The geochemistry, geochronology and petrogenetic characteristics of two granitic suites on the eastern margin of the Namaqua Sector, Namaqua-Natal Mobile Belt, South Africa

Masters THESIS

By
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DECLARATION

I hereby declare that this thesis, submitted for the Masters degree to the Faculty of Natural Science, University of the Western Cape, apart from the help and supervision of Dr R. Bailie and Dr P. Macey, is my own work and has not been previously submitted to any other university or institution of higher education for a degree.

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Date

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Place
Acknowledgements

Yea, though I walk through the valley of the shadow of death, I will fear no evil; For You are with me; Your rod and Your staff, they comfort me (Psalms 23:4, NKJV). Blessed is the man who trusts in the Lord, And whose hope is the Lord. For he shall be like a tree planted by the waters, Which spreads out its roots by the river, And will not fear when heat comes; But its leaf will be green, And will not be anxious in the year of drought, Nor will cease from yielding fruit (Jeremiah 17:7-8, NKJV). Therefore, whether you eat or drink, or whatever you do, do all to the glory of God (2 Corinthians 10: 31, NKJV). Many thanks to God who is always a good Sheppard in my life and always gives strength when I feel weary. I want to also give ALL the glory to God the father, through Jesus Christ my saviors for his faithfulness in this project and in my life and i dedicate to HIM.

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Abstract

The group of granites on the eastern margin of the Mesoproterozoic Namaqua sector of the polydeformed and highly metamorphosed Namaqua-Natal Province of southern Africa is known as the Keimoes Suite. The suite includes mixtures of diverse rock types not belonging to a single intrusive series and so it should be subdivided into more than one intrusive suite. The exact definition, extent, distribution and petrogenesis of these granites have been poorly defined in the past, with various authors defining the suite differently due to the lack of proper geochronology and geochemical data. The exact contact between the Namaqua sector and Kaapvaal Craton together with the role of the suite to the Namaqua tectonic evolution is still unclear. The granites of the Keimoes Suite are thought to mark the contact between the Namaqua sector and the Kaapvaal Craton. This study seeks to address the above mentioned problems by making use of new geochronology, isotope, major and trace element geochemistry together with petrography.

The granites of the Keimoes Suite were previously grouped based on their degree of deformation. The geochronology, undertaken as part of this study, has proven that this classification is unfounded. The degree of foliation in these granites appears to be largely controlled by the abundance of platy minerals, such as biotite and muscovite, together with the intrusion mechanism, with deformational processes, such as shearing, playing a secondary role. The geochronology, together with geochemistry has helped to redefine the previously defined Keimoes Suite so that two well defined separate suites are recognized and the third is poorly defined due to lack of more samples of that age group. The new classification or grouping of the granites of the eastern Namaqua sector allows a more detailed examination of the tectonic evolution of this region.

A member of the 1225 to 1200 Ma early syn-tectonic granites, the Josling Granite, shows a strongly developed foliation and was derived from a depleted source with a relatively low continental crustal component. This granite intruded during the time of arc accretion, and is associated with, and partly responsible for the D₁ deformation and M₁ metamorphism recognized in most of the rocks of the eastern terranes of the Namaqua sector. In terms of age, the syn-tectonic granites of the Augrabies Suite extend from 1200 to 1120 Ma and were largely derived from depleted sources with variable but more substantial amounts of continental crustal components as compared to the early syn-tectonic granite. The granites of this suite intruded during the period of peak D₂ deformation with peak magmatism between 1180 - 1135 Ma, and particularly around 1150 Ma, during the peak of metamorphism (M₂) caused by, and associated with these voluminous intrusions. The Keimoes Suite can now be defined as comprising granites of late- to post-tectonic age relative to the 1.2 - 1.08 Ga Namaquan Orogeny with magmatism occurring on the western side of the Kaapvaal Craton. The 1116 to 1066 Ma Keimoes Suite intruded during the stage of the Namaquan Orogeny in which there was continued indentation of the Kaapvaal Craton into the Namaqua sector with wrenching and shearing causing the development of rifting into which the granites intruded. The Keimoes Suite granites were derived from continental crustal sources and incorporated varying degrees of depleted source components. The intrusives and extrusives of this age occured after the main collisional event between
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The compositions of the granites of the individual suites were mainly controlled by the source with the degree of partial melting exerting a major control. The proportion of entrained peritectic assemblages and accessory minerals played a major role in controlling the compositions of the granites, particularly those of the trace elements. Variations within the compositions of the same suite are due to source heterogeneities. Generally, fractionation processes played a secondary role in influencing the composition of the granites.
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1. Introduction

The Namaqua-Natal Belt, or Namaqua-Natal Province is one of several Grenvillian-aged belts world-wide and is of significance in reconstructions of the Meso- to Neo-Proterozoic supercontinent of Rodinia (Eglington and Armstrong, 2004). The western side of the province is termed the Namaqua sector and is well exposed in the Northern Cape Province of South Africa and into southern Namibia, whereas the eastern part is termed the Natal sector and is well exposed in the KwaZulu-Natal Province of South Africa (Fig. 1.1). The province is geologically, geochemically and structurally complex which resulted in an on-going debate among researchers as to the exact history of the province (e.g. Cornell et al., 2006).

The boundary between the Archean Kaapvaal Craton and the Proterozoic Namaqua-Natal Province, which comprises medium to high-grade polydeformed and metamorphosed granitic gneisses, is still rather poorly understood (Eglington, 2006; Pettersson et al., 2007; Bailie et al., 2011a). The location of the suture zone between the Namaqua sector and the Kaapvaal Craton is still debated (Cornell et al., 2006; Bailie et al., 2011a). Furthermore, the exact nature and tectonic evolution of the eastern Namaqua sector remains unclear. Barton and Burger (1983) and others, as reviewed by Eglington (2006), dated many of the units within these terranes, but were not able to achieve sufficient precision to relate them to the detailed history of crustal evolution (Cornell et al., 2012).

Figure 1.1 The regional geological map of southern Africa showing the location of the granitoids which lie on the eastern margin of the Namaqua sector at its contact with the Kaapvaal Craton (after Cornell et al., 2006; Bailie et al., 2011a). The study area is within the red rectangle.
Cornell et al. (2012) defined the Keimoes Suite as comprised of felsic and mafic intrusions with an age range of 1113 to 1078 Ma which occur within the eastern terranes (namely the Kakamas, Areachap and, to a lesser extent the Kaaien terranes) of the Namaqua sector of the Namaqua-Natal Province (Figs. 1.1, 1.2). The Keimoes Suite, as previously defined by SACS (1980), comprises a group of well foliated to weakly foliated and non-porphyroblastic biotite, biotite-hornblende and charnockitic granitoids (Fig. 1.2) which occur on the eastern margin of the Namaqua sector. The granites of the Keimoes Suite comprise a number of isolated plutonic bodies with chemical characteristics of calc-alkaline, A-type granitoids and granodiorite to alkali granite chemical composition (Cornell et al., 2006).

The Keimoes Suite comprises of approximately 30 individual granitoid plutons within the age range of 1225 to 1066 Ma as shown on the 1:250 000 2920 Kenhardt and 2820 Upington geological map sheets. Many of these granitoids formed in two major magmatic periods, the early Namaquan tectono-thermal event at 1.20 - 1.15 Ga which are related to continental collision, and the late Namaquan, largely thermal event at 1.10 - 1.02 Ga related to continued indention and wrenching, whereas a few may be related to breakup events or arc magmatism in the 1400 - 1200 Ma interval (Pettersson et al., 2009; Bailie et al., 2011a; Cornell et al., 2012).
The granites of the Keimoes Suite were grouped into still three distinct groups but based on age or relative age exhibited by the degree of deformation with respect to the 1.2 Ga Namaquan Orogeny (Stowe, 1983; Geringer et al., 1988; Moen, 2007; Bailie et al., 2011a). Namaquan is a term used to refer to the full tectonothermal cycle from 1.2 to 1.0 Ga relative to the major 1.2 Ga continental collisional event. The groups are: (i) well foliated >1150 Ma early syn-tectonic granitoids (G1) (ii) weakly foliated 1150-1100 Ma syn-tectonic granitoids (G2) and (iii) unfoliated <1100 Ma post-tectonic granitoids (G3). According to Moen (2007), this classification is tenuous, because foliation intensity is not exclusively determined by tectonic age, with compositional factors, such as biotite content and grain size, also playing an important role. Recently, Cornell et al. (2012) dated two granitoids from the Keimoes Suite which occur in the Kaaien, Areachap and Kakamas Terranes of the Gordonia Subprovince of the eastern Namaqua sector. They suggested that the suite can be divided into three clusters relative to the ~1220 Ma collisional events of the Namaqua Orogeny. The groups include: (i) the pre-tectonic 1371 to 1220 Ma granitoids corresponding mainly to the arc-related Areachap and Korannaland Groups; (ii) the syn-tectonic 1203 to 1146 Ma proposed Augrabies Suite and the lower Koras Group extrusives in the Kaaien Terrane; and (iii) the 1113 to 1078 Ma post-tectonic Keimoes Suite proper. The granitoids of the suite are thus poorly studied in terms of a general lack of geochronological data and geochemical data, but represent a critical magmatic group which holds clues to the tectonic development of the western boundary of the Kaapvaal craton at its contact with the Proterozoic Namaqua sector.

During the course of this study, fourteen plutons were sampled and examined and eight plutons were dated and the data combined with six other previously dated granites. This study contributes new whole rock geochemical, isotopic and geochronological characteristics of the individual granitoids in order to characterise and compare the various members, together with determining their role in the tectonic evolution of the eastern Namaqua sector at its boundary with the western margin of the Archean Kaapvaal Craton. As mentioned above, the granitoids were grouped based on their degree of foliation by various authors, including SACS (1980) and Stowe (1983). The current research will also examine and either validate or disprove the current definition of the granitoids grouping by comparing both the degree of deformation/foliation with their accurate U-Pb geochronology and their individual geochemical characteristics. Each granite of the Keimoes Suite is examined geochronologically and geochemically so as to define their exact characteristics in order to group those granites which are related in terms of age and geochemistry. This may involve the redefining of the Keimoes Suite as currently defined based on the findings. These granites are examined to gain a better understanding of their source and origin as well as the crustal level of their intrusion. These as other intrusive rocks will give insights into the tectonic mechanisms that led to the formation of the granitoids and their relation to the other intrusives in this area.

The research uses new geochronological, geochemical and isotopic data for the granitoids of the Keimoes Suite, with the aim of individually determining their age distribution, petrogenesis and their relationships to the surrounding supracrustal gneisses and volcano-sedimentary successions. In addition, their roles in the overall tectonic evolution of the eastern margin of the Namaqua sector will also be investigated.
2. Geological Setting

2.1. Regional Geology

The Namaqua sector occupies the western portion of the Namaqua-Natal Province (Fig. 1.1). This sector is extensively exposed in the Northern Cape Province (where it underlies an area of 100 000km$^2$) and is considered to include the igneous and metamorphic rocks formed during the Namaquan Orogeny at 1200 – 1000 Ma (Cornell et al., 2006). Regional gravity and magnetic surveys, together with crustal xenoliths from kimberlite diatremes in Lesotho and a few deep boreholes drilled through the Phanerozoic cover (Eglington and Armstrong, 2004) prove that the two sectors of the Namaqua-Natal Province, namely the Namaqua and Natal sectors, form part of a continuous 1400 km long and 400 km wide arcuate orogenic belt extending beneath the Phanerozoic Karoo Supergroup (Moen, 2007). The Namaqua sector has major Paleoproterozoic and Mesoproterozoic crust forming events which differs from the Natal sector, which has a largely juvenile character related to a Mesoproterozoic Wilson Cycle (McCourt et al., 2006; Pettersson et al., 2009). There are significant extensions of the Namaqua sector into southern Namibia (Cornell et al., 2006).

The sector is divided into a number of different, discontinuity-bounded domains, amalgamated at various stages during the tectonic development of the Namaqua-Natal Province (Joubert, 1986; Cornell et al., 2006; Bailie et al., 2011a). These terranes subsequently accreted to the Archean Kaapvaal Craton during the ~1.2-1.0 Ga Namaquan Orogeny (Hartnady et al., 1985; Thomas et al., 1994; Cornell et al., 2006; Bailie et al., 2012). Well defined and visible changes in lithostratigraphy across structural discontinuities were used to subdivide the Namaqua-Natal Province into a number of tectonostratigraphic subprovinces and terranes (Cornell et al., 2006). According to Miller (2012), the Namaqua sector is composed of several terranes, some with Palaeoproterozoic basement, while others are more predominantly juvenile Mesoproterozoic terranes. All were involved in the Mesoproterozoic Wilson Cycle and Rodinian terrane amalgamation onto the Kaapvaal Craton (Dalziel et al., 2000).

This study is focused on the Gordonia Subprovince, comprised of the Kaaien, Areachap and Kakamas terranes on the eastern margin of the Namaqua Sector at its contact with the Kaapvaal Craton (Fig. 1.1, 2.1). Various authors have defined the Gordonia Subprovince differently which includes Cornell et al. (2006) and Miller (2012). Miller (2012) defined the Kakamas Terrane alone as comprising the Gordonia Province. According to Cornell et al. (2006) the Gordonia Subprovince is comprised of two terranes, namely the Areachap and Kakamas Terranes, marking the eastern portion of the boundary between the Namaqua sector and the Kaapvaal Craton (Cornel et al., 2006; Bailie et al., 2011a). Pettersson et al. (2009) defined the Kakamas Terrane as containing mature metasedimentary rocks suggesting a shelf environment, possibly followed by arc-related volcanism. The Kakamas Terrane of Cornell et al. (2006) and the Gordonia Subprovince of Miller (2012) are dominated by supracrustal metasedimentary rocks, which include highly deformed granulate to amphibolite facies gneisses, calc-silicates and feldspathic quartzites, as well as intrusions, such as charnockites of magmatic origin in which all have been subjected to varying degrees of deformation. The metasedimentary gneisses have a depositional age of
~1.4 Ga (Thomas et al., 1994), with the granitic rocks emplaced at ~1.10 Ga (Bailie et al., 2011a; Cornell et al., 2012). Voluminous granitoid intrusions and smaller charnockitic bodies of early to late Namaquan age (~1.2 to ~1.1 Ga) and the Keimoes Suite (Geringer et al., 1988) also intrude this terrane. The boundary between the Bushmanland and Kakamas Terranes is marked by an abrupt change from Paleoproterozoic to Mesoproterozoic model ages (Pettersson et al., 2009) (Fig. 1.1). According to Pettersson et al. (2009), the Kakamas Terrane has experienced at least four different deformation phases, with the second, D$_2$, event being the most dominant, pervasive fold phase, related to the main early Namaquan deformation and equivalent to D$_1$ in the Bushmanland Terrane. The doming seen in the western part of the Kakamas Terrane is ascribed to the superposition of D$_3$ open upright folds on the main isoclinal D$_2$ fold phase (Cornell et al., 2006). According to Miller (2012), D$_1$ and D$_2$ were the most intense phases of deformation and produced isoclinal folds. In some localities (the lower Fish River area), D$_1$ involved sheath folding with north-northeast over south-southwest transport resulting from the Kakamas Terrane having been thrust over the Richtersveld Subprovince (Blignault, 1977; Miller, 2012).

The Keimoes Suite intrusions produced thermal aureoles and retrograde assemblages in late-stage shear zones (Cornell et al., 2006). The **Areachap Terrane** is a narrow belt of Mesoproterozoic age comprising amphibolite facies metavolcanic and metasedimentary rocks with magmatic ages between ~1.24 and ~1.29 Ga (Cornell et al., 1990; Pettersson et al., 2007; Cornell and Pettersson, 2007; Pettersson et al., 2009; Bailie et al., 2010, 2011b). This was interpreted as an arc sequence of juvenile character and ~1.1-1.15 Ga granitoids of the eastern margin of the Namaqua sector that developed due to eastward-directed subduction (Geringer et al., 1987, 1988; Bailie et al., 2011a; Cornell et al., 2012). The northern, in particular, and, to a lesser extent, the southern parts, of the Areachap Terrane contain a Palaeoproterozoic component (Geringer et al., 1986) suggesting that an older crustal component was present in the magmatic arc or arcs which gave rise to the Areachap Group (Pettersson et al., 2009). The Areachap Group separates the granitoid dominated, high-grade Kakamas Terrane of the eastern Namaqua sector from the weakly metamorphosed, metasedimentary and metavolcanic rocks of the Kheis Subprovince that define the western margin of the Kaapvaal Craton (Bailie et al., 2012). According to Moen (1980), the Areachap Terrane suggest a back-arc setting behind an active margin and above a westerly dipping subduction zone along which the Namaqua Front or Front zone developed. Sm-Nd model ages obtained for the Areachap Terrane are similar to ages obtained from the Kakamas Terrane suggesting that the Kakamas and Areachap terranes have a common Late Palaeoproterozoic to Mesoproterozoic derivation (Pettersson et al., 2009). Both the Areachap and Kakamas Terranes were intruded between ~1.2 - 1.08 Ga by abundant granitoids along the eastern margin of the Namaqua sector (Stowe, 1983; Geringer et al., 1988; Bailie et al., 2011a) during the Namaqua Orogeny. These granitoids are believed to mark the suture zone between the craton and the Namaqua sector (Bailie et al., 2010, 2011a, 2012).
The Kaaien Terrane comprises metaquartzites, deformed early Namaquan volcano-sedimentary rocks and undeformed, but thermally metamorphosed, bimodal volcanic rocks. According to Miller (2012), the Kaaien Terrane is occupied by four crustal units which includes the granitic basal crust, as indicated by the 2.25 Ga model age of the intrusive Kalkwerf Gneiss (Pettersson et al., 2009) and by ~2.1 to ~1.7 Ga ages of xenocrystic zircons in the Wilgenhoutsdrif and Koras felsic lavas (Botha et al., 1979; Gutzmer et al., 2000; Cornell et al., 2006; Pettersson et al., 2007) (Fig. 2.1). The Kaaien Terrane reflects the influence of a Palaeoproterozoic crust forming event possibly reflecting reworking of the Kaapvaal Craton (Pettersson et al., 2009). The ages obtained from the Kaaien Terrane suggest that a crust-forming event took place at the edge of the Kaapvaal Craton sometime during the Palaeoproterozoic (Pettersson et al., 2009). The Kaaien Terrane has undergone the same deformation phases as the Kakamas and Areachap Terranes, but to a lesser degree (Cornell et al., 2012) and has been subjected to a lower metamorphic grade (Cornell et al., 2006).

According to Cornell et al. (2012), the Namaqua Wilson cycle began at about ~1350 Ma giving rise to rift-related volcanism in the Kaaien Terrane at ~1290 Ma. The subduction progressed from the south, where the ages are coeval with the faulting and trans-tension in the Kaaien Terrane and Kheis Subprovince, to the NE where the arc was active between ~1270 - 1241 Ma (Cornell et al., 2012). This event was closely
followed by the main collision-related orogenic period at ~1220 - 1150 Ma, which reworked crustal material in the Kakamas and Bushmanland Terranes, due to thickening of the crust and partial melting. At about 1100 Ma, a thermal event gave rise to a post-collisional magmatic pulse in the eastern part of the sector, yielding bimodal volcanic sequences as well as several intrusions of both granitic and gabbroic composition, whereas the Bushmanland and Garies Terranes, and parts of the Richtersveld Subprovince underwent a late Namaquan heating of the crust at ~1030 Ma (Cornell et al., 2012).

2.2. Local Geological Setting

The Keimoes Suite intrudes the Korannaland Group of the Kakamas Terrane, along with the Sultanaoord and Areachap groups of the Areachap Terrane together with some older gneisses on a regional scale (Geringer et al., 1988; Moen, 2007) (Fig. 2.1). According to Moen (2007), the Kakamas Terrane is composed of two supracrustal successions, namely the Arribees Group and the Hartbees River Complex. The Arribees Group is dominated by calc-silicate rocks which occur as an S-shaped outcrop south west of the Augrabies falls. The Hartbees River Complex on the other hand consists essentially of high-grade, migmatitic rocks in which the stratigraphic succession is complex to determine (Moen, 2007) (Fig. 2.1). The formations which occur within the Kakamas Terrane include the Sandnoute, Venterskop, Rozynen Bosch and Koekoekop Formations, the Renosterkop Gneiss and the Korannaland Group (Stowe, 1983; Jankowitz, 1986; Geringer et al., 1987, 1988; Moen, 2007). The Korannaland Group comprises a variety of metamorphosed psammitic and semi-pelitic rocks, many with a calc-silicate affinity, and including a prominent calc-silicate and marble horizon which have been grouped together as the Biesje Poort Subgroup (Moen, 2007) (Fig. 2.1). The Biesje Poort Subgroup consists of the Piet Rooisberg, Omdraai, Sandputs, Toeslaan, Puntsit, Rautenbach se Kop, Ganzenmond, Valsvlei, and Goede Hoop Formations (Geringer et al., 1994). The Goede Hoop Formation was intruded by the Friersdale charnockite with the contact marked by biotite gneiss, while the Vaalputs Granite and the Toeslaan Formation were intruded by the Colston Granite.

The Areachap Group is divided into a northern and southern domain, separated by the Boven Rugzeer Shear Zone (Stowe, 1983) (Fig. 2.1). The eastern margin is bounded by the subvertical Trooilapspan Shear Zone in the north and Brackbosch Fault shear to the east (Bailie et al., 2010) (Fig. 2.1).

The Areachap Group contains various formations from Upington in the north to Copperton in the south (Geringer et al., 1994; Bailie et al., 2010) and the formations include: Bethesda, Jannelsepan, Van Wykspan, Kantienpan, Kielder and Copperton Formation (Fig. 2.1). The Areachap Group contains stratiform, volcanogenic Cu-Zn sulphide mineralization in which a depositional Pb-Pb age of 1285 ± 14 Ma was obtained by the evaporation method on the Smouspan Gneiss member of the Copperton Formation (Köppel, 1980). A volcanic-arc environment was proposed by Geringer et al. (1994) due to the predominance of low-K metabasalts at Boksputs. Thomas et al. (1994) described the Areachap Group as a sliver of juvenile oceanic crust.
The Bethesda Formation also form part of the Areachap Group and was first recognized and described by Vajner (1978) and is restricted to an area to the west of the Jannelsepan Formation and extends from the northern portion of Ratel Draai 54 in a northwesterly direction up to the northern boundary of Van Rooi’s Vley 443, where it disappears under the Nama Group (Fig. 2.1). The Bethesda Formation is dominated by lithologies such as biotite ± muscovite gneiss and schist, in places with silimanite and/or garnet. The Bethesda Formation was intruded by the Louisvale Granite on a regional scale, and veins of granite and pegmatite occur on all scales. The Jannelsepan Formation is the term proposed by Vajner (1978), referring to the basal Bethesda Member (metapelitic schist and gneiss), overlain by amphibolitic and calc-silicate rocks (Fig. 2.1). The Jannelsepan Formation is the most characteristic and best exposed unit in the Areachap Group consisting of amphibolite, pyroxene amphibolite, hornblende-biotite gneiss and calc-silicate rocks and is intruded by the Klipkraal Granite of the Keimoes Suite.

The development of the Koras and the Wilgenhoutsdrif Group of the Kaaien Terrane as the back arc-basin or thrust portion on the western margin of the Kaapvaal Craton was linked to the development of the Areachap Belt as a continental arc (Pettersson et al., 2009) (Fig. 2.1). According to Moen (1980), at least three times bimodal volcanic basins were developed within the eastern most Kaaien Terrane to generate the Wilgenhoutsdrif Group (Moen, 1980) which is regarded as the pre-tectonic and the Koras Group which is defined as post-tectonic in relation to the Namaquan Orogeny (Damstra, 1982; Moen, 1987; Pettersson et al., 2009) (Fig. 2.1).

The Koras Group lies to the west of the Brakbosch Fault and is represented by two virtually undeformed and weakly metamorphosed volcanic successions, 1.17 and 1.10 Ga in age (Gutzmer et al., 2000; Pettersson et al., 2007) and has been postulated to be the extrusive equivalents of the Keimoes Suite granitoids (Hartnady et al., 1985; Bailie et al., 2012) (Fig. 2.1). The continental rifting and subduction related setting of the volcano-sedimentary Wilgenhoutsdrif and Koras Groups of the Kaaien Terrane mark the 1290 Ma initiation of oceanic plate subduction in the west of arc magmatism in the Areachap volcanic arc (Cornel et al., 2006; Pettersson et al., 2009) (Fig. 2.1). Bailie et al. (2011b) suggested a back-arc setting for the bimodal Wilgenhoutsdrif volcanic rocks while the Koras Group is interpreted as tensional, pull-apart basins related to early stages of dextral shearing (Stowe, 1983; 1986; Cornell et al., 2006; Dewey et al., 2006; Bailie et al., 2012; Miller, 2012).
3. Methodology

Field work in the Gordonia Subprovince (Kakamas and Areachap terranes) and the southwestern part of the Kaaien Terrane of the Namaqua sector, located around Upington, Northern Cape Province, South Africa, was undertaken from June to July 2013. The granitoids of the eastern margin of the Namaqua sector are well distributed on the 1:250 000 map sheets 2820 Upington and 2920 Kenhardt which were used to locate the different granitoid plutons and exposures. All reported structural measurements and orientations are given in the azimuth method. The granites which were sampled and examined in this study include the Cnydas Subsuite, Colston Granite, Friersdale Charnockite, Vaalputs Granite, Kanoneiland Granite, Keboes Granite, Louisvale Granite, Klipkraal Granite, Straussburg Granite, Josling Granite, Klip Koppies Granite, Gemsbokbult Granite, Kleinbegin Granite and Elsie se Gorra Granite. An average of approximately five samples per pluton was collected depending on the size and accessibility of the outcrops. Most of the outcrops of the Keimoes Suite granitoids are located on private farming property which made it difficult to access most of the outcrops because of farmers and landowners not being present on their property at the time. Most of the Keimoes Suite granitoids are highly weathered which also made it difficult to find fresh samples for geochemical analysis. Weathered material was discarded before crushing and milling. A total of eighty nine samples were collected.

At least four thin sections per pluton were cut and prepared at the Department of Earth Sciences, University of the Western Cape (UWC) and at the Council for Geoscience (CGS), Pretoria, South Africa. For X-ray fluorescence (XRF) and Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) geochemical analysis, the samples were first crushed using a Dickie and Stockler jaw crusher to break rocks into small pieces/fragments and were crushed for approximately 7-15 seconds. The Dickie and Stockler (TS-250 mill) milling machine was used to mill the samples for about 10-20 minutes per sample into very fine powders. All the sample preparation, i.e. the crushing and milling was done at the Geochemistry lab, Department of Earth Sciences, UWC. Samples were placed in glass vials and sent to various laboratories for analysis.

Fifty four samples were analysed for trace elements by ICP-MS analysis at the Central Analytical Facility (CAF), Stellenbosch University (SU). XRF major element analyses were done at the Geochemistry lab, CGS, Pretoria. Major element contents for all representative samples were determined by X-ray Fluorescent Spectrometry at Council for Geoscience, Pretoria, on glass beads prepared from a 0.2 g sample following a lithium metaborate/tetraborate fusion and dilute nitric acid digestion. Loss on ignition (LOI) was calculated by the weight difference after ignition to 1000°C. Powdered whole-rock samples were mixed with flux for a sample-to-flux (lithium tetraborate) ratio of 1:10. Thirty-two USGS and GSJ standard reference samples were used for calibration of the instrument. The trace and rare earth element (REE) abundances were determined using inductively coupled plasma mass spectrometry (ICP-MS) following the same procedure as for the whole rock analyses but also with a separate 0.5 g split digested in Aqua Regia and analysed by ICP-MS. The precision and accuracy of the results were assessed using replicate analyses of international rock standards and are 2–5% (1σ) for most elements. Detection limits of most trace elements are 0.1 ppm except for Th and Co (0.2 ppm), Sr (0.5 ppm), Sc and Zn (1
and V (8 ppm). Most REE have detection limits less than or equal to 0.05 ppm, the exceptions being La and Ce (0.1 ppm), and Nd (0.3 ppm).

Rb-Sr and Sm-Nd isotope analysis, for the same eight samples that were analysed for geochronology, was done at the Department of Geological Sciences, University of Cape Town (UCT). The determination of Rb, Sr, Sm and Nd concentrations in the sample was performed on a PESCIEX Elan 6000 ICP-MS at UCT following dissolution and dilution with 5% HNO$_3$ containing an internal standard, with concentrations determined in duplicate for each sample. The international standard BHVO-2 was analysed with every batch of samples as a measure to achieve accuracy and precision.

The background compositions were measured and the instrumental mass fractionation was corrected using the exponential law and fractionation factors based on the measured $^{86}$Sr/$^{88}$Sr and $^{146}$Nd/$^{144}$Nd ratios. For the assessment of instrument tuning and stability, the Sr solution of the NIST SRM987 Sr isotope standard and the Nd solution of the JNdi-1 Nd isotope standard were analysed twice prior to any samples and after every fifth sample. The external, measured $\sigma^2$ reproducibility of the SRM987 and JNdi-1 standards were determined on the average $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd ratios, respectively. The $^{87}$Sr/$^{88}$Sr data were reported and normalized to 0.710255 and $^{143}$Nd/$^{144}$Nd data normalized to 0.512115. The initial $^{87}$Sr/$^{88}$Sr and $^{143}$Nd/$^{144}$Nd ratios were calculated using decay constants of 1.42 x 10$^{-11}$ y$^{-1}$ (Steiger and Jager, 1977) and 6.54 x 10$^{-12}$ y$^{-1}$ (Begemann et al., 2001), respectively.

The samples were subjected to HF and HNO$_3$ acid digestion. The separation of Sr and Nd isotopes were undertaken by chromatographic techniques as described by Miková and Denková (2007), after that described by Pin and Zalduegui (1997) and Pin et al. (1994). All isotope analyses are performed on a Nu Instruments NuPlasma HR in the AEON EarthLab, housed in the Department of Geological Sciences, UCT, South Africa.

Sr was analysed as a 200ppb 0.2% HNO$_3$ solution. The NIST SRM987 reference standard was used. A normalising value of 0.710255 for $^{87}$Sr/$^{86}$Sr was used. The average $^{87}$Sr/$^{86}$Sr values for the SRM987 standard for these analyses was 0.71083±11 (n = 11). The international rock standard bhvo-2 gave a value of 0.703490±15 relative to a value of 0.703479±20 reported by Weis et al. (2006). The long-term UCT average is 0.703487±32 (n = 28). All Sr isotope data was corrected for Rb interference using the measured signal for $^{85}$Rb and the natural $^{85}$Rb/$^{87}$Rb ratio. Instrumental mass fractionation was corrected using the exponential law and a $^{86}$Sr/$^{88}$Sr value of 0.1194.

Nd isotopes were analysed as 50 ppb 2% HNO$_3$ solutions using Nu Instruments DSN-100 desolvating nebuliser. JNdi-1 was used as a reference standard, with a $^{143}$Nd/$^{144}$Nd normalizing value of 0.512115±7 using the methodology of Tanaka et al. (2000). The average $^{143}$Nd/$^{144}$Nd ratios for the JNdi-1 reference for these analyses is 0.512074±22 (n = 11). For the same standard Tanaka et al. (2000) reported a value of 0.512115±7. The bhvo-2 standard was used giving values of 0.512981±10, relative to a value of 0.512984±11 reported by Weis et al. (2006). All Nd isotope data is corrected for Sm and Ce interference using the measured signal for $^{147}$Sm and $^{140}$Ce, and the natural Sm and Ce isotope abundances. Instrumental mass fractionation was corrected using the exponential law and a $^{146}$Nd/$^{144}$Nd value of 0.7219.

ppm), and V (8 ppm). Most REE have detection limits less than or equal to 0.05 ppm, the exceptions being La and Ce (0.1 ppm), and Nd (0.3 ppm).
The samples for geochronology were not crushed or milled but were kept as rock samples for zircon separation at the heavy mineral separation lab, CGS, Pretoria. Eight plutons which had previously not been dated were selected for geochronology. These include the Cnydas Granite, Colston Granite, Kanoneiland Granite, Keboes Granite, Louisvale Granite, Klipkraal Granite, Josling Granite and Elsie Se Gorra Granite. U–Pb age data were obtained at the Central Analytical Facility (CAF), Stellenbosch University (SU) by laser ablation - single collector - magnetic sector field - inductively coupled plasma - mass spectrometry (LA-SF-ICP-MS) employing a Thermo Finnigan Element 2 mass spectrometer coupled to a Resonetics Resolution S155 excimer laser ablation system. All age data presented here were obtained by single spot analyses with a spot diameter of 30 µm and a crater depth of approximately 15–20 µm. The methods employed for analysis and data processing are described in detail by Gerdes and Zeh (2006) and Frei and Gerdes (2009). For quality control, the Plešovice (Sláma et al. 2008) and M127 (Nasdala et al., 2008; Mattinson, 2010) zircon reference materials were analysed, and the results were consistently in agreement with the published ID-TIMS ages. Full analytical details and the results for all quality control materials analysed are reported in Table B2 in the appendix. The calculation of concordia ages and plotting of concordia diagrams were performed using Isoplot/Ex 3.0 (Ludwig, 2003). The table with more information is attached is appendix B.
4. Lithological description

The classification of the Keimoes Suite granitoids, based on the timing of emplacement relative to deformation, has been examined by various authors (Cornell et al., 2012) and has been found to be unreliable and misleading. This chapter aims to examine the Keimoes Suite granites based on their field description and relationships, along with their petrographic characteristics to validate the previous groupings/classification. This will also be confirmed or examined by means of whole rock geochemistry and geochronology (next chapter). This chapter arranges the descriptions of the Keimoes Suite granites from NW-SE with the SE granites located closer to the Kaapvaal Craton. The interested reader can find extra lithological descriptions in appendix A.

