Available online at www.sciencedirect.com
SCIENCE DIRECT®

Gondwana Research 9 (2006) 3 – 16

www.elsevier.com/locate/gr

GR Focus

Madagascar and the amalgamation of Central Gondwana

Alan S. Collins

Continental Evolution Research Group, Geology and Geophysics, School of Earth and Environmental Sciences, The University of Adelaide, Adelaide, SA 5005, Australia

Received 4 August 2005; accepted 25 October 2005
Available online 10 January 2006

Abstract

Madagascar lay in an interesting position in Gondwana, straddling one of the largest orogens that formed as the supercontinent amalgamated. The Malagasy basement preserves a record of the timing and style of this amalgamation, and in addition contains much information as to the palaeogeography of the eastern Mozambique Ocean.

Madagascar consists of a number of tectonic units that amalgamated in the Ediacaran–Cambrian. The tectonic units are: The Antongil Block; the Antananarivo Block; the Tsaratanana Sheet and the Bemarivo Belt. In addition to these, there are a number of regions dominated by Neoproterozoic metasedimentary rocks, including the Molo, Betsimisaraka, Vohibory and Androyen regions. In this review I outline these units, discuss their amalgamation history and implications for Neoproterozoic–Cambrian palaeogeography, and highlight a few key questions for future study.

Keywords: Madagascar; Gondwana; Azania; Tectonics; Geochronology

Contents

E-mail address: alan.collins@adelaide.edu.au.

1342-937X/$ - see front matter
doi:10.1016/j.gr.2005.10.001

1. Introduction

Madagascar has been the subject of considerable geological interest in recent years, largely because of: 1) its position in Gondwana—straddling one of the major orogens that formed as the supercontinent amalgamated; and, 2) its considerable, and largely untapped, potential for economic mineral deposits. This latter reason has helped the World Bank to instigate a large new project (id. P076245) that before 2008 will result in up-dated geological maps of much of the basement of the island. The considerable amount of recently published geochronological, petrological and structural studies on aspects of the geology of the island and the increased geological awareness stimulated by these studies, makes this an appropriate time for a review of the tectonic evolution of the Malagasy basement. Particularly appropriate is a review of this basement with reference to its Neoproterozoic to Palaeozoic history as so much of Madagascar formed, or was largely reformed, during this time. In this paper I have attempted to be as inclusive as possible, however, this is, by necessity, a personal view of the evolution of the island, I fully recognize that most researchers will disagree with some of my interpretations, whereas some may disagree with all. If these disagreements lead to a more comprehensive understanding of the geology and geological evolution of this fascinating country, then this paper will have served its purpose.

This review is not the only paper to review aspects of the basement geology of Madagascar in recent years. Windley et al. (1994) reviewed much of the early to middle twentieth century work undertaken by geologists from the Service Géologique and attempted to draw correlations with adjacent parts of Gondwana. Since then, much new geochonological data has been collected, which spurred two other major reviews: de Wit (2003), who, in a comprehensive review of the geology of Madagascar from the Archaean to the present, briefly reviewed the basement geology of Madagascar; Collins (2000), who proposed a tectonic subdivision of basement Madagascar; and, Collins and Windley (2002), who summarized much of what was known about north and central basement Madagascar and identified an extensive pre-Neoproterozoic continent that included central Madagascar, parts of Somalia, Ethiopia and Yemen. This continental mass has subsequently been named Azania (Collins and Pisarevsky, 2005).

2. Historical subdivision of the Malagasy basement

The first record of the geology of Madagascar appears early in the nineteenth century (Buckland, 1821). However, systematic geological study of the island had to wait until the colonial period. Geological study was organised by French geologists from the pioneering work of Lacroix (1921–23) on the mineralogy of Madagascar, until the early 1970s. Under the auspices of Henri Besairie, the Service Géologique produced an invaluable series of geological reports and maps at 1 : 100 000, 1 : 200 000: 1 : 500 000 and 1 : 2 000 000 of the

Table 1
Comparison of the tectonic units discussed in this paper with previously used rock sequence names

This study		Besairie (1973)	Hottin (1976)	Windley et al. (1994)
Bemarivo Belt		Systéme du Graphite, Betsiaka, Systéme du Vohibory, Complexe Granodioritique, Daraina, Sahantaha	Groupe Betsiaka-Ambohipato-Vohemar, Le séries volcano-sédimentaire de Daraina Milanoa	Sahantaha, Daraina
Neoproterozoic metasediments	Betsimisaraka	Ambodiriana Manampotsy (part)	Séries de l'Ampasary et de Marolambo Séries de Antenina Séries de Vavatenina Séries de Sahantaha Manampotsy (part)	Antenina
	Molo	Amborompotsy Ikalamavony Tranomaro (part) Vohimena Malakialina	Séries schisto-quartzo-calcaire L'Amborompotsy-Ikalamavony Séries du Vohimena	SQC Vohimena
	Androyen	Androyen, Ampanihy	Fort Dauphin, Tranomaro, Bevinda, Ihosy, Benato-Horombe, Ampanihy, Mafilefy, Mahabo, Iakora	Bekily Belt, Betroka Belt, Tranomaro Belt,
	Vohibory	Vohibory	Vohibory	Vohibory
Tsaratanana Sheet		Systéme du Vohibory, Andriamena, Beforona	Séries calco-ferromagnésiennes du Beforona-Alaotra, Andriamena, Androna et Maevatanana	Maevatenana, Andriomena, Androna-Beforona and Mandritsara
Antananarivo Block		Systéme du Graphite, Ambatolampy, Manampotsy (part), Andriba, Migmatites granitoïdes de Brickaville, Antambohobe, Serie Schisto-Quartzo-Calcaire	Granites and migmatites of the central zone, Granites and migmatites of the borders of the central plateau. Séries graphiteuses de type Manampotsy (part), Séries d'Ambatolampy- Tolongoina, Séries d'Andriba	Anjafy-Vondrozo, Mandalo, Andriba
Antongil Block		Mananara, Granites d'Antongil, Sahantaha, System du Masora, Vohilava-Maha	Group de l'Antongil, Group de la Masora	Antongil, Sahantaha, Masora

whole island. Their work was synthesized in three main publications (Table 1): Besairie (1968–1971), Jourde (1971), and Hottin (1976). Besairie (1968–1971) subdivided the basement rocks of Madagascar into three main groups: 1) the basal "*Système Androyen*"; 2) the "*Système du Graphite*"; and 3) the "*Système du Vohibory*". The distinctions between these systems were based mainly on metamorphic grade decreasing from base to top. Jourde (1971) split central and northern Madagascar into two main systems: a lower "*l'Antongilien*" that crops out in the cores of anticlines and is separated from an upper "*l'Andriaménien*" system. In the extreme north, the Daraina–Milanoa series was interpreted to disconformably overlie the Antongilien system. Hottin (1976) built on both these earlier syntheses and added many interpretations of his own to produce a three-fold subdivision of rocks in central and northern Madagascar based on lithology and structural position. He subdivided the old Antongil rocks from the gneiss and migmatite found throughout the centre of the island. Rocks of the Andriamena, Aloatra, Beforona and Androna belts overlay these rocks and were separated from them by an orogenic event. These three divisions are broadly similar to the Antongil Block, the Antananarivo Block and the Tsaratanana Sheet identified discussed in this paper.

3. Tectonic units of Madagascar

Collins et al. (Collins et al., 2000; Kröner et al., 2000; Collins and Windley, 2002) divided central and north Madagascar into five tectonic units (Fig. 1). All rocks in a unit share a similar tectonic history and each unit is separated from the other units either by a regionally significant unconformity or by a shear zone. Here I present a slightly modified version of these tectonic units including the: Antongil Block; Antananarivo Block; Tsaratanana Sheet; and, Bemarivo Belt.

