Geochronology of granitic rocks from the Ruangwa region, southern Tanzania – links with NE Mozambique and beyond

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A B S T R A C T

New U-Pb zircon LA-ICP-MS data are presented for 4 granitoid bodies which intrude high grade gneisses of the previously unmapped Ruangwa region in southern Tanzania. The study area forms part of the late Neoproterozoic East African Orogen (EAO). The oldest unit, a coarse-grained migmatitic granitic orthogneiss gave an early Neoproterozoic (Tonian) crystallization age of 899 ± 9/16 Ma, which is similar to, but significantly younger than, Stenian-Tonian basement ages in areas relatively nearby. Crust of this age may extend as far north as the major Phanerozoic Selous Basin, north of which Archaean protolith ages predominate (the "Western Granulites"), except for the juvenile Neoproterozoic "Eastern Granulites", which are not represented in the study area. To the south, the Tonian crust of the study area provides a tentative link with the Marrupa Complex in NE Mozambique. A granite pluton, dated at 650 ± 5/11 Ma is broadly coeval with the main Pan-African tectono-thermal event in the East African Orogen that is recorded across Tanzania north of the Selous Basin. Zircons in this granite contain inherited cores at ca. 770 Ma. This age is within the range of dates obtained from south and west of the study area from juvenile granitoid orthogneisses which might be related to a widespread, but poorly understood, early phase of Gondwana assembly along an Andean-type margin.

South of the study area, in NE Mozambique, the latest orogenic events occurred at ca. 550 Ma, and are sometimes attributed to the Ediacaran-aged "Kuunga Orogeny". While metamorphic dates of this age have been recorded from the EAO north of the Selous Basin, magmatic rocks of this event have not been recognized in Tanzania. The two youngest granitoids of the present study are thus the first 500-600 Ma igneous rocks reported from the region. A weakly deformed very coarse-grained granite pluton was dated at 591 ± 4/10 Ma, while a very late, cross-cutting, undeformed granite dyke gave an intrusive age of 549 ± 4/9 Ma.

The granitoids ages presented in this study contain elements that are characteristic of the northern, Tanzania-Kenya, segment of the East African Orogen and of the southern, Mozambique, segment. The Tonian orthogneiss sample is typical of (but somewhat younger than) the Marrupa Complex of NE Mozambique. No zircon inheritance was

recorded in the sample, typical of the juvenile Marrupa Complex. On the other hand, the ca. 650 Ma granite pluton has an age that is typical of the northern segment of the orogen; this is the first recorded granite of that age intruded into the Tonian-dominated crust of southern Tanzania or NE Mozambique. The two younger granites have provided dates that are typical of the southern segment of the orogen, and that of the Kuunga Orogen. The study area thus appears to represent an area of transitional crust straddling two complex and contrasting segments of the East African Orogen, with elements of both segments present and evidence for a ca. 770 Ma event which appears to be quite widespread and may relate to the early phases of Gondwana amalgamation in southern East Africa.

1. Introduction

The Neoproterozoic East African Orogen occupies vast tracts of often remote and poorly accessible land in eastern Tanzania. The southern Tanzanian region in the Lindi-Ruangwa Districts remains one of the most poorly known areas. It lies between the quite well-studied, reasonably accessible, segments of the orogen in eastern Tanzania and southernmost Tanzania into NE Mozambique. The former is characterized by Neoarchaean (2.8 to 2.5 Ga) protolith ages, the latter by Stenian-Tonian (1.2 to 0.8 Ga) protolith ages. Both segments were extensively reworked during the major East African Orogen in the late Neoproterozoic.

The published studies have been particularly focused on a number of scattered granulite terranes which occur along the length of the orogen and which have provided good constraints on the timing and P-T conditions during the late Neoproterozoic, and on the age and nature of the protoliths involved in the “Pan-African” orogeny. To the south of the study area the geological evolution of the orogen, in NE Mozambique has recently been the subject of a World Bank – funded regional mapping project, reported in Bingen et al. (2009) and Boyd et al. (2010).

Our study area in the Ruangwa region, SE Tanzania, constitutes over 1500 km^2 of a previously unstudied part of the East African Orogen in the region between the better-known segments to the north and south. The results presented in this paper are the product of a collaborative project between the Geological Survey of Tanzania (GST) and the British Geological Survey (BGS). It was carried out during the GST regional geological mapping programme in the area north of Ruangwa (Lindi District) in southern Tanzania during the late dry season (September-October) of 2012 (Fig. 1). The purpose of this paper is to provide geochronological data from 4 granitoids in this part of the East African Orogen with a view to providing links with better-known adjacent areas to the north and south.

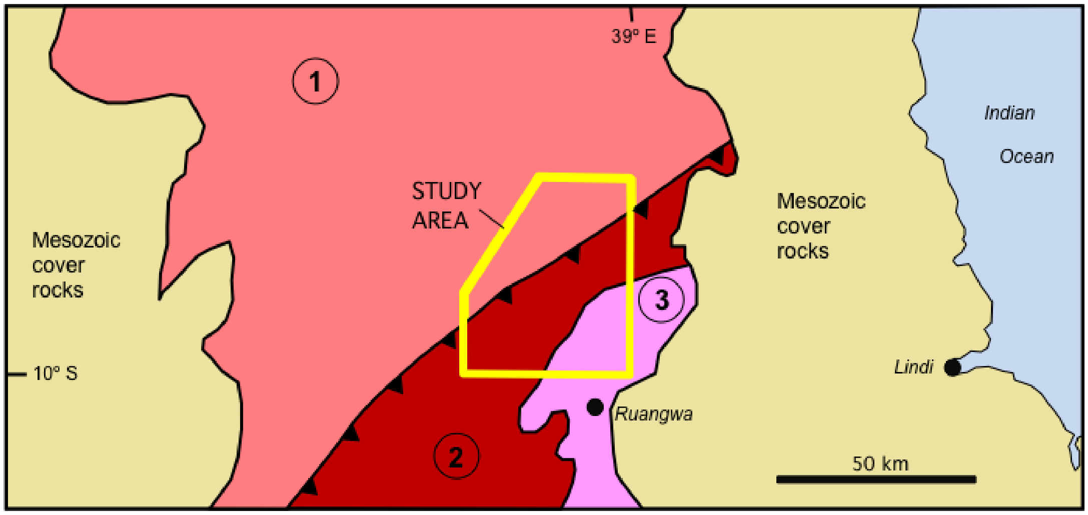


Fig. 1. Location of the study area superimposed on the 1: 2 million scale geological maps of Tanzania by Pinna et al. (2004). The numbers 1, 2 and 3 refer to lithostratigraphic units referred to in the following section.

