Post-collisional magmatism in the central East African Orogen: the Maevarano Suite of north Madagascar

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Abstract

Late tectonic, post-collisional granite suites are a feature of many parts of the Late Neoproterozoic to Cambrian East African Orogen (EAO), where they are generally attributed to late extensional collapse of the orogen, accompanied by high heat flow and asthenospheric uprise. The Maevarano Suite comprises voluminous plutons which were emplaced in some of the tectonostratigraphic terranes of northern Madagascar, in the central part of the EAO, following collision and assembly during a major orogeny at ca. 550 Ma. The suite comprises three main magmatic phases: a minor early phase of foliated gabbros, quartz diorites, and granodiorites; a main phase of large batholiths of porphyritic granitoids and charnockites; and a late phase of small-scale plutons and sheets of monzonite, syenite, leucogranite and microgranite. The main phase intrusions tend to be massive, but with variably foliated margins. New U-Pb SHRIMP zircon data show that the whole suite was emplaced between ca. 537 and 522 Ma. Geochemically, all the rocks of the suite are enriched in the LILE, especially K, and the LREE, but are relatively depleted in Nb, Ta and the HREE. These characteristics are typical of post-collisional granitoids in the EAO and many other orogenic belts. It is proposed that the Maevarano Suite magmas were derived by melting of sub-continental lithospheric mantle that had been enriched in the LILE during earlier subduction events. The melting occurred during lithospheric delamination, which was associated with extensional collapse of the East African Orogen.

Keywords

Madagascar; Maevarano Suite; post-collisional magmatism; East African Orogen

1. Introduction

The island of Madagascar comprises a collage of Precambrian basement terranes, overlain by Phanerozoic sedimentary basins along the west coast. The Precambrian terranes were juxtaposed during the Neoproterozoic to Cambrian (Pan-African) East African and Malagasy orogenies (Collins and Pisarevsky, 2005). The East African Orogen (EAO; Fig. 1) extends from Egypt in the north to Antarctica in the south (Stern, 1994; Meert, 2003; Jacobs and Thomas, 2004) and represents the collision zone between Neoproterozoic India, the Congo-Tanzania-Bangweulu block, and the Saharan metacraton (Meert, 2003; Collins and Pisarevsky, 2005; Collins, 2006). Madagascar lies in the heart of the EAO, and its basement rocks have been studied from a number of viewpoints including metamorphic histories (e.g. Buchwaldt et al., 2003; Jöns et al., 2006); structural geology (Collins et al., 2003a, b; Tucker et al., 2007; Thomas et al., 2009) and magmatic processes (Nédélec et al., 1995; Paquette and Nédélec, 1998; Meert et al., 2001). In this paper we focus on the post-collisional intrusions of the Maevarano Suite of northern Madagascar, in order to understand the lithospheric processes related to the latter stages of this major orogenic event. Our work is the result of a major World Bank sponsored project, which involved re-mapping and sampling the basement rocks of northern Madagascar, undertaken by a consortium of the British Geological Survey (BGS), the United States Geological Survey (USGS), and GLW Conseil (GLW). The results were presented in the form of geological maps of various scales and an unpublished explanation (BGS-USGS-GLW, 2008).

Voluminous post-collisional granitoids are a major feature of the EAO (Black and Liégeois, 1993; Küster and Harms, 1998; Meert, 2003; Jacobs et al., 2008). They are typically alkaline and metaluminous in composition, and can be broadly characterised as A-type granitoids under the classification of Whalen et al. (1987). In the southern part of the EAO, in East Antarctica and Mozambique, peak metamorphism associated with collision-induced crustal thickening occurred at ca. 555 Ma (Bingen et al., 2009) and post-collisional magmas were emplaced between ca. 530 and 485 Ma, with a pulse of voluminous granitoid and charnockite magmatism at 510 – 500 Ma (Jacobs et al., 2008). In central Madagascar, alkaline granite sheets (termed 'stratoid granites') have been dated at ca. 630 Ma (Nédélec et al., 1995; Paquette and Nédélec, 1998) and were considered to be post-collisional, following a high-grade metamorphic episode at ca. 650 Ma (Meert et al., 2003). In northern and central Madagascar, prograde metamorphism occurred between 570 and 520 Ma (Jöns et al., 2006; Tucker et al., 2007), and a number of post-collisional plutons were emplaced during the period 550 – 520 Ma (Tucker et al., 1999; Kröner et al., 1999, 2000; Meert et al., 2001; Buchwaldt et al., 2003). In the northern part of the EAO, many post-collisional potassic granitoids were emplaced, following crustal thickening, between 630 and 470 Ma (Küster and Harms, 1998 (Sudan, Ethiopia and Somalia); Be'eri-Shlevin et al, 2009a (Israel and Egypt)). However, it seems that granitoids of this type are less abundant in the central EAO, in Mozambique north of the Lurio Belt (Jacobs et al., 2008) and in Tanzania, where high-grade metamorphism is also recorded between 655 and 520 Ma (Möller et al., 2000; Johnson et al., 2005). The cause of this localisation of post-collisional granitoids in certain areas of the EAO remains uncertain, although Jacobs et al. (2008) have suggested that it may be related to partial lithospheric delamination in specific areas of the orogen. However, it is notable that post-collisional granitoids in the EAO are commonly associated both spatially and temporally with major shear zones; examples of such magmatic events occurred in the ca. 550 Ma Angavo shear zone of central Madagascar (Grégoire et al., 2009), after ca. 530 Ma in the Lurio Belt of Mozambique (Bingen et al., 2009) and at 570 – 520 Ma in the Palghat-Cauvery shear zone of southern India (Santosh et al., 2005).

2. Geology of northern Madagascar

The Precambrian basement of northern Madagascar consists of four main tectonic units (Collins and Windley, 2002; Collins, 2006, Thomas et al., 2009). The oldest of these is the *Antongil Craton*, on the north-east coast (Fig. 2), which comprises Archaean orthogneisses formed at ca. 3200 Ma and intruded by granitoids at ca. 2500 Ma (Tucker et al., 1999; Paquette et al., 2003). The craton was intruded by a Palaeoproterozoic mafic suite, but was apparently unaffected by Neoproterozoic magmatism (BGS-USGS-GLW, 2008).

Dominating most of central Madagascar, the *Antananarivo Craton* (Fig. 2), comprises Neoarchaean orthogneisses and supracrustal rocks (2520 - 2500 Ma; Tucker et al., 1999; Kröner et al., 2000), including the *Tsaratanana Sheets,* which are generally considered to be allochthonous (Collins et al., 2003a). The Antananarivo Craton is tectonically overlain in the west by Proterozoic metasedimentary rocks of the Itremo and Ikalamavony groups (Cox et al., 1998; Collins, 2006). The gneisses of the Antananarivo Craton and the overlying metasedimentary rocks were intruded at 820 – 720 Ma by extensive granitoid plutons (Handke et al., 1999; Tucker et al., 1999; Kröner et al., 2000), and evidence for earlier magmatism at ca.1000 Ma has recently been reported (Tucker et al., 2007). The northern part of the Antananarivo Craton was intruded by 'stratoid granites' at ca. 630 Ma (Nédélec et al., 1995; Paquette and Nédélec, 1998). High-grade metamorphism, due to crustal thickening, occurred between 570 and 520 Ma (Kröner et al., 2000; de Wit et al., 2001; Tucker et al., 2007; Grégoire et al., 2009) and post-collisional granites were emplaced during the period 550 – 530 Ma (Tucker et al., 1999; Kröner et al., 1999, 2000; Meert et al., 2001).

In the northernmost part of the island, the *Bemarivo Belt* (Fig. 2) comprises two distinct Proterozoic metamorphosed volcano-sedimentary sequences intruded by Neoproterozoic arc-related plutons (Thomas et al., 2009). The southern part of the belt consists of a sequence of high-grade metasedimentary rocks (Sahantaha Group), which were derived from a Palaeoproterozoic source, and were intruded at 750 Ma by an extensive suite of plutonic rocks (Thomas et al., 2009). The northern part comprises two ca. 750 – 720 Ma metamorphosed volcano-sedimentary sequences, the high-grade Milanoa Group and lower-grade Daraina Group. These supracrustal rocks are also intruded by plutonic rocks, which date from between 718 and 705 Ma (Thomas et al., 2009). The components of the Bemarivo Belt are considered to have formed in an arc setting, and were metamorphosed to varying grades during collision with cratonic Madagascar at 560-530 Ma (Jöns et al, 2006; Thomas et al., 2009). They were subsequently intruded by post-collisional granitoids, and one pluton from this suite has previously been dated at ca. 520 Ma (Buchwaldt et al., 2003; Jöns et al., 2006).

The 'suture zone' between the Antananarivo and Antongil cratons, comprising paragneisses with numerous units of mafic and ultramafic rock, has been termed the 'Betsimisaraka Suture Zone' (Kröner et al., 2000; Collins and Windley, 2002). Our mapping (BGS-USGS-GLW, 2008) has defined a broadly equivalent terrane, the *Anaboriana-Manampotsy Belt*, which largely lies between the Bemarivo Belt and Antananarivo Craton (Fig. 2), and extends southwards roughly along the eastern side of the Antananarivo Craton. This terrane consists of Neoproterozoic metasedimentary rocks that underwent metamorphism and extensive migmatisation at the time of collision of the Bemarivo Belt and Antananarivo Craton (BGS-USGS-GLW, 2008), and are intruded by abundant post-collisional granitoids. On its northern margin, the Anaboriana-Manampotsy Belt is separated from the Bemarivo Belt by a steep shear zone, the Sandrakota Shear Zone. To the south, the Anaboriana-Manampotsy Belt appears to pass into the major Angavo Shear Zone of Nédélec et al. (2000).

Between 2005 and 2008 the BGS-USGS-GLW consortium undertook a regional geological survey of northern Madagascar, along with a regional stream sediment sampling programme and representative rock sampling for whole-rock geochemistry and U-Pb zircon geochronology. As part of this work, the voluminous post-collisional intrusions that occur within the northern part of the Antananarivo Craton, the Bemarivo Belt and, most especially, the intervening Anaboriana-Manampotsy Belt, were mapped and termed the '***Maevarano Suite***' after the river of that name, where the various phases of the suite are superbly exposed (Fig. 2, 3). Previous workers had identified many of the plutons, but had not distinguished them from the foliated, Neoproterozoic and older intrusions which are also exposed in the area (e.g. Besairie, 1971; Hottin, 1972). Post-collisional granitoids in the Bemarivo Belt were identified by Buchwaldt et al. (2003) in the Marojejy region, but their full extent and volume has only now been recognised. The geology, petrography, geochemistry, age and petrogenesis of the Maevarano Suite plutons are the subject of this paper.

The components of the Maevarano Suite were identified under a range of names by previous surveys. Most of the Maevarano Suite plutons were shown as "granites et migmatites granitoïdes" and "charnockites" on the compilations of Besairie (1964, 1971), but these also included arc-related plutonic rocks (mainly orthogneisses) in the Bemarivo Belt that are now known to be older, between ca. 750 and 710 Ma (Thomas et al., 2009). The 1: 2 million-scale tectonic compilation of Hottin (1972) showed the post-collisional granitoids in the recently defined Anaboriana-Manampotsy Belt to be older than similar intrusions in the Bemarivo Belt, which were indicated merely as "granitoïds indifférenciés". Our new geological maps are thus the first to show the true extent of this widespread suite of post-collisional plutons (Fig. 2, 3; BGS-USGS-GLW, 2008).

Previous work on the post-collisional plutons in northernmost Madagascar has been limited. Medium- to coarse-grained, weakly foliated "charnockite" plutons, intruding the Bemarivo Belt in the Marojejy area (Fig. 2), gave a U-Pb (single zircon TIMS analysis) emplacement date of 521 ± 4 Ma (Buchwaldt et al., 2003). U-Pb dating (in situ electron microprobe analysis of monazite) allowed Jöns et al. (2006) to identify two metamorphic stages for this area: collisional metamorphism between ca. 560 and 530 Ma, and peak metamorphic temperatures (possibly associated with the post-collisional magmatism) between ca. 520 and 510 Ma.

3. Field relationships of the Maevarano Suite

The Maevarano Suite consists of numerous batholiths and plutons of varying size, extending throughout the Bemarivo and Anaboriana-Manampotsy belts and the northern part of the Antananarivo Craton (Fig. 2). The intrusions are most abundant in the Anaboriana-Manampotsy Belt, where they form around 50% of the total outcrop area. The porphyritic granite and charnockite that make up the greater volume of the suite characteristically form high mountain savannah country, with large whaleback and pavement outcrops (Fig. 4a). These rocks underlie parts of the high mountains (>2200 m) of the Marojejy massif in north-east Madagascar, and the mountain massifs around Sandra Kota, through which the Maevarano River has carved a deep gorge. Around Sandra Kota, a single batholith is exposed over an area of some 15 000 km^2, and affords excellent outcrops which constitute the "Type Area" of the suite (Fig. 3). Rocks of the Maevarano Suite differ from the older intrusions in the area in that they are typically weakly foliated to unfoliated, although a more intense foliation is typically developed at pluton margins and within ductile shear zones (Fig 4b, c). The older intrusions of the suite tend to be more pervasively foliated than the younger intrusions.

