Neoproterozoic extension in the Greater Dharwar Craton: a reevaluation of the "Betsimisaraka suture" in Madagascar[1]

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Abstract: The Precambrian shield of Madagascar is reevaluated with recently compiled geological data and new U–Pb sensitive high-resolution ion microprobe (SHRIMP) geochronology. Two Archean domains are recognized: the eastern Antongil–Masora domain and the central Antananarivo domain, the latter with distinctive belts of metamafic gneiss and schist (Tsaratanana Complex). In the eastern domain, the period of early crust formation is extended to the Paleo–Mesoarchean (3.32–3.15 Ga) and a supracrustal sequence (Fenerivo Group), deposited at 3.18 Ga and metamorphosed at 2.55 Ga, is identified. In the central domain, a Neoarchean period of high-grade metamorphism and anatexis that affected both felsic (Betsiboka Suite) and mafic gneisses (Tsaratanana Complex) is documented. We propose, therefore, that the Antananarivo domain was amalgamated within the Greater Dharwar Craton (India + Madagascar) by a Neoarchean accretion event (2.55–2.48 Ga), involving emplacement of juvenile igneous rocks, high-grade metamorphism, and the juxtaposition of disparate belts of mafic gneiss and schist (metagreenstones). The concept of the "Betsimisaraka suture" is dispelled and the zone is redefined as a domain of Neoproterozoic metasedimentary (Manampotsy Group) and metaigneous rocks (Itsindro–Imorona Suite) formed during a period of continental extension and intrusive igneous activity between 840 and 760 Ma. Younger orogenic convergence (560–520 Ma) resulted in east-directed overthrusting throughout south Madagascar and steepening with local inversion of the domain in central Madagascar. Along part of its length, the Manampotsy Group covers the boundary between the eastern and central Archean domains and is overprinted by the Angavo–Ifanadiana high-strain zone that served as a zone of crustal weakness throughout Cretaceous to Recent times.

Résumé : Le bouclier précambrien du Madagascar est réévalué en se basant sur de récentes compilations de données géologiques et de nouvelles déterminations géochronologiques U–Pb par microsonde ionique haute résolution sensible (SHRIMP). Deux domaines archéens sont reconnus : le domaine oriental Antongil–Masora et le domaine central Antananarivo, ce dernier domaine comportant des ceintures particulières métamafiques de gneiss et de schiste (complexe de Tsaratanana). Dans le domaine oriental, la période de début de formation de la croûte est prolongé jusqu'au Paléo-Mésoarchéen (3,32–3,15 Ga) et une séquence supracrustale (Groupe de Fenerivo), déposée il y a 3,18 Ga et métamorphosée à 2,55 Ga, est identifiée. Dans le domaine central, une période néoarchéenne de métamorphisme élevé et d'anatexie qui a touché à la fois les gneiss felsiques (suite de Betsiboka) et les gneiss mafiques (complexe de Tsaratanana) est documentée. Nous proposons donc que le domaine d'Antananarivo ait été amalgamé dans le craton Greater Dharwar (Inde et Madagascar) par un événement d'accrétion au Néoarchéen (2,55 à 2,48 Ga); cet événement comprenait la mise en place de roches ignées juvéniles, un métamorphisme élevé et la juxtaposition de ceintures disparates de gneiss mafiques et de schistes (méta-roches vertes). Le concept de la « suture de Betsimisaraka » est réfuté et la zone est redéfinie en tant qu'un domaine de roches métasédimentaires du Néoprotérozoïque (Groupe de Manampotsy) et méta-ignées (suite d'Itsindro–Imorona) formé durant une période d'extension continentale et d'activité ignée intrusive entre 840–760 Ma. Une convergence orogénique plus récente (560–520 Ma) a produit un chevauchement à direction est à travers tout le sud du Madagascar; la pente s'est accentuée avec une inversion locale du domaine dans le centre du Madagascar. Le long d'une partie de sa longueur, le Groupe de Manampotsy recouvre la limite entre les domaines archéens oriental et central; il est surimprimé par la zone Angavo–Ifanadiana de grandes déformations qui a servi de zone de faiblesse crustale durant tout le Crétacé jusqu'au temps récent.

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Introduction

The island of Madagascar occupies a keystone position within the reconstructed East African Orogen (Fig. 1) between the Archean cratons of East Gondwana (India–Antarctica–Australia) and West Gondwana (South America – Africa). Over the past decade, several authors have suggested that the Precambrian shield hosts a major boundary, reportedly a convergent continental margin, where vast sections of oceanic crust were consumed in the latest Neoproterozoic (e.g., Collins et al. 2000*a*; Kröner et al. 2000; Rambeloson et al. 2003). The boundary reportedly delineates terranes derived from East Africa and India (Collins and Windley 2002; Cox et al. 2004; Fitzsimons and Hulscher 2005; Raharimahefa and Kusky 2009) and is the suture between the Dharwar Craton (India) and the postulated microcontinent of Azania (Fig. 1). According to some, an allochthonous sheet of Archean mafic gneiss and schist (Tsaratanana Complex) was emplaced onto Azania during this period of Neoproterozoic convergence (Collins and Windley 2002; Collins et al. 2003*b*; Collins 2006).

The present paper challenges this perspective and advances an alternative proposal based on the work of two recent surveys, both supported by loans to the Government of Madagascar (Project de Gouvernance des Ressources Minérales, PGRM). The first was a four-year survey, initiated in 2004 and completed in 2008, by a consortium of scientists from France, Germany, Great Britain, Madagascar, South Africa, and the United States (Projet de Réforme du Secteur Minier (PRSM)-2). The product of their work, including geological maps, geophysical data, and geochemical and geochronologic analyses (BGS et al. 2008; Collins 2006*a*, 2009*b*; GAF–BGR 2008), is available at the office the PGRM in Antananarivo, Madagascar. The second was a two-year synthesis (2008–2009) of the previous data, also involving field work and U–Pb geochronology, undertaken by the present authors from France, Madagascar, and the United States (BRGM–PGRM–USGS consortium).

The conventional view

Kröner et al. (2000) and Collins et al. (2000*a*) first proposed that a major boundary — the "Betsimisaraka suture" — separates the Mesoarchean rocks of east Madagascar ("Antongil–Masora block," i.e., India) from the Neoarchean rocks of central Madagascar ("Antananarivo block," i.e., Azania) (Figs. 1, 2). In their view, the "suture" is the relict of a west-dipping (present-day direction) convergent margin active throughout the Neoproterozoic (800–550 Ma). According to them and subsequent authors, it explains several first-order features of the geology (Collins 2000; Collins et al. 2000*b*, 2003*a*, 2003*b*, 2003*c*; Collins and Windley 2002; Collins 2006; Cox et al. 2004; DeWaele et al. 2009; Fitzsimons and Hulscher 2005; Kröner et al. 2000; Raharimahefa and Kusky 2006, 2009).

(1) The disposition of different Archean blocks (or cratons) — the dominantly Mesoarchean block of east Madagascar (Antongil–Masora) and the exclusively Neoarchean block of central Madagascar (Antananarivo), the latter with an allochthonous sheet of Archean mafic gneiss and schist (Tsaratanana Complex).

(2) A medial Proterozoic platform sequence (Itremo Group) on the central block with detrital zircon ages of proposed African provenance (Cox et al. 1998, 2004; Fitzsimons and Hulscher 2005) — Equivalent rocks are unknown on the eastern block; thus, the two are judged to be independent throughout Archean and Mesoproterozoic times.

(3) Metaigneous rocks, of purported suprasubduction origin (ca. 840–760 Ma, Itsindro–Imorona Suite;Handke et al. 1999; Bybee et al. 2010), scattered throughout the central block and absent in the eastern block; thus, the reported subduction zone had a west-dipping polarity (present-day direction) beneath the central block.

(4) Extensive "Pan-African" (600–520 Ma) overprinting of the central block and **not** the eastern block; thus, the "suture" delineates the eastern margin of the East African Orogen (Collins and Windley 2002; Collins 2006).

(5) Metamafic and ultramafic rocks (gabbro, harzburgite, and serpentinite) of inferred oceanic origin within the

Fig. 1. The microcontinent of "Azania" (Az) and its position within Gondwana (after Collins and Pisarevsky 2005 and Collins 2006). The "Betsimisaraka suture" (*BS*) is interpreted as the Neoproterozoic site of the India–Azania collision, and a provenance boundary between terranes derived from East Africa (*It*, Itremo; *Ant*, Antananarivo) and the Dharwar Craton of India (*A*, Antongil; *M*, Masora). A–A, Afif–Abas terrane; *B*, Bemarivo domain; *MB*, Mozambique belt (accreted southern terranes of Androyen and Vohibory); *Sey*, Seychelles.

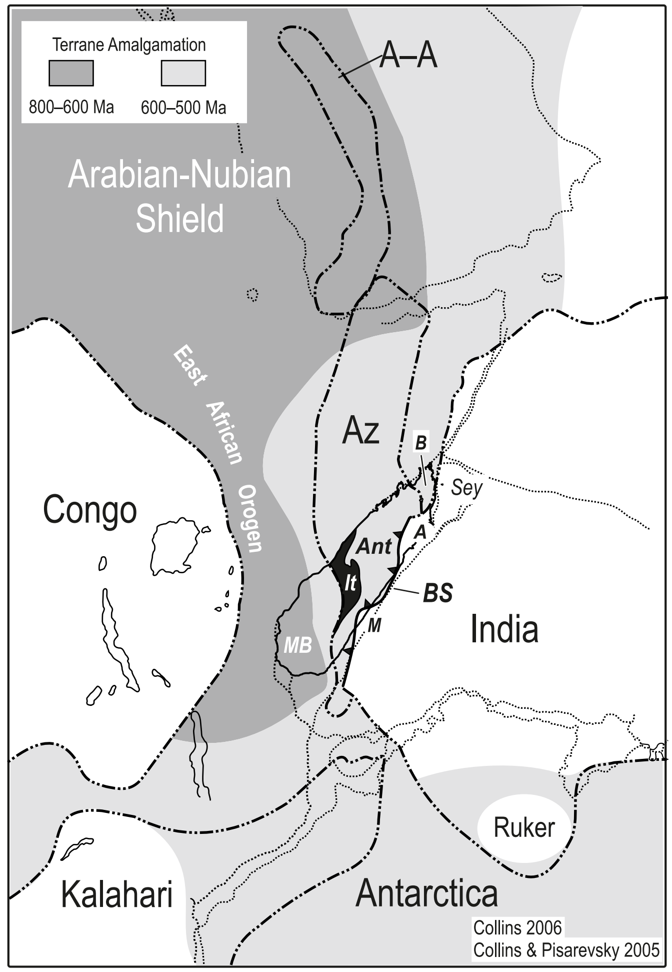
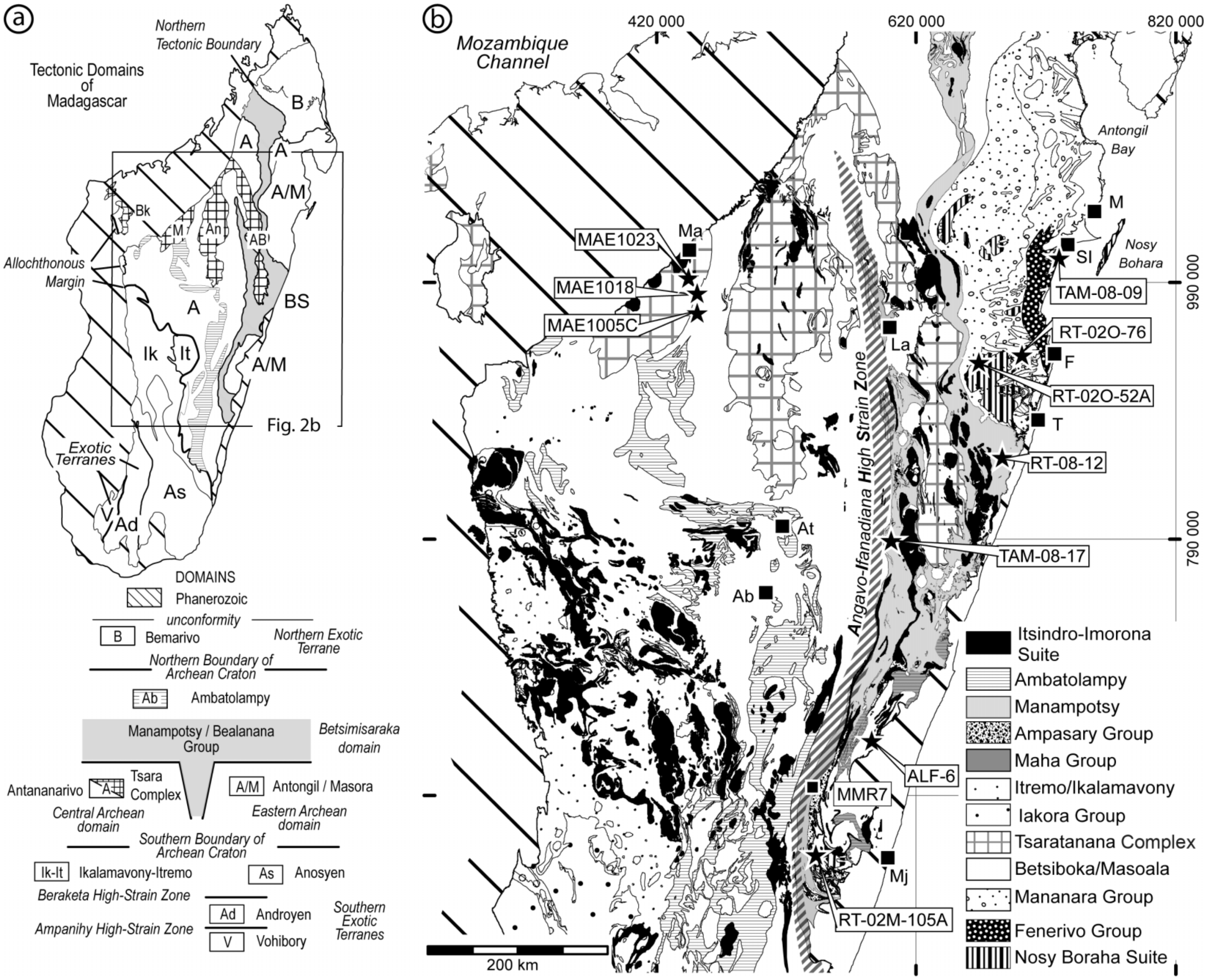


Fig. 2. (*a*) Tectonic domains of the Malagasy shield (exposed Precambrian rocks) after BGS et al. (2008), CGS (2009*a*, 2009*b*), and GAF–BGR (2008). The shield is divided into eight domains most of which are bounded by high-strain zones and thrust faults. They are, from south to north, the Vohibory (V), Androyen (Ad), Anosyen (As), Ikalamavony–Itremo (Ik–It), Antananarivo (A), Betsimisaraka domain (BS), Antongil–Masora (A/M), and Bemarivo (B) domains. The Antananarivo domain includes a major subdomain, the Tsaratanana Complex, comprising the following: Bk, Bekadoka; M, Maevatanana; An, Andriamena; AB, Alaotra–Beforona. No Archean rocks are reported in the domains south of the Antananarivo domain. The eastern boundary of the Antananarivo domain is interpreted as the "Betsimisaraka suture" (BS). The northern boundary of the shield is the Bemarivo domain, a terrane of mostly juvenile Neoproterozoic igneous rocks. (*b*) Enlarged geologic map of central Madagascar showing the major belts of metasedimentary rocks, as well as samples dated in this study. At, Antananarivo; Ab, Ambatolampy; F, Fenerivo; La, Lac Alaotra; SI, Soanierana-Ivongo; T, Tamatave; M, Mananara; Ma, Maevatanana; Mj, Mananjary.



"suture" (Kröner et al. 2000; Collins and Windley 2002).

In early papers, the site of the "Betsimisaraka suture" is the thick, highly strained paragneissic belt (Manampotsy Group of the Graphite System, Besairie 1964), east of Antananarivo, containing mafic and rare ultramafic rocks, and local gem occurrences (emerald and ruby). The suture is classically shown in published illustrations as a west-dipping thrust fault or a steeply inclined shear zone (Kröner et al. 2000; de Wit 2003).

The new domains of Madagascar

The tectonic domains of Madagascar have been redefined through the work of the national consortiums in 2004–2008 (BGS et al. 2008; CGS 2009*a*, 2009*b*; GAF– BGR 2008). For the purpose of this paper, they include the domains of Antongil–Masora, Antananarivo, Itremo–Ikalamavony, and Betsimisaraka (Fig. 2*a*). Each domain is defined by distinctive suites of metaigneous or metasedimentary rocks, or a unique history of Proterozoic reworking. Superimposed within and across the domains are kilometre wide zones of steeply dipping, highly strained rocks that record the effects

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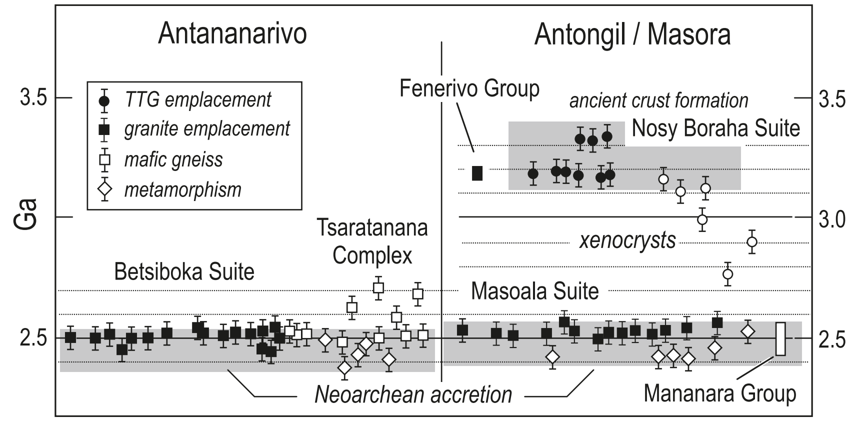
Fig. 3. Chronogram of Archean events across the Antananarivo and Antongil–Masora domains. The data are from published work (cited in the text), as well as information from the report of consultants (presented with permission from the PGRM, Madagascar). Also shown are the major periods of Archean sedimentation and volcanism for the Mananara Group (DeWaele et al. 2008) and the newly defined Fenerivo Group (this paper). TTG, tonalite–trondhjemite–granodiorite.



of latest Neoproterozoic transpressive shortening (Pili et al. 1997; Martelat et al. 2000; Nédélec et al. 2000).

