Electron Backscattered Electron (SEM-BSE) images and the images on the right are QEMSCAN particle maps. (A) Sample number 21848 (B) Sample number 21848 (C) Sample number 21848 (SGS, 2011).

Figure 5.9A shows a cubic uraninite grain that is partially liberated. The grain is bordered by a radiation rim consisting of pyrite, with minor amounts of quartz, K-feldspar and chlorite.

Betafite, a Ti-rich member of the pyrochlore group, is the most dominant U-Ti-oxide phase present. Figure 5.9B shows a large compound grain consisting of intergrown uraninite-betafite-muscovite and pyrite with minor amounts of k-feldspar and galena.

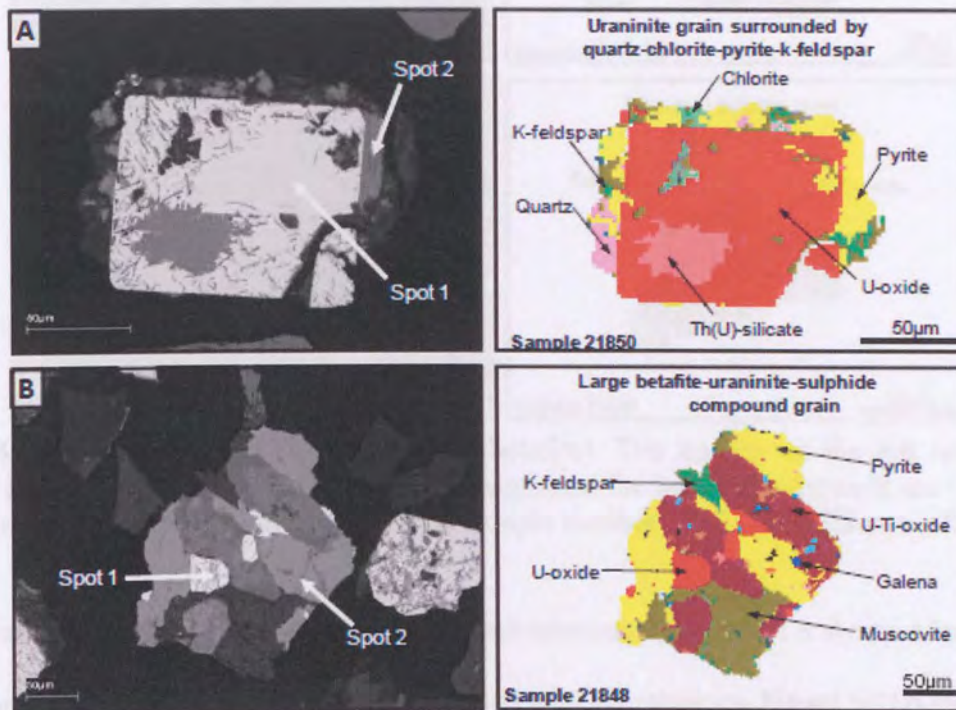


Figure 5.9 Examples of uraninite grains associated with pyrite. The images on the left are Scanning Electron Backscattered Electron (SEM-BSE) images and the images on the right are QEMSCAN particle maps. (A) Sample number 21850 (B) Sample number 21848. (SGS South Africa, 2011).

Figure 5.10A shows a large semi-liberated betafite grain bordered by a thin rim of chlorite with minor amounts of galena and albite. Figure 5.10B shows an angular liberated betafite grain with a minor inclusion of galena.

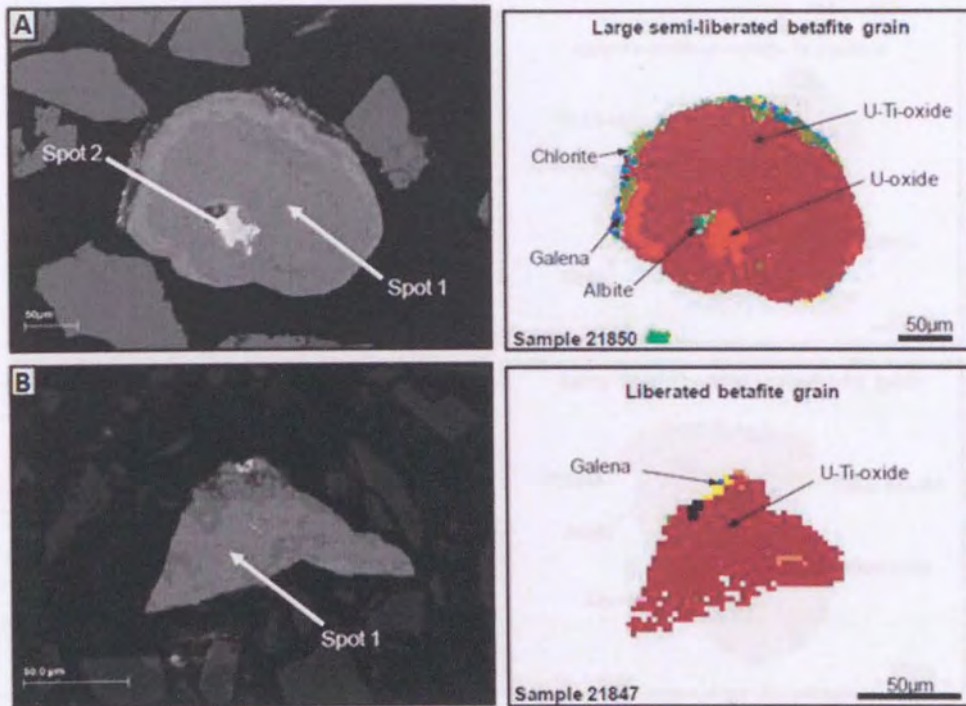


Figure 5.10 Examples of U-Ti-oxide grains (betafite). The images on the left are Scanning Electron Backscattered Electron (SEM-BSE) images and the images on the right are QEMSCAN particle maps. (A) Sample number 21850 (B) Sample number 21847. (SGS South Africa, 2011).

Uranothorite ($(\text{Th,U})\text{SiO}_4$) is present in significant amounts, Figure 5.11A shows a large uranothorite grain with large amounts of albite and calcite inclusions. Figure 5.11B shows a large semi-liberated uranothorite grain bordered by chlorite and albite with minor amounts of zircon, muscovite and pyrite.