Figure 4.1 Local geological map showing the distribution of the granites of the eastern margin of the Namaqua sector (after Moen, 1988; Slabbert, 1989).
4.1. **Cnydas Subsuite**

The Cnydas Subsuite is a genetically coherent group of epizonal granitoids (Geringer and Botha, 1977; Moen, 2007). The subsuite is distributed along a NW-SE strike line (Figs. 4.1). The outcrop shapes and sizes vary from low lying to boulder-dominated, hilly types of outcrop. The local outcrops form small isolated plutons far from each other with their contacts concealed by sand. This subsuite was subdivided into ten distinct granitoid types by Jankowitz (1986) and Bailie et al. (2011a). Three plutons of the ten comprising the Cnydas subsuite which were sampled for this study, show some differences mostly in terms of colour and texture, including foliation and grain size, but with relatively similar mineralogy, were sampled for this study. Previously the subsuite was classified as post-tectonic due to it being unfoliated (Geringer et al., 1988; Moen, 2007; Bailie et al., 2011a). Three different varieties of the Cnydas Subsuite, with relatively similar mineralogy, but differing in terms of colour and texture, including foliation and grain size, were sampled from east (sample Mc 1) to west (sample Mc 9).

#### 4.1.1. **Molopo River Granite (Mc 1)** ($S$ 28° 24'54.1″; $E$ 020° 35'25.1″; elevation 831m)

The Molopo River Granite is a unique member of the Cnydas Subsuite as it has a strong foliation and a coarse grained texture not shown by other members of the subsuite. The strongly foliated texture is likely due to the Cnydas Shear which cuts through the pluton (Figs. 1.2, 4.1). Overall, the Molopo River Granite can be defined as a dark coloured strongly foliated granite composed of quartz, plagioclase, alkali feldspar, biotite, muscovite, hornblende and garnet, with clusters of quartz, alkali feldspar, biotite and garnet aligned parallel to the foliation (Fig. 4.2b, Table 4.1). This granite is dominated by the presence of mafic xenoliths which range in size from 1 cm -10 cm.

The strongly foliated texture of the granite is defined by the alignment of minerals such as biotite, hornblende, quartz, rutile, opaque minerals and muscovite which wrap around the phenocrysts (Fig. 4.2a, b). The rock has a porphyritic texture defined by phenocrysts of plagioclase, microcline, orthoclase and quartz, in order of decreasing abundance, within a groundmass of quartz, plagioclase, microcline, biotite, hornblende and opaque minerals, in order of decreasing abundance (Fig. 4.2b, Table 4.1). The phenocrysts exhibit glomeroporphyritic texture defined by clusters of microcline phenocrysts, as well as cumulophyric texture defined by clustering of microcline, orthoclase and plagioclase phenocrysts (Fig. 4.2b).

#### 4.1.2. **Smalvis Granite** ($S$ 28° 24’47.8″; $E$ 020° 35’18.6″; elevation 837m)

The Smalvis Granite is also a member of the Cnydas subsuite, located northwest of the Molopo River Granite and Upington (Fig. 4.1). The outcrops of this granite are well exposed and located at Smalvis where they are sizeable and form rounded boulder hill outcrops of a height of approximately 8 m (Fig. A1.1e).
Figure 4.2. The granite is medium- to fine-grained, porphyritic and unfoliated to weakly foliated with phenocrysts of quartz, plagioclase, orthoclase, microcline and perthite within an equigranular groundmass of quartz, plagioclase, orthoclase, microcline, biotite and muscovite (Table 4.1). (a-b) Molopo River Granite. (c-d) Smalvis Granite. (e-f) Gous Charnockite.
4.1.3. **Gous Charnockite (Mc 9)** (S 28° 15’10.6”; E 020° 24’23.3”; elevation 834m)

The outcrop characteristics of this granite are the same as those of the Smalvis Granite. The Gous Charnockite outcrops are located north of Smalvis (Fig. 4.1). This is a medium to fine grained, unfoliated to weakly foliated, porphyritic granite composed of phenocrysts of quartz, microcline, orthoclase, plagioclase and perthite in a groundmass of quartz, microcline, orthoclase, plagioclase, muscovite, biotite, hornblende and opaque minerals (Fig. 4.2e-f, Table 4.1). The granite exhibits cumulophyritic and glomeroporphyritic texture of phenocrysts as well myrmekitic texture due to the intergrowth of quartz with plagioclase (Fig. 4.2f). The main difference between the Smalvis Granite and Gous charnockite is the mineral abundances.

4.2. **Colston Granite**

The granitic pluton comprises three main members as mapped by Moen (2007), but only two members were examined in this study (Fig. 4.1). These are the Rooidam Member, which is located to the east, and the Toeslaan Member, which is located more towards the west (Fig. 4.1). The Rooidam member is located at Rooidam 441 along the Rooidam road. There is a slight difference between the two outcrops, with the main difference being that the Rooidam outcrop (sample Mcol 1) is a medium grained and it has weakly to moderately foliated texture, whereas the Toeslaan (sample Mcol 5) outcrop (sample Mcol 5) is a very coarse grained and moderately to strongly foliated biotite granite (Fig. 4.3). Furthermore, the two members differ in terms of mineral abundances, colour and texture.

4.2.1. **Colston Granite - Rooidam member** (S 28° 25’42.4”; E 020° 49’24.9”; elevation 873m)

The Rooidam Granite variety of the Colston Granite can be defined as a coarse grained, porphyritic and weakly foliated granite (Fig. 4.3a,b) composed of quartz, plagioclase, orthoclase, biotite, microcline, hornblende, muscovite and garnet. The granite comprises large microcline phenocrysts (2 mm in size) containing inclusions of quartz and opaque minerals (Fig. 4.3b, Table 4.1). Quartz and biotite together with muscovite (sericite), are oriented defining the slight foliation of the granite (Fig. 4.3b). This member contains mafic xenoliths which are rich in biotite and hornblende. The outcrops are poorly to moderately exposed and less weathered compared to other outcrops of the Colston Granite (Fig. A2.1a-d).

4.2.2. **Colston Granite - Toeslaan Member** (S 28° 18’57.3”; E 020° 44’56.0”; elevation 865m)

The second member of the Colston Granite is located on the farm Toeslaan 440 towards Namibia and can be defined as a gneissic, coarse-grained biotite granite with a strongly developed foliation (Fig. 4.3). The outcrops form boulder-dominated, hilly types of outcrop (Fig. A2.1c). The granite has a porphyritic
texture comprising phenocrysts of orthoclase, plagioclase, microcline and quartz within a groundmass of the same minerals along with biotite, hornblende, muscovite, small clusters of garnet and opaque minerals (Fig. 4.3c-d). Large (2 – 4 cm) phenocrysts of quartz and alkali feldspar also occur (Figs. 4.3c, A2.1c).

Figure 4.3. Photographs of hand specimens and photomicrographs of the Colston Granite. (a) The Rooidam Road outcrop hand specimen. (b) Photomicrograph of the Rooidam road outcrop showing a weak foliation and minor alteration. (c) The Toeslaan 440 outcrop hand specimen. (d) Photomicrograph of the Toeslaan 440 outcrop showing a highly sericitised and moderately foliated granite (mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, ms = muscovite, srt = sericite). The field of view for the photomicrographs is 3 mm.
4.3. **Friersdale Charnockite**

The Friersdale Charnockite is an unfoliated coarse grained granite. The grain size ranges from medium to coarse grained from east to west across the outcrop extent, but it is generally coarse grained (Fig. A3.1a-c). Petrographically, the granite has a porphyritic texture comprising phenocrysts of quartz, plagioclase, microcline, perthite, orthoclase, cordierite, orthopyroxene and garnet within a groundmass composed of quartz, plagioclase, biotite, piemontite, epidote, hornblende, microcline, perthite, opaque minerals and orthoclase (Fig. 4.4a-b). The outcrops, especially towards Kakamas, show clusters of garnet, particularly conspicuous on the weathered surface.

Figure 4.4. (a) Hand specimen and (b-d) photomicrographs of the porphyritic Friersdale Charnockite (Mineral abbreviations: qtz = quartz, plg = plagioclase, mcl = microcline, ort = orthoclase, pth = perthite, crd = cordierite, bt = biotite, hbl = hornblende, ms = muscovite, srt = sericite, opx = orthopyroxene, opq = opaque, grt = garnet). Field of view of the photomicrographs is 3 mm.
Table 4.1. Petrographic summary of the Keimoes Suite granites

<table>
<thead>
<tr>
<th>GRANITE NAME</th>
<th>MINERALOGY (Order of decreasing abundance)</th>
<th>CONTACT AND COUNTRY ROCK</th>
<th>TEXTURE</th>
<th>GRAIN SIZES</th>
<th>ALTERATION</th>
<th>PRESENCE OF FOLIATION</th>
<th>SPECIAL FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cnydas Subsuite</td>
<td>Qtz, Mc, Or, Pl, Bt, Hbl, Chi, Op, Ms, Zrn, Rt</td>
<td>Gradational with the Sandputs Formation</td>
<td>cumulophytic and glomeroporphyritic.</td>
<td>Coarse to fine grained</td>
<td>Sericitisation of pl, Mc and Or</td>
<td>Strongly foliated to unfoliated</td>
<td>Eugen texture on Molopo granite</td>
</tr>
<tr>
<td>Colston Granite</td>
<td>Qtz, Pl, Or, Bt, Mc, Hbl, Ms, Grt</td>
<td>Gradational with the Kuibis Formation</td>
<td>porphyritic texture</td>
<td>Medium to coarse grained</td>
<td>Pl, Mc and Or are sericitised</td>
<td>Strongly foliated</td>
<td>Alignment of bt and Hbl defining foliation</td>
</tr>
<tr>
<td>Friersdale Charnockite</td>
<td>Qtz, Pl, Mc, Or, Prt, Crd, Bt, Hbl, Ms, OpX, Pmt, Op, Ep, Grt, Zrn</td>
<td>Gradational with the Vaalputs Granite and Keboes Granite</td>
<td>Porphyritic texture, myrmekitic texture</td>
<td>Coarse grained</td>
<td>Alteration of Or, Pl and Mc to sericite</td>
<td>Unfoliated</td>
<td>Presence of opx and randomly orientated Pl and Or phenocrysts</td>
</tr>
<tr>
<td>Vaalputs Granite</td>
<td>Qtz, Pl, Or, Mc, Bt, Ms, Op, Hbl, Phl</td>
<td>Gradational contact with the Goede hoop Formation</td>
<td>Partly equigranular</td>
<td>Medium to fine grained</td>
<td>Or, Pl and Mc are sericitised</td>
<td>Strongly foliated</td>
<td>Highly sericitised Or groundmass and alignment of biotite</td>
</tr>
<tr>
<td>Kanoneiland Granite</td>
<td>Qtz, Pl, Or, Bt, Ms, Mc, Hbl, Prt, Phl, Rt, Zrn</td>
<td>Gradational with the Keboes Granite and sharp with the Vaalputs and Louisvale Granites</td>
<td>Porphyritic and glomeroporphyritic texture together with myrmekitic texture</td>
<td>Coarse grained</td>
<td>Pl and Or are altered to sericitised</td>
<td>Moderately foliated</td>
<td>Alignment of platy minerals like biotite</td>
</tr>
</tbody>
</table>

Abbreviations: Qtz = quartz, Pl= plagioclase, Or = orthoclase, Mc = Microcline, Prt = perthite, Crd = cordierite, Bt = biotite, Ms = muscovite, Hbl = hornblende, Phl = phlogopite, Grt = garnet, OpX = Orthopyroxene, Rt = rutile, chi = chlorite, Pmt = piemontite, Ep = epidote, Op= opaque minerals, Zrn = zircon (Minerals abbreviation according to Siivola and Schmid, 2007). Mineralogy: bold-phenocrysts, italic-groundmass, bold+italic- mineral form part of both phenocrysts and groundmass.
Table 4.2. Petrographic summary of the Keimoes Suite granites (cont.)

<table>
<thead>
<tr>
<th>GRANITE NAME</th>
<th>MINERALOGY (Order of decreasing abundance)</th>
<th>CONTACT AND COUNTRY ROCK</th>
<th>TEXTURE</th>
<th>GRAIN SIZES</th>
<th>ALTERATION</th>
<th>PRESENCE OF FOLIATION</th>
<th>SPECIAL FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keboes Granite</td>
<td>Qtz, Pl, Or, Mc, Bt, Ms, Hbl, Phl, Grt, Rt</td>
<td>Sharp with the Friersdale charnockite and gradational with the Kanoneilland Granite</td>
<td>porphyritic texture</td>
<td>Coarse grained</td>
<td>Or, Pl and Mc are replaced by sericite</td>
<td>Unfoliated to weakly foliated</td>
<td>Overgrowth of Or and Bt within Mc</td>
</tr>
<tr>
<td>Louisvale Granite</td>
<td>Qtz, Pl, Or, Bt, Prt, Ms, Hbl, Phl, Grt, Zrn</td>
<td>Gradational with the Klipkraal and Vaalputs Granite</td>
<td>porphyritic texture</td>
<td>Medium to coarse grained</td>
<td>Or and Pl are altered to sericite</td>
<td>Moderately foliated</td>
<td>Alignment of Bt and to some extent Pl phenocrysts</td>
</tr>
<tr>
<td>Klipkraal Granite</td>
<td>Qtz, Pl, Or, Mc, Bt, Ms, Phi, Hbl, Op, Grt</td>
<td>Gradational with the country rock</td>
<td>Porphyritic, cumulophyric texture</td>
<td>Medium to coarse grained</td>
<td>Pl and Or are mildly sericitised</td>
<td>Weakly foliated</td>
<td>Alignment of Pl subhedral phenocrysts</td>
</tr>
<tr>
<td>Straussburg Granite</td>
<td>Qtz, Pl, Or, Mc, Bt, Ms, Hbl, Grt, Op, Zrn</td>
<td>Gradational with the feldspathic quartzite</td>
<td>Porphyritic texture</td>
<td>Coarse grained</td>
<td>Slight sericitization of Mc and Pl</td>
<td>Unfoliated</td>
<td>Contains ferromagnesian+ bt mineral-rich zoned defining foliation</td>
</tr>
<tr>
<td>Josling Granite</td>
<td>Qtz, Pl, Mc, Or, Bt, Ms, Hbl, Prt, Phl, Op, Grt, Zrn, Pm</td>
<td>Gradational contact</td>
<td>Comulophyric texture</td>
<td>Medium to fine grained</td>
<td>Pl, Mc and Or are sericitised</td>
<td>Moderately foliated</td>
<td>Alignment of Pl and Mc subhedral phenocrysts alignment</td>
</tr>
</tbody>
</table>

Abbreviations: Qtz = quartz, Pl = plagioclase, Or = orthoclase, Mc = Microcline, Prt = perthite, Crd = cordierite, Bt = biotite, Ms = muscovite, Hbl = hornblende, Phl = phlogopite, Grt = garnet, Opx = Orthopyroxene, Rt = rutile, chl = chlorite, Pmt = piemontite, Ep = epidote, Op= opaque minerals, Zrn = zircon (Minerals abbreviation according to Siivola and Schmid, 2007). Mineralogy: bold-phenocrysts, italic-groundmass, bold+italic- mineral form part of both phenocrysts and groundmass.
Table 4.3. Petrographic summary of the Keimoes Suite granites (cont.)

<table>
<thead>
<tr>
<th>GRANITE NAME</th>
<th>MINERALOGY</th>
<th>CONTACT AND COUNTRY ROCK</th>
<th>TEXTURE</th>
<th>GRAIN SIZES</th>
<th>ALTERATION</th>
<th>PRESENCE OF FOLIATION</th>
<th>SPECIAL FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klip Koppies Granite</td>
<td>Qtz, Pl, Or, Bt, Mc, Hbl, Ms, Op, Grt, Zrn</td>
<td>Gradational with the Gemsbokbult Granite and feldspathic quartzite</td>
<td>Glomeroporphyritic</td>
<td>Medium grained</td>
<td>Sericitisation of Pl and Or</td>
<td>Strongly foliated</td>
<td>Alignment of bt and hbl defining the foliation</td>
</tr>
<tr>
<td>Gemsbokbult Granite</td>
<td>Qtz, Pl, Or, Mc, Prt, Bt, Ms, Phl, Op, Hbl, Grt</td>
<td>Gradational contact with the Klip Koppies Granite</td>
<td>Porphyritic texture, plagioclase shows compositional zoning</td>
<td>Coarse grained</td>
<td>No alteration observed</td>
<td>Unfoliated</td>
<td>Abundance of Phl and Op clusters</td>
</tr>
<tr>
<td>Kleinbegin Subsuite</td>
<td>Qtz, Pl, Or, Mc, Bt, Ms, Phl, Op, Hbl, Zrn, Grt</td>
<td>No contact found</td>
<td>Porphyritic texture, anhedral phenocrysts</td>
<td>Coarse grained</td>
<td>Pl, Or and Mc are sericitised</td>
<td>Moderately foliated</td>
<td>Alignment of phenocrysts of Or on the outcrop scale</td>
</tr>
<tr>
<td>Elsie se Gorra Granite</td>
<td>Qtz, Or, Pl, Mc, Bt, Ms, Hbl, Grt, Rt, Zrn</td>
<td>No contact, isolated plutons</td>
<td>Porphyritic texture, euhedral to subhedral phenocrysts</td>
<td>Coarse grained</td>
<td>Contains extensively sericitised Or, Pl and Mc</td>
<td>Strongly foliated</td>
<td>Contains ferromagnesian mineral-rich zones</td>
</tr>
</tbody>
</table>

Abbreviations: Qtz = quartz, Pl = plagioclase, Or = orthoclase, Mc = Microcline, Prt = perthite, Crd = cordierite, Bt = biotite, Ms = muscovite, Hbl = hornblende, Phl = phlogopite, Grt = garnet, Opx = Orthopyroxene, Rt = rutile, chl = chlorite, Pmt = piemontite, Ep = epidote, Op= opaque minerals, Zrn = zircon (Minerals abbreviation according to Siivola and Schmid, 2007). Mineralogy: bold-phenocrysts, italic-groundmass, bold+italic- mineral form part of both phenocrysts and groundmass.
4.4. Vaalputs Granite

The Vaalputs Granite outcrops are well exposed west of Kanoneiland on the southern side of the Orange River where the granite is bounded by the Kanoneiland Granite to its east and the Goedehoop Formation of the Korannaland Group on its western side (Fig. 4.1). The Vaalputs Granite is defined as a medium- to coarse-grained, strongly foliated biotite granite (Fig. 4.5a-d).

Figure 4.5. (a) The hand specimen and (b-d) photomicrographs of the Vaalputs Granite showing that the granite is strongly foliated (mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, hbl = hornblende, mcl = microcline, ms = muscovite, opq = opaque minerals and phg = phlogopite). Field of view of all the photomicrographs is 3 mm.
It is composed of phenocrysts of plagioclase, orthoclase, microcline in a groundmass of quartz, biotite, plagioclase, muscovite, phlogopite, minor garnet, opaque minerals and microcline together with hornblende (Fig. 4.5b-d, Table 4.1). The foliation is mostly defined by biotite and minor hornblende together with muscovite (Fig. 4.5b-d). The granite contains xenoliths of approximately 1.5 cm - 18 cm long which are comprised of different mineral assemblages mostly dominated by biotite and hornblende. Most of the xenoliths have the same orientation as the foliation of the granite (Figs. A4.1a-b).

4.5. Kanoneiland Granite

The outcrops of the Kanoneiland Granite are huge and well exposed at Kanoneiland, on the southern side of the Orange River where the granite is bounded by the Keboes Granite to the east and the Vaalputs Granite on its west (Fig. 4.1, Fig. A5.1a-d). The outcrops range from low lying to approximately 3 m in height (Fig. A5.1a). The granite can be defined as a coarse grained, and moderately to weakly foliated biotite granite (Fig. 4.6a-b). The foliation is defined by biotite, muscovite, hornblende and phlogopite enveloping the phenocrysts of quartz, plagioclase, orthoclase, microcline and perthite (Fig. 4.6b). The groundmass includes quartz, plagioclase, orthoclase, biotite and sericite (sericitised feldspars) (Table 4.1).

![Figure 4.6. (a) Hand specimen and (b) photomicrograph of the Kanoneiland Granite showing that is moderately foliated](image)

(mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, ms = muscovite, hbl = hornblende, srt = sericite). Field of view of the photomicrograph is 3 mm.

The Kanoneiland Granite is dominated by dark xenoliths, composed of biotite, muscovite and hornblende (Fig. A5.1a). Most of the xenoliths have the same orientation as the foliation of the granite. The granite also contains fine-grained granitic enclaves along with crosscutting granitic veins. There is a
visible reaction rim/selvedge (0.5 cm thick) composed of biotite, hornblende and muscovite associated with the enclaves and veins.

4.6. Keboes Granite

The Keboes Granite outcrops are well exposed between the villages of Kaboes and Kanoneiland on the southern side of the Orange River (Fig. A6.1a). The granite is coarse-grained and has a weakly developed augen gneiss texture which is mostly defined by augen of alkali feldspar and quartz enveloped by biotite and hornblende (Fig. 4.7a). The groundmass comprises biotite, muscovite, plagioclase, quartz, hornblende, phlogopite, rutile and sericite, replacing the feldspars (Fig. 4.7b, Table 4.1).

Most of the outcrops of the Keboes Granite are highly weathered with crosscutting quartz veins, which are prominent and more resistant to weathering, standing out on weathered surfaces. Clusters of garnet are also evident on weathered surfaces (Fig. A6.1c). Dark xenoliths, comprising biotite, hornblende and muscovite, are present in most of the outcrops.

Figure 4.7. The Keboes Granite. (a) The hand specimen showing moderate foliation. (b) Photomicrograph in cross polarised light showing that the granite is weakly foliated (mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, opq = opaque, hbl = hornblende, mcl = microcline, ms = muscovite, srt = sericite, phg = phlogopite). Field of view of the photomicrograph is 3 mm.
4.7. Louisvale Granite

The Louisvale Granite outcrops are well to fairly well exposed at Louisvale Village, on the southern side of the Orange River (Fig. 4.1; S 28° 34'49.4"; E 021° 11'57.6"; elevation 791m). The granite extends from the settlement of Louisvale, where it is in contact with the Klipkraal Granite, to Raaswater Village, where it is in contact with the Friersdale Charnockite (Fig. 4.1). The granite has a porphyritic texture and ranges from medium to coarse grained (Fig. 4.8a-b).

Phenocrysts of quartz, plagioclase, orthoclase, perthite and garnet occur within a groundmass of quartz, plagioclase, orthoclase, biotite, muscovite, phlogopite and zircon (Fig. 4.8a-b, Table 4.1). The granite contains garnet clusters which stand out prominently on weathered surfaces (Fig. A1.7d). Large clusters of muscovite occur within quartz veins (Fig. A7.1a, c, d). Not all of the outcrops of the Louisvale Granite exhibit foliation, so that some areas are coarse-grained and unfoliated.

Figure 4.8. The Louisvale Granite. (a) Hand specimen showing the moderately foliated medium grained granite. (b) Photomicrograph under cross polarised light showing that, microscopically, the granite is foliated and medium to coarse grained (Mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline). Field of view of the photomicrograph is 3 mm.

4.8. Klipkraal Granite

The outcrops of this unit are well exposed at Klipkraal on the northern side of the Orange River and also north of Louisvale, where the granite is in contact with the Louisvale Granite, on the southern side of the Orange River (Fig. 4.1). The Klipkraal Granite can be defined as an unfoliated and medium to coarse grained granite (Fig. 4.9a-b). The granite shows a porphyritic texture and locally has a cumulophyric texture due to clusters of plagioclase, orthoclase and quartz phenocrysts (Fig. 4.9a-b, Table 4.1). Locally
the granite mostly along the margins contains a weakly foliated magmatic texture defined by alignment of large phenocrysts (approximately 1 cm in size) of quartz, plagioclase and alkali feldspar (Fig. A8.1a). The Klipkraal Granite contains xenoliths which are mostly oriented in the same direction as the magmatic foliation.

The contact between the Klipkraal Granite and the amphibolite of the Jannelsepan Formation is characterised by isoclinal folds defined by Klipkraal Granite magmatic veins intruding the Jannelsepan Formation amphibolite (Fig. A8.1b). The contact is also marked by migmatitic veins. There is evidence in the field that the Klipkraal Granite towards the contact assimilated large portions of the amphibolitic Jannelsepan Formation as indicated by amphibolite xenoliths and migmatitic veins.

Figure 4.9. Samples of the Klipkraal Granite. (a) Medium grained, weakly foliated hand specimen. (b) Photomicrograph under cross polarised light showing a coarse grain size and cumulophyric texture with green hornblende and biotite clustering together (Mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, opq = opaque, pth = perthite, hbl = hornblende, bt = biotite, mcl = microcline, srt = sericite). The field of view of the photomicrograph is 3 mm.

4.9. Straussburg Granite

The outcrops of the Straussburg Granite are well exposed at Straussburg and form outcrops ranging from hill sized to low lying types (Fig. A9.1a). The Straussburg Granite is unfoliated to weakly foliated and porphyritic (Fig. 4.10a,b). The granite comprises subhedral to anhedral phenocrysts of quartz, plagioclase, orthoclase, microcline and garnet enveloped by a groundmass of quartz, plagioclase, microcline, orthoclase, biotite and hornblende (Fig. 4.10a, b, Table 4.1).

This granite is dominated by mafic xenoliths which are biotite and amphibole-rich. The sizes of the xenoliths range from 0.5 cm - 20 cm long. Most xenoliths are oriented NE-SW to ENE-WSW. The xenoliths become larger towards the contact with the feldspathic quartzite of the Dagbreek Formation. The contact between the Straussburg Granite and the Dagbreek Formation is gradational (Fig. A9.1d).
Figure 4.10. (a) The hand specimen and (b) photomicrograph of the Straussburg Granite showing the coarse grained nature and weakly foliated texture of this granite (Mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, mcl = microcline, bt = biotite, hbl = hornblende, ms = muscovite). Field of view of the photomicrograph is 3 mm.

4.10. Josling Granite

The Josling Granite outcrop occurs on the Louisvale farm, located approximately 7 km from Louisvale Village along the road from Louisvale to Kenhardt (Fig. A10.1). The outcrop is well exposed and is a hilly type of outcrop of approximately 65 m height (Fig. A10.1).

Figure 4.11. (a) The hand specimen and (b) photomicrograph of the Josling Granite showing that the granite is weakly foliated and medium grained (Mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, ms = muscovite, srt = sericite, phg = phlogopite). Field of view of the photomicrograph is 3 mm.
The granite can be classified as a medium to fine grained, weakly to moderately foliated leucogranite (Fig. 4.11a, b). The foliation is defined by biotite, hornblende and muscovite which occur within the groundmass and wrap around phenocrysts of quartz, plagioclase, microcline, perthite and orthoclase (Fig. 4.11a, b, Table 4.1). The rock has a cumulophyric texture in which crystals of microcline, plagioclase and orthoclase are clustered together (Fig. 4.11b).

4.11. Klip Koppies Granite

The Klip Koppies Granite is a leucocratic, strongly foliated, porphyritic, medium to coarse grained biotite granite (Fig. A11.1, Fig. 4.12a, b). This granite is extensively exposed on the south-western portion of the farm Klip Koppies 109 and is in contact with the Gemsbokbult Granite (Fig. 4.1). The contact between the Gemsbokbult and Klip Koppies Granites is clear, with the Klip Koppies Granite being strongly foliated and the Gemsbokbult Granite being weakly foliated to unfoliated. The Klip Koppies outcrops range from low lying to bouldery hill types of outcrop with a height of approximately 4 m.

The granite is composed of quartz, plagioclase, orthoclase, biotite, microcline, hornblende, muscovite, opaque minerals, garnet and zircon (Fig. 4.12a, b, Table 4.1). The Klip Koppies Granite shows both magmatic and tectonic foliation. The magmatic foliation is defined by the alignment of quartz, plagioclase and alkali feldspar phenocrysts along the margin of the outcrops (Fig. A11.1). The tectonic foliation is defined by the alignment of biotite and, to a lesser extent, hornblende (Fig. A11.1, 4.12a-b). Quartz phenocrysts form glomeroporphyritic clusters, forming aggregates of approximately 1 – 1 mm in which individual crystals range from 0.08 - 1mm (Fig. 4.12b).

Figure 4.12. The Klip Koppies Granite. (a) Hand specimen showing the strongly foliated medium grained granite. (b) A photomicrograph under cross polarised light showing that, microscopically, the granite is foliated and medium to coarse grained (Mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, hbl = hornblende). Field of view of the photomicrograph is 3 mm.
4.12. Gemsbokbult Granite

This granite is in contact with the Klip Koppies Granite but is better exposed and covers a larger area compared to the latter (Fig. 4.1). The contact between the Gemsbokbult and Klip Koppies Granites is marked mostly by colour changes, with the Klip Koppies Granite being lighter compared to the darker Gemsbokbult Granite. The most common feature between these granites is that both show the same NW-SE outcrop orientation (Fig. 4.1). The Gemsbokbult Granite has a coarse grained, weakly foliated, porphyritic texture composed of phenocrysts of microcline, quartz, orthoclase, perthite, plagioclase and garnet within a groundmass of quartz, plagioclase, orthoclase, microcline, biotite, opaque minerals and hornblende (Fig. 4.13a, b, Table 4.1). It contains fine grained mafic xenoliths comprised of biotite and hornblende.

Figure 4.13. (a) The hand specimen and (b) photomicrograph of the porphyritic Gemsbokbult Granite (qtz = quartz, plg = plagioclase, ort = orthoclase, mcl = microcline, bt = biotite, ms = muscovite, pgt=phlogopite, opq = opaque minerals, hbl = hornblende, srt = sericite). Field of view of the photomicrograph is 3 mm.
4.13. **Kleinbegin Subsuite**

The outcrops of this unit are located at Kleinbegin Village and are small with a relative exposed area of approximately \(30 \text{ m}^2\). The granite is leucocratic, medium to coarse grained and exhibits porphyritic texture with phenocrysts of quartz, plagioclase, orthoclase, microcline and garnet (Fig. 4.14a-b, Table 4.1). The groundmass is composed of quartz, plagioclase, orthoclase, microcline, biotite, muscovite, phlogopite, opaque minerals, hornblende, zircon, and garnet (Fig. 4.14a, b, Table 4.1). The granite is moderately to strongly foliated, with the foliation defined by the alignment of mostly biotite, and hornblende and muscovite to a lesser extent (Fig. 4.14b). Xenoliths are aligned parallel to the foliation in the granite and are composed of biotite, hornblende, alkali feldspar and quartz (Fig. A13b).

![Figure 4.14. (a) Hand specimen and (b) photomicrograph of the Kleinbegin Subsuite illustrating that the granite is moderately foliated (Mineral abbreviations: qtz = quartz, ort = orthoclase, bt = biotite, opq = opaque, hbl = hornblende, srt = sericite). Field of view of the photomicrograph is 3 mm.](image-url)
4.14. Elsie Se Gorra Granite

The Elsie Se Gorra Granite is a leucocratic, coarse grained and moderately to strongly foliated granite (Fig. 4.15a-b, Table 4.1). The Elsie Se Gorra Granite is composed of quartz, orthoclase, plagioclase, microcline, biotite, muscovite, hornblende, opaque minerals, garnet, rutile and zircon (Fig. 4.15a-b, Table 4.1). The foliation is defined by ferromagnesian mineral-rich zones composed of biotite, hornblende and sericitised feldspars which envelope the phenocrysts of quartz, alkali feldspar and plagioclase (Fig. 4.15b). The outcrops of this granite are poorly exposed.

Figure 4.15. (a) Hand specimen and (b) photomicrograph of the foliated porphyritic Elsie Se Gorra Granite (mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, srt = sericite).
5. Geochemistry

This chapter outlines the whole rock major and trace element and isotope geochemistry of these granite suites. The epsilon Nd(t) and epsilon Sr(t) values were calculated for the individual magmatic emplacement ages of each individual granite plutons. Some of the major characteristics which will be examined in this chapter include the nature of the granites, the degree of fractionation, tectonic setting and the magma source. Various diagrams were plotted in order to classify and characterise the granites of the eastern Namaqua sector. This chapter also presents the geochronology of the granites of the eastern Namaqua sector. These granites mostly occur in the Areachap Terrane, with a few extending into the Kakamas and Kaaien Terranes. The Vaalputs Granite was dated by Petterson (2008) and a summary is presented in this work. The Kleinbegin Subsuite/Granites, Gemsbokbult Granite and Klip Koppies Granite were dated by Bailie et al. (2011a), while Cornell et al. (2012) dated the Straussburg Granite and the Friersdale Charnockite. Eight granitoids were dated in this study and their geochronological results will be discussed in detail, whereas for others which were previously dated by other workers, the summary will be provided.

5.1. Cnydas Subsuite

5.1.1. Whole rock geochemistry

The granites of the Cnydas Subsuite are classified as ferroan, alkalic metaluminous, A2-type, varying from granodiorite to monzogranite in composition (Fig. 5.9a-h). The granites of the subsuite have relatively gently negative sloping REE patterns, with the LREE enriched relative to the HREE (Fig. 5.1, Table 5.1). The LREE show a gently negative sloping pattern [(La/Sm)N=2.82-3.64], with a shallowly sloping to shallowly negative sloping HREE pattern and prominent negative Eu anomalies [(Eu/Eu*)N=0.33-0.57] (Table 5.1). The subsuite has relatively high ΣREE values varying from 262.15-451.92 (avg. 382.06) (Fig. 5.1a). The Cnydas Subsuite granites have a gently negative sloping multi-element trace elements pattern. The granites are moderately enriched in Th, U, and Pb, and relatively depleted in Cs, Ba, Nb, Ta, Sr, P, Eu and Ti (Fig. 5.1b, Table 5.1).
5.1.2. Geochronology

Only one sample of the Cnydas Subsuite (Mc 8), from the Smalvis member (S 28° 25′42.9″; E 020° 49′24.4″; elevation 870 m), was dated in this study. Zircon grains form 100 µm - 250 µm euhedral to subhedral grains, in which dark cores are overgrown by angular magmatic overgrowths. Most of the zircons are fractured (Figs. 5.2a, b). Most of the zircons show oscillatory zoning and have sharp to rounded terminations (Figs. 5.2a, b).

Figure 5.1. The multi-element diagrams for the Cnydas Subsuite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

Figure 5.2. Cathodoluminescent (CL) images of magmatic zircons showing analysed spots for the Cnydas Subsuite (Mc 8) with the numbers outside the brackets being analysed spots ($^{207}$Pb/$^{206}$Pb ages in brackets).
Two populations were identified from the analysed spots. The first population is of spots which yield 101% to 102% reversely discordant ages (Table C1). These spots are from weakly zoned dark cores and yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages which range from 1123 ± 54 Ma to 1169 ± 64 Ma. They are characterized by relatively high Th/U ratios ranging from 1.25 to 2.57. The second population is characterized by concordant spots which yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages which range from 1141 ± 51 Ma to 1175 ± 52 Ma with ages mostly older than those obtained from the first population (Table C1). The U-Pb concordia age of 1157 ± 6 Ma is taken as the crystallisation age of the Cnydas Subsuite (Fig. 5.3).

