Crustal assembly of the Antananarivo and Masora domains, central-eastern Madagascar: constraints from U-Pb zircon geochronology and whole-rock geochemistry of meta-granitoids

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In reconstructions of the Gondwana supercontinent, correlations of Archean domains between Madagascar and India remain debated. In this paper, we aim to establish correlations among these Archean domains using whole-rock geochemistry and U-Pb zircon geochronology of meta-granitoids from the Masora and the Antananarivo domains, central-eastern Madagascar. A meta-granitoid from the central part of Masora domain is dated at 3277 Ma and shows a typical Archean tonalite-trondhjemite-granodiorite composition, whereas a tonalitic gneiss from the southeastern part of the Antananarivo domain gives an age of 2744 Ma. The geochemical signature of this tonalitic gneiss differs from that of the ~2500 Ma granitoids of the northwestern part of Antananarivo domain. In addition, the geochemical composition of the ~760 Ma granitic gneisses is consistent with a volcanic-arc origin for the protolith. Based on the geochemical and geochronological results, along with existing data, we identified three episodes of granitic magmatism in central-eastern Madagascar at ~3300, 2700, and 2500 Ma. These three magmatic events are consistent with those reported for the Dharwar Craton in India, suggesting that the Archean Masora and Antananarivo domains in Madagascar were part of the Greater Dharwar Craton during the period of 3300–2500 Ma. The 700–800 Ma volcanic arc granites identified in eastern Madagascar have not been reported in India. Therefore, the subduction of the oceanic plate that led to the formation of these granites likely took place at the western margin of the Greater Dharwar Craton, which included part of eastern Madagascar.

Keywords: Madagascar, Archean, Meta-granitoids, Whole-rock geochemistry, U-Pb zircon geochronology

INTRODUCTION

Located in the central part of the Gondwana supercontinent, Madagascar is an important area for unraveling the history and tectonic processes involved in the formation of the Gondwana supercontinent during the late Neoproterozoic to Cambrian (Stern, 1994; Meert, 2003; Jacobs and Thomas, 2004; Collins and Pisarevsky, 2005; Boger, 2011). The present-day landmass of Madagascar contains four Archean domains and six Proterozoic domains. The former includes the Antananarivo, Tsaratanana, Antongil, and Masora domains, and the latter includes the Bemar-

ivo, Betsimisaraka (a possible suture zone), Ikalamavony, Vohibory, Androyan, and Anosyan domains (Fig. 1; Collins and Windley, 2002; Collins, 2006; Tucker et al., 2011a). Madagascar also hosts a number of crustal-scale shear zones, such as the Angavo, Ampanihy, Beraketa, Ifanadiana, Ihosy and Zazafotsy shear zones (Fig. 1; e.g., Windley et al., 1994; Martelat et al., 2000, 2013; Raharimahefa and Kusky, 2010; Raharimahefa et al., 2013), that provide tectonic constraints on the assembly of the Gondwana supercontinent.

The correlation of Archean domains between Madagascar and India has been extensively studied, especially in the past few years (e.g., Key et al., 2011; Tucker et al., 2011a, 2011b, 2014; Ishwar-Kumar et al., 2013; Rekha et al., 2013, 2014; Brandt et al., 2014; Collins et al., 2014;

Figure 1. Reconstruction of the Greater Dharwar Craton (modified after Tucker et al., 2011a; Peucat et al., 2013; Collins et al., 2014). Domain names: AD, Androyan domain; AG, Antongil domain; AN, Antananarivo domain; AS, Anosyan domain; BM, Bemarivo domain; BS, Betsimisaraka domain (suture zone); C, Coorg Block; CD, Central Dharwar Craton; ED, Eastern Dharwar Craton; IK, Ikalamavony domain; K, Karwar Block; M, Masora domain; MB, Madurai Block; NH, Nilgiri Hills; SEAN, Southeastern Antananarivo domain; TN, Tsaratana domain; WD, Western Dharwar Craton; V, Vohibory domain. Shear zone names: AKSZ, Achankovil shear zone; AGSZ, Angavo shear zone; AMSZ, Ampanihy shear zone; BESZ, Beraketa shear zone; BVSZ, Bhavani shear zone; CSZ, Cauvery shear zone; CHSZ, Chitradurga shear zone; CGSZ, Coorg shear zone; ESZ, Ejeda shear zone; IHSZ, Ihosy shear zone; KSZ, Kumta shear zone; KKSZ, Karur-Kambam shear zone; MSZ, Maroala shear zone; MKSZ, Mettur-Kolar shear zone; MYSZ, Moyar shear zone; NSZ, Nallamalai shear zone; PCSZ, Palghat-Cauvery shear zone; SASZ, Salem-Attur shear zone; SHSZ, SEAN domain; SMSZ, Southern Maharashtra shear zone; TSZ, Tranomaro shear zone; ZSZ, Zazafotsy shear zone; shear zones are after Ishwar-Kumar et al. (2013), Martelat et al. (2013) and Tucker et al. (2014).