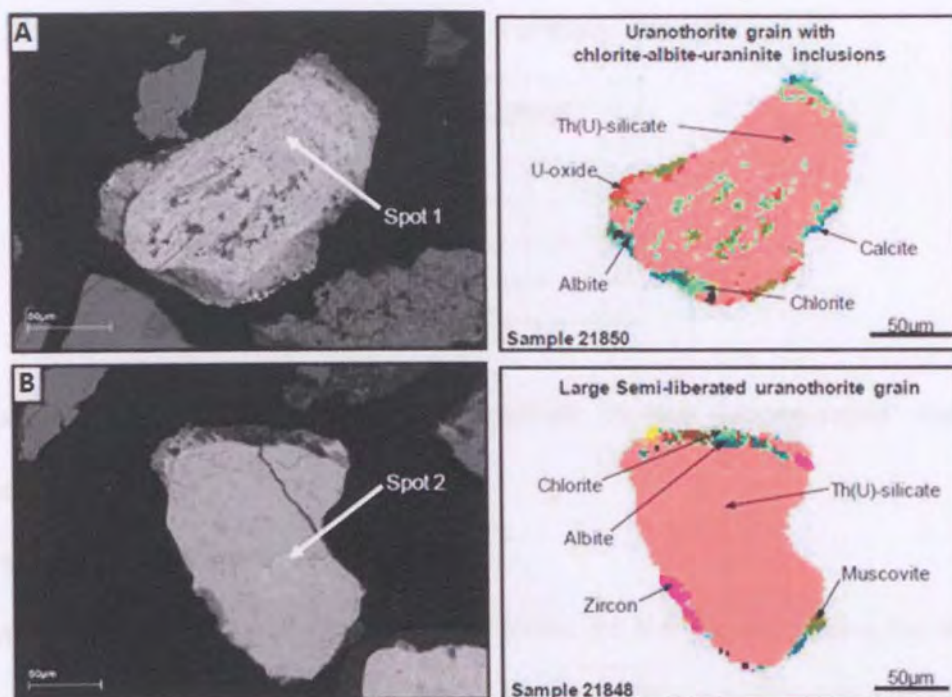


Figure 5.11 Examples of Th(U)-silicate grains (thorite). The images on the left are Scanning Electron Backscattered Electron (SEM-BSE) images and the images on the right are QEMSCAN particle maps. (A) Sample number 21850 (B) Sample number 21848. (SGS South Africa, 2011).

U-silicates minerals are mainly Uranophane. Those were not identified during the uranium phase speciation, but they have been identified during the uranium phase distribution (0 to 0.37%). The uranium phase distribution determined by QEMSCAN, is given in Table 5.2, and the assigned uranium content is given in Table 5.3.

Table 5.2. Uranium phase mineral proportions

Mineral	Mineral Proportions as per sample				
	21846	21847	21848	21849	21850
U-oxide	79.36	9.95	86.44	29.46	35.36
U-silicate	0	0.1	0.24	0	0.21
U-Ti-oxide	4.62	21.76	0.42	0.08	46.1
Th(U)-silicate	0.28	35.63	12.15	0.86	16.9
Monazite	15.74	32.56	0.75	69.6	1.44
Total	100	100	100	100	100

Table 5.2. Assigned uranium content

Assigned U content (%)	
Monazite	0.5
U-oxide	88.15
U-Ti-oxide	17.2
U-silicate	72.6
Th(U)-silicate	9.5

5.5 Controls on the location of the mineralised sheeted leucogranites and uranium enrichment.

5.5.1 Stratigraphic control.

The D-type sheeted leucogranites are emplaced within the Karibib, the Chuos, the Rössing, and the Khan Formations. Stratigraphical control is indicated by the occurrence of the D-type sheeted leucogranites along the contacts between the Karibib-Chuos- Rössing-Kahn Formations. They occur as wider intrusions where the country rocks are absent due to partially melting and are narrower where country rocks have been preserved (Figure 3.2).

5.5.2 Chemical control.

A positive correlation is observed on the diagram of U abundance plotted against silica, which shows that the granitoids containing the highest silica contain the highest U content. This can be explained by the chemical behaviour of U during magmatic evolution. Uranium being a highly incompatible element during magmatic evolution, the element is preferentially enriched in late stage differentiates of evolved silica rich granitoids.

5.6 Summary of uranium mineralisation at Namibplaas.

Based on ground scyntillometre radiometrics; the B-type leucogranites are the least radioactive (220 - 470 c/s). C-type leucogranites (220 - 780 c/s) are moderately radioactive and the D-type leucogranites that have uranium amounts of interest are highly radioactive (480 – 7860 c/s). Uranium-bearing D-type leucogranites are emplaced within the Karibib, the Chuos, the Rössing, and the Khan Formations and at the contacts of those Formations.

Uranium being an incompatible element is expected to show a positive correlation with increasing silica during magmatic evolution. Diagrams of U abundance plotted against SiO_2 show this positive correlation with increasing silica. This can be explained by the chemical behaviour of U during magmatic evolution. Uranium being a highly incompatible element during magmatic evolution, the element is preferentially enriched in late stage differentiates of evolved silica rich granitoids. QEMSCAN investigation shows that uranium phases present in the D-type sheeted leucogranites are U-oxides, U-silicates, U-Ti-oxides, U-Th-silicates.

CHAPTER 6

DISCUSSION

6.1 Source of the sheeted leucogranites.

It is widely accepted that peraluminous granites may be generated by partial melting of meta-sedimentary rocks in the continental crust (Chappell & White 1974; Miller 1985). Brynard and Andreoli (1988) suggested that the sheeted leucogranites might have been derived by partial melting of high heat producing synctectonic red and grey granites. Studies by McDermott *et al.*, (1996) on the Damaran granitoids shows that the red and grey granites are consistent with muscovite dehydration melting of a pelitic source rock. Based on the A/CNK-A/NK plot, the Namibplaas leucogranites are peraluminous to metaluminous indicating that they have also been derived by partial melting of highly evolved meta-sedimentary sources most probably the Abbabis basement gneisses as suggested by Hwakesworth & Marlow (1983) for the Rössing uraniferous leucogranites. Similarly, studies by Nex (1997) on the Goanikontes sheeted leucogranites and Freemantle (2016) on the Valencia and Rössing sheeted leucogranites show that they are all peraluminous.

The Namibplaas B and C-type leucogranites show both negative and positive Eu anomalies whereas the uranium enriched D-type leucogranites show only a negative Eu anomaly. A negative Eu anomaly in peraluminous granitoids is linked to partial melting of the upper crust which has been documented with a negative Eu anomaly by Taylor and McLennan (1985). The positive Eu anomaly within these leucogranites can be explained as a stage of oxidation of Eu^{3+} to Eu^{4+} during crystallisation. Partial melting of the Abbabis basement gneisses which was induced by M_2 resulted in the B and C-type leucogranites. Continued partial melting of the

Abbabis basement gneisses during M_3 resulted into the more uranium enriched D-type leucogranites.

6.2 The sheeted leucogranites at Namibplaas and Goanikontes.

Nex and Kinnaird (1995), Nex (1997) and Nex et al., (2001) examined the alaskites in the Goanikontes area and subdivided them into six types, A, B, C, D, E and F based on field characteristics. Freemantle (2016) pointed out that the aspects of this classification scheme are also applicable to the Central Zone sheeted leucogranite population. This classification scheme has relevance to the Namibplaas study area where three types of leucogranites have been identified, namely B, C and D.

There is a general similarity in field characteristics, petrographic characteristics, major element geochemistry, trace element geochemistry and rare earth element geochemistry of the B and C-type leucogranites at both Namibplaas and Goanikontes. However, there is a difference in U and Th concentrations of the leucogranites found at the two localities.

The B-type leucogranites which are characterised by infrequent accessory garnet are pre- D_3 at both Namibplaas and Goanikontes (Nex and Kinnaird, 1995). However, the Goanikontes B-type leucogranites are Th enriched (up to 53ppm; Nex 1997), compared to a maximum of 17.5ppm at Namibplaas. The B-type leucogranites at Goanikontes have U contents up to 17ppm (Nex 1997) whereas the Namibplaas B-type leucogranites have U contents of up to 9ppm.

