Geochemistry of intrusive rocks in the Aus area, Southern Namibia

Claudia Mutongolume

Geological Survey of Namibia, Windhoek, Namibia
<Claudia.Mutongolume@mme.gov.na>

Abstract :- Aus is located in the southern part of Namibia within the Aus Domain of the Palaeo- to Mesoproterozoic Namaqua-Natal Metamorphic Province. The area is characterised by voluminous granitoids which intruded supracrustal rocks of the pre-tectonic Garup group. In this study, the geochemical characteristics of the intrusive rocks were investigated, showing them to be acidic, peraluminous and derived from shoshonitic and high-K calc-alkaline magmas of an-orogenic origin. Chondrite-normalised spidergrams display characteristics of rocks originated in an arc environment, while plots of K_2O vs SiO_2 exhibit considerable scatter indicative of crustal contamination. Three geotectonic settings are indicated, i. e. Syn-Collisional, Volcanic Arc and Within Plate, supporting collision of continental fragments.

Keywords :- Namaqua – Natal Metamorphic Province, Geochemistry, Tectonic setting, Granitoids

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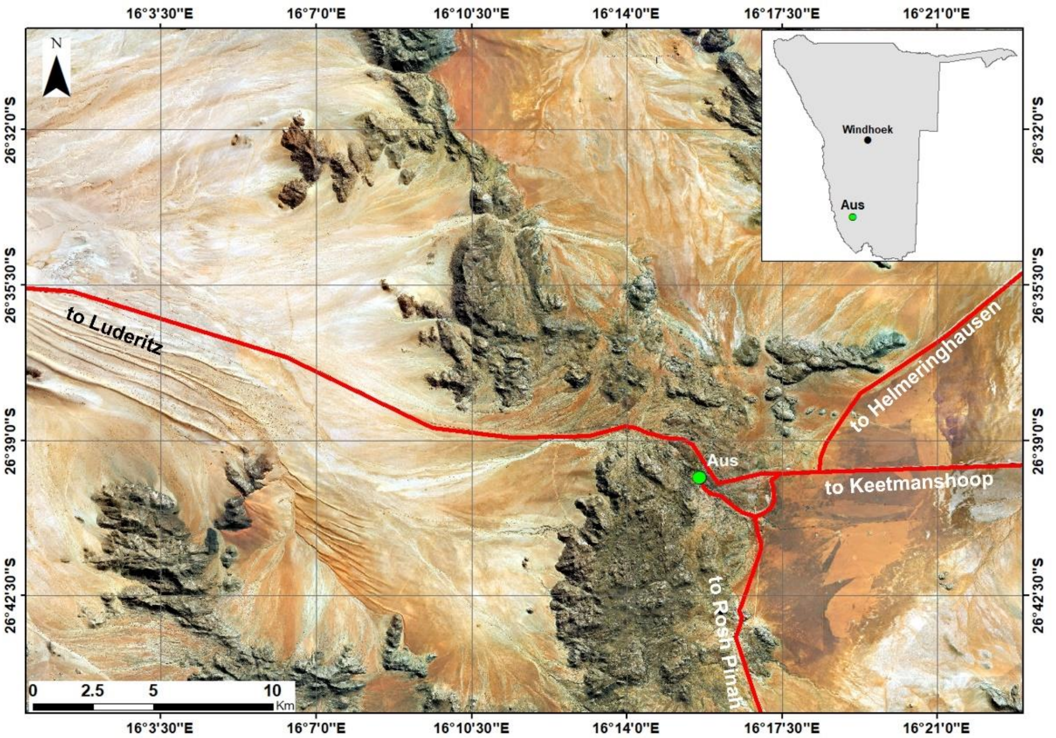

Figure 1. Locality map showing the extent of the study area

Introduction

The study area is located near Aus, southern Namibia, some 125 km northeast of Lüderitz (Fig. 1). Geologically, the area lies within the Aus Domain of the Palaeo- to Mesoproterozoic Namaqua-Natal Metamorphic Province (NNMP). Effects of the ca. 1200 Ma Namaqua Orogeny include voluminous intrusions of syn- and post-tectonic granitoids (e. g. Cornell *et al*., 2006; Miller, 2012) and high-grade metamorphism (amphibolite facies and higher; e. g. Waters, 1986; Moen & Toogood, 2007; Macey *et al*., 2015; Diener *et al*., 2013).

The oldest rocks in the Aus area belong to the pre-tectonic Garub group, which comprises metapelitic and metapsammitic gneisses, quartzite, mafic granulite, marble, calc-silicate and ironstone, metamorphosed under amphibolite to granulite facies conditions (Jackson, 1976). These rocks were extensively intruded by pre-, syn- and post-tectonic granitoids (Figs. 2-6); the garnet-bearing tonalitic to granodioritic Tsirub augen gneiss, represents the oldest igneous suite and pre-tectonic intrusive in this area, having been emplaced shortly before the peak of granulite facies metamorphism (Jackson, 1976; Diener *et al*., 2013). Widespread syn-tectonic magmatism led to the emplacement of the schlieren-rich, leucocratic, sheeted Kubub granite gneiss and the coarse-grained, K-feldspar-megacrystic Aus leucogranite gneiss (Jackson, 1976). U–Pb zircon dating of pre-, syn- and post-tectonic granitoid intrusions indicates that plutonism occurred at ~1120-1085 Ma, whereas metamorphic overgrowths on the same zircons constrains the age of metamorphism to between ~1065 and 1045 Ma (Diener *et al*., 2013). A granite dyke believed to be post-tectonic intruded after the domain cooled to subsolidus temperatures and records an age of 1004±6 Ma (Diener *et al*., 2013). This study investigates the geochemistry of the intrusive rocks in the Aus area with the intention to determine its geotectonic setting.