Plavsa et al., 2014; Kröner et al., 2015; Boger et al., in press; Ratheesh-Kumar et al., in press). In central-eastern Madagascar, the Masora and Antongil domains are separated from the Antananarivo domain by the north-south trending Betsimisaraka suture zone, which lies almost parallel to the Angavo-Ifanadiana shear zones (Collins

et al., 2000; Kröner et al., 2000; Collins and Windley, 2002; Collins, 2006; Raharimahefa and Kusky, 2006, 2009, 2010). It is generally accepted that the Masora and Antongil domains belong to an isolated part of the Western Dharwar Craton of India (e.g., Raval and Veeraswamy, 2003, 2011; Collins, 2006; Schofield et al., 2010; Tucker et al., 2011a, 2014; Ishwar-Kumar et al., 2013; Rekha et al., 2013, 2014; Collins et al., 2014). However, the correlation of the Antananarivo domain with the surrounding Archean domains that are now located in India remains debated. First, Collins and Pisarevsky (2005), Collins (2006), Key et al. (2011), Collins et al. (2014), and Plavsa et al. (2014) suggested that the Antananarivo domain was part of Azania, a microcontinent that consisted of parts of East Africa (Yemen, Somalia, Ethiopia) and the Madurai Block in India (Fig. 1). They also suggested that the Azania microcontinent collided along the Betsimisaraka suture zone with the Masora and Antongil domains that were originally part of the Western Dharwar Craton. However, other researchers have demonstrated different models of the Antananarivo domain. A second model demonstrated by Tucker et al. (2011a, 2011b, 2014) suggested that the Antananarivo domain was originally part of the Eastern Dharwar Craton of India. A third model proposed by Ishwar-Kumar et al. (2013) and Rekha et al. (2014) suggested that the Antananarivo domain was contiguous with the Coorg Block. A fourth model by Brandt et al. (2014) suggested that the Antananarivo domain and the western part of the Madurai Block formed one contiguous unit. Contrasting models have been proposed for the correlation of the Antananarivo domain with the surrounding Archean domains in India in Gondwana reconstructions.

The magmatic ages of meta-granitoids in the Antananarivo domain have been determined by Kröner et al. (2000), Tucker et al. (1999, 2007), and Macey et al. (2009). These studies mainly analyzed meta-granitoids from the north-central and west-central parts of the domain (Fig. 2a), revealing ~ 2490–2550 Ma and ~ 730–820 Ma as pre-collisional magmatic periods in this domain. These meta-granitoids have calc-alkaline signatures that indicate formation in an arc environment (Kröner et al., 2000; Macey et al., 2009). However, comparatively little research has been undertaken on the southeastern part of the Antananarivo domain. The only age dating of Archean meta-granitoids from the Masora domain was performed by Tucker et al. (2011a), who dated a meta-granodiorite on the southern margin of this domain. Therefore, both the geological relationship between the southern and central parts of this domain and the geochemistry of these meta-granitoids remain unclear.

Here, we present new whole-rock geochemical re-

Figure 2. (a) Archean domains in Madagascar (modified after Tucker et al., 2011a) and U-Pb zircon ages from this and previous studies (Kröner et al., 1999, 2000; Tucker et al., 1999, 2007, 2011a; Paquette et al., 2003; Kabete et al., 2006; Smith et al., 2008a, 2008b, 2008c; Raharimahefa and Kusky, 2010; Schofield et al., 2010; Bauer et al., 2011). Abbreviations are same as in Figure 1. (b) Geological map of the central part of the Masora domain (modified after Randriamananjara, 2008). (c) Geological map of the southeastern part of the Antananarivo domain (modified after Boger et al., 2009).

sults along with zircon U-Pb ages for meta-granitoids from central Masora and southeastern Antananarivo domains. These data allow for the establishment of a robust correlation between Archean domains in Madagascar and other Archean domains that formed part of the Gondwana supercontinent and provide constraints on the processes involved in the formation of Gondwana.

GEOLOGICAL SETTINGS

Basement rocks

The Masora domain is dominated by meta-granitoids with lesser amounts of metasedimentary quartzites, pelitic schists, banded iron formation (BIF) units, and calc-silicate gneisses (Randriamananjara, 2008). Tucker et al. (2011a) used the Sensitive High-Resolution Ion Micro Probe (SHRIMP) to determine a U-Pb zircon age of 3313 ± 8 Ma for a meta-granodiorite in the southern margin of this domain (Fig. 2a), and detrital zircons from quartzites in this domain yielded U-Pb ages of ~ 1.8 – 3.1 Ga (De Waele et al., 2011). The rocks exposed in the Masora domain were metamorphosed under greens-

chist- and amphibolite-facies conditions (Key et al., 2011), for which zircon U-Pb SHRIMP ages of ~ 515 – 530 Ma were reported (Smith et al., 2008c).

The Antananarivo domain is dominated by meta-granitoids with lesser amounts of metasedimentary quartzites, pelitic gneisses, metamorphosed BIFs, and calc-silicate gneisses (Boger et al., 2009). The meta-granitoids from the central part of this domain yielded U-Pb SHRIMP zircon ages of ~ 2490 – 2590 Ma (e.g., Kröner et al., 2000; Fig. 2a). The rocks in this domain have undergone amphibolite to granulite facies metamorphism (e.g., Nédélec et al., 2000; Grégoire et al., 2009). The metamorphic zircon U-Pb SHRIMP and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) U-Pb ages of ~ 510 – 560 Ma were reported from meta-granites and metapelites in this domain (Kröner et al., 2000; Collins et al., 2003; Raharimahefa and Kusky, 2010; Tucker et al., 2011a).

Intrusive rocks

Both the Masora and Antananarivo domains contain felsic and mafic intrusive rocks that have been metamor-

Figure 3. (a)–(d) Field photographs of the meta-granitoids from central-eastern Madagascar. (a) Meta-granitoid from the Masora domain (sample MG08101232). (b) Tonalitic gneiss from the Antananarivo domain (sample MG07072010). (c) Granitic gneiss from the Antananarivo domain (sample MG07072201). (d) Granitic gneiss from the Antananarivo domain (sample MG07072502). (e)–(h) Photomicrographs of the meta-granitoids in the study area. (e) Meta-granitoid (sample MG08101232). (f) Tonalitic gneiss (sample MG07072010). (g) Granitic gneiss (sample MG07072201). (h) Granitic gneiss (sample MG07072502).

phosed to produce felsic gneisses and mafic gneisses, respectively (e.g., Handke et al., 1999; Randriamananjara, 2008; Boger et al., 2009). The felsic and mafic gneisses in the Antananarivo domain yielded U–Pb thermal ionization mass spectrometry (TIMS) zircon ages of ~780–800 Ma (Handke et al., 1999); those in the Masora domain yielded U–Pb SHRIMP zircon ages of ~780–850 Ma (Smith et al., 2008b, 2008c, Tucker et al., 2011a). These ages are interpreted to represent the timing of the magmatism that formed the igneous intrusions in these domains.