The C-type leucogranites which are characterised by accessory magnetite and tourmaline are also pre- D_3 at both Namibplaas and Goanikontes (Nex and Kinnaird, 1995). However, the C types at

Goanikontes have low concentrations of Th (up to 12ppm) (Nex 1997) compared to the C types at Namibplaas which have higher Th concentrations (up to 56.5ppm). The C-type leucogranites at Goanikontes have U contents up to 8ppm (Nex 1997) whereas the Namibplaas C-type leucogranites have U contents up to 127ppm.

There is a difference in field characteristics, stratigraphic level of emplacement and U, Th concentrations of the D-type leucogranites at Namibplaas and at Goanikontes. The D-type leucogranites which are characterised by smoky quartz are post- D_3 at both Namibplaas and Goanikontes (Nex and Kinnaird, 1995). There is a major difference in average uranium concentrations with the D-type leucogranites at Namibplaas having lower average uranium concentrations (149.7ppm) compared to Goanikontes where they contain relatively higher average uranium concentrations (204.1ppm) (Nex, 1997). The difference in uranium concentrations may be attributed to the absence of beta-uranophane at Namibplaas. In addition, the medium to coarse-grained, granular D types at Goanikontes are emplaced at the Khan-Rössing Formation boundary with visible beta-uranophane and betafite (Nex and Kinnaird, 1995). The coarse-grained equigranular D-type leucogranites with accessory garnet and magnetite at Namibplaas are emplaced at the Khan- Rössing Formation boundaries, Rössing-Chuos Formation boundaries, Chuos-Karibib Formation boundaries and they also occur within the Chuos and Khan Formations.

6.3 Accessory garnet and magnetite within the D-type sheeted leucogranites at Namibplaas.

According to Jung *et al.*, (2001), garnets in granitoid plutons may have one of three origins: (a) primary crystals, crystallising directly from the melt, (b) xenocrysts brought up from or near the

depth of origin as relict source material, or (c) xenocrysts that entered the melt from the country rocks. Petrographically there is no reliable method to differentiate between granets originating from the three modes (Jung *et al.*, 2001). The garnet minerals within the D-type leucogranites at Namibplaas suits the “xenocrysts that entered the melt from the country rocks” model of Jung *et al.*, (2001). Evidence for such an origin is supported by the fact that the garnet-bearing U-enriched D-type alaskites are only garnetiferous in areas where the leucogranites is emplaced within garnet-bearing country rocks of the Chuos and Karibib Formations.

The magnetite-bearing U-enriched D-type leucogranites are only magnetiferous in areas where the leucogranites are emplaced within magnetite-bearing country rocks of the Khan Formations. The euhedral magnetite grains can be thought to be a result of crystal growth through recrystallisation during a tectonothermal event, probably the D₄ event. Therefore, they could be primary relicts inherited from the alaskite source.

The relationship between accessory garnet and magnetite within the leucogranites and the country rock is not only observed in the D-type leucogranites, but also occurs within B and C-type leucogranites. It seems that the stratigraphic level of emplacement influenced the occurrence of accessory garnet and magnetite within the leucogranites. This probably indicates that the Abbabis basement gneisses source rocks were partially melted at different stages over a long period of time and intruded at different stratigraphic levels preferentially at formation boundaries to produce the three types of leucogranites at Namibplaas. Although the D-biotite and the B types have similar accessory minerals (garnet and magnetite) as well as the C-magnetite

and the D-magnetite types, smoky quartz only occurs in the D-type leucogranites and can thus be used to distinguish the D-type leucogranites from the B and C-type leucogranites.

6.4 Origin of uranium

The origin of uranium mineralisation within the Central Zone remains debatable. Two models have been developed for the Rössing deposit: (a) extreme fractionation of a larger granitic body (Bowden et al. 1995), (b) partial melting of U-rich meta-sedimentary or meta-volcanic rocks (Cuney 1981, 1982)

The mineralized D-type SLG's at Namibplaas can be thought to have resulted from partial melting of the highly evolved Abbabis basement gneisses. Through processes of extreme fractionation, the SLG's were enriched with the highly incompatible element.

6.5 Uranium Deposition.

Uranium enrichment at Namibplaas was controlled by chemistry; Pirajno (2009) points out that the behaviour of U in magmatic fluids is related to the large size of the atoms and their positive valencies, U^{4+} , U^{6+} , U^{3+} and U^{5+} which causes them to be precluded from entry into the common rock forming minerals of igneous rocks. Therefore U (and Th) are concentrated in late stage D-type silicate melts. In addition, REE geochemistry of the leucogranites shows oxidation stages during crystallisation of the B and C-type leucogranites. This means that U^{3+} was continuously oxidized to U^{4+} during the crystallisation of the B and C-type leucogranites resulting in depletion of uranium in these leucogranites, as the element becomes more mobile in its tetravalent state, thus being concentrated in the later D-type leucogranitic melts.

Several authors (Kinnaird and Nex, 2007; Cuney and Kyser, 2008; Covino and Pretorius, 2013) have documented that primary uranium deposition was caused by redox reactions at the Khan and Rössing Formation boundaries at Rössing, Goanikontes and Ida dome. Uranium deposition at Namibplaas took place in leucogranites at Rössing-Chuos-Karibib-Kuiseb Formation boundaries and within the Rössing, Chuos and Karibib Formations. Eventhough there is a difference in stratigraphic position, uranium precipitation at Namibplaas is also expected to have been caused by redox reactions between the leucogranites and country rocks. Uranium ore minerals at Namibplaas are U-oxides as uraninite, U-Ti-oxides as betafite and Th(U)-silicates as uranothorite.

6.6 Metamorphic Grade.

Metamorphic grade attained within the Central Zone is of medium pressure at upper amphibolite facies (plagioclase-alkali-feldspar-quartz-biotite-garnet-cordierite) to higher temperature granulite facies (plagioclase-alkali-feldspar-quartz-biotite-garnet-cordierite+sillimanite) Poli and Oliver, 2001. Namibplaas rocks record amphibolite facies assemblages of plagioclase-cordierite-quartz-biotite-microcline-garnet (Kuiseb, Karibib, Chuos and Rössing Formations), calcite-tremolite (Rössing Formation) and microcline-plagioclase-quartz-biotite-diopside-calcite (Khan Formation) with rock textures varying from schistose banded gneiss to banded and mottled gneiss. The presence of biotite in conjunction with the absence of sillimanite and migmatitic texture suggests that the rocks have not attained granulite facies.

6.7 Structural Setting.

The main structural fabric at Namibplaas S_1 including L_1 and L_2 conforms to the D_3 structural orientation as described by (Oliver 1994 and Miller 2008) at the Rössing SJ dome. F_1 folds which are mainly open folds orthogonal to S_1 conform to the D_1 and D_2 structural orientation as described by Smith (1965) at the Khan Dome. F_2 folds are a combination of open and recumbent folds with axial planes sub-parallel to S_1 , these conform to the D_3 structural orientation as described by Hack (1976), Oliver (1994) and Miller (2008).