There are no inherited ages (Table C1) as ages from cores are in the range of the crystallisation age of the granite (Figs. 5.2a, b). The spot which yielded the youngest $^{207}\text{Pb}/^{206}\text{Pb}$ concordia age of 1123 ± 54 Ma was obtained from a poorly zoned, dark magmatic core (Fig. 5.2b). The core is characterised by a high Th/U ratio of 2.25, suggesting that is a magmatic age rather than being metamorphic. There is no upper intercept ages obtained from this granite.

![U-Pb concordia age plot for the Cnydas Subsuite.](image)

**5.1.3. Isotope geochemistry**

The isotope geochemistry obtained from the Cnydas Subsuite were calculated using the 1157 ± 6 Ma, which includes a fairly moderate Sm/Nd ratio of approximately 0.14 - 0.18 (avg. 0.16), relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ (0.51205) and positive epsilon Nd(t) varying from 1.15 to 5.04, which is higher than for most of the granites. The granite shows large Sm/Nd ratio variation (Table 5.1). The Rb-Sr isotope systematics
were also analysed for the subsuite, in which moderate Rb/Sr ratios varying from 0.88 to 1.27 (avg. 1.08), moderate $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7765 - 0.7943), and relatively high epsilon Sr($\text{t}$) values, varying from 244.30 to 745.73 (avg. 495.01) (Table 5.1). Model ages varying from 1.65 to 2.47 Ga for $T_{\text{CHUR}}$, and 2.04 to 2.81 Ga for $T_{\text{DM}}$ were obtained for the subsuite (Table 5.1).

5.2. Colston Granite

5.2.1. Whole rock geochemistry

The Colston Granite varies in composition from monzo-granite to granodiorite (Fig. 5.9a-b). It has a predominantly ferroan, alkalic peraluminous to metaluminous (Aluminium Saturation Index (ASI) = 0.986-1.117) $A_2$-type composition (Fig. 5.9c-h, Table C1, C2). The REE pattern is relatively shallowly to moderately negatively sloping $[(\text{La}/\text{Lu})_{\text{N}}=5.29-14.05$, with a strongly negative Eu anomaly $[(\text{Eu}/\text{Eu}^*)_{\text{N}}=0.35-0.65]$, (Fig. 5.4a; Table 5.1). Most of the samples of this granite are enriched in Pb, Th, U, and the LREE, relative to the HFSE and HREE, having a strongly developed Nb-Ta “trough “or anomaly, along with depletions in Ba, Sr, P, Eu and Ti on the multi-element trace element (spider) diagram (Fig. 5.4b).

Figure 5.4. The multi-element diagrams for the Colston Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.2.2. Geochronology

A sample of the Colston Granite was taken at Rooidam (S 28° 25′42.9″; E 02° 49′24.6″; elevation 871 m) (Figs. 4.1, D2). The zircons are mostly elongate (100-250 µm), with euhedral to subhedral shapes and predominantly have prismatic shapes with very few rounded grains. Most of the larger (>150 µm) euhedral grains have bright cores and show oscillatory zoning, with the smaller zircons (<100 µm) having mostly dark cores (Figs. 5.5a, b).
Figure 5.5. Cathodoluminescent (CL) images of the zircons showing analysed spots for the Colston Granite (Mcol 1) with the numbers outside the brackets being analysed spots ($^{207}$Pb/$^{206}$Pb ages in brackets).

Figure 5.6. U-Pb upper intercept a) and concordia b) plots for the Colston Granite. Twenty five spots were analysed in which six spots yield $^{207}$Pb/$^{206}$Pb reversely concordant ages ranging between 1140 ± 66 Ma and 1154 ± 82 Ma (Table C1). There are no metamorphic or inherited ages obtained from this granite. A U-Pb upper intercept age of 1161 ± 16 Ma was obtained from the data of the Colston Granite (Fig. 5.6a). The U-Pb concordia age of 1158 ± 6 Ma is taken as the crystallisation age of the Colston Granite (Fig. 5.6b). The emplacement age of this granite can be related to the 1156 ± 8 Ma intrusion age of the Riemvasmaak gneiss, a unit in the Areachap Terrane (Pettersson, 2008; Cornell et al., 2012).
5.2.3. Isotope geochemistry

The granite has relatively high Sm/Nd ratios varying from 0.20 to 0.22 (avg. 0.21), along with relatively high \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios of 0.51200 to 0.51215. It has a relatively high \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio varying from 0.7817 to 0.9566 along with high \(^{87}\text{Rb}/^{86}\text{Sr}\) ratios varying from 2.90 to 13.96 and high Rb/Sr ratios of 1.09 to 5.26 (avg. 3.18) (Table 5.1). \(\varepsilon_{\text{Nd}(t)}\) values vary from -1.40 to 0.16 with relatively high \(\varepsilon_{\text{Sr}(t)}\) ratios of 310.40-431.89 (Table 5.1). Old model ages, varying from 3.11 to 3.39 Ga for \(T_{\text{CHUR}}\) and \(T_{\text{DM}}\) model ages of 3.37 to 3.62 Ga were obtained for the Colston Granite (Table 5.1).

5.3. Friersdale Charnockite

5.3.1. Whole rock geochemistry

The Friersdale Charnockite is classified as a metaluminous, ferroan, alkali-calcic, orthopyroxene-bearing monzogranite to granodiorite with an \(A_2\)-type composition (Fig. 5.9a-h). The composition of this granite does not vary much compared to that of the other granites which show larger compositional variations.

The REE pattern is shallowly negatively sloping \([\text{La/Lu}]_n = 8.98-9.64\), with a moderate negative Eu anomaly \([\text{Eu/Eu*}]_n = 0.64-0.76\) (Table 5.1, Fig. 5.7a). The spider diagram pattern of the charnockite shows slight enrichment in Pb, Th and U, the LREE and Zr relative to the HFSE and HREE, with a prominent Nb-Ta ‘trough’ or anomaly, along with a slight depletion in Ba, and prominent depletions in Sr, Eu, P and Ti, and partly Y and Dy (Fig. 5.7b).

Figure 5.7. The multi-elements diagrams for the Friersdale Charnockite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).
5.3.2. Isotope geochemistry

The isotopic characteristics were calculated or determined from the 1078 Ma emplacement age of the Friersdale Charnockite. The charnockite has moderate Sm/Nd ratios which vary from 0.18 to 0.19, relatively high $^{143}$Nd/$^{144}$Nd values ranging from 0.51198 to 0.51203 and $\varepsilon_{\text{Nd(t)}}$ varying from -1.11 to 0.41. The charnockite has low Rb/Sr ratios ranging from 0.59 to 0.63, a high initial $^{87}$Sr/$^{86}$Sr of 0.7341 - 0.7367 and $\varepsilon_{\text{Sr(t)}}$ which varies from 92.08 - 106.81 (Table 5.1). Paleoproterozoic to Archean model ages were obtained for this granite, with $T_{\text{CHUR}}$ varying from 2.35 to 2.69 Ga, and $T_{\text{DM}}$ varying from 2.70 to 3.00 Ga (Table 5.1).

5.4. Vaalputs Granite

5.4.1. Whole rock geochemistry

The Vaalputs Granite is classified as a monzogranite (Fig. 5.9a-b) with a dominantly high K calc-alkaline affinity. It is classified as a ferroan, alkali-calcic to alkalic, A$_2$-type granite (Fig. 5.9e-g, Table C2). It is dominantly metaluminous to marginally peraluminous with ASI values varying from 0.919-0.984 (Fig. 5.9h).

Figure 5.8. The multi-element diagrams for the Vaalputs Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995) [concentration above the diagrams Cs= 1237.62, 1272.86; Th= 1105.12; U= 1154.25].
The granite has a shallowly dipping negatively sloping pattern \([(\text{La/Lu})_n=5.42-8.70]\), and strongly negative Eu anomalies \([(\text{Eu/Eu^*})_n=0.19-0.55]\) (Fig. 5.8a). The granite is relatively fractionated, characterised by a high \(\Sigma\text{REE}\) (Fig. 5.8a, see Table 5.1). The Vaalputs Granite is strongly enriched in Rb, Th and U and moderately so in Pb, with a slight Nb-Ta ‘trough’ or anomaly, along with depletions in Sr, Zr, Ba and Eu, as well as prominent negative P and Ti anomalies (Fig. 5.8b). The LREE are enriched relative to the HREE, which have a relatively flat pattern. Samples of this granite show variable concentrations, clearly seen in the spider diagram patterns, which vary strongly within the LILE side as compared to the HFSE side (Fig. 5.8b).

5.4.2. Isotope geochemistry

Various authors determined the Sm-Nd isotope systematics for this granite, including Pettersson et al. (2009) and Cornell et al. (2012). The Vaalputs Granite has an emplacement age of 1146 Ma (Cornell et al., 2012) in which all the isotopes data were determined relative to this age. The Sm/Nd ratios for this granite are relatively high, varying from 0.19 to 0.20, with high \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios that range from 0.51202 to 0.51215 (Table 5.1). The granite has \(\epsilon_{\text{Nd}(t)}\) values varying from -0.56 to 1.79 which were calculated using the 1146 Ma emplacement age of the Vaalputs Granite. One sample from this study was analysed for Rb-Sr isotopes and has a Rb/Sr ratio of 1.04 and a \(\epsilon_{\text{Sr}(t)}\) value of 233.05. The granite is characterized by old model ages of approximately 2.80 Ga to 3.06 Ga for \(T_{DM}\) and 2.43 Ga to 2.73 Ga for \(T_{CHUR}\) (Table 5.1).
Figure 5.9. Igneous classification diagrams for the eastern Namaqua granitoids. (a) QAP classification for granitoids, after IUGS (1970). (b) The An-Ab-Or ternary plot to determine the composition of granite (after O’Connor, 1965), with the granites having granitic to quartz monzonitic compositions tending toward granodioritic and trondhjemitic compositions. (c) The Na$_2$O + K$_2$O - CaO vs. SiO$_2$ plot (after Frost et al., 2001) indicating the A-type granite nature of the granites. (d) Fe*/Fe*+ MgO vs. SiO$_2$ plot used to determine if the rocks are ferroan or magnesian (after Frost et al., 2001).
Figure 5.9 (cont.). Igneous classification diagrams for the eastern Namaqua granitoids. (e) FeO$^{\text{tot}}$/FeO$^{\text{tot}}$ + MgO vs. SiO$_2$ plot which is used to determine if the rocks are ferroan or magnesian (after Frost et al., 2001). (f) The K$_2$O+Na$_2$O/CaO vs. Zr+Nb+Ce+Y (ppm) plot indicating the predominant A-type nature of the granites (after Whalen et al., 1987). (g) The Nb-Y-Zr/4 ternary triangular plot for distinguishing between A$_1$ and A$_2$ granitoids (after Eby, 1992). The blue line corresponds to a Y/Nb ratio of 1.2. (h) The molar Na$_2$O+K$_2$O/Al$_2$O$_3$ vs. molar Al$_2$O$_3$/Na$_2$O+K$_2$O+CaO plot to differentiate between peralkaline, metaluminous and peraluminous granites (after Maniar and Piccoli, 1989). The symbols used are the same as the previous figures.
5.5. Kanoneiland Granite

5.5.1. Whole rock geochemistry

The Kanoneiland Granite is classified as a ferroan, $A_{1}$-type granite, with compositions varying from granodiorite to monzogranite, to a lesser degree (Fig. 5.9a-h). The major element composition indicates a metaluminous character with ASI values varying from 0.947-0.966 (Fig. 5.9h, Table C2).

The granite has a relatively gentle, negative sloping REE pattern $[(\text{La}/\text{Lu})_{N}=5.65-16.76]$, with strongly negative Eu anomalies $[(\text{Eu}/\text{Eu}^{*})_{N}=0.39-0.58]$ (Fig. 5.10a, Table 5.1). Relative to the primitive mantle (PM) values of McDonough and Sun (1995), the granite shows Pb enrichment and one sample (Mka 6) also shows slight enrichment in Th, Nd and Sm (Fig. 5.10b, Table 5.1). The granite exhibits a relatively prominent Nb-Ta ‘trough’ or anomaly, along with depletions in Ba, Sr and Eu as well as prominent negative P and Ti anomalies (Fig. 5.10b). The LREE are enriched relative to the HREE (Fig. 5.10a). The samples of this member show slight HFSE variations compared to the LILE which show relatively consistent and similar patterns, the variation in the former suggesting slight source variation (Fig. 5.10b).

Figure 5.10. The multi-element diagrams for the Kanoneiland Granite. a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.5.2. Geochronology

The Kanoneiland Granite sample was collected on the southern side of the Orange River where the outcrops are well exposed. The outcrops of this granite are bound to the east by the Keboes Granite and by the Vaalputs Granite to the west (Fig. 4.1, E2).
The Kanoneiland Granite was previously classified as a syn-tectonic granite of the Keimoes Suite based on its well-developed foliation and was thought to be older than the Keboes Granite. The U-Pb age which was determined in this study indicates that the Kanoneiland Granite is younger than the Keboes Granite even though it has a strongly foliated texture compared to the Keboes Granite. The zircons of the Kanoneiland Granite are dark and mostly unzoned and form subhedral to anhedral 100 µm - 200 µm grains and are mostly fractured. Some of well to moderately zoned dark cores were also recognized (Figs. 5.11a). These irregular cores have U-Pb ages similar to the crystallisation age of the granite which is 1105 ± 6 Ma (Figs. 5.11, 5.12b).

Twenty two spots were analysed in which only one population can be identified from the data. Eleven spots gave reversely discordant ages which range from 1089 ± 49 Ma to 1116 ± 59 Ma (Table D1). The other eleven spots yield largely concordant ages (98% to 100%).

Figure 5.11. Cathodoluminescent (CL) images of the magmatic zircons showing analysed spots for the Kanoneiland Granite (Mka) with the numbers outside the brackets being analysed spots ($^{207}$Pb/$^{206}$Pb ages in brackets).

Figure 5.12. U-Pb upper intercept age and concordia plots for the Kanoneiland Granite.
There are no inherited ages obtained, rather the oldest $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1116 ± 59 Ma which was obtained is a magmatic age since it falls within the crystallisation age range of the granite. A U-Pb upper intercept age of 1088 ± 53 Ma was obtained (Fig. 5.12a). A U-Pb concordia age of 1105 ± 6 Ma is taken to be the crystallisation age of the Kanoneiland Granite (Fig. 5.12b). The youngest $^{207}\text{Pb}/^{206}\text{Pb}$ age recorded from this granite is 1063 ± 57 Ma, obtained from a well zoned core, suggesting a magmatic age rather than a metamorphic age (Table D1).

5.5.3. Isotope geochemistry

The granite has Sm/Nd ratios which vary from 0.19 to 0.20, relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios varying from 0.51197 to 0.51208, together with relatively low $\varepsilon_{\text{Nd}}(t)$ values varying from -2.16 to 0.65 which were calculated from 1105 ± 6 Ma crystallisation age of the Kanoneiland Granite (Table 5.1). Moderate Rb/Sr ratios varying from 0.24 to 1.63, with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying from 0.7175-0.7911, together with $\varepsilon_{\text{Sr}}(t)$ values varying from 56.32 to 273.12, were obtained from the Kanoneiland Granite. Relatively old model ages, varying from 1.94 to 2.60 Ga for $T_{\text{CHUR}}$, and 2.41 to 2.93 Ga for $T_{\text{DM}}$, were also obtained from the granite (Table 5.1).

5.6. Keboes Granite

5.6.1. Whole rock geochemistry

This granite is classified as a ferroan, alkalic, dominantly metaluminous to partly peraluminous, predominantly A-type to fractionated I-type monzogranite (Fig. 5.9a-h). The composition of this granite also varies from an A$_1$ to A$_2$ type (Fig. 5.9g) (Table C2).

The REEs were normalised to the chondritic values of Sun and McDonough (1989) and generally show a gently, negative sloping pattern {[(La/Lu)$_N$=9.43-10.91], except for sample Mkb 4 which has a [(La/Lu)$_N$=18.44. The REE pattern is characterised by relatively strong negative Eu anomalies [(Eu/Eu$^*$)$_N=0.41$-0.71] (Table 5.1, Fig. 5.13a). The granite is enriched in the LILE (Pb), along with slight Th and U, relative to the HFSE and has a prominent Nb-Ta ‘trough’ or anomaly, along with depletions in Ba, Sr and Eu, as well as prominent negative P and Ti anomalies (Fig. 5.13b). The granite has significant LILE enrichment compared to the HFSE (Fig. 5.13b). There is quite variable in trace elements concentration between the samples of this granite.
5.6.2. Geochronology

The sample of the Keboes Granite was collected from the west of the Kaboes farmhouse on the southern side of the Orange River (S 28° 38'30.8’’; E 021° 07'04.3’’; elevation 769m) (Fig. 5.1). To the west the granite is in contact with the Kanoneiland Granite and is in contact with the Friersdale Charnockite to the east. The Keboes Granite was previously classified as a post-tectonic granite due to its weakly foliated texture (Geringer et al., 1988; Moen, 2007; Baillie et al., 2011a) and was also classified as younger than the Kanoneiland Granite which is relatively more foliated than the Keboes Granite.

The zircons of this granite form 80 µm – 250 µm euhedral to subhedral crystals, mostly have dark magmatic rims and bright cores and show oscillatory zonation (Fig. 5.14a-b). Some grains have sharp
terminated edges and a few euhedral grains are fractured. An inherited $^{207}\text{Pb}/^{206}\text{Pb}$ concordia age of $1345 \pm 46$ Ma was obtained from a dark, strongly oscillatory zoned core. The inheritance is of a similar same age to the $1371 \pm 9$ Ma Swanartz Gneiss of the Kaaien Terrane (Pettersson et al., 2007).

Figure 5.15. U-Pb upper intercept and concordia plots for the Keboes Granite.

A U-Pb upper intercept age of $1111 \pm 10$ Ma was obtained, as shown by the Wetherill Discordia plot (Fig. 5.15a). The concordant spots yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages which range between $1097 \pm 50$ Ma and $1137 \pm 53$ Ma. The U-Pb concordia age of $1110 \pm 6$ Ma is taken as the crystallisation age of the Keboes Granite (Fig. 5.15a, Table 5.2). The upper intercept and concordia ages largely correspond (Figs. 5.15a, b). There are no metamorphic ages obtained from the zircons of the Keboes Granite.

### 5.6.3. Isotope Geochemistry

The granite has a relatively high Sm/Nd ratio of 0.21, a moderate $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.51198, with a low $\varepsilon_{\text{Nd}(t)}$ value of -2.60 calculated using the $1110 \pm 6$ Ma emplacement age of the Keboes Granite. It has a relatively low Rb/Sr ratio of 0.63 together with a high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7978 and high $\varepsilon_{\text{Sr}(t)}$ of 964.32 compared to the other granites investigated in this study (Table 5.1). Relatively old model ages of approximately 3.25 Ga for $T_{\text{CHUR}}$ and 3.50 Ga for $T_{\text{DM}}$ were also obtained from this granite (Table 5.1).
5.7. Louisvale Granite

5.7.1. Whole rock geochemistry

The Louisvale Granite is variably classified as tonalite, trondhjemite, and monzo-granite (Fig. 5.9a-b). The granite has a ferroan, predominantly A2-type composition (Fig. 5.9d-g). Despite having a low average K content of 2.78 wt.%, it has an alkalic composition (Fig. 5.9c). The samples are metaluminous in composition, with ASI values varying from 0.967-1.026 (Table C2, Fig. 5.9h).

The REE-chondrite normalization after Sun and McDonald (1989) shows a relatively shallowly negative sloping REE pattern \((\text{La/Lu})_n=8.84-10.60\) with a moderate negative overall Eu anomaly \((\text{Eu/Eu}^*)_n=0.42-0.64\) (Fig. 5.16a). Trace element compositions are variable with a general enrichment in Pb and Th, with a relatively significant negative Nb anomaly (less so for Ta), and with strong depletions in Ba, Sr, and Eu, as well as negative P and Ti anomalies (Fig. 5.16b).

Figure 5.16. The multi-element diagrams for the Louisvale Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.7.2. Geochronology

The Louisvale Granite sample which was analysed (MI 3) was collected from the southern side of the Orange River and is bounded to the east by the Klipkraal Granite and to the west by the Friersdale Charnockite (Fig. 4.1). The Louisvale Granite was previously classified as a syn-tectonic granite of the Keimoes Suite due to its well-developed foliation (Moen, 2007; Bailie et al., 2011a). The Louisvale Granite was thought to be of similar age to, and slightly younger than the Vaalputs Granite.

Zircons of this granite range from euhedral to subhedral in shape and have no metamorphic overgrowths or rims. The size ranges from 100 µm to 200 µm. The zircons range from those that have bright cores to those which have dark, moderately to poorly zoned cores. Most of the grains core are
well zoned and contains slight overgrowth (Fig. 5.17). The well zoned rims have high Th/U ratios greater than 1 (Table D1) and so are magmatic.

Fourteen spots were analysed from this granite, in which four yielded less than 96 % concordancy. Only two spots within the data yield reversely discordant ages and the rest show concordant ages. There were no inherited ages for this granite. Only one population was identified from the age data taking into account the errors associated with the ages.

![Figure 5.17. Cathodoluminescent (CL) images of the magmatic zircons showing analysed spots for the Louisvale Granite with the numbers outside the brackets being analysed spots.](image)

A U-Pb upper intercept age of 1134 ± 16 Ma was obtained from extrapolating through the discordant results (Fig. 5.18a). The spots which yield concordant ages are characterized by high Th/U ratios which
range from 0.80 to 1.29 confirming the magmatic nature of these zircons. The $^{207}$Pb/$^{206}$Pb ages obtained from these spots ranges from 1112 ± 49 Ma to 1143 ± 48 Ma (Fig. 5.17a, spot 4, Fig. 5.17b, spot 24). A U-Pb concordia age of 1128 ± 7 Ma is taken to be the crystallisation age of the Louisvale Granite (Fig. 5.18b, Table 5.2). There were no metamorphic ages obtained from this granite.

5.7.3. Isotope geochemistry

The Sm/Nd ratio varies from 0.15 to 0.21, with moderate to relatively high $^{143}$Nd/$^{144}$Nd ratios of 0.51196 to 0.51228 together with high $\varepsilon_{\text{Nd}}(t)$ values of 1.92-3.21 calculated from 1123 ± 7 Ma emplacement age for the Louisvale Granite (Table 5.1, Table 5.2). The granite has an initial $^{87}$Sr/$^{86}$Sr ratio of 0.7139-0.9766, highly variable Rb/Sr ratios varying from 0.18 to 5.02, and epsilon Sr($t$) varying from 41.93 to 821.80 calculated from 1128 ± 7 Ma emplacement age of the granite. The $T_{\text{CHUR}}$ model ages varying from 1.98 to 2.83 Ga and $T_{\text{DM}}$ model ages vary from 2.34 to 3.16 Ga (Table 5.1).

5.8. Klipkraal Granite

5.8.1. Whole rock geochemistry

The Klipkraal Granite is classified as a ferroan, metaluminous A$_2$-type granite, which varies from granodiorite to monzogranite in composition, with some samples showing a quartz-monzonitic composition (Fig. 5.9a-h) (Table C2). The granodioritic composition mainly suggests those granites which are rich in plagioclase compared to monzogranitic compositions which have less plagioclase.

Figure 5.19. The multi-elements diagrams for the Klipkraal Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).
The REE show a gently negative sloping pattern \([(La/Lu)_N = 7.52-14.46]\) with a moderate negative Eu anomaly \([(Eu/Eu^* )_N = 0.43-0.52]\) (Table 5.1, Fig. 5.19a). Relative to the primitive mantle (PM) values of McDonough and Sun (1995), the granite shows enrichment in Pb and Th, with a prominent Nb-Ta ‘trough’ or anomaly, along with depletions in Cs, Ba, Sr and Eu, as well as prominent negative P and Ti anomalies (Fig. 5.19b).

### 5.8.2. Geochronology

The Klipkraal Granite sample was collected from the southern side of the Orange River, where the granite is bounded to the south by the Louisvale Granite and to the north by the Jannelsepan amphibolite and amphibole gneiss of the Areachap Group. The granite was previously classified as post-tectonic because of its lack of foliation and was considered to be younger than the Louisvale Granite (Moen, 2007; Bailie et al., 2011a).

The sample provided very few elongated zoned grains with flat terminations and rounded subhedral edges (of 80 µm to 150 µm size), as well as elongate zoned zircon grains and grain fragments (20 µm to greater than 100 µm) (Figs. 5.20a, b). There are no inherited cores observed in the zircons. The 8 analyzed spots yield moderately to strongly discordant data on the Wetherill plot (Table D1, Fig. 5.21). However, the best fit line through all the data provides an upper intercept age of 1270 ± 26 Ma (Fig. 5.21). The interpretation of this age is difficult since the Klipkraal Granite is only weakly deformed and is unlikely to have a pre-tectonic (older than 1.2 Ga) crystallisation age and was formerly regarded as being post-tectonic (e.g. Moen, 2007). Instead, the 1270 Ma age obtained from the Klipkraal Granite is an
inherited age of similar age to the Jannelsepan Formation into which the Klipkraal Granite intrudes and which has been dated with a 1275 ± 7 Ma extrusion age (Cornell and Pettersson, 2007).

![U-Pb discordia plot for the Klipkraal Granite.](image)

**5.8.3. Isotope geochemistry**

The samples of the Klipkraal Granite have moderate to high Sm/Nd values, varying from 0.19-0.20 together with relatively high $^{143}$Nd/$^{144}$Nd ratios varying from 0.51192 to 0.51197 calculated from 1270 ± 26 Ma inherited age of the Klipkraal Granite (Table 5.1, Table 5.2). The granite has $\varepsilon_{Nd(t)}$ values, varying from -1.46 to 0.45, together with moderate to high Rb/Sr ratios, which range from 1.09 - 1.33, as well as a $^{87}$Sr/$^{86}$Sr ratio varying from 0.7648 - 0.7724 (Table 5.1). The granite has relatively moderate $\varepsilon_{Sr(t)}$ values varying from 67.50 – 129.93. Old model ages of 2.73 to 3.12 Ga (T$_{CHUR}$) and 3.04 - 3.37 Ga for T$_{DM}$ were obtained for the granite (Table 5.1).
5.9. Straussburg Granite

5.9.1. Whole rock geochemistry

The Straussburg Granite is classified as a ferroan, alkalic, metaluminous A2-type monzogranite (Fig. 5.1a-h, Table C2). The REEs show a relatively shallow negative sloping pattern \([\text{[La/Lu]}_N=3.58-5.50]\) with prominent negative Eu anomalies \([\text{[Eu/Eu*]}_N=0.43-0.56]\) (Table 5.1, Fig. 5.22a). The granite is enriched in Pb, Th, U and the LREE (in some samples) relative to the HFSE and HREE, with a prominent negative Nb-Ta anomaly (exhibiting a “trough”), along with depletions in Cs, Ba, Sr and Eu, along with prominent negative P and Ti anomalies (Fig. 5.22b).

![REE diagram](image)

Figure 5.22. The multi-element diagrams for the Straussburg Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.9.2. Geochronology

A Rb-Sr age of 1264 ± 604 Ma and two zircon Pb-Pb dates of 1080 and 1094 Ma were reported by Barton and Burger (1983). The old Rb-Sr age is likely due to xenocrysts inherited from old crust and is likely unreliable due to the fact that Rb and Sr are highly mobile trace elements and unreliable geochronometers in high grade metamorphic terrains. The Straussburg Granite was dated by Pettersson (2008) and has an age of 1092 ± 12 Ma (Table 5.1). The granite was also dated by Cornell et al. (2012) who subjected it to more detailed ion probe U-Pb dating. According to Cornell et al. (2012), the granite contains large zircons which show oscillatory magmatic zoning with few cores which might represent xenocrysts (Table 5.1). The twenty nine main points which were analysed are all less than 11% discordant and gave an upper intercept age of 1090 ± 9 Ma which is interpreted as the emplacement age. An age of 322 ± 170 Ma was determined for the non-zero lower intercept which is likely associated with ancient lead loss during basement erosion, sedimentation and diagenesis of Karoo basin sediments (Cornell et al., 2012).
5.9.3. Isotope geochemistry

The Sm-Nd and Rb-Sr isotopic data for this granite were determined by Pettersson et al. (2009). The granite shows large Sm/Nd ratio variations varying from 0.13 to 0.20, low to moderate \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios varying from 0.51176 to 0.51197, together with \(\varepsilon_{\text{Nd(t)}}\) varying from -2.59 to -0.49 calculated from 1089 ± 9 Ma emplacement age of the Straussburg Granite (Table 5.1). A moderate Rb/Sr ratio of 0.69 and a high initial \(^{87}\text{Sr}/^{86}\text{Sr}\) of 0.7461, together with moderate to low \(\varepsilon_{\text{Sr(t)}}\) of 199.67 (Table 5.1) were also obtained from the Straussburg Granite. Model ages obtained from this granite vary from 1.80 to 3.07 Ga for \(T_{\text{CHUR}}\), and with \(T_{\text{DM}}\) varying from 2.14 – 3.34 Ga (Table 5.1).

5.10. Josling Granite

5.10.1. Whole rock geochemistry

The composition of the Josling Granite varies from granodiorite, trondhjemitic to monzo-granite, being ferroan and alkali-calcic (Fig. 5.9a-e) (Table C2). The trondhjemitic composition likely suggests a granite dominated by albitic plagioclase. The samples show a spread from fractionated I-type to A-type characteristics, and have an A\textsubscript{2}-type of composition, but have relatively low \(\text{Na}_2\text{O+K}_2\text{O}/\text{CaO}\) values of <3, in general (Fig. 5.9f-g). The granite is predominantly metaluminous, and, to a lesser extent, peraluminous, with ASI values varying from 0.997 to 1.027 (Fig. 5.9h) (Table C2).

![REE diagram](image1)

![Spider diagram](image2)

Figure 5.23. The multi-element diagrams for the Josling Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

The granite shows a relatively gently dipping negative sloping rare earth element (REE) pattern \([\text{La/Lu}_n=15.09-16.09]\), with a relatively small negative Eu anomaly \([\text{Eu/Eu}^*]_n=0.66-0.83\) (Table 5.1).
The LREE are enriched relative to the HREE (Fig. 5.23a). The granite is relatively enriched in Pb, is slightly enriched in Nd and Zr, and shows a slight Nb-Ta ‘trough’ or anomaly, along with depletions in Cs, Sr, and Eu, as well as prominent negative P and Ti anomalies relative to the primitive mantle values of McDonough and Sun (1995) (Fig. 5.23b).

5.10.2. Geochronology

The Josling Granite sample was collected from an outcrop located approximately 5 km east of Louisvale village (S 28° 39’44.8”; E 021° 15’57.7”; elevation 866m) (Fig. 4.1, E2). Zircons of this granite are euhedral to subhedral, mostly fractured and range from 50 µm to 150 µm in size (Figs. 5.24a, b). Most of the zircons have dark cores showing oscillatory zoning and gave \(^{207}\text{Pb}/^{206}\text{Pb}\) concordia ages ranging from 1197 ± 54 Ma to 1214 ± 63 Ma (Figs. 5.24a, b). Rounded dark cores are mostly found on the unzoned grains and are mostly characterised by a high U content (411 - 582 ppm) compared to other spots of this granite; they mostly yield discordant ages. The zircons are mostly prismatic and exhibit broken to rounded terminations (Figs. 5.24a, b).

Twenty three spots were analysed in which 12 yielded greater than 98% concordancy with the rest yielding less than 61% concordancy i.e. discordant ages. \(^{207}\text{Pb}/^{206}\text{Pb}\) concordia ages of 1235 ± 109 Ma and 1236 ± 62 Ma were obtained from two dark cores of euhedral oscillatory zoned grains and are similar to those of the Jannelsepan Formation located on the western side of the Josling Granite of the Areachap Terrane (Table D1). The zircons of this granite have some spots which show 98 to 100% concordancy and have relatively low U contents (46 to 297 ppm) and gave relatively old \(^{207}\text{Pb}/^{206}\text{Pb}\) ages ranging from 1214 ± 63 Ma to 1236 ± 62 Ma (Table D1). A U-Pb upper intercept age of 1222 ± 16 Ma was obtained from the zircons of this granite (Fig. 5.25a). The U-Pb concordia age of 1217 ± 8 Ma is taken as the crystallisation age for the Josling Granite (Fig. 5.25b, Table 5.2).

The crystallisation age of this granite can be related to the 1220 ± 10 Ma intrusion age of the Dyasons Klip Granite and the 1203 ± 11 Ma Polisiehoek Granite (Pettersson, 2008), together with the 1205 ± 12 Ma protolith age of the Kenhardt Formation migmatite (Fransson, 2008) all within the Kakamas Terrane. Within the Areachap Terrane, the Josling Granite is possibly partly responsible for, or associated with the 1204 ± 50 Ma metamorphism obtained from the Boksputs Formation metaquartzite (Cornell and Pettersson, 2007).
5.10.3. Isotope geochemistry

Sm/Nd ratios vary from 0.12 to 0.18 along with relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.51200 to 0.51203, together with relatively high $\epsilon_{\text{Nd}(t)}$ values varying from 1.79-6.71 calculated from 1217 ± 8 Ma emplacement age of the Josling Granite (Table 5.1). The granite has a relatively low Rb/Sr ratio varying from 0.43-0.55 and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios varying from 0.7266 to 0.7337 together with low $\epsilon_{\text{Sr}(t)}$ values varying from 50.03-70.98. The samples have model ages which vary from 1.47 to 2.44 Ga for $T_{\text{CHUR}}$ and 1.84 to 2.78 Ga for $T_{\text{DM}}$ (Table 5.1).
5.11 Klip Koppies Granite

5.11.1 Whole rock geochemistry

This granite is classified as a ferroan, alkalic metaluminous (ASI= 0.941-0.960) A2-type monzogranite which varies toward quartz monzonitic compositions (Fig. 5.9a-h). The REE pattern is moderately negative sloping [(La/Lu)_N=10.02-10.92], with the LREE moderately enriched relative to the HREE (Table 5.1). There is a relatively prominent negative Eu anomaly [(Eu/Eu*)_N=0.51-0.52]. The granite is enriched in Th, Pb, Nd and Sm, has a prominent Nb-Ta “trough” or anomaly, and is characterized by depletions in Cs, Ba, Sr, Zr, and Eu, as well as prominent negative P and Ti anomalies, as shown by the spider diagram normalised to primitive mantle (Fig. 5.26b, Table 5.1).