In the centre of the island, a series of Proterozoic metasedimentary and metabasic rocks and gneisses were combined as the Itremo Sheet by Collins et al. (2000). The

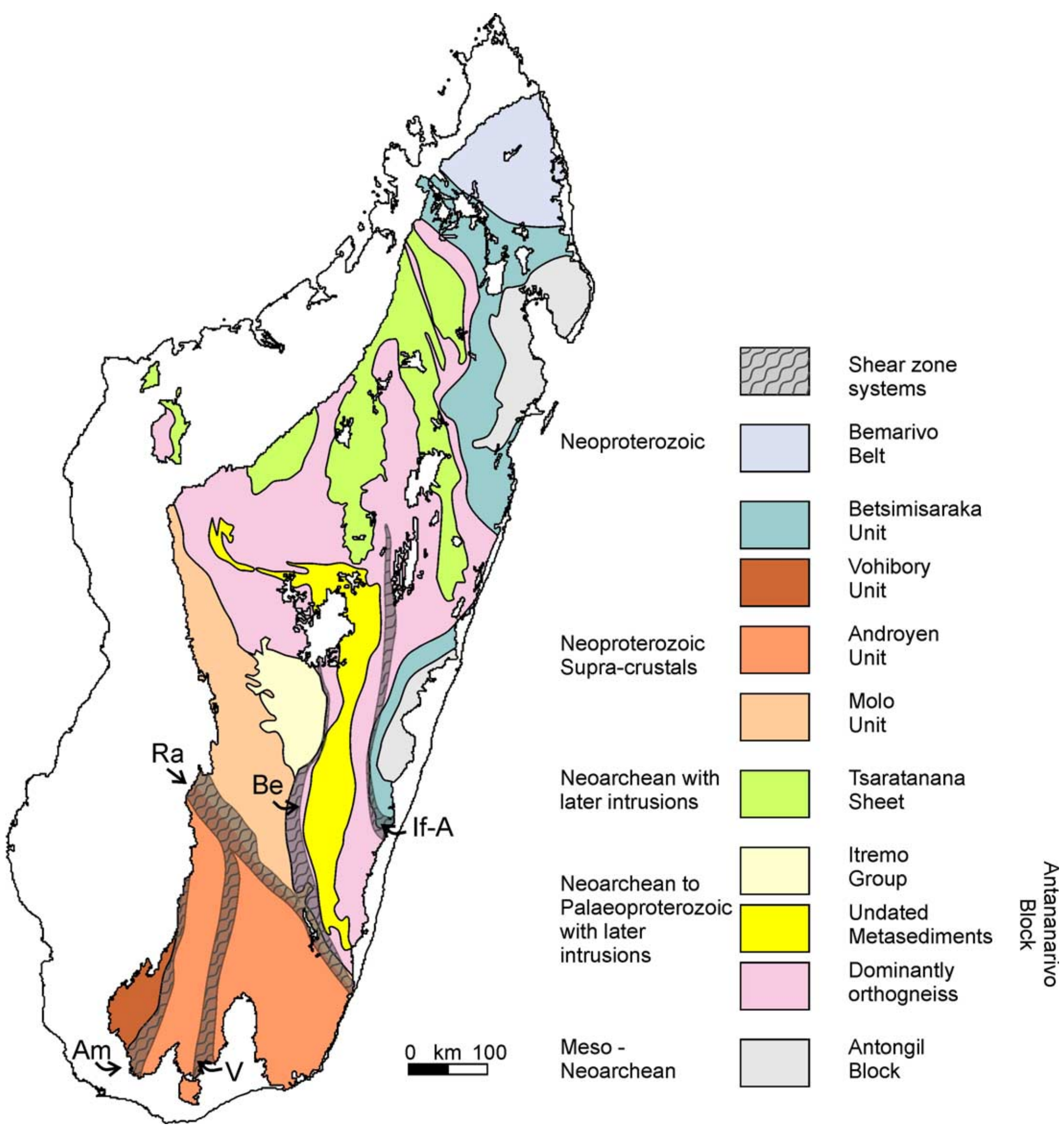


Fig. 1. Geological map of the basement of Madagascar (after Besairie, 1969–1971, 1973; Rolin, 1991; Collins and Windley, 2002 and subsequent observations). Shear zone systems: Am = Ampanihy; Be = Betsileo; If-A = Ifanadiana-Angavo; Ra = Ranotsara; V = Vorokafotra.

metasedimentary rocks of this unit consist of quartzites, dolomites and pelites of the ~1700–800 Ma Itremo Group (Cox et al., 1998; Huber, 2000; Cox et al., 2004) interleaved in the east with quartzites of the Neoproterozoic Molo Group (Cox et al., 2001, 2004). Metasedimentary rocks of the western Amborompotsy–Ikalamavony Group were interpreted by Moine (1968b) as high-grade equivalents of the Itremo Group and were also included by Collins et al. (2000) in their Itremo Sheet. Rocks within this Itremo Sheet experienced considerable Neoproterozoic E–W shortening (Collins et al., 2003b) and lie in a similar structural position to the Tsaratanana Sheet—that is, directly above the Antananarivo Block. The boundary between the Itremo Sheet and the Antananarivo Block was split into two domains based on kinematic and structural style by Collins et al. (2000). West of Antsirabe (Fig. 2), the boundary is imbricated and preserves evidence of contractional deformation (top-to-the-east—up-foliation—shear sense). South of Antsirabe, the boundary forms an extensional shear zone (the Betsileo shear zone) of >200 km strike length (Collins et al., 2000). However, metasedimentary rocks of the Itremo Group unconformably overlie gneisses (Cox et al., 1998) that have elsewhere been dated as of equivalent age (Tucker et al., 1999b) as those in the Antananarivo Block. In addition, quartzites and pelites occur beneath the Betsileo shear zone, interlayered with granitic gneisses of Antananarivo Block (Moine, 1968a; Collins et al., 2003b). These observations suggest that the Itremo Group may have originally been deposited on the Antananarivo Block and that, therefore, it may not be appropriate to consider rocks of the Itremo Sheet as a separate tectonic unit, distinct from the Antananarivo Block (c.f. Collins et al., 2000).

3.1. The Antongil Block

The Antongil Block consists of a granitic and gneissic core, semi-encircled by metasedimentary rocks. It is characterized by lower temperature metamorphic assemblages (greenschist-lower amphibolite facies) than those found within rocks from

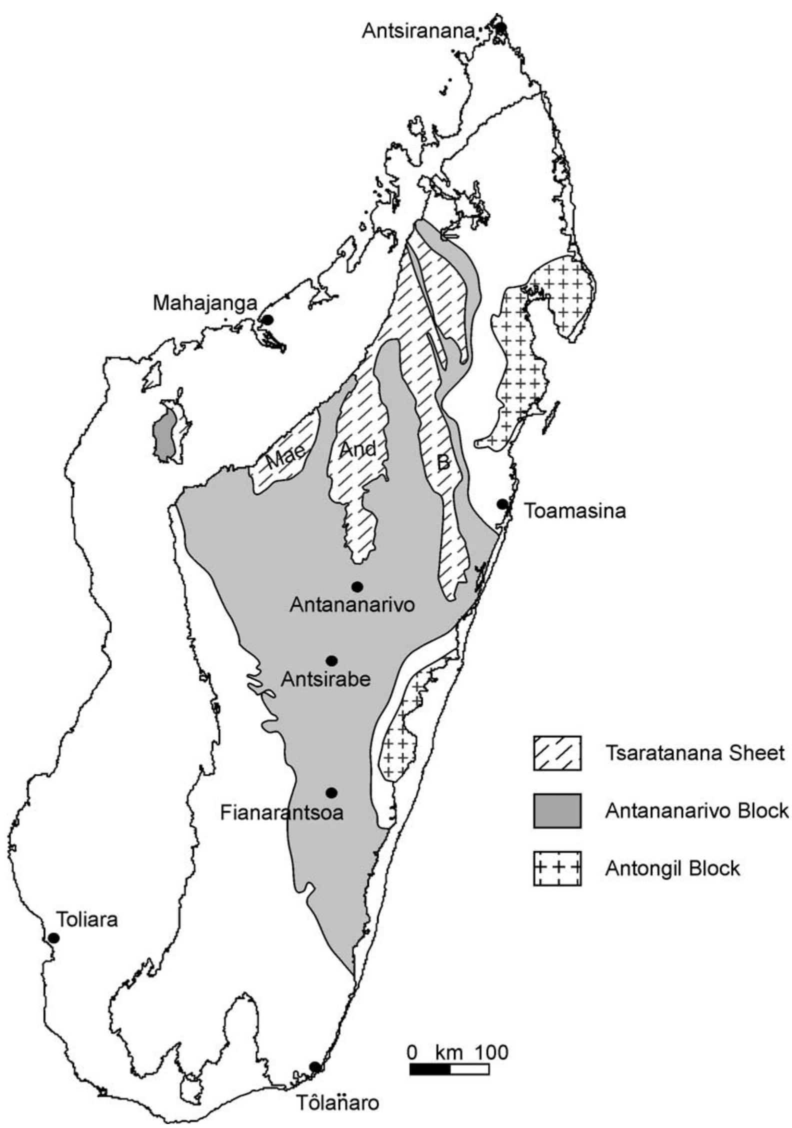


Fig. 2. Pre-Neoproterozoic tectonic units of Madagascar and major cities. And = Andriamena Belt, B = Beforona Belt, Mae = Maevatanana Belt.