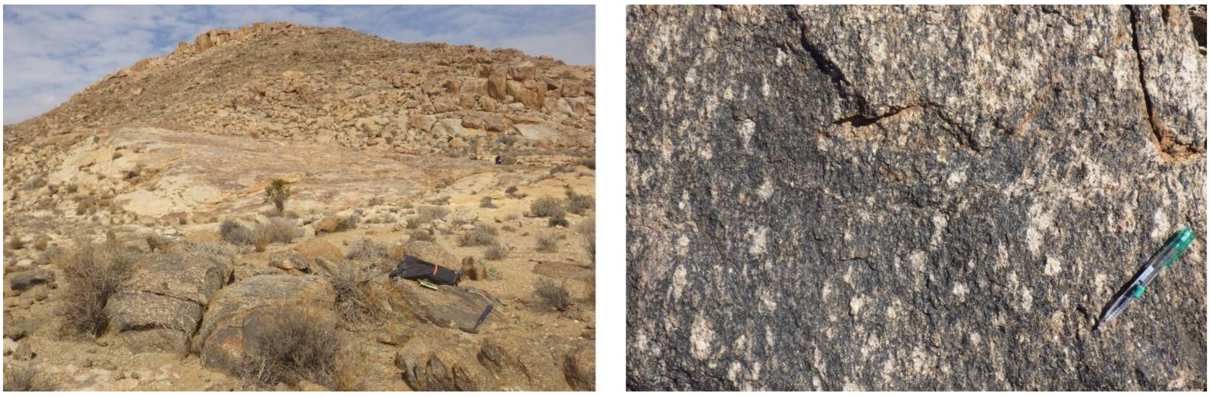

Figure 2. Coarse-grained megacrystic granodioritic Tsirub augen gneiss

Figure 3. Coarse-grained megacrystic Aus granite gneiss

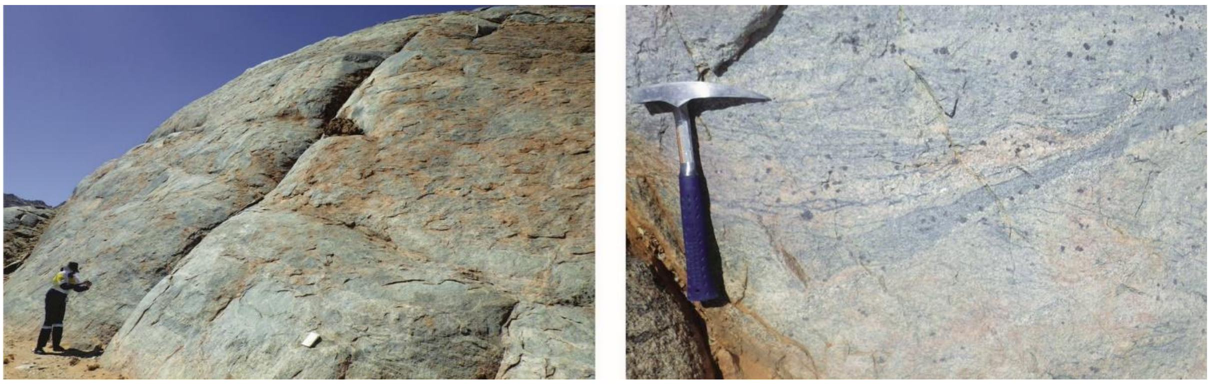

Figure 4. Medium- to coarse-grained Kubub granite gneiss (Type 1) with schlieren texture

Figure 5. Very coarse-grained pegmatitic Kubub granite gneiss (Type 2)

Figure 6. Weakly foliated leucocratic Warmbad granite

Regional Geology

The Namaqua - Natal Metamorphic Province is represented by a ~400 km wide belt extending for more than 1500 km from southern Namibia to southeastern South Africa (Blignault, 1977; Blignault *et al*., 1983; Hartnady *et al*., 1985; Joubert, 1986; Thomas *et al*., 1994; Frimmel, 2000; Cornell *et al*., 2006). Rocks along the belt were assembled during the Namaqua Orogeny between ca. 1200 and 1000 Ma, and are variably deformed and metamorphosed (Cornell *et al*., 2006; Miller, 2012). They form the southern African portion of the global Mesoproterozoic orogen linked to the assembly of the Rodinia Super-continent between ca. 1350 and 1050 Ma (Hoffman, 1991, 1992). This amalgamation has traditionally been associated with a series of crustal blocks being accreted onto the southern and southwestern margins of the Kaapvaal Craton of southern Namibia and South Africa, (Hartnady *et al*., 1985; Joubert, 1986; Humphreys & Van Bever Donker, 1987; Eglington & Armstrong, 2003; Colliston & Schoch, 2013), which led to the establishment of different litho- and tectonostratigraphic subdivisions. However, Macey *et al*. (2015) hold some rather different views about these domains, which they consider to have resulted from reworking rather than accretion.

The NNMP has been divided into two segments, i. e. the Natal Sector in southeastern South Africa and the Namaqua Sector in southern Namibia and northwestern South Africa (Cornell *et al*., 2006; Frimmel, 2000). Recent work by Macey *et al*. (2015) redefined and recognised different crustal blocks within the Namibian part of the Namaqua Sector (Fig. 7). These are from north to south a) the Konkiep Domain (formerly Konkiep Sub-province), b) Kakamas Domain (formerly Gordonia Subprovince, subdivided into the Kakamas and Grünau Terranes), c) Aus Do-main (formerly Aus Terrane) and d) Rich-tersveld Magmatic Arc (formerly Richtersveld Subprovince), which comprises the Vioolsdrift, Pella and Sperrgebiet Domains (Blignault *et al*., 1983; Hartnady *et al*., 1985; Joubert, 1986; Thomas *et al*., 1994; Colliston

& Schoch, 2000; Miller, 2008; Macey *et al*., 2015). These crustal blocks are separated by major structural discontinuities and differentiated on the basis of lithostratigraphy, tectonic history and metamorphic grade (Hartnady *et al*., 1985; Colliston & Schoch, 1996; Cornell *et al*., 2006; Miller, 2008). However, many of the determining criteria remain debatable, and multiple interpretations have evolved (Joubert, 1986; Thomas *et al*., 1994; Moen & Toogood, 2007; Macey *et al*., 2017).