The plutons of the Maevarano Suite are chiefly granitic, including some charnockitic (orthopyroxene-bearing) types, but range through granodiorites to monzonites and syenites (generally quartz-bearing). Some minor mafic (dioritic to gabbroic) intrusions, which have igneous textures, are intimately associated with the acid rocks in the field (Fig. 4 e,f). The whole suite can be broadly divided into three magmatic phases: an early phase of foliated intrusions, which are most commonly granodioritic; a main phase of voluminous granitoid and charnockite plutons; and a late phase comprising chiefly granites and monzogranites.

3.1 Early phase

The early phase of the Maevarano Suite includes both the most mafic and the most pervasively deformed intrusions. For example, early biotite- and hornblende-bearing granodioritic to monzodioritic orthogneisses form elongate intrusions that crop out in the Maevarano River valley (Fig. 3). One such body has been dated for this study. The Maevarano Suite also includes minor volumes of early mafic phases, including homogeneous, medium- to coarse-grained, greenish-grey, foliated quartz-diorite, and coarse- to medium-grained, dark-grey to blue-grey gabbro. The gabbros in particular are typically associated with, and cut by, intrusions of porphyritic granite, often in complex associations, with several cross-cutting phases (Fig. 4e, f). For this reason these mafic intrusions are attributed to the early phase of the suite, but they have not been dated.

Small pyroxenite pods occur at a few locations, though their relationship to the rest of the suite is uncertain.

3.2 Main phase

The most common lithology of the Maevarano Suite is very coarse-grained, fairly homogeneous, pinkish, typically porphyritic, biotite ± hornblende granite, with subhedral to euhedral, pink K-feldspar megacrysts up to 2.5 cm in size. These granites form some of the largest intrusions in the Maevarano Suite, irregular in shape and of batholithic proportions. Large bodies of orthopyroxene-bearing granite are commonly associated with the porphyritic granites and have been mapped as charnockite (BGS-USGS-GLW, 2008). Typically, they are coarse- to very coarse-grained, locally potassium feldspar- or plagioclase-phyric (phenocrysts up to 2 cm across), and fresh samples are characterised by the classic dark green colouration and resinous lustre, together with the presence of macroscopic orthopyroxene (Fig. 4d). Many of these charnockite bodies occur in association with pink porphyritic granite, but contacts between the two are rarely exposed. Medium- to coarse-grained, non-porphyritic granitoids are also relatively common, and considered to be part of the main granite-charnockite phase.

The central parts of the main phase plutons are typically unfoliated or weakly foliated, but a fabric defined by orientation of planar minerals commonly appears towards pluton margins. Locally, the porphyritic granitoids have been transformed to strongly flattened augen gneisses in ductile shear zones up to several hundreds of metres wide (Fig. 3). In undeformed zones, a primary, igneous flow orientation of K-feldspar phenocrysts has been locally observed.

Enclave-rich zones are common within the Maevarano Suite granitoids. The enclaves either take the form of well-defined, discoidal, magmatic enclaves, or more diffuse, partially digested and feldspathised mafic xenoliths stoped from the enclosing country rock gneisses. In some areas, rafts up to hundreds of metres long of country rock granite and gneiss occur within the granite, particularly close to its margins. Enclaves are less commonly observed within the charnockites and, where seen, tend to have much higher contents of mafic minerals than those within the granites.

3.3 Late phase

Within the Anaboriana-Manampotsy Belt, a number of later plutons intrude the porphyritic granites of the main phase (Fig. 3). In the northern part of the belt, elliptical monzogranite plutons up to 5 km across intrude the porphyritic granitoids, and one of these has been dated during this study. These monzogranites are typically coarse-grained, equigranular, weakly foliated (strongly foliated at the margins), grey to pinkish-grey, and biotite- and amphibole-bearing. Syenite plutons are also reported from inaccessible regions in the Bealanana area (BGS-USGS-GLW, 2008). Other intrusions belonging to the late phase, which also intrude main phase plutons, include variably foliated leucogranite sheets (Fig. 3), one of which has been dated in this study, and late, dyke-like intrusions up to 2 km long of unfoliated microgranite. One of the most distinctive of the late phase intrusions is the ring-like Tampoketsa massif in the southern part of the Anaboriana-Manampotsy Belt. It forms a pronounced circular topographic feature that attains an altitude of nearly 1400 m and appears to be a primary igneous feature, not due to late domal folding. The Tampoketsa intrusion is extremely magnetic compared to the surrounding rocks and forms a major positive aeromagnetic anomaly. Summit exposures show the main lithology to be light grey-pink, fine- to medium-grained, biotite-hornblende alkaline microgranite with a variably-developed foliation. It is included with the Maevarano Suite on the basis of lithological, petrographical and fabric similarities, but it has not been dated.

Late minor veins, sheets and irregular intrusions are not common but do occur locally. They include pegmatitic and aplitic granite intrusions, which tend to occur in small swarms, and larger bodies of fine- to medium-grained granite. These are considered to represent the youngest part of the late phase of the Maevarano Suite.

4. Petrography

4.1 Early phase

The early phase intrusions are the most mafic parts of the Maevarano Suite, ranging from granodiorites, monzonites and monzodiorites, to diorites and gabbros. All are medium- to coarse-grained. In the granitoids, plagioclase (20-30%) dominates over K-feldspar (up to 10%). Up to 25% quartz is present, and mafic minerals include biotite, clinopyroxene and amphibole in varying amounts. Minerals are typically allotriomorphic and show a strong preferred orientation.

Samples of gabbro consist of plagioclase (~30-40%), clinopyroxene (25-35%), amphibole (10-20%), biotite (5-10%), and opaque minerals (up to 5%) along with accessory titanite and apatite. Up to 5% quartz occurs in some samples. While the hydrous minerals (amphibole and mica) are clearly of secondary origin, primary sub-ophitic textures are locally preserved.

4.2 Main phase

Typical porphyritic granite samples are coarse-grained hypersolvus granites, with microperthitic potassium feldspar phenocrysts up to 2.5 cm in size, though averaging 1.5 cm. Overgrowths of plagioclase on the potassium feldspar phenocrysts are present in a few samples. The modal mineralogy comprises quartz (~20-30%), poikilitic K-feldspar (microperthitic microcline, ~30-40%), plagioclase (~15-20%), greenish-brown amphibole (~10%), brown biotite (5-10%), clinopyroxene relics (up to 5 %) and accessory opaque mineral phases (up to 3%), apatite, zircon ± allanite, with epidote, chlorite and muscovite as minor alteration products. Myrmekitic quartz-feldspar intergrowths are common. Feldspars are generally fresh, showing only limited amounts of alteration, and textures are most commonly granoblastic. The charnockitic phases have broadly similar mineralogy to the porphyritic granites, but with 5-20% orthopyroxene. In most samples, the orthopyroxene is highly altered, and largely replaced by amphibole.

4.3 Late phase

Late phase granitoids are predominantly medium-grained, with allotriomorphic textures, and are commonly quite fresh, although feldspars are locally sericitised. K-feldspar (microperthitic microcline, ~ 25-40%) predominates over plagioclase (10-20%) with up to 30% quartz. Mafic minerals are amphibole and biotite, with similar accessories to the granitoids of the main phase.

5. Geochronology

Four samples belonging to the Maevarano Suite were selected for U-Pb zircon geochronology. All the samples are from plutons emplaced into the Anaboriana-Manampotsy Belt, where the Maevarano Suite intrusions are at their most voluminous. Location information for the samples is given as grid references using the Laborde grid, and localities are shown on Figs. 2 and 3. The zircon data are given in electronic supplemental data tables A-D. The samples were chosen from older and younger phases, on the basis of field relations, in order to bracket the emplacement age of the entire suite. The charnockite phase from the Marojejy area in the Bemarivo Belt has been dated at 521 ± 4 Ma (Buchwaldt et al., 2003), so was not reinvestigated in this study. Three of our samples were taken from the Maevarano River valley, where the field relationships between the phases are clear. From this region we collected samples of: the early phase (foliated quartz monzodiorite), which occurs as raft-like bodies in the porphyritic granite; a foliated late phase leucogranite sheet cutting the porphyritic granite; and a late phase monzonite pluton which intrudes both leuco- and porphyritic granite. The fourth sample was collected from further south, where late veins and irregular bodies of granite cut migmatitic gneisses of the Anaboriana-Manampotsy Belt.

5.1 Methodology

Zircons were separated from large, fresh rock samples using standard crushing, washing, heavy liquid separation (LST and MI liquids) and magnetic separation (Frantz Isodynamic Separator) techniques, followed by hand-picking under a binocular microscope. The grains were mounted in epoxy, and polished mid-section to expose their centre. Mounts were imaged using transmitted and reflected optical microscopy as well as by cathodoluminescence (CL) on a Scanning Electron Microscope.

The zircons were dated using the Sensitive High Resolution Ion Microprobe (SHRIMP) at Curtin University of Technology, Perth, Western Australia. Methodologies for SHRIMP analyses followed those described in De Waele and Pisarevsky (2008). Common Pb correction was carried out, using measured ^{204}Pb, and applying a common Pb composition appropriate for the age of the zircon, following Stacey and Kramers (1975). All pooled ages are reported at 95% confidence levels, while single data are reported at 1σ confidence level. SHRIMP data were reduced using the Squid plug-in for

Excel (Ludwig, 2001a), and plotted and interpreted using the Isoplot plug-in for Excel (Ludwig, 2001b). All data are plotted uncorrected for non-radiogenic Pb.

5.2 Sample BT/07/12 [grid ref. 617845 1280192]

Sample BT/07/12 is a foliated quartz monzodiorite of the early phase, taken from large river outcrops and pavements in the Maevarano River near Ambodirafia (Fig. 3). The sampled lithology is medium- to coarse-grained, fresh, grey, hornblende-biotite quartz monzodiorite, with a strong, sub-vertical foliation trending SSE-NNW. It is fairly homogeneous, but locally has a weak layering defined by variations in grain size and mineralogy, and most notably by layers with more or less K-feldspar. The rocks are weakly migmatitic, with <5% layer-parallel leucocratic veins. These foliated quartz monzodiorites to granodiorites occur as large enclaves, up to several hundreds of metres wide, surrounded and veined by very coarse-grained, pink, porphyritic granite of the main phase of the Maevarano Suite.

Zircons from sample BT/07/12 range in size from 50 to 200 μm and have length to width ratios between 1:1 and 3:1. The crystals are rounded to subrounded and appear colourless to pale pink in transmitted light. Most zircons contain some cracks, but have only very small amounts of inclusions. CL images reveal dark CL-response, and faint parallel zoning patterns (Fig. 5a-b). Some zircons appear to be overgrown by large high-response domains that show no zoning. Large invasive zones of homogenisation, recognised in many zircons, are interpreted to record solid-state recrystallisation.

16 analyses were conducted on this sample and indicate low f_{206} values up to 1.14% (Table A). U and Th are in the range 71-379 and 91-495 ppm respectively, with the exception of analysis 6 (1196 and 2066 ppm). Th/U ratios are between 0.29 and 2.82, extending well beyond the typical ratios expected for magmatic zircon ($0.5 < Th/U < 1.0$), possibly due to some Th/U fractionation during solid-state recrystallisation.

Apart from three data points that record the highest common lead (Pb_c) values, the data on cores define a concordant cluster (Fig. 6). The seven most concordant analyses yield a concordia age of 531 ± 5 Ma (MSWD of concordance = 2.0). The relatively high MSWD of concordance indicates some scatter in the dataset, but the age represents the best estimate for crystallisation of zircon cores in sample BT/07/12. Six analyses conducted on unzoned high-CL rims, although discordant due to incorrect correction for Pb_c, seem to record slightly younger crystallisation ages around ~520 Ma. Although this age cannot be fully resolved based on the data obtained, it does suggest crystallisation of these rims immediately after the emplacement of the granite, perhaps from late-stage fluids associated with the intrusion of the main phase granites.

5.3 Sample BT/07/22 [grid ref. 610788 1269827]

Sample BT/07/22 is from a small elliptical, late phase pluton near the Maevarano River, where tor-like outcrops are characterised by a curious "fluted", pot-holed appearance. This pluton intrudes the main, porphyritic phase of the Maevarano Suite, and is foliated within a few tens of metres of its margins, but elsewhere essentially unfoliated. The sample is a homogeneous, slightly foliated, pinkish-grey, medium- to coarse-grained, biotite-amphibole monzogranite. Sparse K-feldspars, up to 8 mm in size, are largely perthitic. The rock contains a few discrete, spherical microdiorite xenoliths which were carefully excluded from the analysed sample.

Zircon grains range in size from 100 to 300 μm and have aspect ratios between 2:1 and 4:1 (Fig. 5c-d). The crystals are clear, colourless to pale pink, and are commonly cracked. CL imaging indicates single sector zoning, with alternating dark- and light-CL zones (Fig. 5c-d). Zoning patterns and the high aspect ratios of most crystals suggest a magmatic origin.