2. Regional geological setting

The Ruangwa area is underlain by crystalline basement rocks that form part of the East African Orogen, formerly known as the Mozambique Belt, and constituting in general terms, part of the complex collision zone that led to the amalgamation of Gondwana in the Ediacaran (latest Neoproterozoic) as shown in Fig. 2. The crystalline basement outcrops of southern Tanzania are obscured in the north by the Phanerozoic rocks of the Selous Basin (Fig. 2).

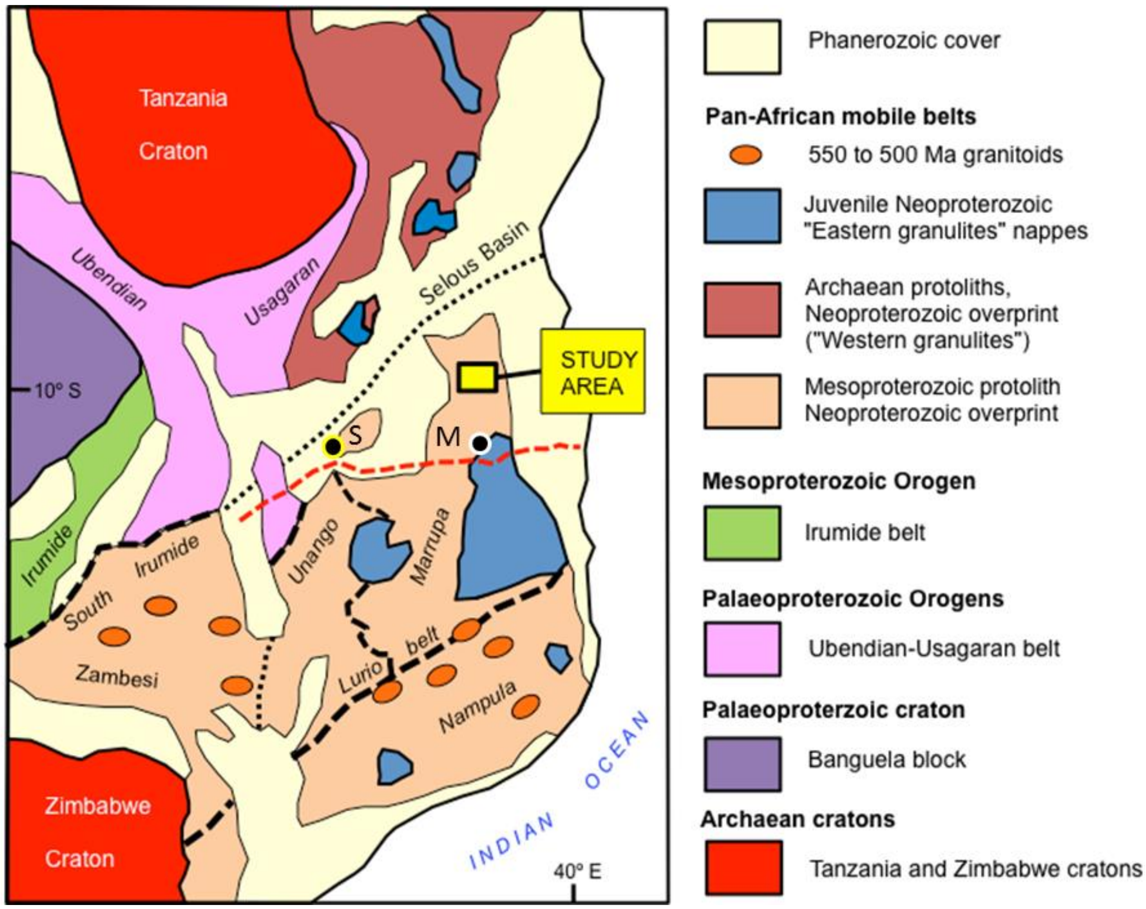


Fig. 2. Location of the study area in southern Tanzania in relation to the crustal blocks of southern East Africa (modified after Bingen et al., 2009 and Fritz et al., 2013). The dashed red line is the border with Tanzania (north) and Mozambique (south). The terms "Eastern" and "Western" granulites are specific to Tanzania. M = Masasi; S = Songea.

While the geological evolution of the orogen further north in central-east Tanzania and to the south in NE Mozambique is reasonably well studied, the rocks of the Ruangwa region are largely unknown. In the immediate environs of the study area, the only pre-existing published geological map is that of the 1:2 000 000 scale compilation of Tanzania (Pinna et al., 2004). This compilation shows that the exposure of metamorphic rocks in the study area is made up of two major subdivisions separated by a thrust fault (Fig. 1):

1) Northwest of the thrust are Mesoproterozoic orthogneisses (ca. 1.9 - 0.945 Ma) affected by Neoproterozoic high grade metamorphism (Unit 1 on Fig. 1);

2) To the southeast there are two Neoproterozoic units of the Mozambique Belt shown - high grade mafic and felsic granulite gneiss and migmatite (ca. 640 Ma), interlayered with amphibolite, marble, quartzite, schist and mylonite (Unit 2 on Fig. 1) and a unit of metasediments (Unit 3 on Fig. 1). Pinna et al. (2004)

> considered the protoliths of these high grade rocks to be mostly “Meso- to Neoproterozoic age, with scarce Archaean to Palaeoproterozoic xenocrysts.

No source for this information is quoted and no other description of the geology of the study area is available in the published literature.

The only published geochronological data from the southern part of SE Tanzania is given in Kröner et al. (2003) in the Masasi region over 50 km south of our study area (Fig. 2). This area is underlain by granitoid gneisses dated between 1100 and 950 Ma with Nd isotopic evidence showing they were derived from the remelting of Archaean continental crust. The rocks were subsequently deformed, metamorphosed and migmatised during the East African orogeny at around 630 Ma, together with extensive tectonically interleaved 800–650 Ma granitoid gneisses derived predominantly from Neoproterozoic juvenile melts, along with some clastic metasediments. The recognition of Archaean protoliths in the Masasi region is different from the nearby Unango and Marrupa Complexes of NE Mozambique, where the oldest protolith ages are Mesoproterozoic (Bingen et al., 2009).

In the only other recent study in southern Tanzania, Sommer and Kröner (2013) describe granulite and amphibolite-grade gneisses from the basement area of Songea some 400 km to the west (Fig. 2). Granitic gneisses with protolith ages defining two clusters at about 1150 and 750 Ma, interpreted as the age of protolith emplacement and high-grade metamorphism, including charnockite formation respectively. No Archaean protolith ages were reported from this study.