A number of authors (e. g. Cornell *et al*., 1992; Colliston & Schoch, 2013; Bial *et al*., 2015; Macey *et al*., 2015; Indongo, 2017) have described the processes which led to the current configuration of tectonic domains, in an attempt to understand the specific geodynamic setting responsible for the regional Mesoproterozoic upper amphibolite to granulite signature. Their various interpretations of the regional tectonic setting encompass 1) a continental collision model (e. g. Blignault *et al*., 1983; Thomas *et al*., 1994; Eglington, 2006), 2) a continental back-arc setting (e. g. Waters, 1986; Bial *et al*., 2015), and 3) magmatic under- or intraplating accompanied by compressional tectonics (e. g. Diener *et al*., 2013) under medium- to low-pressure and high-temperature granulite facies metamorphic conditions. Colliston & Schoch (2013) and Colliston *et al*. (2015) presented evidence for extended compressional tectonics and proposed a model involving the collision of crustal fragments. A detailed review on the evolution of the NNMP is given by Cornell *et al*. (2006) and Macey *et al*. (2015), and references therein.

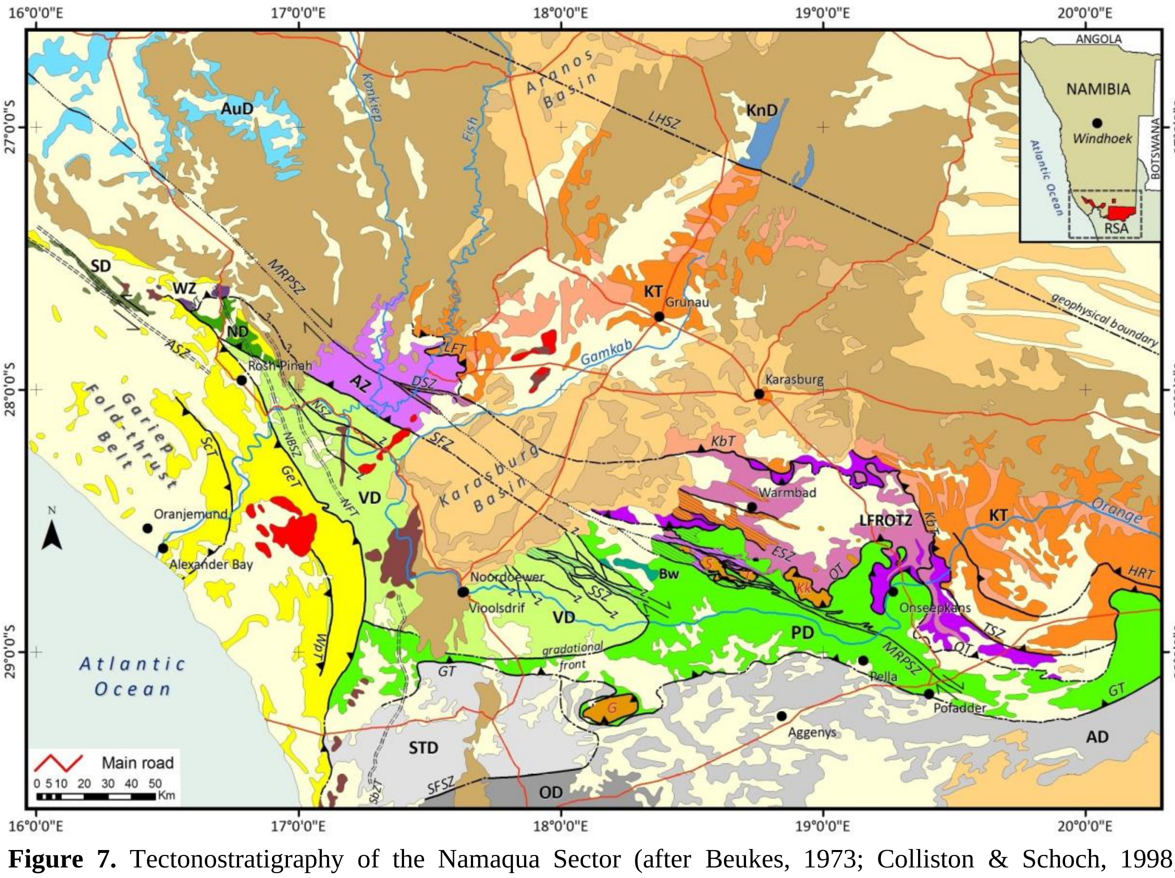

Figure 7. Tectonostratigraphy of the Namaqua Sector (after Beukes, 1973; Colliston & Schoch, 1998; Cornell *et al*., 2006; Moen & Toogood, 2007; Moen, 2007; Miller, 2008; Macey *et al*., 2015; Gresse *et al*., 2016; Thomas *et al*., 2016). KnD – Konkiep Domain; AuD – Aus Domain; KT- Kakamas Domain; LFROTZ + WZ + AZ – Lower Fish River-Onseepkans Thrust Domain; SD – Sperrgebiet Domain; VD – Vioolsdrif Domain; PD – Pella Domain

Local Geology

The Aus Domain is dominated by voluminous and extensive Mesoproterozoic (1220-1050 Ma) upper amphibolite to granulite facies, aluminous paragneisses and granitoids rocks (Blignault *et al*., 1983; Macey *et al*., 2015). Similar rock types and metamorphic grades occur in the adjacent Kakamas Domain, although the age of tectonism and metamorphism differs (Diener *et al*., 2013). The high-grade gneisses and granitoids of the two domains are believed to be derived from pre-existing older crust of the Palaeoproterozoic Richtersveld Magmatic Arc and the early Mesoproterozoic Areachap Arc (South Africa; Joubert, 1986; Macey *et al*., 2015) through reworking during mid-Mesoproterozoic high-grade metamorphism and associated intense plutonism. Subsequently, this reworked crust, represented by the high-grade rocks of the Kakamas and Aus Domains, was thrusted as imbricate sheets over the medium- to low-grade rocks of the Richtersveld Magmatic Arc along the Lower Fish River-Onseepkaans Thrust Zone during the mid- to late-Mesoproterozoic D_2 phase of the Namaqua Orogeny (Nordin, 2009; Samskog, 2009; Macey *et al*., 2015; Blignault *et al*., 1983; Colliston & Schoch, 2000, 2013; Macey *et al*., 2015; Miller, 2008, 2012; Moen & Toogood, 2007).