Relating S_1 , F_1 and F_2 to the three sheeted leucogranite generations; the B and C-type leucogranites are pre- D_3 because they are boudinaged within the meta-sediments and folded together with the country rocks along D_3 folds. Since the D-type leucogranites have not been boudinaged within or folded together with the meta-sediments. These were most likely emplaced post- D_2 and D_3 , making them the youngest of the three sheeted leucogranite generations. However, quartz grains within the D-type leucogranites show strain extinction in thin section indicating that even the later D-type leucogranites have been deformed. This deformation might have been a result of a later D_4 event.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The Damaran stratigraphy at Namibplaas comprises essentially of substantially attenuated representatives of Khan, Rössing, Chuos, Karibib and Kuiseb Formations. The Khan Formation is the lowermost Damaran unit and outcrops mainly as meta-arkose, biotite-amphibole gneisses and calcsilicate gneisses. White banded marbles, calcsilicate rocks, schistose cordierite gneisses and pure quartzites are representative of the Rössing Formation. The Chuos Formation is dominantly schistose to gneissic diamictites, the Karibib Formation comprises schistose biotite gneiss and the uppermost Kuiseb Formation is predominantly schistose cordierite gneiss. The Namibplaas country rocks have attained amphibolite facies and were deformed together with the sheeted leucogranites during the four deformation phases from D1 to D4.

The sheeted leucogranites intrude the whole stratigraphic sequence from the Khan to the Kuiseb Formation. The pegmatitic leucogranites are characterised by a sheet-like style of intrusion conformable and transgressive to country rock foliation (S_1). The B and C-type sheeted leucogranites are post D₁-D₂ but pre- D₃ and the D-type sheeted leucogranites are post D₃. The syn- to post- deformation sheeted leucogranites range in composition from tonalite to syenogranite and have been subdivided into three main types; B, C and D based on field and mineralogical characteristics. The pegmatitic B-type sheeted leucogranites are boudinaged, foliated and folded together with the country rocks along open folds of the D₃ structural evolution. They are characterised by infrequent garnet with a porphyritic texture. The pegmatitic C-type leucogranites are boudinaged, foliated and folded together with the country rocks along open folds of the D₃ event. They are characterised by tourmaline nests and coarse-grained magnetite. The D-type sheeted leucogranites are characterised by smoky to black smoky quartz

with a coarse equigranular to pegmatitic rock texture. The country rocks are considered as the most likely sources of the accessory garnet and magnetite which are characteristic of the Namibplaas D-type sheeted leucogranites.

The Namibplaas leucogranites are peraluminous to metaluminous indicating a highly evolved crustal source most probably the Abbabis basement gneisses. Partial melting of the Abbabis basement gneisses which was induced by M_2 resulted in the B and C-type leucogranites. Continued partial melting of the Abbabis basement gneisses during M_3 resulted into the more uranium enriched D-type leucogranites. The individual sheeted leucogranite types are distinguished from each other by a number of major, trace and rare earth element discrimination plots. The U/Th ratio is also a useful tool to distinguish between the C and D-type sheeted leucogranites.

Uranium enrichment within the D-type sheeted leucogranites at Namibplaas was controlled by the chemical behaviour of the highly incompatible and mobile U element during magmatic evolution which concentrated U in late stage magmatic differentiates which now occur as sheeted leucogranites. QEMSCAN investigations show that uranium phases present in the U-rich D-type leucogranites are uraninite (U-oxide), betafite (U-Ti-oxide) and uranothorite (Th(U)-silicate).

The Namibplaas uranium project is typically a low grade - high tonnage deposit with a resource in the measured category; 25 Mt at an average grade of 206 ppm U_3O_8 at a cut-off grade of 160 ppm. The project may not be economically viable under the current global uranium price; however, the project may become viable if the global uranium price reaches US\$60 a lb, in the near future. Further work which can be carried out at Namibplaas may include age dating of the

leucogranites in order to establish the sequence of formation of the various leucogranites as well as fluid inclusion studies to determine the pressure and temperature regime, types and compositions of the ore forming fluids, as well as more detailed structural studies to better constrain the various deformation phases of the Damaran Orogen in relation to uranium mineralization.

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APPENDIX A: GPS LOCATION OF FIELD PHOTOS

Figure ID	Easting_ UTM-GPS	Northing_ UTM-GPS
Figure 3.5 A	528800	7533350
Figure 3.5 B	528650	7533400
Figure 3.5 C	528500	7533300
Figure 3.5 D	528750	7534000
Figure 3.5 E	528750	7534100
Figure 3.5 F	527900	7533500
Figure 3.6 A	529100	7534050
Figure 3.6 B	529050	7534100
Figure 3.6 C	528200	7533300
Figure 3.6 D	528500	7534100
Figure 3.6 E	528700	7534250
Figure 3.6 F	528700	7534600
Figure 3.7 A	529000	7534300
Figure 3.7 B	529000	7534300
Figure 3.7 C	528150	7533700
Figure 3.7 D	528150	7533700
Figure 3.23 A	528950	7534250
Figure 3.23 B	528920	7534210
Figure 3.23 C	528950	7533600
Figure 3.23 D	528950	7534700
Figure 3.24 A	528870	7534050
Figure 3.24 B	528110	7533670
Figure 3.24 C	528540	7533700

APPENDIX B: NAMIBPLAAS SAMPLE CATALOGUE

Table B1: Thin section sample localities

Samp_ID	Drill hole ID	Easting_UTM-GPS	Northing_UTM-GPS	From (m)	To (m)	Samp_int	Litho
13101	NA24-011	528513.3	7533256.2	42.21	42.48	0.27	D-bio
13102	NA24-011	528513.3	7533256.2	73.66	73.82	0.16	D-bio
13103	NA24-011	528513.3	7533256.2	74.21	74.29	0.08	SCHTKAR
13104	NA24-011	528513.3	7533256.2	94.09	94.21	0.12	SCHT
13105	NA24-011	528513.3	7533256.2	99.21	99.74	0.53	D-bio
13106	NA24-011	528513.3	7533256.2	154.6	154.74	0.14	C-tour
13107	NA24-011	528513.3	7533256.2	202.67	202.81	0.14	D-bio
13108	NA24-011	528513.3	7533256.2	216.21	216.46	0.25	C-mag
13109	NA24-011	528513.3	7533256.2	340.76	340.87	0.11	KHMG
13110	NA24-011	528513.3	7533256.2	343.71	343.87	0.16	D-mag
13111	NA24-036	528669.6	7533336.7	33.72	34	0.28	B SLG
13112	NA24-036	528669.6	7533336.7	122.35	122.51	0.16	D-bio
13113	NA24-036	528669.6	7533336.7	157.32	157.59	0.27	D-bio
13114	NA24-008	528875.6	7533867.4	105	105.24	0.24	B SLG
13115	NA24-013	528974.6	7534577.3	214.71	214.87	0.16	C-mag
13116	NA24-010	529206.6	7534556.5	31.83	32	0.17	C-tour
13117	NA24-009	529001.5	7534105.2	0.2	0.37	0.17	C-tour
13118	NA24-008	528875.6	7533867.4	67.08	67.15	0.07	D-bio
13120	NA24-015	528825.9	7534185.4	5.41	5.61	0.2	C-tour
13121	NA24-012	529033.6	7533791.1	3.88	4.08	0.2	B SLG
13122	NA24-014	528697.8	7533918.5	9.14	9.28	0.14	C-tour
13123	NA24-013	528974.6	7534577.3	72.58	72.7	0.12	C-mag
13125	Sample1	528331	7533482	Outcrop sample			D-bio
13135	NA24-016	528904.7	7534404.1	171.95	172.09	0.14	C-mag
13136	NA24-016	528904.7	7534404.1	172.75	172.87	0.12	C-mag
13137	NA24-016	528904.7	7534404.1	173.17	173.34	0.17	C-mag
13138	NA24-016	528904.7	7534404.1	174.11	174.26	0.15	C-mag
13139	NA24-016	528904.7	7534404.1	174.26	174.45	0.19	C-mag
13140	NA24-016	528904.7	7534404.1	174.56	174.73	0.17	C-mag
13141	NA24-016	528904.7	7534404.1	174.73	174.86	0.13	C-mag
13142	NA24-016	528904.7	7534404.1	175.1	175.26	0.16	C-mag