DESCRIPTION OF ANALYZED SAMPLES

In this section, we describe the field relations and petrography of the meta-granitoids. Representative field photographs and photomicrographs of the meta-granitoids are presented in Figure 3, and a normative An–Ab–Or ternary diagram of the meta-granitoids is described in Figure 4. The classification of the granitoids is based on Barker (1979). Mineral assemblages of the analyzed samples are described in Table 1 and all mineral abbreviations used in this paper are after Whitney and Evans (2010).

Figure 4. Normative An-Ab-Or ternary diagram (after Barker, 1979) showing variations in the compositions of meta-granitoids within the Masora and Antananarivo domains.

Basement rocks

In the central part of the Masora domain near the town of Ambodilafa, the main lithology is meta-granitoid with subordinate amounts of metasedimentary rock composed of quartzite and BIF (Fig. 2b). The meta-granitoid locally contains layers and lenses of amphibolite (Fig. 3a). The meta-granitoids of the Masora domain consist mainly of plagioclase, K-feldspar, quartz, and biotite (Fig. 3e and Table 1). Epidote, muscovite, apatite, zircon, and opaque minerals are accessory phases. Plagioclase is euhedral to anhedral. Biotite is normally the only mafic mineral. On the basis of the normative An-Ab-Or composition, these meta-granitoids plot in the field of trondhjemite (Fig. 4).

In the southeastern part of the Antananarivo domain near the Ifanadiana-Ambatofotsy area, the dominant lithology is metasedimentary rock with subordinate amounts of meta-granitoid (Fig. 2c). Archean metasedimentary rock is observed in the eastern part of the area, and Proterozoic metasedimentary rock is observed in the west (Boger et al., 2009). Tonalitic gneiss is locally observed and exposed near Ambatofotsy village (Fig. 2c), associated with metasedimentary rock composed of garnet-sillimanite gneiss, quartzite, and metamorphosed BIF (meta-BIF). The tonalitic gneiss generally has pervasive foliations (Fig. 3b) dominantly composed of hornblende, biotite, plagioclase, K-feldspar, and quartz (Fig. 3f). Zircon and opaque minerals are accessory phases. Garnet and muscovite rarely occur as an accessory phase (Table 1). Biotite is usually more abundant than hornblende, and both have a shape-preferred orientation. Based on the

normative An-Ab-Or composition, the tonalitic gneisses plot in the fields of tonalite and trondhjemite (Fig. 4).

Intrusive rocks

Previously published geological mapping identified the occurrence of Proterozoic alkaline granite and mafic-ultramafic rocks in the central part of the Masora domain (Fig. 2b; Randriamananjara, 2008) and alkaline granite, diorite, and syenite units in the southeastern part of the Antananarivo domain (Fig. 2c; Boger et al., 2009).

In the southeastern part of the Antananarivo domain near Ifanadiana village, these diorites, syenites, and granites are intruded into the Archean and Proterozoic metasedimentary rocks (Fig. 2c, Boger et al., 2009). Based on the age and geochemical results, the granitic gneisses analyzed in this study are ascribed to the intrusive rocks into the Proterozoic metasedimentary rocks. The granitic gneisses locally contain a leucocratic part (Fig. 3c) and layers of amphibolite (Fig. 3d). The granitic gneiss mainly consists of hornblende, biotite, plagioclase, K-feldspar and quartz (Fig. 3g). Zircon and opaque minerals are accessory phases. Hornblende and biotite are present in almost equal abundance, and both have a shape-preferred orientation that helps to define the gneissosity. Garnet rarely occurs as an accessory phase (sample MG07072502; Fig. 3h).

GEOCHEMISTRY AND U-Pb ZIRCON GEOCHRONOLOGY

The major and trace element compositions of samples were determined by X-ray fluorescence spectrometry (XRF) on glass beads (with a 10:1 dilution factor) and pressed powder pellets, respectively. In this analysis, a Rigaku Simultix 12 instrument was used for major element analysis, and a Rigaku RIX 3000 instrument was used for trace elements, both of which are housed at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). These analyses followed the methods outlined in Tani et al. (2005). Additional trace elements were analyzed by using alkali fusion and acid digestion methods (Senda et al., 2014) by inductively coupled plasma-mass spectrometry (ICP-MS) with an Agilent 7500ce instrument at JAMSTEC, following the techniques outlined in Chang et al. (2003). Total Fe concentrations are reported as $\text{Fe}_2\text{O}_3^{\text{T}}$ (as indicated by the superscript T), and Mg numbers (Mg#) are calculated as the molar ratio of $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$. The alumina saturation index (A/CNK) is calculated as the molar ratio of $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$, and A/NK is calculated as the molar ratio of $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$. Rare earth element (REE) variation

Table 1. Summary of analyzed samples, mineral assemblage and age data of the meta-granitoids within central-eastern Madagascar