In these two studies, the older ages provide a link with the basement of NE Mozambique, specifically the northernmost Unango and Marrupa Complexes, which have comparable protolith ages between 1090 and 950 Ma (Bingen et al., 2009). The ca. 750 Ma event in the Songea region is described as a granulite facies event by Sommer et al. (2013), equates temporally with late magmatism, including mangerite intrusion in the Unango and Marrupa Complexes of NE Mozambique, dated between 750 and 800 Ma (Bingen et al., 2009).

The ca. 630 Ma events in the Masasi area correspond closely with the age of the main Neoproterozoic (“Pan-African”) collision-related tectono-thermal event in the greater part of the East African Orogen (formerly known as the “Mozambique Belt”) in the rest of the belt in Tanzania to the north (e.g. Muhongo et al, 2001). However, this event is not recorded from the Unango and Marrupa Complexes of northern Mozambique, which was experiencing localized sedimentation of the Geci Group at that approximate time (Melezhik et al., 2006).

The other important aspect of the study area is that it lies at the centre of a region where two branches of two important orogenic belts intersect almost at right angles; the generally older, north-south East African Orogen and the younger east-west, Kuunga Orogen. The configuration and evolution of this “orogenic crossroads” has proved controversial over the years (e.g. Meert, 2003, Jacobs and Thomas, 2004, Boger, 2011; Satish-Kumar et al., 2013).

3. Geology

The Ruangwa area is underlain by metamorphic "basement" with sedimentary and igneous parentage. The geological map resulting from this study is given in Fig. 3.

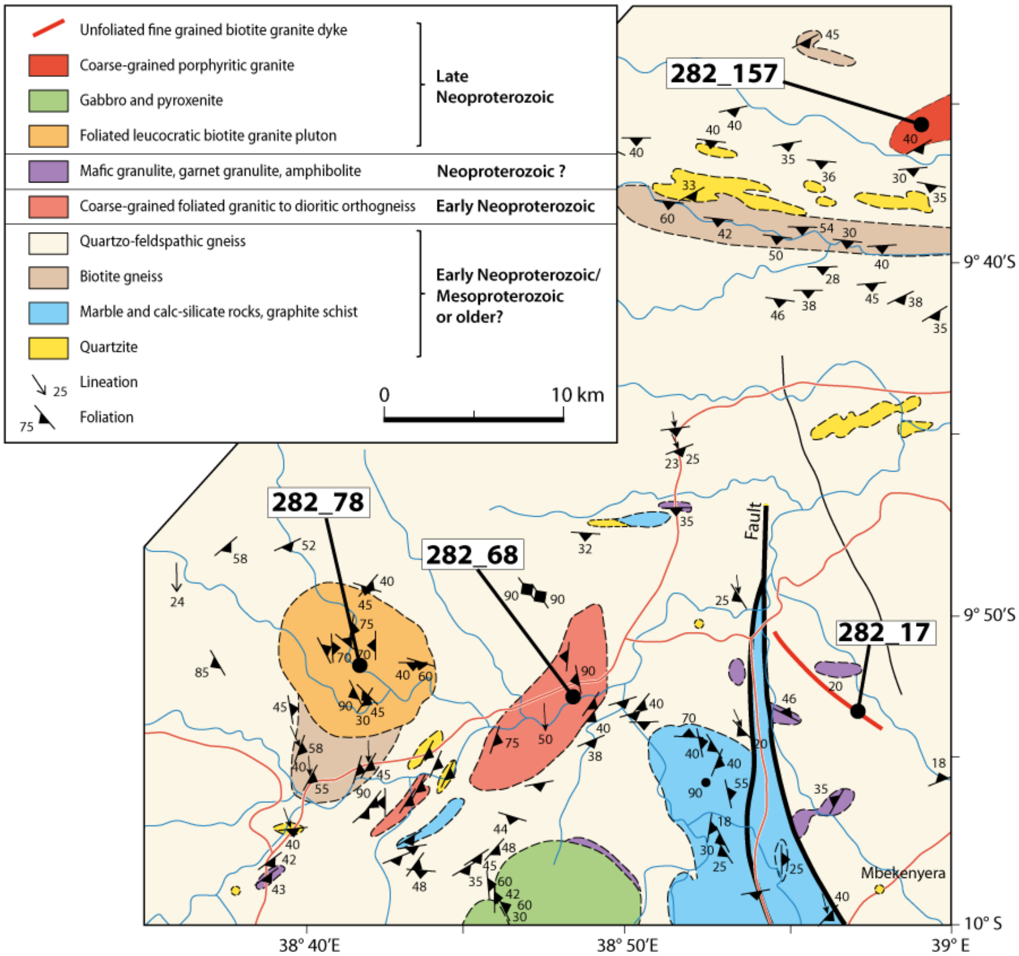


Fig. 3. Geological map of the study area showing geochronology sample sites.

By comparison with known age relations in southern Tanzania from the Masasi area in Kröner et al. (2003), south of the study area and the Songea area in Sommer and Kröner (2013), west of the study area, the gneisses are considered to probably have Meso- to Neoproterozoic protolith ages that were extensively reworked during the Neoproterozoic East African Orogen at ca. 650 Ma. No igneous rocks younger than this have been reported in southern Tanzania prior to this study. From the field survey, the lithostratigraphic units mapped, in probable increasing age are shown in Table 1.

LITHOLOGY	GROUP	POSSIBLE AGE
Unfoliated fine grained biotite granite dyke	Intrusive rocks	Neoproterozoic, Pan-African?
Coarse-grained porphyritic granite		
Foliated leucocratic biotite granite (pluton)		
Gabbro and pyroxenite		
Mafic granulite, garnet granulite	Granulite (lenses?)	Meso- or Neoproterozoic?
Coarse-grained foliated granitic to dioritic orthogneiss	Orthogneiss	Meso- or Neoproterozoic?
Quartzo-feldspathic gneiss, garnet leucogranite, amphibolite, quartzite, marble and calc-silicate, graphite schist	Metasedimentary (supracrustal) rocks	Meso- or Neoproterozoic?

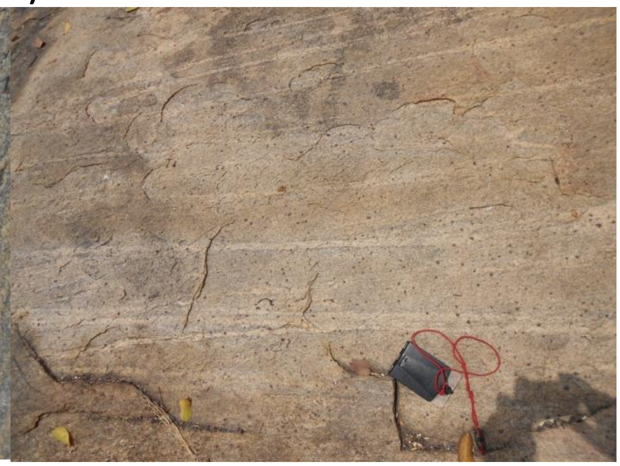
Table 1. Lithostratigraphic units identified in the Ruangwa area. Dated lithologies presented in this study shown in bold font.