the centre of the island (Hottin, 1976). The crystalline core of the Antongil Block consists of *ortho*- and *para*gneisses that date back to 3127 Ma intruded by ~2520–30 Ma granitic bodies (Tucker et al., 1999b; Collins et al., 2001; Paquette et al., 2003). Whole-rock Rb/Sr Archaean ages (Vachette and Hottin, 1971) demonstrate that on a sample-scale this isotopic system remained closed throughout the Proterozoic, in contrast to similar data from the Antananarivo Block that show considerable Proterozoic isotopic disturbance (Vachette, 1979; Cahen et al., 1984). This suggests that the Antongil Block was not affected by the high-grade Neoproterozoic tectono-thermal events so characteristic of the rest of Madagascar. Psammitic metasedimentary rocks unconformably (Hottin, 1976) overlie the crystalline core to the north and to the west of the outcrop. In the north, these sediments pass up into the overthrust Bemarivo Belt. To the west, the metasediments pass up into a highly deformed belt of graphitic pelites associated with lensoid outcrops of harzburgites, chromitites, and emerald deposits that separate the Antongil Block from the structurally overlying Antananarivo Block. This broad metasedimentary belt is interpreted as the remains of a strand of the Mozambique Ocean and has been called the Betsimisaraka suture (Collins et al., 2000; Kröner et al., 2000; Collins and Windley, 2002; Collins et al., 2003c; Raharimimahefa and Kusky, in press).

3.2. The Antananarivo Block

The Antananarivo Block forms the largest pre-Palaeozoic tectonic unit of Madagascar (Fig. 1). It consists of 2550–2500 Ma granitoids that are tectonically interlayered with voluminous 824–719 Ma granites, syenites and gabbros (Tucker et al., 1999b; Kröner et al., 2000) that have chemistries consistent with forming above a subduction zone (Brewer et al., 2001). The whole of the Antananarivo Block was thermally and structurally reworked between 700 and 532 Ma with pre-existing rocks being metamorphosed to granulite facies and with the development of gneissic fabrics. Granitoid magmatism between 630 and 561 Ma produced the 100 m- to km-scale granitoid sills (the stratoid granites of Emberger, 1958) that are characteristic of this tectonic unit. These granites intruded at the same time as extensional deformation (Nédélec et al., 1995) associated with the Betsileo shear zone (Collins et al., 2000). The eastern Antananarivo Block was deformed by top-to-the-east thrusts between 630 and ~530 Ma, which emplaced the then amalgamated central Madagascar over the Antongil Block (Collins et al., 2003a). The 537–527 Ma Carion granite (Kröner et al., 2000; Meert et al., 2001) seals this deformation.

The Itremo Group consists of dolomitic marbles, quartzites, pelites and metasiltstones that non-conformably overlie amphibolite and gneiss that can be correlated with orthogneisses of the Antananarivo Block (Moine, 1968a, 1974; Cox et al., 1998; Tucker et al., 1999b). These metasedimentary rocks have also been called the "Séries Schisto-Quartzo-Calcaire" (Besairie, 1968–1971) and the "Série Schisto-Quartzo-Dolomitique" (Moine, 1968a). Rocks of the Itremo Group increase in metamorphic grade from east to west with its lowest-grade rocks (lower greenschist facies) preserved in the hanging-wall of the Betsileo shear zone (Moine, 1974; Collins et al., 2000). The protolith sediments were deposited after ~1700 Ma (Fernandez et al., 2003; Cox et al., 2004) and appear to be derived from East Africa (Cox et al., 1998, 2004; Fitzsimons and Hulscher, 2005). The Itremo Group rocks are deformed into large (amplitudes of >20 km) recumbent isoclinal folds that are intruded by a set of gabbros and syenites between 804 and 779 Ma (Handke et al., 1999; Collins et al., 2003b; Tucker et al., in press). These intrusions show supra-subduction zone chemical affinities (Handke et al., 1999) and are much less deformed than coeval intrusions in the Antananarivo Block. After 789 Ma, the Itremo Group was re-deformed into open, upright folds, divergent reverse faults and strike-slip faults that are sealed by 570–539 Ma granitoid intrusions (Handke et al., 1997). The eastern margin of the Itremo Group outcrop forms an extensive extensional detachment (the Betsileo shear zone, Collins et al., 2000), the hanging-wall of which was not extensively deformed during extensional deformation and appears to have passively slid during shear zone movement.

3.3. The Tsaratanana Sheet

The Tsaratanana Sheet is composed of mafic gneiss, tonalites, chromite-bearing ultramafic rocks and meta-pelites, some of which were metamorphosed to ultra-high temperatures (Nicollet, 1990; Goncalves et al., 2004) at ~2.5 Ga (Goncalves et al., 2004; Paquette et al., 2004). This tectonic unit is formed of three main belts (the Maevatanana, Andriamena and Beforona) of similar lithology, geochronology and structural position (Fig. 2). Early intrusions have been dated between 2.75 and 2.49 Ga with zircon xenocrysts extending back to 3.26 Ga (Tucker et al., 1999b; Collins et al., 2001; Paquette et al., 2004) and Middle Archaean Nd isotope signatures (Tucker et al., 1999b). 800–770 Ma gabbros cut the earlier deformed older rocks (Guérrot et al., 1993; Tucker et al., 1999b) that, in the Andriamena Belt, are coeval with a second granulite-facies metamorphic event (Goncalves et al., 2004), and are themselves deformed into asymmetric folds and cut by east-directed thrusts. Top-to-the-east thrusting in the Beforona Belt post-dates intrusion of a granitoid at 637 Ma (Tucker et al., 1999b; Collins et al., 2003a) and is presumably responsible for the general synformal nature of the Tsaratanana Sheet today. A mylonite zone separates the Tsaratanana Sheet from the underlying Antananarivo Block. Goncalves et al. (2003) demonstrated that in the west this mylonite zone has top-to-the-east kinematics, but as yet the timing of this thrusting is uncertain.

3.4. The Bemarivo Belt

The Bemarivo Belt forms a tectonic region in the north of Madagascar. At map-scale this tectonic unit crosscuts the Antananarivo Block, the Antongil Block and the Betsimisaraka suture (Figs. 1 and 2). The Bemarivo Belt comprises two discrete regions: a southern region dominated by upper amphibolite- and granulite-grade metasedimentary gneiss and a northern region characterized by granitic dome-like massifs that intrude through migmatites and orthogneisses (Jourde et al., 1974). Tucker et al. (in Ashwal, 1997) dated one of these intrusions at 753.8±1.7 Ma. Three major meta-volcanosedimentary regions also occur in this northern region: the Daraina, Milanoa and Betsiaka series (together forming the Daraina Group). Rhyolites within the Dariana Group formed at ~715 Ma (Tucker et al., 1999a) and were later deformed into upright isoclinal folds. Detrital monazite cores have also yielded ages of 717 Ma (Jöns et al., 2005a). The southern region was deformed by top-to-the-south thrusting coeval with granulite-grade metamorphism that has been dated at 519.2±0.7 Ma (Buchwaldt et al., 2003). North-east Madagascar has been linked with the Seychelles and north-west India because of the presence in each of these areas of ~750 Ma volcanic and/or magmatic rocks (Tucker et al., 1999a; Torsvik et al., 2001; Ashwal et al., 2002).