Sample preparation and analytical procedure

A total of eighteen granite samples were submitted for geochemical analysis at the University of Stellenbosch Laboratories, South Africa. Five of these samples were prepared at the Geological Survey of Namibia Laboratories by the author. The samples were crushed with a jaw crusher into <2 cm chips, which were milled to <75 μ powder fraction. Some 50 – 100 g of the sample were submitted for major and trace element analysis. Major elements were analysed by X-Ray Fluorescence (XRF) and trace elements by Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

For major element analysis, the milled sample (<75 μ fraction) was roasted at 1000°C for at least three hours to oxidise Fe^{2+} and S and determine the loss on ignition (LOI). Glass disks were prepared by fusing 1.5 g of the roasted sample and 9 g flux consisting of 66.67% $Li_2B_4O_7$, 32.83% $LiBO_2$ and 0.50% LiI at 950°C. For trace element analysis, 12 g of the milled sample and 3g Hoechst wax were mixed and pressed into a powder briquette by a hydraulic press with an applied pressure of 25 tonnes per square metre. The glass disks and wax pellets were analysed by a PANalytical Axios X-ray fluorescence spectrometer equipped with a 4 kW Rh tube. ICP-MS trace element and rare earth element (REE) analyses were carried out on a Perkin-Elmer ELAN 6000. A three-step HNO_3 acid digestion described by Le Roex *et al*. (2001) was used to obtain solutions. Approximately 50 mg of sample were placed in Teflon containers (Savilex beakers) and 4 ml of a 3:1 HF/HNO_3 were added. The container underwent a 48-hour digestion on a hot plate. After drying, 2 ml of concentrated nitric acid (HNO_3) were added and reheated until dry again. This process was repeated once. Following the final addition of 5% nitric acid, the container was transferred to a centrifuge tube and placed in an ultrasonic bath for dissolution, after which the sample was ready for use in the ICP-MS spectrometer. Errors were better than 3% and detection limits within the lower ppb range.

Granitoid geochemistry

Major elements

The granitoid samples display trends of decreasing Al_2O_3, CaO, FeO_t, MgO, TiO_2, P_2O_5 and MnO, but a slight increase in K_2O and Na_2O with increasing SiO_2 on the Harker variation diagram (Fig. 8). Some trends are much better defined (e. g. CaO, MgO, Na_2O and P_2O) than others which appear more scattered (K_2O and MnO). The positive trends of K_2O and Na_2O against SiO_2 could relate to contamination of the granitic magma by silicate rocks. Cr_2O_3 is present in very insignificant amounts of 0.002 - 0.01 wt.%. Similarly, samples show very low volatile (LOI) content between 0.15 and 1.58 wt.%, which implies a low degree of weathering.

The analysed granitoids have SiO_2 contents of between 65 and 73 wt.% (mean 70 wt.%), and Na_2O + K_2O between 5.5 and 9.1 wt.% (mean 7.3 wt.%), while the SiO_2/Al_2O_3 ratio varies between 3.9 and 6.4. They range in composition from granodioritic to granitic and plot in the sub-alkaline field as defined by Cox *et al*. (1979) on the total alkali versus silica (TAS) diagram (Fig. 9a). In the K_2O versus SiO_2 diagram (Fig. 9b) the granitoid samples fall in the shoshonitic and high-K calc-alkaline fields. The high content of SiO_2 in all the granitoids shows that they are highly fractionated.