16 analyses were conducted and give f_{206} values between 0 and 2.66 (Table B). U and Th values are low, between 26-128 and 46-239 ppm respectively, leading to high proportions of apparent Pb_c based on very low counts on ^{204}Pb. None of the analyses recorded more than 1 count over 10 second intervals, similar to measurements on background, and this is taken to indicate extremely low Pb_c. Uncorrected data plot on concordia and define a concordia age of 522 ± 6 Ma (MSWD of concordance = 0.50, Fig. 6), which we take to reflect the emplacement age of the monzogranite. One younger analysis could represent crystallisation of zircon at ca. 464±10 Ma (analysis 8), but more likely represents a zircon that lost Pb.

5.4 Sample BT/07/25 [grid ref. 606786 1267524]

Sample BT/07/25 is from a late phase intrusion of the Maevarano Suite which largely comprises fine- to medium-grained, foliated, biotite-bearing microgranite, and which intrudes the porphyritic granite. The foliation in rocks of this microgranite is variable, but commonly quite strong, and defined by small variations in mineralogy and grain size. A slightly coarser-grained quartz-feldspar facies forms discontinuous layers and blebs, defining a weak, diffuse layering. No mafic enclaves, blebs or schlieren have been observed – the rocks are typically homogeneous at the outcrop scale. The sample is a light grey, medium- to fine-grained, pinkish microgranite with a weak foliation formed by alignment of mafic aggregates.

Zircon crystals are between 100 and 250 µm in size, and have aspect ratios between 2:1 and 5:1 (Fig. 5e-f). The crystals are sub- to euhedral in shape, and have well-defined crystal terminations. The crystals are virtually free of inclusions and cracks, and vary between colourless and pale pink. CL images show concentric and parallel zones that suggest a magmatic origin (Fig. 5e-f). A small number of larger zircons appear to have a homogenous inner dark-CL core, overgrown by a medium-CL homogenous rim.

15 analyses were conducted on 15 zoned crystals and indicated low contents of Pb_c with f_{206} between 0 and 1.09%, corresponding to less than one count on ^{204}Pb every ten seconds (Table C). U and Th contents are in the range 161-734 and 116-1936 ppm respectively, giving Th/U ratios between 0.57 and 2.85.

The data plot in a broad cluster on concordia, and the nine most concordant points (after correction for non-radiogenic Pb) correspond to a concordia age of 527 ± 5 Ma (MSWD of concordance=0.005), which we take to represent the best age estimate for the emplacement of the microgranite (Fig. 6). The data points that plot slightly away from this concordant cluster correspond to analyses that either recorded higher counts on ^{204}Pb, or some noise resulting in background counts in excess of counts on ^{204}Pb (but always less than 1 count every 10 seconds). One analysis (15) recorded a concordant $^{206}Pb/^{238}U$ age of 541 ± 8 Ma, and may represent a slightly older xenocrystic component in the sample.

5.5 Sample RK7248A [grid ref. 632500 1175988]

Sample RK7248A was collected from a ridge within the Anaboriana-Manampotsy Belt (Fig. 2), with numerous rock pavements of agmatitic gneiss with a blocky grey gneiss palaeosome surrounded by granitic leucosome, and cut by discrete veins and irregular bodies of granite. The analysed sample was taken from one of the late granite bodies.

Zircon crystals range in size from 100 to 200 μm and have aspect ratios between 2:1 and 5:1. The crystals are sub- to euhedral with well-developed terminations, colourless to pale pink, with very few inclusions and virtually no cracks. CL images reveal broad parallel or concentric zoning patterns consistent with magmatic crystallisation (Fig. 5g-h). Several zircon grains are overgrown by narrow high-CL unzoned rims, possibly related to a thermal episode that led to neocrystallisation of low-U rims.

21 analyses yielded f_{206} values between 0 and 0.96%. U and Th are in the ranges 104-495 ppm and 53-217 ppm respectively, giving Th/U ratios between 0.25 and 1.12, largely within the range expected for magmatic zircon (Table D). The data define a broad cluster around concordia with weighted mean $^{206}Pb/^{238}U$ age of 532 ± 6 Ma (MSWD=5.4) (Fig. 6). The high MSWD value for this calculation indicates significant scatter of $^{206}Pb/^{238}U$ ratios, interpreted to reflect some Pb-loss in the zircons. Using only concordant data, a concordia age of 537 ± 5 Ma (MSWD=0.35) can be calculated, which is interpreted as the best estimate for the age of crystallisation of zircon in the sample. High CL rims and magmatically zoned core domains provide similar ages, and this may indicate that emplacement of the granitic protolith took place during a thermal event that induced migmatisation and fluid mobility in the rock.

In summary, the four analysed samples show a narrow spread of emplacement ages from 537 ± 5 to 522 ± 6 Ma. The younger end of this range is consistent with the emplacement of the Marojejy charnockite in the southern Bemarivo Belt at 520.9 ± 4.2 Ma (Buchwaldt et al., 2003) and in keeping with the age ranges of metamorphism in the same area (Jöns et al., 2006, 2009). Very few older, inherited zircons were found, suggesting that these magmas did not undergo substantial crustal contamination.

6. Geochemistry

30 whole-rock samples from representative Maevarano Suite intrusions and phases have been analysed for major, trace and rare earth elements. Fresh rock samples selected for geochemistry were crushed and milled in agate at the DMG Laboratory of the Ministry of Energy and Mines in Antananarivo, and analysed at ACTLABS, Canada (by their Code 4 Lithoresearch package). Major oxides and some trace elements were analysed by Li-metaborate / tetraborate fusion with an ICP analysis, and these sample solutions were further diluted and spiked for ICP-MS analysis. The samples were run for major oxides and selected trace elements on a combination simultaneous/sequential Thermo Jarrell-Ash ENVIRO II ICP or a Spectro Cirros ICP, and for other trace elements on a Perkin Elmer SCIEX ELAN 6000 or 6100 ICP-MS. The data are given in Table 1; details of repeat analyses on standards are presented as supplemental data in Table E..

The majority of samples (20) are granitoid rocks, including porphyritic granites and charnockites, of the main granite-charnockite phase of the Maevarano Suite. Just one (dated) granitoid sample is from the early phase, and four samples are gabbros that are also considered to belong to the early phase. Five samples are from the late phase, and include the dated monzogranite and leucogranite, along with the Tampoketsa alkaline granite.

The analysed samples show a wide range in SiO_2 content, from 45 to 78 wt%, the gabbros having < 55 wt% SiO_2 (Fig. 7). The majority of samples are low in MgO (<3%) and show a negative correlation with SiO_2 (Fig. 7a), although the early phase samples (gabbros and foliated quartz monzodiorite) have notably higher MgO (> 3.0%) than granitoid samples with similar SiO_2. As would be expected, Fe_2O_3 shows a strong negative correlation with SiO_2 (Fig. 7b), with the highest Fe_2O_3 contents in the gabbros (> 10%) although some charnockites are also Fe_2O_3-rich. All granitoid samples are high in K_2O (>3.5%) whereas gabbro samples have K_2O < 3.5% (Fig. 7c), and there is no apparent correlation between K_2O and SiO_2 (Fig. 7c); this suggests buffering by a K-bearing phase such as amphibole, phlogopite or K-feldspar during evolution of the magmas (Williams et al., 2004). K_2O/Na_2O is >1 in most samples, again with the exception of the four gabbro samples which have K_2O/Na_2O < 1. In the Total Alkalis vs

Silica (TAS) plot (Fig. 7d), most of the samples are alkalic under the classification of Miyashiro (1974). This plot is most appropriate for volcanic rocks, and only provides a crude method of classifying plutonic rocks. However, it is notable that, despite high modal contents of K-feldspar, very few Maevarano Suite samples actually have the bulk composition of true granite; many fall in the broad syenite and syeno-diorite fields, which also encompass monzonitic compositions. The analysed samples are largely metaluminous (molar A/CNK < 1) (Fig. 8a), although the most SiO_2 rich samples are weakly peraluminous, suggesting the possibility of some crustal contamination of these magmas.

In magmatic suites, such as the Maevarano Suite, that do not appear to have suffered extensive post-crystallisation alteration, it is common to attempt to discriminate the tectonic setting of granitoids using discrimination diagrams such as those of Pearce et al. (1984). Granitoid samples from the Maevarano Suite are plotted on the (Y+Nb) vs Rb plot of Pearce et al. (1984) (Fig. 8b) and although most plot in the within-plate granite field, there is an overlap into the volcanic arc and syn-collisional granite fields. This spread across fields is common in post-collisional granites (Pearce, 1996) and the Maevarano Suite shows the same spread as other post-collisional granitoids from the EAO (e.g. Roland, 2004; Küster and Harms, 1998). On the Ga/Al vs. Zr plot of Whalen et al. (1987) the Maevarano Suite granitoids plot in the field of A-type granites (Fig. 8c), as do other EAO post-collisional granites (Roland, 2004; Küster and Harms, 1998). In the A-type granite classification of Eby (1990, 1992) the Maevarano Suite granitoids spread across the A_1 and A_2 fields (Fig. 8d). Post-collisional granitoids would normally be expected to fall in the A_2 field, which indicates magmas that may have been derived by re-melting of crust. In contrast, magmas in the A_1 field are more likely to have been derived from mantle sources (Eby, 1992).

Samples from the early phase show many consistent trace element characteristics (Fig. 9a). Most are relatively enriched in Ba, K, and the LREE, with negative Ta-Nb anomalies and depletion in the HREE relative to the LREE (La_N/Yb_N typically > 10). One analysed sample, KGM48, lacks a Nb-Ta anomaly and has a relatively flat slope from the LREE to the HREE, and it is possible that this intrusion was derived a different source to the other Maevarano Suite magmas. Sample 497-JM-07 shows positive Sr, Ti and Eu anomalies, suggesting that its bulk composition has been modified by crystal accumulation (plagioclase and ilmenite) and cannot be used to approximate a magmatic composition.

The more evolved samples of the main granite-charnockite phase show higher contents of some of the Large Ion Lithophile Elements (LILE) (especially Rb, Th and K) than the mafic samples of the early phase (Fig. 9b), but have many similar characteristics including negative Nb-Ta anomalies and fractionated REE patterns ($La_N/Yb_N > 10$). Strong negative Sr and Ti anomalies (and in one case a weak Eu anomaly) in the main phase samples indicate that plagioclase and a Ti-rich mineral such as titanite or ilmenite were fractionated as the magmas evolved.

Samples from the late magmatic phases can be divided into two groups on the basis of their trace element patterns (Fig. 9c). Monzogranites and leucogranites of the Maevarano River area have similar trace element patterns to the main phase granites, though strong Eu and Sr negative anomalies indicate that these magmas are highly evolved. Two samples from the Tampoketsa granite have pronounced negative Nb-Ta anomalies and very low contents of the HREE ($La_N/Yb_N > 80$). These differences may indicate a different source for this unusual intrusion. Low contents of HREE commonly indicate the presence of garnet in the source of the magmas, and so it is possible that the parental magma of the Tampoketsa granite was derived from greater depth than those of other parts of the Maevarano Suite.

The similarity in geochemistry between most phases of the Maevarano Suite supports the assignation of these intrusions to a single magmatic suite. These intrusions show many of the typical features that have been recognised in post-collisional granitoids of the EAO (Küster and Harms, 1998; Nédelec et al., 1995; Roland, 2004), including: high contents of the LILE, especially K; negative Nb-Ta anomalies; and enrichment of the LREE over the HREE. Perhaps the single most distinctive feature of these and other post-collisional granitoids is that they plot in the A-type granite fields on discrimination diagrams, yet have strong negative Nb-Ta anomalies which would not be expected in granitoids formed in an intracontinental rift setting (Whalen et al., 1987).

7. Discussion

The Maevarano Suite of northern Madagascar comprises three recognisable phases of intrusion, of which the second, main phase was the most voluminous. Both field and geochronological evidence show that the suite was emplaced shortly after the main deformation associated with the Malagasy orogeny – the last orogenic event to affect the East African Orogen in Madagascar (Collins and Pisarevsky, 2005; Collins, 2006). In the field, some exposures show that the intrusive rocks, particularly of the late phase, cut the main foliation in their country rocks. However, the contacts of granitoids of the main phase are commonly broadly parallel to the regional fabrics and the granites are themselves foliated at pluton margins, but unfoliated in their cores. Components of the early phase tend to be pervasively foliated and form elongate bodies that are parallel to the foliation in the host rocks. This indicates that the Maevarano Suite magmatism largely post-dated the main crustal thickening event, but that the early phase intrusions were emplaced during its waning stages.

In its type area, the Maevarano Suite is associated with a number of ductile shear zones. This is a common association for post-collisional granites in the EAO, and in some areas the later deformation on the shear zones has been associated with orogenic collapse (Jacobs and Thomas, 2004; Jacobs et al., 2008; Bingen et al., 2009; Grégoire et al., 2009; Viola et al., 2008). Although field evidence for this is limited in northern Madagascar, we can use these analogies to tentatively suggest that the earliest Maevarano Suite magmas were emplaced at the end of the collisional event, but that voluminous main phase magmatism was associated with extensional collapse of the orogen, with extensional shear zones providing the pathways for magma ascent.