Figure 5.26. The multi-elements diagrams for the Klip Koppies Granite. a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.11.2 Geochronology

Zircons of the Klip Koppies Granite are predominantly rounded, dark, unzoned to weakly zoned and show thin, bright unzoned rims and dark, weakly zoned cores (Bailie et al., 2011a). According to Bailie et al. (2011a), the zircons are dominated by bright, unzoned metamorphic overgrowths or metamorphic disturbance. The ages obtained from magmatic zircon grains gave a weighted mean ^{207}Pb/^{206}Pb age of 1096 ± 10Ma which is likely the emplacement age (Table 5.2). The bright, weakly zoned grains and overgrowths with relatively high U, and low to very low Th contents (<50 ppm) gave ages which range between 1150 and 1180 Ma. The dark, weakly zoned cores gave an age bracket ranging between 1200 and 1300 Ma (Bailie et al., 2011a).
5.11.3. Isotope geochemistry

The Sm-Nd and Rb-Sr isotope data for this granite were obtained by Bailie et al. (2011a). The granite has fairly moderate Sm/Nd ratios varying from 0.16-0.20, moderate $^{143}$Nd/$^{144}$Nd ratios varying from 0.51195-0.51202, together with an epsilon Nd$_{(t)}$ value of -1.07 calculated using the 1096 ± 10 Ma crystallization age of the granite (Table 5.1, Table 5.2). The Klip Koppies Granite contains relatively high Rb/Sr ratio of 1.40 together with a $^{87}$Sr/$^{86}$Sr ratio of 0.7239 and a low positive $\epsilon_{\text{Sr}}(t)$ value of 94.31. The T$_{DM}$ model ages vary from 2.42-3.14 Ga, and 2.06-2.84 Ga for T$_{CHUR}$. The isotope composition of this granite is comparable to that of the older Colston Granite (Table 5.1).

5.12. Gemsbokbult Granite

5.12.1. Whole rock geochemistry

The Gemsbokbult Granite is classified as a ferroan, alkalic metaluminous A$_2$-type monzogranite to granodiorite (Fig. 5.9a-h). The compositions of this granite vary less compared to the older granites.

The samples of the Gemsbokbult Granite show relatively consistent REE and spider diagram patterns (Fig. 5.27a). The granite has a moderately negative sloping REE pattern [(La/Lu)$_{chondrite}=$8.79-10.81], and a relatively moderate negative Eu anomaly ((Eu/Eu*)$_{chondrite}=$0.59-0.67) (Table 5.1). The Gemsbokbult Granite is enriched in Th, U, Pb, Nd and Sm, having a prominent Nb-Ta “trough” or anomaly, along with depletions in Cs, Rb, Ba, Sr and Eu, as well as prominent negative P and Ti anomalies (Fig. 5.27b).

Figure 5.27. The multi-element diagrams for the Gemsbokbult Granite. a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).
5.12.2. Geochronology

The Gemsbokbult Granite geochronology was done by Bailie et al. (2011a) who described the zircons of the granite as varying from euhedral to subhedral (150 - 200 µm) showing significant alteration, cracking and inclusions. The granite is dominated by dark, unzoned, euhedral metamict zircons with dark embayments. Zircons which are weakly zoned and also contain weakly zoned dark cores are also present but in small proportions. The dark unzoned overgrowths are mostly characterized by Th/U ratios between 0.4 and 0.6 together with negative discordance and yield ages of around 1100 Ma, whereas ages between 1120 to 1218 ± 120 Ma were obtained from positively discordant spots which are characterized by having high U contents and low Th/U ratios (0.45 - 0.20) and are likely to be xenocrysts. These latter spots are characterized by having dark, weakly to unzoned zonation. A magmatic age of approximately 1104 ± 14 Ma was determined for the Gemsbokbult Granite (Table 5.2). Historically, an age of approximately 1200 Ma was reported for this granite by Linstrom (1977), which, according to Bailie et al. (2011a), likely represents inheritance.

5.12.3. Isotope geochemistry

The granite shows a moderate Sm/Nd value of 0.18 and a relatively high $^{143}$Nd/$^{144}$Nd ratio of 0.51198 (Table 5.1). A negative $\varepsilon_{Nd(t)}$ value of -0.32 was also obtained calculated using the 1104 ± 11 Ma emplacement age of this granite. A relatively old $T_{CHUR}$ model age of 2.49 Ga and an age of 2.82 Ga for $T_{DM}$ were obtained for the Gemsbokbult Granite (Table 5.1).

5.13. Kleinbegin Subsuite

5.13.1. Whole rock geochemistry

The granites within this subsuite vary in composition from monzo-granite to granodiorite, tending slightly toward trondhjemitic compositions (Fig. 5.9a-b). They are predominantly ferroan, varying, to a lesser extent, toward magnesian. Overall the granite is calc-alkaline, alkali-calcic, metaluminous and an $A_{1}$-type, but not as alkaic as other members of the Keimoes Suite (Fig. 5.9c-h).

The granite shows a shallow negative sloping REE pattern $[(La/Lu)_{n}=3.58-5.50]$, and relatively high negative Eu anomaly $[(Eu/Eu^{*})_{n}=0.43-0.56]$ (Fig. 5.28a). The granite is slightly enriched in Th and enriched in Pb, showing a prominent Nb-Ta ‘trough’ or anomaly with greater depletion in Nb than Ta, along with depletions in Cs, Sr, and Eu, as well as prominent negative P and Ti anomalies relative to the PM values of McDonough and Sun (1995; Fig. 5.28b).
5.13.2. Geochronology

The geochronology for this subsuite was determined by Bailie et al. (2011a). Zircons of the subsuite form predominantly euhedral (large 250 - 350 µm) grains having bright, zoned cores and thin dark zoned overgrowths, with bright unzoned cores present in some grains. The upper intercept intersects concordia at 1101 ± 10 Ma, which is similar to the concordia age of 1099 ± 7 Ma (Table 5.2). Similar $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 1103 ± 14 Ma and 1101 ± 21 Ma were obtained from two concordant grains. An age of 1101 ± 10 Ma was found to be the possible age of emplacement for the Kleinbegin Subsuite. A 1020 ± 20 Ma age was also obtained which likely represents a younger metamorphic age which is not associated with any post-tectonic magmatism in the area (Table 5.2). The Kleinbegin Subsuite was also previously classified as post-tectonic by previous workers (Moen, 2007; Bailie et al., 2011a), even though some of the members of this subsuite show strongly foliated textures; the granite in this work, and is classified as a late- to post- tectonic granite.

5.13.3. Isotope geochemistry

The granite has a low Sm/Nd ratio of 0.15, moderate $^{143}\text{Nd}/^{144}\text{Nd}$ varying from 0.51164 to 0.51170, together with a relatively strongly negative $\varepsilon_{\text{Nd}(t)}$ values varying from -3.09 to -4.87 calculated from 1101 ± 10 Ma emplacement age of this granite (Table 5.1). The granite has a Rb/Sr ratio of approximately 1.23, a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7638 and $\varepsilon_{\text{Sr}(t)}$ of 124.56 (Table 5.1). Relatively old $T_{\text{DM}}$ model ages, which range from 2.53 to 2.75 Ga, and $T_{\text{CHUR}}$ varying from 2.22 to 2.46 Ga (Table 5.1), were obtained.
5.14. Elsie se Gorra Granite

5.14.1. Whole rock geochemistry

The Elsie se Gorra Granite is classified as a ferroan, alkali-calcic to alkalic, metaluminous, A$_2$ to A$_2$-type monzogranite to granodiorite (Fig. 5.9a-h). The granite has a strongly negative sloping REE pattern \([(La/Lu)_{chondrite}=24.80-51.27]\), with a largely variable Eu anomaly, which varies from relatively strongly negative to slightly positive \([(Eu/Eu^*)_{chondrite}=0.44-0.62]\) (Table 5.1, Fig. 5.29a). The multi-element trace element plot (spider diagram) of the Elsie se Gorra Granite has a steeply dipping saw tooth pattern with enrichments in Pb, Nd and Sm, showing a Nb-Ta “trough” or anomaly, along with depletions in Ba, Ce and Sr as well as prominent negative P and Ti anomalies (Fig. 5.29b). The two samples of the granite show a significant multi-element trace element (spider diagram) and REE pattern variation, particularly in terms of the LILE (Fig. 5.29b, Table 5.1).

![REE diagram](image)

**Figure 5.29.** The trace element multi-element diagrams for the Elsie se Gorra Granite. (a) REE diagram normalised to the chondritic values of Sun and McDonough (1989). (b) Spider diagram normalised to the primordial mantle values of McDonough and Sun (1995).

5.14.2. Geochronology

The sample of the Elsie se Gorra was collected from a road cut located along the N10 national road approximately 35 km from Kenhardt heading toward Keimoes (S 29° 09’ 48.6”; E 021° 09’ 45.9”; elevation 906 m) (Figs. 4.1, D3). The zircons of this granite range from 100 µm to 200 µm in size, and are mostly euhedral to subhedral. The grains are characterized by magmatic overgrowths with rounded terminations. The whole zircon euhedral grains are zoned to weakly zoned whereas other crystals have an indication that the zonation has been overgrown by later magmatic overgrowth (Figs. 5.30a,b). The prismatic euhedral crystals contain moderately bright magmatic inclusions which are parallel to the length of the zircon whereas most of the subhedral zircons contain dark rounded inclusions (Figs. 5.30a, b). Twenty one spots were analysed in which only ten gave 99% to 101 % concordant to reversely
discordant ages and the rest have less than 92% concordancy. Only two populations were identified from the concordant data (Table D1). The first population generally reflects the emplacement or crystallisation $^{207}\text{Pb}/^{206}\text{Pb}$ age of the granite, with ages ranging from 1182 ± 45 to 1197 ± 50 Ma (Table 5.2), whereas the second population shows inheritance, with ages ranging from 1337 ± 45 to 1342 ± 44 Ma (Table D1). Inherited cores are mostly found in zircon grains which have oscillatory zoned magmatic overgrowths and yield $^{207}\text{Pb}/^{206}\text{Pb}$ concordia ages of 1337 ± 45 Ma and 1342 ± 44 Ma which similar to the 1371 ± 9 Ma Swanartz Gneiss (Pettersson et al., 2007). Two reversely discordant ages of 1180 ± 45 Ma and 1181 ± 47 Ma were also obtained (Figs. 5.30a, spot 23 and 5.30b, spot 5). The dark, unzoned cores give ages around 1180 Ma (Fig. 5.30a, spot 18).

An upper intercept U-Pb age of 1196 ± 17 Ma was obtained from 11 spots analysed from this granite (Fig. 5.31a). The U-Pb concordia age of 1186 ± 9 Ma is taken to be the crystallisation age of the Elsie se Gorra Granite (Fig. 5.31a, Table 5.2).

Figure 5.30. Cathodoluminescent (CL) images of the magmatic zircons showing analysed spots for the Elsie se Gorra Granite with the numbers outside the brackets being the ages for the analysed spots ($^{207}\text{Pb}/^{206}\text{Pb}$ ages in brackets).
5.14.3. Isotope geochemistry

The one sample of the Elsie se Gorra Granite in which isotopes were analysed shows a moderate Sm/Nd ratio of 0.16, a moderate to high \( ^{143}\text{Nd} / ^{144}\text{Nd} \) ratio of 0.51192 and a positive \( \varepsilon_{\text{Nd}(t)} \) value of 1.55 calculated from 1186 ± 9 Ma emplacement age of the Elsie se Gorra Granite (Table 5.1). The granite has a relatively high Rb/Sr ratio of approximately 4.60, a high \( ^{87}\text{Sr} / ^{86}\text{Sr} \) ratio of 0.9551 together with a high \( \varepsilon_{\text{Sr}(t)} \) value of 629.06 (Table 5.1). Old model ages of Paleoproterozoic age were obtained for the granite with 2.11 Ga for \( T_{\text{CHUR}} \) and 2.45 Ga for \( T_{\text{DM}} \).
Table 5.1 Whole rock geochemistry summary table. The numbers within the brackets next to the granite names represent total samples collected.

<table>
<thead>
<tr>
<th>Pluton</th>
<th>(La/Sm)N</th>
<th>(Gd/Sm)N</th>
<th>(Eu/Eu*)N</th>
<th>Depleted</th>
<th>Sm/Nd</th>
<th>LILE to HFSE slope</th>
<th>(143Nd/144Nd)0</th>
<th>εNd(t)</th>
<th>Rb/Sr</th>
<th>εSr(τ)</th>
<th>TCHUR (Ga)</th>
<th>TDM (Ga)</th>
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<tr>
<td>Friersdale Charnockit e (4)</td>
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Table 5.2 Whole rock geochemistry summary table. The numbers within the brackets next to the granite names represent total samples collected.

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<th>Pluton</th>
<th>(La/ Lu)</th>
<th>(La/ Lu)</th>
<th>(Gd/ Lu)</th>
<th>(Eu/ Eu*)</th>
<th>Depleted</th>
<th>Enriched</th>
<th>Sm/ Nd</th>
<th>LILE to HFSE slope</th>
<th>(143)Nd/ (144)Nd, 1.07</th>
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<th>(87)Sr/ (86)Sr, εSrCHUR</th>
<th>TDM (Ga)</th>
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<td>Cs, Ba, Nb, Ta, Sr, P, Eu, Ti</td>
<td>Th, Pb, Nd</td>
<td>0.19-0.20</td>
<td>Shallow</td>
<td>0.51192-0.51197</td>
<td>1.91</td>
<td>1.33</td>
<td>0.772-0.765</td>
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<td>1.48-1.71</td>
<td>0.41-0.62</td>
<td>Cs, Ba, Nb, Ta, Sr, P, Eu, Ti</td>
<td>Th, U, Pb,</td>
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<td>Moderate</td>
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<td>2.1</td>
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<td>Pb, Nd, Zr</td>
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<td>Th, U, Pb, Nd, Sm</td>
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<td>N/A</td>
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<td>Th, Pb</td>
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<td>3.21-5.67</td>
<td>0.49-1.67</td>
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<td>Steep</td>
<td>0.51192</td>
<td>1.55</td>
<td>4.6</td>
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</table>
Geochronological grouping of Keimoes Suite

Cornell et al. (2012) dated two of the Keimoes Suite granites, namely the Straussburg Granite and Friersdale Charnockite and defined the Keimoes Suite as comprising exclusively post-tectonic granites with $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1113-1078 Ma, excluding the Vaalputs Granite, which was thought to be the oldest member of the suite with an age of 1145 Ma and was placed into the 1203 to 1146 Ma Augrabies Suite. In this study, fourteen granites of the Keimoes Suite were examined and new age grouping has been proposed.

The granites which were studied gave ages which range from 1217 Ma, obtained from the Josling Granite, to 1078 Ma obtained from the Friersdale Charnockite. There is an age gap of approximately 32 Myr. from the Josling Granite to the Elsie se Gorra Granite. The Josling Granite is the only granite with an age older than 1200 Ma. The Keboes Granite was previously grouped with the Straussburg Granite and Friersdale Charnockite which were classified as the post-tectonic Keimoes Suite. There is an age gap of approximately 18 Myr. between the 1128 Ma Louisvale Granite, which corresponds with the Vaalputs Granite group and the 1110 Ma Keboes Granite. The main difference between the Louisvale Granite and the Keboes Granite is the degree of foliation even though they are located 3 km distance from each other. Based on this evidence, the new grouping of the Keimoes Suite granites is proposed which is a modification of that of Cornell et al. (2012). This grouping is more broad-based compared to that of Cornell et al.(2012), which examined only two granites of the Keimoes Suite, whereas in this study fourteen granites of the Keimoes Suite were examined. The new geochronological data obtained from these studied granites together with lithological features allows the granites of the eastern Namaqua sector to be grouped into three major age groups which are:

(i) **Early syn-tectonic granites (1225-1200 Ma)**
- Josling Granite

(ii) **Syn-tectonic granites (1200 - 1120 Ma)**
- Elsie se Gorra Granite
- Colston Granite
- Cnydas Subsuite
- Vaalputs Granite
- Louisvale Granite
- Klipkraal Granite

(iii) **Late to post-tectonic granites (1116 - 1066 Ma)**
- Keboes Granite
- Kanoneiland Granite
- Gemsbokbult Granite
- Kleinbegin Granite
- Klip Koppies Granite
- Straussburg Granite
- Friersdale Charnockite

The proposed 1200 to 1120 Ma syn-tectonic granite age grouping is an extension of the 1203 to 1146 Ma Augrabies Suite proposed by Cornell et al. (2012). The common granite between these suites is the Vaalputs Granite which was classified both by Cornell et al. (2012) and in this study as a syn-tectonic granite. The 1113-1078 Ma Keimoes suites correspond with the 1116-1066 Ma Keimoes Suite proposed in this study taking into account the errors.
### Table 5.3. Geochronology results summary table

<table>
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<tr>
<th>Sample no.</th>
<th>Rock unit</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Emplacement age (Ma)</th>
<th>Spots</th>
<th>Type</th>
<th>Inheritance age (Ma)</th>
<th>Metamorphic age (Ma)</th>
<th>Miner</th>
<th>Method</th>
<th>Source</th>
<th>Zircon morphology</th>
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<td>Mkn 4</td>
<td>Josling Granite</td>
<td>28° 39'44.8&quot;</td>
<td>021° 15'57.7&quot;</td>
<td>1217 ± 8</td>
<td>23</td>
<td>concordia</td>
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<td>zircon LA-ICPMS</td>
<td>this study</td>
<td>Well to moderately zoned subhedral grains</td>
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<tr>
<td>Me 1</td>
<td>Elsie se Gorra Granite</td>
<td>29° 09'48.6&quot;</td>
<td>021° 09'45.9&quot;</td>
<td>1185 ± 9</td>
<td>21</td>
<td>concordia</td>
<td>1337 ± 45; 1342 ± 44</td>
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<td>this study</td>
<td>Oscillatory zoned subhedral grains</td>
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<td>Mcol 3</td>
<td>Colston Granite</td>
<td>28° 25'42.3&quot;</td>
<td>020° 49'24.4&quot;</td>
<td>1158 ± 6</td>
<td>25</td>
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<td>this study</td>
<td>elongate, subhedral grains</td>
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**Early syn-tectonic granite**

**Syn-tectonic granites**
### Table 5.2. The geochronology results summary table (cont.)

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<td>LA-ICPMS</td>
<td>this study</td>
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<td>this study</td>
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Table 5.2. The geochronology results summary table (cont.)

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6. Discussion

Since it was noted from the previous chapter that three distinct groups can be extracted from what was previously termed the Keimoes Suite in terms of their long age distribution, these granites will no longer be referred to as the Keimoes Suite but will be referred to as the early syn-tectonic granite, syn-tectonic granites and late to post-tectonic granites. This chapter aims to investigate the petrogenesis of the age groupings, their magma source characteristics, their possible relationship to each other and their tectonic setting. This also incorporates other intrusive rocks occurring within the Kakamas, Areachap and Kaaien Terranes dated by other authors such as Pettersson (2008, 2009), Moen and Armstrong (2008) and Bailie et al. (2011a). This chapter further evaluates and discusses the duration of the granitic magmatism, as well as their relationship to deformation and metamorphism on the margin of the eastern Namaqua sector. The chapter also focuses on evaluating the tectonic evolution of the eastern margin of the Namaqua sector as portrayed by these granitoid groups. The intrusion of each age group has geological significance and will be linked to, or associated with a specific Namaquan tectonic event.

The geochronology makes it clear that there are three major age groups within the granites which were previously grouped as the Keimoes Suite. These are (i) 1225-1200 Ma early syn-tectonic granite, (ii) 1200-1120 Ma syn-tectonic granites, and (iii) 1116-1066 Ma late to post-tectonic granites.

6.1. Petrogenesis

The isotopic composition of the early syn-tectonic 1217 ± 8 Ma Josling Granite suggests that it was likely derived from a mixed, but predominantly depleted source, as shown by samples of this granite plotting within the field characterized by high Rb/Sr and high Sm/Nd ratios (Fig. 6.1a). This granite is represented by the cross symbol in all the geochemistry diagrams. Relatively high $^{143}$Nd/$^{144}$Nd ratios (0.51200 - 0.51203), together with high positive $\varepsilon_{Nd(t)}$ values (1.79 - 6.71) and a large model age variation which ranges from 1.47 to 2.44 Ga for $T_{CHUR}$ and 1.84 to 2.78 Ga for $T_{DM}$, confirms derivation from a depleted source, likely to be depleted mantle, with varying degrees of crustal contribution (Table C2). This is likely due to the fact that this granite is associated with subduction related to the development of the juvenile Areachap Group volcanic arc with little crustal influence (Bailie et al., 2011; Cornell et al., 2012. Thus it is likely that the Josling Granite formed by partial melting of volcanic arc material that had no mature crustal input.

The 1195-1120 Ma syn-tectonic granites are represented by closed circles symbol on all the geochemistry diagrams. Excluding the Cyndas Subsuite which is comprised of a series of granites, the $^{143}$Nd/$^{144}$Nd ratios for these granites vary from 0.51192 - 0.51203, with epsilon Nd values largely around 0 and varying from -1.91 to 2.05 (Fig. 6.1b), suggesting derivation from a depleted source with some contribution from crustal source, possibly subcontinental lithospheric mantle, or depleted mantle
with a minor crustal contribution. The enrichment of the LREE and LILE (Fig. 6.2a) together with the peraluminous compositions shown by some of the samples of the Colston Granite on the NK/A vs. A/ CNK plot (Fig. 5.1h) also suggest a crustal component. The Sm-Nd variation with time suggests derivation from various sources. Old Nd model ages suggest multiple reworking events.

Figure 6.1. (a) epsilon Nd(t) vs. time (Ma) mostly suggesting the degree of reworking and source variation. (b) Epsilon Nd(t) vs. time (Ma) showing the source of the different granitic magmas. (c) Sm/Nd vs. time (Ma) of emplacement diagrams for evaluating or comparing the source for the eastern Namaqua sector granites.

The late to post-tectonic granites (1116 – 1066 Ma) are shown by closed squares in all the geochemistry diagrams in both this and the previous chapter, have relatively low epsilon Nd(t), ranging from negative (-4.92) to positive (0.65) with more samples having negative epsilon Nd(t) indicating derivation from continental crustal source with some contribution from depleted source. The relatively high epsilon Sr(t) ranging from 56.32 to 964.32, high LILE abundances on spider diagrams (Fig. 6.2b) and some granites showing peraluminous together with A2-type compositions a continental crustal derivation. The metaluminous compositions, some positive epsilon Nd(t) values (0.65) obtained from the Kanoneiland Granite, relatively young TCHUR model ages of 1.80 Ga, as shown by the Straussburg Granite members of the late to post-tectonic granites. The relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.51208 together with some samples plotting within the depleted source field on the epsilon Nd(t) vs. epsilon Sr(t) binary diagram,
such as some samples of the Kanoneiland and Straussburg Granites and the Friersdale Charnockite (Fig. 6.1a) suggests some contribution of depleted source. All these trend observed suggests that the late to post-tectonic granites were derived from a predominantly continental crustal source with varying degrees or influences of a depleted source or mantle-derived.

These granites mostly plot below the crustal derivation line and also show large Sm-Nd variation suggesting continental crustal derivation with some degree of source heterogeneity as well as source reworking (Fig. 6.1b-c). The isotopes denote a general continuum for the granites from the early syn-tectonic to the late- to post-tectonic granites. The early syn-tectonic granite is derived from a depleted source which incorporated minimal amount of continental crustal components (Fig. 5.9e, 6.1a-b). Relative to the late- to post-tectonic granites the syn-tectonic granites were derived from partial melting of depleted sources which incorporated varying degrees of continental crustal materials (Fig. 5.9e, 6.1a-b). The late to post-tectonic granites are derived preferentially from more enriched / continental crustal sources with varying degrees of depleted source components (Fig. 5.9e, 6.1a-b).

The relatively similar trends for the granites of the same age group within the REE and spider diagram patterns suggest derivation from similar sources (Fig. 6.2a-b, 6.3a-b). The slight variation seen within the patterns of the granites of the same suites indicate source heterogeneities helping to control the compositional differences. Not only the source controlled the composition of the granites but other internal factors or geological processes, such as fractional crystallisation, degree of partial melting and amount of entrained accessory and peritectic mineral assemblages, as shown by the maficity diagrams (Fig. 6.5a-d, Fig. C4), also played a role. The syn-tectonic granites show a larger compositional variation compared to the early syn-tectonic granite and the late to post-tectonic granites, as shown by the multi-element spider diagrams (Fig. 5.23, 6.2). This is likely due to the fact that the syn-tectonic granites mark magmatism associated with the major deformational event of theNamaquan Orogeny which involve reworking of older crust together with introducing new component into the magma which resulted in this large variation (Fig. 6.2a-b, 6.3a-b).

Figure 6.2. Spider diagrams normalised to the primordial mantle values of McDonough and Sun (1995). (a) The syn-tectonic granites [Vaalputs Granite (blue circles): [concentration above the diagrams Cs= 1237.62, 1272.86; Th= 1105.12; U= 1154.25]. (b) Late- to post-tectonic granites.
The trondhjemitic composition of some of the granites in each group such as the Josling Granite of the early syn-tectonic, Louisvale Granite of the syn-tectonic and Kleinbegin Subsuite of the Keimoes Suite indicate plagioclase-rich granites (Fig. 6.2a-b, Fig. 6.3a-b). The significant negative Eu and Sr anomalies (Fig. 6.2a-b, Fig. 6.3a-b), within all the granites groups suggest that plagioclase retention within the source, and to a lesser extent plagioclase fractionation, has influenced the compositions of the granites in both suites. Overall the late- to post-tectonic granites have higher REE contents, in general, than do the syn-tectonic granites confirming some degree of fractionation.

The Ni vs. Pb and Co vs. Rb (ppm) binary diagrams (Fig. 6.4) indicates that fractional crystallization did not play the major role in controlling the overall composition of the granites. If fractional crystallisation had taken place or was the dominant factor controlling the composition of the granites, the trends on these diagrams would be to be clear and show which mineral was fractionated. Increasing amounts of feldspar fractionation is denoted by increasing amounts of Pb and Rb on these diagrams. Such trends toward increasing Rb and Pb are not seen, but rather decreasing Ni and Co suggesting that crystallization fractionation of feldspars, particularly relevant for feldspars, was not dominant. Rather the degree of partial melting appears to have played the significant role (Fig. C2). The trends of samples observed on Harker diagrams (Fig. C3), suggest, however, that minor alkali feldspar and, to a lesser extent, plagioclase feldspar and biotite fractionation took place causing the local compositional variations within a granitic pluton.

The Harker diagrams to some extent suggest that slight fractionation did occur within individual granite plutons. The fractionation effect increases with decreasing time, with the syn-tectonic granites showing relatively poorly defined fractionation trends. The late to post-tectonic granites show the greatest fractionation trends of the eastern Namaqua Sector granites. Crystal fractionation is shown by relatively clear trends for the late to post-tectonic granites on the Harker diagrams and spider diagrams which show steeper slopes than older granites groups (Fig. C3). The negative trend on the MnO and MgO against SiO$_2$ plots for all the suites suggests either that the fractionation of a Mg-bearing mineral, such as the pyroxenes, or, more likely, the entrainment of a Mg-bearing peritectic assemblage, could also

![Figure 6.3. REE diagram normalised to the chondritic values of Sun and McDonough (1989). (a) The syn-tectonic granites. (b) The late to post-tectonic granites.](image)
have contributed to the compositional variations (Fig. C3, C4). The secondary control of fractional crystallisation is quite clearly seen in the Al\textsubscript{2}O\textsubscript{3} vs. SiO\textsubscript{2} plot where there is no fixed trend for any particular suite.

Figure 6.4. The Co vs. Rb and Ni vs. Pb binary diagrams indicating that partial melting (PM) played the major role compared to fractional crystallization (FC) in controlling the chemical composition of the granites of the early syn-tectonic granite (cross), syn-tectonic granites (circles) and the late to post-tectonic granites (squares) (after Cocherie, 1986). The beginning and ends of the trends were derived from original study of Cocherie (1986).

Peritectic assemblages entrainment refers to the process in which once a partial melt has formed from the source, it may segregate from its complementary solid residue carrying small crystals of peritectic phase assemblage (e.g. pyroxene, garnet etc.), formed in a melting reaction (Clemens and Stevens, 2012). Thus ratios of individual peritectic minerals in the entrained assemblage remains fixed in the ratio decreed by the stoichiometry of the melting reaction (Clemens and Stevens, 2012).

All granite groups shows positive correlation between the maficity and the Fe, Mg, Ti, Mn, Ca and P, and shows partially negative correlation with Na and K and no clear trends in Al indicating source heterogeneities (Fig. C4). The positive relationship between the maficity and the Fe and Ti are produced by entrainment of Ti-bearing minerals (biotite and/or other Ti-free ferromagnesian silicates co-fractionating with Fe-Ti oxides (Clemens and Stevens, 2012). The positive correlation of P against maficity suggests entrainment of apatite into the melt which formed the granite (Fig. C4). The retention of ilmenite and rutile and, to a lesser extent, sphene during magmatic evolution also influenced the composition of the granites, as seen in the depletion of Ti, Nb and Ta (Fig. 6.2). The maficity diagram also shows that biotite and hornblende accumulation played a secondary role in influencing the composition of the granites of both suites (Figs. 6.5a, b). There is no correlation between the geographic location and the degree of partial melting or degree of entrainment of the accessory minerals or peritectic assemblages. The trends are similar for both granitic suites. Melting of biotite-rich and
hornblende-rich sources giving rise to opx-rich peritectic assemblages, which could include Ti-bearing phases like magnetite, which then get taken up into, or entrained into the magma is controlled the chemical composition of the granites (Fig. 6.5a-d). Major controlling factors of the compositional variation within the granites appear to be, rather, the source composition, together with peritectic entrainment and equilibrium/disequilibrium melting (Fig. 6.5).

Incongruent melting of biotite to produce a leucogranitic melt and a garnet-dominated peritectic assemblage where there is no equilibration of the melt with accessory phases such as zircon and monazite prior to escaping the source is called Trace Element Disequilibrium Melting (TEDM), whereas trace element equilibrium melting (TEEM) is a scenario in which the melt and accessory minerals attain or reach complete equilibration with the melt (Villaros et al., 2009). TEDM results in all the REE and HFSE being trapped in retained accessory minerals and the melt itself being depleted in these elements whereas these elements are incorporated into the melt in the case of TEEM. The compositions of the granitic magma are thus a function of melt composition, proportion of entrained peritectic assemblage (Stevens et al., 2007) and the amount and compositions of unreacted zircon and monazite entrained to the magma (Villaros et al., 2009). TEEM results in the melt being richer in the HFSE and REE due to the fact that monazite and zircon are completely dissolved (Villaros et al., 2009). The negative trends of trace elements such as Sc, V, Zr and Hf against maficity (molar Mg+Fe) suggest the entrainment of both the peritectic assemblage and accessory minerals (Fig. C3).

The enrichment of Zr, Hf, Nd and Sm concentrations on the multi-element diagrams (Fig. 6.6), together with the positive correlation or relationship of the same elements against SiO$_2$ on the Harker diagrams (Figs. C3, C4) suggests TEEM than TEDM. The trends shown by these trace elements against maficity also confirms that the granites were derived from different sources at different times which underwent varying degrees of TEEM in which accessory minerals such as zircon and monazite reached equilibrium with the melt at the source.
Figure 6.5. Diagrams for assessing the variables which controlled the composition of the granitoids of the eastern Namaqua Sector (after Clemens and Stevens, 2012). (a-b) K and Ti vs. maficity plots for I-type granites with the upper blue arrow indicating the compositional trend resulting from biotite accumulation and the lower orange arrow representing the trend for hornblende accumulation, with compositions between the two arrows produced by the simultaneous accumulation of both these minerals. Accumulation played a secondary role in controlling the composition of the granites. (c-d) K and Ti vs. maficity plots for I-type granitic rocks, comparing the trends in the rocks with the model trends for magma compositions produced by peritectic assemblage entrainment in broadly K-rich andesitic systems in which both biotite and hornblende partially melt. The A-type granite shows clear and closely related or similar trends as those observed on the I-type granites. The blue arrow represents the trends produced by increasing degrees (from left to right) of peritectic assemblage entrainment.
Figure 6.6. Diagrams showing the variations of trace element concentrations versus atomic Fe + Mg (maficity). Co-entrainment refers to the entrainment of both accessory minerals and the peritectic assemblage (Villaros et al., 2009; Clemens and Stevens, 2012). The co-entrainment trend shown (in green) is an example leading to the “maximum” composition of magma possible (end of the arrow). The orange arrow represents trace element disequilibrium melting (TEDM) the case in which the accessory minerals are not in equilibrium with the melt prior to leaving the source. The blue arrow represents trace element equilibrium melting (TEEM), the case where there is equilibration between the melt and accessory mineral assemblage prior to segregation from the source. The green arrow represents co-entrainment (after Villaros et al., 2009). These arrows have been taken from the original reference and are broadly representative of the trends applicable to metaluminous melts. The trends, in general, suggest that the trace element compositions of the syn-tectonic and late to post-tectonic granites were likely partly controlled by co-entrainment of accessory minerals and peritectic phases to the melt with TEEM having occurred with regards to the accessory phases. All the trends were taken as they are from the study of Villaros et al. (2009) as referenced.