Sample No.	Rock Name	Geographical coordinates		Analyses undertaken during this study			
				Major element	Trace element	Rare-earth element	U-Pb zircon age
Masora domain							
MG08101225GS	Meta-granitoid	20°30'41.0"S	48°7'40.4"E	○	○ (XRF)		
MG08101232	Meta-granitoid	20°30'41.0"S	48°7'35.8"E	○	○ (ICP-MS)	○	○
MG08101301	Meta-granitoid	20°30'52.6"S	48°4'42.2"E	○	○ (XRF)		
MG08101310	Meta-granitoid	20°30'24.5"S	48°5'44.5"E	○	○ (XRF)		
MG08101312	Meta-granitoid	20°30'33.8"S	48°5'52.4"E	○	○ (XRF)		
MG08101316	Meta-granitoid	20°31'1.9"S	48°6'47.9"E	○	○ (XRF)		
Antananarivo domain							
MG07072001	Tonalitic gneiss	21°46'40.0"S	47°32'38.8"E	○	○ (XRF)		
MG07072005A	Tonalitic gneiss	21°46'33.8"S	47°32'36.1"E	○	○ (XRF & ICP-MS)	○	
MG07072008	Tonalitic gneiss	21°46'46.9"S	47°33'14.9"E	○	○ (XRF)		
MG07072009	Tonalitic gneiss	21°46'46.9"S	47°33'14.9"E	○	○ (XRF)		
MG07072010	Tonalitic gneiss	21°46'37.5"S	47°32'25.4"E	○	○ (XRF & ICP-MS)	○	○
MG07072012	Tonalitic gneiss	21°46'35.5"S	47°32'15.2"E	○	○ (XRF)		
Intrusive Rocks							
MG07072201	Granitic gneiss	21°16'45.8"S	47°31'46.5"E	○	○ (XRF & ICP-MS)	○	○
MG07072502	Granitic gneiss	21°15'1.7"S	47°26'27.1"E	○	○ (XRF & ICP-MS)	○	○

Sample No.	Mineral assemblage										Age (Ma)
	Qz	Pl	Kfs	Bt	Ms	Grt	Hbl	Ep	Opq	Others	
Masora domain											
MG08101225GS	++	++	+	+							
MG08101232	++	++	+	+				-		Ap, Zrn	3277 ± 49
MG08101301	++	++	+	+				-		Zrn	
MG08101310	++	++	+	+							
MG08101312	++	++	+	+				-			
MG08101316	++	++	+	+	-						
Antananarivo domain											
MG07072001	++	++	+	+	-	-	+		-	Zrn	
MG07072005A	++	++	+	+			+		-	Zrn	
MG07072008	++	++	+	+			+				
MG07072009	++	++	+	+			+		-	Zrn	
MG07072010	++	++	+	+			+			Zrn	2744 ± 69
MG07072012	++	++	+	+			+		-	Zrn	
Intrusive Rocks											
MG07072201	++	++	++	+			+		-	Zrn	763.5 ± 8.3
MG07072502	++	++	++	+		-	+		-	Zrn	758.2 ± 5.7

Geographical coordinates are based on the WGS84 datum. ++, abundant; +, present; -, minor. Mineral abbreviations are after Whitney and Evans (2010).

diagrams are all normalized to chondrite by using the chondrite composition of Boynton (1984), and europium anomaly values (Eu/Eu^*) are calculated with respect to the neighboring REE (Sm and Gd) following the method of Taylor and McLennan (1985).

U-Pb age dating of zircons was undertaken by using an Agilent 7500cx quadrupole ICP-MS coupled with a New Wave Research UP-213 laser ablation system (LA) installed at Kyushu University, Japan. This analysis used spot sizes of 30–55 μm . Details of the analytical procedures and data reduction methods are given in Adachi et

al. (2012).

Detailed geochemistry was carried out on fourteen samples out of which four samples were selected for U-Pb age dating (Table 1). These samples are representative of the igneous activities in each domain and include a meta-granitoid from the central part of the Masora domain (sample MG08101232) and a tonalitic gneiss (sample MG07072010) and two granitic gneisses (samples MG07072202 and MG07072502) from the southeastern part of the Antananarivo domain. The geochemical data obtained during this study are provided in Tables 2 and 3.

Table 2. Major element concentrations within meta-granitoids of central-eastern Madagascar

Domain Name	Masora domain						Antananarivo domain							
Rock Name	Meta-granitoid						Tonalitic gneiss						Granitic gneiss	
Sample No.	MG0810 1225GS	MG081 01232	MG081 01301	MG081 01310	MG0810 1312	MG081 01316	MG0707 2001	MG070 72005A	MG0707 2008	MG070 72009	MG070 72010	MG070 72012	MG0707 2201	MG070 72502
(wt%)														
SiO ₂	67.81	67.73	70.98	72.32	69.82	67.80	66.31	71.06	73.16	71.94	71.00	70.29	72.82	66.98
TiO ₂	0.32	0.17	0.40	0.22	0.23	0.27	0.92	0.23	0.20	0.18	0.20	0.22	0.39	0.86
Al ₂ O ₃	18.08	18.69	15.86	15.70	17.60	18.44	16.00	16.20	15.89	16.31	16.33	16.87	14.05	14.37
Fe ₂ O ₃ ^T	2.35	1.28	2.91	1.77	1.79	2.08	6.01	2.05	1.41	1.44	1.86	2.10	2.52	6.15
MnO	0.03	0.01	0.03	0.02	0.02	0.03	0.09	0.02	0.01	0.01	0.02	0.01	0.04	0.10
MgO	0.62	0.34	0.78	0.49	0.36	0.47	1.07	0.72	0.50	0.55	0.58	0.64	0.25	0.49
CaO	2.24	2.64	1.90	2.62	2.16	1.94	4.55	3.29	3.54	3.82	0.34	3.03	1.51	2.66
Na ₂ O	5.96	6.12	5.35	5.10	5.71	5.98	3.54	4.67	4.41	4.53	4.61	4.80	3.30	2.71
K ₂ O	2.65	2.86	1.64	1.27	2.73	2.51	1.30	1.65	1.04	1.07	1.71	1.51	5.30 ^a	5.16 ^a
P ₂ O ₅	0.11	0.09	0.08	0.03	0.07	0.05	0.31	0.08	0.06	0.06	0.08	0.06	0.11	0.30
Total	100.15	99.93	99.94	99.54	100.48	99.55	100.11	99.97	100.21	99.91	99.80	99.53	100.28	99.78
A/NK	1.43	1.42	1.50	1.61	1.43	1.47	2.21	1.71	1.90	1.90	1.73	1.77	1.26	1.43
A/CNK	1.08	1.04	1.13	1.08	1.08	1.15	1.03	1.05	1.07	1.05	1.05	1.12	1.01	0.97
K ₂ O/ Na ₂ O	0.44	0.47	0.31	0.25	0.48	0.42	0.37	0.35	0.24	0.24	0.37	0.31	1.61	1.90
Mg# ^b	0.34	0.35	0.35	0.35	0.28	0.31	0.26	0.41	0.42	0.43	0.38	0.37	0.16	0.14