The observed field relationships are consistent with the geochronology; high-grade metamorphism in north Madagascar peaked at ca. 560 – 530 Ma (Jöns et al., 2006, 2009), and our work has shown that the earlier, foliated phases of the Maevarano Suite were emplaced at ca. 537 – 531 Ma, with magmatism continuing until 520 Ma. A similar pattern is recognised in central Madagascar, where metamorphism on the Angavo Shear Zone occurred at ca. 550 Ma (Grégoire et al., 2009) followed by magmatism at ca. 550 – 530 Ma (Tucker et al., 1999; Kröner et al., 1999, 2000; Meert et al., 2001).

Petrography and geochemical analyses demonstrate that the Maevarano Suite intrusions share many features - such as LILE enrichment, negative Nb-Ta anomalies, and LREE enrichment over the HREE - with other post-collisional granitoids along the length of the EAO. A number of apparent contradictions characterise these post-collisional granitoids: for instance, charnockites typically indicate water-undersaturated magmas, yet they are associated with amphibole-bearing granites that are likely to have formed from hydrous magmas. Similarly, discrimination diagrams indicate that these are A-type granites, yet they have the strong Nb-Ta negative anomaly commonly found in arc settings. Such Nb-Ta anomalies could be partly caused by contamination with local crustal material, but it is notable that the anomalies are present even in the most mafic magmas that are likely to be relatively uncontaminated. The lack of older xenocrystic zircons in the dated samples also provides an argument against substantial crustal contamination of the magmas.

The consistency of many main geochemical features of post-collisional intrusions along the EAO suggests the likelihood of a common source for the majority of these magmas. The granitoids are largely metaluminous, rather than peraluminous, indicating that they were not generated solely by the melting of local crustal material, although the more silica-rich magmas are likely to have been affected by some crustal contamination. Recent studies have proposed that the source of post-collisional magmas elsewhere in the EAO was in the mafic lower crust (e.g. Jacobs et al., 2008); but the lower crust is likely to be depleted in the LILE rather than enriched (Pearce, 1996), and so does not represent a feasible source for the K-rich Maevarano Suite. A growing consensus (e.g. Pearce, 1996; Liégeois et al., 1998; Bonin, 2004) is that the source for K-rich post-collisional magmas is in the sub-continental lithospheric mantle (SCLM), which has been heterogeneously enriched through metasomatism by LILE-enriched fluids derived by dehydration of a subducting slab. Such slab fluids are typically characterised by low Nb-Ta contents (Fitton, 1995) and thus the enriched SCLM would also have low amounts of these elements. Partial melting of such a source could produce the LILE-enriched, Nb-Ta- poor magmas of the Maevarano Suite, and we suggest that other post-collisional magmas in the EAO were also derived from metasomatised SCLM. In northern Madagascar, there is abundant evidence for subduction during the Neoproterozoic, prior to collision of the terranes that make up the island (e.g., arc-like magmas; Thomas et al., 2009), and enrichment of the SCLM could have occurred at this time. In the north of the EAO, alkaline parts of the post-collisional granitoid suite have similarly been attributed to a lithospheric mantle source that was metasomatised during Neoproterozoic subduction (Be'eri-Shlevin et al., 2009b).

The transition from crustal shortening to extension in many orogenic belts, including the EAO, has been explained in terms of delamination of part, or all, of the sub-continental lithospheric mantle (Houseman and Mackenzie, 1981; Black and Liégeois, 1993; Jacobs et al., 2008). Such delamination allows hot asthenospheric material to well up, heating the upper part of the lithospheric mantle and promoting melting (Schott and Schmeling, 1998). Bonin (2004) proposed a model for collisional to post-collisional magmatism that commences with lithospheric stacking, producing peraluminous magmas derived by melting of continental crust which mingle with small-degree potassic melts from the SCLM. This is followed by slab break-off and lithospheric delamination, removing part of the lithospheric mantle keel and melting the upper part of the SCLM to produce medium- to high-K magmas. Finally, this model (Bonin, 2004) suggests that over a period of millions of years the SCLM thickens by cooling and underplating of deeper material, and alkaline magmas of within-plate type are derived from deeper levels. The majority of the Maevarano Suite magmas can be related to the slab break-off/ lithospheric delamination stage of this model. However, the youngest Tampoketsa granite may have been formed by melting of deeper SCLM and could represent the evolution to a true within-plate setting; it is possible that it is rather younger than the rest of the Maevarano Suite.

Within northern Madagascar, the Maevarano Suite intrusions are abundant within some crustal units (the Anaboriana-Manampotsy and Bemarivo belts, and parts of the Antananarivo Craton) but are absent in others (the Antongil Craton). Two explanations can be postulated: 1) a suitable source was not present beneath the Antongil Craton; 2) structural controls led to the emplacement of magmas only in certain areas.

Evidence to support the first explanation comes from study of the Neoproterozoic history of the terranes of northern Madagascar. The Bemarivo Belt and the Antananarivo

Craton both contain abundant Neoproterozoic subduction-related magmatic suites (820-700 Ma; Handke et al., 1999; Tucker et al., 1999; Kröner et al., 2000; Thomas et al., 2009), which provide evidence for a subduction event prior to collision that could have enriched the SCLM. The country rocks of the Anaboriana-Manampotsy Belt are entirely Neoproterozoic (BGS-USGS-GLW, 2008) and may represent an arc sequence preserved within the suture zone between continental fragments. In contrast, there is no evidence of Neoproterozoic magmatism within the Antongil Craton (BGS-USGS-GLW, 2008). We therefore postulate that the SCLM beneath the Antongil Craton was not enriched by subduction-related fluids prior to continental collision, and thus was less hydrous and more viscous than the SCLM beneath other parts of northern Madagascar. This unaltered lithospheric mantle may simply not have delaminated (e.g. Elkins-Tanton, 2005), or may have lacked fusible material that could be melted to produce post-collisional magmas.

Evidence for the second explanation comes from the common association of Maevarano Suite granitoids with major shear zones, which seem to be focused particularly along terrane boundaries. As suggested above, the Antongil Craton may have had a thicker, more viscous lithospheric root than the surrounding mobile belts, and so may have behaved in a rigid fashion, leading to the development of shear zones along the craton margins during collapse of the orogen (cf. Black and Liégeois, 1993). Magmas were then emplaced along these shear zones.

It is likely that both these possible explanations are valid, and indeed linked. Areas which had undergone Neoproterozoic subduction had hydrous, relatively dense metasomatised SCLM that was a candidate both for delamination and for partial melting. In contrast, areas that were unaffected by Neoproterozoic subduction were relatively rigid, with anhydrous lithospheric roots that were not highly susceptible to either delamination or melting. Shear zones, which developed at the boundaries between these two types of terranes, focused the post-collisional magmas.

8. Conclusions

The Maevarano Suite of northern Madagascar consists largely of granitoid intrusions, with minor early mafic phases, which were emplaced between ca. 537 and 522

Ma during the waning stages of the East African Orogen. Plutons of the Maevarano Suite are commonly associated with ductile shear zones, which may have developed during extensional collapse of the orogen. Distinctive geochemical features of these intrusions, including LILE enrichment, negative Nb-Ta anomalies, and LREE enrichment over HREE, point to a source in metasomatised sub-continental lithospheric mantle. Maevarano Suite plutons are situated in areas where there is evidence for Neoproterozoic subduction, but absent from areas that were not reworked at that time. We therefore propose that the SCLM was metasomatised during Neoproterozoic subduction events and subsequently melted during lithospheric delamination; areas such as the Antongil Craton whose SCLM was not metasomatised, either did not delaminate, or were less susceptible to partial melting. The magmas were then emplaced along crustal-scale shear zones.

Many of the conclusions drawn from this work can be applied along the length of the EAO, where similar post-collisional plutons are common. We suggest that the source for most of these post-collisional magmas is likely to lie in the SCLM, and that abundant post-collisional plutons will be focused in areas where that SCLM was metasomatised through Proterozoic subduction.

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Figure list for Maevarano Paper

Figure 1: Reconstruction of the East African Orogen, showing the palaeoposition of Madagascar in Gondwana, after Jacobs and Thomas (2004) and Thomas et al. (2009).

Figure 2: Simplified geological map of northern Madagascar, showing the outcrop pattern of the Maevarano Suite. The inset shows the main geological units of the whole of Madagascar. BE – Bemarivo Belt; AB – Anaboriana-Manampotsy Belt; AN – Antongil Craton; NT – Antananarivo Craton; IT – South Madagascar domains, including Itremo Group; VO – Vohibory Domain; NB- Northern Bemarivo terrane; SB – Southern Bemarivo terrane. The site of one of the dated samples is shown (RK7248A); other sample locations are shown on Fig. 3.

Figure 3: Geological map of the type area of the Maevarano Suite, in the Maevarano River valley south of Sandra Kota, showing the localities of three of the dated samples.

Figure 4: a) Typical Maevarano Suite landscape, with high mountain and valley outcrops; b) Typical unfoliated porphyritic granitoid of the main phase; c) Typical foliated porphyritic granitoid from margin of main phase pluton; d) Pegmatitic facies of main phase charnockite with dark-brown weathering orthopyroxenes and dark green hornblende; e) Foliated layered gabbro of early phase of Maevarano Suite intruded by coarse-grained pegmatite veins associated with the main phase; f) Foliated layered gabbro of early phase cut by foliated felsic sheets, in turn intruded by main phase granitoid (upper third of picture) with foliated margin.

Figure 5: CL images of zircons from the dated samples, showing some of the analysed spots: a) and b) – zircons from BT/07/12; c) and d) – zircons from BT/07/22; e) and f) – zircons from BT/07/25; g) and h) – zircons from RK7248A.

Figure 6: Tera Wasserburg data plots for the four dated samples. Error crosses at 2σ. Data not corrected for common Pb.

Figure 7: a-c) Harker plots for Maevarano Suite samples; d) Total Alkali vs Silica plot for Maevarano Suite samples. Classification fields from Gillespie and Styles (1999) after Le Bas et al. (1986). Alkalic/sub-alkalic division from Miyashiro (1974)

Figure 8: a) Plot of A/CNK (molar $Al_2O_3/(CaO + Na_2O + K_2O)$) vs A/NK (molar $Al_2O_3/(Na_2O + K_2O)$) for Maevarano Suite samples. b): (Y+Nb) vs Rb granite discrimination plot for granitoid samples from the Maevarano Suite, after Pearce et al. (1984). Dashed line indicates field of other post-collisional granitoids from the East African Orogen, from the Northern EAO, Mozambique, and Antarctica; data from Kuster and Harms, 1998; Roland, 2004; Norconsult, 2007. c): Ga/Al vs Zr granite discrimination plot for granitoid samples from the Maevarano Suite, after Whalen et al. (1985). Dashed line indicates field of other post-collisional granitoids from the East African Orogen, from Mozambique and Antarctica; data from Roland, 2004; Norconsult, 2007. d): Granitoid samples from the Maevarano Suite plotted on the Y-Nb-Ce discrimination plot for A-type granites of Eby (1992). Dashed line indicates approximate field of other post-collisional granitoids from the East African Orogen, from the Northern EAO, Mozambique, and Antarctica; data from Küster and Harms, 1998; Roland, 2004; Norconsult, 2007.

Figure 9: Primitive mantle-normalised trace element patterns for selected samples from the early phase (a), main phase (b) and late phase (c) of the Maevarano Suite. Normalising factors from McDonough and Sun (1995).

Table 1: Whole-rock major, trace and rare earth element data for all analysed samples.

<u>Supplemental data tables</u>

Table A: Geochronological data table for Sample BT/07/12

Table B: Geochronological data table for Sample BT/07/22

Table C: Geochronological data table for Sample BT/07/25

Table D: Geochronological data table for Sample RK7248A

Table E: Measured and certificated results for standards, measured with two analytical batches in which the samples described in this paper were run.