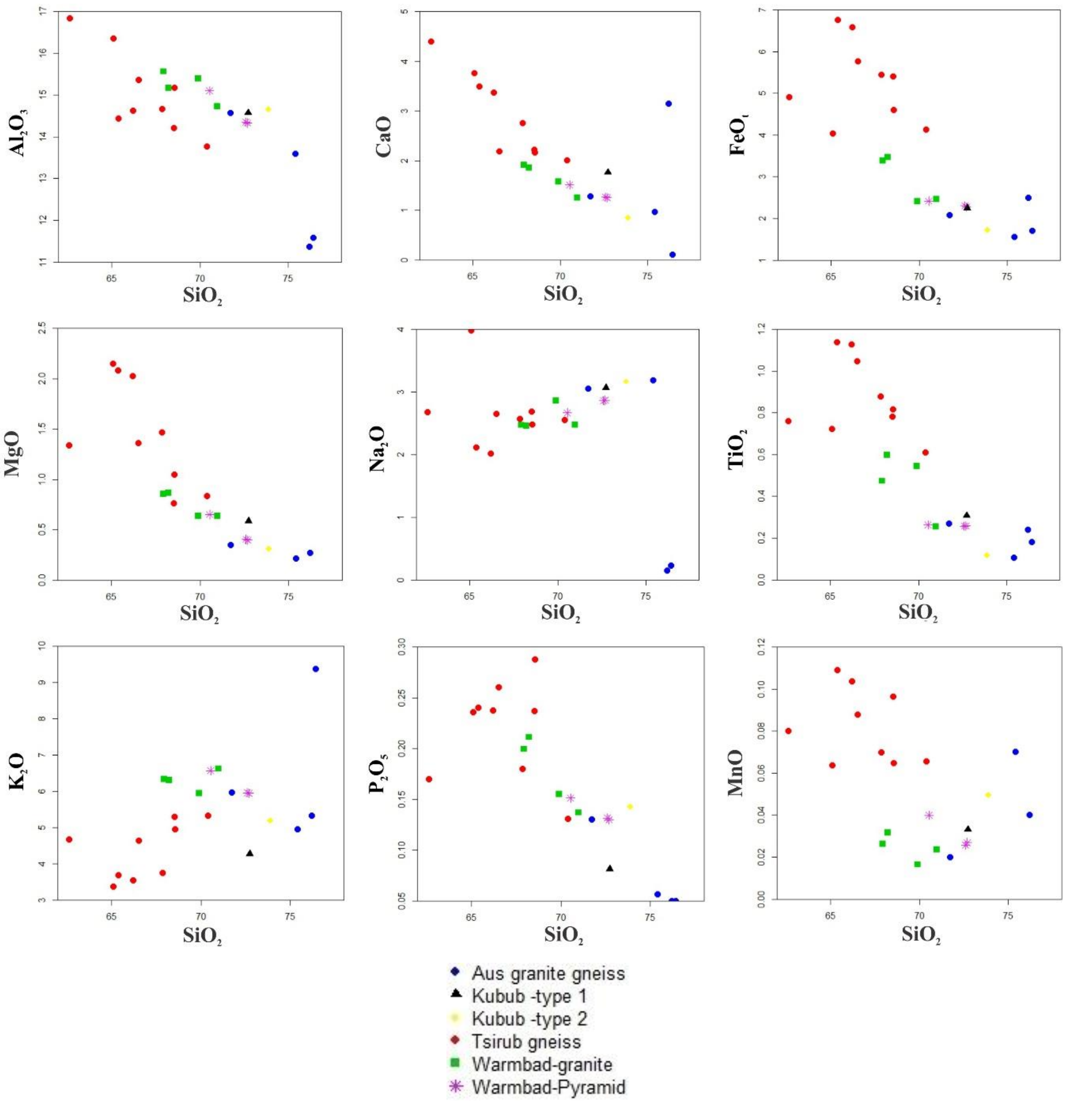

Figure 8. Harker (1909) diagrams for bivariate major elements (in wt.%)

The granodiorite and granites display a linear trend that falls in the calc-alkaline field on the AFM diagram, with high Na_2O and K_2O and moderate FeO_t and MgO (Fig. 9c). However, four samples of the Tsirub augen gneiss plot at the boundary between the tholeiite and calc-alkaline series (Fig. 9c). The samples are strongly peraluminous with an average Alumina Saturation Index (ASI) of 1.5; only three samples plot in the metaluminous field on the A/NK vs A/CNK diagram (Fig. 9d).

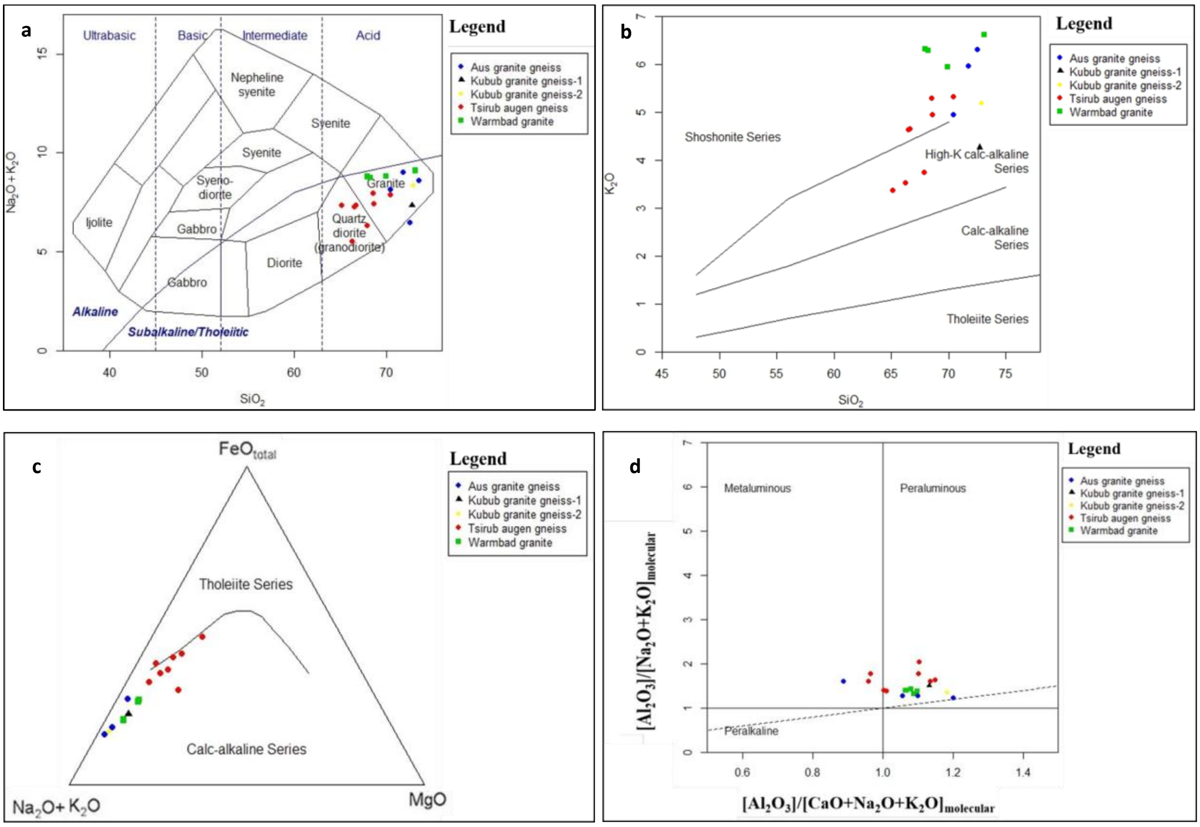

Figure 9. a) TAS plutonic classification by Cox *et al*. (1979); b) SiO_2-K_2O plot (Peccerillo & Taylor, 1976); c) AFM diagram (Irvine & Baragar, 1971); d) Shand (1943) classification of peralkaline, metaluminous and peraluminous rocks