The syn-tectonic granites and late to post-tectonic granites generally show depletion in Ba, Nb, Ta, Sr and P on the multi-element trace element (spider) diagram (Fig. 6.2) and negative correlations on the Harker diagrams of Zr, Hf, Nd and Sm against SiO₂ (Fig. C3) as well as negative correlations against Mg + Fe on the maficity plots (Fig. C4). These trends indicate that the melts which formed the granites reach equilibrium with the accessory minerals i.e. TEEM occurred prior to melt segregation in which accessory
minerals such as zircon and monazite dissolved resulting in the melt being HFSE and REE richer (Villaros et al., 2009). In general it appears both suites underwent TEEM, along with peritectic assemblage entrainment (i.e. co-entrainment) leading to sloping positive trends on the trace element vs. maficity plots (Fig. C2). The scatter trends shown by the Rb, Sr Ba and Eu on the multi-element diagram (Fig. 6.2) is due to the fact that they are concentrated on the reactant minerals in the melting process, and show considerable scatter within the granites (Villaros et al., 2009). The LREEs, Th, Hf and Zr versus maficity diagrams (Fig. 6.6, C2) indicate that the youngest granites of each suite experienced higher degrees of peritectic and accessory mineral entrainment as they have high maficity concentrations.

The Josling Granite experienced a relatively low degree of mineral entrainment compared to all the granites of the later suites, and together with the isotopes (Fig. 6.1a). This suggests that it was derived from a different source compared to the granites from the other suites (Fig. 6.6c-d). The late-tectonic Kleinbegin Granite shows similar characteristics to the Josling Granite and was so subjected to similar processes. The granites of each suite start a new entrainment trends on the maficity diagrams with the youngest granite of each suite with the highest maficity and the oldest granite within the suite with the lowest maficity (Fig. C4). The Josling Granite was derived from an essentially pure melt (Fig. C2) which did not experience much entrainment of accessory minerals or a peritectic mineral assemblage, with the source being mafic, as shown by its high Sm - Nd and low Rb - Sr contents. The same observation applies to the syn-tectonic granites group. Each granitic group has well-defined trends. The granites of both groups form well defined maficity trends supporting differences in their sources i.e. every group was derived from a different source. The overall compositional trends, along with peritectic assemblage and accessory mineral entrainment, indicates that the late to post-tectonic granites indeed form a unique and separate suite and were derived from similar sources as shown by their isotopic and whole rock major and trace element compositions (Fig. 6.1).

The volcanic arc signature of the Josling Granite was likely inherited from its source. The signature is likely due to the inheritance from the Areachap Group volcanic arc itself, as also evidenced by the $^{207}\text{Pb}/^{206}\text{Pb}$ concordia age of 1235 ± 109 Ma obtained from some of the zircons of this granite reflecting development of the Areachap Group at this time (Pettersson et al., 2007; Cornell and Pettersson, 2007). The isotopic systematics of the Josling Granite suggest an association with juvenile crust formation possibly related to the Areachap arc volcanism.
Figure 6.7. Tectonic setting discrimination diagrams for the granites of the eastern Namaqua sector. (a) Tectonomagmatic discriminant function diagram for distinguishing the tectonic setting using major elements only (after Verma et al., 2013). (b) Tectono-magmatic discriminant function diagram for determining tectonic setting using major and trace elements only one diagram has been selected from five and the rest are in appendix (Fig. C1e-h) (after Verma et al., 2013). (c) Tectonomagmatic discriminant function diagram for determining tectonic setting using trace elements only. Only one has been selected and more diagrams on appendix (Fig. C1i-l) (after Verma et al., 2013). Abbreviations: IA = Island arc, CA = Continental arc, CR = Continental rift, OI = Ocean Island and Col = Collisional tectonic setting. (d) Nb (ppm) vs. Y (ppm) diagram indicating the tectonic setting of the granites (after Pearce et al., 1984). (e) The normative Qtz-Ab-Or compositional ternary diagram indicating melting pressure for the source (after Anderson and Bender, 1989).
All the granites intruded into a within plate collisional to continental rift tectonic setting, as shown by the trace element tectonic setting discriminant diagrams of Pearce et al. (1984) and tectonomagmatic discrimination diagrams of Verma et al. (2013) (Fig. 6.7a-d). The collisional tectonic setting together with peraluminous composition suggests that the syn-tectonic granites intruded during continental collision and are characterized by a minor crustal contribution. The late to post-tectonic granites, on the other hand, intruded much later after collision had occurred and melted crustal material which carried a subduction-related signature as shown by high negative epsilon Nd\(_{(t)}\) (-4.94 to 0.74) resulting in large Nb-Ta anomalies together with a significant crustal component in their source, as shown by the composition of these granites (Fig. 6.1a-b). The A\(_2\) type nature of the granites of both suites also suggests that the granites were derived from continental crust or underplated crust that had been through a cycle of continent-continent collision or island-arc magmatism (Eby, 1992) (Fig. 5.1g).

From the geochronology, it was clear that three groups or suites can be extracted from the previously defined Keimoes Suite, which are: early syn-tectonic granite, syn-tectonic granites and the late to post-tectonic granites. The petrogenesis together with the geochronology makes it clear that two suites are clearly defined and the third, namely the early syn-tectonic group, is not yet well defined due to the fact that only one granite of this time age was analysed. The grouping includes from the oldest to the youngest, the early syn-tectonic suite with ages between 1225-1200 Ma, the syn-tectonic suite which is the extension of the Augrabies Suite of Cornell et al. (2012), with ages ranging from 1200 – 1120 Ma. The Augrabies Suite in this study is just extension following the granites of the same source. The youngest suite which is the late to post-tectonic granites which is the Keimoes Suite proper with ages from 1116 Ma to 1120 Ma. The Augrabies and Keimoes Suite are the extension of the Cornell et al. (2012) definitions, who only analysed two granites of the Keimoes Suite, with this study offering a far more comprehensive age database of all the granites of the eastern Namaqua sector together with the petrogenesis which allows proper grouping of these granite both in terms of age and source. They each mark a specific event of the Namaquan Orogeny which will be discussed in section 6.4. The early syn-tectonic granite was derived from a depleted source. The Augrabies Suite was derived from depleted sources which incorporated varying degrees of continental crustal source or materials whereas the Keimoes Suite granites were derived from partial melting of continental crustal sources and incorporated varying degrees of depleted source. The granites of the eastern Namaqua Sector can be grouped into three groups in which the new groups include:

(iv) Early syn-tectonic granites (1225-1200 Ma) \textbf{(Early syn-tectonic granites)}
- Josling Granite

(v) Syn-tectonic granites (1200 - 1120 Ma) \textbf{(Augrabies Suite)}
- Elsie se Gorra Granite
- Colston Granite
- Cnydas Subsuite
- Vaalputs Granite
- Louisvale Granite
• Klipkraal Granite

(vi) Late to post-tectonic granites (1116 - 1066 Ma) (Keimoes Suite Proper)
• Keboes Granite
• Kanoneiland Granite
• Gemsbokbult Granite
• Kleinbegin Granite
• Klip Koppies Granite
• Straussburg Granite
• Friersdale Charnockite

6.2. Duration of magmatism

The granites of the eastern Namaqua sector which were examined in this study cover the age period between 1217 and 1078 Ma. The magmatism for this period likely started farther toward the east with the older Josling Granite, and progressed westward, where the youngest Friersdale Charnockite is located (Fig. 5.1). There was an age gap of approximately 30 m.yr. between the early arc-related, syntectonic granite, represented by the Josling Granite, and the oldest granite of the Augrabies Suite. Based on the sampled granites in this study, there is an age gap of approximately 19 m.yr. between the Augrabies Suite and the Keimoes Suite.

6.3. Tectonic evolution of the eastern Namaqua sector

The Josling Granite sampled for this study is located toward the east, close to the Kaapvaal Craton and shows a volcanic arc-related to syn-COLG setting on the tectonic setting discriminant diagrams (Fig. 6.8d). This signature was likely inherited from the Areachap Group volcanic arc. An age of 1275 ± 7 Ma for the Josling Granite (Pettersson, 2008), is interpreted as an inherited age from older rocks of the same age group, indicating that there was minor crustal reworking of the older crust during the period of the early syn-tectonic magmatism likely due to progressive subduction and arc accretion along the eastern margin of the Namaqua sector.

The early syn-tectonic magmatism, recorded by the Josling Granite, occurred during the early stages of collision or arc accretion between the Namaqua sector and the Kaapvaal Craton as evidenced by its dominantly juvenile signature and a syn-collisional and continental rift tectonic setting (Fig. 6.7a-d), as well as the A 2 nature of the granites (Eby, 1992) (Fig. 5.10g). These geochemical signatures indicate that the collision between the Namaqua sector and Kaapvaal Craton began after 1217 Ma i.e. after the intrusion of the Josling Granite as it shows less crustal signatures due to the fact that less crustal materials were melted during this time. This finding corresponds with previous studies in the area which concluded that the continental collision between the Kaapvaal Craton and the Bushmanland
Subprovince of the Namaqua sector occurred at 1.20–1.18 Ga (Cornell et al., 1992; Eglington, 2006; Pettersson et al., 2007; Cornell and Pettersson, 2007; Bailie et al., 2011a).

This continental collision led to the extensive magmatism of the 1200 to 1120 Ma Augrabies Suite which intruded during the collisional period of the two crustal blocks i.e. the Kaapvaal Craton and Namaqua sector. The Augrabies Suite intruded in a collisional within plate tectonic setting environment, as shown by the tectonic setting diagrams (Fig. 6.7).

The granites of the Augrabies Suite were predominantly derived from depleted sources with minor, enriched and/or continental crustal material likely due to the fact that less crustal materials were melted compared to the later period (the Keimoes Suite period) during the time these granites formed (Fig. 6.1a-c). The depleted source composition observed for the Augrabies Suite granites is likely due to melting of mantle together with the materials from the Areachap Group which were combined with some of the Paleoproterozoic to Archean material from the western margin of the Kaapvaal Craton. The depleted source composition observed for the Augrabies Suite granites is likely due to melting of mantle together with the materials from the Areachap Group which were combined with some of the Paleoproterozoic to Archean material from the western margin of the Kaapvaal Craton. The crustal signature observed in the Augrabies Suite granite is likely due to melting of the Paleoproterozoic crust of the Richtersveld Subprovince as well as some material from the western margin of the Kaapvaal Craton (Cornell et al., 2006; Bailie et al., 2011). The 1337 ± 45 and 1342 ± 44 Ma inherited ages obtained from the Elsie se Gorra Granite (Table 5.2) of the Augrabies Suite together with volcanic arc signature on some of the granites of this suite (Fig. 6.7d) give evidence of some degree of reworking. The Sm/Nd and \( \varepsilon_{Nd(t)} \) and \( \varepsilon_{Sr(t)} \) isotopes large variation also emphasizes some degree of reworking of the source (Fig. 6.1c).

The predominantly depleted mantle signature with minor continental crustal contribution, along with the trace element characteristics, as seen in the spider diagram patterns and on some tectonic setting diagrams (Fig. 6.7a-c), suggest that these granites were formed during continental collision and indentor-induced wrenching (Colliston and Schoch, 2013) which led to partial melting of older materials of the Kaapvaal Craton and the surrounding rocks (Fig. 6.8b). The indentor induced wrenching is an important environment as it provides an extensional environment into which A-type granites can intrude (Bailie et al., 2011).

The collisional tectonic setting, combined with the within plate and continental rift tectonic settings of the granites, as well as the timing of the 1.20-1.17 Ga peak metamorphism and peak deformation (Cornell et al., 2012), suggests that the granites intruded during, and mark the major deformational, metamorphic and collisional period of the Namaquan orogeny when all these processes were taking place. This interpretation correlates with the observation that the composition of the granites vary with time in that the contribution of a continental crustal component increased with decreasing time so that the older granites contain a smaller continental crustal component to their source and more of a depleted source component.

The continued indentation and wrenching led to the development of a transpressional shear environment and the opening of rifts combined with some degree of orogenic collapse. This likely led to lithospheric thinning which resulted in mantle upwelling and melting at around 1116 to 1066 Ma to give
rise to the Keimoes Suite magmatism (Fig. 6.8c-d). This is shown by the granites in the form of continental rifting signatures on the tectonic setting diagrams of Verma et al. (2013). The source composition observed from the Keimoes Suite is due to the reworking of the materials that intruded at 1.18 - 1.14 Ga which was combined with material from both the Bushmanland Subprovince and some of the Kaapvaal Craton giving rise to more dominant crustal signatures compared to the older granites of the early syn-tectonic granite and Augrabies Suite. The inherited ages like 1345 ± 46 Ma and some of the 1132 ± 55 Ma, 1126 ± 47, and 1137 ±53 Ma obtained from zircons of the Keboes Granite of the Keimoes Suite together with some old model ages which are much similar to those of the Augrabies Suite emphasizes the reworking of the Augrabies Suite during Keimoes Suite magmatism.

Late members of the post-tectonic granites of the Keimoes Suite, namely the Straussburg Granite and Friersdale Charnockite, tend to show greater amounts of more depleted components compared to the older granites of the same age grouping. The voluminous late-tectonic charnockite has a predominantly depleted source composition compared to the older granites of the Keimoes Suite likely due to either lithospheric thinning giving rise to upwelling asthenosphere or lithospheric underplating at that time and magmatic fluxing which gave rise to melting of a more depleted source which was mixed with a crustal component.

Overall, the Keimoes Suite has a greater continental crustal component or signature compared to the early syn-tectonic granite and Augrabies Suite. The Keimoes Suite granites intruded after the collisional and subduction periods of the eastern Namaqua Sector and Kaapvaal Craton as shown by its relative age together with the minor compositional variation and homogeneity between the granites on the multi-elements diagrams as compared to the previous granites (Fig. 6.2).

The greater continental crustal component or derivation of these granites, as evidenced by the enrichment of the LILE relative to the HFSE as well as isotopic signatures such as negative epsilon Nd(t) values, relatively high epsilon Sr(t) and plotting within the continental crustal field on the εNd(t) vs. εSr(t) plot (Fig. 6.1a-b), suggests that the Keimoes Suite granites mark the period in which the Namaqua Orogeny was waning as less geochemical variation is observed and deformation textures in the granites are less. The late- to post-tectonic nature of these granites is also, to some extent, reflected in the degree of foliation developed within these granites, with the Kanoneiland Granite being more foliated compared to the far younger Straussburg Granite despite having relatively similar biotite contents. The large continental crustal component is associated with a greater degree of continental crustal materials being melted due to crustal blocks having being juxtaposed during collision. This partial melting gave rise to the voluminous Keimoes Suite granites which were largely derived from crust that has a subduction related signature. Some of this crust was of juvenile origin, as shown by some of the inherited ages within these granites together with a volcanic arc signature, likely associated with the Areachap Group (Fig. 6.8).
Figure 6.8. Simplified schematic Namaquan Orogeny tectonic evolution diagrams, modified from Bailie et al. (2011a). The diagrams also show the relative proportions of the granites which intruded during each stage, with most of the granites emplaced during the late- to post-tectonic period as well as their relative depth and geographic location (relative to the Craton). (a) The period of arc accretion and early tectonic stage magmatism. This resulted in intrusion of the Josling Granite, Dyasons Klip Granite and the Polisiehoek Granite. Only the Josling granite from this time period was sampled in this study. These intrusives are associated with arc accretion of the Areachap Group volcanic arc onto the western margin of the Kaapvaal Craton. (b) This period marked the onset of continental collision with peak magmatism between 1200-1120 Ma resulting in peak metamorphism caused by the voluminous intrusions of the Augrabies Suite due to crustal thickening. Six granites which were examined in this study belong to this group and were mostly derived from partial melting of a depleted source. (c) The period between 1116 and 1100 Ma marks the later stage of magmatism of the eastern margin of the Namaqua Sector. During this period there was a continuation of indentation of the Kaapvaal Craton into the Namaqua Sector with wrenching and shearing causing the development of rifting. The granites which intruded during this period include the Keboes Granite, Kanoneiland Granite, Gemsbokbult Granite and Kleinbegin Subsuite. The volcano on the eastern margin is associated with the Koras Group. (d) During the period between 1100 and 1065 Ma, there was lithospheric thinning which may have caused mantle upwelling and melting giving rise to the post-tectonic granites of the Keimoes Suite which are the Klip Koppies Granite, Straussburg Granite and the Friersdale Charnockite.
6.4. Relationship to deformation and metamorphism

Due to continental collision, which resulted in a number of granitic intrusions mostly within the Areachap Group, the western margin of the Kaapvaal Craton experienced several tectono-magmatic events which include deformation, folding and metamorphism. The granitoids of the eastern margin of the Namaqua sector record the tectonometamorphic events which took place between 1225 and 1066 Ma related to the Namaquan Orogeny. Arc accretion, associated with magmatism, as recorded by the early syn-tectonic Josling Granite, resulted in slight reworking of the older crust, possibly the Areachap Group. The degree of reworking is reflected by an inherited U-Pb zircon age of 1270 ± 7 Ma of the Josling Granite obtained by Pettersson (2008) within the Areachap Terrane along with other similar-aged intrusives and extrusives. Metamorphism within the Kakamas Terrane associated with the early syn-tectonic magmatism (taking into consideration the errors associated with these rocks) of the eastern Namaqua sector includes that recorded by the ion probe zircon dates obtained from the Kenhardt Formation migmatite (1190 ± 15 Ma) and biotite gneiss (1194 ± 23 Ma) (Cornell et al., 2012). The metamorphism caused by the early syn-tectonic magmatism is designated M1 and is associated with D1 deformation giving rise to F1 folding within the eastern Namaqua sector (Cornell et al., 2006; Bailie et al., 2010).

The ages associated with this metamorphic event suggest that the magmatism at this time did not only affect one terrane but covers a large area as it is observed in more than one terrane. The arc accretion of the Areachap Group onto the western margin of the Kaapvaal Craton resulted is the first deformation which affected most of the older gneisses of the Areachap and Kakamas Terranes. This observation is also supported by Cornell et al. (1992), who concluded that the first tectono-magmatic event is related to intrusion of the early syn-tectonic granitoids of the eastern margin of the Namaqua sector, which were associated with lower amphibolite M1 metamorphic conditions (Cornell et al., 1992) and the development of F1 folding that occurs in the Kheis Subprovince, and westward through the Wilgenhoutsdrif and Areachap Groups (Stowe, 1983; Bailie et al., 2011b). The Josling Granite shows a strong tectonic foliation rather than a magmatic foliation (Fig. 6.9).

The intrusion of the 1200 - 1120 Ma Augrabies Suite, together with other related magmatism (in terms of age) occurring within the Kakamas, Areachap and Kaaien Terranes, such as the Riemsasmaak Gneiss and extrusion of the Swartkopsleegte Formation of the lower Koras Group (Figs. 2.1, E1) are associated with the peak metamorphic conditions, at 1.2-1.17 Ga (M2) of the eastern Namaqua sector, as the ages of this metamorphism, as determined by Cornell et al. (1992), Pettersson et al. (2007) and Bailie et al. (2010), correspond with the intrusion age of the Augrabies Suite. The 1200 to 1120 Ma syn-tectonic granites mark the major tectonothermal period of the Namaquan Orogeny being associated with both peak metamorphism (M2) and peak deformation (D2) when the Bushmanland Subprovince collided with the western margin of the Kaapvaal Craton and the Gordonia Subprovince (Fig. 6.9B). The 1.20–1.18 Ga
(Cornell et al., 1992; Eglington, 2006; Pettersson et al., 2007; Cornell and Pettersson, 2007; Bailie et al., 2011a) continental collision led to extensive magmatism, as seen in the eastern Namaqua sector by the intrusion of the Augrabies Suite which led to peak metamorphism ($M_2$) (Cornell et al., 1992; Pettersson et al., 2007). According to Bailie et al. (2010), the peak $M_2$ metamorphic event was characterized by a temperature range of $\sim$700 to 800$^\circ$C, i.e. upper amphibolite to granulite facies at a pressure of 4.5 kbar and likely occurred from approximately 1.20 to 1.17 Ga. The rocks which record this metamorphism include the Jannelsepan Formation Lava (1142 ± 11 Ma) (Bailie, 2008), and the Jannelsepan Migmatite (Pettersson et al., 2007) with an 1165 ± 10 Ma metamorphic age, both units from the Areachap Terrane. Peak $D_2$ deformation occurred between 1.18 and 1.15 Ga resulting in the dominant NW–NNW-oriented $F_2$ folds that dominate the Areachap and Kakamas Terranes and die out eastward into the Kheis Subprovince (Bailie et al., 2011a).

The prominent shear zones of the eastern Namaqua sector, to some extent, influenced the development of foliation within the granites, as shown by the Cnydas Subsuite wherein the Molopo River Granite has a strongly foliated texture whereas other outcrops of the same subsuite, such as the Smalvis Granite, do not show any foliation. This is likely due to the fact that the Cnydas shear zone passes through the Molopo River Granite (Figs. 4.1, 6.10a-b). The Cnydas shear likely developed during the continental collision.

Three factors might have affected or caused the strongly foliated texture of the Vaalputs Granite, the first being the presence of the Boven Rugzeer shear (Fig. 4.1), the second being the age that it intruded during the collisional period between the Kaapvaal Craton and the Namaqua sector, and the third related to it being biotite-rich and the mechanisms associated with its intrusion (Cornell et al., 2012). The presence of the crosscutting Boven Rugzeer shear zone suggests that the foliation is dominantly due to tectonism and shearing. The foliation within the Louisvale Granite is likely due to the Louisvale shear zone (Fig. 4.1, 6.10c). The foliation observed on the Vaalputs and Louisvale Granite is mostly tectonic related.
Figure 6.9. Photomicrograph of the moderately to weakly foliated early syn-tectonic Josling Granite (mineral abbreviations: qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, mcl = microcline, srt = sericite). Field of view of the photomicrograph is 3 mm. (a) sericitised orthoclase. (b) quartz showing undulose extinction.

Figure 6.0. Photomicrograph of the Augrabies Suite granites. (a) Strongly foliated Molopo Granite of the Cnydas Subsuite. (b) Unfoliated to weakly foliated Smalvis Granite of the Cnydas Subsuite. (c) Foliated Louisvale Granite (d) Mildly foliated Klipkraal Granite showing some degree of deformation. Note the plagioclase which shows deformation twinning.
Figure 6.11. Photomicrographs of the Keimoes Suite granites. (a) Strongly foliated Klip Koppies Granite (b) unfoliated Straussburg Granite. (mineral abbreviations: qtz = quartz, plg = plagioclase, hbl = hornblende, bt = biotite, srt = sericite). Field of view of the photomicrographs are 3 mm. The granite has tectonic foliation as a dominant foliation.

The preferred orientation of the minerals within the Augrabies Suite, to some extent, is due to the intrusion mechanism together with deformation that occurred during the time of intrusion of these granites. Shearing affected the foliation of such granites as the Louisvale Granite and the Molopo Granite, a member of the Cnydas Subsuite, in that, moving away from the shear zone the degree of foliation decreases and grain size increases. Some of the granites which form part of the Augrabies Suite do not have any significant development of foliation. This includes the Klipkraal Granite (Fig. 6.11d) and certain members of the Cnydas Subsuite.

The intrusion of the Keimoes Suite, together with other related magmatism of the period between 1120 and 1066 Ma, such as the intrusion of the 1113 ± 7 Ma Beenbreek Gneiss (Pettersson et al., 2008) of the Kakamas Terrane, the 1093 ± 11 Ma Rooiputs Granophyre (Pettersson et al., 2008) and 1093 ± 10 Ma Bloubos Granite (Pettersson et al., 2009) of the Areachap Terrane and extrusion of the 1095 ± 10 Ma Leeuwdraai Formation (Pettersson et al., 2007) of the upper Koras Group are likely responsible for the metamorphism of the older granites and country rocks in the Areachap and Kakamas terranes. The Vaalputs Granite records a metamorphic age of 1062 ± 27 Ma (Pettersson, 2009) while the Kanoneiland Granite of the Keimoes Suite has metamorphic ages of 1063 ± 57 Ma (this study) which corresponds with the intrusion ages of the post-tectonic granites of the Keimoes Suite. The Keimoes Suite together with other related magmatism or intrusives during that time period, contributed to the M₃ metamorphism as recorded by the feldspathic quartzite of the Goede Hoop Formation of the Korannaland Group of the Areachap and Kakamas terranes (Bailie et al., 2011; Cornell et al., 2012).

The Keimoes Suite intruded predominantly to the east of the Augrabies Suite, with the Keimoes Suite found within the Areachap Terrane and, to a lesser extent, within the Kakamas and Kaaien Terranes (Fig. 1.1). The Keimoes Suite is associated with the development of the open, large-scale NE–ENE-trending F₃
folds following on from the earlier NW-SE-oriented \( F_2 \) folds supporting a NW–NNW directed stress and a collisional event from the NW (Bailie et al., 2011). The degree of foliation within the Keimoes Suite varies with ages so that no generalizations can be made as to whether it increases or decreases with time or not. The granites which show strongly developed foliation include the Kanoneiland Granite, the Kleinbegin Subsuite, and the Klip Koppies Granite, with slight foliation developed in the Keboes Granite. The foliation within the Kleinbegin Subsuite granites together with that of the Klip Koppies Granite is likely due to both the abundance of platy minerals in these granites together with being close to the Boven Rugzeer shear (Fig. 4.1). The Boven Rugzeer Shear might have played a role, to some extent, in the development of the foliation of the Klip Koppies Granite. The Gemsbokbult Granite is cut by the Boven Rugzeer shear but it does not have as strongly developed a foliation compared to the Klip Koppies Granite likely due to having less platy minerals compared to the latter (Fig. 4.1). The Gemsbokbult Granite is weakly foliated to unfoliated and is biotite-poor. The Kleinbegin Subsuite has a strongly foliated texture which is likely associated with the abundance of platy minerals within these granites together with the fact that it is crosscut by the Trooilapspan Shear (Figs. 4.1, E2).

The Kanoneiland Granite is moderately to strongly foliated and is not close to any shear zone but it intruded during the later stages of deformation. The Keboes Granite, which is of approximately the same age but outcrops more to the east, shows a weakly to unfoliated texture suggesting that deformation, largely, did not affect this granite with the abundance of platy minerals being a major control in the development of any foliation in this granite. The Straussburg Granite is also close to the Louisvale and Trooilapspan Shears yet shows an unfoliated texture (Fig. 6.12b) suggesting that the shear did not influence the granite.

This study agrees with the interpretation of Van Zyl (1981), in that the slight preferred orientation and elongate shape of xenoliths near the pluton margins is rather due to the intrusion mechanism of the viscous, partly crystallised granitic magma with entrained xenoliths, which was similar to the inflation of a balloon, rather than due to some induced tectonic force. This study also agrees with the interpretation of Cornell et al. (2012), in that the foliation present in many of the granites not crosscut by major shear zones is due to abundance of platy minerals which naturally develop a foliation even in the absence of an external force i.e. magmatic foliation.
7. Conclusion

SACS (1980) acknowledged that the previously defined Keimoes Suite included mixtures of diverse rock types likely not belonging to a single intrusive series and so should be subdivided into more than one intrusive suite. This study evaluated in detail, and with more reliable data, the group of granites of the eastern Namaqua sector previously known as the Keimoes Suite. U-Pb zircon age determinations have helped to redefine these granitoids so that three separate suites are recognized based on timing of intrusion or emplacement together with petrogenesis. One of the early syn-tectonic granites, the Josling Granite, was sampled. Granitoids of ages between 1371 Ma to 1200 Ma need to be sampled and studied properly in order to determine the characteristics of the suite which covers that time period and which will also assist in examining the tectonic evolution. The second suite is the 1200-1120 Ma Augrabies Suite which is largely derived from a depleted source with varying degrees of continental crustal components. The youngest suite recognized is the 1116 – 1066 Ma Keimoes Suite which is largely derived from partial melting of continental crust with a variable depleted source signature. The findings of the study also give clues as to the Mesoproterozoic tectonic evolution of the eastern Namaqua Sector at its junction with the western margin of the Kaapvaal Craton. This includes confirming that the collision occurred between approximately 1200 and 1180 Ma, as observed on changing or increasing continental crustal materials within the source of the Augrabies Suite. The three suites enable a closer examination of the tectonic evolution of the western margin of the Kaapvaal Craton and also enable determination of the stages of Namaquan Orogeny due to the fact that the granites change in composition with time or with each progressive stage of the tectonic evolution. The major difference between the three suites is that of source variation, with a greater enriched or crustal component signature with time.

The granites of the eastern margin of the Namaqua sector were derived from mixed sources which can be broadly categorized as depleted and continental crustal sources as indicated by the isotopic compositions with dominantly positive \( \varepsilon_{Nd(t)} \) values denoting a dominantly depleted source and dominantly negative \( \varepsilon_{Nd(t)} \) values denoting a crustal source. The degree of continental crustal material in the parental melts increased with decreasing age. The two youngest granites of the Keimoes Suite, namely the Straussburg Granite and Friersdale Charnockite contain smaller crustal components and more of a depleted source signature than most of the older granites. This was likely caused by the late Namaquan orogeny transcurrent movement accompanying rifting which led to decompression melting in the mantle resulting in more mafic components being melted and incorporated into the magma which formed the late post-tectonic granites of the Keimoes Suite. The early syn-tectonic Josling Granite has a small enriched source component due to the fact that minimal continental crustal material was melted at the time this granite was formed because it was associated with arc accretion of a juvenile arc. The Augrabies Suite has a greater amount of continental crustal components compared to the Josling Granite because of the collision between two crustal blocks, namely the Namaqua sector and Kaapvaal Craton which occurred during the period in which these granites intruded resulting in a greater degree
of partially melted material being incorporated from the Kaapvaal Craton. The continued indentation of the Kaapvaal Craton resulted in partial melting of thinned largely crustal materials giving rise to the voluminous, largely crustally derived Keimoes Suite.

Crystal fractionation has had a minimal influence on the compositions of the granites, but its effect increases with decreasing age, with the early syn-tectonic granite showing slight fractionation trends and the Keimoes Suite showing greater and clearer fractionation trends compared to the Augrabies Suite and early syn-tectonic granite. Fractionation of alkali feldspar, plagioclase feldspar, biotite and hornblende was, to a lesser extent, noted. Fractionation played a secondary role in controlling the compositions of the granites. The composition of the granites was controlled largely by compositional variations in the source that gave rise to the parental magmas together with the proportions of both the entrained accessory minerals and peritectic mineral assemblages. Maficity diagrams, combined with the trace element compositions of the granites, show the effect of partial melting and peritectic assemblage and accessory minerals entrainment very well so that from these diagrams three separate suites can be noted. The early syn-tectonic granite experienced small amounts of accessory mineral and peritectic assemblage entrainment as compared to most of the syn- and late- to post-tectonic granites and represents virtually pure melts. Within each suite, the oldest granites experienced smaller degrees of entrainment than the younger ones.

The deformation and metamorphism associated with the early syn-tectonic granites are \( D_1 \) and \( M_1 \), respectively, which occurred at temperatures of 400 to 550°C, with pressures ranging from 4.8 to 6.2 kbar (Cornell et al., 1992) which were associated with arc accretion. The \( D_1 \) deformation resulted in the development of the \( F_1 - F_2 \) folding events (Cornell et al., 1992). \( D_2 \) deformation and \( M_2 \) metamorphism, which occurred at temperatures of 700 - 800°C and a pressure of 4.5 kbar (Cornell et al., 1992), are the main deformational and metamorphic events, respectively, recognized in the rocks on the eastern margin of the Namaqua sector. These are associated with the emplacement of the Augrabies Suite, and are well recognized within both the Kakamas and Areachap terranes of the Gordonia Subprovince. The \( D_2 \) deformation resulted in the NW oriented \( F_2 \) folds of the Gordonia Subprovince (Bailie et al., 2010). \( D_3 \) deformation, associated with \( M_3 \) metamorphism, which occurred at a temperature of 640°C and a pressure of 4.8 kbar (Cornell et al., 1992), is recognized within the Kaaiken, Areachap and Kakamas terranes, and are associated with the intrusion of the Keimoes Suite granites and other intrusives such as the 1113 Ma Beenbreek Gneiss of the Kakamas Terrane and the 1093 Ma Bloubos Granite of the Areachap Terrane as well as contemporaneous extrusives such as the 1095 Ma Leeuwdraai Formation of the Koras Group. The structural features which are associated with the \( D_3 \) deformation and \( M_3 \) metamorphic events include the NE - ENE oriented \( F_3 \) folds (Bailie et al., 2010). The Keimoes Suite marks the late- to post-tectonic stages of the Namaquan Orogeny. By the end of the early syn-tectonic intrusion (before 1200 Ma), the 1217 Ma Josling Granite, occur across the boundary of the Kakamas and Areachap terranes indicating that the terranes were already sutured together by that stage. The role of the Kakamas terrane is thus still enigmatic and the western margin of the Kaapvaal Craton still unclear.

The Augrabies Suite, according to Cornell et al. (2012), was defined as a group of 1200 to 1150 Ma syn-tectonic granitoids which have similar origins as magmas formed in crust thickened by collision. The Augrabies Suite in this study is defined as a suite which comprises the 1200 - 1120 Ma syn-tectonic
granites derived from a depleted source with varying degrees of continental crustal contribution. Cornell et al. (2012) defined the Keimoes Suite as post-tectonic in relation to the 1200 Ma collisional orogeny, and which comprises felsic and mafic intrusions ranging in age from 1113 to 1078 Ma, occurring in the Kakamas, Areachap and Kaaiken terranes of the Namaqua Sector which lack a foliation. Based on this study, the Keimoes Suite can be defined as a suite which comprises the late to post-tectonic felsic igneous rocks ranging in age from 1116 Ma to 1066 Ma occurring within the Kakamas, Areachap and Kaaiken terranes of the Namaqua Sector.

This study supports the idea that the Areachap Group volcanic arc developed between 1.29 and 1.24 Ga on the western margin of the Kaapvaal Craton (Pettersson et al., 2007), as evidenced by geochemical composition together with inherited ages which were likely inherited from the Areachap Group. This is also seen by the arc signature in the Josling Granite and the inheritance seen in an age of 1270 Ma for the Klipkraal Granite. This work also supports the idea that the suture between the western margin of the Kaapvaal Craton and the Namaqua Province occurs to the west of the Areachap Group volcanic arc which developed on the western margin of the Kaapvaal Craton. This is likely to be along the zone marked by the voluminous intrusion of the highly foliated granitoids of both the early syn-tectonic granite, Augrabies Suite and the Keimoes Suite. The suture zone is also characterised by high-grade granulite facies metamorphic rocks in the Kakamas terrane, as suggested by Van Niekerk (2006).