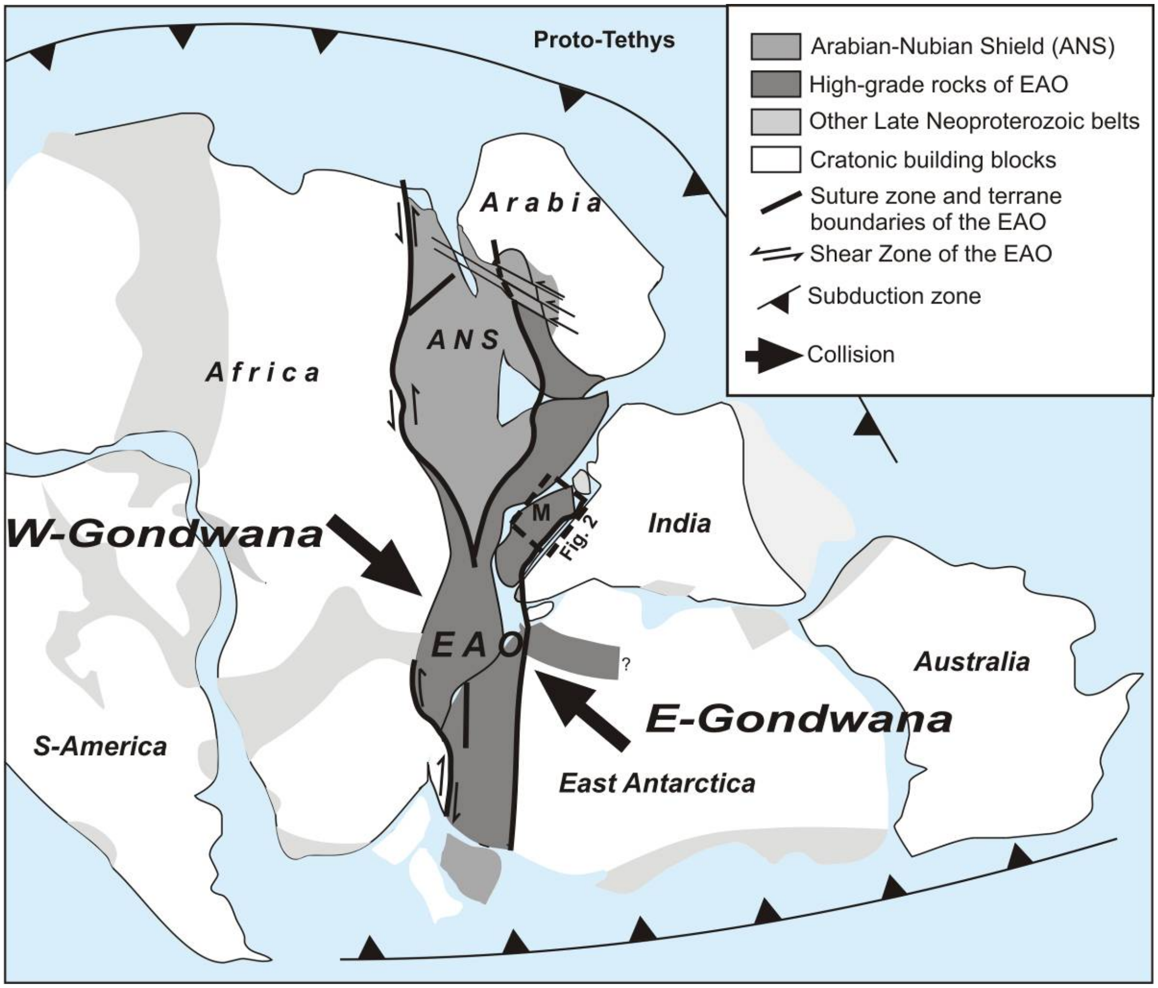

Proto-Tethys
Arabian-Nubian Shield (ANS)
High-grade rocks of EAO
Other Late Neoproterozoic belts
Cratonic building blocks
Suture zone and terrane boundaries of the EAO
Shear Zone of the EAO
Subduction zone
Collision
Arabia
ANS
Africa
W-Gondwana
M
Fig. 2
India
EAO
?
Australia
E-Gondwana
S-America
East Antarctica

Fig. 1

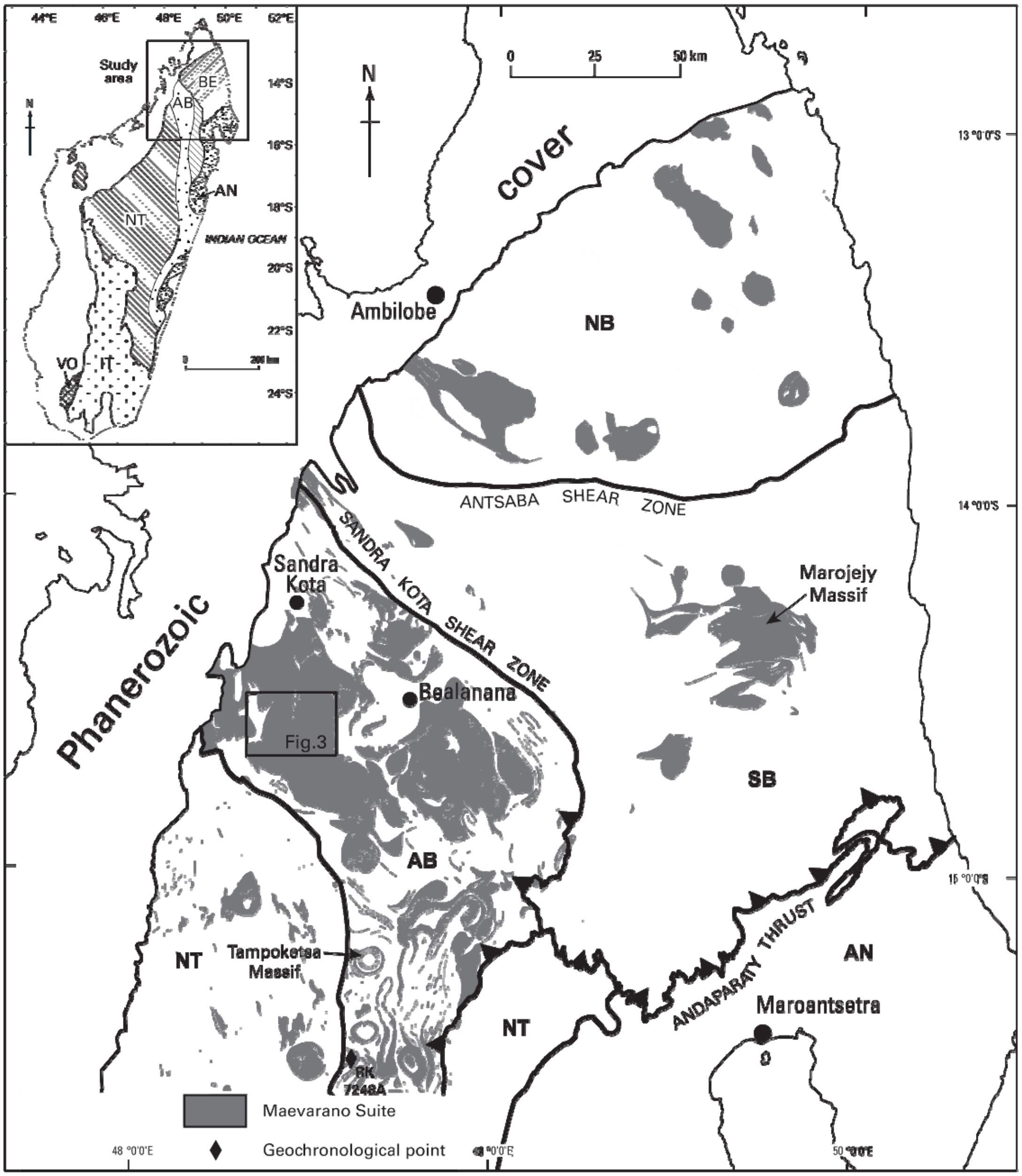
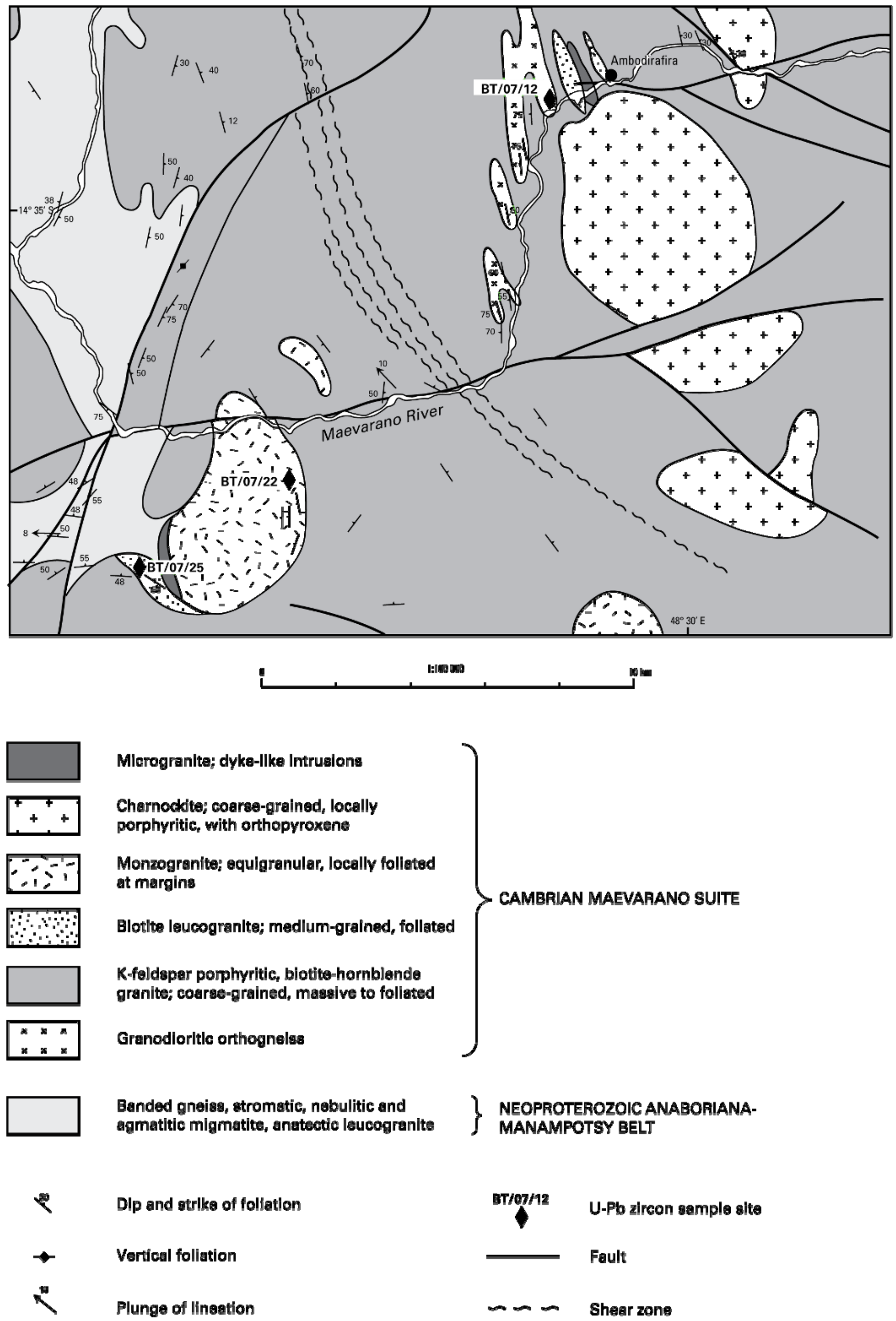

44°E
46°E
48°E
50°E
52°E
Study area
BE
AB
14°S
16°S
18°S
20°S
22°S
24°S
AN
NT
INDIAN OCEAN
VO
IT
N
0
25
50 km
cover
Ambilobe
NB
13 °0'0"S
ANTSABA SHEAR ZONE
14 °0'0"S
SANDRA KOTA SHEAR ZONE
Sandra Kota
Marojejy Massif
Phanerozoic
Bealanana
Fig.3
SB
AB
15 °0'0"S
ANDAPARATY THRUST
AN
NT
Tampoketsa Massif
NT
Maroantsetra
RK 7248A
Maevarano Suite
Geochronological point
48 °0'0"E
50 °0'0"E

Fig 2



Ambodirafira
BT/07/12
BT/07/22
BT/07/25
Maevarano River
14° 35' S
48° 30' E
Microgranite; dyke-like intrusions
Charnockite; coarse-grained, locally porphyritic, with orthopyroxene
Monzogranite; equigranular, locally foliated at margins
Biotite leucogranite; medium-grained, foliated
K-feldspar porphyritic, biotite-hornblende granite; coarse-grained, massive to foliated
Granodioritic orthogneiss
CAMBRIAN MAEVARANO SUITE
Banded gneiss, stromatic, nebulitic and agmatitic migmatite, anatectic leucogranite
NEOPROTEROZOIC ANABORIANA-MANAMPOTSY BELT
Dip and strike of foliation
Vertical foliation
Plunge of lineation
BT/07/12
U-Pb zircon sample site
Fault
Shear zone