All Fe is expressed as Fe₂O₃^T. ^a Values above the detection limit. ^b Mg# = molar ratio of Mg/(Mg + Fe²⁺).

The results of geochemical standard analyses are given in Tables S1 and S2. LA-ICP-MS U-Pb ages are presented in the concordia diagrams in Figure 8 and data are presented in Table S3. The result of geochronological standard FC-1 sample is given in Table S4 (Tables S1-S4 are available online from <http://doi.org/10.2465/jmps.141225>).

Masora domain

The meta-granitoids within the Masora domain contain moderate amounts of SiO₂ (67.7–72.3 wt%), Al₂O₃ (15.7–18.7 wt%), MgO (0.3–0.8 wt%), CaO (1.9–2.6 wt%), Na₂O (5.1–6.1 wt%), and K₂O (1.3–2.9 wt%) and have moderate K₂O/Na₂O ratios (0.25–0.48; Table 2). They have low Mg# values (0.28–0.35) and are peraluminous (A/CNK = 1.04–1.15). These samples are classified as calcic to alkali-calcic in a modified alkali index (MALI) diagram (Fig. 5a; Frost et al., 2001) and are magnesian (Fig. 5b). They contain low concentrations of Yb but have high La/Yb ratios and tonalite-trondhjemite-granodiorite (TTG) compositions (Fig. 5c). They contain low concentrations of Y and Nb and plot in the volcanic arc and syn-collisional granite fields on the Nb–Y tectonic discrimination diagram of Pearce et al. (1984; Fig. 5d). The meta-granitoid sample (MG08101232) has a strong-

ly fractionated chondrite-normalized REE pattern [(La/Yb)_{CN} = 127] and has generally low concentrations of heavy REE (HREE; Yb = 0.4 ppm; Fig. 6a). This sample has insignificant Eu anomalies (Eu/Eu* = 0.81).

Zircon grains within the sample of MG08101232 are subrounded and are 100–200 µm long (Fig. 7a). Cathodoluminescence (CL) imaging identified two types of zircon grains: those with oscillatory zoning, bright cores, and dark rims (Fig. 7a; grains 19 and 53) and those characterized by oscillatory zoning and dark cores without apparent rims (Fig. 7a; grains 5 and 54). The bright cores of these zircon grains yield high Th/U ratios (0.42–0.95), whereas the dark cores are highly discordant and yield low ratios (0.02 and 0.06). U-Pb analyses define a discordia line with an upper-intercept age of 3277 ± 49 Ma (Fig. 8a).

Antananarivo domain

The tonalitic gneisses within the Antananarivo domain contain 66.3–73.2 wt% SiO₂, 15.9–16.9 wt% Al₂O₃, 0.5–1.1 wt% MgO, 0.3–4.6 wt% CaO, 3.5–4.8 wt% Na₂O, and 1.0–1.7 wt% K₂O, and have K₂O/Na₂O ratios of 0.24–0.37 (Table 2). They also have low Mg# values (0.26–0.43) and are peraluminous (A/CNK = 1.03–1.12). These samples are classified as calcic in the MALI dia-

Table 3. Trace element and rare earth element (REE) concentrations within meta-granitoids of central-eastern Madagascar