The geochronology has proven that the previous classification of the Keimoes Suite based on degree of foliation is unfounded. Magmatism resulted due to different tectonic events at different times. The previous classification of the Keimoes Suite based on foliation is not reliable since the granites and the minerals which comprise them responded differently to deformation and/or metamorphism. An example of a young post-tectonic, but strongly foliated granite is the Klip Koppies Granite (1096 ± 10 Ma Mammagean age) which was dated by Bailie et al. (2011a). The Keboes Granite and Cnydas Subsuite are examples of older granites which have an unfoliated texture except for one member of the subsuite which outcrops adjacent to, and along the Cnydas Shear which shows a strongly foliated texture. It was therefore concluded in this study that the tectonic foliation/deformation groupings should be abandoned, since, to a large extent, they were misleading and led to the incorrect age classification of the rocks. The rocks which tend to have more biotite and muscovite tend to be more strongly foliated. However, more field work is required in order to examine the role of various deformational features, such as shearing, in determining the development of foliation or a fabric in the granites and the extent of that foliation.
References


Appendix A. Lithological description

The eastern Namaqua syn- to post-tectonic granitoids vary from coarse grained, slightly porphyritic, grey granites to medium-grained, charnockitic monzogranite (Geringer et al., 1987). The Keimoes Suite granites of the Namaqua Sector intruded metasediments of the Korannaland Group (Blignault and Geringer, 1980), and display an intimate relationship with the calc-alkaline volcanic sequence of the Areachap Group (Geringer et al., 1986, 1988).

The granites can be described based on their outcrop characteristics and relationships, hand-specimen and microscopic characteristics to validate the previous groupings / classification. All the measurements are given in dip direction / dip method.

A1. Cnydas Subsuite

Different varieties of the Cnydas Granite were sampled from east (sample Mc 1) to west (sample Mc 9), with the samples examined both petrographically and geochemically to investigate their differences and to determine whether they ought to be classified as a single plutonic entity, or must be separated (Fig. E2).

A1.1 Molopo River Granite (Mc 1) (S 28° 24'54.1"; E 020° 35'25.1"; elevation 831m)

The Molopo Granite is strongly sheared, coarse grained and strongly foliated granite. This granite is composed of 21% quartz, 20% microcline, 20% orthoclase, 15% plagioclase, 10% biotite, 5% hornblende, 3% chlorite, 2% opaque minerals, 2% muscovite, 1% zircon and 1% rutile (Fig. A1.1a, b). The foliation is defined by the alignment of minerals such as biotite, hornblende, quartz, rutile, opaque minerals and muscovite which wrap around the phenocrysts (Fig. A1.1a, b). The rock has a porphyritic texture defined by phenocrysts of plagioclase, microcline, orthoclase and quartz, in order of decreasing abundance, within a groundmass of quartz, plagioclase, microcline, biotite, hornblende and opaque minerals, in order of decreasing abundance. The phenocrysts exhibit glomeroporphyritic texture defined by clusters of microcline phenocrysts, as well as cumulophyric texture defined by clustering of microcline, orthoclase and plagioclase phenocrysts.

Quartz forms 0.03 - 0.5 mm subhedral to anhedral crystals. Locally, it is concentrated between phenocrysts of other minerals and forms part of the minerals which are defining a foliation in the granite. Microcline occurs as 0.05 - 1.5 mm subhedral to anhedral crystals. Orthoclase comprises 0.05 - 1 mm crystals. Crystals of orthoclase are subhedral to anhedral and contain overgrowths of quartz of approximately 0.1 mm size. Plagioclase forms 0.08 - 0.8 mm subhedral to anhedral crystals and mostly occurs as phenocrysts, with lesser amounts as groundmass. Biotite forms approximately 0.08 - 0.8 mm
anhedral grains between the phenocrysts and defines the foliation of the rock. Biotite shows pleochroism which ranges from dark brown through brown to green. Hornblende forms subhedral to anhedral crystals of approximately 0.08 - 0.5 mm in size and occurs in the biotite-rich zone in the groundmass. Chlorite occurs along the zones dominated by biotite, hornblende and muscovite defining the foliation of the granite. Opaque minerals form grains 0.1 - 0.3 mm in size and mostly crystallise within the biotite-rich zone and are anhedral in shape. Muscovite occur as 0.05 - 0.3 mm grains and crystallises within the biotite-rich zone. Zircon forms 0.05 mm prismatic crystals which occur between the mineral boundaries of mostly highly sericitised phenocrysts of orthoclase, plagioclase and microcline. Rutile forms approximately 0.05 mm crystals which mostly occur between the grain boundaries of quartz in the groundmass and also occurs as inclusions within phenocrysts of sericitised plagioclase and orthoclase.

The feldspars have been variably altered to form sericite and locally no longer show any traces of twinning, but are completely sericitisited with their crystal shapes usually preserved as subhedral to anhedral shapes. Phenocrysts of microcline are the most highly sericitised compared to the groundmass. Plagioclase is mildly altered to form sericite, whereas orthoclase is more sericitised, but the original subhedral to anhedral crystal shapes of the phenocrysts are still evident.

The Molopo Granite member is dark in colour and is dominated by the presence of mafic xenoliths (Fig. A1.2c). The xenoliths range in size from 1 cm - 10 cm. The granite comprises both tectonic and magmatic related foliation and is coarse grained. The magmatic foliation is poorly developed and is only found in a few outcrops along the margin of the pluton. The granite has a pitted surface marked by voids on its surface due to weathering (Fig. A1.2d).

The granite is crosscut by quartz and quartzofeldspathic veins with widths of approximately 0.2 cm - 15 cm (Fig. A1.1b). The quartzofeldspathic veins are composed of quartz, plagioclase, alkali feldspar and minor biotite. The veins are poorly developed, with lengths of approximately 30 cm. Some of the quartzofeldspathic veins have the same orientation as the regional foliation of the outcrop with the veins oriented 220°/20° and 012°/06°. The granite contains some quartz-filled joints. The quartz veins have been slightly faulted so that they show a slight displacement of approximately 15 cm.

A1.2. Smalvis Granite (S 28° 24’47.8’’; E 020° 35’18.6’’; elevation 837m)

The Smavis Granite member of the Cnydas Shear is a medium grained, porphyritic and unfoliated, composed of 28% quartz, 20% plagioclase, 15% orthoclase, 10% microcline, 10% perthite, 5% biotite, 4% hornblende, 4% muscovite, 3% opaque minerals, and 1% zircon (Fig. A1.1c; d). The granite contains phenocrysts of orthoclase, plagioclase, quartz and microcline, in order of decreasing abundance (Fig. A1.1d).
Quartz forms 0.02 - 0.5 mm subhedral to anhedral crystals. It mostly occurs within the groundmass of the rock, with lesser amounts present as phenocrysts. Plagioclase forms 0.05 - 0.5 mm subhedral to anhedral crystals which mostly occur within the groundmass. Orthoclase forms 0.05 - 1.5 mm anhedral crystals present mostly as phenocrysts with lesser amounts within the groundmass of the rock. Orthoclase contains overgrowths of quartz. Microcline forms 0.05 - 1 mm subhedral to anhedral crystals which mostly form the phenocrysts with lesser amounts present within the groundmass. It contains overgrowths of sericite, quartz, biotite and hornblende. Perthite forms anhedral 0.08 - 0.5 mm crystals which mostly occur as phenocrysts rather than as groundmass. Phenocrysts of perthite contain overgrowths of quartz. Biotite forms 0.1 - 0.5 mm pleochroic dark brown to light brown grains.

Cumulophyric texture is defined by clustering of quartz, microcline, plagioclase and orthoclase phenocrysts. The rock is dominated by anhedral phenocrysts, with an interlocking texture for both the groundmass and the phenocrysts. Clusters of hornblende, opaque minerals, muscovite, and sericitised feldspars are present within the groundmass. Euhedral crystal shapes are rarely present, but rather crystals are poorly developed due to simultaneous crystal growth and some degree of deformation and recrystallisation. The rock is moderately to slightly altered. The minerals which are altered include plagioclase, microcline and orthoclase which are variably sericitised. The phenocrysts are more altered compared to the groundmass.

The outcrops of this granite contains very small, fine grained, poorly developed (short and thin) quartz veins of approximately 15 cm length. The granite also shows a pitted weathered surface. Some parts of this granite contain alkali feldspar phenocrysts which are randomly oriented so that they do not define any foliation. Moving towards the east, the granite becomes more alkali- and plagioclase feldspar-rich (S 28° 13’36.0”; E 020° 23’37.6”; elevation 827m). Towards the east, the granite becomes more medium to coarse grained and contains small shear zone which crosscuts the granite (Fig. A1.2g). The outcrops at Smalvis are “clean” compared to those to the west in the sense that they do not show many features in terms of magmatic processes, such as quartz veins, xenoliths or phenocrysts.
Figure A1.1. The hand specimens (left) and their photomicrographs (right) of the Cnydas Subsuite arranged from east ((a) and (b)) to west ((e) and (f)). (a; b) The hand specimen and photomicrograph of the Molopo River Granite at the Cnydas shear zone at Cnydas West (sample Mc 1) showing a very coarse augen-texture and strongly foliated granite. (c-d) Samples from the outcrop located at Smalvis showing a medium grained and moderately foliated granite (sample Mc 5). (e-f) Samples collected from north of Smalvis (sample Mc 9) showing a coarse grained and weakly to unfoliated granite with the foliation defined by the fine grained groundmass of quartz concentrating between the phenocrysts (qtz = quartz, plg = plagioclase, ort = orthoclase, opq = opaque, pth = perthite, hbl = hornblende, bt = biotite, mcl = microcline, srt = sericite). Field of view is 3 mm for all photomicrographs.
Figure A1.2. Outcrops of the Cnydas Subsuite. (a) Poorly exposed outcrops along the Cnydas shear zone. (b) Highly weathered granite crosscut by poorly developed quartz veins crosscutting the Cnydas Granite near the Cnydas shear zone. (c) Alkali feldspar xenocryst oriented in the same direction as the major foliation of the rock. (d) Pitted texture on the surface of the Cnydas Granite due to weathering of other minerals. (e) The well-developed and extensive outcrops of the Cnydas Granite towards Namibia. (f) Isolated outcrops of the Cnydas Granite. (g) Shearing within the granite.
A1.3. Gous Charnockite (Mc 9) (S 28° 15’10.6”; E 020° 24’23.3”; elevation 834m)

The granite is porphyritic, coarse grained and unfoliated composed of phenocrysts of quartz, microcline, orthoclase, plagioclase and perthite, whereas the groundmass is composed of quartz, microcline, orthoclase, plagioclase, muscovite, biotite, hornblende and opaque minerals (Fig. A1.1f). The rock also shows myrmekitic texture due to the intergrowth of quartz with plagioclase and also exhibits glomeroporphyritic texture defined by quartz, orthoclase and plagioclase phenocrysts. The plagioclase phenocrysts contain sericite veins which do not continue to other neighboring grains. The phenocrysts contains hornblende overgrowth.

The minerals are arranged in the order of abundance. Quartz forms 0.05 - 2 mm euhedral to subhedral crystals (Fig. A1.2e, f). Microcline ranges from 0.08 - 2 mm and forms subhedral to anhedral phenocrysts enveloped by the quartz-rich groundmass. Orthoclase forms 0.08 - 0.8 mm euhedral to subhedral crystals. The phenocrysts of orthoclase contain overgrowths of opaque minerals and biotite and are crosscut by sericite micro-veins. Plagioclase forms 0.08 - 1.5 mm subhedral to anhedral crystals. Perthite is represented by 0.8 - 1.5 mm grains which mostly occur as phenocrysts. The phenocrysts are enveloped by medium grained quartz, biotite and hornblende. The cores of the phenocrysts are more sericitised compared to the edges, with the twinning planes in some of the phenocrysts overgrown by sericite and hornblende. Muscovite forms 0.05 - 0.1 mm crystals and occurs as an overgrowth of the plagioclase phenocrysts. Biotite forms pleochroic dark green to brown lath-like crystals within the groundmass and also occurs as an overgrowth on the phenocrysts. Hornblende forms 0.05-0.1 mm pleochroic dark brown to green anhedral crystals found between the phenocrysts. Hornblende, biotite and opaque minerals, locally, occur as veins crosscutting the plagioclase phenocrysts. Opaque minerals occur as subhedral to anhedral 0.05 - 0.3 mm crystals which occur with the biotite and hornblende. Apatite crystals are 0.05 - 0.2 mm in size and occur as inclusions within the altered subhedral phenocrysts of microcline and plagioclase. Zircon forms 0.05 mm euhedral prismatic crystals which occur along with the opaque minerals in the biotite-rich zone and also as inclusions in biotite.

A2. Colston Granite

The members which are examined in this study are the Rooidam Member, which is located to the east, and the Toeslaan Member, which is located more towards the west.

A2.1. Colston Granite - Rooidam member (S 28° 25’42.4”; E 020° 49’24.9”; elevation 873m)

This granite is composed of 25% quartz, 20% plagioclase, 15% orthoclase, 12% biotite, 10% microcline, 8% hornblende, 8% muscovite and 2% garnet (Figs. A2.1a,b). Quartz crystals range from 0.08 - 0.5 mm and mostly occur as subhedral to anhedral grains exhibiting undulose extinction in the groundmass and occur between the phenocrysts as 0.2 - 0.5 mm grains. Some quartz crystals (0.07 mm in size) form an interlocked texture with other minerals in the groundmass such as plagioclase. Plagioclase forms 0.5-3 mm crystals and mostly occurs as phenocrysts containing overgrowths of quartz. The phenocrysts of
plagioclase show Carlsbad twinning. The phenocrysts, which are mostly sericitised to varying degrees, are enveloped by small crystals of quartz which show undulose extinction. The plagioclase and alkali feldspars phenocrysts are enveloped by biotite, quartz and sericitised feldspar, forming interlocking textures. Orthoclase forms 0.1 - 2.5 mm crystals and are mostly highly sericitised. Orthoclase forms anhedral phenocrysts. Biotite (0.8 mm) forms pleochroic dark reddish brown to green to light brown anhedral or lath like crystals which occur mostly between the phenocrysts and define the foliation of the rock. Biotite also occurs as overgrowths within phenocrysts of quartz, plagioclase, orthoclase and microcline. Microcline forms 0.2 - 2 mm grains in size which are mostly phenocrysts up to 2 mm in size. The phenocrysts of microcline are mostly sericitised. Hornblende forms 0.05 - 0.2 mm grains, occurring within the zones dominated by biotite and muscovite defining the foliation of the granite. Muscovite forms 0.01 - 0.5 mm lath like clusters forming part of the groundmass within the same biotite-rich zone defining the foliation of the rock. Sericitic aggregates range from 0.2 - 1 mm in size. Sericite was formed as a result of sericitization of feldspars such as orthoclase, microcline and plagioclase. Garnet occurs as 0.08 - 0.5 mm subhedral crystals within the zone of minerals which define the foliation. The foliation wrapped around the garnets.

The Rooidam outcrop is poorly to moderately exposed and is less weathered compared to other outcrops of the Colston Granite (Fig. A2.1a,d). The outcrops have pitted, weathered surfaces and are dark on the weathered surface and lighter on the fresh surface. The Rooidam Granite variety of the Colston Granite is coarse grained, porphyritic and weakly foliated to unfoliated containing mafic inclusions of biotite and hornblende-rich (Fig. A2.1a, A2.2b)).
Figure A2.1. Photographs of hand specimens and photomicrographs of the Colston Granite. (a) The Rooidam Road outcrop hand specimen. (c) The Toeslaan 440 outcrop hand specimen. (b) Photomicrograph of the Rooidam road outcrop showing a weak foliation and minor alteration. (d) Photomicrograph of the Toeslaan 440 outcrop showing a highly sericite and moderately foliated granite (qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, ms = muscovite, srt = sericite). The field of view for the photomicrographs is 3 mm.
Figure A2.2. The Colston Granite at Rooidam 441. (a) The outcrops of the Colston Granite by the Rooidam road. (b) Xenocrysts of feldspathic quartzite oriented in the same direction as the poorly defined magmatic foliation. (c) Alkali feldspar phenocrysts defining a magmatic foliation. (d) Highly weathered Colston Granite but still showing the foliation which has been enhanced by weathering.

A2.2. Colston Granite - Toeslaan Member (S 28° 18’ 57.3”; E 020° 44’ 56.0”; elevation 865m)

The Toeslaan Granite is a porphyritic, coarse grained, strongly foliated and biotite-rich granite (Fig. A2.1c). The granite comprises microcline, orthoclase and plagioclase phenocrysts of 15 cm size (Fig. A2.1c). This granite is composed of 25% plagioclase, 20% quartz, 15% orthoclase, 15% microcline, 10% biotite, 6% muscovite, 5% hornblende, 3% garnet, and 1% zircon (Fig. A2.1c; d).

The granite has a porphyritic texture comprising phenocrysts of orthoclase, plagioclase, microcline and quartz within a groundmass of the same minerals along with biotite, hornblende, muscovite and opaque
minerals (Fig. A2.1d). The granite foliation is locally defined by microphenocrysts (0.5 - 1 mm) of quartz which show undulose extinction crystallizing between, and wrapped around the phenocrysts of plagioclase, microcline and orthoclase. The foliation is also defined by minerals such as biotite, hornblende and muscovite which envelop the phenocrysts.

Quartz ranges from 0.05 - 1 mm in size and forms subhedral to anhedral crystals. Plagioclase forms 0.3 - 2.5 mm euhedral to subhedral crystals. Microcline crystals range from 0.5 - 3 mm in size and form euhedral to subhedral crystals and contains overgrowths of quartz (0.3 - 0.8 mm) and biotite (0.3 mm). The overgrowths go extinct at different angles suggesting that they are not part of one large crystal but are rather small crystals that were formed separately or are due to recrystallization. The microcline phenocrysts are mildly sericitised and are enveloped mostly by groundmass of sericitised alkali feldspars and quartz. Orthoclase forms highly sericitised crystals which range between 0.2 - 2 mm in size and is enveloped by biotite and hornblende. The orthoclase phenocrysts are enveloped by small quartz crystals. Biotite forms 0.08 - 0.5 mm lath-like crystals with brownish to greenish pleochroism. Biotite and hornblende partially replace the highly sericitised phenocrysts of orthoclase. Muscovite ranges from 0.05 - 0.1 mm in size, partially replaces the sericitised phenocrysts, and occurs in the zones dominated by biotite and opaque minerals. Hornblende forms 0.5 - 1 mm crystals with pleochroism ranging from green to dark brown. Phenocrysts of hornblende form anhedral to subhedral crystals with most of the subhedral als occurring on the sericitised plagioclase. The hornblende in the groundmass forms an interlocking texture in which it occurs between the phenocrysts. Hornblende crystallises within the mafic mineral zone which is largely composed of biotite which defines the foliation. Zircon forms 0.05 mm prismatic crystals occurring within the biotite-rich zone.

A3. Friersdale Charnockite

The Friersdale Charnockite can be defined as medium to coarse grained from east to west across the outcrop extent, but it is generally coarse grained. The charnockite is composed of 19% quartz, 19% plagioclase, 15% microcline, 8% orthoclase, 7% perthite, 5% cordierite, 5% biotite, 5% hornblende, 4% muscovite, 4% orthopyroxene, 3% piemontite, 2% opaque minerals, 2% epidote, 1% garnet and 1% zircon (Fig. 3.3.7.1a-d). The Friersdale Charnockite contains alkali feldspar phenocrysts which do not define any foliation or show any orientation, either magmatic or tectonic related, but a few small outcrops located at Koekoeb show a slight magmatic foliation (Fig. A3.1b, A3.2b).

The rock has a porphyritic texture comprising phenocrysts of quartz, plagioclase, microcline, perthite, orthoclase, cordierite, orthopyroxene and garnet within a groundmass composed of quartz, plagioclase, biotite, piemontite, epidote, hornblende, microcline, perthite, opaque minerals and orthoclase. Cumulophyric texture is defined by clustering of plagioclase, microcline, quartz and orthoclase phenocrysts. Most of the phenocrysts, particularly those of plagioclase and perthite, anhedral so that the crystals are enveloped by medium grained (0.05 mm) quartz showing undulose extinction.
Plagioclase phenocrysts show a Carlsbad twinning texture. Quartz grains exhibit undulose extinction. The groundmass is equigranular and is medium to fine grained. The charnockite contains overgrowths of biotite and opaque minerals replacing altered plagioclase. Myrmekitic texture, which is the intergrowth of quartz and plagioclase, is also present.

Quartz forms 0.05 - 3 mm subhedral to anhedral crystals. Plagioclase forms subhedral to anhedral 0.1 - 1.5 mm crystals. Plagioclase phenocrysts exhibit Carlsbad twinning defined by polysynthetic twinning. Microcline forms 0.08 - 0.6 mm crystals which are enveloped by the quartz-rich groundmass, with most of the crystals forming interlocking crystals with the same minerals and also of different mineral types. Microcline forms subhedral to anhedral crystals and is mostly found as phenocrysts.

Orthoclase forms 0.08 - 0.8 mm subhedral to anhedral crystals and perthite forms 0.08 – 1 mm euhedral to subhedral crystals, and is enveloped by the quartz groundmass. Cordierite forms 0.05 – 1.5 mm subhedral to anhedral crystals which contain quartz, biotite, muscovite and plagioclase inclusions. Biotite occurs as pleochroic brown to green lath-like anhedral 0.05-0.5 mm crystals. Hornblende occurs as anhedral 0.08 - 0.5 mm, pleochroic green to brown grains. Hornblende occurs within the biotite-rich zone. Muscovite and small biotite crystals are associated with the sericitic alteration of the feldspars. Sericite forms as an alteration product of feldspar minerals and forms aggregates or clusters ranging from 0.01 - 1 mm mostly where it is replacing the plagioclase phenocrysts. Orthopyroxene forms 0.1 - 0.8 mm anhedral to subhedral crystals occurring within the biotite-rich zone and mostly occurs in the zones dominated by hornblende and biotite. Piemontite forms subhedral 0.3 mm crystals enveloped by pleochroic green hornblende. Opaque minerals range from 0.05 - 0.8 mm forming clusters within the biotite-rich zone along with strained quartz and anhedral groundmass minerals between the phenocrysts. Garnet crystals range from 0.08-0.8 mm forming euhedral to subhedral shapes which are enveloped by quartz. Zircon forms 0.05 mm crystals and occurs in the biotite- and hornblende-rich zone.

The Koekoeb outcrops also show some sickenline features which define a minor lineation and show top-down to the NE direction of movement. This granite also shows some folding, defined by fine grained xenoliths (Fig. A3.2c). The charnockite contains quartz clusters which are composed of quartz and contain minor biotite which define or show minor foliation. The Friersdale Charnockite forms tors to low lying types of outcrop which range in shape from rounded to irregular.
Figure A3.1. (a) Hand specimen and (b-d) photomicrographs of the porphyritic Friersdale Charnockite (qtz = quartz, plg = plagioclase, mcl = microcline, ort = orthoclase, pth = perthite, crd = cordierite, bt = biotite, hbl = hornblende, ms = muscovite, srt = sericite, opx = orthopyroxene, opq = opaque, grt = garnet). Field of view of the photomicrographs is 3 mm.
Figure A3.2. The Friersdale Charnockite outcrops. (a) An epidote vein and the associated alteration zone. The oxidation halo around the epidote vein is marked by pink feldspars. (b) Alkali feldspar phenocrysts. (c) The shear zone within the Friersdale Charnockite.
A4. Vaalputs Granite

The Vaalputs Granite ranges from medium to coarse grained and is strongly foliated, with the foliation mostly defined by biotite and minor hornblende together with muscovite (Fig. A4.1a). The granite is composed of 22% quartz, 16% plagioclase, 15% orthoclase, 15% microcline, 10% biotite, 10% muscovite, 5% opaque minerals, 4% hornblende and 3% phlogopite (Fig. A4.1a-d). The granite has porphyritic texture defined by phenocrysts of plagioclase, orthoclase and microcline in a groundmass of quartz, biotite, plagioclase, muscovite, opaque minerals and microcline together with hornblende. The granite also show glomeroporphyritic texture defined by phenocrysts of orthoclase.

Quartz ranges from 0.05 - 0.8 mm subhedral to anhedral crystals showing undulose extinction. Plagioclase ranges from 0.05 - 1 mm in size forming euhedral crystals with some highly sericitised grains having poorly defined grain boundaries and containing randomly oriented muscovite overgrowths. Crystals of plagioclase also contain biotite overgrowths which are aligned in the direction of the twinnings. Orthoclase forms 0.05 - 1.5 mm anhedral to subhedral crystals. Microcline forms 0.08 - 1.5 mm crystals. Biotite forms 0.1 - 0.8 mm lath-like crystals showing greenish to brownish pleochroism forming part of the groundmass and showing interlocking texture. Muscovite forms 0.05 - 0.1 mm grains and mostly occurs in the zone dominated by biotite and opaque minerals defining the foliation of the granite. Muscovite mostly occurs as fine-grained clusters. Opaque minerals range from 0.05 - 0.5 mm in size and occur in the zone dominated by mafic minerals defining the foliation of the granite. The opaque minerals mostly concentrate along the zones dominated by hornblende. Hornblende crystals range from 0.08 - 1 mm in size showing pleochroism which ranges from greenish to brownish; crystals with subhedral to anhedral shapes, locally, form lath like elongate crystals. Phlogopite forms 0.05 - 0.5 mm lath like crystals and is concentrated in the same zone dominated by muscovite and biotite showing the same size and shape as biotite.

The foliation is created by minerals such as biotite, hornblende, muscovite and the opaque minerals which cluster together along the boundaries of the phenocrysts (Fig. A4.1c, d). Another feature defining the foliation of this rock is the clustering and alignment of coarser grains, which mostly includes the phenocrysts, in the same orientation as the finer grained groundmass which is mostly comprised of quartz which shows undulose extinction (Fig. A4.2d).
Figure A4.1. (a) The hand specimen and (b-d) photomicrographs of the Vaalputs Granite showing that the granite is strongly foliated (qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, hbl = hornblende, mcl = microcline, ms = muscovite, opq = opaque minerals and phg = phlogopite). Field of view of all the photomicrographs is 3 mm.

Some of the altered plagioclase shows Carlsbad twinning. Plagioclase, orthoclase and microcline are the most altered minerals so that their grain boundaries are no longer distinct (Figs. A4.1b, d). The most sericitized minerals are the feldspars in the groundmass associated with biotite, hornblende and opaque minerals. Sericite forms 0.05 - 1 mm clusters mimicking the shape of previously altered subhedral.
The Vaalputs Granite outcrops are characterised by onion skin type weathering patterns where the outer layers peel off like the layers of an onion (Fig. A4.2b). The top part of the outcrop is unfoliated whereas the bottom part is strongly foliation. The Vaalputs Granite contains xenoliths of approximately 1.5 cm - 18 cm long which are comprised of different mineral assemblages mostly dominated by biotite and hornblende. Most of the xenoliths have the same orientation as the foliation of the granite. The granite contains large xenoliths of feldspathic quartzite which are also oriented in the same direction as the major foliation of the rock.

The quartz veins mostly intrude along weak areas of the granite, such as along joints. The width of quartz veins ranges between 0.3 cm and 200 cm, with lengths of 1 cm - 300 cm. The area into which the veins intruded is characterised by compressional stresses which resulted in strongly developed foliation within the contact zones of the granite and quartz veins. The quartz veins then intruded along these sheared areas causing a small alteration zone around the veins. Most of the quartz veins are randomly distributed and oriented. The quartz veins show various different phases of brittle deformation (Fig. A4.2b). This deformation has resulted in the displacement of the original orientation of the quartz veins. The alteration zone or selvedge around the quartz veins, of approximately 0.5 cm thickness, is marked by minerals such as quartz, alkali feldspar, biotite and muscovite.

Figure A4.2. Outcrops of the Vaalputs Granite. (a) Strongly developed regional foliation in well exposed outcrops. (b) A quartz vein which has been displaced by brittle deformation.

The boundary between the Vaalputs Granite and the Goede Hoop Formation (feldspathic quartzite) of the Korannaland Group is characterised by a tectonic foliation. The foliation is defined by a different mineral assemblage than that which characterised the tectonic foliation in other areas of the same granite such as epidote that is not found elsewhere. This foliation is dominated by epidote together with biotite, and the contact zone is highly oxidised so that the Vaalputs Granite has a reddish colour.
The Vaalputs Granite is widely distributed and is one of the dominant granites covering a vast area of the central Gordonia Subprovince. The outcrops can be found at Kanoneiland village/town, where the Vaalputs Granite is in contact with the Kanoneiland Granite. Other well exposed outcrops of the Vaalputs Granite are widely distributed in and around Keimoes, in which they are in contact with the Friersdale Charnockite (Fig. 4.2.3). Most of the contacts of the Vaalputs Granite with other lithologies and successions are characterised by massive vein quartz pebbles. Massive and boulder hill-type outcrops of the Vaalputs Granite are well exposed at Curries Camp. At this location, the Vaalputs Granite is medium to coarse grained and is cross-cut by large quartz veins of approximately 25 m long and approximately 2.5 m width oriented NW-SE. The granite also shows magmatic foliation and biotite-hornblende rich xenoliths which are oriented NW-SE.

A5. Kanoneiland Granite

The Kanoneiland Granite can be classified as a foliated late syn-tectonic granite. The granite has a moderately to strongly foliated, coarse grained porphyritic texture composed of 25% quartz, 20% plagioclase, 15% orthoclase, 15% biotite, 8% muscovite, 5% microcline, 5% hornblende, 3% perthite, 2% phlogopite, 1% rutile and 1% zircon (Fig. A5.1a, b). The granite has a myrmekitic texture mostly occurring between quartz and orthoclase phenocrysts.

Quartz forms 0.05 - 1.5 mm crystals forming part of both the groundmass and phenocrysts. Crystals of quartz within the groundmass cluster together. Phenocrysts of quartz form an interlocking texture with orthoclase and plagioclase. Quartz grains are also elongated, helping define the foliation of the rock, with quartz and orthoclase subhedral to anhedral and forming glomeroporphyritic texture. Plagioclase forms part of both the groundmass and phenocrysts of the rock, with crystals ranging from 0.05 - 1.5 mm in size and being subhedral to anhedral and sericitised. Plagioclase mostly forms phenocrysts enveloped by biotite. Plagioclase phenocrysts contain overgrowths of biotite and quartz. Orthoclase ranges from 0.08 - 1.5 mm in size, forming subhedral to anhedral crystals enveloped by the quartz groundmass and lath-like biotite crystals. Biotite forms 0.05 - 0.5 mm pleochroic brown to green lath-like crystals defining the foliation of the rock. Muscovite forms part of the groundmass associated with biotite and also occurs as an overgrowth on orthoclase and sericitised orthoclase. Microcline forms 0.05 - 0.8 mm crystals mostly occurring as anhedral phenocrysts. Hornblende forms pleochroic green to brown, subhedral 0.05 - 0.1 mm crystals. Perthite crystals range from 0.3 - 2 mm in size comprising subhedral to anhedral crystals. Perthite contains overgrowths of biotite and quartz. Sericitised phenocrysts are enveloped by biotite and quartz. Phlogopite forms lath-like crystals within the quartz-rich groundmass. Rutile forms 0.08 mm anhedral crystals associated with muscovite. Zircon forms 0.05 mm crystals within the same zone as biotite and muscovite but mostly concentrated between phenocryst crystal boundaries.
The Kanoneiland Granite is dominated by dark xenoliths, composed of biotite, muscovite and hornblende (Fig. A5.2a). Most of the xenoliths have the same orientation as the foliation of the granite. The outcrops contain xenoliths of feldspathic quartzite, composed of quartz, alkali feldspars and minor biotite, and are fine grained compared to the granite. The weathered surface contains garnet. The xenoliths range in size from approximately 1 cm to 500 cm in width. The Kanoneiland Granite contains a large, dark fine-grained magmatic enclaves (on the southern side of the Orange River, next to the contact with the Vaalputs Granite) which is approximately 500 cm long. Th enclave is composed of quartz, alkali feldspar, biotite, hornblende and minor muscovite (Fig. A5.2c). The boundary/contact between the enclave and the granite is gradational especially in terms of colour and texture in which, from the xenolith towards the granite, the texture of the xenolith becomes coarser grained and lighter in colour (Fig. A5.2c). There is a visible alteration zone (0.5 cm) which is composed of mostly biotite, hornblende and muscovite.

The Kanoneiland Granite is crosscut by granitic veins which mostly have the same orientation as the tectonic foliation and intrudes along the joints (Fig. A5.2d). The mineral assemblage within the granitic veins includes quartz, alkali feldspar, plagioclase, muscovite and minor biotite. There is a visible alteration zone between the granitic vein and the granite which is very thin and dominated by fine grained biotite. The granitic veins range in size from approximately 0.3 cm - 30 cm width.
Figure A5.2. The outcrops of the Kanoneiland Granite. (a) Massive and well exposed outcrop containing mafic xenoliths oriented in the same direction as the tectonic foliation. (b) Regional foliation defined by segregation of mafic minerals against felsic or lighter minerals and magmatic foliation defined by alignment of quartz, alkali feldspar and plagioclase phenocrysts. (c) Massive outcrops showing the huge country rock enclaves (right hand side and dark) which is in contact with the granite (left side and light). (d) Granitic veins intruded along the foliation of the granite and have the same orientation as the foliation.

A6. Keboes Granite

The Keboes Granite occurs between Louisvale and Keimoes and was classified as a syn-tectonic granite ($G_2$) due to its weakly foliated texture (Stowe, 1983). The granite was placed under this group based on its concordant contacts with the country rocks and weakly foliated texture. In outcrop the Keboes Granite texture ranges from unfoliated to weakly foliated. The weakly foliated texture occurs about 2 m from the contact with the Friesrdale Charnockite on the eastern side of the Keboes Granite pluton, whereas the granite is unfoliated more towards the western side of the pluton where it is in contact with the Kanoneiland Granite (Fig. 4.2.4).

The Keboes Granite can be defined as coarse grained, weakly foliated to unfoliated granite (Fig. A6.1a). The Keboes Granite is composed of 24% quartz, 20% plagioclase, 15% orthoclase, 15% microcline, 10%
biotite, 9% muscovite, 3% hornblende, 2% phlogopite, 1% garnet and 1% rutile (Fig. A6.1b). The rock is
weakly foliated, coarse grained and porphyritic with large quantities of quartz phenocrysts. The
groundmass comprises biotite, muscovite, plagioclase and quartz. Biotite laths are randomly oriented
and distributed with the minerals defining the weakly foliation which include hornblende, muscovite,
phlogopite and rutile. The feldspars are highly sericitised so that it is hard to identify if the mineral
before alteration was orthoclase, plagioclase or microcline. The twinning patterns within the feldspars
are completely obliterated or overgrown. Sericite replacing the feldspars, mostly plagioclase and to
lesser extent alkali feldspars is also a common feature in this granite.