Antongil–Masora domain

The Antongil domain historically includes the area of east Madagascar, north of Tamatave to the Bay of Antongil, as well as the smaller southern segment of Masora near Mananjary village (Fig. 2; Hottin 1976; Kröner et al. 2000; Collins et al. 2003*a*).

The oldest rocks of Antongil are stromatic and nebulitic migmatites (Nosy Boraha Suite), of tonalite, trondhjemite, and granodiorite (TTG) composition, dated to 3.2–3.1 Ga (Tucker et al. 1999; BGS et al. 2008). A second major generation of metaigneous rocks (monzogranite, granodiorite, and syenogranite), of Neoarchean age (Masoala Suite, 2.55–2.51 Ga), form a ubiquitous suite of weakly deformed batholiths, stocks, and small intrusive massifs (Fig. 3; Tucker et al. 1999; Paquette et al. 2003; BGS et al. 2008).

Archean stratified rocks (Mananara Group) make up about 65% of the Antongil (Fig. 2*b*), and they vary dramatically across the domain in lithology, rock association, and metamorphic grade. In the type locality of Mananara, they are quartz–chlorite and chlorite–actinolite schist, whose field relations are poorly known. In the central coastal area, between Fenerivo and Soanierana-Ivongo, they comprise hundreds of metres of kyanite (± fuschite) schist, garnet amphibolite gneiss, quartzo-feldspathic schist, talc schist, and garnet–magnetite quartzite (banded iron formation) extensively migmatized and polydeformed. In the south part of the domain, they form a largely unmapped package of metasedimentary rocks (Ambodiriana Unit of the Mananara Group) composed of psammitic and semipelitic schist and gneiss (kyanite ± muscovite), commonly migmatized, with lesser concordant sheets and lenticular masses of amphibolite and meta-ultramafite (harzburgite, pyroxenite, peridotite, and serpentinized varieties). The depositional age of the Mananara Group is contentious; near Fenerivo, Collins et al. (2003*b*) assert that it is younger than 710 Ma (sample M99/20), whereas in the type area near Mananara village, it is intruded by Neoarchean stocks and dikes of the Masoala Suite, implying that the Mananara Group is older than ca. 2.50 Ga (Paquette et al. 2003). Its age has been further refined by U–Pb dating of volcanic strata and detrital zircons that suggest deposition between 2.54–2.51 Ga (Fig. 3; DeWaele et al. 2008). Proterozoic rocks of the region include the Ankavanana Suite of mafic dikes (2.147 Ga) and sedimentary rocks of the Andrarona Group (<2.355 Ga, BGS et al. 2008). Igneous rocks of the Itsindro–Imorona Suite (840–760 Ma) are unknown in the Antongil domain, and the effects of latest Neoproterozoic overprinting are limited to rare examples of metamorphic zircon (ca. 537 Ma, BGS et al. 2008).

Like the Antongil, the Masora domain is underlain by orthogneiss (Nosy Boraha Suite) of Mesoarchean age (3.2 Ga) and paragneiss (Vohilava Group) of unknown, but presumed, Mesoarchean age (BGS et al. 2008). In contrast to the Antongil, the Masora domain has rare Neoarchean gneiss (our interpretation of RK449, BGS et al. 2008), an important sequence of medial Proterozoic supracrustal rocks (Maha Group), and abundant Neoproterozoic metaigneous rocks of the Itsindro–Imorona and Kiangara suites (840–760 and 660–630 Ma, respectively). The distinctiveness of the Masora domain is further highlighted by polyphase deformation and intense metamorphism of late Neoproterozoic age (560–520 Ma) that affects the entire domain, including the early Neoproterozoic intrusive igneous rocks.

Antananarivo domain

Extensive tracts of migmatitic gneiss of Neoarchean to earliest Paleoproterozoic age make up the oldest rocks of the Antananarivo domain (Fig. 3). The ancient gneisses are divided into supracrustal units — the Vondrozo Group in the south and Sofia Group in the north — and migmatitic gneiss of intrusive igneous origin (Betsiboka Suite, BGS et al. 2008). The supracrustal rocks consist of a variety of metasedimentary rocks (quartzite, metawacke, calc-silicate gneiss), as well as metaluminous quartzo-feldspathic gneiss and schist of andesite–dacite composition. The age of these is unknown, but they are inferred to be at least of Neoarchean age because they host the intrusive Betsiboka Suite. The Betsiboka Suite consists of orthogneiss and migmatite of calc-alkaline and potassic granite chemistry dated between 2.72 and 2.48 Ga (Fig. 3). The domain is also host to clastic

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metasedimentary rocks (Ambatolampy Group), of Neoproterozoic age, that form a north-striking belt up the spine of the island (Fig. 2*b*). All of the previously mentioned units are intruded by voluminous Neoproterozoic intrusive igneous rocks of both the Itsindro–Imorona (840–760 Ma) and Ambalavao suites (560–520 Ma).

In addition to Neoarchean granite and migmatite gneiss, the Antananarivo domain includes three large synformal belts of mafic gneiss and schist also of Neoarchean age (2.7–2.5 Ga): Bekadoka–Maevatanana, Andriamena, and Alaotra–Beforona, (Fig. 2*a*). Collectively known as the Tsaratanana Complex (or "sheet"), the belts are heterogeneous in lithology and metamorphic grade, contrasting sharply with the granite gneiss and migmatite beneath them. The Tsaratanana Complex is interpreted as an allochthonous sheet (Kröner et al. 2000; Collins and Windley 2002; Goncalves et al. 2003; BGS et al. 2008) emplaced en masse above the Antananarivo domain in the latest Neoproterozoic (630–595 Ma). There are several problems with this interpretation: (1) rocks of the "allochthon" differ greatly in lithology and metamorphic grade from region to region, (2) both "autochthon" and "allochthon" are intruded by Neoproterozoic (840–760 Ma) igneous rocks of the Itsindro–Imorona Suite (Handke et al. 1999), and (3) the "allochthon" never resides above the Itremo and Ambatolampy groups as it might if it was a Neoproterozoic nappe. The first observation implies that each synformal belt consists of an assemblage of rocks unique to its setting. The last two observations imply that the allochthon, if it exists, was emplaced before 840 Ma, perhaps as early as the Paleoproterozoic. In many regards (e.g., rock types and rock associations), the mafic gneisses of the Antananarivo domain are no different from "greenstones" in other Archean cratons (de Wit 2003). The principal difference is its somewhat higher metamorphic grade (upper amphibolite and granulite grade) and structural complexity, which is the product of intense Neoproterozoic reworking (Goncalves et al. 2004; Paquette et al. 2004). Because Archean rocks of central Madagascar share a common history of Proterozoic magmatism, deformation, and metamorphism, we consider them part of the same tectonic domain.

Itremo–Ikalamavony domain

The Itremo–Ikalamavony domain defines the southern end of the Archean shield (Fig. 2*a*). Recent mapping and U–Pb geochronology demonstrate that the Itremo–Ikalamavony domain represents a fold-thrust belt, and a stack of allochthonous sheets, translated eastwards over the Antananarivo domain in late Neoproterozoic–Cambrian times (Nédélec et al. 2003; Tucker et al. 2007; CGS 2009*a*, 2009*b*). The domain is divided into two subdomains based on differences in lithology, structural complexity, and metamorphic grade. The upper amphibolite- to granulite-grade rocks of the Ikalamavony subdomain (in the west) consist of a stack of allochthons thrust eastward over the greenschist- to low amphibolite-grade rocks of the Itremo subdomain (in the east). The Itremo subdomain consists of Paleoproterozoic metasedimentary rocks of the Itremo Group (Moine 1974; Cox et al. 1998; Fernandez et al. 2003) intruded by, and tectonically interleaved with, Neoproterozoic metaigneous rocks of the Itsindro–Imorona Suite (840–760 Ma); all of these have been translated eastward as giant fold-thrust nappes. The higher grade Ikalamavony subdomain is more heterogeneous and includes medial Proterozoic (1020–990 Ma) metasedimentary and metaigneous rocks (Dabolava Suite, Tucker et al. 2007), as well as latest Neoproterozoic sedimentary rocks (Molo Group, Cox et al. 2004). Thrust slices of Neoarchean gneiss (ca. 2.5 Ga), belonging to the Antananarivo domain, also occur within the Ikalamavony subdomain. The age of their emplacement, as well as regional metamorphism and polyphase deformation, is latest Proterozoic to earliest Cambrian (560–540 Ma).

Betsimisaraka domain: a mélange of oceanic sediments?

The "Betsimisaraka suture" is redefined by BGS et al. (2008) as a domain (mélange) of Neoproterozoic oceanic and continental margin sediments containing disrupted blocks of mafic and ultramafic gneiss (BS, Fig. 2*a*). In Fig. 2, the supracrustal rocks are represented by the Manampotsy and Ampasary groups that are highly deformed, locally metamorphosed to amphibolite grade, and intruded by granitoids of early and latest Neoproterozoic age (Itsindro–Imorona Suite, 840–760 Ma; Ambalavao Suite, 560–530 Ma). According to BGS et al. (2008), most of the supracrustal rocks consists of oceanic sediments (Manampotsy and Bealanana groups), the exception being a sliver of rocks (Ampasary Group) interpreted as the continental shelf to the Masora domain. The age of the Bealanana and Manampotsy groups is ∼830–780 Ma, based on the age of its youngest detrital zircons and syndepositional volcanic rocks (DeWaele et al. 2008). In the view of BGS et al. (2008), the postulated ocean basin closed in latest Neoproterozoic time (560–520 Ma). We find little evidence that the metasedimentary rocks are of oceanic origin, and we offer an alternative proposal in a later section.

Angavo–Ifanadiana high-strain zone

Superimposed on the domains discussed previously is the high-strain zone of Angavo–Ifanadiana (Martelat et al. 2000; Nédélec et al. 2000). This steeply dipping structure, 15–30 km wide, is oriented north–south and is traceable by satellite imagery and ground observations for at least 600 km (Fig. 2). Along its southern length, the zone of highly strained rocks is within, but not restricted to, metasedimentary rocks of the Betsimisaraka domain. North of Lac Alaotra, the Angavo–Ifanadiana high-strain zone (AIHSZ) turns to the northwest and is within Archean and younger rocks of the Antananarivo domain between the Andriamena and Beforona–Alaotra belts of the Tsaratanana Complex.

The fabrics within the AIHSZ are consistent with strong east–west horizontal shortening within a broad regime of coaxial strain. Related fabrics include steeply dipping foliations and subhorizontal lineations, conjugate shear bands in both *X–Z* and *Y–Z* of the finite strain ellipsoid, and isoclinal folds with hinges plunging vertically or steeply southwest. Because these fabrics are especially well developed in the schistose rocks of the Manampotsy Group, they have been confused with postulated structures in the "Betsimisaraka suture" (Raharimahefa and Kusky 2006). In fact, the AIHSZ is superposed on rocks of the suture, and the age of deformation within the zone (550–500 Ma) is significantly younger than the purported age of ocean closing (800–550 Ma).

In 2007–2008, the present authors evaluated key geological relationships established by the national consortiums (BGS et al. 2008; CGS 2009*a*, 2009*b*; GAF–BGR 2008). Our principal objective was to reconcile conflicting interpretations, and to synthesize the work into a new geological map of Madagascar (scale 1 : 1 000 000). In addition to field work, we also collected several samples for U–Pb geochronology, intended to (1) define the age of a purported Archean supracrustal succession in the Antongil domain, (2) confirm the presence of Archean metamorphism in west Madagascar, and (3) evaluate the claim of a Neoproterozoic suture in east Madagascar.

Analytical methods and results of U–Pb geochronology

U–Pb ages of zircon were measured on the sensitive high-resolution ion microprobe – reverse geometry (SHRIMP RG) system at the Research School of Earth Sciences (RSES), the Australian National University, Canberra, using the methods described by Williams (1998) and Hiess et al. (2009). The data were collected during seven analytical sessions between April and October 2009. A ca. 3–5 nA mass-filtered O_2 primary beam was focused to elliptical spots with the sizes between 17 μm × 24 μm and 25 μm × 30 μm. Before data were acquired, the beam was rastered for 120 s to clean the mount surface. The magnet was stepped through peaks of $^{90}Zr_2{}^{16}O$, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, $^{232}Th^{16}O$, and $^{238}U^{16}O$; each analysis included 5–8 cycles. The data were reduced using the SQUID+ISOPLOT® software package (Ludwig 2001, 2003). Uranium concentrations were calculated relative to U = 238 ppm in the SL13 zircon reference material, and U/Pb ratios were calculated relative to the $^{206}Pb/^{238}U$ age of 417 Ma for the Temora standard (Black et al. 2004). The ages were calculated using the decay constants of uranium of Jaffey et al. (1971), and the $^{238}U/^{235}U$ ratio of 137.88. Non-radiogenic Pb was subtracted from the measured Pb isotopic composition using measured ^{204}Pb and the present-day average terrestrial Pb isotopic composition in the model of Stacey and Kramers (1975). Concordia regressions, concordia age, and weighted average age values are calculated with ISOPLOT (Ludwig 2003). The errors of the ages are reported at 95% confidence level.

U–Pb isotopic data are reported in Table S1[3] , and the ages are summarized in Table 1 and Figs. 6, 9, 12, and 14. Cathodoluminescence images of selected grains are presented in Figs. 5, 8, 11, and 13.

Indications of Paleo- and Mesoarchean crust

Nosy Boraha Suite, Antongil–Masora domain

The oldest rocks reside in the Antongil domain where previous dating established their age between 3.18 and 3.15 Ga (Tucker et al. 1999; BGS et al. 2008). Our collection extends the geographic range of the Nosy Boraha Suite in the Antongil domain and establishes its presence in the Masora domain. We analyzed two samples of migmatitic tonalite gneiss west of Foulepoint (Antongil domain) and a third sample of migmatitic granodiorite gneiss west of Mananjary (Masora domain) (Figs. 2*b*, 4).

Sample RT-02O-76A

The recovered zircons reveal three types of crystalline domains under cathodoluminescence (CL): (1) CL-bright cores with oscillatory or sector zoning, (2) CL-dark inner rims, and (3) CL-bright outer rims or overgrowths too thin to be analyzed by SHRIMP (Figs. 5A, 5B).

A regression of all core and inner analyses yields intercepts of 3300 ± 29 and 642 ± 98 Ma. Most domain 1 core analyses plot in the upper part of the array (<20% discordant), whereas all domain 2 rim data are discordant. In the group of nine least discordant analyses (<6%), seven yield consistent $^{207}Pb/^{206}Pb$ dates with a weighted average of 3314 ± 6 Ma. The upper intercept age for the same data is 3320 ± 14 Ma, which we interpret as the emplacement age of the tonalite protolith (Fig. 6A).

Sample RT-02O-52A

The recovered zircons consist of two types of crystalline domains recognized in CL (Figs. 5C, 5D): (1) cores with oscillatory zoning and CL brightness ranging from high to medium, and (2) thin CL-bright rims. The rims are too thin for SHRIMP analysis, and, in some cases, the domain 1 zones are truncated, suggesting resorption of cores before growth of rims.

Nineteen domain 1 core analyses are concordant to slightly discordant, and yield $^{207}Pb/^{206}Pb$ dates between 3.23 and 2.55 Ga. Sixteen of 19 analyses define a field of discordant data, with a uniform distribution of $^{207}Pb/^{206}Pb$ dates between 3.00 and 3.23 Ga (Fig. 6B). The dates are not correlated with the Th/U ratios that are generally higher than 0.3.

The age distribution, Th/U composition, and overall appearance suggest that the domain 1 cores belong to a population of magmatic zircon that experienced ancient and variable Pb loss. All data fall into a wedge-shaped field defined by the model chord intercepts 3230, 2600, and 0 Ma. Based on these data and our knowledge of the regional geology, we infer that the zircons in this sample experienced a dual history of Neoarchean (ca. 2.6 Ga) and Neoproterozoic (or younger) Pb loss. The oldest of our domain 1 analyses are concordant and overlapping at 95% confidence, and their weighted average $^{207}Pb/^{206}Pb$ age is a good approximation of the date of crystallization: 3231 ± 6 Ma. We conclude that this gneiss was emplaced in the Paleoarchean and was profoundly disturbed in the Neoarchean (ca. 2.6 Ga) and again throughout Neoproterozoic and younger time.

Sample RT-02M-105A

The CL domains of the recovered zircons consist of (1) CL-bright cores with oscillatory or sector zoning, (2) CL-dark inner rims, and (3) CL-bright outer rims too thin for SHRIMP analysis (Fig. 5C). All of our analyses are from domain 1, with the exception of spots 13.2 and 14.1, which are of domain 2 inner rims (Table S1)[3].

The SHRIMP analyses show similar pattern to RT-020–76 but with less dispersion (mean square of weighted deviation (MSWD) = 3.5). Regression of all data yields intercepts of 3319 ± 12 and 851 ± 84 Ma, wherein the upper intercept is

Table 1. Summary of U–Pb zircon ages, central Madagascar.