3.5. Neoproterozoic metasedimentary belts

Large metasediment-dominated regions divide the Antongil and Antananarivo Blocks (Betsimisaraka, Fig. 1), and occur south and west of the Antananarivo Block (Molo, Androyen and Vohibory, Fig. 1).

The Betsimisaraka metasediments crop out within a broad, highly sheared region that is interpreted to mark the remains of an oceanic suture zone (Kröner et al., 2000; Collins and Windley, 2002; Collins et al., 2003c). This interpretation is supported by the presence of numerous entrained ultramafic and mafic rocks that may represent the highly attenuated remains of oceanic lithosphere. U–Th–Pb ion microprobe zircon ages from pelites suggest that: 1) these rocks were deposited between ~800 and 550 Ma, and; 2) that they were sourced from the southern Indian Dharwar craton (Collins et al., 2003c).

The Molo metasediments (Cox et al., 2004) occur in a triangular region west of the Itremo Group and north of the Ranotsara shear zone (Fig. 1, Cox et al., 2004; Fitzsimons and Hulscher, 2005, note that the latter authors refer to these rocks as the Amborompotsy Group). The protoliths to these rocks were deposited between ~620–560 Ma (Cox et al., 2004) in an Ediacaran basin that separated central Madagascar from East Africa (Cox et al., 2004; Collins and Pisarevsky, 2005; Fitzsimons and Hulscher, 2005).

The Androyen region (Fig. 1) forms a vast high-grade metasedimentary terrane south of the Rantosara shear zone (Fig. 1) that has been metamorphosed to ultra-high-temperature conditions (Nicollet, 1990; Ackermand et al., 1991; Martelat et al., 1997; Markl et al., 2000). It has been suggested that an Archaean basement exists in this region (de Wit et al., 2001), but geochronological evidence for this is equivocal. Neoproterozoic zircons have been retrieved from metasedimentary gneisses (Kröner et al., 1996, 1999; de Wit et al., 2001) demonstrating that, at least, some of the sediment protoliths were deposited in Neoproterozoic times. A number of workers have suggested that the metasediments south of the Ranotsara shear zone correlate with the Molo metasediments, north of the crustal-scale shear (e.g. de Wit, 2003), whereas detrital zircons suggest a similar provenance as the Itremo Group (Collins et al., 2005). The geochronological resolution is not precise enough at the moment to correlate directly, but at least some of the Androyen metasediments must pre-date 620–560 Ma deposition of the Molo metasediments (Cox et al., 2004) as ~630 Ma anorthosite intrusions (Ashwal et al., 1998) cut metasedimenary rocks in the south of this region.

The Vohibory region in the far southwest of the Malagasy basement experienced higher-pressure metamorphic conditions than recorded in the rest of the island (>10 kbar, Nicollet, 1990; Martelat et al., 1997) and consists of pelites, marbles, extensive amphibolites and granitoids. Detrital zircon U–Th–Pb ages from pelites within the Vohibory region form a prominent age cluster at ~850 Ma, suggesting that they were sourced from a restricted-aged Neoproterozoic source (Collins et al., 2005). Amphibolites from the same region were sourced from a depleted mantle (Jöns et al., 2005b). Jöns et al. (2005b) suggested that the chemistry of these rocks pointed to their origin as slices of ocean crust and interleaved arcs that today form a complex tectonic mélange. However, the lithological continuity over large areas suggest that the meta-igneous bodies more likely represent extrusive flows, or sill-like bodies, extruded/intruded into a coeval package of Neoproterozoic metasedimentary rocks. In this scenario, the Vohibory region represents an early Neoproterozoic volcanic rift succession.

4. Origin and Pre-Ediacaran evolution of the Malagasy tectonic units

The different tectonic units in Madagascar preserve different records of pre-Neoproterozoic crustal growth (Table 2, Fig. 3), suggesting that they originated in different geographic locations. Rocks within the Antongil Block date back to ~3.1 Ga and are intruded by voluminous ~2.5 Ga granitoids. This history is very similar to that of the Dharwar craton of southern India (Chadwick et al., 2000; Jayananda et al., 2000), and a number of authors have suggested that this unit is an isolated part of the Dharwar craton left behind as India rifted off Madagascar in the Mesozoic (Agrawal et al., 1992; Collins and Windley, 2002; Collins et al., 2003a,c; Raval and Veeraswamy, 2003).

The Antananarivo Block appears to have formed at ~2500 Ma, with U/Pb zircon ages and Sm/Nd model ages yielding similar dates (Tucker et al., 1999b; Kröner et al., 2000; Collins et al., 2001). The extensive metasedimentary rocks of the Itremo Group (and possibly the poorly known Ambatolampy series) were most likely deposited in the late Palaeoproterozoic or early Mesoporoterozoic (Cox et al., 2004). They contain detrital zircon and monazite age spectra that show sources extremely similar to rocks found in the Tanzania Craton and Bangweulu Block of East Africa (Cox et al., 1998; Fernandez et al., 2003; Cox et al., 2004; Fitzsimons and Hulscher, 2005), suggesting that at the time of deposition the Antananarivo Block was connected to this region. The Itremo Group was

Table 2
Summary of tectonic events recorded in the various tectonic units

Tectonic unit		Major tectonic events
Bemarivo Belt		• 717–754 Ma granite magmatism • 715 Ma rhyolite extrusion coeval with deposition of sandstones and conglomerates • 510–520 Ma granulite-grade metamorphism coeval with south-west directed thrusting • Extensional deformation
Neoproterozic metasediments	Betsimisaraka	• Post-720 Ma deposition of protolith mudrocks • Metamorphism at ~520 Ma
	Molo	• Post-620 Ma deposition of protolith quartzites and mudrocks • Metamorphism and deformation at ~560 Ma
	Androyen	• 750–630 Ma deposition of protolith mudstones, sandstones and limestones • Intrusion by ~630 Ma anorthosites • Metamorphism between 645–545 Ma
	Vohibory	• Post-850 Ma deposition of protolith mudrocks, carbonates and possible coeval basic volcanism. No earlier detritus
Tsaratanana Sheet		• 2747–2494 Ma granitoid intrusion through crust dating back to 3260 Ma • Deformation and emplacement over Antananarivo Block • 787–779 Ma gabbro magmatism coeval with high-temperature metamorphism in the country rock • 637–627 Ma granitoid intrusion • Intense deformation transposing earlier rocks into gneissic tectonites. • 549 Ma late diorite magmatism • Deformation
Antananarivo Block (including the Itremo Group)		• ~2500 Ma crust formation • 2189–1007 Ma zircon xenocrysts in later granites, whose significance is unknown. • Post 1850 Ma deposition of Itremo Group- quartzites, mudrocks and carbonates • Pre ~820 Ma deformation into large recumbent isoclinal folds • 824–719 Ma supra-subduction zone gabbro and granitoid intrusion • 633–561 Ma granitoid magmatism •pre-550 Ma granulite-grade metamorphism and contractional deformation • Intrusion of post-tectonic granitoids 572–530 Ma possibly coeval with: • Extensional deformation along the the Betsileo shear zone
Antongil Block		• 3200–2500 Ma continental crust formation and deformation • 2500 Ma Granite intrusion • Palaeozoic sediments deposited on erosion surface