Quartz forms the bulk of the groundmass, with subhedral to euhedral grains 0.05 - 0.5 mm in size, as
well as subhedral to euhedral showing undulose extinction. Plagioclase forms 0.05 - 1 mm crystals and
form part of the phenocrysts (Fig. 4.8b). Plagioclase also forms part of the groundmass, with crystals
interlocking with minerals such as quartz and biotite with the texture suggesting simultaneous growth.
Plagioclase phenocrysts are overgrown by biotite and muscovite. Orthoclase forms subhedral to
euhedral 0.8 - 2.5 mm crystals forming part of both the phenocrysts and groundmass. Microcline forms
0.5 - 3 mm crystals and contains overgrowths of sericite, muscovite and biotite. Microcline crystals are
enveloped by the quartz groundmass (0.05 - 0.1 mm). Biotite varies in size but is typically 0.05 - 0.5 mm
forming lath-like crystals with pleochroism ranging from brown to dark brown to green. The biotite
shows some twinning. Muscovite forms 0.05 - 0.5 mm crystals. Muscovite and phlogopite mostly occur
in the biotite-rich zones and also as overgrowths of the feldspars phenocrysts. Muscovite is most
dominant mineral within the sericitized groundmass wrapping around the phenocrysts and marks the
boundary between the phenocrysts of different minerals. Sericite forms 0.08 - 2 mm aggregates which
formed from alteration of plagioclase, orthoclase and microcline. Hornblende occurs as pleochroic
brown to green 0.05 - 0.1 mm crystals forming part of the groundmass and associated with biotite.
Garnet forms 0.2 - 0.8 mm anhedral crystals mostly occurring as phenocrysts. Rutile forms 0.05 mm
anhedral crystals occurring within the biotite- and hornblende-rich zones.

![Image](image_url)

Figure A6.1. The Keboes Granite. (a) The hand specimen showing weakly foliation. (b) Photomicrograph in cross polarised light
showing that the granite is weakly foliated (qtz = quartz, plg = plagioclase, ort = orthoclase, opq = opaque, hbl = hornblende,
mcl = microcline, ms = muscovite, srt = sericite, phg = phlogopite). Field of view of the photomicrograph is 3 mm.
Quartz veins of approximately 1 cm – 200 cm width crosscut the Keboes Granite. Alteration zones or selvedges due to intrusion of the quartz veins into the granite mostly contain biotite, muscovite and hornblende. The zones are very thin, with an average thickness of approximately 3 cm. The quartz veins fill the joints of the Keboes Granite and are generally oriented at 338°/20° and 318°/35°. Not all the joints, which are oriented NE-SW are, however, filled with quartz veins. Some of the veins are folded. Locally, the granite is dominated by coarse grained to pegmatitic granitic veins (Fig. A6.2d).

Figure A6.1. The Keboes Granite. (a) The voluminous outcrops of the Keboes Granite. (b) The shaering occouring within the granite and has the same orientation as the foliation of the granite. (c) The garnet clusters on the Keboes Granite outcrop. (d) Pegmatite containing clusters of quartz, garnet, muscovite, alkali feldspar and biotite likely due to partial melting.
A7. Louisvale Granite

The Louisvale pluton was classified as a syn-tectonic granite because of its concordant contact and intense foliation (Stowe, 1983). The granite is moderately to well foliated. Not all of the outcrops of the Louisvale Granite exhibit foliation, so that some areas are coarse-grained and unfoliated. This variation is not uniform in that it cannot be generalised as occurring from east to west or north to south. The Louisvale Granite is composed of 25% quartz, 18% plagioclase, 15% orthoclase, 11% biotite, 10% perthite, 8% muscovite, 6% hornblende, 3% phlogopite, 3% garnet and 1% zircon (Fig. A7.1a, b).

The rock is characterised by porphyritic texture with phenocrysts of quartz, plagioclase, orthoclase, perthite and garnet within a groundmass of quartz, plagioclase, orthoclase, biotite, muscovite, phlogopite and zircon. The granite is medium to coarse grained. The rock is moderately to strongly foliated with the foliation defined by the alignment of mafic minerals such as biotite, muscovite, hornblende, phlogopite and garnet. The rock also shows cumulophyric texture defined by clustering of orthoclase and plagioclase phenocrysts. The feldspars within the groundmass are extensively sericitised to varying degrees. Biotite wraps around the plagioclase phenocrysts suggesting a pre- or syn-kinematic origin to the phenocrysts.

Quartz ranges from 0.05 - 0.08 mm subhedral to anhedral crystals and shows undulose extinction. Plagioclase ranges from 0.05 - 1.5 mm in size and forms subhedral to anhedral grains. Phenocrysts of plagioclase contain overgrowths of biotite and muscovite along with inclusions of clusters of quartz showing undulose extinction within the phenocrysts. Orthoclase ranges from 0.01 - 1 mm in size forming subhedral to anhedral crystals. It is partly overgrown by muscovite. Biotite forms lath-like crystals which are elongated and define the foliation of the rock. Biotite forms 0.05 - 0.5 mm grains forming part of the groundmass and are pleochroic dark brown to light brown to a greenish colour. Perthite forms 0.08 - 1.5 mm crystals with subhedral shapes, partially overgrown by muscovite and mildly sericitized. Sericitised feldspars in the groundmass are aligned contributing to defining the foliation of the rock. Muscovite forms 0.01 - 0.1 mm grains within the biotite-rich zone. Sericite aggregates range from 0.05 - 1 mm and form as a result of feldspar alteration and are associated with muscovite crystals. Hornblende forms 0.08 -0.5 mm lath-like to anhedral crystals and mostly occurs within the biotite-rich zones. Phlogopite forms 0.05 - 0.5 mm elongated lath-like crystals within the biotite-rich zone. Garnet ranges from 0.5 - 2 mm in size forming subhedral to anhedral phenocrysts containing quartz inclusions. Zircon forms 0.05 mm prismatic crystals and occurs within the biotite-rich zone. Zircon occurs between crystal boundaries of the phenocrysts.
Figure A7.1. The Louisvale Granite. (a) Hand specimen showing the moderately foliated medium grained granite. (b) Photomicrograph under cross polarised light showing that, microscopically, the granite is foliated and medium to coarse grained (qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline). Field of view of the photomicrograph is 3 mm.

This granite is extensively crosscut by massive quartzofeldspathic and pegmatitic veins which vary in size from 1 cm - 90 cm in width (Fig. A7.2c, d). The granite also contains some quartz veins which are mostly perpendicular to the joints. Alteration zones of approximately 1 cm width occur adjacent to the quartz veins and contain minerals such as quartz, alkali feldspar, muscovite, phlogopite and garnet (Fig. A7.2d). The contact between the granite and the quartz veins is marked by a zone which is strongly foliated compared to the granite itself indicating that the veins used shear zones in order to intrude and propagate. Some of the contacts between the quartz veins and the granite are reddish in colour being dominated by alkali feldspar, whereas at some outcrops the veins are poorly developed and cross-cut each other. Some veins define the asymmetrical folds within the granite. The granite shows slicken-lines which are defined by biotite and phlogopite which are oriented in the direction of the foliation which is NE-SW.
A8. Klipkraal Granite

The Klipkraal Granite can be defined as an unfoliated and medium to coarse grained granite (Fig. A8.1). The granite shows porphyritic texture and locally has a cumulophyric texture due to clusters of plagioclase, orthoclase and quartz phenocrysts. The Klipkraal Granite is composed of 30% quartz, 20% plagioclase, 15% orthoclase, 10% microcline, 10% biotite, 5% muscovite, 4% phlogopite, 3% hornblende, 2% opaque minerals, and 1% garnet (Fig. A8.1a, b). The phenocrysts are crosscut by muscovite/sericite micro-veins (<0.08 mm thick) which cut across most of the phenocrysts.

Quartz forms 0.03 mm - 1.5 mm subhedral to anhedral crystals. Plagioclase ranges from 0.05 - 1 mm subhedral to anhedral crystals. Phenocrysts of plagioclase contain overgrowths of biotite which have lath-like shapes (0.05 - 0.2 mm in size) and have mostly the same orientation as the host mineral. Orthoclase ranges from 0.08 - 0.8 mm in size forming interlocking texture in which the orthoclase...
phenocrysts are interlocking with the groundmass minerals. Microcline forms 0.08 - 1 mm subhedral to anhedral crystals enveloped by biotite. Microcline contains sericite overgrowth. Biotite forms 0.05 - 0.2 mm lath-like brown-coloured crystals which form part of the groundmass and wrap around quartz and orthoclase phenocrysts. Muscovite and phlogopite occur mostly as sericite clusters and form 0.01 - 0.25 mm anhedral to lath like crystals. Muscovite is concentrated in the zones dominated by biotite and hornblende. Pleochroic brown to green 0.05 - 0.3 mm hornblende occurs within the biotite-rich band, with the crystals wrapping around orthoclase phenocrysts. Opaque minerals form anhedral crystals associated with biotite and hornblende in the mafic mineral-rich zone. Garnet forms 0.1 - 0.25 mm subhedral crystals, mostly occurring in the zone dominated by biotite and opaque minerals.

Figure A8.1. Samples of the Klipkraal Granite. (a) Medium grained, weakly foliated hand specimen. (b) Photomicrograph under cross polarised light showing a coarse grain size and cumulophyric texture with green hornblende and biotite clustering together (qtz = quartz, plg = plagioclase, ort = orthoclase, opq = opaque, pth = perthite, hbl = hornblende, bt = biotite, mcl = microcline, srt = sericite). The field of view of the photomicrograph is 3 mm.

Most of the feldspars in the groundmass are sericitised. Plagioclase is the most altered mineral with the twinning still preserved within the cores of the mineral, whereas the rims or edges of the crystals are the most altered parts so that the grain boundaries are obscured by the alteration. Orthoclase is mildly altered still having clearly defined subhedral crystal shapes.

Migmatitic veins composed of quartz and alkali feldspar also occur in this granite (Fig. A8.2b). The 0.5 cm alteration zone between the leucogranitic veins and the granite is composed of quartz, alkali feldspar, plagioclase, hornblende and muscovite (Fig. A8.2b). The leucogranitic veins range in size from approximately 1 cm - 100 cm in width. In general, the Klipkraal Granite is extensively crosscut by massive intrusions of later leucogranitic veins with the same mineralogy, which locally intrude as veins, with others as more voluminous masses. The Klipkraal Granite intrudes into the Jannelsepan Formation amphibolite. Most of the leucogranitic veins intruded along the major joints of the rock, whereas others occur on the weathered surface of the rock. The veins are oriented 066°/78° and 140°/88°. Some of the
quartz veins or joints filled with quartz veins are oriented $268^\circ/62^\circ$, $280^\circ/58^\circ$, $260^\circ/64^\circ$, $308^\circ/88^\circ$ and $310^\circ/98^\circ$.

There are small inclusions or xenoliths of amphibolite within the granitic body. Measurements of the xenoliths (lineation) ($84^\circ-315^\circ$, $64^\circ-338^\circ$ and $88^\circ-324^\circ$) were obtained. The composition of the Klipkraal Granite varies considerably from one area to another, especially in terms of mineral abundance in which, in some areas, it is more amphibole-rich towards its contact with the Jannelsepan amphibolite, whereas towards its contact with the Louisvale Granite it is more biotite-rich.

The contact between the Klipkraal Granite and the amphibolite of the Jannelsepan Formation is characterised by isoclinal folds defined by Klipkraal Granite magmatic veins intruding the Jannelsepan Formation amphibolite. The contact is also marked by migmatitic veins. The foliation of the country rock within the amphibolite is $106^\circ/64^\circ$ whereas the foliation of the Klipkraal Granite was oriented $173^\circ/73^\circ$ at Virginia, North west of Louisvale (Fig. 4.2.3). There is evidence in the field that the Klipkraal Granite towards the contact assimilated large portions of the amphibolitic Jannelsepan Formation as indicated by amphibolite xenoliths and migmatitic veins.

The outcrops of the Klipkraal Granite on the northern side of the Orange River are also coarse grained, containing clusters of biotite, and is unfoliated to weakly foliated. The foliation is magmatic only. In general, the granite is composed of quartz, alkali feldspar, plagioclase, hornblende, biotite, muscovite and some minor garnet. This granite also contains some xenoliths composed of quartz and alkali feldspar. The granite contains large veins which range in width from approximately 0.5 cm - 100 cm in which most of them are oriented N-S ($268^\circ/86^\circ$) ($S 28^\circ 31'07.3''$; $E021^\circ 10'19.5''$; elevation 976m). These quartz veins which intrude the Klipkraal Granite did not intrude along the joints. An alteration/selvedge zone associated with the veining is composed of quartz, alkali feldspar, biotite and muscovite. The
contact between the Klipkraal Granite and the Louisvale Granite is also marked by migmatite veins and some quartz pebbles. Locally, the contact has the same characteristics as that with the Jannelsepan Formation amphibolite to the south of the Orange River.

**A9. Straussburg Granite**

The Straussburg Granite is an unfoliated to weakly foliated coarse grained granite of the Keimoes Suite having phenocrysts of microcline, plagioclase and quartz (Fig. A9.1a). The granite is composed of 22% quartz, 20% plagioclase, 20% orthoclase, 15% microcline, 10% biotite, 6% muscovite, 4% hornblende, 1% garnet, 1% opaque minerals and 1% zircon (Fig. A9.1a,b). The quartz and plagioclase grains of the groundmass are interlocking indicating that they grew together.

Quartz forms 0.05 - 1.5 mm subhedral to euhedral crystals which show undulose extinction. The granite is slightly foliated with to some extent the foliation defined by the alignment of the quartz grains in the groundmass present between the phenocrysts. The quartz grains show some degree of recrystallization, subgrain rotation and migration. Plagioclase forms 0.08 - 1.5 mm crystals mostly forming part of the phenocrysts and, to a lesser extent, the groundmass. Orthoclase ranges from 0.1 - 2 mm forming euhedral to anhedral crystals with opaque minerals and zircon occurring along the mineral boundaries. Microcline forms 0.1 - 2.5 mm subhedral to anhedral crystals. Microcline contains small (0.05 - 0.09 mm) muscovite and biotite overgrowths within the anhedral phenocrysts, whereas the euhedral phenocrysts contain mostly overgrowths of quartz and sericite. Biotite forms lath-like, anhedral, pleochroic brown to green 0.05 - 1 mm crystals which are mostly defining the foliation between the phenocrysts and forms part of the groundmass. Muscovite ranges from 0.05 - 0.1 mm forming part of the groundmass and concentrates along the zone dominated by the mafic minerals such as biotite and hornblende which are defining a slight foliation to the Straussburg Granite. Muscovite forms lath-like crystals. Hornblende occurs as pleochroic brown to green subhedral 0.5 - 1.5 mm crystals. It concentrates along the same zone as biotite and also occurs as an overgrowth within the feldspar phenocrysts, namely plagioclase and microcline. Garnet forms 0.1 - 0.5 mm subhedral phenocrysts enveloped by the biotite and muscovite in the groundmass. Opaque minerals occur as 0.05 - 0.1 mm crystals mostly within the biotite-rich zone. Zircon ranges from 0.05 - 0.08 mm in size occurring mostly as euhedral crystals within the groundmass between phenocrysts of feldspars.
Figure A9.1. (a) The hand specimen and (b) photomicrograph of the Straussburg Granite showing the coarse grained nature and weakly foliated texture of this granite (qtz = quartz, plg = plagioclase, ort = orthoclase, mcl = microcline, bt = biotite, hbl = hornblende, ms = muscovite). Field of view of the photomicrograph is 3 mm.

The granite is crosscut by quartz veins which range from 0.3 cm - 150 cm width and 600 cm long (Fig. 3.3.6.1b, c), with a visible alteration zone which marks the contact between the granite and vein of approximately 3 cm width and comprised of green quartz, alkali feldspar, biotite, minor muscovite and epidote. The quartz veins mostly have orientations of approximately 350°/10° (and 285°/85°) whereas other quartz veins are oriented 204°/89°.

The Straussburg Granite has intruded the feldspathic quartzite of the Dagbreek Formation with the contact well exposed. At this contact, the feldspathic quartzite has a width of approximately 100 cm and is weakly foliated (Fig. A9.2). The feldspathic quartzite is biotite rich resulting in a strongly foliated texture. There is a gradational contact between the two rock types. The granite is coarse grained whereas the feldspathic quartzite is more medium to fine grained. The feldspathic quartzite contains quartz veins of approximately 5 cm width. This granite has a pitted weathered surface but is less weathered compared to the other granites examined in this study.
A10. Josling Granite

Outcrops, hand specimens and petrographic studies indicate that the granite has a medium to fine grained, equigranular and weakly to moderately foliated texture (Fig. A10.1a, b). The Josling Granite is composed of 22% quartz, 17% plagioclase, 15% microcline, 13% orthoclase, 9% biotite, 7% muscovite, 6% hornblende, 3% perthite, 2% phlogopite, 2% opaque minerals, 2% garnet, 1% zircon and 1% piemontite (Fig. A10.1a, b). The foliation is defined by biotite, hornblende and muscovite which occur within the groundmass and wrap around phenocrysts of quartz, plagioclase, microcline, perthite and orthoclase. The rock has a cumulophyric texture in which crystals of microcline, plagioclase and orthoclase are clustered together (Fig. A10.1b). The phenocryst sizes ranges from 0.5 cm - 1.5 cm.

Quartz ranges from 0.05 - 3 mm in size forming subhedral to anhedral crystals and showing strained, undulose extinction. Plagioclase ranges from 0.1 - 1.5 mm in size, being anhedral to subhedral in shape. Microcline ranges from 0.08 - 0.6 mm and occurs as anhedral to subhedral crystals. The growth of the microcline has been hindered by other crystals that are interlocking with the microcline thereby forming subhedral to anhedral crystal shapes for the microcline. Orthoclase forms 0.08 - 0.8 mm anhedral to
subhedral crystals. Biotite forms 0.05 - 0.5 mm anhedral crystals showing brown-green pleochroism. Muscovite (sericite) aggregates range in size from 0.05 - 1 mm, forming as a product of the alteration of the feldspars. Hornblende occurs as pleochroic green to brown anhedral crystals. Perthite forms 0.08 - 1 mm subhedral to euhedral crystals and is enveloped by the quartz-rich groundmass. Phlogopite forms 0.05 - 1 mm yellowish-greenish elongated grains occurring within the zones dominated by biotite and muscovite. Opaque minerals, which range from 0.05 - 0.8 mm in size, being anhedral in shape, and form part of the groundmass, occur between the phenocrysts associated with fine grained quartz which show undulose extinction. Garnet forms 0.08 - 0.8 mm anhedral to subhedral microphenocrysts, which are enveloped by the quartz groundmass. Zircon forms 0.05 mm crystals within the zone comprising sericitised feldspars, biotite and hornblende. Piemontite forms 0.3 mm subhedral crystals forming part of the individual microphenocrysts enveloped by green hornblende and biotite.

Figure A10.1. (a) The hand specimen and (b) photomicrograph of the Josling Granite showing that the granite is weakly foliated and medium grained (qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, ms = muscovite, srt = sericite, phg = phlogopite. Field of view of the photomicrograph is 3 mm.
A11. Klip Koppies Granite

The Klip Koppies Granite is strongly foliated, and medium to coarse grained (Fig. A11.1). The granite is composed of 25% quartz, 20% plagioclase, 18% orthoclase, 17% biotite, 6% microcline, 5% hornblende, 4% muscovite, 2% opaque minerals, 2% garnet and 1% zircon (Fig. A11.1a, b). Quartz phenocrysts form glomeroporphyritic texture, in which they cluster together and form aggregates of approximately 1 – 1.5 mm in which individual crystals range from 0.08 - 1mm. The rock is strongly foliated with the foliation defined by biotite within the groundmass between the quartz, plagioclase and orthoclase phenocrysts.

Quartz occurs as 0.03 - 1 mm subhedral to anhedral crystals. Plagioclase ranges from 0.05 - 1.5 mm in size forming subhedral to anhedral crystals with most crystals sericitised and containing biotite overgrowths. Orthoclase forms 0.1 - 1.5 mm subhedral to anhedral crystals, with the phenocrysts enveloped by biotite. Biotite forms 0.05 - 0.8 mm pleochroic light brown to dark brown lath-like crystals wrapping around the phenocrysts. Microcline ranges from 0.5 - 1.5 mm and form anhedral to subhedral crystals. Hornblende forms 0.08 mm crystals with alteration along the cleavage planes of the
hornblende composed of opaque minerals and biotite. Muscovite forms 0.01 - 0.08 mm crystals occurring in the same zone with biotite. Opaque minerals form 0.08 mm crystals within the biotite-rich bands. Garnet forms 0.1 - 0.5 mm anhedral to euhedral phenocrysts enveloped by the biotite and muscovite in the groundmass. Zircon forms 0.03 – 0.08 mm crystals and occurs mostly as inclusions within biotite.

Figure A11.1. The Klip Koppies Granite. (a) Hand specimen showing the strongly foliated medium grained granite. (b) A photomicrograph under cross polarised light showing that, microscopically, the granite is foliated and medium to coarse grained (qtz = quartz, plg = plagioclase, ort = orthoclase, bt = biotite, hbl = hornblende). Field of view of the photomicrograph is 3 mm.

Figure A11.2. The Klip Koppies Granite outcrop showing a foliation defined by the alignment of phenocrysts.

Plagioclase phenocrysts are the most altered minerals together with orthoclase which is mildly altered to form sericite. The altered crystal shapes are still preserved. The contact between the Gemsbokbult
and Klip Koppies granites is clear, with the Klip Koppies Granite being strongly foliated and the Gemsbokbult Granite being weakly foliated to unfoliated. The Klip Koppies Granite shows both magmatic and tectonic foliation. The magmatic foliation is defined by the alignment of quartz, plagioclase and alkali feldspar phenocrysts along the margin of the outcrops (Fig. A11.2). The tectonic foliation is defined by the alignment of biotite and, to a lesser extent, hornblende. The Klip Koppies outcrops range from low lying to bouldery hill types of outcrop with a height of approximately 4 m.

A12. Gemsbokbult Granite

The Gemsbokbult Granite can be defined as a coarse grained, weakly foliated Granite. The granite is composed of 25% quartz, 20% plagioclase, 15% orthoclase, 12% microcline, 10% biotite; 5% muscovite, 5% phlogopite, 4% opaque minerals, 3% hornblende and 1% garnet (Fig. A12.1a, b). The granite has porphyritic texture defined by phenocrysts of microcline, quartz, orthoclase, perthite and plagioclase and groundmass of quartz, plagioclase, orthoclase, microcline, biotite, opaque minerals and hornblende in order of decreasing abundance. (Fig. A12.1b).

Quartz crystals range from 0.08 - 2 mm in size. Quartz phenocrysts are enveloped by the quartz-dominated groundmass (<0.08 mm) with the quartz in the groundmass showing undulose extinction. The phenocrysts of quartz contain overgrowths of biotite (0.02 mm) and muscovite (0.01 - 0.05 mm). Plagioclase crystals range from 0.4 - 3 mm in size and are highly sericitised. Phenocrysts of plagioclase contain biotite, muscovite and quartz overgrowths. Plagioclase grains vary in shape from euhedral through subhedral to anhedral, with phenocrysts enveloped by the quartz groundmass. Orthoclase forms anhedral to subhedral 0.3 - 1 mm crystals enveloped by the quartz crystals of the groundmass (Fig. A12.1b). Microcline crystals range from 0.5 - 1.5 mm in size forming subhedral to anhedral crystal shapes and forming interlocking textures with the plagioclase crystals. The crystals have poorly defined grain boundaries due to extensive sericitisation. Overgrowths within the poorly developed phenocrysts of microcline include biotite, muscovite and quartz. Biotite and phlogopite forms 0.05 - 0.5 mm anhedral lath-like crystals in the groundmass, with some of the crystals occurring as overgrowths within the phenocrysts. Muscovite forms 0.01 - 0.2 mm lath like crystals forming part of the groundmass and occurs along with biotite. Opaque minerals range from 0.08 - 0.5 mm in size and mostly concentrate along the biotite-rich zone. Hornblende forms 0.05 - 0.5 mm subhedral to anhedral crystals which occur as anhedral grains in the groundmass with pleochroism ranging from dark brownish to greenish. Garnet forms 0.05 - 0.5 mm subhedral crystals, mostly occurring in the biotite- and hornblende-rich zone.
The contact between the Gemsbokbult and Klip Koppies granites is marked mostly by colour changes, with the Klip Koppies Granite being lighter whereas the Gemsbokbult Granite is darker. In addition, the Klip Koppies Granite is strongly foliated compared to the weakly to unfoliated Gemsbokbult Granite. The most common feature between these granites is that both show the same NW-SE outcrop orientation. The Gemsbokbult Granite outcrops are well exposed (Fig. A12.2).
A13. Kleinbegin Subsuite

The outcrops of the Kleinbegin Subsuite west of Kleinbegin village are weakly to moderately foliated (Fig. A13.1b). The granites of this subsuite within the 2920 1:250 000 Kenhardt sheet are grouped as unfoliated post-tectonic granites (Geringer et al., 1988; Moen, 2007; Bailie et al., 2011a). The Kleinbegin Subsuite is composed of 25% quartz, 19% plagioclase, 15% orthoclase, 15% microcline, 10% biotite, 5% muscovite, 3% phlogopite, 3% opaque minerals, 3% hornblende, 1% zircon, and 1% garnet (Fig. A13.1a; b). The granites of the Kleinbegin Subsuite are medium to coarse grained. The foliation is defined by the alignment of biotite and muscovite. The granite contains porphyritic texture defined by phenocrysts of quartz, plagioclase, orthoclase, microcline and garnet.

Quartz crystals range from 0.01 - 0.4 mm in size and are euhedral to subhedral in shape. Quartz phenocrysts are enveloped by the biotite, muscovite and quartz groundmass. Plagioclase forms 0.03 - 0.7 mm crystals. Plagioclase grains in the groundmass are interlocking with other minerals such as quartz and microcline. Plagioclase phenocrysts contain quartz and biotite overgrowths (Fig. A13.1a,b). Orthoclase crystals range from 0.05 - 1 mm in size and form subhedral to anhedral crystals within the fine grained groundmass of quartz, plagioclase and orthoclase. Microcline forms 0.03 - 0.5 mm anhedral crystals. Biotite forms 0.05 - 0.5 mm lath-like crystals. Muscovite forms 0.01 - 0.3 mm lath-like crystals and is associated with biotite. Phlogopite forms small crystals in the groundmass of approximately 0.05 mm size and occurs within the biotite-rich zone along the edges of the phenocrysts. Opaque minerals form 0.05 mm anhedral crystals within the biotite-rich bands of the groundmass. Hornblende forms 0.08 - 0.5 mm crystals and occurs within the zone dominated by biotite. It is pleochroic green-brown and is elongate along with the biotite. Zircon forms approximately 0.08 mm crystals and occurs mostly between the boundaries of garnet with phenocrysts of quartz and plagioclase and also within the biotite-rich bands. Garnet forms 0.08-0.8 mm anhedral to euhedral phenocrysts enveloped by the biotite and muscovite in the groundmass.

Most of the phenocrysts of plagioclase, orthoclase and microcline have anhedral shapes and poorly defined crystal boundaries due to extensive sericitisation and are enveloped by a sericitised groundmass.
Figure A13.1. (a) Hand specimen and (b) photomicrograph of the Kleinbegin Subsuite illustrating that the granite is moderately foliated (qtz = quartz, ort = orthoclase, bt = biotite, opq = opaque, hbl = hornblende, srt = sericite). Field of view of the photomicrograph is 3 mm.

The outcrops of this unit are located at Kleinbegin village and are small with a relative exposed area of approximately 30 m$^2$. The granite is coarse grained and exhibits porphyritic texture. The granite is strongly foliated, with the foliation defined by the alignment of phenocrysts and xenoliths. The granite contains both tectonic and magmatic foliation, with the tectonic foliation defined by the alignment of quartz, plagioclase feldspar, alkali feldspar, biotite and muscovite and the magmatic foliation defined by alignment of quartz, alkali feldspar and plagioclase phenocrysts on the weathered surface of the outcrops (Fig. A13.2).

Figure A13.2. The Kleinbegin Granite at Kleinbegin village. (a) The poorly exposed outcrop of the Kleinbegin Granite covered by sand and some rock fragments. (b) The outcrops showing well-developed foliation.
The xenoliths are composed of biotite, hornblende, alkali feldspar and quartz. Biotite-rich xenoliths have the same orientation as the major joints and are oriented $120^\circ/82^\circ$. The quartzofeldspathic xenoliths are oriented in the direction of the foliation. Biotite and, to a lesser extent, hornblende are the major mafic minerals which are defining the foliation of the Kleinbegin Granite. The granite is crosscut by thick quartz veins with widths which range between 2 cm and 20 cm and have alteration selvedges composed of biotite and minor muscovite. The quartz veins are randomly oriented. Locally, some of the quartz veins are oriented in the direction of foliation. The Kleinbegin Granite outcrops are poorly exposed and highly weathered (Fig. A13.2a). The outcrops are in contact with feldspathic-quartzite Dagbreek Formation and the exact contact zone is concealed by sand.

**A14. Elsie Se Gorra Granite**

The Elsie Se Gorra Granite shows moderately to well-developed foliation. The granite is very coarse grained comprising phenocrysts (0.5 - 3 mm in size) of quartz, orthoclase, plagioclase and microcline in order of decreasing abundance (Fig. A14.1b). Due to the limited outcrop, only one outcrop was sampled, so that there is no comparison between any possible members within this unit. The Elsie se Gorra Granite is composed of 25% quartz, 20% orthoclase, 15% plagioclase, 10% microcline, 10% biotite, 7% muscovite, 4% hornblende, 4% opaque minerals, 3% garnet, 1% rutile and 1% zircon (Fig. A14.1b).

The rock exhibits 0.5 - 2 mm glomeroporphyritic clusters defined by phenocrysts of plagioclase, orthoclase and microcline. The granite is composed of groundmass of quartz, plagioclase, biotite, muscovite, garnet and sericitised microcline, plagioclase and orthoclase in order of decreasing abundance (Fig. A14.1b). The minerals form an interlocking texture. The plagioclase microlites are randomly oriented. The rock comprises of ferromagnesian mineral-rich zones which define the weakly developed foliation of the rock and are composed of biotite, hornblende and sericitised feldspars which occur between, and envelope the phenocrysts.

Quartz forms 0.05 - 3 mm euhedral to subhedral crystals. Quartz contains overgrowths of biotite, plagioclase, orthoclase and opaque minerals, especially within the anhedral phenocrysts. The phenocrysts are mostly enveloped by sericitised feldspars. Orthoclase forms 0.05 - 1 mm euhedral to subhedral crystals. Crystals of orthoclase are highly sericitised, with the edges of the crystals being highly altered so that crystal boundaries are obscured. Plagioclase forms approximately 0.5 - 3 mm euhedral to subhedral crystals. Plagioclase occurs as both groundmass and phenocrysts, with the latter containing overgrowths of biotite and sericite. Microcline forms 0.1 - 1.5 mm euhedral to subhedral crystals with inclusions of quartz (Fig. 4.1b). Biotite forms 0.05-1 mm pleochroic greenish to brown subhedral to anhedral crystals with most of the crystals occurring within the mineral bands dominated by hornblende. Biotite forms lath-like crystal shapes. The biotite-rich zones define the weakly developed foliation of the rock. Muscovite forms approximately 0.05 - 0.1 mm crystals forming part of the groundmass and occurs within the biotite and hornblende-rich zones. Hornblende forms approximately 0.5 - 1 mm pleochroic green to brown subhedral crystals forming part of the groundmass. Opaque
minerals form 0.1 - 0.2 mm subhedral crystals forming part of the groundmass mostly within the biotite-rich zones. Garnet forms approximately 0.5 - 1 mm subhedral crystals enveloped by the quartz-rich groundmass. Rutile forms 0.1 - 0.5 mm crystals, with pleochroism ranging from reddish to dark brown or reddish brown. Zircon forms 0.05 mm crystals within the groundmass.

Figure A14.1. (a) Hand specimen and (b) photomicrograph of the foliated porphyritic Elsie se Gorra Granite (qtz = quartz, plg = plagioclase, ort = orthoclase, hbl = hornblende, bt = biotite, mcl = microcline, srt = sericite). Field of view of the photomicrograph is 3 mm.
Appendix B. Geochronology methodology

Table B. LA-SF-ICP-MS U-Th-Pb dating methodology CAF, Stellenbosch University

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Table B. LA-SF-ICP-MS U-Th-Pb dating methodology CAF, Stellenbosch University (cont.)

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**Data Processing**

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<td>Data processing package used / Correction for LIEF</td>
<td>In-house spreadsheet data processing using intercept method for LIEF correction</td>
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<td>Other information</td>
<td>For detailed method description see Frei &amp; Gerdes (2009)</td>
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## Appendix C. Whole rock geochemistry

Table C1. The average whole rock geochemistry of the Keimoes Suite granites of the eastern Namaqua Sector.

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Table C1. The average whole rock geochemistry of the Keimoes Suite granites of the eastern Namaqua Sector (cont.).

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Abbreviations: Mkn = Josling Granite, Me = Elsie se Gorra Granite, Mcol = Colston Granite, Mc = Cnydas Subsuite, Mv = Vaalputs Granite, Mi = Louisvale Granite, Mkb = Keboes Granite, Mka = Kanoneland Granite, Mkle = Kleinbegin Subsuite, Mge = Gemsbokbult Granite, Mkl = Klipkraal Granite, Mks = Klip Koppies Granite, Ms = Straussburg Granite, Mf = Friersdale Charnockite.
Table C2. Whole rock geochemistry summary table for the granites of the eastern Namaqua Sector.