Sample	Laborde	Age (Ma)	Comments
Antongil domain			
RT-02O-76A migmatite gneiss (Nosy Boraha Suite)	700673/930512	3320 ± 14[b]	Emplacement age defined by the upper intercept of nine near-concordant domain 1 core analyses (MSWD = 0.96). Weighted mean ^{207}Pb/^{206}Pb age of the same population is 3314 ± 6 Ma . Lower intercept age of 642 ± 98 Ma approximates the time of Neoproterozoic Pb-loss
RT-02O-52A migmatite gneiss (Nosy Boraha Suite)	669307/925807	3231 ± 6[a]	Emplacement age defined by weighted average ^{207}Pb/^{206}Pb age of three oldest domain 1 core analyses (U < 1000 ppm) (MSWD = 0.61). Wedge-shaped field of discordant analyses implies Neoarchean and Neoproteozoic (or younger) Pb-loss. Model chord intercepts are 2.6 and 0 Ga
TAM-08-9A metarhyolite (Fenerivo Group)	730904/1006312	3178 ± 2[a]	The zircons have a short prismatic habit. Their crystallization age is defined by the weighted mean ^{207}Pb/^{206}Pb age of 47 oldest core analyses (35 grains) < 4% discordant (MSWD = 2.2). Eight younger analyses, generally from crystals with 3.18 Ga cores, indicate a small component of Neoarchean Pb-loss in some grains
TAM-08-9C leucosome in the Fenerivo Group	730904/1006312	2550 ± 42[b]	Age of partial melting is defined by the upper concordia intercept of 18 domain 1 core analyses of the highest U zircons (MSWD = 8.5); two analyses with slightly older ^{207}Pb/^{206}Pb ages inply Neoarchean inheritence. Lower intercept implies Neoproterozic Pb-loss in these high U zircons
		661 ± 120[b]	
TAM-08-9D granite dike in the Fenerivo Group (Masoala Suite)	730904/1006312	2502 ± 8[a]	Emplacement age defined by the weighted mean ^{207}Pb/^{206}Pb age of 12 concordant core analyses < 3% discordant (MSWD = 0.61). Weighted mean ^{206}Pb/^{238}U age of 3 grains indicates early Neoproterozoic zircon growth (MSWD = 1.93)
		834 ± 50[a]	
Masora domain			
RT-02M-105A migmatite granodiorite gneiss (Nosy Boraha Suite)	543269/545473	3313 ± 8[a]	Regression of all data yields upper intercept age of 3319 ± 12 Ma (MSWD = 3.5). Given the magnitude of Neoarchean melting, the most reliable age is the weighted mean ^{207}Pb/^{206}Pb age of seven core analyses < 5% discordant: 3313 ± 8 Ma (MSWD = 1.4). Lower intercept age of the regression implies Neoproterozoic Pb-loss
		851 ± 84[b]	
ALF-06 gabbro pegmatite (Itsindro–Imorona Suite)	584766/629068	806 ± 8[a]	Emplacement age defined by ten concordant analyses < 4% discordant (MSWD of concordance = 9.0, probability of concordance = 0.003)
Antananarivo domain			
MAE-1005C leucosome in Betsiboka Suite	451810/967701	2501 ± 15[b]	Age of partial melting is defined by the upper concordia intercept of 13 inner and outer core analyses (MSWD = 2.9); weighted mean ^{207}Pb/^{206}Pb age of outer rims dates the time of recrystallization and metamorphic zircon growth
		546 ± 11[a]	
MAE-1018B aplite dike in the Betsiboka Suite	447959/986700	760 ± 11[a]	Emplacement age defined by weighted mean ^{206}Pb/^{238}U age of nine concordant core analyses (MSWD = 1.06); weighted mean ^{206}Pb/^{238}U age of zircon rims defines age of metamorphism (510 ± 27 Ma)
		510 ± 27[a]	

[3] Supplementary data Table S1 can be found on the CJES Web site (cjec.nrc.ca) beside the article.

Table 1 (*concluded*).

Sample	Laborde	Age (Ma)	Comments
MAE-1023B aplite dike in Tsaratanana Complex	445383/989070	770 ± 10[a]	Emplacement age defined by weighted mean $^{206}Pb/^{238}U$ of 20 concordant analyses (MSWD=1.3). Partial melting in this outcrop predates 770 Ma
Betsimisaraka domain			
RT-08-12 metaquartzite of Manampotsy Group	686114/850015	2950 – 1550[c]	50 SHRIMP analyses of detrital zircons, 70% of the population, define two major age modes at 2.55–2.38 and 2.05–1.86 Ga; 30% define age modes at 2.60–2.95, 2.2–2.0, and 1.84 –1.55 Ga. Six concordant rims yield weighted mean $^{206}Pb/^{238}U$ age of metamorphism (ca. 538 Ma)
		538 ± 16[a]	
TAM-08-17 metaquartzite of Manampotsy Group	601149/785723	3642-1800[c]	55 SHRIMP analyses of detrital ziricons define three major age modes: 2.66–2.49, 2.0–1.9, and 1.84–1.80 Ga. Two grains have $^{207}Pb/^{206}Pb$ ages > 3.5 Ga; these are the oldest zircons in Madagascar

Note: MSWD, mean square of weighted deviates.

[a]Weighted age calculated with ISOPLOT (Ludwig 2003).

[b]Regression age calculated using algorithm of Ludwig (2003).

[c]Range of concordant (±10%) detrital zircon ages.

defined by 21 analyses of domain 1 cores, and the lower intercept is controlled by analyses of high-U, low-Th/U inner rims (domain 2). Regression of all domain 1 cores yields a precise upper intercept of 3314 ± 10 Ma, but given the pervasive nature of secondary anatexis, our best estimate is given by seven core analyses (domain 1) <5% discordant (Fig. 6C) that yield a weighted mean $^{207}Pb/^{206}Pb$ age of 3313 ± 8 Ma (MSWD = 1.4) (Fig. 6C). This date, interpreted as the emplacement age of the granodiorite protolith, is identical (at 95% confidence) to the age of RT-02O-76A.

A new Mesoarchean supracrustal sequence

BGS et al. (2008) introduced the name "Mananara Group" for xenoliths of quartz–chlorite schist and mafic schist in granitoids of the Masoala Suite (2.5 Ga), and they broadened it to include mappable units of stratified gneiss and schist between Fenerivo and Soanierana-Ivongo (Figs. 2*b*, 7). In a key outcrop (TAM-08-9) north of Fenerivo, we observed (A) kyanite semipelitic paragneiss and sheets of quartzo-feldspathic gneiss; (B) sheets and boudins of amphibolite, possibly metamafic dikes; (C) layer-parallel sheets and discordant dikes of quartz–plagioclase leucosomes partially melted from the paragneiss; and (D) a medium-grained granite dike, 1–2 m thick and weakly deformed near its margin, that intrudes (A) to (C) (Note that the letters A to D correspond with those circled in Figs. 7E–7F). Our samples include the oldest quartzo-feldspathic gneiss (A), a leucosome of anatectic origin (C), and the youngest, post-metamorphic granite dike (D).

Sample TAM-08-9A

Sample TAM-08-9A is a sheet of feldspar-rich leucocratic gneiss (2 m thick) within kyanite–muscovite quartzo-feldspathic gneiss of the Mananara Group. Given its stratified nature, fine grain size, and granitic composition, it was collected as a metarhyolite gneiss. The zircons are uniform in appearance with short, prismatic shapes and euhedral or subhedral habit. Their CL brightness varies from moderate to very bright, and all grains display well-preserved oscillatory or sector zoning (Figs. 8A, 8B). Most grains have no distinct cores and rims, but a couple contain CL-dark, structureless tips and rims, too thin to be analyzed by SHRIMP. Based on field relationships, grain morphology, measured uranium concentrations (31–403 ppm), and Th/U ratios (0.41–0.79), we propose they belong to a single population of igneous (volcanic) zircon (Table S1)[3].

Our spot analyses (56 in total) yielded U–Pb data that are concordant at 95% confidence, and thus, the $^{207}Pb/^{206}Pb$ dates are a good approximation of their crystallization age. The weighted average $^{207}Pb/^{206}Pb$ date of 47 spot analyses (from 35 grains) is 3178 ± 2 Ma, which is considered the best estimate for the timing of volcanism (Fig. 9A). This is the first direct date of the stratified rocks near Fenerivo, and it establishes a Mesoarchean age for that part of the Mananara Group. A small subset of analyses, with slightly younger $^{207}Pb/^{206}Pb$ dates (3015–2990 Ma, Table S1)[3], are interpreted to be the product of ancient Pb loss in late Archean or early Proterozoic time. This interpretation is consistent with the morphology and zoning characteristics of the analyzed grains, as well as the geologic history of the Antongil domain.

Neoarchean reworking of the Malagasy shield

The effects of Neoarchean high-grade metamorphism are well documented in the Tsaratanana Complex (Goncalves et al. 2004). We obtained U–Pb SHRIMP dates from the Antongil and Antananarivo domains to document the age of Archean metamorphism elsewhere in Madagascar.

Metamorphism in the Antongil domain

Partial melting of the Mananara Group (north of Fenerivo) has produced granitic leucosomes of variable texture and thickness. Some are fine- and medium-grained sill-like masses, millimetres to centimetres thick, that are parallel to, and are folded with, the metamorphic layering; others are tightly folded, quasi-concordant sheets and disrupted boudins; still others are demonstrably younger discordant dikes

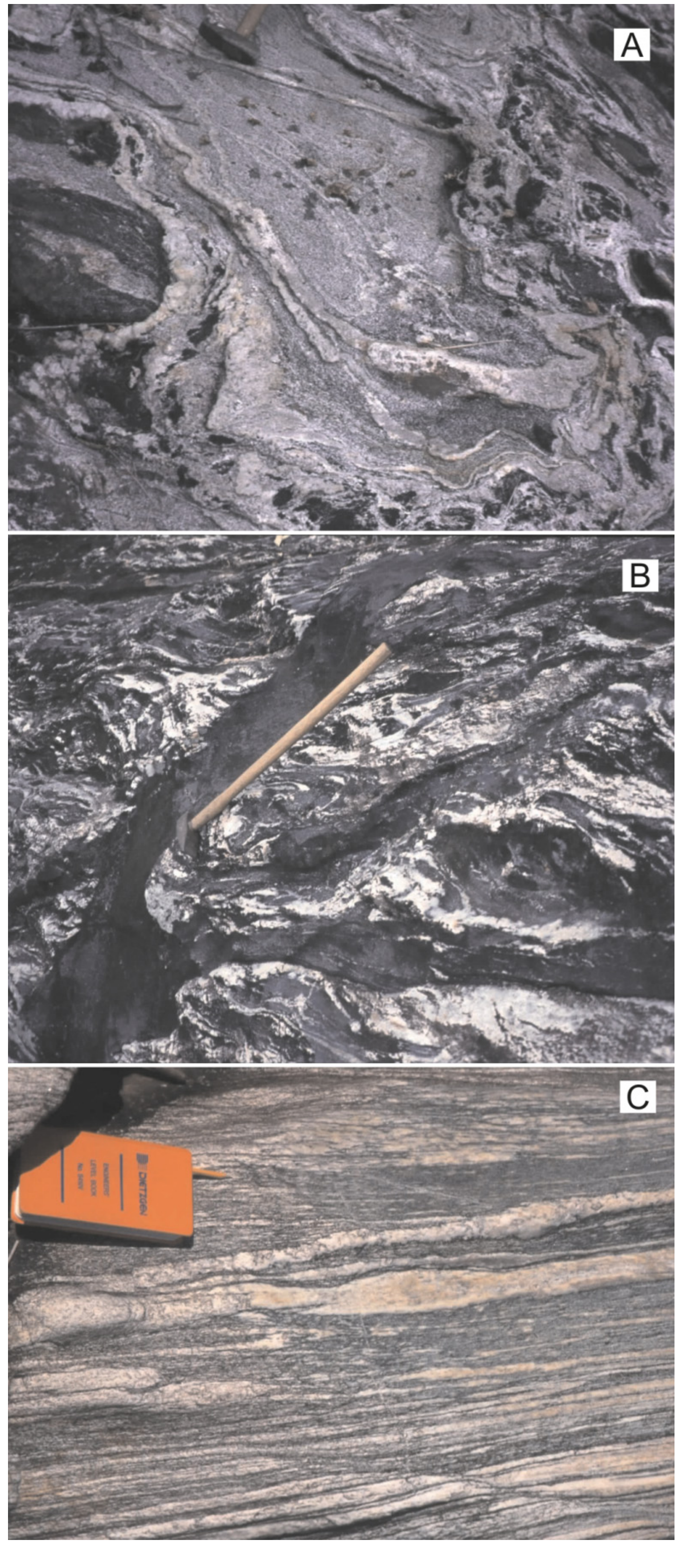


Fig. 4. Ancient Paleoarchean gneisses of Madagascar (Nosy Boraha Suite). (A) Sample RT-02O-52A, west of Foulpointe (Fig. 2*b*, Antongil domain). Dated sample was collected from the homogeneous mass in the center of the photograph. (B) Outcrop RT-02O-76, on the Onibe River (Fig. 2*b*, Antongil domain). Sample RT-02O-76A is the medium-grained tonalite gneiss where least affected by partial melting. (C) Sample RT-02M-105A, west of Vohilava (Fig. 2*b*, Masora domain). Biotite granodiorite migmatite gneiss.

of medium-grained leucogranite that appear to have coalesced from the sill-like layers. Sample TAM-08-9C is the youngest discordant granite leucosome (Figs. 7D, 7E).

Sample TAM-08-9C

Almost all zircons in this pegmatitic leucosome are dark and structureless in CL (domain 3, Fig. 8C) with high-U content (4500–652 ppm) and modest Th/U (0.10–0.05, Table S1)[3]. A few grains contain regions of weak luminescence with barely recognizable zoning (domain 2, spots 3.1 and 2.1, Table S1)[3]. One grain is CL bright and shows clear zoning (domain 1, spot 6.1, Fig. 8D). No core–rim relationships can be seen in these zircons suggesting they all share a common igneous origin.

Regression of 18 data points with the highest U values produces a scattered array (MSWD = 8.5) with intercepts of 2550 ± 42 and 682 ± 91 Ma, implying a history of Neoarchean crystallization and Neoproterozoic Pb loss (Fig. 9B). The significant scatter is a product of Neoproterozoic and younger Pb loss, expected in high-U and metamict zircons such as these. Excluding from the regression the very highest U subpopulation (>1500 ppm), the quality-of-fit is improved (MSWD = 5.5), but the upper intercept age is not appreciably different (2550 Ma). If we add to the regression another analysis from a slightly lower U domain (analysis 6.26, 580 ppm), the precision of the regression improves slightly (MSWD = 5.0), but, again, the upper intercept age does not change appreciably (2548 ± 36 Ma). Thus, the upper intercept for the regression of the highest U domains is quite robust (2550 ± 42 Ma), and we interpret it as the crystallization age of the pegmatitic leucosome and a direct age of anatectic metamorphism at this outcrop. We interpret the $^{207}Pb/^{206}Pb$ ages of analyses 6.3 and 6.4 (2.659 and 2.676 Ga, respectively) to reflect trace inheritance of older zircon from the metasedimentary host of the leucosome.

Sample TAM-08-9D

This sample, a crosscutting granite dike, establishes the minimum age of anatectic metamorphism and deformation (Figs. 7E, 7F). The zircons in this sample have uniform appearance and display moderate to very high CL brightness, well-preserved sector or oscillatory zoning, and no visible core–rim relationships (domain 1, Figs. 8E, 8F). Domain 2 types are dark, structureless rims surrounding domain 1 cores.

Most of our domain 1 analyses are concordant with a weighted average $^{207}Pb/^{206}Pb$ age of 2502 ± 8 Ma (MSWD = 0.61) (Fig. 9C). Because the bulk of these are concordant, showing no indication of inherited or xenocrystic components, this is our best estimate for the date of dike emplacement and the minimum age of anatectic melting.

A regression through all the data, excluding those from grain 4, domain 2 types, yields a lower intercept of 861 ± 32 Ma that agrees well with the concordant analyses of grains 5, 6, and 17. The weighted mean $^{206}Pb/^{238}U$ age of analyses 5.1, 6.1, and 17.1 is 834 ± 50 Ma (MSWD = 1.93), which we accept as the time of early Neoproterozoic metamorphic or hydrothermal zircon growth in this sample. This is the first such evidence of early Neoproterozoic zircon growth in the Antongil domain. Two other analyses,

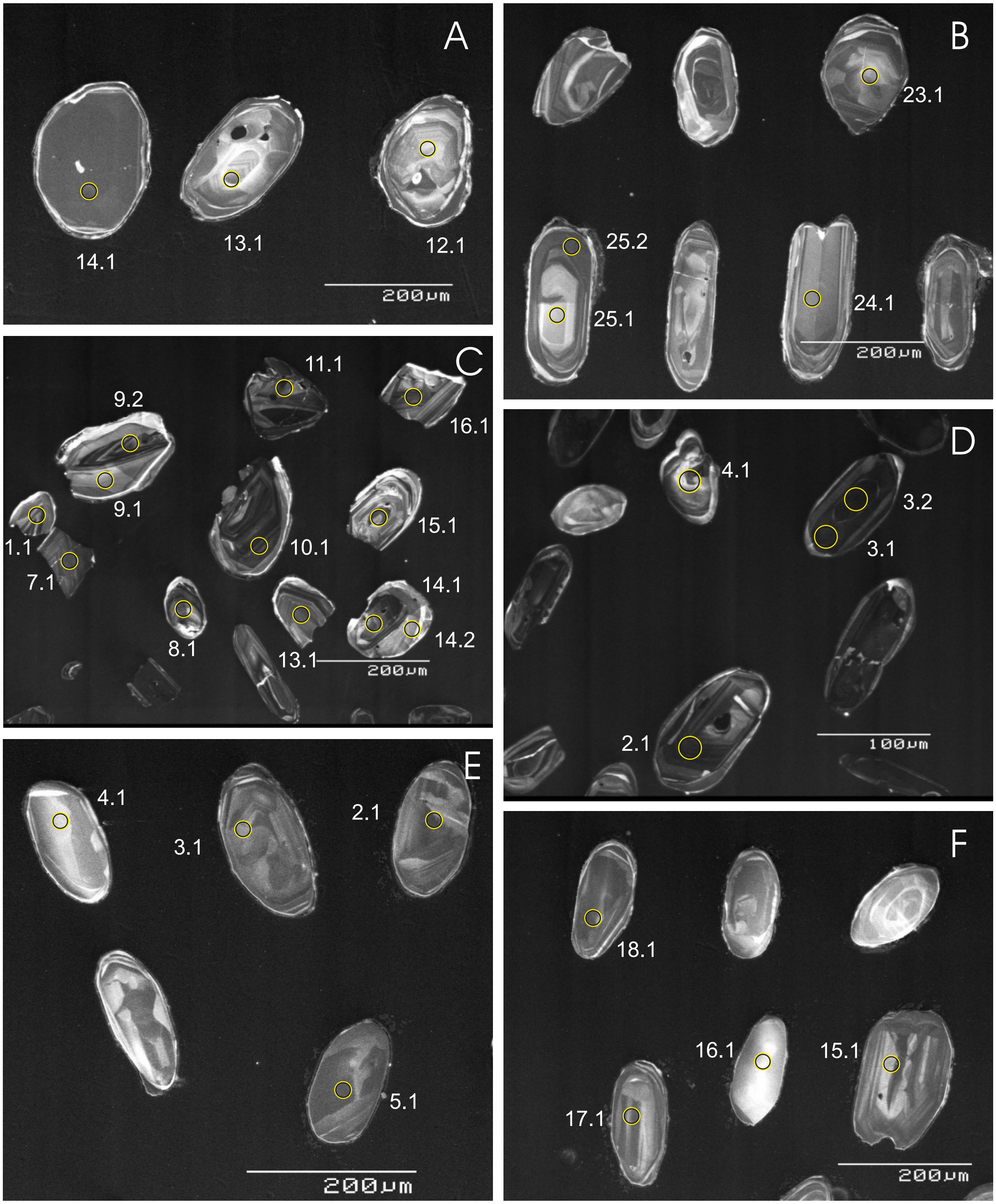


Fig. 5. Cathodoluminescence images of zircon. (A, B) From sample RT-02O-76A. (C, D) From sample RT-02O-52A. (E, F) From sample RT-02M-105A. Numbers refer to spot analyses in Table S1.

from a core and a rim of grain 4, yielded concordant ages of 582 and 535 Ma, respectively. The rim of this grain is unusually CL-dark, and has high U and low Th/U, suggesting a metamorphic or hydrothermal origin.