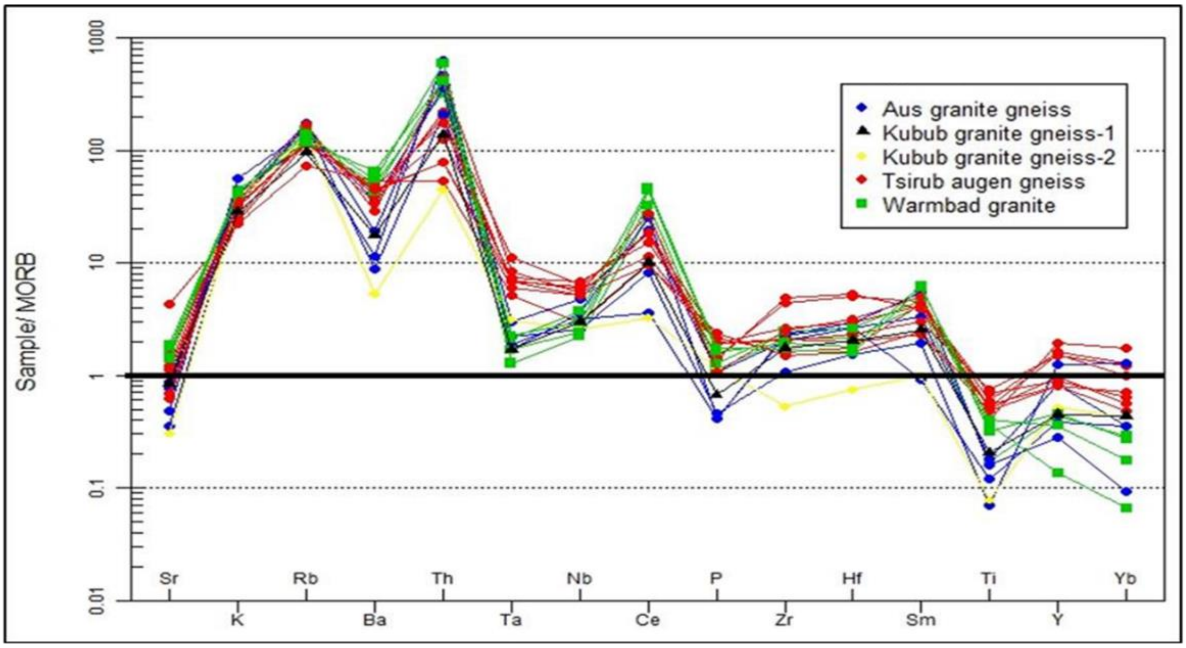

Figure 10. MORB-normalised spidergram after Pearce (1984)

Trace elements

Trace element analytical results are presented in Figure 10, showing high concentrations of Rb (up to 353 ppm), Sr (up to 511 ppm), Zr (up to 443 ppm), Ba (up to 1298 ppm), La (up to 216 ppm), Ce (up to 458 ppm) and Nd (up to 164 ppm). V and Cu show moderate concentrations of up to 90 and 86 ppm, respectively. Other trace elements have concentrations of < 50 ppm.

Rare Earth elements (REE)

The REE diagram exhibits enrichment of light rare earth elements (LREE) relative to heavy rare earth elements (HREE), with a sharp negative Eu anomaly related to plagioclase fractionation (Fig. 11). The slope of LREE is distinctly steeper than for HREE, which is generally very shallow. All samples are enriched in REE relative to chondrite-normalised values (Nakamura, 1974). A degree of fractionation in HREE toward Lu is evident.

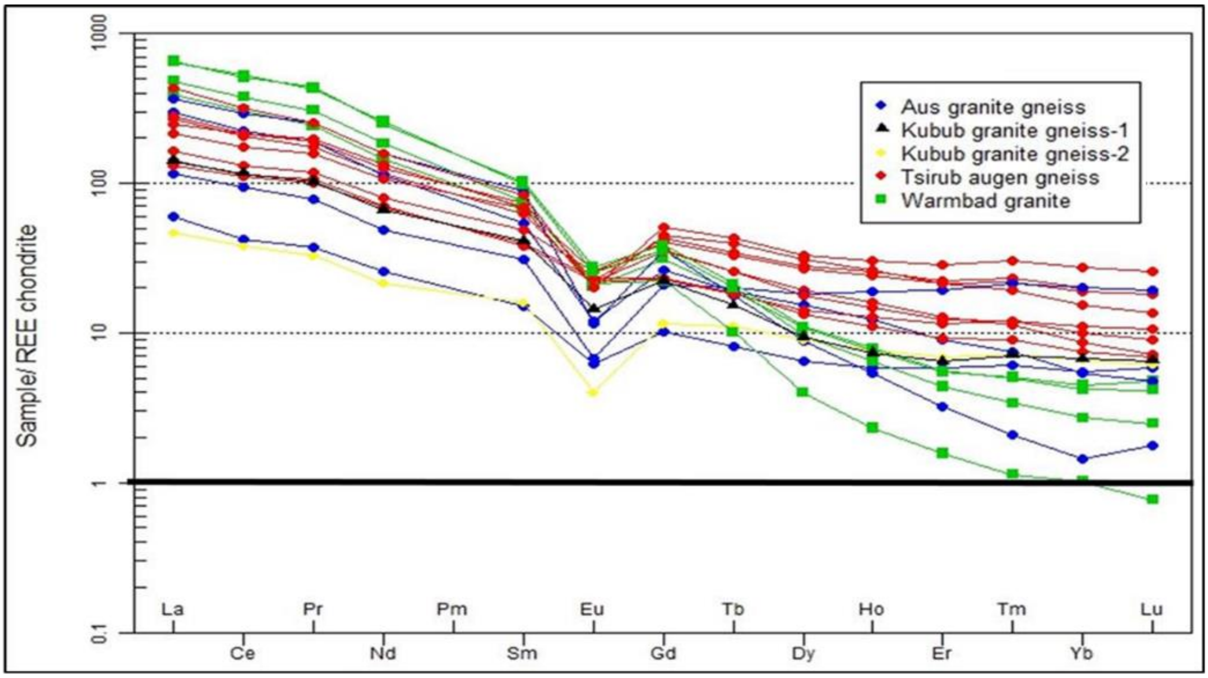

Figure 11. Chondrite-normalised REE concentration patterns of the sampled granitoids (normalised values from Nakamura, 1974)