Domain Name	Masora domain						Antananarivo domain							
Rock Name	Meta-granitoid						Tonalitic gneiss						Granitic gneiss	
Sample No.	MG0810	MG081	MG081	MG081	MG0810	MG081	MG0707	MG070	MG070	MG070	MG070	MG070	MG0707	MG0707
	1225GS	01232	01301	01310	1312	01316	2001	72005A	72008	72009	72010	72012	2201	2502
XRF-analyzed trace element (ppm)														
Ba	410.9		288.8	170.9	309.4	271.3	365.0	338.8	228.6	274.5	607.3	343.5	1525.7	1922.5
Ni	5.3		10.7	<LLD	<LLD	<LLD	<LLD	9.5	6.6	<LLD	6.8	7.2	5.3	6.2
Cu	3.0		2.4	1.7	1.8	5.2	<LLD	12.3	1.6	5.0	11.1	1.6	6.6	10.8
Zn	60.9		70.2	38.6	54.9	66.6	82.3	35.5	17.5	17.5	28.4	29.7	50.0	91.7
Pb	16.9		14.6	12.0	20.3 ^a	20.1 ^a	9.0	14.9	12.2	9.5	11.2	15.7	37.2	29.1
Th	23.3		17.0	1.8	7.5	10.7	7.4	<LLD	2.4	3.0	0.5	<LLD	13.5	7.4
Rb	81.8		72.3	45.3	66.1	72.0	47.6	49.3	34.4	32.2	42.7	43.2	131.5	168.1
Sr	564.4		615.4	600.1	505.4	589.6	294.4	437.7	372.3	378.0	467.3	539.8	219.7	326.0
Y	5.6		8.8	<LLD	<LLD	<LLD	26.4	<LLD	<LLD	<LLD	<LLD	<LLD	19.7	39.6
Zr	188.9		202.2	48.6	141.4	109.3	184.6	78.4	68.4	69.0	88.4	71.6	327.1	369.0
Nb	5.0		4.6	3.9	3.5	4.7	7.4	2.5	2.1	2.0	2.0	2.1	8.3	16.7
ICP-MS-analyzed trace element (ppm)														
Sc		1.47						1.89			1.32		3.78	10.1
Co		6.18						6.28			4.27		2.55	7.08
Ni		8.56						8.52			4.40		0.828	1.15
Cu		64.9						12.8			9.67		6.32	11.4
Rb		34.7						46.0			39.1		125	166
Sr		563						407			428		207	314
Y		4.59						2.19			2.96		18.4	38.0
Zr		157						96.2			95.6		336	370
Nb		3.38						2.47			2.13		9.36	16.80
Cs		0.378						0.158			0.17		0.356	1.96
Ba		178						395			669		1,624	2,061
La		68.1						9.04			10.6		52.7	48.9
Ce		130						12.1			16.4		99.8	97.0
Pr		12.4						1.42			1.63		10.8	12.5
Nd		40.1						4.91			5.57		37.9	49.7
Sm		5.07						0.831			0.868		6.13	9.84
Eu		1.000						0.615			0.689		1.89	3.03
Gd		2.81						0.690			0.729		4.76	8.95
Tb		0.354						0.095			0.112		0.721	1.42
Dy		1.30						0.445			0.580		3.84	8.04
Ho		0.213						0.083			0.115		0.738	1.59
Er		0.540						0.206			0.331		2.13	4.60
Tm		0.060						0.026			0.048		0.295	0.647
Yb		0.362						0.134			0.307		1.89	4.18
Lu		0.058						0.022			0.049		0.283	0.623
Hf		4.45						2.42			2.64		8.38	9.96
Ta		0.086						0.082			0.113		0.479	0.996
Tl		0.270						0.214			0.187		0.533	0.675
Pb		13.8						12.1			10.6		33.8	26.1
Th		12.8						0.258			0.207		11.7	8.13
U		0.537						0.044			0.150		0.550	1.15
(La/Yb) _{CN}		127						45			23		19	7.9
Eu/Eu*		0.81						2.48			2.65		1.07	0.99

^a Values above the detection limit. <LLD denotes values below the lower limit of detection. (La/Yb)_{CN}, chondrite-normalized La/Yb. Eu/Eu* = Eu_{CN}/√(Sm_{CN} × Gd_{CN}), the CN subscript indicates values normalized to chondrite (Boynton, 1984).

gram (Fig. 5a) and are generally magnesian (Fig. 5b). They contain low concentrations of Yb but have high La/Yb ratios and plot within the Archean TTG field in

Fig. 5c. These tonalitic gneisses also contain low concentrations of Y and Nb and plot within the volcanic arc and syn-collisional granite field on the tectonic discrimina-

Figure 5. (a) and (b) Variations in the $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ (modified alkali-lime index; MALI) and $\text{FeO}^T/(\text{FeO}^T + \text{MgO}) - \text{SiO}_2$ compositions of samples from the study area, showing leucogranite, A-type granite (ferroan), and Cordilleran-type granite compositional fields; ranges of alkalic, alkali-calcic, calc-alkalic, and calcic rock series compositions in (a) and the boundary between ferroan and magnesian plutons in (b) are from Frost et al. (2001). (c) Variations in La/Yb for samples from the study area. The gray field is the Archean tonalite-trondhjemite-granodiorite (TTG) field; the other field is the island arc magmatic rock field (field determinations after Martin, 1994). (d) Variations in compositions of samples from the study area plotted on the granitoid discrimination diagram of Pearce et al. (1984). COLG, collision zone granite; ORG, ocean ridge granite; VAG, volcanic arc granite; WPG, within-plate granite. MH73 shows the composition of the tonalitic gneiss sample from the Antongil domain (Schofield et al., 2010).

tion diagram (Fig. 5d). Sample MG07072010 has a fractionated chondrite-normalized REE pattern $[(\text{La/Yb})_{\text{CN}} = 23]$, contains low concentrations of HREE ($\text{Yb} = 0.3$ ppm), and has a positive Eu anomaly ($\text{Eu}/\text{Eu}^* = 2.65$; Fig. 6c).

The granitic gneisses in the study area contain 67.0–72.8 wt% SiO_2 , 14.1–14.4 wt% Al_2O_3 , 0.25–0.49 wt% MgO , 1.5–2.7 wt% CaO , 2.7–3.3 wt% Na_2O , and 5.2–5.3 wt% K_2O and have $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios between 1.61 and 1.90 (Table 2). They have low $\text{Mg\#}$ values (0.16–0.14) and are metaluminous to slightly peraluminous ($\text{A}/\text{CNK} = 0.97$ –1.01). These gneisses are classified as alkali-calcic in the MALI diagram (Fig. 5a) and are ferroan (Fig. 5b). They contain low concentrations of Yb, have low La/Yb ratios, and most likely formed in an island arc setting (Fig. 5c). Samples MG07072201 and MG07072502 have chondrite-normalized REE patterns that are less fractionated $[(\text{La/Yb})_{\text{CN}} = 8$ –19] than the other samples analyzed during this study. They contain high concentrations of HREE ($\text{Yb} = 1.9$ –4.2 ppm; Fig. 6e) and do not have significant Eu anomalies ($\text{Eu}/\text{Eu}^* = 1.0$ –1.1).