Metamorphism in the Antananarivo domain

Field observations demonstrate that many of the Archean gneisses of the Antananarivo domain acquired their anatectic fabrics prior to emplacement of the Itsindro–Imorona Suite (Figs. 10A–10E; Goncalves 2002). We offer three such examples from west Madagascar (Fig. 2*b*). Two of them are in the Betsiboka Suite, and a third is in the nearby, and overlying, Maevatanana Series of the Tsaratanana Complex (Rantoanina et al. 1969).

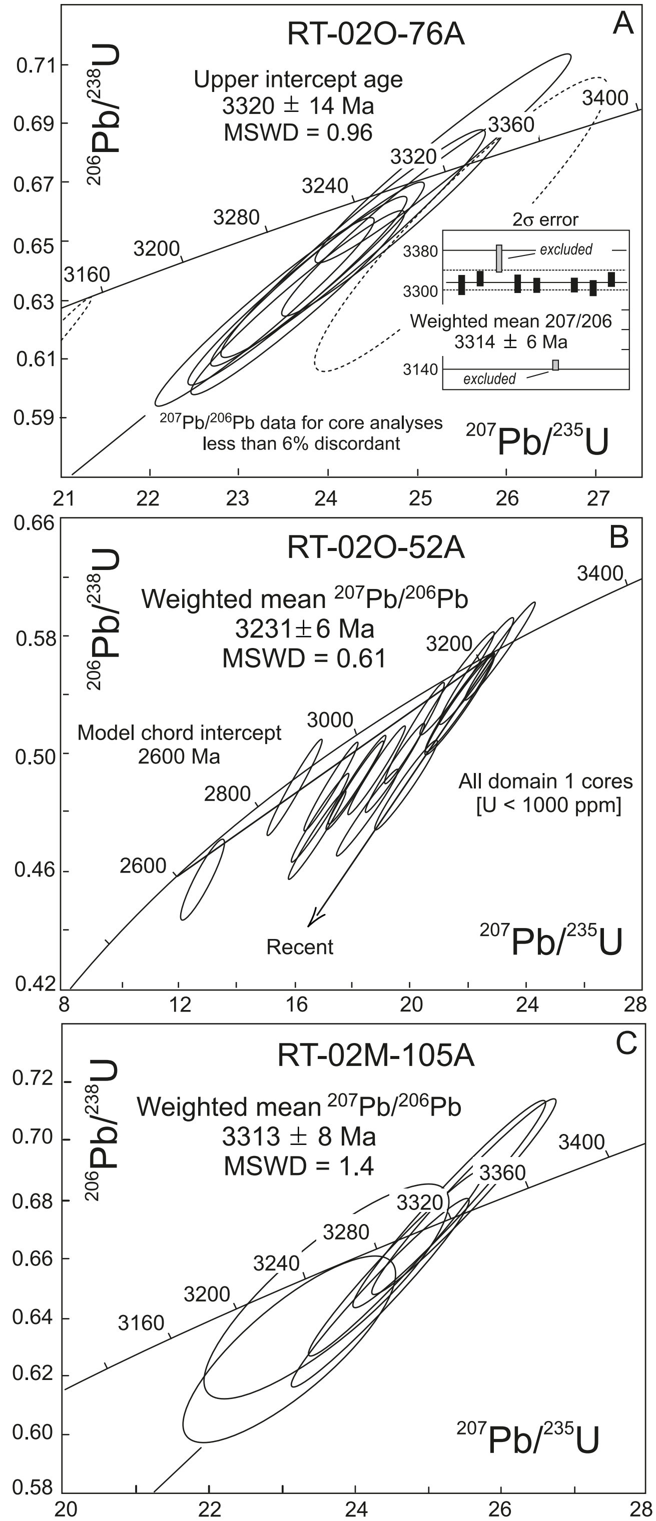


Fig. 6. (A) Concordia diagram of domain 1 core analyses from RT-02O-76A (Nosy Boraha Suite), Antongil domain. Upper intercept of 3320 ± 14 Ma is interpreted as the age of tonalite emplacement. Inset shows the mean $^{207}Pb/^{206}Pb$ age for the same analyses. (B) Concordia diagram of domain 1 core analyses from RT-02O-52A (Nosy Boraha Suite), Antongil domain. Domain 1 cores define a wedge-shaped field with model chord intercepts of 3.23, 2.60, and 0 Ga implying a history of Neoarchean and time-integrated Pb loss. Weighted mean $^{207}Pb/^{206}Pb$ age of 3231 ± 6 Ma (oldest concordant analyses) is the emplacement age of the gneiss. (C) Concordia diagram of domain 1 core analyses (<5% discordant) from RT-02M-105A, granodiorite migmatite gneiss, Masora domain. Upper intercept is interpreted as the age of granodiorite emplacement. MSWD, mean square of weighted deviation.

Sample MAE-1005C

South of Maevatanana (Fig. 2*b*), granite gneiss and migmatite of the Betsiboka Suite dip beneath the overlying rocks of the Tsaratanana Complex; both groups are of Neoarchean age (2.52–2.51 Ga, Tucker et al. 1999) and exhibit textures indicative of high-grade metamorphism and partial melting. Sample MAE-1005C is a thin, 2–4 cm, quartz–plagioclase–K-feldspar leucosome (Figs. 10A, 10B) deflected by stretching into the neckline of a boudin. Based on shear-sense indicators within this leucosome and others, we conclude that anatexis was synchronous with (or slightly older than) ductile extension in this outcrop.

The zircons in the leucosome define four CL domain types: (1) inner cores with faint oscillatory zoning and moderately dark CL, (2) outer cores with dark CL and no zoning; (3) inner rims with bright CL and no zoning, and (4) outer rims with moderately bright CL and barely visible zoning (Fig. 11A). Most of the inner and outer core analyses, domains 1 and 2, can be interpreted as a single population that formed in a series of events, close in time, and under varying chemical conditions. The inner cores are typically less U rich and more concordant than high-U outer cores (Table S1)[3]. Two inner cores, sampled by analyses 1.1 and 2.1, are structurally separated from the non-luminescent outer cores and represent a population of older zircon (2652 ± 25 Ma), perhaps inherited from the host tonalite gneiss. The other core analyses (13 in total of domains 1 and 2) define a discordia with an upper intercept age of 2501 ± 15 Ma (MSWD = 2.9). We interpret this as the age of leucosome formation and partial melting in this outcrop (Fig. 12A; Table 1). Spot analyses of the outer rims (Fig. 11A), excluding two points with high common Pb, define a weighted mean $^{206}Pb/^{238}U$ date of 546 ± 11 Ma (Fig. 12B), interpreted as the date of recrystallization and metamorphic growth of rim zircon.

Sample MAE-1018B

Outcrop MAE-1018 is situated south of Maevatanana within the Betsiboka Suite of the Antananarivo domain (Fig. 2*b*). Sample MAE-1018B is an aplite granite dike that cuts across the anatectic fabric of the host gneiss (Fig. 10D). Zircon in this sample consist of CL-bright cores with sector zoning (domain 1), surrounded by CL-dark inner rims (domain 2) that are, in turn, surrounded by outer rims (domain 2) with moderate to high brightness of CL and no visible structure (Figs. 11C, 11D). Two of 12 analyses of domain 1 cores are excluded on technical grounds; analysis 4.1 has high content of common Pb, and spot analysis 10.2 is situated on a small core, possibly overlapping an inner rim.

Cores and rims form two distinct age groups. Domain 1 cores have $^{206}Pb/^{238}U$ dates between 736 and 806 Ma (Figs. 12C, 12D). Nine of 10 analyses are consistent, within error, yielding a weighted average of $^{206}Pb/^{238}U$ date of 760 ± 11 Ma. This is our best estimate for the age of aplite emplacement and the minimum date of partial melting in

Fig. 7. The newly defined Mesoarchean Fenerivo Group. (A) Kyanite–fuschite schist. (B) Layered garnet–magnetite quartzite (banded iron formation). (C) Recumbently folded kyanite schist and amphibolite. (D) Migmatitic quartzo-feldspathic gneiss and boudin of amphibolite. Sample TAM-08-9A is feldspar–quartz-rich layer within the paragneiss. (E) The key outcrop of TAM-08-9 showing the relationship between quartzo-feldspathic gneiss (circled A) sheets and boudins of amphibolite (mafic dikes, circled B), leucocratic migmatite (circled C), and youngest crosscutting granite dike (circled D). (F) Close-up of the granite dike (TAM-08-9D) showing xenoliths of paragneiss migmatite. Photos C, D, E, and F courtesy of E. Ortega.

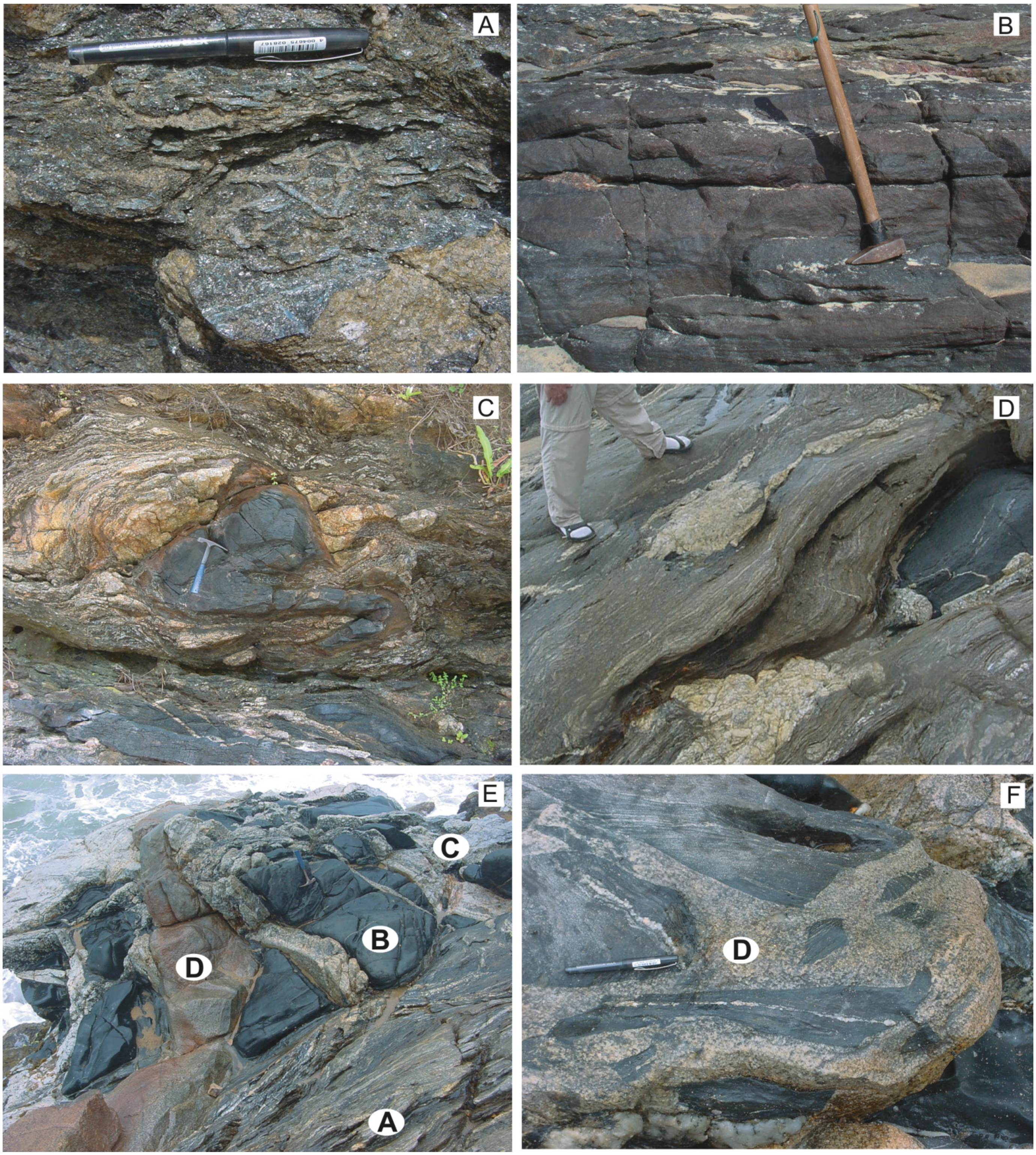
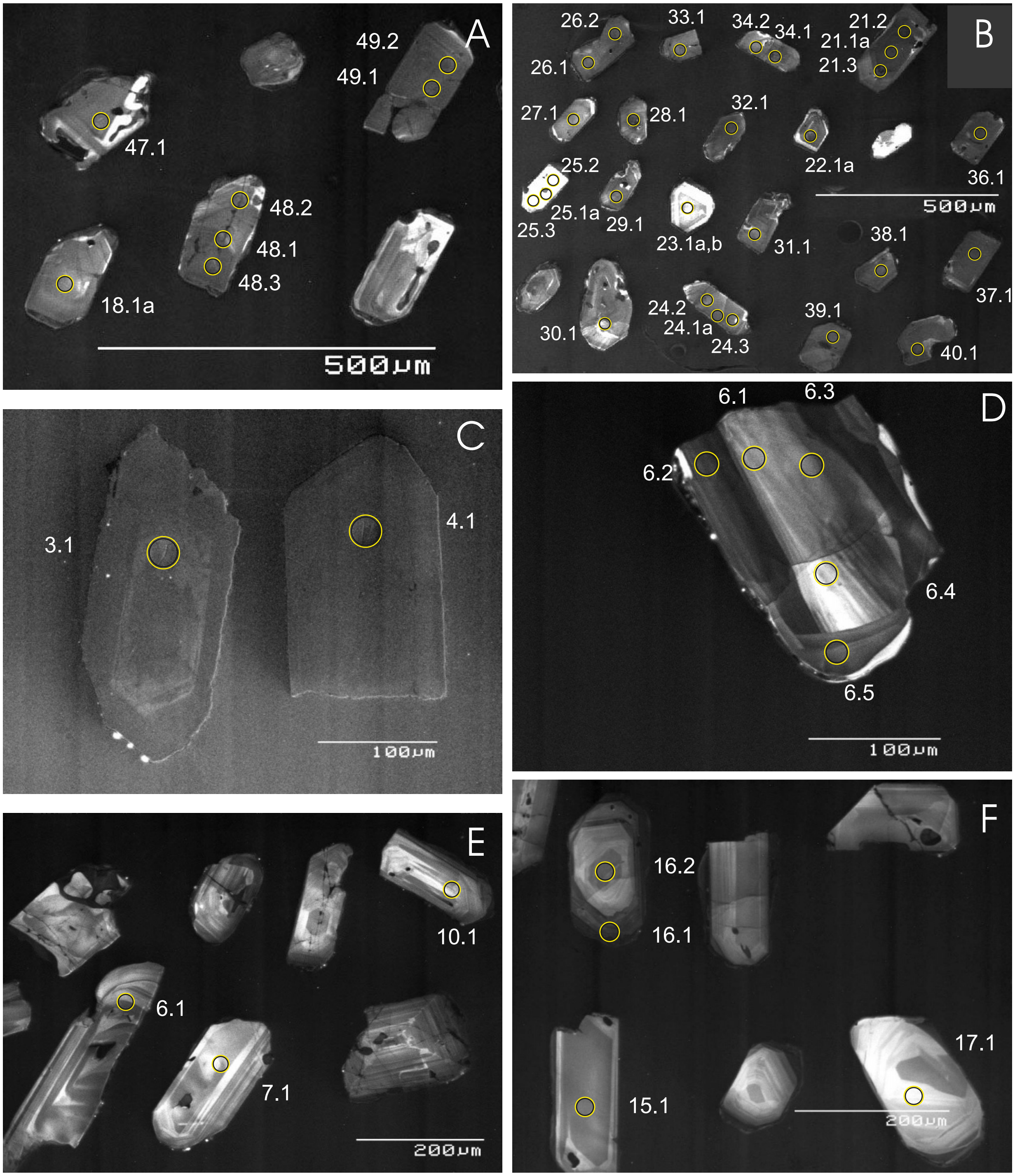


Fig. 8. Cathodoluminescence images of zircon. (A, B) From sample TAM-08-9A. (C, D) From sample TAM-08-9C. (E,F) From sample TAM-08-9D. Numbers refer to spot analyses in Table S1.[3]



this outcrop. Spot analysis 7.3 (Table S1)[3] was made on a narrow, dark zone having a significantly higher U and Th/U than other domain 1 analyses, and it yielded a precise but slightly older $^{206}Pb/^{238}U$ date of 806 ± 25 Ma (2σ). We suggest that it is an old, inherited zircon component. The weighted average of the $^{206}Pb/^{238}U$ ages of the rims give an imprecise date of metamorphism of 510 ± 27 Ma (Table S1)[3].