3.1 Meta-sedimentary (supracrustal) rocks

The greater proportion of the study area is underlain by a sequence of supracrustal rocks of predominantly metasedimentary origin. The age of deposition, deformation and metamorphism of the sequence is unknown, although they most probably form the northerly continuation of the East African Orogen of NE Mozambique, where the protoliths ages are typically Meso- to Neoproterozoic in age and the latest (main) deformation and metamorphic events are late Neoproterozoic in age.

By far the most widespread lithology are medium- to coarse-grained, **quartzo-feldspathic gneisses**, typically pinkish-weathering, though light grey when fresh, and extremely leucocratic, almost always with <10% (and typically <5%) mafic minerals (Fig. 4a, b). Two distinct, but inter-related mineralogical variants are seen: those with biotite as the only mafic phase and those containing additional garnet, including very pale leucocratic rocks with garnet alone, locally accompanied by magnetite spots. There is typically a pronounced layering defined by differences in grain size and mineralogy, with biotite-rich schlieren common. The layering is often accentuated by layer-parallel to sub-parallel stromatic leucosomes and most outcrops show some evidence of migmatisation. The gneisses are often rather heterogeneous at outcrop scale, but regionally homogeneous. They are often associated with coarse pegmatite veins up to 2 m thick and more irregular coarse-grained segregations.

a) **b)**



c) **d)**

e) **f)**

Fig. 4. Field photographs of gneisses and granulites: gneiss. a) Garnet- and biotite-bearing migmatitic quartzo-feldspathic gneiss with stromatic leucosomes; b) Very leucocratic gneiss with garnet (small spots) as only mafic component, with magnetite spots; c) Disrupted disharmonically folded calc-silicate layers in recrystallised white foetid marble; d) Blebby leucosome segregations in grey biotite gneiss; e) Amphibolitic gneiss, showing boudinaged

hornblendic pods and disrupted garnetiferous leucosomes; f) Mafic garnet granulite with large garnet porphyroblasts.

The protoliths of such quartzo-feldspathic gneisses with granitic compositions are often unclear with clastic sedimentary, felsic volcanic/volcano-clastic or intrusive granitic sheets origins possible, or any combinations of these. In the current case, where the rocks are interlayered with obvious sedimentary rocks such as quartzites and marbles, a sedimentary or volcanic origin is probably the most likely.

Quartzites are common in the metasedimentary sequence, typically forming pods lenses and dismembered layers a few tens or hundreds of metres in strike length to more continuous deformed bodies that can be traced over 10 km along strike, often as ranges of wooded hills. Most outcrops are made up of very coarse-grained, glassy, white totally recrystallised orthoquartzite with little internal fabric, though layered types also occur, long with rare ferruginous quartzite. Lenses and layers of ***Marble*** form an important part of the paragneiss succession. Most are white to pale-grey in colour, locally contain diopside and are sometimes foetid. They are typically interbedded with ***calc-silicate rocks*** with variable modal proportions of carbonate, quartz, plagioclase, diopside, titanite and garnet, often interlayered with, or occurring as deformed boudins within, marble (Fig. 4c).

Layers of grey ***Biotite gneiss*** occur within the supracrustal sequence, forming continuous belts up to 3 km wide within the quartzo-feldspathic gneisses. The unit comprises grey, well banded (on all scales) gneisses composed of quartz, feldspar and biotite with varying proportions and hornblende in more mafic layers. The layering is locally isoclinally folded. Blebs and boudins of amphibolite are found within the sequence. The gneisses are migmatitic, with blebby hornblende-bearing leucosomes (Fig. 4d), or stromatic. In a few localities the gneiss contains sparse layers of garnet-biotite gneiss, which resemble meta-pelites and perhaps suggests that the biotite gneiss may have a semi-pelitic sedimentary protoliths. Layers and lenses of ***Amphibolite*** are fairly common in the sequence, but nowhere form extensive masses. They are made up of well foliated, banded gneisses dominated by varying proportions of hornblende and plagioclase and are typically migmatitic, with felsic veins and segregations that are quite often garnet-bearing (Fig. 4e). Some layers are Ca-rich with abundant dark green diopside accompanying hornblende; other localities contain garnet throughout the sequence. The metasedimentary sequence contains conspicuous ***Graphite schist*** layers in some places. These tend to be easily weathered and so are most likely under-represented in terms of observed outcrop. Outcrops of graphite schist with quartz and feldspar ± biotite locally occur on low-rounded hills where they form slabby, fissile plates, locally interbedded with graphitic quartzites.

3.2 Mafic and felsic granulite

The 1: 2 million compilation of Pinna et al. (2004) shows the supracrustal rocks to have been be thrust NW over a continuous belt of granulites. Our mapping has shown this to be erroneous. There are granulites in the area, but these are quite small in size, no more than 100 m or so in length, occurring in pods and lenses, probably tectonically interleaved/transposed within the supracrustal gneisses. The boundaries between the two units are nowhere exposed, but may be tectonic (cf. the Ocua Complex granulites tectonically interleaved with migmatitic gneisses in the region of the Lurio Belt in NE Mozambique (Boyd et al. 2010). The granulites are medium- to coarse grained, well-foliated, dark grey, very hard, dense rocks with large garnet porphyroblasts often conspicuous (Fig. 4f). The rocks are composed of variable proportions of hornblende, ortho- and clinopyroxene, garnet and plagioclase ± minor biotite. Some outcrops of the granulites are associated with pods of coarse-grained massive green diopside-garnet rocks, with complex garnet-pyroxene symplectites. These rocks are identical to the well-known granulites of the Cabo Delgado Nappe Complex in northern Mozambique (Viola et al., 2008; Bingen et al., 2009; Boyd et al., 2010) and the "Eastern Granulites" of central and northern Tanzania (Fritz et al., 2013 and references therein).