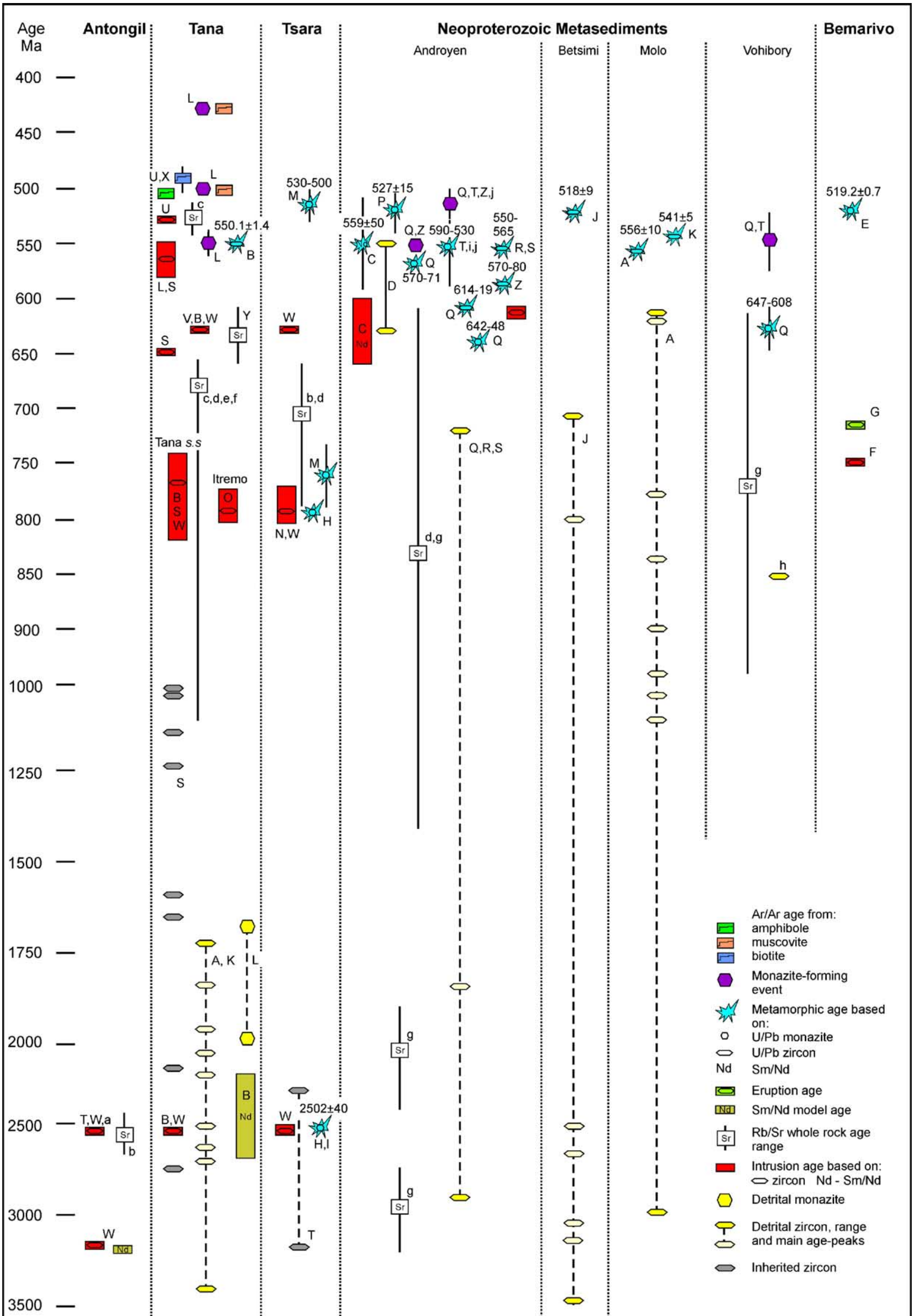
deformed into large amplitude isoclinal folds before being intruded by ~800 Ma gabbros and granites (Handke et al., 1999; Collins et al., 2003b; Fernandez and Schreurs, 2003; Fernandez et al., 2003). The age of this deformation is very poorly constrained to ~1.7–0.8 Ga, but may represent deformation forelandward of the Irumide Orogen before Azania rifted off the Congo/Tanzania/Bangweulu Block (c.f. Fitzsimons and Hulscher, 2005).

The Tsaratanana Sheet contains rocks that formed more than 200 Ma before the oldest known Antananarivo Block rock and contain inherited zircons that stretch back to the Mesoarchaean. The Tsaratanana Sheet preserves evidence for ultra-high-temperature metamorphism at ~2.5 Ga (Goncalves et al., 2004; Paquette et al., 2004). Similar-aged granulite-facies metamorphism is reported from both the northern Tanzania Craton (Schenk et al., 2004) and from the southern Dharwar Craton of India (Peucat et al., 1993), making any definitive correlation difficult. However, a metasedimentary gneiss of the northern Andriamena Belt has yielded discordant U/Pb ages from detrital zircons that are similar to those from the Itremo Group (Kabete et al., in press) and therefore may indicate an African origin.

By the mid-Neoproterozoic, similar events begin to be seen in both the Tsaratanana Sheet and the Antananarivo Block, for example, ~800–700 Ma magmatism occurs in both tectonic units. In the Tsaratanana Sheet, high-temperature metamorphism occurred at the same time as these intrusions (Goncalves et al., 2004; Paquette et al., 2004), whereas the only evidence of ~800 Ma metamorphism in the Antananarivo Block is low-pressure metamorphism in the aureole of mid-Neoproterozoic intrusions (Collins et al., 2003b). The evidence of higher-grade metamorphism in the Tsaratanana Sheet suggests that these rocks were at deeper crustal levels than the Antananarivo Block rocks at the time. The opposite relationship occurs today, where the Tsaratanana Sheet structurally overlies the Antananarivo Block (Collins, 2000; Goncalves et al., 2003).

No conclusive evidence has yet been found that the terranes south of the Ranotsara shear zone and the Bemarivo Belt in the far north contain any rocks that formed before Neoproterozoic times. Protoliths of at least some of the Androyen metasediments were deposited in the early mid Neoproterozoic, although it is certainly possible that others may correlate with the Itremo Group. The Vohibory metasediments were deposited after ~800 Ma and contain a single population of ~850 Ma zircons (Collins et al., 2005). These metasediments are associated with voluminous amphibolites that may represent original basaltic volcanism, formed in a Neoproterozoic rift as Azania rifted off the Congo/Tanzania/Bangweulu Block (Collins and Pisarevsky, 2005).

Greenschist-facies metasedimentary and metavolcanic rocks in the northern Bemarivo Belt (the Daraina Group) have been dated at ~715 Ma (Tucker et al., 1999a) In this region supracrustal terranes are separated from each other by domal granitoid masses, one of which has been dated at ~750 Ma (Tucker et al., 1999a). No older rocks are known from this region, which has been correlated with similar aged-rocks in the Seychelles (Tucker et al., 2001).



Age Ma
Antongil
Tana
Tsara
Neoproterozoic Metasediments
Androyen
Betsimi
Molo
Vohibory
Bemarivo
Tana s.s
Itremo
530-500
527±15
559±50
Q,Z
590-530
550-565
570-80
614-19
642-48
570-71
Q,T,Z,j
T,i,j
R,S
518±9
556±10
541±5
647-608
519.2±0.7
550.1±1.4
V,B,W
c,d,e,f
b,d
d,g
Q,R,S
2502±40
H,I
T,W,a
B,W
A, K
Ar/Ar age from:
amphibole
muscovite
biotite
Monazite-forming event
Metamorphic age based on:
U/Pb monazite
U/Pb zircon
Nd Sm/Nd
Eruption age
Sm/Nd model age
Rb/Sr whole rock age range
Intrusion age based on:
zircon Nd - Sm/Nd
Detrital monazite
Detrital zircon, range and main age-peaks
Inherited zircon

5. Ediacaran/Cambrian amalgamation of Madagascar

Ediacaran/Cambrian metamorphism and deformation has strongly affected all of the basement of Madagascar, with the exception of the far north-eastern core of the Antongil Block (Fig. 3) where $^{40}Ar-^{39}Ar$ data from muscovites and amphibolites demonstrate that temperatures at that time did not exceed ~350 °C (Collins unpublished data). Tucker et al. (1999b) interpreted the majority of basement Madagascar to be a western extension of India throughout the Neoproterozoic, with this Ediacaran/Cambrian deformation and metamorphism forming a wide orogenic belt along eastern India, and the major Mozambique Ocean suture lying to the west. The subsequent recognition of the Neoproterozoic age of the protoliths of the Betsimisaraka paragneisses (Collins et al., 2003c) and their interpretation as a high-grade suture zone (Collins, 2000; Collins and Windley, 2002; Raharimimahefa and Kusky, in press) led to a microcontinental interpretation for central Madagascar in the Neoproterozoic (Collins and Windley, 2002; Collins et al., 2003c; Fitzsimons and Hulscher, 2005). Collins and Windley (2002), traced this central Malagasy continent through the Horn of Africa and up into Arabia, forming a large Neoproterozoic continent (named Azania by Collins and Pisarevsky, 2005) bound by suture zones both to the east (the Betsimisaraka suture) and west (probably exposed in the Pare Mountains and Taita Hills of Tanzania and Kenya, respectively, Hauzenberger et al., 2004). The southern extension of Azania is, as yet, unknown. There is little evidence for pre-Neoproterozoic rocks exposed south of the Ranotsara shear zone (Fig. 1), but the sinistral movement of this shear zone means that any southern prolongation may lie in southern India (Fig. 4). Collins and Windley (2002) suggested that the eastern Madurai Block, south of the Palghat–Cauvery shear zone and north of the Karur–Kambam–Painavu–Trichur (KKPT) lineament (Ghosh et al., 2004) may represent this extension, but this requires a correlation between the Ranotsara shear zone and the Palghat–Cauvery shear zone system. A difficulty with this is that recent studies of the kinematic evolution of the Palghat–Cauvery shear zone system suggest that it formed as a dextral transpressional zone (Chetty et al., 2003)—an opposite sense of shear to that of the Ranotsara shear zone.