Table B1 (Continued): Thin section sample localities continued.

Sample ID	Drill hole ID	Easting UTM-GPS	Northing UTM-GPS	From (m)	To (m)	Sample int	Lithology
13143	NA24-036	528669.6	7533336.7	36.61	36.84	0.23	B SLG
13150	NA24-029	528909.8	7534247.2	176.35	176.49	0.14	D-mag
13151	NA24-033	528649.6	7533688.9	194.64	194.84	0.2	D-mag
13152	NA24-034	528878.8	7534030.8	204.26	204.37	0.11	D-mag
13153	NA24-030	529053.6	7534171.6	234.48	234.65	0.17	D-mag
KS01	NA24-012	529033.6	7533791.1	102.1	102.2	0.1	Karibib
KrS02	NA24-012	529033.6	7533791.1	109.35	109.45	0.1	Karibib
KrS03	NA24-012	529033.6	7533791.1	123.16	123.26	0.1	Karibib
ChS04	NA24-012	529033.6	7533791.1	131.72	131.82	0.1	Chuos
RSc07	NA24-012	529033.6	7533791.1	204.78	204.88	0.1	Rossing
ChS08	NA24-012	529033.6	7533791.1	227.51	227.61	0.1	Chuos
RSc09	NA24-012	529033.6	7533791.1	271.4	271.5	0.1	Rossing
RMb10	NA24-012	529033.6	7533791.1	276.9	277	0.1	Rossing
khn11	NA24-011	528513.3	7533256.2	185.21	185.31	0.1	Khan
calc12	NA24-011	528513.3	7533256.2	185.91	186.01	0.1	Karibib
calc13	NA24-011	528513.3	7533256.2	195.45	195.55	0.1	Karibib
khn14	NA24-011	528513.3	7533256.2	219.82	219.92	0.1	Khan
khn15	NA24-011	528513.3	7533256.2	224.3	224.4	0.1	Khan
Etq16	NA24-011	528513.3	7533256.2	280.77	280.87	0.1	Etusis
Etq17	NA24-011	528513.3	7533256.2	293.94	294.04	0.1	Etusis
Kao18	NA24-012	529033.6	7533791.1	106.16	106.26	0.1	Karibib

Table B2: Geochem sample localities.

Sample_ID	Drill hole ID	Easting_UTM-GPS	Northing_UTM-GPS	From (m)	To (m)	Sample_int	Weight (kg)	Lithology
13119	NA24-008	528870	7533865	105	105.24	0.24	0.8	B
13149	NA24-036	528665	7533336	36.61	36.84	0.23	0.8	B
13144	SAMPLE2	528571	7533277	Outcrop sample			1.5	B
13145	SAMPLE3	528701	7533274	Outcrop sample			1.7	B
13673	NA24-013	528971	7534574	51.65	52.05	0.4	1.4	C mag
13674	NA24-013	528971	7534574	217.81	218.18	0.37	1.3	C mag
13146	NA24-015	528818	7534184	97.05	97.24	0.19	0.7	C mag
13127	NA24-016	528900	7534399	171.95	172.09	0.14	0.5	C mag
13128	NA24-016	528900	7534399	172.75	172.87	0.12	0.4	C mag
13129	NA24-016	528900	7534399	173.17	173.34	0.17	0.6	C mag
13130	NA24-016	528900	7534399	174.11	174.26	0.15	0.5	C mag
13131	NA24-016	528900	7534399	174.26	174.45	0.19	0.7	C mag
13132	NA24-016	528900	7534399	174.56	174.73	0.17	0.6	C mag
13133	NA24-016	528900	7534399	174.73	174.86	0.13	0.5	C mag
13134	NA24-016	528900	7534399	175.1	175.26	0.16	0.6	C mag
13147	NA24-016	528900	7534399	69.88	70.13	0.25	0.9	C mag
13677	NA24-029	528902	7534244	54.74	54.96	0.22	0.8	C mag
13665	NA24-009	528994	7534102	35.1	35.7	0.6	2.1	C tour
13666	NA24-010	529195	7534551	33.4	34.9	1.5	5.3	C tour
13675	NA24-013	528971	7534574	10.75	11	0.25	0.9	C tour
13668	NA24-014	528692	7533916	23.78	25.28	1.5	5.3	C tour
13669	NA24-014	528692	7533916	70.6	72.1	1.5	5.3	C tour
13124	NA24-015	528818	7534184	5.41	5.61	0.2	0.7	C tour
12950	NA24-034	528876	7534029	23	25	2	7	C tour
12955	NA24-037	528840	7533694	71	73	2	7	C tour
12959	NA24-039	528607	7533387	47	49	2	7	C tour
13663	NA24-008	528870	7533865	78.92	80.42	1.5	5.3	D bio
13667	NA24-012	529030	7533787	124.75	125.92	1.17	4.1	D bio
13670	NA24-017	528667	7533751	36.38	38	1.62	5.7	D bio
13672	NA24-021	529092	7533991	137.4	138.9	1.5	5.3	D bio
13676	NA24-024	529152	7534461	97.04	97.32	0.28	1.0	D bio
21846	NA24-027	528957	7533946	133	135	2	7	D bio
12945	NA24-030	529050	7534168	65	67	2	7	D bio
12946	NA24-030	529050	7534168	129	131	2	7	D bio
21849	NA24-032	529206	7534549	115	117	2	7	D bio
12952	NA24-036	528665	7533336	106	108	2	7	D bio

Table B2: Geochem sample localities continued.