The tonalitic gneiss sample (MG07072010) contains zircon grains that are long and prismatic and euhedral to

subhedral. They exhibit oscillatory zoning, have long axes that vary in length between 100 μm and 450 μm (Fig. 7b), and have Th/U ratios of 0.11–0.98. These zircon grains are well aligned in the concordia diagram defining an upper-intercept age of 2744 ± 69 Ma [Fig. 8b; mean square weighted deviation (MSWD) = 5.8].

The granitic gneiss sample analyzed during this study (MG07072201) contains long and prismatic zircon grains that exhibit both oscillatory and sector zoning and are 130–360 μm long (Fig. 7c). Nine analyses of these zircon grains with Th/U ratios of 0.52–1.40 yield a concordia age of 763.5 ± 8.3 Ma (MSWD = 2.4, probability of concordance = 0.12; Fig. 8c). The other granitic gneiss sample (MG07072502) contains ovoid zircon grains that exhibit oscillatory zoning and are 130–320 μm long (Fig. 7d). Nine analyses of these zircon grains with Th/U ratios of 0.76–1.37 yield a concordia age of 758.2 ± 5.7 Ma (MSWD = 1.9, probability of concordance = 0.17; Fig. 8d).

INTERPRETATION OF U-Pb ZIRCON AGES

The majority of the zircon grains analyzed during this

Figure 6. Chondrite-normalized rare earth element (REE) variation diagrams for (a)–(b) meta-granitoids from the Masora domain, (c)–(d) tonalitic gneisses from the Antananarivo domain, and (e) intrusive granitic gneisses from the Antananarivo domain.

study (barring those from sample MG08101232) are long and prismatic, euhedral to subhedral, and they exhibit oscillatory and sector zoning under CL images. These zircon grains have Th/U ratios between 0.1 and 1.4 (samples MG07072210, MG07072201 and MG07072502) during this study, which are typical Th/U ratios of the magmatic zircon grains (e.g., Hoskin and Schaltegger, 2003). This indicates that the ages obtained from the zircon grains analyzed during this study are indicative of the timing of granitoid crystallization. The rounded zircon

grains within the meta-granitoid from the Masora domain (sample MG08101232) likely have either a metamorphic or sedimentary origin. The fact that these zircon grains have high Th/U ratios, are sometimes zoned (e.g., grain 54), and yield two concordant ~ 3300 Ma ages suggest that originally igneous zircon grains have undergone local isotopic resetting, again suggesting that this ~ 3300 Ma age is indicative of the timing of granitoid crystallization.

The ~ 3300 Ma TTG magmatism recorded within

Figure 7. Representative cathodoluminescence (CL) images of zircons analyzed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) during this study. Each analysis spot is labeled with the Th/U ratio and the $^{206}\text{Pb}/^{238}\text{U}$ age (including 2σ error). Scale bars are 50 μm for sample MG08101232 and 100 μm for samples MG07072010, MG07072201, and MG07072502.

the central part of the Masora domain has also been identified along the southern margin of the Masora domain (Tucker et al., 2011a), within the Antongil domain (Schofield et al., 2010), and in the Western Dharwar Craton of India (Taylor et al., 1984). The TTG unit in the central part of the Masora domain has a strongly fractionated REE pattern that is similar to the REE patterns of TTG units within the Antongil domain (Fig. 6a; Schofield et al., 2010) and within the Western Dharwar Craton in India (Fig. 6b; Charan et al., 2009; Naqvi et al., 2009). This suggests that a contemporaneous ~ 3300 Ma TTG magmatic event occurred in the Masora and Antongil domains and in the Western Dharwar Craton. The new geo-

chemical and geochronological data, combined with previously published geophysical, geological, and geochronological data, suggest that the Masora and Antongil domains originally belonged to an isolated part of the Western Dharwar Craton of India (e.g., Raval and Veeraswamy, 2003; Tucker et al., 2011a; Ishwar-Kumar et al., 2013; Rekha et al., 2013, 2014).

Figure 2a summarizes the geochronological data for Archean domains in Madagascar. These data indicate that ~ 2700 Ma magmatism has been identified only in the southeastern part of the Antananarivo domain and in the Tsaratanana domain (Fig. 2a; Kabete et al., 2006). Recently, a number of ~ 2700 Ma magmatic ages from the meta-granitoids largely located in the eastern part of the Antananarivo domain have been reported by Tucker et al. (2014). This suggests that the ~ 2700 Ma magmatism was local rather than regional in this domain. The units that formed during this ~ 2700 Ma granitoid magmatism are classified as calcic in the MALI diagram (Fig. 5a) and have high La/Yb ratios (Fig. 5c), whereas the ~ 2500 Ma granitoids are calcic to alkali-calcic (Fig. 5a) and have low La/Yb ratios (Fig. 5c). Although one of these two sets of granitoids has similar REE patterns (Fig. 6c), the ~ 2700 Ma granitoid is geochemically distinct from the ~ 2500 Ma granitoid in the Antananarivo domain. Granitoids older than ~ 2500 Ma have also been reported in the Coorg and Madurai Blocks and within the Central Dharwar Craton of India. The Coorg Block and the Madurai Block are dominated by ~ 2900 – 3100 and 2500 – 2600 Ma charnockites, respectively (Plavsa et al., 2012; Peucat et al., 2013; Santosh et al., 2013). In addition, the igneous ages of the main protolith lithologies differ between the Coorg Block (Peucat et al., 2013; Santosh et al., 2013) and the Antananarivo domain. The ~ 2600 Ma felsic granulites in the Central Dharwar Craton have chondrite-normalized REE patterns similar to those of the tonalitic gneisses in the southeastern part of the Antananarivo domain, and both units are characterized by positive Eu anomalies and relatively fractionated REE patterns (Fig. 6d; Peucat et al., 2013). The ~ 2690 Ma granodioritic gneisses of the northwestern part of the Madurai Block (Plavsa et al., 2012) also have chondrite-normalized REE patterns similar to the tonalitic gneisses within the southeastern Antananarivo domain (Fig. 6d). This suggests that contemporaneous ~ 2600 – 2700 Ma granitoid magmatism occurred in the southeastern Antananarivo domain, the Central Dharwar Craton, and the northwestern part of the Madurai Block.