3.3 Coarse-grained granitic orthogneiss

The study area contains relatively extensive bodies of very heterogeneous K-feldspar porphyroblastic orthogneiss. The lithology at outcrop is extremely variable, with a wide range of compositions and textures. The least deformed and contaminated outcrops are coarse-grained, quartz-feldspar-biotite gneiss with K-feldspar megacrysts 1 to 2 cm in length (Fig. 5a). With increasing strain, the rocks become augen gneiss, with stretched K-feldspar crystals strongly aligned and elongated parallel to a strong ductile foliation. This foliation is typically sheared and folded into asymmetrical folds which, with increasing tightness form ductile shear zones along sheared out fold limbs, giving rise to a second, spaced foliation which is the locus of axial plane-parallel leucosomes (Fig. 5b). In many localities the planar foliation is supplanted by a strong stretching lineation, giving rise to "L-tectonites" with rod-shaped K-feldspar megacrysts (Fig. 5c). In some high strain zones, the foliation is deformed into small-scale rootless isoclinal folds, in which the grain size is greatly reduced and the megacrystic texture disappears (Fig. 5d). The heterogeneity of outcrop is greatly enhanced by the locally highly contaminated nature of the orthogneiss which contains trains of deformed, streaked out mafic enclaves and schlieren in most outcrops (Fig. 5e), often accompanied by rafts of partially assimilated quartzo-feldspathic gneiss. The orthogneiss is typically intruded by leucocratic veins and sheets of several generations, most of which are strongly deformed (Fig. 5f).

Fig. 5. Biotite granite orthogneiss. a) Weathered orthogneiss in its most undeformed state, showing K-feldspar megacrysts; b) sheared orthogneiss with asymmetrical folds and a second, spaced foliation with parallel leucosome development; c) L-tectonite showing strong lineation (on left hand surface) and no planar fabric on perpendicular surface to right; d) rootless isoclinal folds in highly deformed orthogneiss; e) deformed amphibolitic gneiss enclave; f) two generations of deformed felsic veins.

3.4 Late igneous intrusions

The foregoing gneisses form the country rocks to three generations of granite intrusions and a large gabbroic body.

3.4.1 Foliated leucocratic biotite granite (pluton)

The area contains one major, sub-circular granite pluton about 10 km across which broadly corresponds to a regional aeromagnetic anomaly as shown on the Tanzanian national aeromagnetic map. The pluton consists of medium- to coarse-grained, generally equigranular, grey, biotite-bearing leucogranite. The granite is fairly homogeneous and massive but is locally foliated, particularly near the margins of the pluton (Fig. 6a). It locally contains mafic (biotite-rich) enclaves and schlieren and is rarely intruded by deformed intrusive mafic dykes (Fig 6b) and thin pegmatite veins. The granite intruded the layered quartzo-feldspathic gneisses of the metasedimentary package and has domed the foliation in the country rocks which is oriented concentrically around the pluton. Many outcrops within the pluton are composed of large rafts of quartzo-feldspathic gneiss.

a)

b)

c)

d)

Fig. 6. Intrusive rocks a) Typical texture of the granite pluton showing locally-developed strong foliation b) Folded mafic dyke intruded into the granite c) Coarse-grained porphyritic granite showing the contaminated nature, with clots and schlieren of coarse biotite and large K-feldspar megacrysts; d) Biotite microgranite dyke containing a rare blocky amphibolitic xenolith.

3.4.2 Coarse-grained porphyritic granite

A small, poorly exposed area in the eastern part of the study area is composed of very coarse-grained, pinkish-grey K-feldspar porphyritic granite. The granite is highly contaminated at the margins, where it intrudes the metasedimentary sequence which includes quartzo-feldspathic gneiss, quartzite, amphibolite, biotite gneiss and garnet granulite, all of which are present as enclaves. The granite contains many clots and aggregates of coarse biotite into which are set large K-feldspar megacrysts up to 8 cm in size (Fig. 6c); it is intruded by coarse diffuse pegmatite bodies.

3.4.3 Unfoliated fine grained biotite granite (dyke)

In the SE part of the area, a series of prominent outcrops comprise rounded granite tors rising up to 25 m above the surrounding land surface. These are strung out in a NW-SE direction and form a prominent linear feature that can be traced over about 8 km on the Landsat imagery. The body is thus dyke-like in form, with a maximum width of about 100 m. The outcrops are composed of pinkish-grey, medium-grained biotite granite, with abundant pink K-feldspar, subordinate plagioclase and low volumes of biotite (5 to 10%). The granite has a thin (metre-scale) chilled margin on both sides, where it can be classified as microgranite. The granite is unfoliated and contains a few blocky mafic enclaves (Fig. 6d). The undeformed and dyke-like form of the granite clearly shows it to be a late, post-tectonic intrusion.

3.4.4 Gabbro and pyroxenite

A large sub-circular pluton of coarse-grained massive homogeneous gabbro, measuring about 10 km across, intrudes the quartzo-feldspathic gneisses along the southern margin of the study area. The margins of the pluton are expressed as an arcuate series of dark hills, with rounded, boulder, tor-like outcrops. The gabbro is unfoliated except immediately at the contacts with the country rocks where it shows a faint mineral alignment parallel margin and is slightly finer-grained. It is composed of plagioclase, clinopyroxene and minor biotite and rarely contains small (5 cm) hornfels xenoliths. The gabbro is so pristine that it could conceivably be a Karoo-aged intrusion, but it is locally cut by thin (about 1 cm wide) straight granite veins, showing it to be Precambrian in age.

A small pyroxenite body, a few hundreds of metres in length, was mapped north of the gabbro. It is composed of very coarse-grained (ca. 1 cm-sized grains) homogeneous black clinopyroxenite, with typical knobbly-weathered surfaces and locally contains enclaves of well foliated two-pyroxene mafic granulite.

4. Structural geology

No detailed structural analysis of the study area was undertaken. A strong, but variable regional ductile foliation is present in all the rock units except the two late granites and the gabbro. No major high-strain ductile shear or mylonite zones were encountered, possibly due to the generally poor outcrop; certainly the major NE-SW-trending thrust shown on Pinna et al (2004) is not present in the indicated location. The distribution of measured foliations and lineations is shown on Fig. 3. The area can be broadly sub-divided into two structural domains. The northern area is characterized by regular, almost east-west striking foliations with consistent moderate dips of 20 to 60°to the south. The southern domain is characterized by much more variable foliation dips. This is in part due to the disruption caused by the intrusion of the granite and gabbro plutons, which have deflected the regional foliations parallel to the intrusion margins. In both domains the foliations tend to be fairly regular at the outcrop scale, but small-scale, tight to isoclinal folding is common, and particularly well seen in migmatised rocks, where leucosomes are folded. Stretching lineations are not particularly common, in line with the generally moderate strain regime over the area. Where recorded, lineations plunge consistently to the SSE. Evidence of a second fabric is locally seen, particularly in the granitic orthogneisses as described above. Asymmetrical shear folds show attenuation of the shorter limbs to form a spaced foliation which is the locus of partial melting and occupied by thin, diffuse leucosomes (See Fig. 5b).