Sample MAE-1023B

Two rocks are present at outcrop MAE-1023, within the Tsaratanana Complex: (1) a lineated and ductilely folded migmatite gneiss, and (2) an aplite granite dike, 50 cm thick, that cuts across the anatectic fabric of the gneiss (Fig. 10E). Both gneiss and aplite are highly deformed and folded, but the field relations indicate that the older gneiss (1) was partially melted and injected by coarse granite peg-

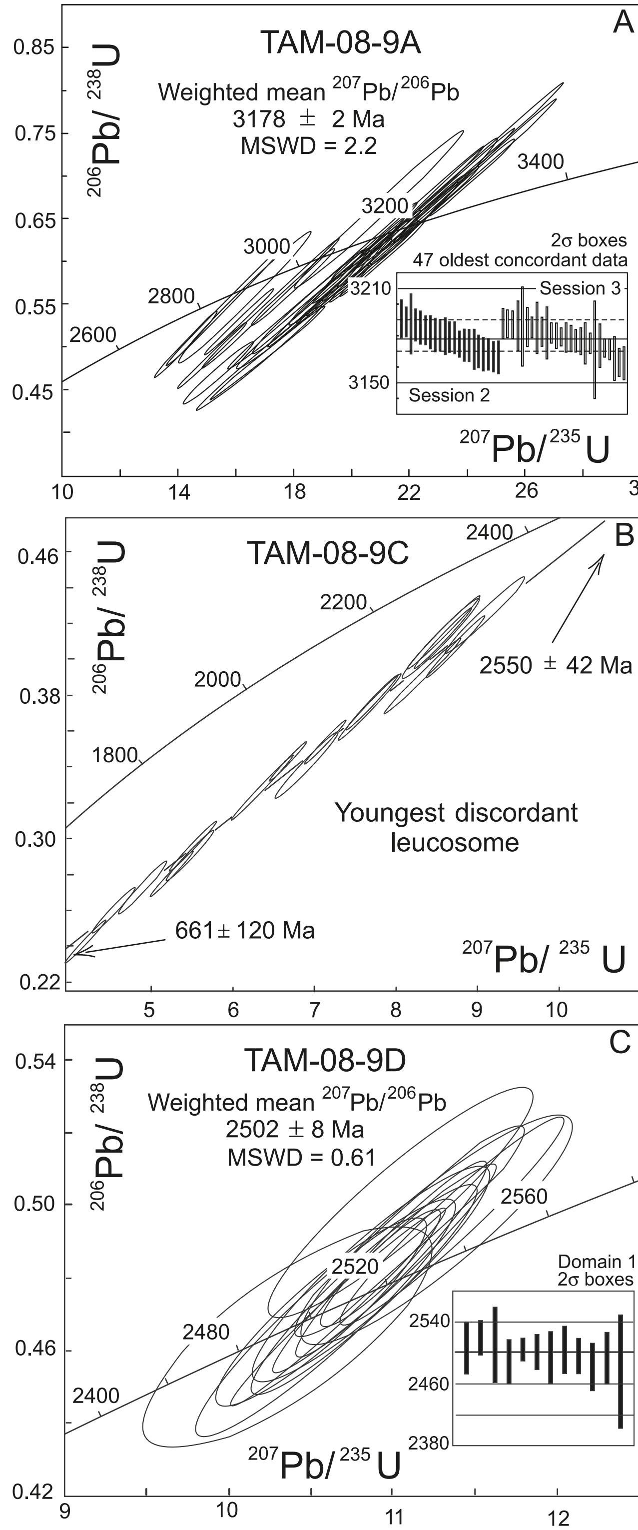


Fig. 9. (A) Concordia diagram of domain 1 zircons from the metarhyolite (TAM-08-9A) south of Soanierana-Ivongo (Antongil domain). Weighted mean $^{207}Pb/^{206}Pb$ age of 47 concordant analyses (inset) is 3178 ± 2 Ma, interpreted as the crystallization age of the rhyolite protolith and the depositional age of the Fenerivo Group. (B) Concordia diagram of 18 high-U zircons from the discordant leucosome (TAM-08-9C) south of Soanierana-Ivongo (Antongil domain). Upper intercept of all analyses (2550 ± 42 Ma) is interpreted as the crystallization age of the leucosome and minimum age of anatectic melting at this outcrop (Fenerivo Group). (C) Concordia diagram of domain 1 cores from the discordant granite dike (TAM-08-9D) south of Soanierana-Ivongo (Antongil domain). The upper intercept closely approximates the age of emplacement, but the weighted mean $^{207}Pb/^{206}Pb$ age of the concordant analyses (2502 ± 8 Ma, inset) is best interpreted as the age of the granite dike and the terminal date of Archean metamorphism and granite emplacement in the Antongil domain.

matite, prior to the emplacement of the aplite dike. Our sample is MAE-1023B, the younger crosscutting aplite dike.

Zircons in this sample comprise three domains: (1) rare CL-dark, high-U cores; (2) brightly luminescent cores with sector zoning; and (3) CL-bright rims with sharp, wellpreserved oscillatory zoning (Figs. 11E, 11F). In most grains, domains 1 and 2 are euhedral and domain 3 rims overgrow them without visible discontinuities. The very low-U content of all cores and rims limits the counting statistics of SHRIMP analysis, thus reducing precision of the isotopic ages.

Twenty-two analyses from 17 grains plot as a compact cluster of data points; two are excluded from the age calculation. Analysis 2.2, a high-U zircon, is quite different from the larger population, and its anomalously young $^{206}Pb/^{238}U$ date suggests substantial loss of radiogenic Pb. The second rejected analysis, spot 5.2, is a zircon with low Th/U within a larger population having high and uniform Th/U between 0.9 and 2.9 (Table S1)[3]. The other 20 data points, from all domain types, plot as a compact cluster of concordant analyses that define a weighted average date of 770 ± 10 Ma (Figs. 12E, 12F). This is the best estimate for the age of aplite dike emplacement. As is the case for MAE-1018B, ductile folding and anatexis of the gneissic protolith must be older than ca. 770 Ma.

Archean detritus in the Betsimisaraka domain

Three points in favour of the “Betsimisaraka suture” are (BGS et al. 2008) (1) the composition of the protoliths is consistent with an oceanic setting, (2) the reported unimodal Neoproterozoic provenance (790 Ma) demonstrates its young age, and (3) the lack of Archean detritus proves that it was deposited far from continental sources of the Antananarivo and Antongil–Masora domains. We address the provenance of the Betsimisaraka domain with detrital zircon geochronology of two metaquartzites in the Manampotsy Group (Fig. 2*b*).

Metaquartzite in the eastern Manampotsy Group

Sample RT-08-12

Sample RT-08-12 is a coarse-grained very pure metaquartzite, 15 m thick, in the Manampotsy Group south of Tamatave (Figs. 2, 10F). Zircons in this sample consist of four domain types (Figs. 13A, 13B): (1) CL-bright cores and grains with sector zoning, (2) CL-bright cores and grains with oscillatory zoning, (3) CL-dark cores with no zoning, and (4) CL-dark rims. Fifty zircon cores from domain types 1–3 were analyzed, and their actinide concentrations and elemental rations are consistent with derivation from igneous or metamorphic rocks of granitic composition

Fig. 10. (A, B) Field photographs of sample MAE-1005, south of Maevatanana. (A) Tonalite migmatite gneiss with pencil-thin layer-parallel leucosomes, coalesced into a shear zone with top-to-the-south -southwest extension (Antananarivo domain). (B) Layer-parallel leucosomes, 2–3 cm thick, deflected and collected to the neck of a boudin; boudinage deflects the gneissic foliation. (C) Xenolith of Archean migmatite gneiss in gabbro of the Itsindro–Imorona Suite (Bekadoka inlier, photo from CGS 2009b). (D) Archean migmatite gneiss intruded by foliated aplite dike (MAE-1018B), south of Maevatanana (Antananarivo domain). (E) Archean migmatite gneiss intruded by granite aplite dike (MAE-1023D, Tsaratanana Complex). (F) RT-08-12, massive cliff of coarse-grained, very pure metaquartzite of Manampotsy Group (between Tamatave and Brickaville). Hammer for scale in (A) to (E). People for scale in (F).

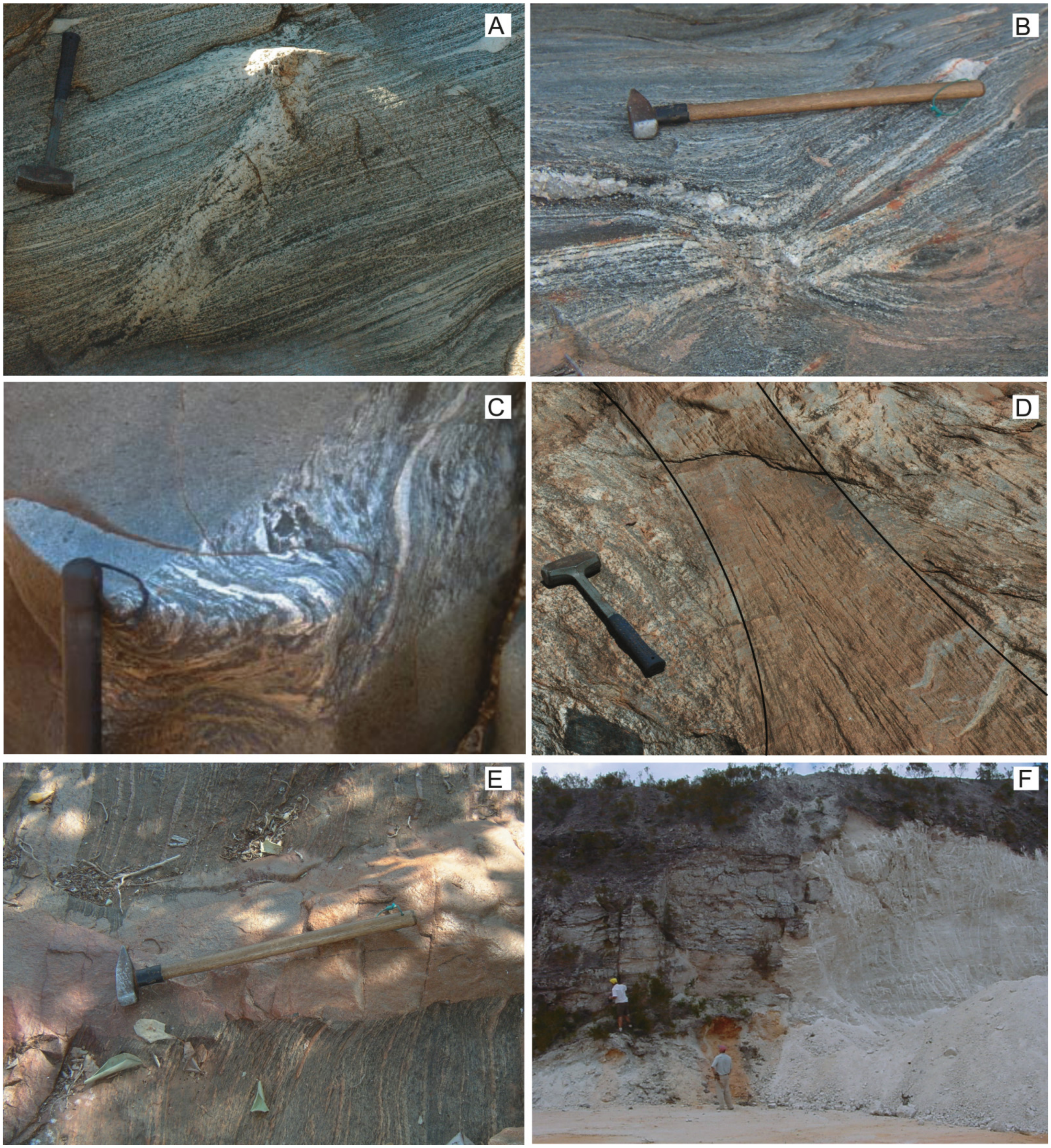
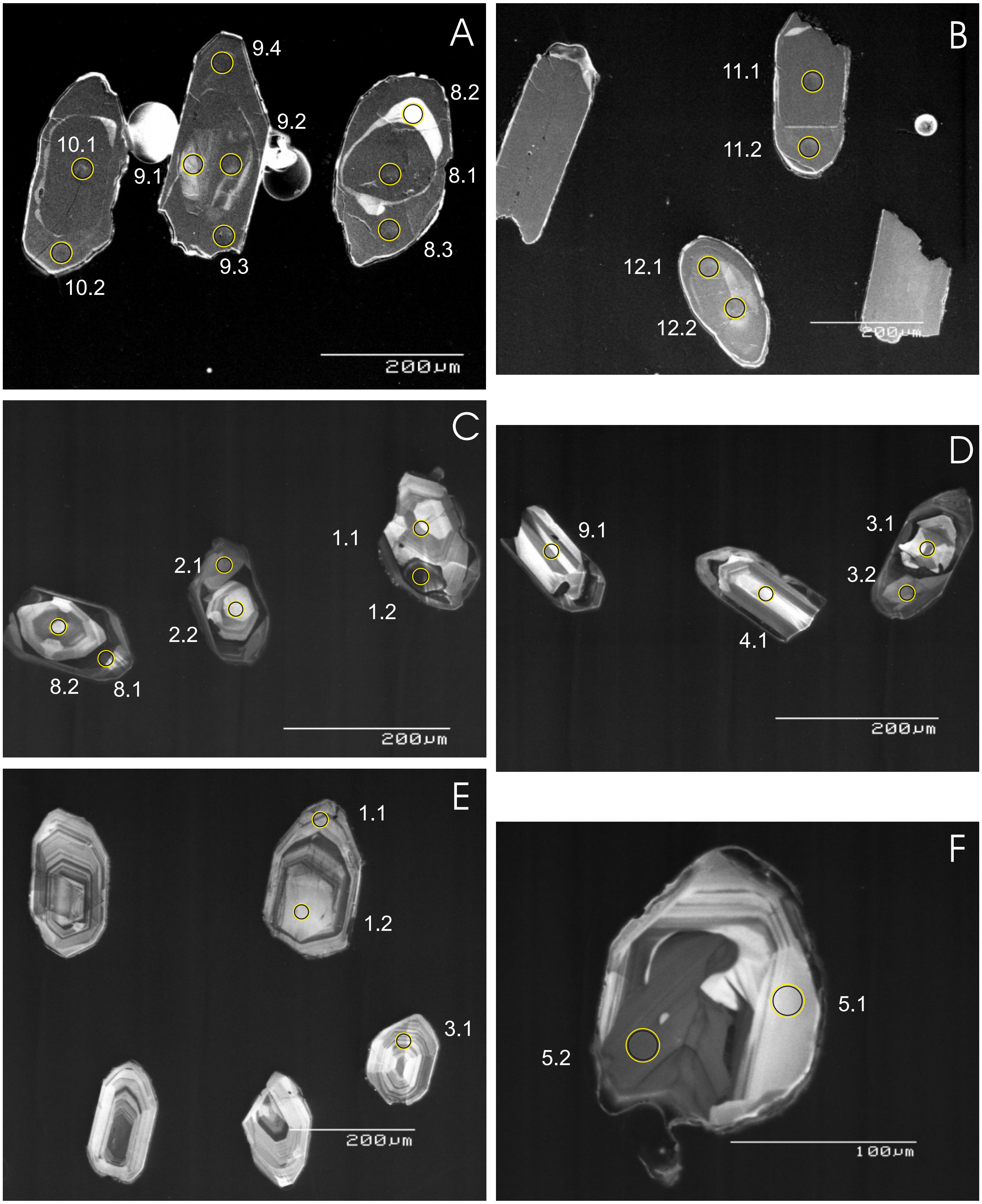


Fig. 11. Cathodoluminescence images of zircon. (A, B) From sample MAE-1005C. (C, D) From sample MAE-1018B. (E, F) From sample MAE-1023B. Numbers refer to spot analyses in Table S1.[3]



(Table S1)[3]. Because all analyses are concordant (or nearly so), their individual $^{207}Pb/^{206}Pb$ dates closely approximate the age of their source rocks (Fig. 14A). At first inspection, nine age groups are represented: ca. 2.95, 2.71, 2.61, 2.52, 2.42, 2.35, 2.21, 2.00, and 1.91 Ga. The distribution, however, of $^{207}Pb/^{206}Pb$ ages is broadly bimodal (70% of the population) with two major peaks at 2.55–2.38 Ga and 2.05–1.86 Ga. The remaining 30% of the population include concordant grains dated between 2.60 and 2.95, 2.2 and 2.0, and 1.84 and 1.55 Ga. All rim analyses yield concordant and consistent U–Pb data with a weighted average $^{206}Pb/^{238}U$ date of 538 ± 16 Ma that we interpret as the age of metamorphic recrystallization and zircon growth (Fig. 14A, inset).

Metaquartzite in the western Manampotsy Group

Sample TAM-08-17

Sample TAM-08-17 is a foliated metaquartzite in quartzo-feldspathic gneiss of the Manampotsy Group from the western part of the Betsimisaraka domain (Fig. 2*b*; Delbos et al. 1962). The detrital zircons are well rounded, reflecting a high degree of mechanical abrasion, and they consist of three types (Figs. 13C, 13D): (1) CL-medium to bright, sector-zoned cores, (2) CL-dark, structureless cores, and (3) rims of variable CL brightness, representing a small part of the population. Domain type 3 rims are too thin to be analyzed by SHRIMP.

A total of 55 grains were analyzed (Fig. 14B). The U concentrations are low to moderate (34–656 ppm), the Th/U ratios are variable (0.21 to 0.37), and the CL brightness is negatively correlated with U concentration (Table S1)[3]. All data are consistent with zircon crystallization in igneous or metamorphic rocks of granitic composition.