Sample_ID	Drill hole ID	Easting_UTM-GPS	Northing_UTM-GPS	From (m)	To (m)	Sample_int	Weight (kg)	Lithology
12957	NA24-038	528772	7533497	72	74	2	7	D bio
12958	NA24-038	528772	7533497	96	98	2	7	D bio
13126	Sample1	528331	7533482	Outcrop sample				D bio
13664	NA24-008	528870	7533865	273.46	274.96	1.5	5.3	D mag
13671	NA24-020	528489	7533824	85.2	86.7	1.5	5.3	D mag
21847	NA24-029	528902	7534244	175	177	2	7	D mag
13148	NA24-029	528902	7534244	152.08	152.29	0.21	0.7	D mag
21848	NA24-030	529050	7534168	235	237	2	7	D mag
21850	NA24-033	528646	7533687	203	205	2	7	D mag
12947	NA24-033	528646	7533687	229.5	231.5	2	7	D mag
12948	NA24-033	528646	7533687	164	166	2	7	D mag
12949	NA24-033	528646	7533687	194	196	2	7	D mag
12951	NA24-034	528876	7534029	203.68	205.68	2	7	D mag
12953	NA24-036	528665	7533336	150	152	2	7	D mag
12954	NA24-036	528665	7533336	258	260	2	7	D mag
12956	NA24-037	528840	7533694	328	330	2	7	D mag

Table B3: Uranium ore mineralogy sampling localities.

Sample_ID	Drill hole ID	Easting_UTM-GPS	Northing_UTM-GPS	From (m)	To (m)	Sample_int	Lithology
21846	NA24-027	528957	7533946	133	135	2	D bio
21847	NA24-029	528909.8	7534247.2	175	177	2	D mag
21848	NA24-030	529050	7534168	235	237	2	D mag
21849	NA24-032	529206	7534549	115	117	2	D bio
21850	NA24-033	528649.6	7533688.9	203	205	2	D mag

APPENDIX C: NAMIBPLAAS SAMPLE LABORATORY RESULTS

Table C1: Thin section analysis results; modal percentages of major and accessory mineral proportions of the countryrocks.

Sample ID	Litho	Qtz %	Bio %	Cord %	Micro %	Plag %	Feld %	Amph %	Cal %	Diop %	Trem %	Ser %	Musc %	Sili %	Chl %	Kao %	Opaq %	Zir %	Sphene %	Garn %	Apa %
KS01	Cordierite Gneiss	35	25	15	13	10			<1			<1	<1				<1	<1			
KrS02	Calcsilicate	35				<1			50			<1	10				<1		<1		
KrS03	Biotite Schist	20	45				20		<1			<1	9				<1	<1			
ChS04	Garnet - Biotite Schist	40	50			5			<1				<1				<1	<1		<1	
RSc07	Cordierite Schist	30	15	20	5	15						5	<1				<1	<1			
ChS08	Garnet - Biotite Schist	30	25	15		20			<1								2	<1		8	
RSc09	Cordierite - Biotite Schist	1	30	24		44			1			1					<1	<1			
RMb10	Tremolite Marble	<1							95		4		<1		<1		1				
Khn11	Weathered Calcsilicate	25				10			12			40	1								
Calc12	Calcsilicate	15			<1	10			40				35				<1				
Calc13	Calcsilicate	1	5						45	45		1	1				<1		2		<1
Khn14	Biotite Schist	20	10	10	10	20			4	15		10					4	<1			<1
KHN15	Biotite Schist	20	30	30	10	3						3					4	<1			<1
ETQ16	Hornfels	20	2		5	25		35	<1			<1	10					4	<1		
ETQ17	Hornfels	25	1		5	30		35	<1			<1	1						<1		
KA018	Weathered Marble	20							35							45	<1		<1		
Acovol	Quartzite	90	<1			4						<1	<1	<1			5				

Table C2: Thin section analysis results; modal percentages of major and accessory mineral proportions within the SLG's.

Sample_ID	Litho	Qtz (%)	Albite (%)	Micro (%)	Perth (%)	Garn (%)	Tour (%)	Bio (%)	Chlo (%)	Musc (%)	Seri (%)	Cal (%)	Fe ox (%)	Zir (%)	Opaq (%)	Sphene (%)
13111	B SLG	35	15	35		10		1		1	<1	<1	<1	<1		
13114	B SLG	30	7	35	25	3		1		1	<1	<1	<1		<1	
13121	B SLG	30	20	20	20	10		5		1						
13143	B SLG	35	10	30	10	10		2		<1	<1		1		<1	
13106	C tour	32	32	32						2		<1				
13116	C tour	45	20	33				2				<1	<1		<1	
13117	C tour	40	30	15	10			5		1	<1	<1	<1	<1	<1	
13120	C tour	41	12	41			5			1			<1		<1	
13122	C tour	30	17	48		5				1	<1		<1			
13108	C mag	25	30	30					10	1		<1	<1		<1	
13115	C mag	30	10	40	15	1						<1	<1		<1	
13123	C mag	30	10	40				2		<1		10	<1	<1	<1	
13135	C mag	30	20	40	1	1				2	<1		1		4	
13136	C mag	30	20	35	10	<1		<1		2	<1	<1	<1		1	
13137	C mag	40	25	25					2	2	3					
13138	C mag	27	27	27	10	1		2	<1	1	1				2	
13139	C mag	27	18	35	15	<1		1	<1	<1	<1				<1	
13140	C mag	35	25	25	10	<1		<1	1	1	1					
13141	C mag	35	30	20	7	1		<1		1					3	
13142	C mag	40	35	10	10	<1		<1	<1	<1	<1				<1	
13101	D bio	30	25	10		35		2		1	1	<1	<1	<1	<1	
13102	D bio	30	30	15		15		5		2	<1	<1	<1	<1		
13105	D bio	45	45			4		1		1		<1	<1		<1	
13107	D bio	25	35	30				5		1		10	<1	<1	<1	
13112	D bio	30	35	10				10	1	1		<1	<1	<1	3	
13113	D bio	30	30	30			1	1	1			<1	<1		3	<1
13118	D bio	30	30	30		10		2	<1	1		<1			<1	
13125	D bio	25	35	35			1	1		1	<1		<1	<1		

Table C2 (Continued): Thin section analysis results; modal percentages of major and accessory mineral proportions within the SLG's.

Sample_ID	Litho	Qtz (%)	Albite (%)	Micro (%)	Perth (%)	Garn (%)	Tour (%)	Bio (%)	Chlo (%)	Musc (%)	Seri (%)	Cal (%)	Fe ox (%)	Zir (%)	Opaq (%)	Sphene (%)
13110	D mag	35	35	15				1	1	1		<1	<1		<1	
13150	D mag	35	20	20	20	1		2	1	<1	<1		<1		1	
13151	D mag	20	25	50				1	2	<1	<1		<1		1	
13152	D mag	40	30	20		<1		2	2	1	<1		1		3	
13153	D mag	40	30	20				1	1	1	1		<1		2	