Typically, granites are classified as A (anorogenic), I (igneous), or S (sedimentary) -type. The Ga/Al ratio in granites serves as an indicator of petrogenesis, tectonic setting, magmatic processes and potential for associated mineralisation (Whalen *et al*., 1987). Plots of Ga/Al versus certain major and trace elements identify the granitoid rocks of the Aus area as A-type granites; on plots of Zr+Nb+Ce+Y versus major element ratios such as FeO*/MgO and $(K_2O+Na_2O)/CaO$ some samples plot in the I and S- type fields (Fig. 12). Samples classified as granites (Fig. 9a; Aus granite gneiss, Kubub granite gneiss types 1 & 2, Warmbad granite) plot within the syn-collisional Granite (syn-COLG) and Volcanic Arc Granite (VAG) fields, whereas samples classified as granodiorite (Tsirub augen gneiss) fall in the Within Plate Granite field (WPG) on tectonic discriminations diagrams after Pearce *et al*. (1984; Fig. 13) on the basis of Nb, Y, Ta, Yb and Rb trace element concentrations.

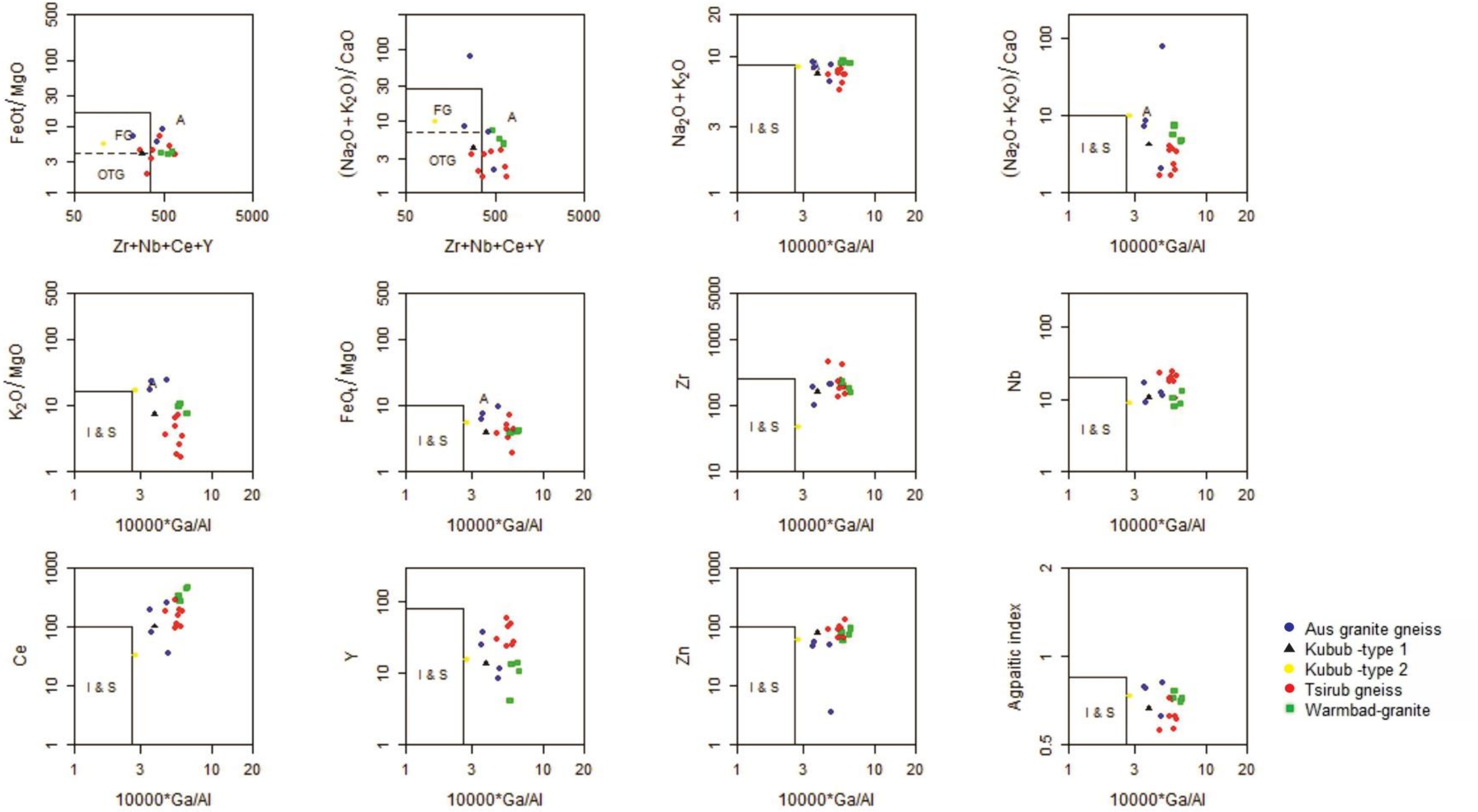

Figure 12. A-S-I-type classification of granitoids in the Aus area (after Whalen *et al*., 1987; FG – Fractionated, OTG – unfractionated I- & S-type granite)