The analyzed population includes two cores with very old $^{207}Pb/^{206}Pb$ date of 3571 ± 74 Ma (2σ) and 3642 ± 16 Ma (2σ); these are the oldest known zircons in Madagascar. The youngest of these (3571 Ma) was obtained from a small sector-zoned grain (grain 11, Table S1[3]) with a CL-dark rim (2444 Ma). Thus, this single grain exhibits the periods of Archean zircon growth that mimic the history of the Antongil domain.

The main population of cores is concordant (Fig. 14B), and almost half of the analyzed grains have $^{207}Pb/^{206}Pb$ ages between 1.90 and 2.00 Ga. Two smaller but still prominent peaks are at 2.66 ± 0.05 and 2.49 ± 0.05 Ga. Five grains with $^{207}Pb/^{206}Pb$ ages between 1.80 and 1.84 Ga constitute the fourth peak, and the youngest grain is 1.67 Ga. As with sample RT-08-12, there is no correlation among U concentration, Th/U, CL appearance, and age.

Neoproterozoic harzburgite–gabbro

The tiny disrupted lenses of metamorphosed mafic and ultramafic rocks in the Manampotsy Group are a compelling point in favour of an oceanic suture, but little is known about their age or geochemistry. We report below our new isotopic age for the Ambodilafa ultramafic–mafic intrusion at the western margin of the Masora domain only a few kilometres from the site of the proposed suture.

Amboodilafa Ultramafic Complex, Masora domain

Sample ALF-6

The intrusion of Ambodilafa (also known as Vohipaka) is an arcuate, north–south-trending rectangular complex of mafic and ultramafic igneous rock, situated 150 km north-northwest of Mananjary (Fig. 2*b*). Geologic mapping has delineated both ultramafic and mafic divisions. The ultramafic rocks, consisting of layered peridotite, harzburgite, and olivine clinopyroxenite, are most common in the south and northwest part of the body. The mafic rocks, consisting of olivine gabbro, olivine gabbronorite, gabbro, and magnetite gabbro, exhibit well-defined cyclic layers with shallow to moderate outward dips, suggesting an overall domical shape for the intrusion. Our sample (ALF-6) is a medium-grained clinopyroxene hornblende gabbro, sampled at 192–194 m depth, from a drill hole at the east margin of the intrusion (Mineral Resources of Madagascar, Jubilee Platinum PLC).

The zircons comprise a simple population of stubby, euhedral, CL-dark crystals, mostly homogeneous or showing faint zoning (Figs. 13E, 13F). There are no clear core–rim relationships, but some grains contain inclusions of apatite, and their U concentrations and Th/U ratios are moderate to high (Table S1)[3]. All factors are consistent with their crystallization in magma of gabbroic composition.

U–Pb data are concordant to slightly (negatively) discordant. The $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ dates are consistent and yield weighted average dates of 815.4 ± 8.4 and 794.2 ± 9.4 Ma, respectively. These values are slightly discrepant, and this complicates the determination of a precise age. Our best estimate is given by the $^{207}Pb/^{206}Pb$ age of all analyses that are concordant within 4% or better (10 of 17 analyses). The age of emplacement and gabbro crystallization is, therefore, 806 ± 8 Ma (Fig. 14C).

Discussion

New indications of Paleo- and Mesoarchean crust

We present three new U–Pb SHRIMP ages for the Nosy Boraha Suite that extend the age of the oldest rocks in Madagascar to the Paleoarchean era. Two of our samples, RT-02O-76A and RT-02O-52A, are tonalite–granodiorite migmatites from the southern part of the Antongil domain. The third, RT-02M-105A, is granodiorite migmatite gneiss from the eastern part of the Masora domain. Together with published data, a period of crust formation dated between 3.313 and 3.154 Ga is established for the Nosy Boraha Suite (Fig. 3). The ancient rocks of Madagascar are thus broadly coeval with oldest parts of the Western Dharwar Craton (Peninsular Gneiss Complex) whose period of formation is 3.4–2.5 Ga (Peucat et al. 1995, Jayananda et al. 1995, 2000, 2006, and Chadwick et al. 2000). Both suites consist of complex migmatitic orthogneisses of TTG composition.

Our new data from the Mananara Group (north of Fenerivo) demonstrates that part of it is of Mesoarchean age (3.178 Ga) and was subject to polyphase deformation, metamorphism, and partial melting at 2550 ± 42 Ma (TAM-08-9A, TAM-08-9C, Fig. 3). BGS et al. (2008) have shown the supracrustal rocks (metavolcanics and quartzite) of the "type" Mananara Group were deposited between 2.541 and 2.507 Ga, and Collins et al. (2003*b*) proposed that the supracrustals near Fenerivo are <710 (± 11) million years old. Both interpretations are incompatible with our data.

We are confident that the Collins et al. (2003*b*) determination is incorrect because the supracrustal rocks near Fenerivo are partially melted and invaded by granite of Neoarchean age (e.g., Schofield et al. submitted). The data of BGS et al. (2008), however, are analytically sound, and we propose a modification of the nomenclature. Because the "type" Mananara Group crops out west and north of Soanierana-Ivongo, and the two units differ in rock association and metamorphic grade, we propose our section of newly identified Mesoarchean rocks be named the Fenerivo Group after the foreshore exposures between Fenerivo and Soanierana-Ivongo (Fig. 2*b*). Thus we suggest there are two

Fig. 12. (A) Concordia diagram of zircon cores (domains 1 and 2) from the leucosome (MAE-1005C) south of Maevatanana (Antananarivo domain). Regression of 13 discordant analyses of high-U zircons yields an upper intercept age of 2501 ± 15 Ma, interpreted as the crystallization age of the leucosome and the time of anatexis of the Betsiboka Suite. (B) Concordia diagram of zircon outer rims (domain 4) from the leucosome (MAE-1005C) south of Maevatanana (Antananarivo domain). Weighted mean $^{206}Pb/^{238}U$ age of the concordant analyses is 546 ± 11 Ma, interpreted as the age of the metamorphic rims on the leucosome zircons. (C) Concordia diagram of sector-zoned cores (domain 2) from the aplite granite (MAE-1018B) south of Maevatanana (Antananarivo domain). Weighted mean $^{206}Pb/^{238}U$ age of the concordant analyses is 760 ± 11 Ma, interpreted as the emplacement age of the aplite and the minimum age of partial melting in this outcrop. (D) Weighted mean calculation of $^{206}Pb/^{238}U$ age of concordant sector-zoned cores from the aplite dike (MAE-1018B) south of Maevatanana (Antananarivo domain). Weighted mean $^{206}Pb/^{238}U$ age of the concordant analyses is 760 ± 11 Ma, interpreted as the emplacement age of the aplite and the minimum age of partial melting in this outcrop. (E) Concordia diagram of concordant sector-zoned cores from the aplite dike (MAE-1023B) south of Maevatanana (Tsaratanana Complex). Weighted mean $^{206}Pb/^{238}U$ age of the concordant analyses is 770 ± 10 Ma, interpreted as the emplacement age of the aplite and the minimum age of partial melting in this outcrop. (F) Weighted mean calculation of $^{206}Pb/^{238}U$ age of concordant sector-zoned cores from the aplite dike (MAE-1023B) south of Maevatanana (Tsaratanana Complex). Weighted mean $^{206}Pb/^{238}U$ age of the concordant analyses is 770 ± 10 Ma, interpreted as the emplacement age of the aplite and the minimum age of partial melting in this outcrop.

(or more) Archean supracrustal successions in the Antongil domain: the older, the Fenerivo Group (3.178 Ga), is broadly coeval with the Sargur Group of the Western Dharwar Craton (Nutman et al. 1992) that overlies, and is deformed with, the Peninsular Gneisses. The younger, the Mananara Group (2.541–2.507 Ga), is coeval with part of the Dharwar Supergroup (3.02–2.52 Ga; Peucat et al. 1995, Nutman et al. 1996, Trendall et al. 1997*a*, 1997*b*).

Both the Fenerivo and Mananara groups are intruded by weakly foliated granitoids of the Masoala Suite (2.55–2.51 Ga), whose period of emplacement we extend to 2.502 Ga (Fig. 3). The oldest of these are coeval with the period of metamorphism and anatexis we identify at Fenerivo. Thus, while we are unsure of the mechanism that generated the suite, we are confident that an event (or series of events) of Neoarchean age affected the whole of the Antongil beginning as early as 2.55 Ga and continuing to 2.48 Ga. In a general way, this period of Neoarchean–Paleoproterozoic reworking corresponds to the major episode of crust formation in the south and eastern part of the Dharwar Craton (Peucat et al. 1993, Jayananda et al. 2000, 2006, Chardon et al. 2002, Clark et al. 2009). Like the granitoids of the Masoala Suite (Tucker et al. 1999), their Nd and Sr isotopic characteristics (Krogstad et al. 1995) demonstrate a major juvenile input to their genesis. In this same period of time, the sedimentary rocks of the "type" Mananara Group were apparently deposited.

Reconsidering the "Betsimisaraka suture"

Our SHRIMP geochronology forces a reassessment of the "Betsimisaraka suture" whose primary tenets include the following:

(1) Distinctively different Archean histories of the Antananarivo and Antongil–Masora domains.

(2) Uniquely African-sourced rocks in the Antananarivo domain.

(3) Neoproterozoic (840–760 Ma) supra-subduction igneous rocks of the Antananarivo domain.

(4) Absence of late Neoproterozoic overprinting of the Antongil–Masora domain.

(5) Presence of metamafic and ultramafic rocks of purported oceanic origin.

(6) Oceanic provenance and age of the Manampotsy Group.

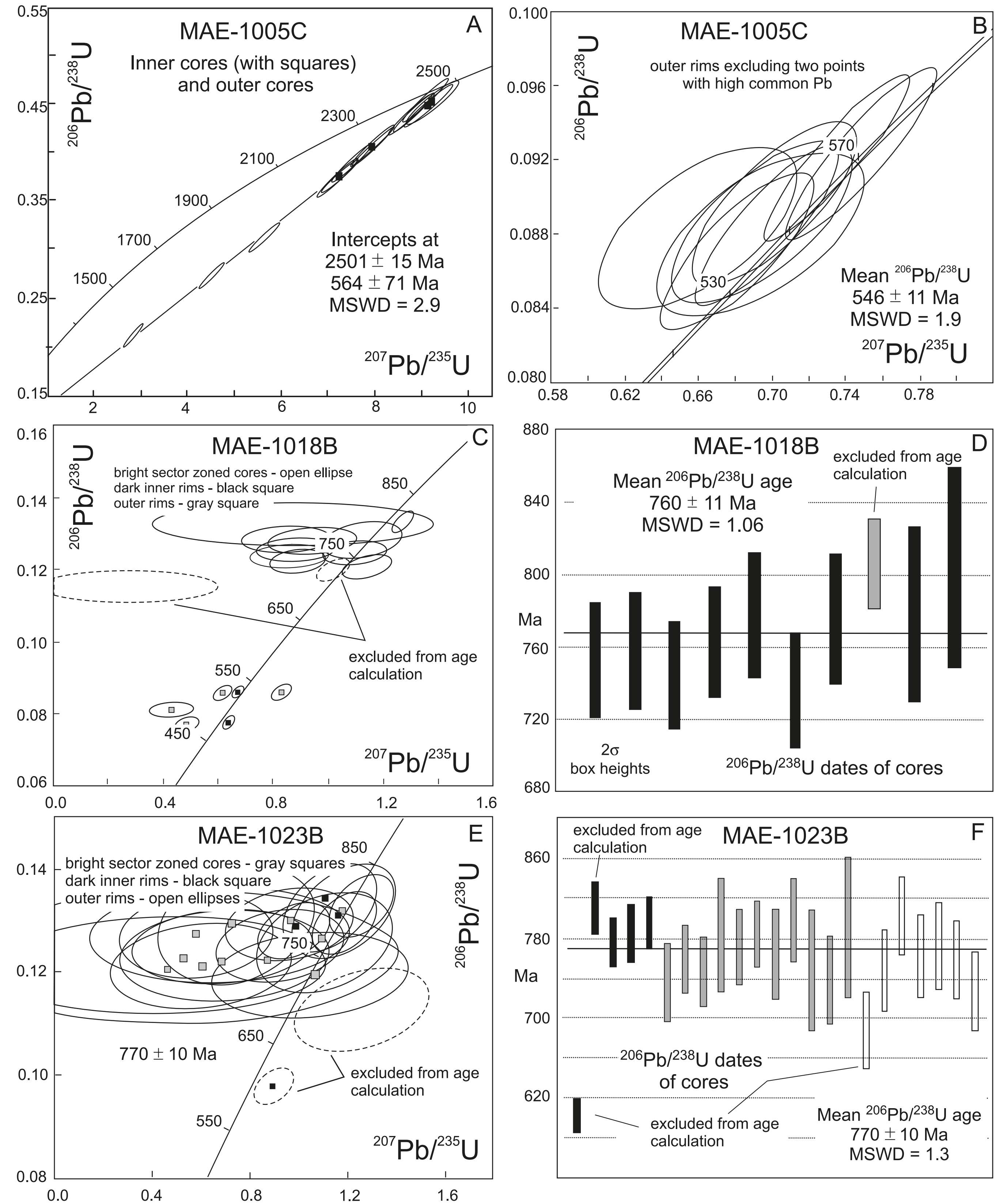
Is Archean distinctiveness proof of Neoproterozoic suturing?

The "Betsimisaraka suture" reportedly joins blocks of different Archean age and history (Kröner et al. 2000; Collins and Windley 2002). Although some differences are real, two lines of evidence suggest they were **not** joined in the Neoproterozoic:

(1) The depleted mantle ages (Sm/Nd) of 2.55–3.21 Ga for gneisses of the Antananarivo domain (including the Tsaratanana Complex) implies their derivation from sources that were variably mixed with, or melted from, ancient crust (Paleo- and Mesoarchean) (Tucker et al. 1999). A likely candidate is the Antongil–Masora domain.

(2) Both Archean domains (Antananarivo and Antongil–Masora) share a common history of Neoarchean–Paleoproterozoic magmatism, deformation, metamorphism, and anatexis (Fig. 3). The established period of reworking in the Antananarivo–Tsaratanana domain is 2506–2390 Ma (Paquette et al. 2004; Kabete et al. 2006; BGS et al. 2008, CGS 2009*b*); in the Antongil–Masora domain, it is 2550–2497 Ma (BGS et al. 2008; this paper). Our U–Pb SHRIMP data near Maevatanana (MAE-1005C) demonstrates that the Betsiboka Suite was subject to amphibolite-grade metamorphism, partial melting in Neoarchean time (2501 ± 15 Ma). From field evidence, we show that the overlying Tsaratanana Complex (Maevatanana Series) was deformed and partially melted prior to emplacement of aplite dikes dated at 780–770 Ma. The date of this early melting is inferred to be 2.5 Ga, the established age of partial melting at MAE-1005C. We suggest, therefore, that all the Archean rocks of Madagascar, including the mafic and felsic gneisses of the Antananarivo domain, were accreted to form a cratonic entity at ca. 2.5 Ga.

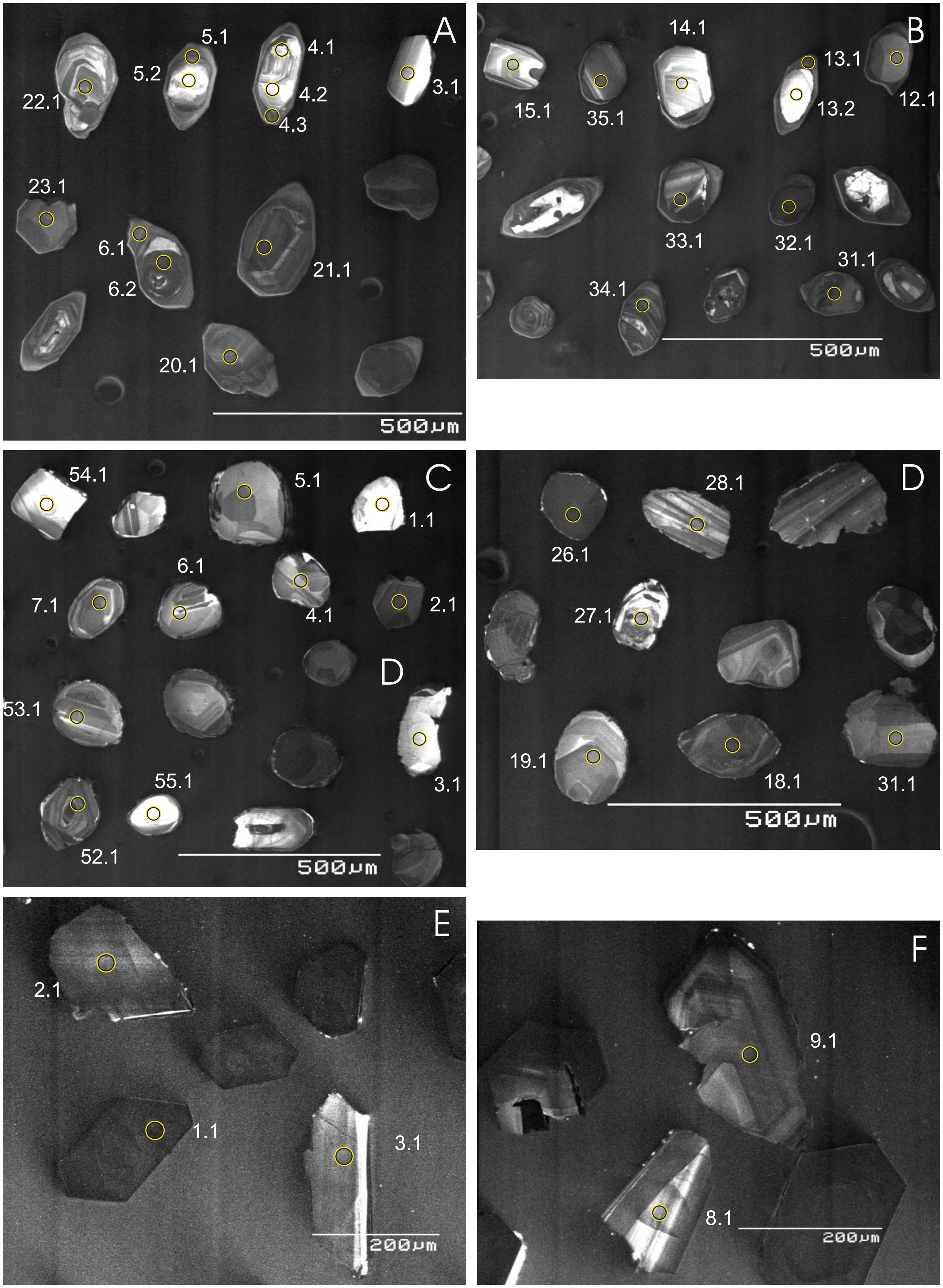
Thus Proterozoic suturing of different Archean blocks is not required. Indeed, many Archean cratons were assembled in latest Archean time (2.5 Ga), and the Dharwar Craton is a case in point, where the ancient gneisses and "greenstones" of its western part (3.5–2.7 Ga) were welded with juvenile elements of the eastern part (2.7–2.53 Ga) during a Neoarchean magmatic accretion event (Chardon et al. 2002). We propose a similar scenario for the development of the Malagasy shield.