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<th>Granite</th>
<th>Granite type</th>
<th>Alkalinity</th>
<th>Fe-number</th>
<th>Peralkalinity</th>
<th>Aluminium saturation index (ASI)</th>
<th>Tectonic setting (Verma)</th>
<th>Tectonic setting (Pearce)</th>
<th>Approximate Pressure (kbar)</th>
<th>ΣREE</th>
</tr>
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<tbody>
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<td>0.622-0.828</td>
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<td>WPG</td>
<td>6 kbar (22 km)</td>
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<tr>
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<td>Col, CR</td>
<td>WPG</td>
<td>2 kbar (7 km)</td>
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<td>ferroan</td>
<td></td>
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<td>0.919-0.984</td>
<td>Col, CR</td>
<td>WPG</td>
<td>7 kbar (26 km)</td>
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<td>WPG, VAG + syn-COLG</td>
<td>5 kbar (19 km)</td>
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<td>Col and IA, CR</td>
<td>WPG, VAG+syn-COLG</td>
<td>6 kbar (22 km)</td>
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Table C2. Whole rock geochemistry summary table for the granites of the eastern Namaqua Sector (cont.)

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Figure C1. Tectonic setting discrimination diagrams for the eastern Namaqua Sector. (a-d) Tectonomagmatic discriminant function diagrams for distinguishing the tectonic setting using major elements only (after Verma et al., 2013). (e-h) Tectonomagmatic discriminant function diagrams for determining tectonic setting using major and trace elements. (i-l) Tectonomagmatic discriminant function diagrams for determining tectonic setting using trace elements only. IA=Island arc, CA=Continental arc, CR=Continental rift, OI=Ocean Island and Col=Collisional tectonic setting. (m-n) Nb (ppm) vs. Y (ppm) and Ta vs. Yb (ppm) diagrams indicating the tectonic setting (after Pearce et al., 1984).
Figure C1. Tectonic setting discrimination diagrams for the eastern Namaqua Sector. (e-h) Tectono-magmatic discriminant function diagrams for determining tectonic setting using major and trace elements. (i-l) Tectonomagmatic discriminant function diagrams for determining tectonic setting using trace elements only. IA=Island arc, CA=Continental arc, CR=Continental rift, OI=Ocean Island and Col=Collisional tectonic setting. (m-n) Nb (ppm) vs. Y (ppm) and Ta vs. Yb (ppm) diagrams indicating the tectonic setting (after Pearce et al., 1984).
Calculations for the construction of the tectonomagmatic diagrams of Verma et al. (2013)

Tectonomagmatic diagrams using major elements

(For Figure 6.8a)

\[ DF1 = \log (\text{adj}) \left( 0.051 \times \frac{\text{TiO}_2}{\text{SiO}_2} - 1.77 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} + 1.83 \times \frac{\text{FeO}}{\text{SiO}_2} - 0.065 \times \frac{\text{MnO}}{\text{SiO}_2} + 0.134 \times \frac{\text{MgO}}{\text{SiO}_2} + 0.225 \times \frac{\text{CaO}}{\text{SiO}_2} + 0.742 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} - 2.12 \right) \]

\[ DF2 = \log (\text{adj}) \left( 1.09 \times \frac{\text{TiO}_2}{\text{SiO}_2} - 1.65 \times \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} - 1.19 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} + 1.03 \times \frac{\text{FeO}}{\text{SiO}_2} + 0.82 \times \frac{\text{MnO}}{\text{SiO}_2} + 0.023 \times \frac{\text{CaO}}{\text{SiO}_2} + 0.212 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} - 2.12 \right) \]

(For Figure C1a)

\[ DF1 = \log (\text{adj}) \left( 0.130 \times \frac{\text{TiO}_2}{\text{SiO}_2} + 0.62 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} - 0.76 \times \frac{\text{FeO}}{\text{SiO}_2} - 0.083 \times \frac{\text{MnO}}{\text{SiO}_2} - 0.147 \times \frac{\text{MgO}}{\text{SiO}_2} + 0.520 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} + 2.04 \times \frac{\text{K}_2\text{O}}{\text{SiO}_2} + 0.164 \times \frac{\text{P}_2\text{O}_5}{\text{SiO}_2} - 2.65 \right) \]

\[ DF2 = \log (\text{adj}) \left( -0.045 \times \frac{\text{TiO}_2}{\text{SiO}_2} + 5.10 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} - 5.15 \times \frac{\text{FeO}}{\text{SiO}_2} + 1.16 \times \frac{\text{MnO}}{\text{SiO}_2} + 0.253 \times \frac{\text{MgO}}{\text{SiO}_2} - 0.451 \times \frac{\text{CaO}}{\text{SiO}_2} - 2.45 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} + 1.40 \times \frac{\text{K}_2\text{O}}{\text{SiO}_2} + 0.0017 \times \frac{\text{P}_2\text{O}_5}{\text{SiO}_2} - 2.98 \right) \]

(For Figure C1b)

\[ DF1 = \log (\text{adj}) \left( -0.489 \times \frac{\text{TiO}_2}{\text{SiO}_2} + 2.27 \times \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} + 0.62 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} - 1.24 \times \frac{\text{FeO}}{\text{SiO}_2} - 0.91 \times \frac{\text{MnO}}{\text{SiO}_2} + 0.156 \times \frac{\text{MgO}}{\text{SiO}_2} - 1.23 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} + 1.15 \times \frac{\text{K}_2\text{O}}{\text{SiO}_2} + 0.409 \times \frac{\text{P}_2\text{O}_5}{\text{SiO}_2} - 3.22 \right) \]

\[ DF2 = \log (\text{adj}) \left( 0.68 \times \frac{\text{TiO}_2}{\text{SiO}_2} + 2.24 \times \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} - 3.90 \times \frac{\text{Fe}_2\text{O}_3}{\text{SiO}_2} + 3.69 \times \frac{\text{FeO}}{\text{SiO}_2} - 0.374 \times \frac{\text{MnO}}{\text{SiO}_2} + 0.255 \times \frac{\text{MgO}}{\text{SiO}_2} + 3.04 \times \frac{\text{Na}_2\text{O}}{\text{SiO}_2} + 1.16 \times \frac{\text{K}_2\text{O}}{\text{SiO}_2} - 0.226 \times \frac{\text{P}_2\text{O}_5}{\text{SiO}_2} + 12.69 \right) \]
DF1_{(IA-CR+OI-Col)}_{macid} = (-0.144*\ln(\text{TiO}_2/\text{SiO}_2)_{adj}) + (-0.74*\ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{adj}) + (-0.443*\ln(\text{MnO}/\text{SiO}_2)_{adj}) + (0.075*\ln(\text{CaO}/\text{SiO}_2)_{adj}) + (0.383*\ln(\text{Na}_2\text{O}/\text{SiO}_2)_{adj}) + (2.58*\ln(\text{K}_2\text{O}/\text{SiO}_2)_{adj}) + (-0.0243*\ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{adj}) + 4.29

DF2_{(IA-CR+OI-Col)}_{macid} = (-0.87*\ln(\text{TiO}_2/\text{SiO}_2)_{adj}) + (1.54*\ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{adj}) + (-0.75*\ln(\text{MnO}/\text{SiO}_2)_{adj}) + (0.150*\ln(\text{CaO}/\text{SiO}_2)_{adj}) + (0.383*\ln(\text{Na}_2\text{O}/\text{SiO}_2)_{adj}) + (2.58*\ln(\text{K}_2\text{O}/\text{SiO}_2)_{adj}) + (0.75*\ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{adj}) - 2.60

DF1_{(CA-CR+OI-Col)}_{macid} = (-0.0218*\ln(\text{MgO}/\text{TiO}_2)_{adj}) + (1.06*\ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{adj}) + (-1.65*\ln(\text{Fe}_2\text{O}_3/\text{SiO}_2)_{adj}) + (1.89*\ln(\text{FeO}/\text{SiO}_2)_{adj}) + (-0.296*\ln(\text{MnO}/\text{SiO}_2)_{adj}) + (0.119*\ln(\text{MgO}/\text{SiO}_2)_{adj}) + (0.65*\ln(\text{Na}_2\text{O}/\text{SiO}_2)_{adj}) + (-2.43*\ln(\text{K}_2\text{O}/\text{SiO}_2)_{adj}) + (0.212*\ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{adj}) - 4.33

DF2_{(CA-CR+OI-Col)}_{macid} = (-1.08*\ln(\text{TiO}_2/\text{SiO}_2)_{adj}) + (1.63*\ln(\text{Al}_2\text{O}_3/\text{SiO}_2)_{adj}) + (0.99*\ln(\text{Fe}_2\text{O}_3/\text{SiO}_2)_{adj}) + (-0.80*\ln(\text{FeO}/\text{SiO}_2)_{adj}) + (-0.78*\ln(\text{MnO}/\text{SiO}_2)_{adj}) + (-0.018*\ln(\text{MgO}/\text{SiO}_2)_{adj}) + (-0.223*\ln(\text{Na}_2\text{O}/\text{SiO}_2)_{adj}) + (0.65*\ln(\text{K}_2\text{O}/\text{SiO}_2)_{adj}) + (0.73*\ln(\text{P}_2\text{O}_5/\text{SiO}_2)_{adj}) - 0.92

Tectonomagmatic diagrams using major and trace elements

DF1_{(IA+CA-CR+OI-Col)}_{macid} = (-0.091*\ln(\text{MgO}/\text{TiO}_2)_{adj}) + (-0.228*\ln(\text{P}_2\text{O}_5/\text{TiO}_2)_{adj}) + (0.73*\ln(\text{Nb}/\text{TiO}_2)_{adj}) + (-0.237*\ln(\text{Y}/\text{TiO}_2)_{adj}) + (0.58*\ln(\text{Zr}/\text{TiO}_2)_{adj}) + 4.70

DF2_{(IA+CA-CR+OI-Col)}_{macid} = (-0.268*\ln(\text{MgO}/\text{TiO}_2)_{adj}) + (1.25*\ln(\text{P}_2\text{O}_5/\text{TiO}_2)_{adj}) + (-0.476*\ln(\text{Nb}/\text{TiO}_2)_{adj}) + (0.209*\ln(\text{Y}/\text{TiO}_2)_{adj}) + (-0.082*\ln(\text{Zr}/\text{TiO}_2)_{adj}) - 3.71

DF1_{(IA-CA-CR+OI)}_{mtacid} = (-0.018*\ln(\text{MgO}/\text{TiO}_2)_{adj}) + (-0.025*\ln(\text{P}_2\text{O}_5/\text{TiO}_2)_{adj}) + (1.06*\ln(\text{Nb}/\text{TiO}_2)_{adj}) + (-0.53*\ln(\text{Y}/\text{TiO}_2)_{adj}) + (0.301*\ln(\text{Zr}/\text{TiO}_2)_{adj}) + 4.70

DF2_{(IA-CA-CR+OI)}_{macid} = (-0.197*\ln(\text{MgO}/\text{TiO}_2)_{adj}) + (0.118*\ln(\text{P}_2\text{O}_5/\text{TiO}_2)_{adj}) + (-0.72*\ln(\text{Nb}/\text{TiO}_2)_{adj}) + (1.10*\ln(\text{Y}/\text{TiO}_2)_{adj}) + (0.74*\ln(\text{Zr}/\text{TiO}_2)_{adj}) + 3.70
(For Figure C1f)

DF$_1$$_{(IA-CA-Col)_{macid}}$ = (0.248*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (1.18*In(Nb/TiO$_2$)$_{adj}$) + (-0.86*In(Y/TiO$_2$)$_{adj}$) + (0.136*In(Zr/TiO$_2$) + 3.99

DF$_2$$_{(IA-CA-Col)_{macid}}$ = (1.13*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (0.382*In(Nb/TiO$_2$)$_{adj}$) + (1.13*In(Y/TiO$_2$)$_{adj}$) + (0.68*In(Zr/TiO$_2$)$_{adj}$) + 7.28

(For Figure C1g)

DF$_1$$_{(IA-CR+OI-Col)_{macid}}$ = (0.095*In(MgO/TiO$_2$)$_{adj}$) + (-0.079*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (1.10*In(Nb/TiO$_2$)$_{adj}$) + (-0.90*In(Y/TiO$_2$)$_{adj}$) + (0.333*In(Zr/TiO$_2$)$_{adj}$) + 2.77

DF$_2$$_{(IA-CR+OI-Col)_{macid}}$ = (-0.298*In(MgO/TiO$_2$)$_{adj}$) + (-1.00*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (-0.279*In(Nb/TiO$_2$)$_{adj}$) + (0.339*In(Y/TiO$_2$)$_{adj}$) + (0.171*In(Zr/TiO$_2$)$_{adj}$) - 0.80

(For Figure C1h)

DF$_1$$_{(CA-CR+OI-Col)_{macid}}$ = (-0.081*In(MgO/TiO$_2$)$_{adj}$) + (-0.432*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (0.444*In(Nb/TiO$_2$)$_{adj}$) + (-0.131*In(Y/TiO$_2$)$_{adj}$) + (0.82*In(Zr/TiO$_2$)$_{adj}$) + 3.73

DF$_2$$_{(CA-CR+OI-Col)_{macid}}$ = (-0.341*In(MgO/TiO$_2$)$_{adj}$) + (-1.11*In(P$_2$O$_5$/TiO$_2$)$_{adj}$) + (-0.75*In(Nb/TiO$_2$)$_{adj}$) + (0.271*In(Y/TiO$_2$)$_{adj}$) + (-0.377*In(Zr/TiO$_2$)$_{adj}$) - 5.42

Tectonomagmatic diagrams using trace elements

(For Figure 6.8c)

DF$_1$$_{(IA+CA-CR+OI-Col)_{tacid}}$ = (-4.99*In(La/Yb)$_{adj}$) + (7.81*In(Ce/Yb)$_{adj}$) + (-4.33*In(Sm/Yb)$_{adj}$) + (0.82*In(Nb/Yb)$_{adj}$) + (0.063*In(Th/Yb)$_{adj}$) + (0.64*In(Y/Yb)$_{adj}$) + (-0.57*In(Zr/Yb)$_{adj}$) - 9.50

DF$_2$$_{(IA+CA-CR+OI-Col)_{tacid}}$ = (2.32*In(La/Yb)$_{adj}$) + (-3.62*In(Ce/Yb)$_{adj}$) + (2.62*In(Sm/Yb)$_{adj}$) + (0.25*In(Nb/Yb)$_{adj}$) + (0.84*In(Th/Yb)$_{adj}$) + (-1.14*In(Y/Yb)$_{adj}$) + (-1.27*In(Zr/Yb)$_{adj}$) + 10.25

(For Figure C1i)
DF1_{(IA-CA-Col)} = (-5.21*In(La/Yb)_{adj}) + (6.62*In(Ce/Yb)_{adj}) + (-3.63*In(Sm/Yb)_{adj}) + (1.69*In(Nb/Yb)_{adj}) + (0.33*In(Th/Yb)_{adj}) + (1.56*In(Y/Yb)_{adj}) + (-0.49*In(Zr/Yb)_{adj}) - 9.61

DF2_{(IA-CA-Col)} = (-3.72*In(La/Yb)_{adj}) + (4.79*In(Ce/Yb)_{adj}) + (-2.68*In(Sm/Yb)_{adj}) + (0.16*In(Nb/Yb)_{adj}) + (-0.50*In(Th/Yb)_{adj}) + (1.04*In(Y/Yb)_{adj}) + (-0.34*In(Zr/Yb)_{adj}) - 4.93

(For Figure C1j)

DF1_{(IA-CA-Col)} = (-0.047*In(La/Yb)_{adj}) + (1.08*In(Ce/Yb)_{adj}) + (-0.96*In(Sm/Yb)_{adj}) + (0.84*In(Nb/Yb)_{adj}) + (0.59*In(Th/Yb)_{adj}) + (-0.88*In(Zr/Yb)_{adj}) - 0.73

DF1_{(IA-CA-Col)} = (-4.07*In(La/Yb)_{adj}) + (4.74*In(Ce/Yb)_{adj}) + (-0.077*In(Sm/Yb)_{adj}) + (-0.23*In(Nb/Yb)_{adj}) + (0.77*In(Th/Yb)_{adj}) + (-2.49*In(Zr/Yb)_{adj}) + 5.10

(For Figure C1k)

DF1_{(IA-CR+OI-Col)} = (0.26*In(La/Yb)_{adj}) + (1.05*In(Ce/Yb)_{adj}) + (-1.00*In(Sm/Yb)_{adj}) + (0.90*In(Nb/Yb)_{adj}) + (0.54*In(Th/Yb)_{adj}) + (0.089*In(Y/Yb)_{adj}) + (-0.62*In(Zr/Yb)_{adj}) - 2.91

DF2_{(IA-CR+OI-Col)} = (-5.36*In(La/Yb)_{adj}) + (8.41*In(Ce/Yb)_{adj}) + (-5.37*In(Sm/Yb)_{adj}) + (0.48*In(Nb/Yb)_{adj}) + (-0.41*In(Th/Yb)_{adj}) + (1.12*In(Y/Yb)_{adj}) + (0.37*In(Zr/Yb)_{adj}) - 13.95

(For Figure C1l)

DF1_{(CA-CR+OI-Col)} = (-5.41*In(La/Yb)_{adj}) + (8.44*In(Ce/Yb)_{adj}) + (-4.78*In(Sm/Yb)_{adj}) + (0.78*In(Nb/Yb)_{adj}) + (-0.079*In(Th/Yb)_{adj}) + (0.64*In(Y/Yb)_{adj}) + (-0.26*In(Zr/Yb)_{adj}) - 11.34

DF2_{(CA-CR+OI-Col)} = (1.68*In(La/Yb)_{adj}) + (-1.73*In(Ce/Yb)_{adj}) + (0.52*In(Sm/Yb)_{adj}) + (0.84*In(Nb/Yb)_{adj}) + (1.04*In(Th/Yb)_{adj}) + (-0.98*In(Y/Yb)_{adj}) + (-1.41*In(Zr/Yb)_{adj}) + 6.09
Figure C1. Tectonic setting discrimination diagrams for the eastern Namaqua Sector. (m-n) Nb (ppm) vs. Y (ppm) and Ta vs. Yb (ppm) diagrams indicating the tectonic setting (after Pearce et al., 1984).

Figure C2. Trace element versus Fe + Mg variation diagrams for the granites of the eastern margin of the Namaqua Sector to test whether accessory mineral entrainment influenced the trace element composition of the granites. The blue bordered areas represent the Fe + Mg range in experimental melt compositions (after Villaros et al., 2009). The blue bordered area is the field in which melting has occurred without the dissolution of any accessory phases in the melt, although peritectic minerals are entrained (pure melts). The legend is the same in all figures.
Figure C2 (cont.). Trace element versus Fe + Mg variation diagrams for the granites of the eastern margin of the Namaqua Sector to test whether accessory mineral entrainment influenced the trace element composition of the granites. The blue bordered areas represent the Fe + Mg range in experimental melt compositions (after Villaros et al., 2009). The blue bordered area is the field in which melting has occurred without the dissolution of any accessory phases in the melt, although peritectic minerals are entrained (pure melts). The legend is the same in all figures.
Figure C2 (cont.). Trace element versus Fe + Mg variation diagrams for the granites of the eastern margin of the Namaqua Sector to test whether accessory mineral entrainment influenced the trace element composition of the granites. The blue bordered areas represent the Fe + Mg range in experimental melt compositions (after Villaros et al., 2009). The blue bordered area is the field in which melting has occurred without the dissolution of any accessory phases in the melt, although peritectic minerals are entrained (pure melts). The legend is the same in all figures.
Figure C3. Harker diagrams for assessing overall fractionation trends.
Figure C3 (cont.). Harker diagrams for assessing overall fractionation trends.
Figure C3 (cont.). Harker diagrams for assessing overall fractionation trends. Legend is the same as the previous page.
Figure C3 (cont.). Harker diagrams for assessing overall fractionation trends.

Figure C4. The maficity vs. major elements diagrams assessing the compositional and source variation between the granites and between suites.
Figure C4 (cont.). The maficity vs. major elements diagrams assessing the compositional and source variation between the granites and between suites.
## Appendix D. Geochronology

Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector

<table>
<thead>
<tr>
<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]$^a$</th>
<th>Pb [ppm]$^a$</th>
<th>Th/U meas</th>
<th>$^{207}$Pb/$^{235}$U$^b$</th>
<th>2 $\sigma$$^d$</th>
<th>$^{206}$Pb/$^{238}$U$^b$</th>
<th>2 $\sigma$$^d$</th>
<th>$^{207}$Pb/$^{206}$Pb$^e$</th>
<th>2 $\sigma$$^d$</th>
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<td>Bright well zoned core</td>
<td>113</td>
<td>22</td>
<td>0.68</td>
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<td>0.1937</td>
<td>0.006</td>
<td>0.0779</td>
<td>0.0021</td>
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<td>0.19564</td>
<td>0.006</td>
<td>0.0786</td>
<td>0.0024</td>
<td>1162 ± 60</td>
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Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

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<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]</th>
<th>Pb [ppm]²</th>
<th>Th/U meas</th>
<th>(^{207} \text{Pb}/^{235} \text{U} )</th>
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<th>(^{206} \text{Pb}/^{238} \text{U} )</th>
<th>2 ( \sigma^d )</th>
<th>(^{207} \text{Pb}/^{206} \text{Pb} )</th>
<th>2 ( \sigma^d )</th>
<th>conc. %</th>
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<td>Slightly dark weakly zoned rims</td>
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<td>0.0777</td>
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<td>0.0791</td>
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<td>Bright anhedral unzoned core</td>
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<tr>
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<td>CL dark oscillatory zoned core</td>
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<td>Dark oscillatory zoned core</td>
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Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

<table>
<thead>
<tr>
<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]$^a$</th>
<th>Pb [ppm]$^b$</th>
<th>Th/U meas</th>
<th>$^{207}\text{Pb}/^{235}\text{U}$</th>
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<td>69</td>
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Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

<table>
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<tr>
<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]$^a$</th>
<th>Pb [ppm]$^a$</th>
<th>Th/U meas</th>
<th>$^{207}$Pb/$^{206}$U$^b$</th>
<th>$^{206}$Pb/$^{238}$U</th>
<th>$^{238}$U/$^{206}$Pb</th>
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$^a$U and Pb concentrations are from LA-ICP-MS analyses.

$^b$Th/U and $^{207}$Pb/$^{206}$U ratios are from LA-ICP-MS analyses.
Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

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Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

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<th>207Pb/235U&lt;sup&gt;b&lt;/sup&gt;</th>
<th>2 &lt;sup&gt;σ&lt;/sup&gt;d</th>
<th>206Pb/238U&lt;sup&gt;b&lt;/sup&gt;</th>
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<tr>
<td>Mkn5 - 14</td>
<td>CL dark poorly zoned rim</td>
<td>1858</td>
<td>191</td>
<td>0.02</td>
<td>1.146</td>
<td>0.0</td>
<td>0.1030</td>
<td>0.003</td>
<td>0.0807</td>
<td>0.0018</td>
<td>1213 ± 44</td>
<td>52</td>
</tr>
<tr>
<td>Mkn5 - 15</td>
<td>CL dark weakly zoned rim</td>
<td>2572</td>
<td>115</td>
<td>0.01</td>
<td>0.401</td>
<td>0.0</td>
<td>0.0449</td>
<td>0.001</td>
<td>0.0648</td>
<td>0.0015</td>
<td>768 ± 48</td>
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<tr>
<td>Mkn5 - 16</td>
<td>CL bright oscillatory zoned core</td>
<td>92</td>
<td>19</td>
<td>0.65</td>
<td>2.325</td>
<td>0.1</td>
<td>0.2079</td>
<td>0.006</td>
<td>0.0811</td>
<td>0.0021</td>
<td>1224 ± 51</td>
<td>99</td>
</tr>
<tr>
<td>Mkn5 - 17</td>
<td>CL dark poorly zoned rim</td>
<td>1335</td>
<td>130</td>
<td>0.03</td>
<td>1.089</td>
<td>0.0</td>
<td>0.0977</td>
<td>0.003</td>
<td>0.0808</td>
<td>0.0019</td>
<td>1216 ± 45</td>
<td>49</td>
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<tr>
<td>Mkn5 - 18</td>
<td>CL dark oscillatory zoned core</td>
<td>337</td>
<td>70</td>
<td>0.58</td>
<td>2.315</td>
<td>0.1</td>
<td>0.2084</td>
<td>0.006</td>
<td>0.0806</td>
<td>0.0019</td>
<td>1210 ± 46</td>
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<tr>
<td>Mkn5 - 19</td>
<td>CL dark elongated weakly zoned core</td>
<td>113</td>
<td>23</td>
<td>0.87</td>
<td>2.298</td>
<td>0.1</td>
<td>0.2083</td>
<td>0.006</td>
<td>0.0800</td>
<td>0.0022</td>
<td>1197 ± 54</td>
<td>102</td>
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<tr>
<td>Mkn5 - 20</td>
<td>CL dark moderately zoned core</td>
<td>2632</td>
<td>172</td>
<td>0.07</td>
<td>0.741</td>
<td>0.0</td>
<td>0.0652</td>
<td>0.002</td>
<td>0.0825</td>
<td>0.0027</td>
<td>1258 ± 64</td>
<td>32</td>
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<tr>
<td>Mkn5 - 21</td>
<td>Bright weakly zoned rim</td>
<td>968</td>
<td>106</td>
<td>0.05</td>
<td>1.231</td>
<td>0.0</td>
<td>0.1096</td>
<td>0.003</td>
<td>0.0815</td>
<td>0.0023</td>
<td>1233 ± 54</td>
<td>54</td>
</tr>
<tr>
<td>Mkn5 - 22</td>
<td>CL bright oscillatory zoned core</td>
<td>297</td>
<td>61</td>
<td>0.30</td>
<td>2.288</td>
<td>0.1</td>
<td>0.2057</td>
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<td>0.0807</td>
<td>0.0026</td>
<td>1214 ± 63</td>
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</tr>
<tr>
<td>Mkn5 - 23</td>
<td>CL bright poorly zoned core</td>
<td>182</td>
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<td>2.331</td>
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<td>0.2073</td>
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<td>0.0816</td>
<td>0.0046</td>
<td>1235 ± 109</td>
<td>98</td>
</tr>
</tbody>
</table>

<sup>a</sup> ppm = parts per million
<sup>b</sup> Pb/235U and 206Pb/238U ratios
<sup>c</sup> 2σ uncertainties on radiogenic Pb ages
<sup>d</sup> 2σ uncertainties on U and Pb concentrations
<sup>e</sup> 7/8 ratios of 207Pb/206Pb and 208Pb/206Pb
Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua Sector

<table>
<thead>
<tr>
<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]</th>
<th>Pb [ppm]</th>
<th>Th/U meas</th>
<th>207Pb/235U</th>
<th>2σd</th>
<th>206Pb/238U</th>
<th>2σd</th>
<th>207Pb/206Pb</th>
<th>2σd</th>
<th>206Pb/208Pb</th>
<th>2σd</th>
<th>Conc. %</th>
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<tbody>
<tr>
<td><strong>Josling Granite</strong></td>
<td>Mkn5 - 25 CL dark poorly zoned rim</td>
<td>1609</td>
<td>141</td>
<td>0.04</td>
<td>0.970</td>
<td>0.0</td>
<td>0.0878</td>
<td>0.03</td>
<td>0.0820</td>
<td>0.021</td>
<td>1202 ± 52</td>
<td>45</td>
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</tr>
<tr>
<td><strong>Elsie se Gorra Granite</strong></td>
<td>Me1 - 01 Dark unzoned acircular core</td>
<td>2110</td>
<td>283</td>
<td>0.29</td>
<td>1.400</td>
<td>0.0</td>
<td>0.134</td>
<td>0.04</td>
<td>0.0758</td>
<td>0.0031</td>
<td>1090 ± 42</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Me1 - 02 Dark unzoned acircular core</td>
<td>2214</td>
<td>241</td>
<td>0.26</td>
<td>1.143</td>
<td>0.0</td>
<td>0.109</td>
<td>0.03</td>
<td>0.0763</td>
<td>0.0031</td>
<td>1102 ± 43</td>
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<tr>
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<td>Me1 - 03 Bright unzoned rim</td>
<td>325</td>
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<td>0.67</td>
<td>2.009</td>
<td>0.1</td>
<td>0.183</td>
<td>0.05</td>
<td>0.0795</td>
<td>0.0031</td>
<td>1184 ± 77</td>
<td>92</td>
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<tr>
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<td>Me1 - 04 Dark well zoned core</td>
<td>519</td>
<td>105</td>
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<td>2.229</td>
<td>0.1</td>
<td>0.203</td>
<td>0.06</td>
<td>0.0797</td>
<td>0.0026</td>
<td>1190 ± 63</td>
<td>100</td>
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<tr>
<td></td>
<td>Me1 - 05 Bright oscillatory zoned core</td>
<td>526</td>
<td>107</td>
<td>0.12</td>
<td>2.222</td>
<td>0.1</td>
<td>0.203</td>
<td>0.06</td>
<td>0.0794</td>
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<tr>
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<td>Me1 - 06 Bright oscillatory zoned core</td>
<td>549</td>
<td>111</td>
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<td>0.0800</td>
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<tr>
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<td>Me1 - 07 Dark oscillatory zoned core</td>
<td>353</td>
<td>81</td>
<td>0.21</td>
<td>2.727</td>
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<td>0.230</td>
<td>0.07</td>
<td>0.0860</td>
<td>0.0020</td>
<td>1337 ± 45</td>
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<tr>
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<td>Me1 - 08 Dark well developed zonation around inherited core</td>
<td>330</td>
<td>76</td>
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<td>2.753</td>
<td>0.1</td>
<td>0.232</td>
<td>0.07</td>
<td>0.0862</td>
<td>0.0020</td>
<td>1342 ± 44</td>
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<tr>
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<td>Me1 - 14 Unzoned slightly bright rim</td>
<td>3748</td>
<td>327</td>
<td>0.05</td>
<td>0.961</td>
<td>0.0</td>
<td>0.087</td>
<td>0.03</td>
<td>0.0798</td>
<td>0.0017</td>
<td>1193 ± 42</td>
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<tr>
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<td>Me1 - 15 Weakly zoned rim</td>
<td>3470</td>
<td>332</td>
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<td>0.096</td>
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<td>0.0789</td>
<td>0.0020</td>
<td>1170 ± 51</td>
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<td>Me1 - 16 Bright weakly zoned core</td>
<td>2462</td>
<td>216</td>
<td>0.10</td>
<td>0.931</td>
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<td>0.088</td>
<td>0.03</td>
<td>0.0770</td>
<td>0.0017</td>
<td>1121 ± 43</td>
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<tr>
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<td>Me1 - 17 CL bright oscillatory zoned core</td>
<td>1913</td>
<td>281</td>
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<td>1.604</td>
<td>0.1</td>
<td>0.147</td>
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<td>0.0793</td>
<td>0.0017</td>
<td>1180 ± 43</td>
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<tr>
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<td>Me1 - 18 CL bright irregular core</td>
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<td>0.198</td>
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<td>0.0827</td>
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<td>1262 ± 44</td>
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<td>Me1 - 19 CL bright core with poorly developed zonation</td>
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<td>55</td>
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<td>2.218</td>
<td>0.1</td>
<td>0.202</td>
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<td>0.0795</td>
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<td>861</td>
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<td>2.007</td>
<td>0.1</td>
<td>0.181</td>
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<td>0.0805</td>
<td>0.0026</td>
<td>1210 ± 63</td>
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<td>Me1 - 21 CL bright well zoned core</td>
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<td>0.1</td>
<td>0.202</td>
<td>0.06</td>
<td>0.0793</td>
<td>0.0018</td>
<td>1180 ± 45</td>
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<td>Me1 - 22 CL bright weakly zoned core</td>
<td>1024</td>
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<td>0.169</td>
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<td>0.0796</td>
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<td>1186 ± 45</td>
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<td>0.201</td>
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<td>0.0795</td>
<td>0.0019</td>
<td>1184 ± 46</td>
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Table D1. LA-ICP-MS geochronological data for zircons of the granites on the eastern margin of the Namaqua sector (cont.)

<table>
<thead>
<tr>
<th>Samples-Analysis</th>
<th>Comment</th>
<th>U [ppm]$^a$</th>
<th>Pb [ppm]$^b$</th>
<th>Th/U meas</th>
<th>$^{207}\text{Pb}/^{235}\text{U}$</th>
<th>$^{206}\text{Pb}/^{238}\text{U}$</th>
<th>$^{207}\text{Pb}/^{206}\text{Pb}$</th>
<th>$^{207}\text{Pb}/^{206}\text{Pb}$</th>
<th>Conc. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elsie se Gorra Granite</td>
<td>Me1 - 27</td>
<td>CL dark poorly zoned rim</td>
<td>965</td>
<td>194</td>
<td>0.28</td>
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<td>Bright slightly zoned core</td>
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<td>45</td>
<td>0.21</td>
<td>2.207</td>
<td>0.1</td>
<td>0.201</td>
<td>0.006</td>
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</tbody>
</table>

$^a$U and Pb concentrations and Th/U ratios are calculated relative to the GJ-1 reference zircon. $^b$Corrected for background and within-run Pb/U fractionation and normalised to reference zircon GJ-1 (ID-TIMS values/measured value); $^{207}\text{Pb}/^{235}\text{U}$ calculated using $(^{207}\text{Pb}/^{206}\text{Pb})/(^{238}\text{U}/^{206}\text{Pb} * 1/137.88)$. $^c$Rho is the error correlation defined as the quotient of the propagated errors of the $^{206}\text{Pb}/^{238}\text{U}$ and the $^{207}\text{Pb}/^{235}\text{U}$ ratio. $^d$Quadratic addition of within-run errors (2 SD) and daily reproducibility of GJ-1 (2 SD). $^e$Corrected for mass-bias by normalising to GJ-1 reference zircon (~0.6 per atomic mass unit) and common Pb using the model Pb composition of Stacey & Kramers (1975). Abbre. Mkn = Josling Granite, Mc = Cnydas Subsuite, Me = Elsie se Gorra Granite, Mcol = Colston Granite, Ml = Louisvale Granite, Mkl = Klipkraal granite, Mkb = Keboes Granite, Mka = Kanoneiland Granite.
Appendix E. Geological maps of the granites of the eastern Namaqua sector

Figure E1. The regional map of the eastern Namaqua sector showing different formations (after Moen, 1988; Slabbert, 1989).
Figure E2. Local geological map showing the distribution of the granites of the eastern margin of the Namaqua Sector (after Moen, 1988; Slabbert, 1989)