Fig 3

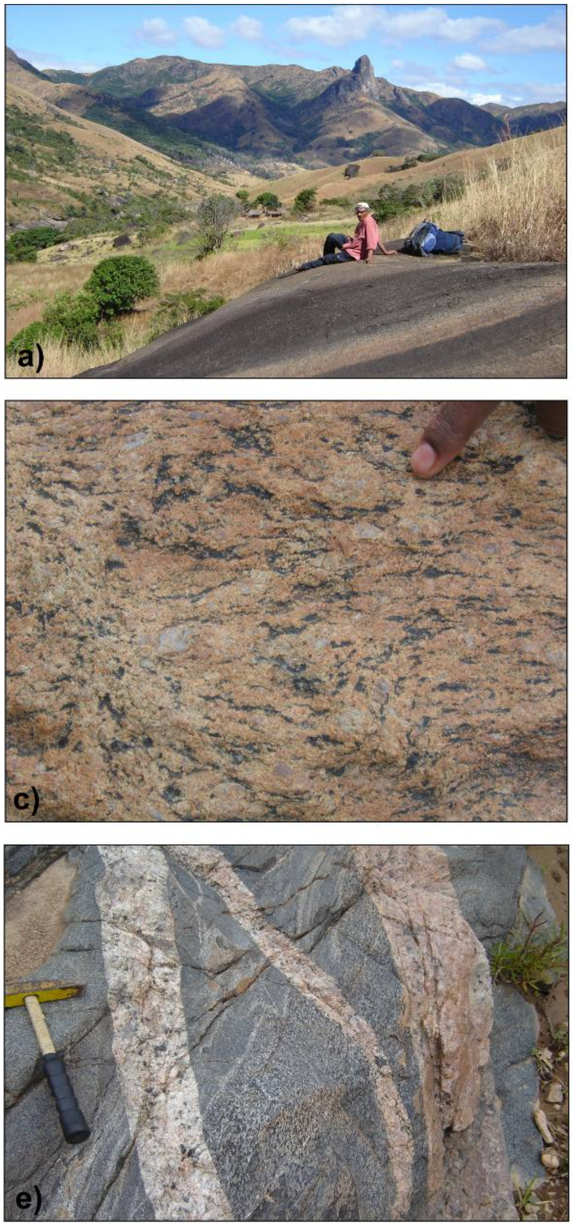


Fig 4

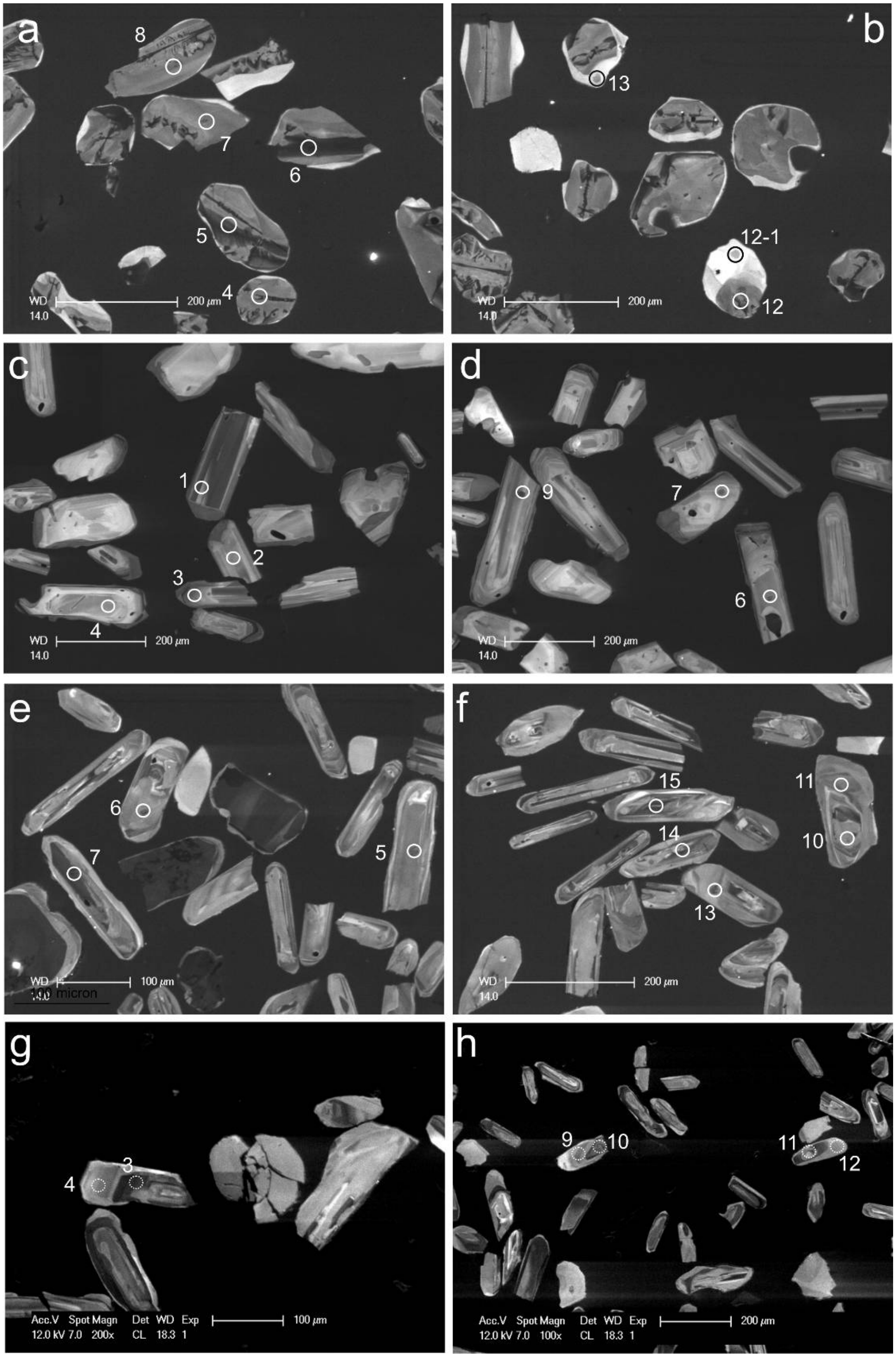
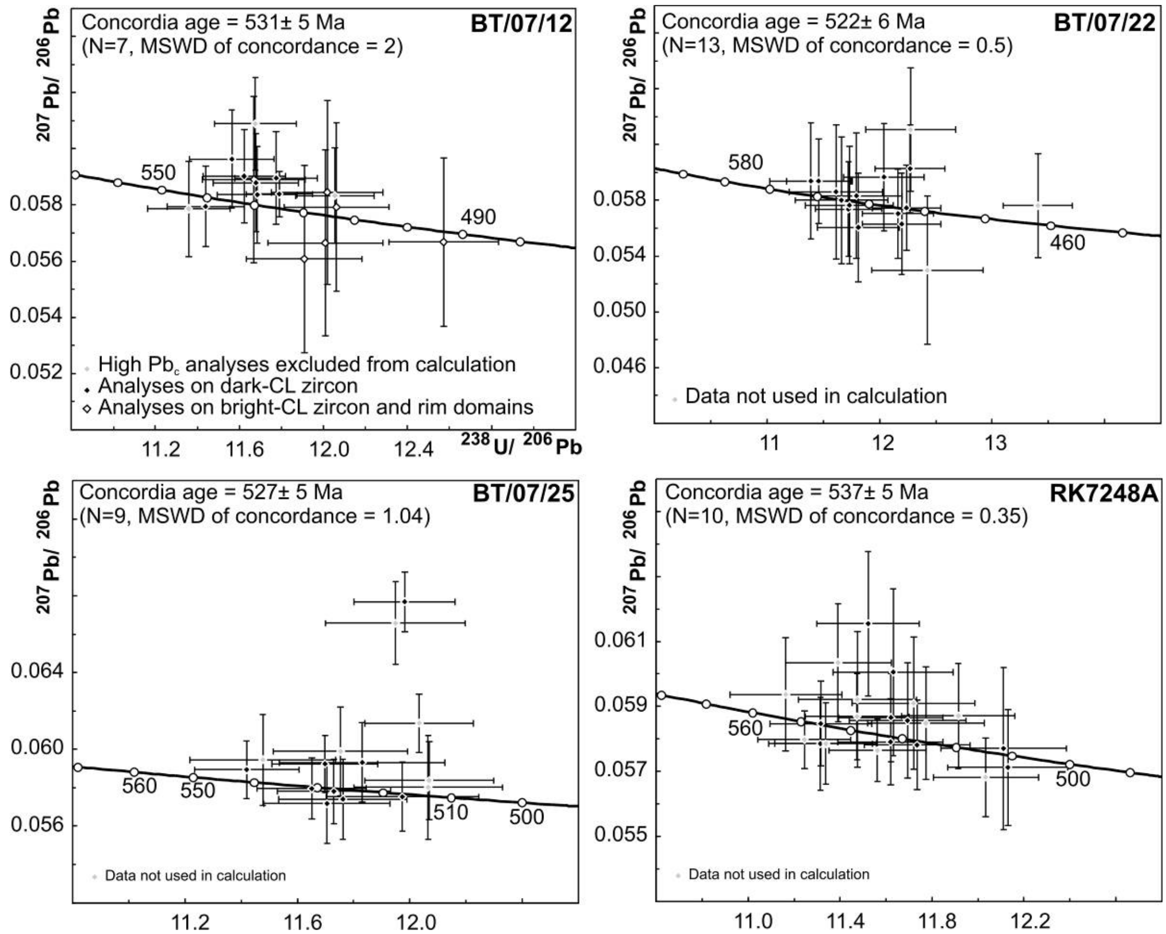

a
8
7
6
5
4
WD 14.0
200 μm
b
13
12-1
12
WD 14.0
200 μm
c
1
2
3
4
WD 14.0
200 μm
d
9
7
6
WD 14.0
200 μm
e
6
7
5
WD 14.0
100 μm
100 micron
f
15
11
14
10
13
WD 14.0
200 μm
g
3
4
Acc.V Spot Magn Det WD Exp
12.0 kV 7.0 200x CL 18.3 1
100 μm
h
9
10
11
12
Acc.V Spot Magn Det WD Exp
12.0 kV 7.0 100x CL 18.3 1
200 μm

Fig 5

960 
Concordia age = 531± 5 Ma
(N=7, MSWD of concordance = 2)
BT/07/12
High Pbc analyses excluded from calculation
Analyses on dark-CL zircon
Analyses on bright-CL zircon and rim domains
Concordia age = 522± 6 Ma
(N=13, MSWD of concordance = 0.5)
BT/07/22
Data not used in calculation
Concordia age = 527± 5 Ma
(N=9, MSWD of concordance = 1.04)
BT/07/25
Data not used in calculation
Concordia age = 537± 5 Ma
(N=10, MSWD of concordance = 0.35)
RK7248A
Data not used in calculation
207Pb/206Pb
238U/206Pb

961 Fig 6

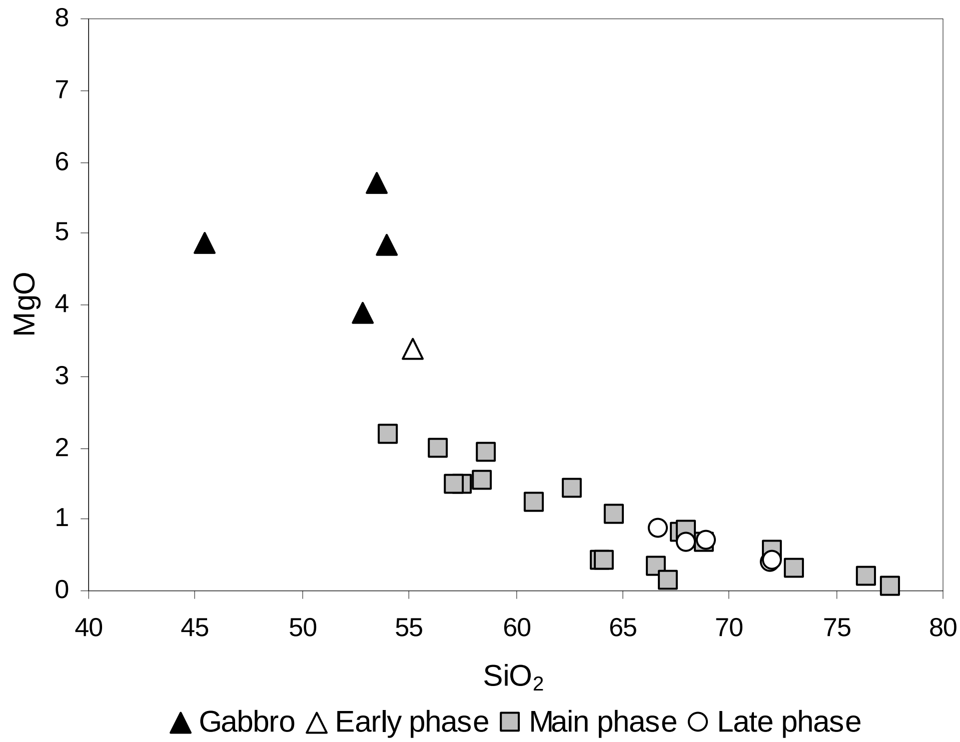

MgO
SiO2
▲ Gabbro △ Early phase ■ Main phase ○ Late phase

Fig. 7 a)