Is Paleoproterozoic detritus unique to the Antananarivo domain?

It is suggested that the Itremo Group is of African provenance and that it, and its Neoarchean substrate, was joined with East Gondwana along the "Betsimisaraka suture" (Cox et al. 1998, 2004; Fitzsimons and Hulscher 2005; Collins 2006). The suggestion is based on a subset of detrital zircons, dated between 2.2 and 1.8 Ga, whose source rocks are

Fig. 13. Cathodoluminescence images of zircon. (A, B) From sample RT-08-12. (C, D) From sample TAM-08-17. (E, F) From sample ALF-6. Numbers refer to spot analyses in Table S1.[3]



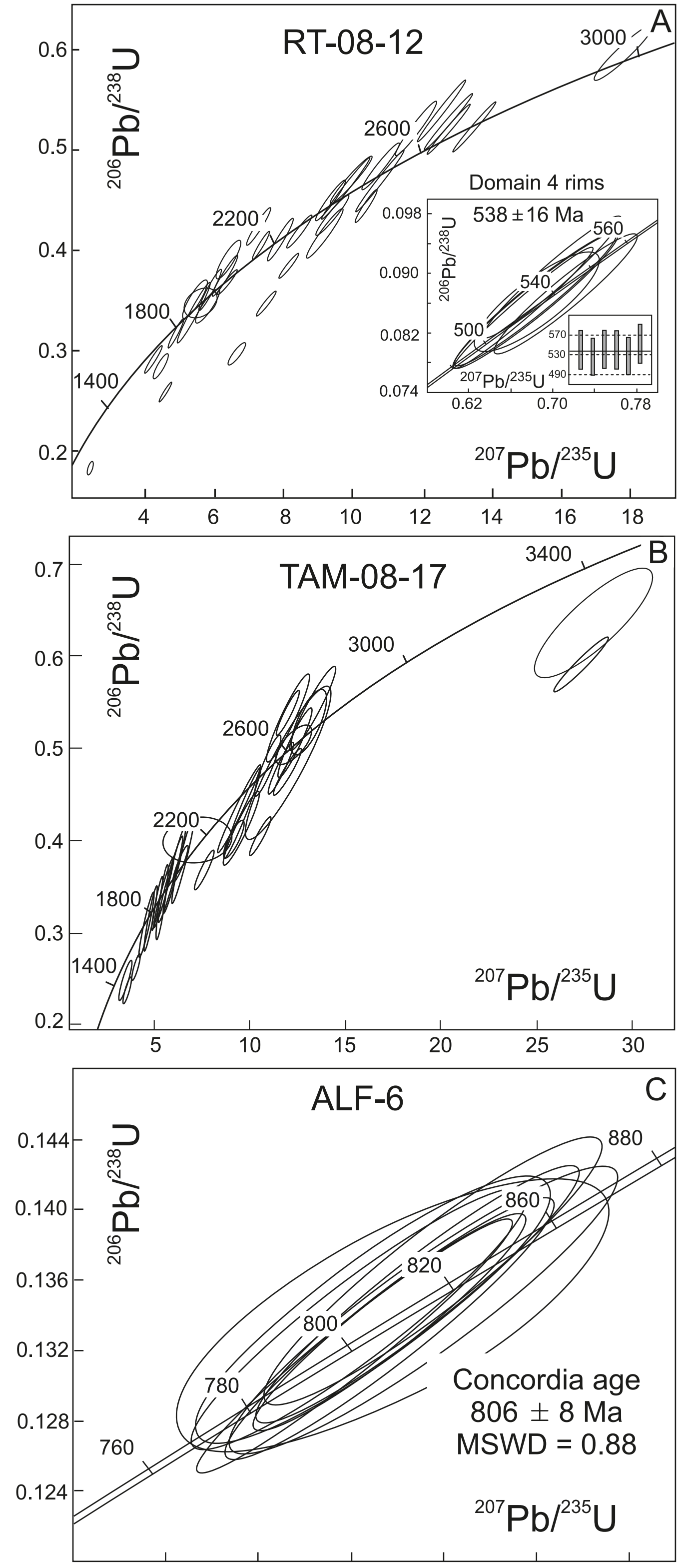


Fig. 14. (A) Concordia diagram of detrital zircons from the metaquartzite (RT-08-12, Manampotsy Group) in the eastern part of the Betsimisaraka domain. All analyses are concordant, and thus, the $^{207}Pb/^{206}Pb$ ages are a good approximation of the age of the source rocks. Note the abundance of Archean and Paleoproterozoic grains (inset). Weighted mean $^{206}Pb/^{238}U$ age of rim analyses (538 ± 16 Ma) interpreted as the time of rim growth and metamorphism of the quartzite. (B) Concordia diagram of detrital zircons from the metaquartzite (TAM-08-17, Manampotsy Group) in the western part of the Betsimisaraka domain. Note the abundance of Archean and Paleoproterozoic source rocks. (C) Concordia diagram of zircon analyses from the metagabbro of the Ambodilafa intrusion (ALF-6), Masora domain. All analyses are concordant and indicate crystallization of the gabbro protolith at 806 ± 8 Ma.

absent in Madagascar (Fig. 15). According to proponents of the "suture," bedrock of this age is known in the Tanzanian and Congo cratons, and thus, the source of detritus is from there or terranes derived from there. In a unique twist to the "out-of-Africa" hypothesis, DeWaele et al. (2008) propose that the Itremo and Maha groups are of African provenance but emplaced on the Antananarivo and Masora domains as an allochthonous sheet.

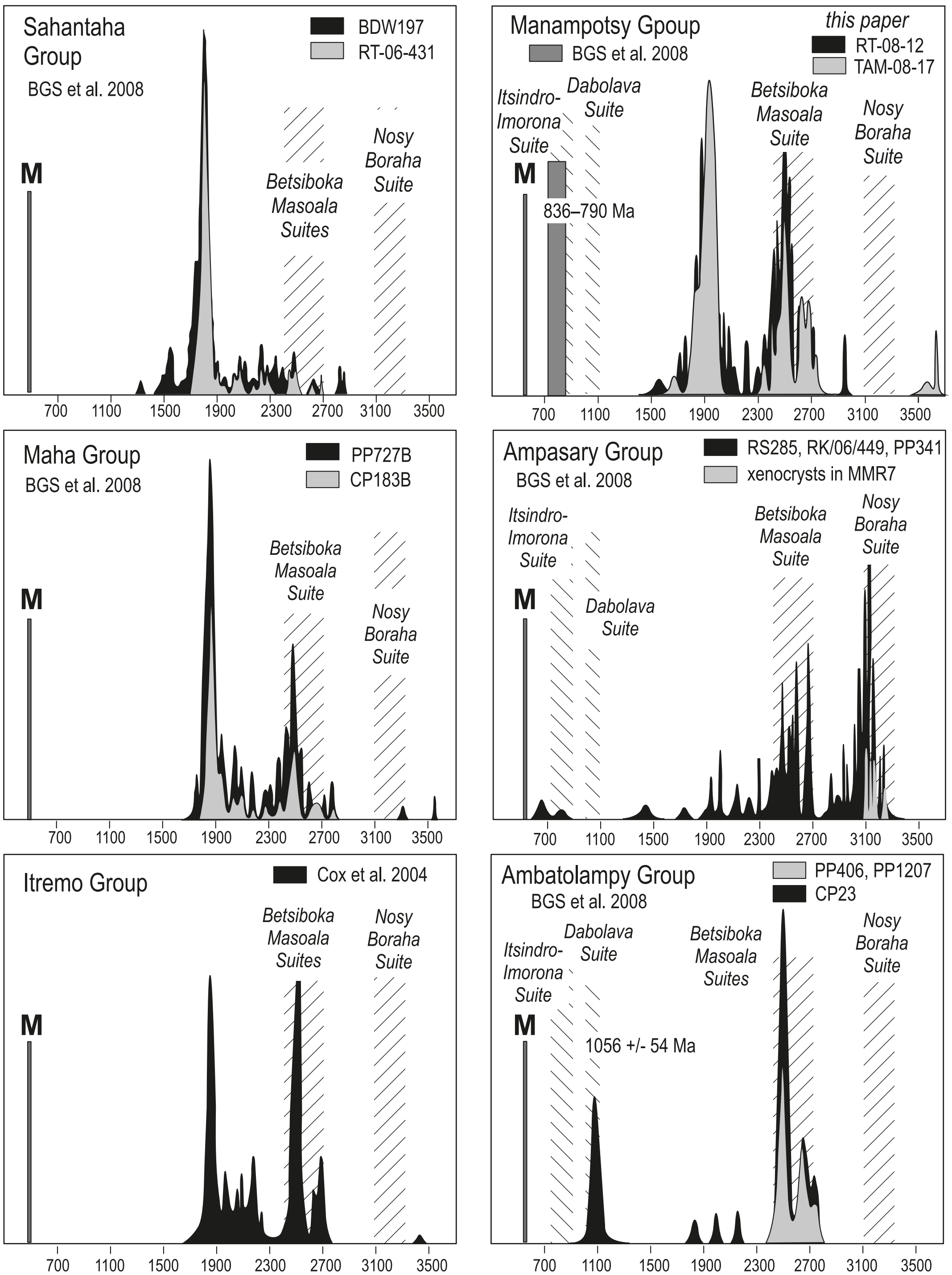
The analysis is flawed because (1) an identical age spectrum (2.2–1.8 Ga) is reported in clastic rocks west of the "suture" (Itremo Group, Ambatolampy Group), east of the "suture" (Maha Group), and within the "suture" (Manampotsy Group, Figs. 2*b*, 15). No matter the source of the Paleoproterozoic detritus, the signature is present across all the domains of central Madagascar, and thus, a "suture" does not explain its distribution. (2) There is no compelling evidence that the sedimentary groups constitute an allochthonous sheet **independent of their Archean substrates**. Indeed, if the Itremo and Maha groups comprise an allochthonous sheet, and we doubt that, the sheet must have been emplaced before 840–760 Ma, the age of the Itsindro–Imorona Suite that intrudes both "allochthon" and "autochthon" (Handke et al. 1999; BGS et al. 2008; GAF–BGR 2008; CGS 2009*a*). Unfortunately for advocates of the suture, the Masora domain was purportedly on the other side of the Mozambique Ocean at this time (840 Ma, Collins and Pisarevsky 2005; Raharimahefa and Kusky 2009). We propose, instead, that (1) detrital zircons may come from sources hundreds of kilometres from their final basin of deposition, (2) zircon may be recycled many times from many sources, and (3) geochronology (alone) cannot match detritus to specific source rocks. We posit that Palaeoproterozoic sources are not unique to Africa, and, indeed, potential sources may be present in Madagascar and other parts of East Gondwana (e.g., Sarkar et al. 1989; Wiedenbeck and Goswami 1994; Verma and Greiling 1995).

Is the Itsindro–Imorona Suite unique to the Antananarivo domain?

According to proponents, the "Betsimisaraka suture" is the relict of west-dipping (present-day direction) oceanic subduction (ca. 840–760 Ma). Thus, igneous rocks of suprasubduction origin (Itsindro–Imorona Suite) are widespread in the Antananarivo domain and purportedly absent in the Antongil–Masora domain.

The argument fails on two grounds: (1) New U–Pb geochronology and published data demonstrate that igneous rocks of the Itsindro–Imorona Suite are present across the Malagasy shield (Fig. 2*b*). BGS et al. (2008) have identified several granitic massifs in the Masora domain, and we have identified a mafic–ultramafic complex also in the Masora

Fig. 15. Synthesis of detrital zircons ages from the principal Proterozoic metasedimentary groups of Madagascar (after Cox et al. 2004, 2008; Fitzsimons and Hulscher 2005; BGS et al. 2008; DeWaele et al. 2008; this paper). The data are presented as a relative probability-density diagram (concordant data, 100 ± 10%). The left column illustrates the detrital age modes for the Sahantaha, Maha, and Itremo groups and their potential source rocks in Madagascar (the shaded fields of the Nosy Boraha, Betsiboka, and Masoala suites). The right column illustrates the detrital age modes for the Manampotsy, Ampasary, and Ambatolampy groups and their potential source rocks in Madagascar (the preceding plus the Dabolava and Itsindro–Imorona suites). The spectrum of xenocrystic zircons from gabbro sample MMR7 within the "Betsimisaraka suture" are shown in the box of Ampasary data (shaded). M, the age of metamorphism of the groups defined by concordant analyses of zircon rims.



(ALF-6). If a common suite of early and medial Neoproterozoic intrusions is present on both sides of the "suture," and indeed within the "suture" (i.e., Kröner et al. 2000), the Betsimisaraka domain is not the likely locus of Neoproterozoic convergence. (2) We challenge the supra-subduction origin of the Itsindro–Imorona Suite. Handke (2001) and

McMillan et al. (2003) both agree that the gabbroic rocks of the suite have trace element concentrations typical of melts from enriched lithospheric mantle (60–70 km depth). But McMillan et al. (2003) have shown that granitic rocks of the suite are best modelled as anatectic melts of garnet-bearing source rocks (lower continental crust); this is consistent with crustal anatexis triggered by advection of gabbroic magma. Moreover, the general bi-modal nature of the suite (gabbro and granite), and the nested geometry of the complexes, implies their emplacement via a system of pre-existing fractures in an active rift. Thus, the Itsindro–ImoronaS uite is compatible with an origin by crustal dilation and pressure-reduced melting of upwelling mantle, perhaps induced by magmatic underplating (plume generation) or lithospheric mantle delamination during continental breakup (e.g., Kröner et al. 2000). If the Itsindro–Imorona Suite is a reflection of continental of arc magmatism, the active convergent margin was likely west (present-day) of the Antananarivo domain (Handke et al. 1999; Bybee et al. 2010).

The "Betsimisaraka suture" as the margin of the East African Orogen

Proponents have suggested that the pristine nature of Archean rocks (Collins et al. 2003*a*), the robust quality of Rb/Sr data (Collins and Windley 2002) and the lower grade of Neoproterozoic metamorphism (ca. 550–530 Ma) in the Antongil–Masora domain (Collins 2006) delineate the "suture" as the eastern margin of the East African Orogen.

New and published isotopic age data indicate a regional Pan-African event between 524 and 516 throughout the Antongil–Masora domain, the same age as the Pan-African event in the Antananarivo domain. BGS et al. (2008) report extensive evidence of polyphase deformation and high-grade metamorphism throughout the Masora domain of latest Neoproterozoic age (524–516 Ma). In the northern Antongil domain, BGS et al. (2008) have documented metamorphic zircon growth between 553 and 526 Ma, and we report concordant zircons with ages of 582–535 Ma in the south. We concur that the intensity of Pan-African deformation is noticeably low in the Antongil domain. In the Masora domain, however, clearly east of the proposed suture, there is no clear difference, either in deformational intensity or grade of metamorphism, between it and the Antananarivo domain. The eastern margin of the East African Orogen does not coincide with the Betsimisaraka suture.

Are the mafic and ultramafic rocks of oceanic origin?

The mafic and ultramafic rocks of inferred oceanic origin are a compelling point in favour of a "suture," but a close examination suggests a different origin. Sample MMR7 (BGS et al. 2008) is one of many elongate masses of gabbro, pyroxenite, and harzburgite within the highly strained rocks of the Betsimisaraka domain west of Mananjary (Fig. 2*b*). Gem quality ruby is reported in the outcrop, both within the metagabbro and in desilicated contact zones between quartz-rich veins and metagabbro.

The isotopic data of MMR7 indicate assimilated of Archean zircon during gabbro emplacement. The recovered zircons are described as subround, with core and rim relationships, and SHRIMP analyses of zircon cores produced a range of dates between 3187 and 2958 Ma (Fig. 15; BGS et al. 2008). The isotopic data are not consistent with gabbro emplacement in oceanic lithosphere; rather, they require assimilation of Archean crust or sediment with Archean detritus. Moreover, the ultramafic–mafic igneous complex of Ambodilafa, now shown to be of the Itsindro–Imorona Suite (806 Ma), is situated close to the Betsimisaraka domain, only a few kilometres east of the Angavo–Ifanadiana high-strain zone. We suggest that the mafic–ultramafic rocks within the Betsimisaraka domain zone are tectonically deformed pieces of Neoproterozoic intrusions.

Age and provenance of the Betsimisaraka domain

BGS et al. (2008) and DeWaele et al. (2008) raise three points with regard to the Betsimisaraka domain: (1) the composition of the protoliths is consistent with marine deposition; (2) the protoliths, excluding those of the Ampasary Group, contain detrital zircons exclusively of Neoproterozoic age; and (3) two volcanic rocks have unimodal ages of 800 and 790 Ma, and a third paragneiss has a near-unimodal population at 840 Ma (DeWaele et al. 2008). Thus, it is inferred that the Neoproterozoic sedimentary protoliths, except those of the Ampasary Group, were deposited far from the Archean cratons of Antananarivo and Antongil and in a marine basin proximal to an active arc (hence volcaniclastic debris).