5. Geochronology of the granitoids

Four samples of granitic rocks from the area were taken for U-Pb zircon analysis to ascertain their age of crystallization and any evidence of inheritance and/or later metamorphism. The sample locations are shown on Fig. 3). Each sample consisted of about 10 kg of fresh rock, broken into hand-sized fragments and trimmed of all weathered material on site. Crushing, mineral separation, cathodoluminescence (CL) imagery and ICP-MS isotopic analysis were all completed at the NERC Isotope Geosciences Laboratory (NIGL) facility at British Geological Survey in Keyworth, UK.

Analyses were acquired using a Nu Instruments Attom single-collector ICP-MS, coupled to a New Wave Research UP193SS laser ablation system with a two-volume large format cell. The full method is described in Thomas et al. (2013). In brief, ablation was conducted using 25µm spots, for 30 seconds, at 5Hz, with a fluence of 2.5 j/cm2. Measured masses were ^{202}Hg, ^{204}Hg+Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{235}U. Common lead was not corrected for, but ^{204}Pb was monitored and analyses with counts above the background were discarded. A standard sample bracketing routine was used to normalise the Pb/Pb and Pb/U ratios, utilising 91500 as the reference material. Secondary reference materials GJ-1 and Plešovice zircon were analysed throughout the session to quantify accuracy and precision, these gave ages of 599 +/- 18 Ma (2SD; accepted age 602 Ma; Jackson et al., 2004) and 338 +/- 10 Ma (2SD; accepted age 337 Ma; Sláma et al., 2008), respectively. The data tables are held as a supplementary file on the journal’s website (Thomas_et_al_SuppTable).

Representative CL images are shown in Fig. 7 and Concordia plots are given in Fig. 8. The ages quoted are weighted mean $^{206}Pb/^{238}U$ ages, given as age ± x/y, where x is the 2σ uncertainty without propagation of systematic uncertainties, and y is the 2σ uncertainty with propagation of systematic uncertainties; for comparison between these ages and those of other studies, the latter should be used.

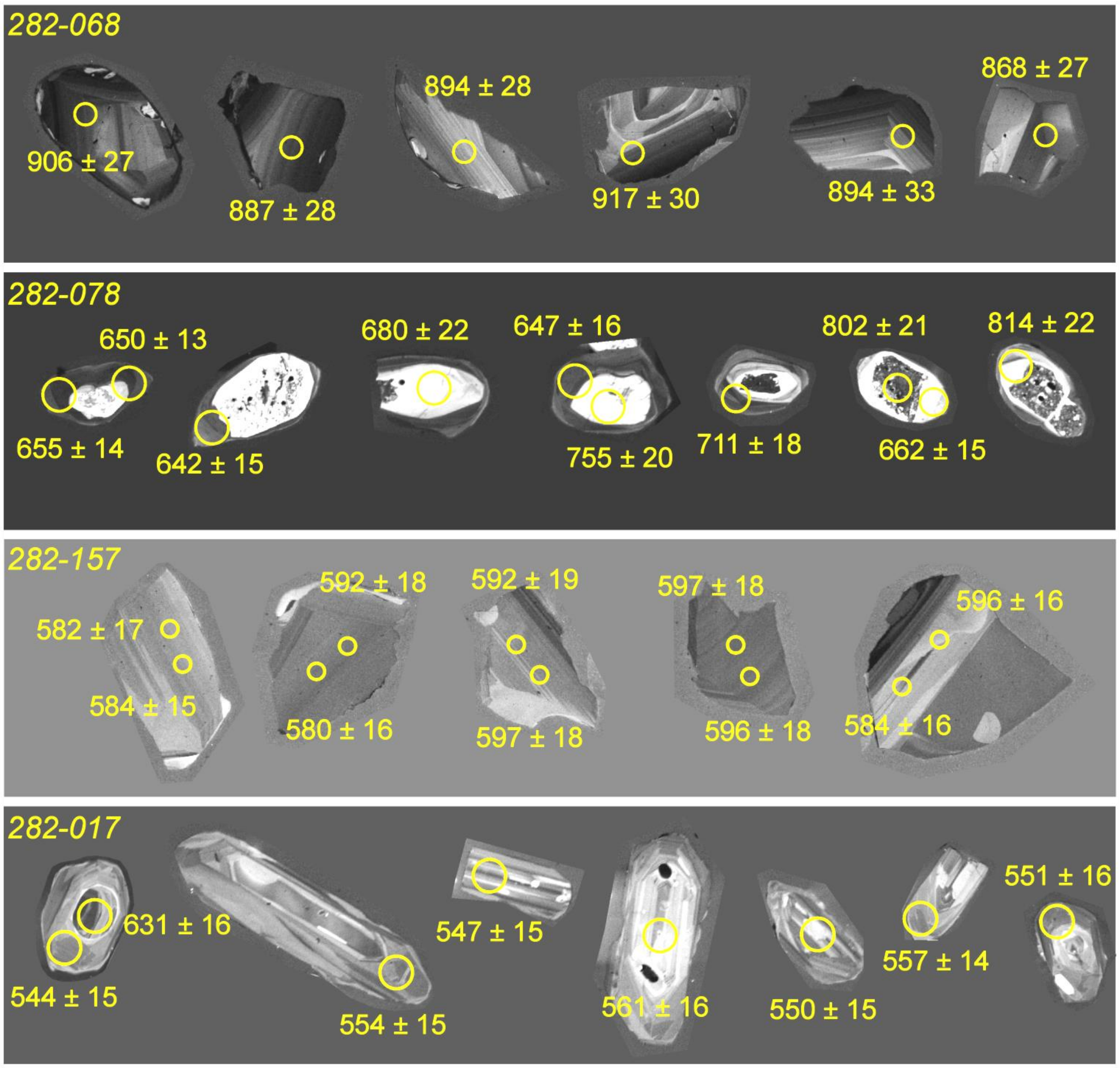


Fig. 7. Typical CL images of zircons from the granitoids, with analytical spots.