The Tsaratanana Sheet appears to have inhabited a lower-crustal position at ~800 Ma and was thrust over the Antananarivo Block between then and the Cambrian (Collins et al., 2003a; Goncalves et al., 2003). Goncalves et al. (2003) suggested that this unit was thrust eastward after 630 Ma based on kinematic indicators seen along the western margin of the

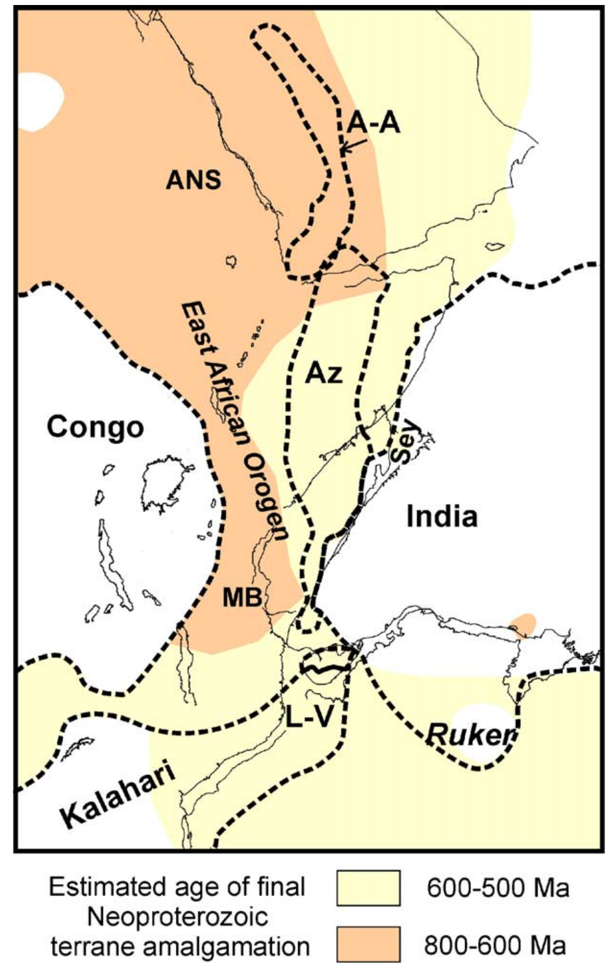


Fig. 4. Madagascar and its neighbours in Gondwana, Gondwana reconstruction after Reeves and de Wit (2000) geology after Collins and Pisarevsky (2005) with modifications in Antarctica after Phillips et al. (2005). Dashed thick lines outline pre-Neoproterozoic continental crust.

Andriamena Belt (Fig. 2) and the observation that 630 Ma granitoid sills in the Antananarivo Block do not occur in the Tsaratanana Sheet. Collins et al. (2003a) suggested that the emplacement of the Beforona Belt (the eastern Tsaratanana Sheet, Fig. 2) preceded their ~640–560 Ma E–W shortening event. These authors constrained large-scale east-directed thrusting in eastern Madagascar to post-640 Ma and presented evidence that it occurred between 530–515 Ma (Collins et al., 2003a). This thrusting locally imbricates the Antananarivo Block over the Beforona Belt, demonstrating that the original emplacement of the Tsarantanana Sheet over the Antananarivo Block preceded this event. Conclusive evidence for the original location of the Tsaratanana Sheet does not exist at present. However, one possible scenario is that it represents the roots of

Fig. 3. Time–space plot of published geochronological data from the basement of Madagascar. Antongil = Antongil Block, Bemarivo = Bemarivo Belt; Betsimi = Betsimisaraka, Tana = Antananarivo Block, Tsara = Tsaratanana Sheet. A = Cox et al. (2004); B = Kröner et al. (2000); C = Ashwal et al. (1998); D = Ashwal et al. (1999); E = Buchwaldt et al. (2003); F = Ashwal (1997); G = Tucker et al. (1999a); H = Paquette et al. (2004); I = Goncalves et al. (2004); J = Collins et al. (2003c); K = Fitzsimons and Hulscher (2005); L = Fernandez et al. (2003); M = Goncalves et al. (2003); N = Guérrot et al. (1993); O = Handke et al. (1999); P = Ito et al. (1997); Q = de Wit et al. (2001); R = Kröner et al. (1996); S = Kröner et al. (1999); T = Collins et al. (2001); U = Meert et al. (2001); V = Paquette and Nédélec (1998); W = Tucker et al. (1999b); X = Meert et al. (2003); Y = Nédélec et al. (1999); Z = Paquette et al. (1994); a = Paquette et al. (2003); b = Vachette and Hottin (1971); c = Vachette and Hottin (1974); d = Vachette and Hottin (1975); e = Vachette and Hottin (1977); f = Vachette et al. (1969); g = Vachette and Hottin (1979); h = Collins et al. (2005); i = Andriamarofahatra et al. (1990); j = Martelat et al. (2000). Ages of inferred metamorphic events (in Ma) are displayed.

a rift succession (related to back-arc extension?) that formed west of its present location that was later thrust east over the Antananarivo Block when Azania collided with the Congo/Tanzania/Bangweulu Block.

The Molo Group (Cox et al., 2004) was deposited in a sedimentary basin that has been interpreted as a passive margin deepening west to an Ediacaran/Cambrian ocean basin between Madagascar and East Africa (Fitzsimons and Hulscher, 2005). No direct evidence of an oceanic suture of this age has been found, which led Collins and Pisarevsky (2005) to suggest that the basin formed as rift after ~640–630 Ma amalgamation of Azania with the Congo/Tanzania/Bangweulu continent. The basin was over-thrust from the west before ~560 Ma (the age of metamorphic zircon overgrowths Cox et al., 2004) and metamorphosed to granulite-facies conditions.

Some of the youngest ages of metamorphism come from the Betsimisaraka suture in the east of the island (Collins et al., 2003c) and the Bemarivo Belt in the north (Buchwaldt et al., 2003; Jöns et al., 2005a). The Betsimisaraka suture is over-thrust by the combined Antananarivo Block and the Tsaratanana Sheet and passes east into the Antongil Block. It is beaded with lenses of gabbro, peridotite and chromitite, lithologies characteristic of suture zones. The suture is also the site of the island's emerald mineralization (Moine et al., 2004). Detrital zircons from the Betsimisaraka metasediments suggest that the protoliths were sourced from a region consistent with Dharwar Craton/Antongil Block, a distinct contrast to similar aged sediments elsewhere in the island (Collins et al., 2003c).

The Bemarivo Belt consists of two distinct terranes: a greenschist-facies terrane in the north made up of domal granites and broadly synformal supracrustal basins and a granulite-facies metasediment-rich terrane to the south that was metamorphosed and intruded by meta-granitoids (now charnockites) at ~520 Ma (Buchwaldt et al., 2003). The southern Bemarivo Belt forms a broadly east-west orogen that thrusts the northern terrane (that has been correlated with the Seychelles, Tucker et al., 2001) south over the northern margin of the Antongil Block. It therefore suggests that Neoproterozoic Seychelles was, at least in part, allochthonous with respect to the Dharwar Craton.