Table C3: Major element data of the sheeted leucogranites

Samp ID	Litho	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	MnO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	LOI	Total
Units		%	%	%	%	%	%	%	%	%	%	%	%
Detection Limit		0.01	0.01	0.01	0.001	0.01	0.01	0.01	0.01	0.001	0.01		0.01
13119	B	75.08	13.71	1.34	0.12	0.17	0.67	2.60	6.01	0.07	-0.02	0.76	100.5
13144	B	73.64	13.91	1.38	0.02	0.08	0.52	3.31	5.04	0.19	0.03	0.48	98.6
13145	B	77.01	13.02	1.32	0.07	0.08	0.54	2.42	4.94	0.13	0.03	0.43	100.0
13149	B	76.35	13.51	1.57	0.09	0.16	0.61	2.39	4.83	0.16	0.02	0.31	100.0
13665	C tour	71.57	14.96	3.19	0.90	0.04	0.93	3.44	4.38	0.10	0.29	0.88	100.7
13666	C tour	73.05	14.26	1.30	0.21	0.03	0.40	2.31	6.43	0.08	0.09	0.47	98.6
13668	C tour	79.07	12.01	1.82	0.10	0.03	0.11	2.74	4.42	0.05	0.09	0.65	101.1
13669	C tour	75.71	14.07	1.00	0.07	0.02	0.12	2.84	6.27	0.04	0.06	0.91	101.1
13675	C tour	75.30	14.14	0.72	0.03	0.02	0.42	2.43	7.68	0.10	0.02	0.39	101.3
13124	C tour	76.15	13.71	0.47	0.03	0.01	0.21	2.37	8.19	0.06	-0.02	0.52	101.7
12950	C tour	73.90	14.10	1.41	0.50	0.01	1.48	4.04	4.61	0.14	0.21	0.84	101.2
12955	C tour	74.40	13.80	0.96	0.36	0.01	1.07	3.58	5.49	0.15	0.12	0.65	100.6
12959	C tour	71.60	16.30	1.10	0.36	0.01	1.41	4.83	5.00	0.14	0.18	0.61	101.5
13673	C mag	73.80	14.25	1.43	0.00	0.02	0.61	2.81	7.34	0.15	0.15	0.60	101.2
13674	C mag	75.08	14.12	0.76	0.09	0.02	0.72	3.14	5.78	0.02	0.02	0.30	100.0
13677	C mag	74.42	14.47	1.18	0.01	0.02	0.45	2.80	6.03	0.04	0.02	0.32	99.8
13127	C mag	76.67	13.29	1.25	0.09	0.02	1.46	3.05	3.04	0.04	0.02	1.04	100.0
13128	C mag	75.27	13.56	1.30	0.24	0.02	1.63	2.71	3.55	0.07	0.03	0.90	99.3
13129	C mag	75.35	13.11	1.45	0.09	0.02	1.71	4.16	2.84	0.08	0.02	0.71	99.6
13130	C mag	75.94	13.42	0.79	0.07	0.01	0.58	2.89	6.61	0.05	0.01	0.47	100.8
13131	C mag	74.72	13.42	0.79	0.07	0.01	0.66	2.83	6.30	0.05	0.03	0.85	99.7
13132	C mag	76.85	13.19	0.82	0.03	0.01	1.18	4.28	4.04	0.04	0.01	0.67	101.1
13133	C mag	76.21	12.90	0.95	0.01	0.01	1.14	3.88	3.73	0.04	0.01	0.83	99.7
13134	C mag	78.33	13.11	0.61	0.01	0.01	1.60	4.03	2.68	0.03	0.01	0.70	101.1
13146	C mag	73.21	13.05	1.90	0.30	0.03	0.70	1.55	7.90	0.05	0.06	1.25	100.0
13147	C mag	75.63	11.69	3.72	0.16	0.04	1.20	1.69	6.23	0.06	0.31	1.14	101.9
13663	D bio	71.50	14.57	2.42	0.19	0.03	1.17	3.13	4.81	0.06	0.05	1.03	98.9
13670	D bio	76.79	13.33	0.91	0.11	0.03	0.97	3.48	3.96	0.04	0.05	1.70	99.6
13667	D bio	69.82	14.80	2.52	0.79	0.06	1.59	2.79	5.20	0.10	0.18	0.61	100.3
13672	D bio	75.08	13.89	0.94	0.12	0.03	0.55	1.68	5.27	0.11	0.06	0.66	98.4
13676	D bio	74.91	12.58	2.87	0.88	0.05	0.29	1.73	6.40	0.07	0.32	0.79	100.9
13126	D bio	78.93	11.05	0.70	0.08	0.01	0.15	2.36	5.86	0.03	0.05	0.54	99.8
21846	D bio	67.80	15.90	2.04	0.66	0.13	1.61	3.11	7.15	0.20	0.24	0.92	99.8
21849	D bio	75.40	13.20	0.90	0.20	0.03	1.12	3.29	4.71	0.04	0.10	0.76	99.8
12945	D bio	75.30	13.40	0.64	0.20	0.01	0.82	3.30	6.01	0.08	0.08	0.67	100.5
12946	D bio	73.90	13.40	0.91	0.33	0.01	1.43	3.62	4.99	0.07	0.10	0.94	99.7
12952	D bio	77.00	13.50	0.58	0.17	0.03	0.87	3.76	5.16	0.03	0.06	0.57	101.7
12957	D bio	76.50	12.80	0.72	0.15	0.02	1.18	4.32	3.39	0.07	0.07	0.6	99.8
12958	D bio	74.10	12.50	2.29	0.76	0.02	0.78	3.25	4.75	0.10	0.36	0.48	99.4
13664	D mag	73.23	14.60	0.86	0.15	0.03	0.54	2.87	6.46	0.02	0.03	0.35	99.1
13671	D mag	75.62	14.04	0.93	0.01	0.02	0.95	3.91	4.38	0.01	0.03	0.43	100.3
21847	D mag	75.20	13.30	0.94	0.13	0.06	0.89	3.37	5.48	0.01	0.07	0.86	100.3
21848	D mag	75.40	13.00	0.56	0.05	0.04	0.91	3.45	4.77	0.01	0.07	0.67	98.9
21850	D mag	76.30	13.50	0.98	0.06	0.04	0.89	3.51	5.41	0.01	0.10	0.53	101.3

Table C3 (Continued): Major element data of the sheeted leucogranites continued.

Samp ID	Litho	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	MnO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	TiO ₂	LOI	Total
Units		%	%	%	%	%	%	%	%	%	%	%	%
Detection Limit		0.01	0.01	0.01	0.001	0.01	0.01	0.01	0.01	0.001	0.01		0.01
12947	D mag	76.90	13.30	0.62	0.10	0.01	0.91	3.92	5.15	0.03	0.06	0.4	101.4
12948	D mag	74.80	14.30	0.80	0.22	0.01	0.81	3.89	5.87	0.01	0.06	0.73	101.5
12949	D mag	71.20	16.00	0.75	0.09	0.01	0.95	4.11	7.37	0.01	0.07	0.66	101.2
12951	D mag	74.90	13.70	0.77	0.18	0.01	1.03	3.89	5.26	0.02	0.09	0.55	100.4
12953	D mag	77.70	11.80	1.80	0.18	0.02	1.02	3.40	4.22	0.04	0.11	0.67	101.0
12954	D mag	77.40	13.10	0.44	0.18	0.01	0.91	3.19	5.83	0.03	0.04	0.5	101.6
12956	D mag	75.00	13.80	0.52	0.11	0.01	0.77	3.66	6.57	0.03	0.05	0.4	100.9
13148	D mag	73.18	14.12	1.45	0.10	0.02	0.74	3.62	5.46	0.04	0.07	0.71	99.5

Table C4: Trace element data of the sheeted leucogranites.