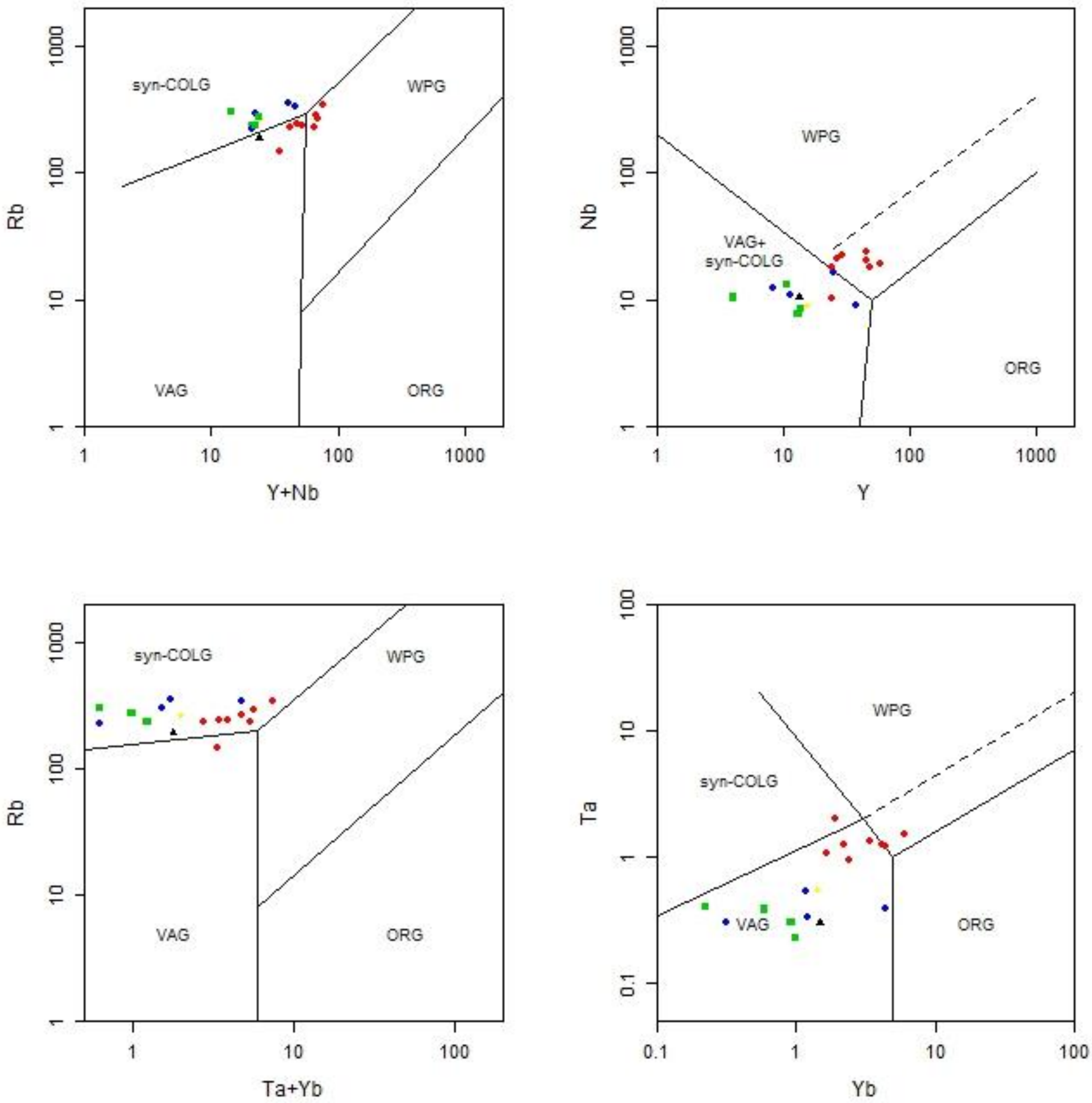

Figure 13. Tectonic discrimination diagrams for granitoids around Aus (after Pearce *et al*., 1984; for symbol explanation see Fig. 12).

Summary and Discussion

Geochemical analyses reveal that all plutonic rocks of the Aus area are acidic, with compositions ranging from granitic to granodioritic. These granitoids are products of shoshonitic to high-K calc-alkaline magmas within the calc-alkaline series, which points to their formation in a magmatic arc environment (Liégeois *et al*., 1998; Clarke, 2019). They are also strongly peralumious, with only a few samples plotting in the metalumious field (Fig. 9d), reflecting their commonly garnetiferous, pelite xenolith-rich nature; on the discriminatory diagram after Whalen *et al*. (1987) they are identified as A-type granites (Fig. 12). On Harker diagrams, the granitoids display trends of decreasing Al_2O_3, CaO, FeO_t, MgO, TiO_2, P_2O_5, MnO, Sr, Ba, Ta and Nb, but an increase in K_2O, Na_2O, Th, Ce, Sm, Y, Hf and Rb with increasing SiO_2 (Fig. 8). The MORB-normalised spidergram displays a strong depletion in Sr, P, Ti, Y and Yb and a simultaneous strong enrichment in K, Rb, Th and Ce. These trends suggest the progressive fractional crystallisation of plagioclase, amphibole, monazite, sphene and zircon, but limited fractional crystallisation of K-feldspar and biotite (Macey *et al*., 2015). The broadly coherent trends of mobile elements such as Rb, Sr and Ba indicate little or no alteration during metamorphism or weathering (Whalen *et al*., 1987). Ba, Ta, Nb, Hf and Sm are mildly enriched relative to MORB (values from Pearce, 1984). Figure 10 shows the Aus and Kubub (type 2) granite gneisses as the most depleted in Sr, P and Ti.

Relatively higher Al_2O_3 and K_2O, and lower Fe contents of the Aus area granitoids are probably due to a greater contamination by pelitic rocks. Negative Ta, Nb, P and Ti anomalies, with enrichments in Th and LREE, which are typical of arc-derived rocks (Whalen *et al*., 1987) suggest continental crust involvement.

Based on the tectonic discrimination diagrams (Fig. 13), three geotectonic settings are indicated, i. e. syn-collisional-Granite (syn-COLG), Volcanic Arc Granites (VAG) and Within Plate Granites (WPG). These inconsistent results may be attributed to hydrothermal alteration and / or sharing of varying degrees of fractionation within multiple flows. They are, however, in support of the collision of crustal fragments model proposed by Colliston & Schoch (2013) and Colliston *et al*. (2015). Additionally, plots of K_2O vs SiO_2 (Fig. 8) show a considerable degree of scatter, which may be attributed to the effects of crustal contamination in an active continental margin environment (Wilson, 1968). Similarly, the geochemistry of high-silica rocks, such as the Tsirub augen gneiss, indicates crustal participation in their parental melts and within-plate extensional affinities (Whalen *et al*., 1987). Based on this evidence it is inferred that the peraluminous A-type granitoids of the Aus area formed as a result of crustal contamination during the continental extensional phase and subsequently were subjected to compressional deformation.

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