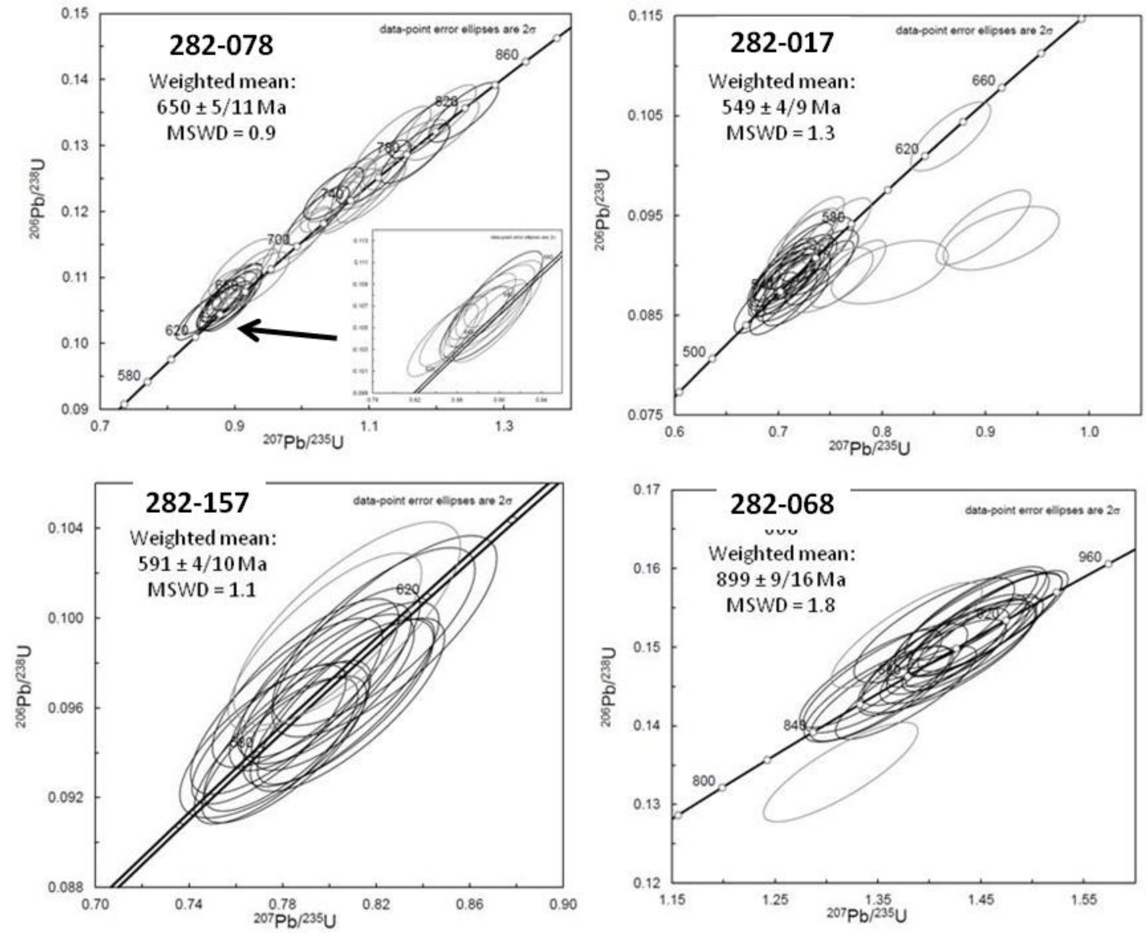


Fig. 8. U-Pb Concordia plots of the granitoids

5.1 Sample 282_068: Granitic orthogneiss (38° 47.44'E; 9°54.12'S)

A fresh granitic K-feldspar porphyritic orthogneiss sample was taken from locality BT_113, from part of the outcrop showing the least strain, contamination with xenoliths or leucocratic veins (e.g. Fig. 5a). The sample has slightly augen-shaped K-feldspar megacrysts up to 2 cm in size set in a coarse-grained groundmass of quartz, K-feldspar, plagioclase and biotite with accessory opaque minerals, zircon and apatite.

Sample 068 contains short prismatic (2:1 length/width) zircon grains up to 300 µm long. The zircons are colourless to pale pink, and transparent to slightly opaque. Inclusions are rarely visible. In CL, zircons have a coarse oscillatory zoning, some zircons are sector-zoned (Fig. 7a).

Twenty-two areas were analysed in 22 grains. Typical U ranges from 80-500 ppm (Th/U: 0.2-0.7). Two analyses are slightly discordant (05, 08), the remaining 20 analyses give a weighted mean $^{206}Pb/^{238}U$ date of **899 ± 9/16 Ma** (MSWD= 1.8). This date is interpreted as the crystallisation age of the granite (Fig. 8).

5.2 Sample 282_078: Granite Pluton: 38° 41.45'E; 9°50.99'S

The granite pluton was sampled from boulder outcrops at locality BT_078, and is made up of light grey, homogeneous, equigranular, coarse-grained leucocratic biotite granite, with a fairly strong, west-dipping foliation. It contains a number of stretched mafic xenoliths that were avoided in the sample. It is made up of quartz, 2 feldspars, biotite and accessory minerals including opaque mineral, apatite and zircon.

Sample 078 has small, short prismatic (2:1 to 3:1 length/width), transparent or colourless to very pale pink zircons, seldom exceeding more than 100 µm in length. Many zircons have rounded terminations. Metamict cores appear opaque and inclusions are visible in a few grains. In CL, a complex internal structure is apparent. Many cores are metamict and appear recrystallized. These cores have a light mantle of low-U zircon that again is overgrown by dark-CL zircon rims. This overgrowth itself is also zoned, however it is often too narrow to be analysed wholly. Therefore a number of analyses overlap different zircon domains. Thirty-five areas were analysed in 26 grains, including 6 core analyses, 10 analyses from the dark rims, and one analysis from the bright-CL mantle. The remaining analyses are from overlapping domains.

The complexity of the zircons is reflected in their U-Pb age data. A number of analyses are slightly reverse discordant, the remaining analyses straddle along Concordia between ca. 640 and 820 Ma. The complex cores have a significant age scatter from ca. 720-820 Ma, with an average $^{206}Pb/^{238}U$ age of ca. 770 Ma. Analyses of the dark rims have typical U-conc. of 300-500 ppm (Th/U: 0.1-0.3), whilst one bright intermittent mantle has low-U of ca. 70 ppm. The analysis from this one bright rim cannot be differentiated in age from the darker rims. Together the rims provide a weighted mean $^{206}Pb/^{238}U$ date of **650 ± 5/11 Ma** (MSWD= 0.94). Since the rim analyses also show slight igneous zoning, the date of ca. 650 Ma is interpreted as the crystallisation age of the granite, whilst the cores probably record inheritance.

5.3 Sample 282_157: Coarse-grained porphyritic granite: 38° 58.96'E; 9°36.11'S

The sample of this unit was taken quite close to the margin of the intrusion at BT_282. This very weakly foliated, coarse-grained porphyritic granite contains large pink K-feldspar phenocrysts up to 4 cm in size, irregularly scattered in an inequigranular quartz-2 feldspar matrix with clots of coarse biotite.