Sample ID	Litho	Ba	Ga	Ni	Pb	Rb	Sc	Sr	Th	U	V	Zn	Zr	Y	Nb
Units		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		3	1	1	3	2	1	2	1	1	1	1	4	2	1
13119	B	230	20	5	56	352	11	40	5	9	1	5	18	25	10
13144	B	140	16	8	47	294	7	41	5	3	4	24	26	17	15
13145	B	320	12	12	48	221	7	81	17.5	8.5	2	14	57	41	1
13149	B	50	14	8	50	240	12	25	6.5	9	1	16	32	35	1
13665	C tour	95	18.8	20	36	254	7.5	43	28	13	52	62	44	11.6	25
13666	C tour	119	14	10	41	394	5	36	21	6	10	38	39	7.3	15
13669	C tour	154	18	5	35	405	1	38	47	18	18	20	44	13.9	10
13675	C tour	190	19	5	66	573	2	42	94	54	12	9	15	49.9	15
13124	C tour	200	15	1	53	477	1.5	35	10	7	6	1	19	5	5
13673	C mag	139	17.4	5	30	504	2.5	34	38	7	14	17	69	13.4	30
13674	C mag	88	17	5	29	318	0.5	33	7	5	4	17	8	2	1
13677	C mag	138	16.2	10	40	344	1.5	39	46	9	10	11	31	7.9	5
13127	C mag	20	20	2	23	161	1	24	43.5	33	12	8	34	14	10
13128	C mag	40	18	2	23	187	8	28	47	34	10	12	52	7	10
13129	C mag	40	18	2	18	146	4	29	54.5	41	16	8	54	5	5
13130	C mag	120	16	2	24	357	2	32	39	15	6	6	36	4	10
13131	C mag	120	16	2	43	343	2	32	40	14.5	6	44	46	4	5
13132	C mag	80	18	4	18	231	1	34	11.5	8.5	6	10	32	2	1
13133	C mag	60	18	2	14	221	1	33	15	11	4	2	54	2	5
13134	C mag	40	18	1	14	130	1	30	12	8.5	1	2	75	5	10
13146	C mag	350	16	12	46	567	3	62	38	15	10	8	50	29	60
13147	C mag	220	12	10	32	357	4	63	32.5	4	28	16	45	9	30
13663	D bio	132	17.6	1	52	253	3	48	34	100	12	15	94	10.1	10
13667	D bio	271	20	15	44	265	6.5	68	26	78	32	60	26	9.8	20
13670	D bio	108	18	10	47	319	3	36	39	94	12	24	61	8.7	15
13672	D bio	75	14.2	5	44	299	3.5	29	25	84	8	26	91	13	10
13126	D bio	130	15	1	42	390	2	40	56.5	22.5	20	1	65	11	10
13664	D mag	82	18.6	5	40	484	2.5	21	25	74	4	28	21	10.5	10
13671	D mag	19	20.8	5	35	374	0.5	14	25	98	10	21	23	13.8	30
13148	D mag	180	22	10	32	402	2	55	39	63.5	10	6	33	16	25

Table C5: Rare earth element data of the sheeted leucogranites.

Samp ID	Litho	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Units		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection limit		0.1	0.1	0.05	0.1	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.1
13119	B	7	11	1.2	4	0.5	0.5	0	0.2	3	1	4	0.8	8	1.4
13144	B	4.5	9	1	4	1	-0.2	0	0.2	2.5	0.6	2	0.4	3	0.4
13145	B	12.5	24	2.8	9.5	3	0.8	2	0.8	5.5	1.4	4.5	1	7.5	1.2
13149	B	7	10	1.2	4	1.5	-0.2	0	0.4	3.5	1	4	1	8	1.6
13665	C tour	28	55	6	19.5	6	0	8	1.5	9	3	8.5	2	13	2
13666	C tour	13.5	25.5	2.5	9.5	3.5	0	3	0	4.5	1	2.5	0	3	0
13669	C tour	31	51	5.5	14	4.5	0	3	0	3.5	1	3	0	3	0
13675	C tour	8.5	21.5	3	9.5	4	0	5	1.5	8.5	2	6.5	1	6	1
13124	C tour	9.5	15.5	1.2	4	0.5	0.5	0	0.2	1	0.2	0	0	0.5	0
13673	C mag	10.5	18.5	2	8	2	0	2	0	4	0	2.5	0	4	0
13674	C mag	3.5	4	0	0	1	0	0	0	0	0	0	0	0	0
13677	C mag	28.5	52	5.5	15	4	0	3	0	3	0	1.5	0	0	0
13127	C mag	4.5	8.5	0.8	4	1	0.2	0	0	2	0.4	1.5	0	1.5	0.2
13128	C mag	4.5	7	0.8	3	0.5	0.2	0	0	1	0.2	0.5	0	0	0.2
13129	C mag	4.5	7	0.8	2	0.5	0.2	0	0	1	0	0.5	0	0	0
13130	C mag	3.5	5.5	0.6	2	0	0	0	0	0.5	0	0.5	0	0	0
13131	C mag	2.5	4	0.4	1.5	0	0.2	0	0	0	0.2	0.5	0	0	0
13132	C mag	3	4	0.4	1	0	0.2	0	0	0	0	0	0	0	0
13133	C mag	2.5	3	0.2	1.5	0	0	0	0	0	0	0	0	0	0
13134	C mag	4	6.5	0.6	2.5	1	0	0	0	1	0.2	1	0	0	0
13146	C mag	30.5	51	5	15	3	0.4	2	0.6	3.5	0.8	3	0.8	5	1
13147	C mag	22.5	33.5	3.2	9.5	2	0.2	0	0.2	2	0.4	1	0.2	1.5	0.2
13663	D bio	29.5	49	5	17	3.5	1	4	0	3	1	2	0	2	0
13667	D bio	21.5	37	4.5	13.5	4.5	0	4	0	3.5	1	3	0	4	0
13670	D bio	18	32	4	13	3.5	0	3	0	3.5	1	3	0	3	0

Table C5 (Continued): Rare earth element data of the sheeted leucogranites.

Samp ID	Litho	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Units		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection limit		0.1	0.1	0.05	0.1	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.1
13672	D bio	18	34.5	4	11.5	4.5	0	3	1	6.5	2	6	1	8	1
13126	D bio	4.5	7	0.8	3.5	1	0.5	0	0.2	1.5	0.4	1.5	0.4	1.5	0.2
13664	D mag	5.5	8.5	1	2.5	2	0	0	0	1.5	0	1	0	2	0
13671	D mag	12	21	2	7.5	2	0	2	0	3.5	1	2.5	0	3	0
13148	D mag	27	44	4	13.5	3	0.4	2	0.4	2.5	0.6	2	0.4	2.5	0.4

APPENDIX D: THIN SECTION SAMPLE NUMBERS AND GEOCHEM SMPLE NUMBERS TO WHICH THEY CAN BE CORRELATED

Table D1: Thin section sample numbers and corresponding geochem sample numbers

Thin Section Sample ID	Geochem Sample ID
13111	13149
13112	12952
13113	12953
13114	13119
13115	13674
13116	13666
13120	13669
13122	13668
13123	13673
13125	13126
13135	13127
13136	13128
13137	13129
13138	13130
13139	13131
13140	13132
13141	13133
13142	13134
13150	21847
13151	21850
13152	12951
13153	21848