These data suggest that three separate granitoid magmatic events occurred at ~ 3300 , 2700 , and 2500 Ma in central-eastern Madagascar, indicating an affinity to the three crustal provinces of the Dharwar Craton (Fig.

Figure 8. $^{207}\text{Pb}/^{206}\text{Pb}$ - $^{238}\text{U}/^{206}\text{Pb}$ concordia plots for zircon grains from meta-granitoids in central-eastern Madagascar. Error ellipses represent 2σ uncertainties; ellipses used in the regression analysis are shaded light gray. Calculated average concordant ages are shown using 2σ confidence values (dark gray ellipses).

1) in terms of both geological characteristics and igneous ages (Jayananda et al., 2013; Peucat et al., 2013). In addition, the whole-rock geochemical and geochronological data presented here suggest that the Masora and Antananarivo domains are equivalent to the isolated western part of the Dharwar Craton, thereby supporting the Greater Dharwar Craton hypothesis of Tucker et al. (2011a, 2011b, 2014). This model suggests that the Angavo-Ifanadiana shear zone represents a reactivated shear zone located between different Archean domains in central-eastern Madagascar.

Alternatively, the Masora domain may be the equivalent of the western part of the Dharwar Craton, with the Antananarivo domain being equivalent to the Madurai Block. Collins (2006), Santosh et al. (2009), Collins et al. (2014), and Plavsa et al. (2014) suggested that the Antananarivo domain represents an extension of the Madurai Block and that both of these terranes collided with the Dharwar Craton during the Neoproterozoic. However, recently obtained geochronological and geochemical data for meta-granitoids from the Madurai Block led Brandt et al. (2014) to suggest that the accretion of the Madurai Block to the Dharwar Craton along the Moyar-Bhavani-Cauvery suture (MBCS) occurred during the earliest Paleoproterozoic and that the Betsimisaraka suture formed an extension of the MBCS. Other research has suggested that the Betsimisaraka suture formed in either

the Neoproterozoic (e.g., Collins, 2006) or the Paleoproterozoic (Ishwar-Kumar et al., 2013), indicating that further work is needed to clarify this model. If the Betsimisaraka suture formed in the Neoproterozoic, the Azania model also needs to be considered, although we suggest here that the earlier-presented Greater Dharwar Craton model is likely the most suitable of all of these models.

Widespread ~ 760 Ma igneous activity has been identified in central Madagascar and is thought to have formed as a result of subduction zone magmatism in a continental arc setting (e.g., Kröner et al., 2000). This interpretation is supported by the U-Pb geochronological and whole-rock geochemical data presented here. However, this contrasts with the model of Tucker et al. (2011a), who suggested that this magmatism was the result of either crustal dilation and decompression-related upwelling of the mantle, delamination of a region of the lithospheric mantle, or magmatic underplating during mantle plume activity. However, this ~ 700 – 800 Ma igneous activity has not been identified in the Dharwar Craton. Instead, it has been reported in the Sør Rondane Mountains of East Antarctica, where it was interpreted to be the result of oceanic plate subduction prior to the formation of the Gondwana supercontinent (Nakano et al., 2013). A continental arc magmatism model is supported by petrographic and geochronological data obtained from metasedimentary rocks in contact with these

igneous intrusions (Moine et al., 2014), strongly suggesting that this ~ 700–800 Ma magmatic event is related to oceanic plate subduction. The absence of ~ 700–800 Ma magmatism in the Indian Dharwar Craton suggests that the subduction proceeded from west to east along the western margin of the Greater Dharwar Craton (i.e., along the side of the Greater Dharwar Craton within Madagascar) prior to the formation of Gondwana. This indicates that the central-eastern part of Madagascar, which originally formed part of the western margin of the Greater Dharwar Craton, most likely underwent this continental arc magmatism.

ACKNOWLEDGMENTS

We would like to express our gratitude to Y. Osanai, N. Nakano and T. Adachi for U–Pb age dating of zircons at Kyushu University, and we also grateful to them for suggestions to prepare our manuscript. We would also like to thank three anonymous reviewers for constructive comments to improve our manuscript. We express our gratitude to M. Satish-Kumar and T. Hirajima for their editorial support. We thank M. Arima and N. O. T. Rakotonandrasana for fieldwork support in Madagascar, and K. Tani and T. Hokada for analytical support. This work was partly supported by a Grant-in-Aid for Scientific Research No. 19403013.

SUPPLEMENTARY MATERIALS

Supplementary materials (Tables S1–S4) are available online from <http://doi.org/10.2465/jmps.141225>.

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Manuscript received December 25, 2014

Manuscript accepted February 24, 2015

Published online April 14, 2015

Manuscript handled by M. Satish-Kumar