Sample 157 provided isometric broken zircon fragments up to 400 µm in size. Grains are transparent and colourless, and inclusions are not visible. In CL, zircons appear with broad irregular zoning or sector-zoning. Eighteen areas were analysed in 9 grains. The zircons have U ranging from ca. 100-300 ppm (Th/U: 0.4-1.1). Two analyses are discordant, the remaining 16 analyses provide a $^{206}Pb/^{238}U$ date of **591 ± 4/10 Ma** (MSWD= 1.1). This date is interpreted as the crystallisation age of the porphyritic granite.

5.4 Sample 282_017: Late granite dyke: 38° 56.24'E; 9°52.91'S

The geochronology sample was taken from bouldery outcrops near the core of the 100 m wide cross-cutting dyke in the SE part of the study area. The dyke here is composed of unfoliated pinkish-grey medium- to coarse-grained biotite granite, composed of quartz, K-feldspar, plagioclase, biotite and accessory minerals.

The sample contains abundant zircons which are transparent, colourless, elongate prismatic zircons (3:1 to 8.1 length/width ratio) with simple shapes, rarely exceeding 200 µm in length. Some zircons have inclusions and cores are not visible. CL reveals oscillatory and complex zoning, and some zircons appear in part recrystallised. A few zircons have apparent inherited cores.

Thirty areas were analysed from 25 grains, mostly from the oscillatory-zoned areas including one distinct core. Nine analyses are discordant and are not further considered. The remaining analyses have typical U from 80-500 ppm (Th/U: 0.1-1.4). Two analyses (07, 29) are slightly older than the main age group and probably represent inheritance; one of these was from a core that is distinct in CL. The remaining concordant analyses provide a weighted mean ^{206}Pb /^{238}U date of **549 ± 4/9 Ma** (MSWD= 1.3). This date is interpreted as the crystallisation age of the granite.

Discussion and conclusions

The oldest granitic orthogneiss dated in this study at **899 ± 9/16 Ma** shows that the Tonian basement protolith ages of southernmost Tanzania (Kröner et al., 2003) and the Marrupa Complex of NE Mozambique (Bingen et al., 2009), continue at least another 100 km northwards into Tanzania. Given this finding, crust of this age may extend as far north as the major Phanerozoic Selous Basin. The basin may obscure a major Precambrian basement discontinuity, separating the Tonian gneisses to the south from the Precambrian rocks which outcrop to the north which are characterized by Archaean protolith ages (the "Western Granulites"). While Nd studies in the area south of the study area by Kröner et al (2003) revealed evidence of an Archaean component to the protoliths of the Tonian gneisses, our study did not reveal the presence of any inherited older zircons.

Both the Tonian and Archaean protolith terranes were extensively re-worked by the Neoproterozoic East African Orogeny during which granulite grade nappes composed of juvenile Neoproterozoic rocks were emplaced at about 640 Ma. These nappes are known as the "Eastern Granulites" in Tanzania and the "Cabo Delgado Nappes" in NE Mozambique (e.g. Viola et al., 2008). A thrust-bound package of such granulites is shown on the geological compilation of Pinna et al. (2004) in the NW part of the study area, but our fieldwork showed that this is erroneous. Only small lenses of mafic garnet granulite were found within the layered gneisses of the area and their structural status is uncertain. The granulite lenses could be the dismembered remnants of a larger nappe structure, but their limited size suggests that they are more probably small transposed slices.

To the north of the Selous Basin, the peak of high-grade metamorphism, attributed to the main collision during Gondwana assembly, took place at ca. 640 Ma (Muhongo et al., 2001) or between 655 to 610 Ma (Möller et al, 2000). This event is manifested in the study area by a deformed, sub-circular granitic pluton dated at **650 ± 5/11 Ma**. The zircons in this granite contain inherited cores with an average age of about 770 Ma. This age is within the range of dates obtained by Kröner et al. (2003) and Sommer and Kröner (2013) from south and west of the study area, respectively. Here, the Tonian-Stenian crust was intruded by juvenile granitoid orthogneisses, mainly of tonalitic composition, dated at between ca. 790 and 700 Ma. These probably provide a link with a similar event in southern Malawi (Kröner et al., 2001) and the northern segment of the East African Orogen in Tanzania (e.g. Muhongo et al., 2001). Kröner et al. (2001) speculated that this event might be related to an early phase of Gondwana assembly along an Andean-type margin.

A large circular gabbro body south of the granite pluton may also be of this age, but was not dated during this study. In the south, in NE Mozambique, the latest orogenic events took place in the late Ediacaran at ca. 550 Ma and are sometimes attributed to the "Kuunga Orogeny" (e.g. Meert, 2003). While metamorphic dates of this age have been recorded from the Western Granulites (e.g. Cutten et al., 2006; Kabete et al, 2012), magmatic rocks of this event have not been recognized in Tanzania. The ca. 550 Ma metamorphic event is not ubiquitous throughout the "Western Granulite" terrane; Johnson et al. (2003) only recorded Archaean metamorphic rims to Archaean zircons in an area apparently well within the limits of the East African Orogen west of Dar-es-Salaam. Other workers have considered that the 550 Ma metamorphic ages in the Western granulites represent cooling ages (e.g. Maboko, 2001). The two youngest granitoids of the present study are therefore the first igneous rocks of this approximate age to be recognized in the region. A weakly deformed granitoid pluton was dated at **591 ± 4/10 Ma**, while a very late cross-cutting undeformed granite dyke gave an intrusive age of **549 ± 4/9 Ma**.

The ages obtained on the granitoids in this study contain elements that are characteristic of the Tanzania-Kenya segment of the East African Orogen and of the Mozambique segment. The Tonian orthogneiss sample is typical of (but somewhat younger than) the Marrupa Complex of NE Mozambique. No Archaean zircon inheritance was recorded in the sample, a feature also typical of the juvenile Marrupa Complex. The report of Archaean protoliths in the Tonian gneisses of the Masasi region south of our study area is, however, more typical of the northern part of the orogen. Similarly, the age of the ca. 650 Ma sub-circular granite pluton is typical of the northern segment of the orogen, and this is the first recorded granite of that age intruded into the Tonian-dominated crust of southern Tanzania or NE Mozambique. The younger granites at 600 to 550 Ma are typical of the southern segment of the orogen, and that of the Kuunga Orogen.

The study area thus appears to represent an area of transitional crust straddling two complex and contrasting segments of the East African Orogen, with elements of both segments present and evidence for a ca. 770 Ma event which appears to be quite widespread and may relate to the early phases of Gondwana amalgamation in southern East Africa.

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