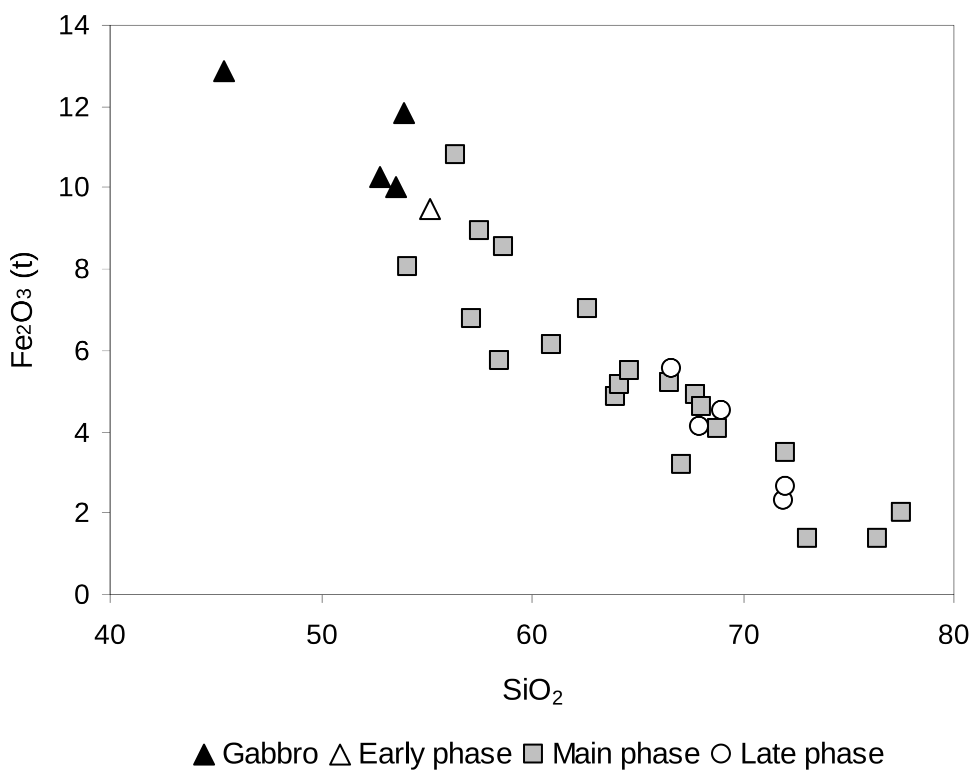
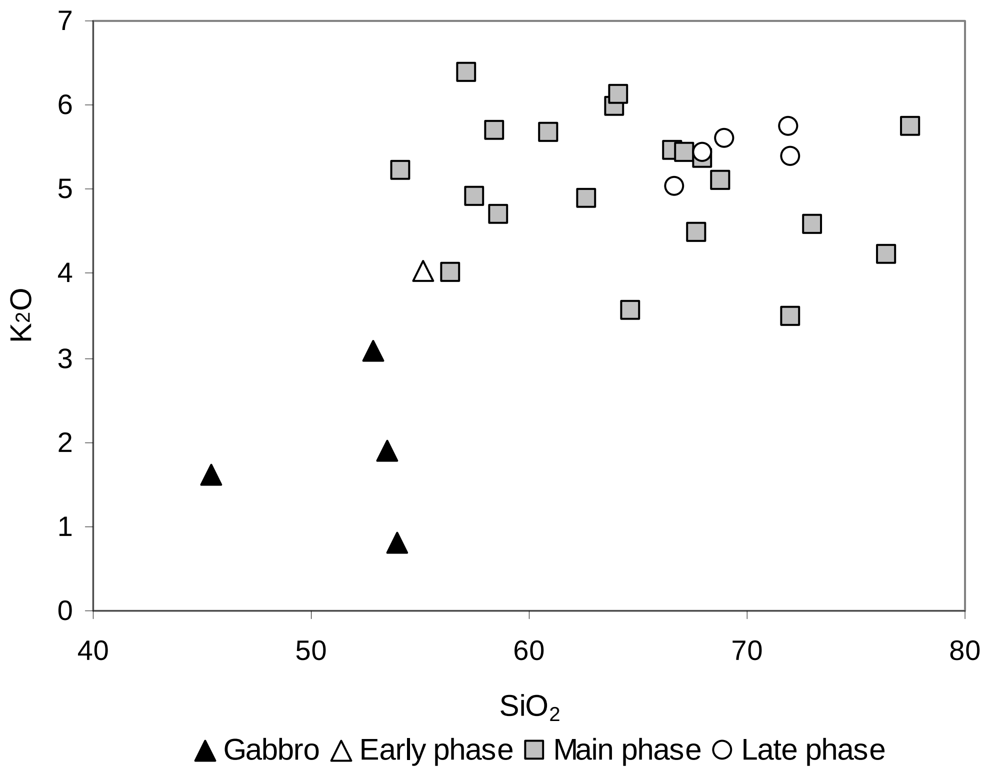
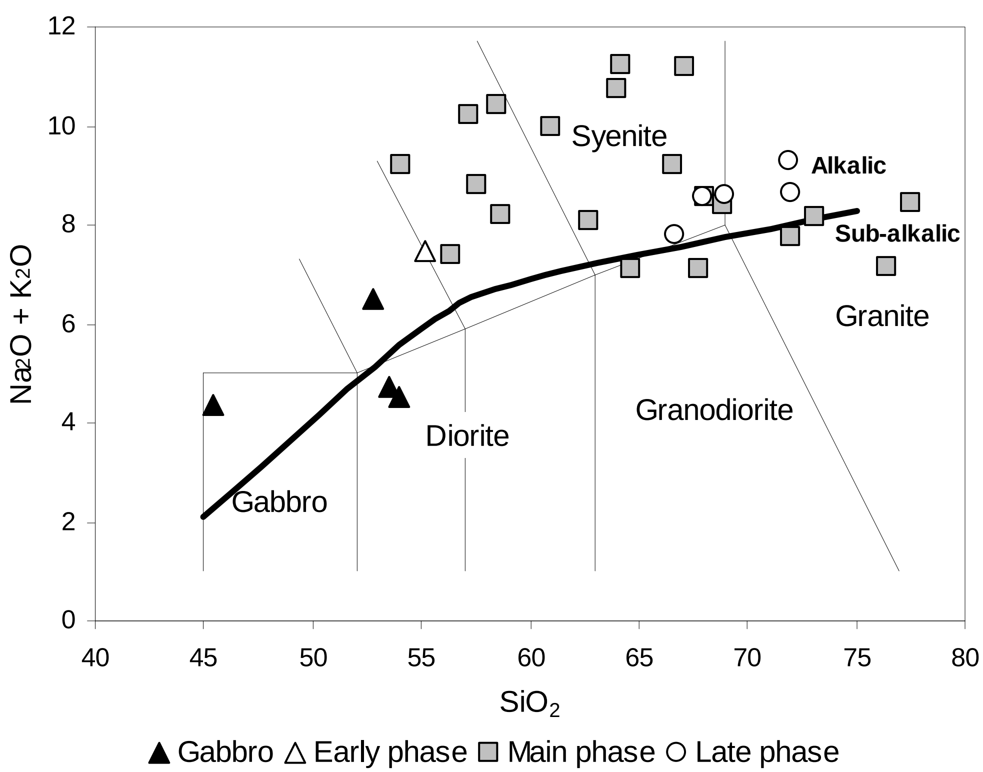

Fe2O3 (t)
SiO2
▲ Gabbro △ Early phase ■ Main phase ○ Late phase

Fig. 7 b)



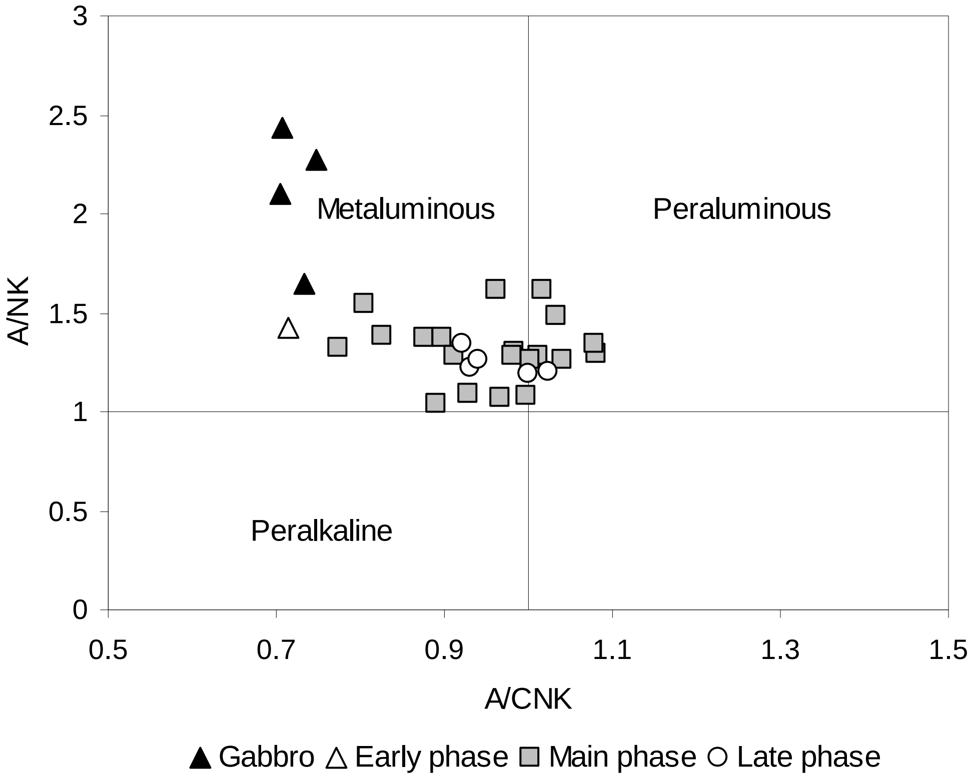
7
6
5
4
3
2
1
0
K2O
40
50
60
70
80
SiO2
Gabbro
Early phase
Main phase
Late phase

Fig. 7 c)



12
10
8
6
4
2
0
Na2O + K2O
Syenite
Alkalic
Sub-alkalic
Granite
Granodiorite
Diorite
Gabbro
40
45
50
55
60
65
70
75
80
SiO2
Gabbro
Early phase
Main phase
Late phase

Fig. 7 d)



971
972 Fig. 8 a)