6. Madagascar in the Neoproterozoic–Cambrian world

The basement rocks of Madagascar preserve evidence of a diverse range of Neoproterozoic/Cambrian tectonic events that can be used to help constrain the palaeogeography of the region (Fig. 5). In particular, there is evidence in Madagascar for two Neoproterozoic ocean basins either side of an ancient continent—Azania (Collins and Pisarevsky, 2005). Azania appears to have originated adjacent to the Congo–Tanzania–Bangweulu Block based on the detrital zircon record preserved in the Palaeoproterozoic–Mesoproterozoic Itremo Group (Cox et al., 2004; Fitzsimons and Hulscher, 2005). Fitzsimons and Hulscher (2005) argued that the lack of late Mesoproterozoic deformation and metamorphism suggested that Azania had split from the Congo–Tanzania–Bangweulu Block before the 1050–1000 Ma Irumide Orogen that affected the southeast part of this continent. However, it is unknown where on the margin of the Congo–Tanzania–Bangweulu Block Azania originated, the Irumide Orogen only affected a relatively small part of this margin. In addition, as discussed above, the Irumide Orogen may well be represented in Azania—as the early deformation in the Itremo Group. An alternative view is that Azania split off the Congo–Tanzania–Bangweulu Block at ~850 Ma, forming the supracrustal rocks of the Vohibory region. Arc-like magamatism in central Madagascar began ~30 Ma later (Handke et al., 1999; Kröner et al., 2000; Brewer et al., 2001), suggesting that the preceding extension may well have occurred during the early stages of west-dipping subduction situated where the Betsimisaraka suture now lies.

Azania has been interpreted to have re-amalgamated with East Africa at ~640–630 Ma (Collins and Pisarevsky, 2005) by the subduction of an intervening back-arc basin. This event is correlated with final amalgamation of the Arabian–Nubian Shield (Abdelsalam et al., 2003; Johnson and Woldehaimanot, 2003) and high-grade metamorphism in Kenya and Tanzania (Appel et al., 1998; Sommer et al., 2003), which has a Gondwanan footprint of similar dimensions as Azania (Fig. 4). The Molo basin opened after this re-amalgamation possibly as a consequence of orogenic collapse that may correlate with the voluminous granitoid sills of the Antananarivo Block (Nédélec et al., 1994, 1995; Paquette and Nédélec, 1998). This basin later closed and was metamorphosed during the pervasive ~560–540 Ma deformation and metamorphism that affected the Antananarivo Block, Tsaratanana Sheet and Molo, Androyen and Vohibory metasediments. Final closure of the Mozambique Ocean separating the then amalgamated Azania and Congo–Tanzania–Bangweulu Block from Neoproterozoic India occurred before 520 Ma—the age of metamorphism in the Betsimisaraka suture (Collins et al., 2003c) and Bemarivo Belt (Buchwaldt et al., 2003).

7. Existing problems and future directions: where now?

Despite the excellent work that has been undertaken by many workers over the last decade or so, we really have only scratched the surface of understanding the tectonic evolution of Madagascar. There are still many fundamental tectonic problems that remain in Madagascar. Below I list a number of what I consider are the most pressing.

7.1. What were the Neoproterozoic tectonic environment, original location and time of emplacement of the Tsaratanana Sheet?

Excellent work has been done in the last years on understanding the metamorphic (Goncalves et al., 2004; Paquette et al., 2004) and structural evolution of the region (Goncalves et al., 2003). However, much could be still learnt about the ~800 Ma tectonic environment from a geochemical

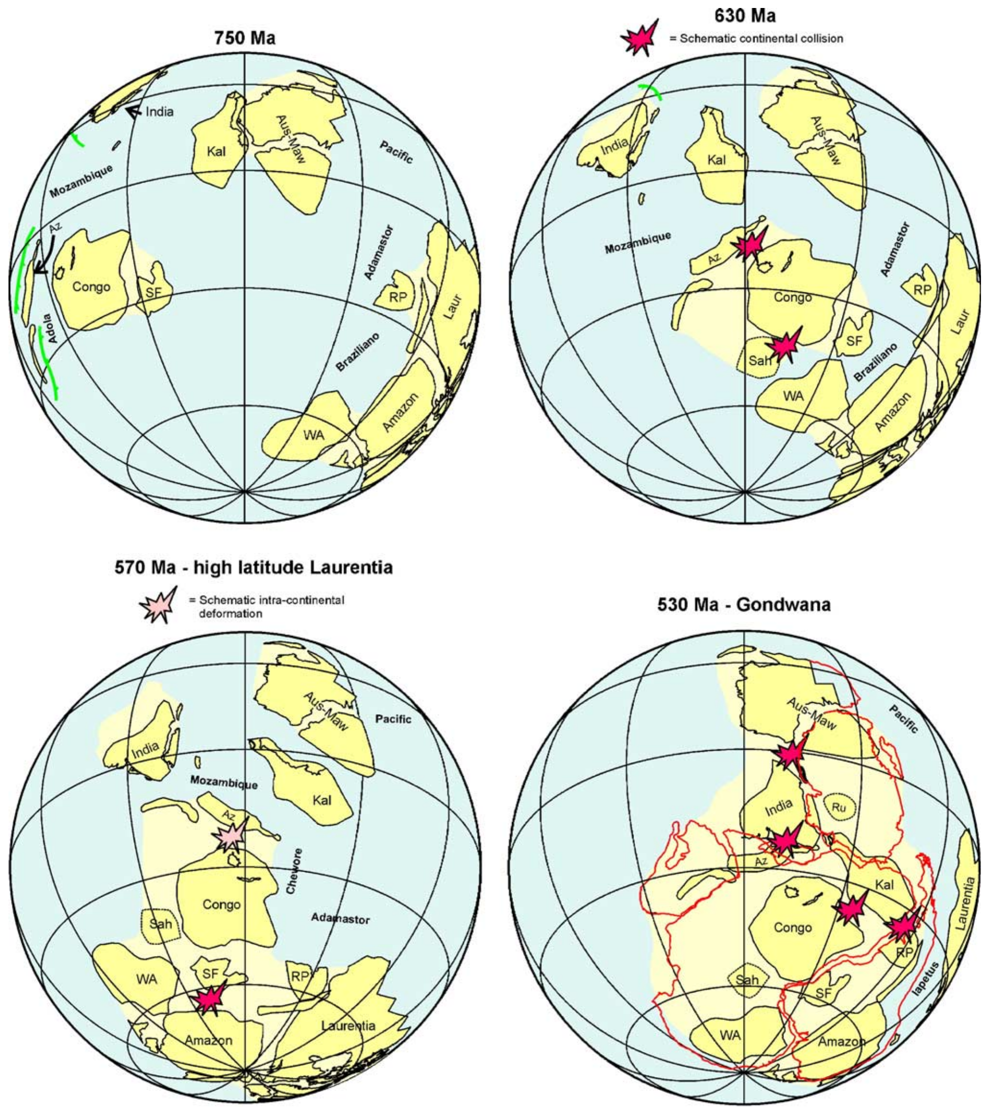


Fig. 5. Azania and the amalgamation of Gondwana. Global palaeogeographic reconstrictions based on palaeomagnetic and geological data for 750, 630, 570, and 530 Ma (after Collins and Pisarevsky, 2005). Amazon = Amazonia; Aus-Maw = Australia-Mawson continent; Az = Azania; Kal = Kalahari; Laur = Laurentia; Rp = Rio de la Plata; Sah = Saharan metacraton; WA = West Africa. Note that India probably extended to the (present) southeast to include the Ruker Terrane of the Southern Prince Charles Mountains of Antarctica (Phillips et al., 2005).

study of the Neoproterozoic plutons. In addition, a systematic study of the kinematic and strain history of the basal mylonites from around the outcrop of the tectonic unit should elucidate its movement history.

7.2. What were the timing of metamorphism and deformation in the Antananarivo Block?

Very little work has been done on directly dating the metamorphism in the Antananarivo Block. Suggestions have been made that the region was metamorphosed and contractionally deformed before ~630 Ma (Paquette and Nédélec, 1998; Nédélec et al., 2000, 2003), but the only directly dated metamorphic minerals (zircons) have yielded ages of ~550 Ma (Kröner et al., 2000). A study integrating the structural work of Nédélec et al. with detailed geo- and thermo-chronology would be extremely useful.