We address these points in sequence: (1) In addition to graphite schist and mafic–ultramafic rocks, the Manampotsy Group consists of abundant quartzo-feldspathic schist and paragneiss, pure metaquartzite, calc-silicate gneiss, and marble. Some sheets of metaquartzite are very thick (Fig. 10F), exceeding 25 m, and traceable for many kilometres (Delbos and Vionnet 1958; Delbos et al. 1962). (2) Our U–Pb geochronology demonstrates that Archean zircons are abundant in the Manampotsy Group, and their size, zoning patterns, and chemistry (U and Th concentrations) imply that they were derived from medium- to coarse-grained granitic rocks of igneous or metamorphic origin. The spectrum of Archean dates matches the age of bedrock in east and central Madagascar, and, in one case, the age of adjacent growth zones matches precisely the Archean history of the Antongil domain. (3) We do not recognize a "unimodal" provenance, nor do our observations demand deposition in an oceanic realm. Indeed, the composition of our samples (quartzite) and the spectrum of Archean to Proterozoic detrital zircons are consistent with deposition in an intra-continental setting.

The depositional age of the group, defined by our data, is between ca. 1.67 Ga and 838 Ma; the minimum age is constrained by the date of the Brickaville granite (838 Ma, BGS et al. 2008) that intrudes the group. The data of BGS et al. (2008), DeWaele et al. (2008), and Collins et al. (2003*b*) imply that part of the group is significantly younger than 838 Ma, perhaps as young as 780 Ma. Thus, it appears that sedimentation in the domain was synchronous with emplacement of the Itsindro–Imorona Suite (840–760 Ma) that intrudes it (Fig. 15).

An alternative proposal

The "Betsimisaraka suture" was proposed, in part, to explain the juxtaposition of different Archean domains. With its abandonment, we suggest that the Dharwar Craton (India) and the Malagasy shield represent parts of the same Archean entity — the Greater Dharwar Craton — reconstructed in Fig. 16 and described in the following text.

In common with many Archean cratons, the ancient rocks of Madagascar include a tripartite assemblage of the following:

(1) An oldest suite of TTG gneisses (Nosy Boraha Suite).
(2) Two or more generations of volcano-sedimentary sequences (i.e., Fenerivo and Mananara groups).
(3) A youngest suite of late to syntectonic calc-alkaline and potassic granitoids (Masoala Suite).

All paleo-reconstructions place the Dharwar Craton adjacent to Madagascar at the start of the Cambrian Period (e.g., Reeves et al. 2004). The Dharwar Craton is classically divided into a western and eastern part (Swami Nath et al. 1976). The Western Dharwar is underlain by the Peninsular gneisses (3.4–2.5 Ga) and two packages of volcano-sedimentary “greenstone” belts (Sargur Group, 3.3–3.0 Ga, and Dharwar Supergroup, 3.0–2.5 Ga). The Eastern Dharwar craton is dominated by late Archean granitic rocks (2.70–2.53), with minor TTG (ca. 3.1–3.0 Ga) and thin elongate volcano-sedimentary belts (3.0–2.5 Ga). The boundary between the two parts is a zone of mylonitic rocks that roughly follows the eastern margin of the Peninsular Gneisses. On the basis of conspicuous age and isotopic differences within the Eastern Dharwar, some have suggested there may be other cryptic sutures, for example, between the “greenstone belts” and adjacent gneissic terranes (e.g., Krogstad et al. 1989, 1991).

In its reconstructed position, the distribution of Neoarchean rocks about the Western Dharwar nucleus is striking (Fig. 16). To a first approximation, the Antongil–Masora domain is an extension of the Western Dharwar Craton; both share a common suite of ancient gneisses (3.30–3.17 Ga) and supracrustal packages (3.3 and 2.5 Ga), as well as a similar suite of younger granitoids (2.53–2.50 Ga) (Agrawal et al. 1992; Tucker et al. 1999; Paquette et al. 2003; Ghosh et al. 2004). Symmetrically disposed about this nucleus are, to the east, mostly juvenile belts of the Eastern Dharwar and, to the west of the ancient core, mostly juvenile rocks of the Antananarivo domain, including its distinctive belts of mafic gneiss and schist (Tsaratanana Complex). Structural and geochronologic investigations in the Andriamena district have led Roig et al.[4] to a similar conclusion. In broad terms, therefore, the Greater Dharwar Craton (Agrawal et al. 1992) consists of an ancient central nucleus, greater than 3.2 Ga, bordered on both sides by mostly (but not entirely) juvenile “granite–greenstone belts” (2.70–2.53 Ga). All of these have been metamorphosed and invaded by younger granitoids at 2.5 Ga. In the case of Madagascar, this western terrane of “juvenile” greenstone and granitic gneisses was strongly reworked during the Neoproterozoic, making identification of its Archean architecture difficult.

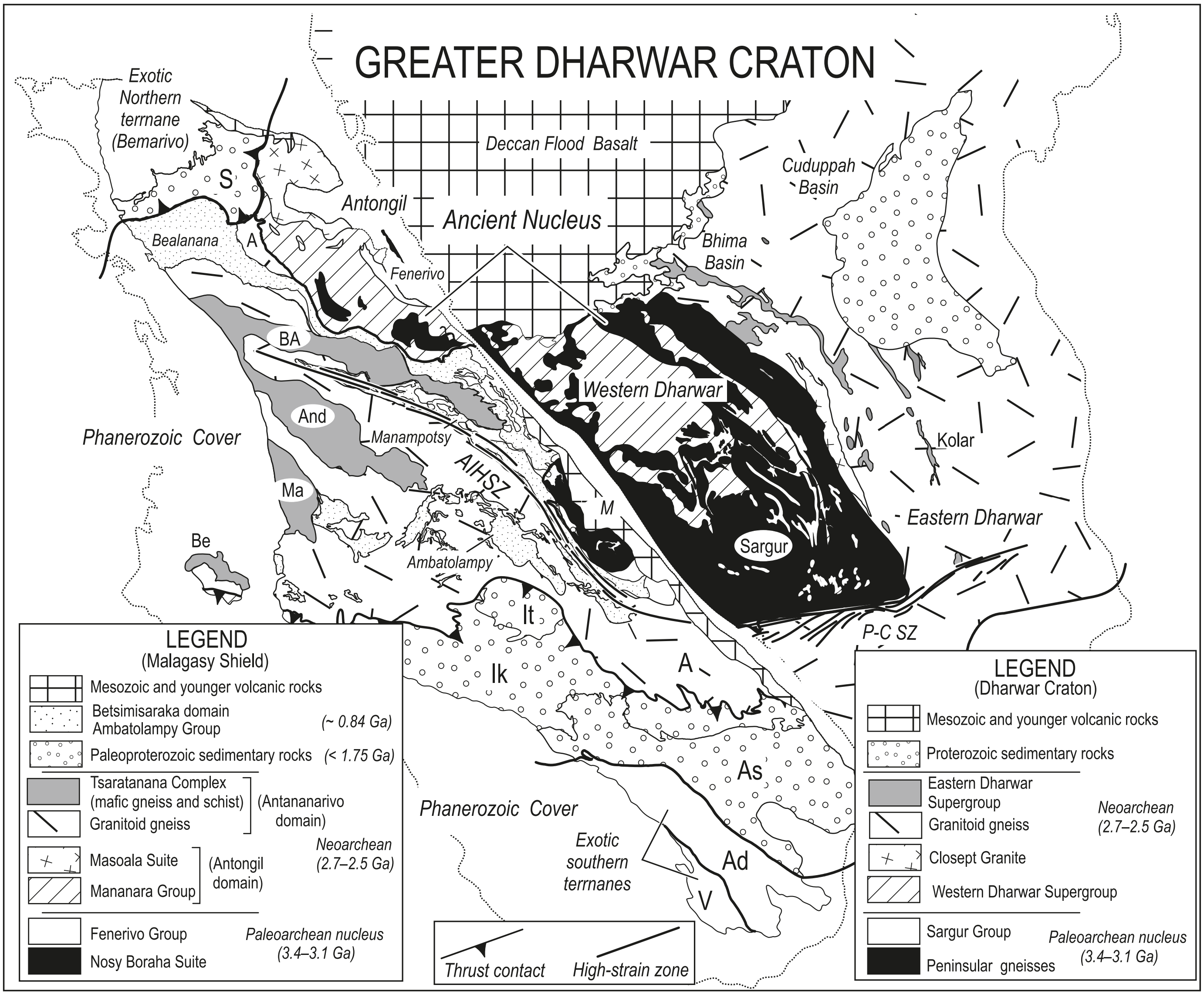
The Eastern and Western Dharwar experienced a “super accretion event” over a short time period (2.55–2.52 Ga) and over a wide area (>60 000 km^2) (Chadwick et al. 2000; Jayananda et al. 2000; Chardon et al. 2002). The development of the dominant north–south structural grain of the craton, and the emplacement of the Closepet batholith, were coeval with regional partial melting and granulite peak metamorphism at ca. 2.5 Ga (Friend and Nutman 1991; Peucat et al. 1993; Jayananda et al. 1995; Moyen et al. 2003). The period of this “super event” is synchronous with the terminal phase of Neoarchean reworking in Madagascar (2.55–2.50 Ga), and so we infer that the north–south grain of the Malagasy shield, including the synformal geometry of the Tsaratanana Complex, was established between 2.55 and 2.50 Ga (Roig et al.)[4]. Archean juxtaposition of the Tsaratanana Complex with the Antananarivo domain comports with all available geologic evidence, including its intrusive relationships with the Itsindro–Imorona Suite (840–760 Ma) and its structural relationship with the Manampotsy Group.

Stabilization of the craton was signaled by deposition of medial Proterozoic sedimentary rocks around its margins and interior. In Madagascar, these include the Itremo–Molo and Sahantaha groups (on the southern and northern shelf, respectively), and the Maha Group (also possibly of medial Proterozoic–Mesoproterozoic age) on the ancient nucleus of Masora. These are broadly correlative with the Paleo- and Neoproterozoic basins of central India (e.g., Cuddapah, Vindhyan, Chattisgarh, and Bhima), which consist of unconformity bound sequences, some as young as ~650 Ma (Ray 2006).

Sometime in the early Neoproterozoic, the stable shield began to founder by (1) creation of two (or more) linear rift basins (or series of basins), and (2) the coeval emplacement of scores of composite batholiths and intrusive igneous massifs of gabbro–diorite and monzonite–syenite composition (Itsindro–Imorona Suite, Fig. 2*b*). The north–south geometry of the basins was controlled, in part, by the inherited grain of the Archean craton, and the Eastern basin (Manampotsy) closely follows the Archean boundary between the ancient nucleus (Antongil – Western Dharwar) and the “juvenile” Antananarivo domain (Fig. 16). We propose that the Ambatolampy Group represents another western belt of intracontinental sediments, also of medial Proterozoic age, that trends north–south, except in the region of the Tana virgation ,where it strikes east–west.

Emplaced into all of these are voluminous Neoproterozoic igneous rocks of the Itsindro–Imorona Suite (840–740 Ma). Previous authors have ascribed a subduction origin to them (Handke et al. 1999; Kröner et al. 2000; Bybee et al. 2010), but recent geochemical modelling suggests that the gabbroic and granitic components evolved from different, independent sources (McMillan et al. 2003); the gabbros by partial melting of lithospheric mantle, and the granites by anatectic melting of the lower crust. The very wide domain of igneous activity (Fig. 2*b*), the general bi-modal nature of the suite and the nested geometry of the complexes (Moine 1974) are consistent with their paired emplacement into the upper crust via a system of pre-existing fractures. Thus, we suggest that the Itsindro–Imorona Suite and the elongate Neoproterozoic sedimentary basins (outline of the Ambatolampy and Manampotsy groups, Fig. 2*b*) are the product of continental dilation (and pressure-reduced melting of upwelling lithosphere) that reworked the Malagasy shield throughout early and medial Neoproterozoic time. To a first approximation, this period of crustal extension lasted approximately 80 Ma or the approximate duration of the Itsindro–Imorona Suite (840–760 Ma). The relationship of the enigmatic Dabolava Suite (1020–990 Ma, Tucker et al.

Fig. 16. The Greater Dharwar Craton: a reconstruction of Madagascar and India (after Reeves et al. 2004 and Ghosh et al. 2004), illustrating the symmetry of "juvenile" Neoarchean crust about an old (>3.2 Ga) central nucleus (Western Dharwar and Antongil–Masora domain). The "juvenile" Neoarchean accreted belts include the Antananarivo domain (plus Tsaratanana Complex) in Madagascar and the Eastern Dharwar in India. The boundary between the central ancient nucleus and the Antananarivo domain is mostly covered by the Manampotsy Group and is interpreted as a zone of weakness throughout Proterozoic and younger time. A, Antananarivo domain; Ad, Androyen domain; AIHSZ, Angavo–Ifanadiana high-strain zone; As, Anosyen; Ik, Ikalamavony subdomain; It, Itremo subdomain; M, Masora domain; P-C SZ, Palghat–Cauvery strain zone; S, Sahantaha Group; V, Vohibory domain. Tsaratanana Complex divisions: And, Andriamena; BA, Beforona–Alaotra; Be, Bekadoka; M, Maevatanana. Also shown (fine stipple) are the Neoproterozoic metasedimentary rocks of the Betsimisaraka domain and Ambatolampy Group.



2007; CGS 2009*a*, 2009*b*) to the Itsindro–Imorona Suite is unknown.

Throughout the latest Neoproterozoic (580–520 Ma), the Malagasy shield was the site of east-directed translation of crystalline nappes (Tucker et al. 2007; GAF–BGR 2008; CGS 2009*a*, 2009*b*), high-grade metamorphism (Nicollet 1990; Goncalves et al. 2004), and widespread granitic magmatism (Paquette and Nédélec 1998; Goodenough et al. 2010). In this period of orogenic convergence, the medial Proterozoic basins were (locally) inverted such that schist of the Manampotsy Group is interleaved with Paleo- and Mesoarchean rocks of the Antongil–Masora domain (e.g., Maroala zone), or Archean rocks of the Antananarivo domain (both Tsaratanana Complex and granitic gneiss) are thrust over the Neoproterozoic rocks of the Manampotsy Group (i.e., western Betsimisaraka domain). Most significantly, the schistose rocks of the Manampotsy Group developed zones of very high strain. The longest of these zones is the AIHSZ, which, for most of its trace, is within graphitic schist and paragneiss of the Manampotsy Group. This inher-

[4] Roig, J.-Y., Bosch, D., and Delor, C. Are the "greenstone belts" of Madagascar allochthonous? In preparation.

ited zone of weakness persisted throughout Mesozoic to Pliocene time, first as the site of Cretaceous rifting and volcanism and later as the site of alkaline volcanic eruptions as young as 4 Ma (Lacroix 1938; BGS et al. 2008).

Conclusions

The oldest rocks in Madagascar have been identified in the Antongil and Masora domains of the east coast region. Emplacement ages of 3320 ± 14 and 3231 ± 6 Ma for TTG gneisses (RT-02O-76A, RT-02O-52A) extend the age and geographic range of the ancient rocks of Madagascar. The emplacement age of 3314 ± 8 Ma for sample RT-02M-105A confirms the extension of the Paleoarchean basement to the enigmatic Masora domain and its linkage to the Antongil domain. The common ages, isotopic signatures, and geologic histories imply the Antongil–Masora and Western Dharwar cratons are the same Archean entity.

We establish a Mesoarchean age (3178 ± 2 Ma) for a newly recognized package of supracrustal rocks in east Madagascar between the villages of Fenerivo and Soanierana-Ivongo. The newly recognized package (the Fenerivo Group) was deformed and metamorphosed (ca. 2550 ± 42 Ma) before, or as, the Mananara Group was deposited (2.45–2.51 Ga). Synchronous with its metamorphism, or at a slightly younger time, the Fenerivo Group was invaded by granitic rocks of the Masoala Suite now dated to the interval 2546–2502 Ma.

This interval of Neoarchean crust formation, deformation, and high-grade metamorphism is widespread throughout the Archean domains of Madagascar and India. In Madagascar, it is represented by the distinctive belts of mafic gneiss and schist (Tsaratanana Complex), thin tracts of Archean sedimentary rocks (Sophia Group), and vast amounts of granodioritic crust (tonalite to granite, Betsiboka–Mangoro Suite) all formed in the interval 2.7–2.51 Ga. We speculate that in the later part of the Neoarchean, the broad architecture of the Archean shield was established. This involved the accretion of felsic and mafic gneisses in the Antananarivo domain and the welding of the eastern Antongil–Masora with the central Antananarivo domains. Accretion was accomplished by juvenile magmatic addition, high-grade metamorphism, and ductile deformation across the Greater Dharwar Craton. This Neoarchean "granite–greenstone" pattern was strongly modified and locally inverted (overturned) by later penetrative strain and high-grade metamorphism during the latest Neoproterozoic.

The concept of the "Betsimisaraka suture" should be abandoned on several grounds. In its place, we suggest that the Malagasy shield experienced active rifting, intra-continental sedimentation, and extensive bi-modal magmatism throughout the early Neoproterozoic. A consequence was the formation of two (or more) elongate belts of Neoproterozoic sedimentary rocks, the Ambatolampy Group and the Bealanana–Manampotsy groups, and the emplacement of an extensive suite of Neoproterozoic igneous rocks (Itsindro–Imorona Suite). The eastern belt of Neoproterozoic sediments (Manampotsy Group) mostly covers the boundary between two Archean domains of very different age, lithological association, and isotopic characteristics. Based on paleo-reconstructions and geological considerations, we suggest that the Manampotsy Group mostly hides the join between the ancient nucleus (Antongil–Masora domain) and the juvenile western domain of the larger Dharwar Craton. The western margin of the Manampotsy Group is also the site of younger, latest Neoproterozoic, structural rejuvenation defined by the Angavo–Ifanadiana high-strain zone. In this perspective, the boundary is not the eastern edge of a Proterozoic micro continent ("Azania") nor is it the convergent margin to the Mozambique Ocean.

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