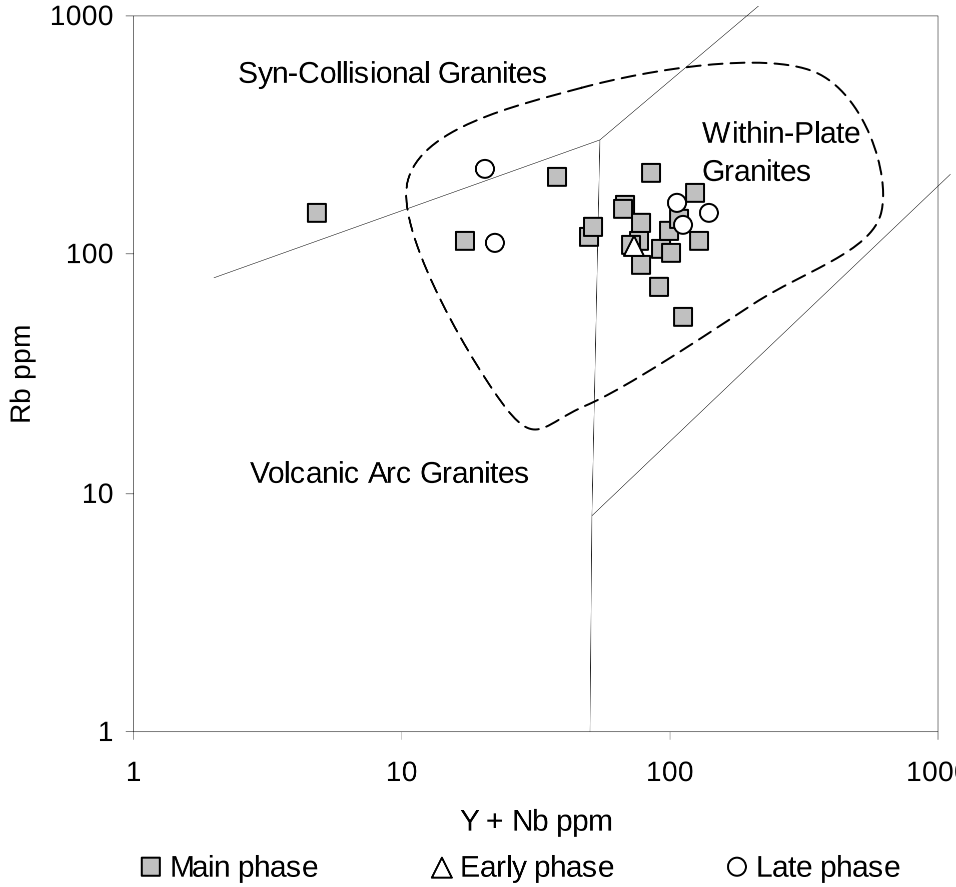
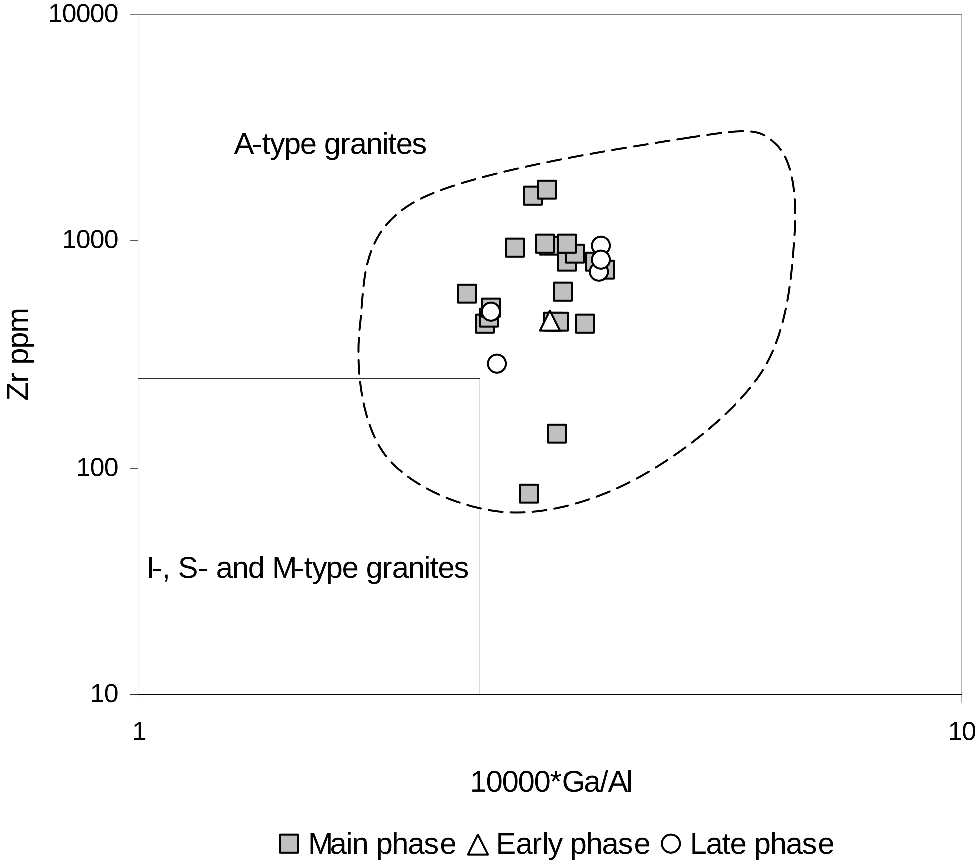
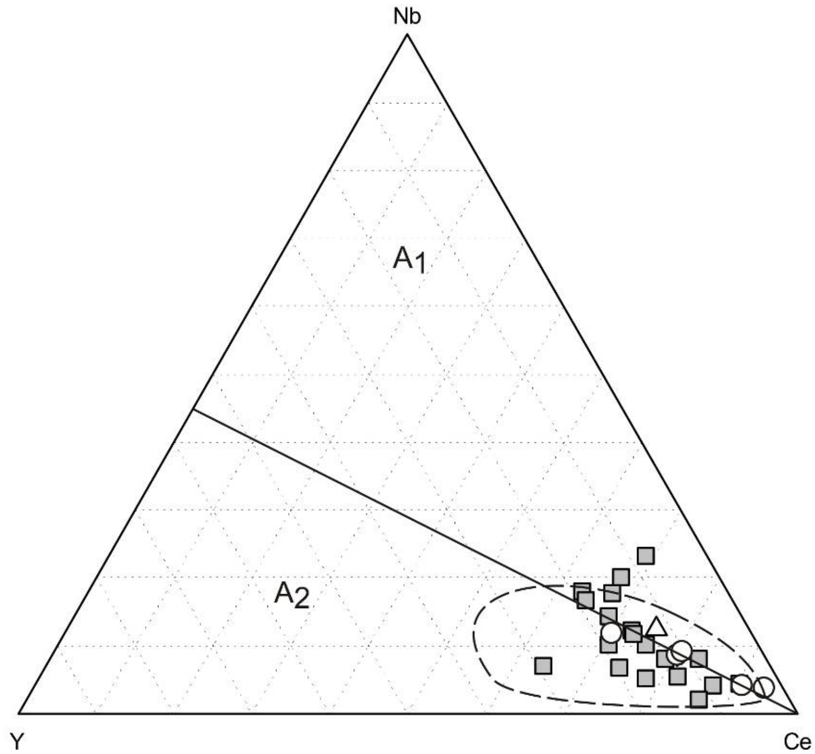

1000
100
10
1
Rb ppm
1
10
100
1000
Y + Nb ppm
Syn-Collisional Granites
Within-Plate
Granites
Volcanic Arc Granites
Main phase
Early phase
Late phase

Fig. 8 b)

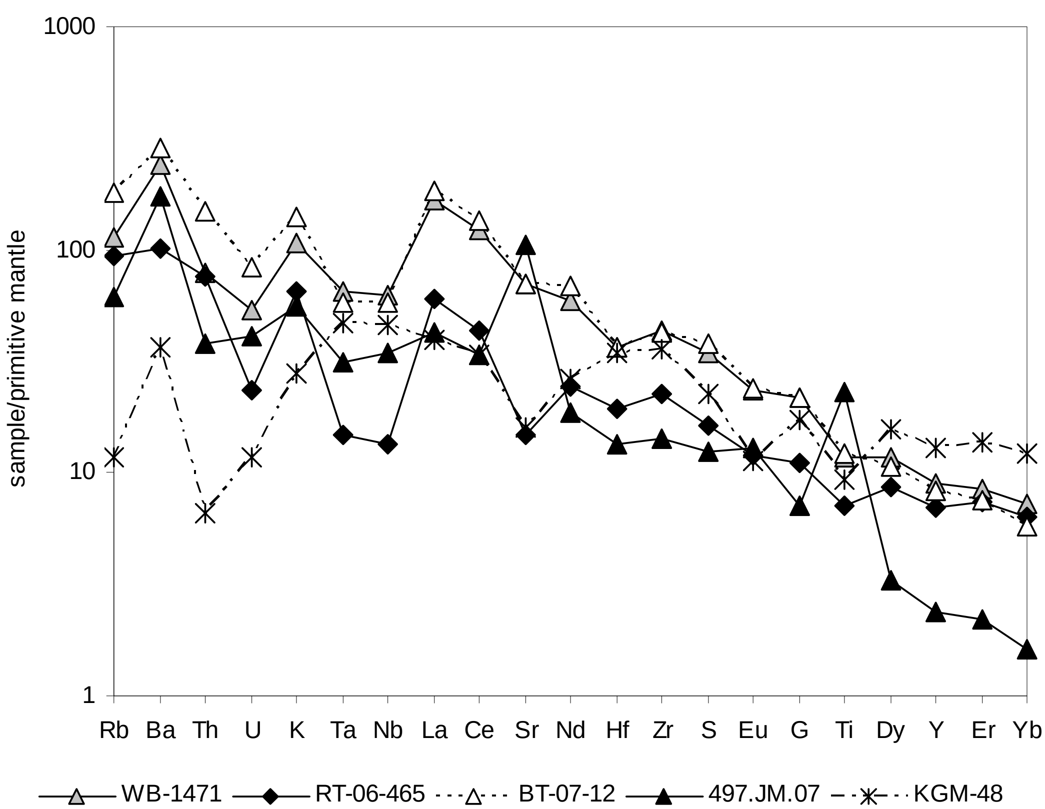


10000
1000
100
10
1
10
Zr ppm
10000*Ga/Al
A-type granites
I-, S- and M-type granites
Main phase
Early phase
Late phase

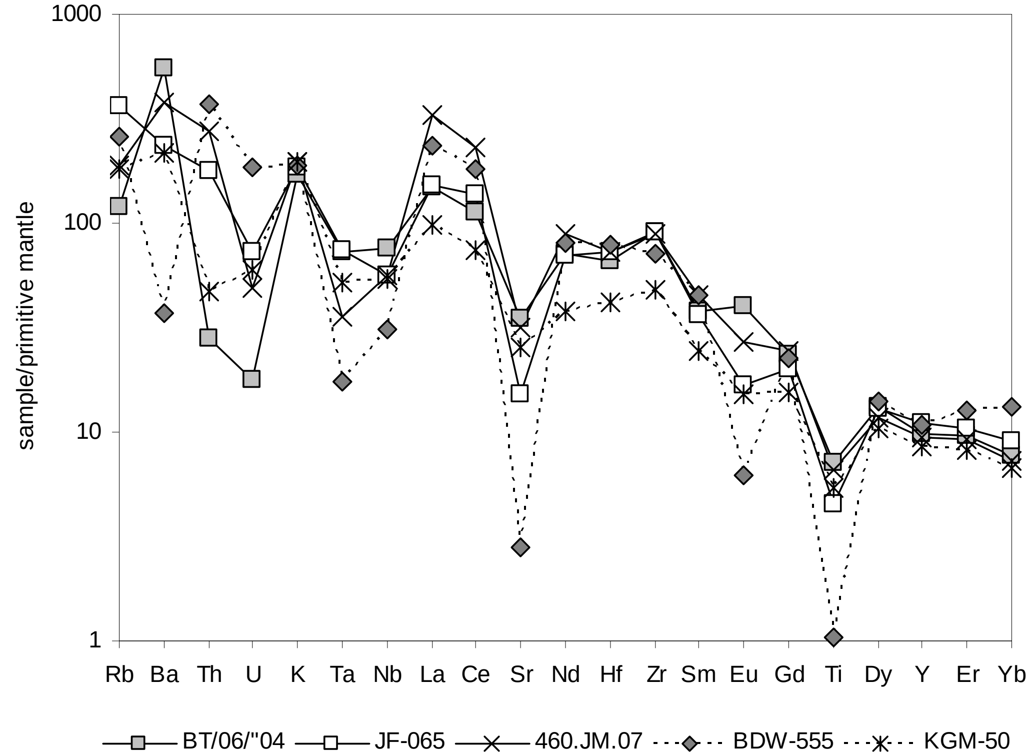
Fig. 8 c)



977
978 Fig. 8 d)

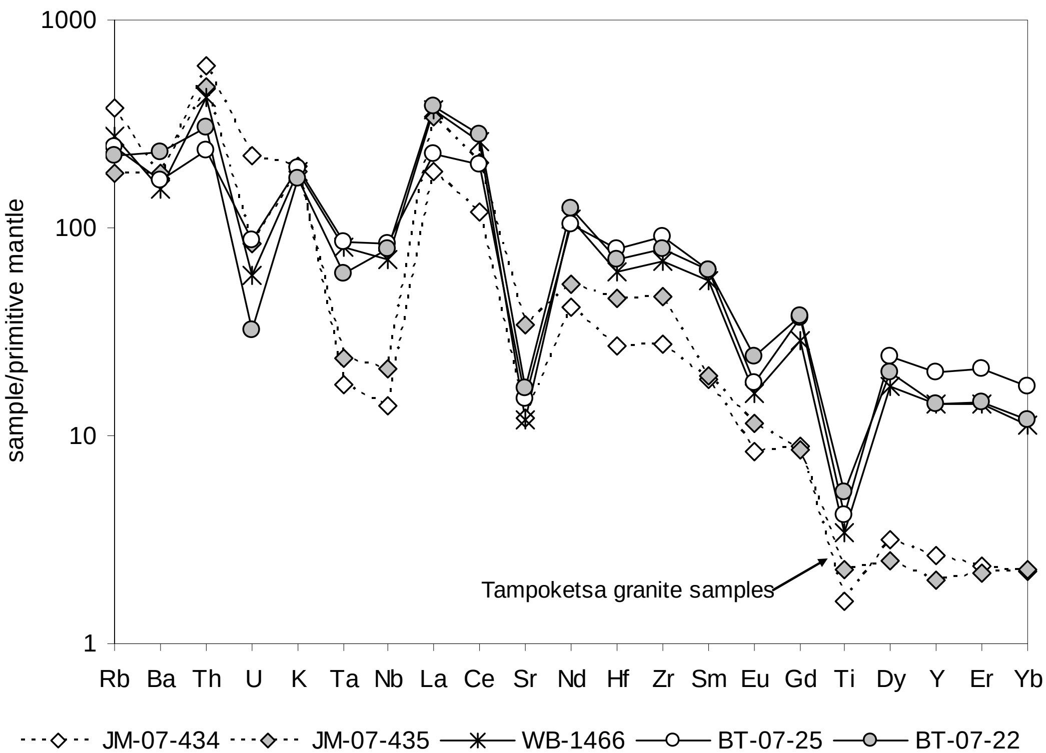


979
980 9 a)



1000
100
10
1
sample/primitive mantle
Rb Ba Th U K Ta Nb La Ce Sr Nd Hf Zr Sm Eu Gd Ti Dy Y Er Yb
BT/06/"04
JF-065
460.JM.07
BDW-555
KGM-50

9 b)



1000
100
10
1
sample/primitive mantle
Tampoketsa granite samples
Rb Ba Th U K Ta Nb La Ce Sr Nd Hf Zr Sm Eu Gd Ti Dy Y Er Yb
JM-07-434
JM-07-435
WB-1466
BT-07-25
BT-07-22

9 c)