7.3. What are the ages and detrital record of the protoliths to the Androyen metasediments?

Detrital zircons are revealing that at least some of these rocks were deposited in the Neoproterozoic (Kröner et al., 1996, 1999; de Wit et al., 2001), but other rocks appear to have detrital signatures very similar to the Palaeoproterozoic–Mesoproterozoic Itremo Group (Collins et al., 2005). Also, are there any basement rocks in the region? Existing geochronological data (de Wit et al., 2001) are equivocal.

Many other questions exist. Hopefully, this review will stimulate work over the coming years to answer some of them.

Acknowledgements

Brian Windley and Théodore Razakamanana introduced me to the geology of Madagascar and have continuously supported and guided my work on Malagasy geology, to both of them, I am very grateful. Constant discussions with members of the Tectonics Special Research Centre have moulded my ideas over many years. Special acknowledgements are due to Ian Fitzsimons, Peter Cawood, Chris Powell, Sergei Pisarevsky, Steve Reddy, Alfred Kröner, Peter Kinny and Craig Buchan. This manuscript also contributes to IGCP project 509 (Palaeoproterozoic Supercontinents and Earth Evolution). Simon Johnson, Tim Kusky and Ingo Braun are thanked for constructive reviews.

References

Abdelsalam, M.G., Abdel-Rahman, E.-S.M., El-Faki, E.-F.M., Al-Hur, B., El-Bashier, F.-R.M., Stern, R.J., Thurmond, A.K., 2003. Neoproterozoic deformation in the northeastern part of the Saharan Metacraton, northern Sudan. Precambrian Research 123, 203–221.

Ackermand, D., Windley, B.F., Razafiniparany, A.H., 1991. Kornerupine breakdown reactions in paragneisses from southern Madagascar. Mineralogical Magazine 55, 71–80.

Agrawal, P.K., Pandey, O.P., Negi, J.G., 1992. Madagascar; a continental fragment of paleo-super Dharwar craton of India. Geology 20, 543–546.

Andriamarofahatra, J., de la Boisse, H., Nicollet, C., 1990. Datation U–Pb sur monazites et zircons du dernier épisode tectono-métamorphique granulitique majeur dans le Sud-Est de Madagascar. Comptes Rendus de l'Académie des Sciences de Paris, Série II, Méchanique-Physique-Chimie-Sciences de la Terre et de l'Univers 310, 1643–1648.

Appel, P., Möller, P., Schenk, V., 1998. High-pressure granulite facies metamorphism in the Pan-African belt of eastern Tanzania: P–T–t evidence against granulite formation by continent collision. Journal of Metamorphic Geology 16, 491–509.

Ashwal, L.D., 1997. Proterozoic Geology of Madagascar. Guidebook to Field Excursions. Miscellaneous Publications vol. 6. Gondwana Research Group.

Ashwal, L.D., Hamilton, M.A., Morel, V.P.I., Rambeloson, R.A., 1998. Geology, petrology and isotope geochemistry of massif-type anorthosites from southwest Madagascar. Contributions to Mineralogy and Petrology 133, 389–401.

Ashwal, L.D., Tucker, R.D., Zinner, E.K., 1999. Slow cooling of deep crustal granulites and Pb-loss in zircon. Geochimica et Cosmochimica Acta 63, 2839–2851.

Ashwal, L.D., Demaiffe, D., Torsvik, T.H., 2002. Petrogenesis of Neoproterozoic Granitoids and Related Rocks from the Seychelles: the Case for an Andean-type Arc Origin. Journal of Petrology 43, 45–83.

Besairie, H., 1968–1971. Description géologique du massif ancien de Madagascar. Document Bureau Géologique Madagascar. no. 177. no. 177a: centre nord et centre nord-est; 177b: région côtière orientale; 177c: région centrale-système de graphite; 177d: région centrale- système du Vohibory; 177e: le sud; 177f: le nord. Bureau Géologique Madagascar, Antananarivo.

Besairie, H., 1969–1971. Carte géologique à 1/500000, de Madagascar, in 8 sheets: 1: Diego Suarez; 2: Antalaha; 3: Majunga; 4: Tamatave; 5: Tananarive; 6: Morondava; 7: Fianarantsoa; 8: Ampanihy. Bureau Géologique Madagascar, Antananarivo.

Besairie, H., 1973. Carte géologique à 1\2000000 de Madagascar. Service Géologique de Madagaskara., Antananarivo.

Brewer, T.S., Collins, A.S., Kröner, A., Windley, B.F., Razakamanana, T., 2001. Multiphase Granitoid Magmatism in Central Madagascar: Evidence for Subduction of the Mozambique Ocean. EUG, vol. XI, pp. 362. Strasbourg.

Buchwaldt, R., Tucker, R.D., Dymek, R.F., 2003. Geothermobarometry and U–Pb Geochronology of metapelitic granulites and pelitic migmatites from the Lokoho region, Northern Madagascar. American Mineralogist 88, 1753–1768.

Buckland, W., 1821. Notice on the geological structure of a part of the Island of Madagascar. Transactions of the Geological Society V, 476–481.

Cahen, L., Snelling, N.J., Delhal, J., Vail, J.R., Bonhomme, M., Ledent, D., 1984. The Geochronology and Evolution of Africa. Clarendon Press, Oxford. 512 pp..

Chadwick, B., Vasudev, V.N., Hegde, G.V., 2000. The Dharwar craton, southern India, interpreted as the result of Late Archean oblique convergence. Precambrian Research 99, 91–111.

Chetty, T.R.K., Bhaskar Rao, Y.J., Narayana, B.L., 2003. A structural cross section along Krishnagiri–Palani Corridor, Southern Granulite Terrain of India. In: Ramakrishnan, M. (Ed.), Tectonics of Southern Granulite Terrain, Geological Society of India, Memoir, vol. 50, pp. 255–278.

Collins, A.S., 2000. The tectonic evolution of Madagascar: its place in the East African Orogen. Gondwana Research 3, 549–552.

Collins, A.S., Windley, B.F., 2002. The tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana. Journal of Geology 110, 325–340.

Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: the evolution of the Circum–Indian Orogens. Earth Science Reviews 71, 229–270.

Collins, A.S., Razakamanana, T., Windley, B.F., 2000. Neoproterozoic extensional detachment in central Madagascar: implications for the collapse of the East African Orogen. Geological Magazine 137, 39–51.

Collins, A.S., Fitzsimons, I.C.W., Kinny, P.D., Brewer, T.S., Windley, B.F., Kröner, A., Razakamanana, T., 2001. The Archaean rocks of Central Madagascar: their place in Gondwana. In: Cassidy, K.F., Dunphy, J.M., Van Kranendonk, M.J. (Eds.), 4th International Archaean Symposium 2001, Extended Abstracts, AGSO– Geoscience Australia, Record 2001/37, pp. 294–296.

Collins, A.S., Fitzsimons, I.C.W., Hulscher, B., Razakamanana, T., 2003a. Structure of the eastern margin of the East African Orogen in central Madagascar. Precambrian Research 123, 111–133.

Collins, A.S., Johnson, S., Fitzsimons, I.C.W., Powell, C.M., Hulscher, B., Abello, J., Razakamanana, T., 2003b. Neoproterozoic deformation in central Madagascar: a structural section through part of the East African Orogen. In: Yoshida, M., Windley, B., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, Special Publication of the Geological Society, London, vol. 206, pp. 363–379.

Collins, A.S., Kröner, A., Fitzsimons, I.C.W., Razakamanana, T., 2003c. Detrital footprint of the Mozambique ocean: U/Pb SHRIMP and Pb evaporation zircon geochronology of metasedimentary Gneisses in Eastern Madagascar. Tectonophysics 375, 77–99.

Collins, A.S., Kinny, P.D., Santosh, M., Razakamanana, T., 2005. Depositional age and provenance record of ultra-high temperature metasediment protoliths of southern Madagascar and India. In: Wingate, M.T.D., Pisarevsky, S.A. (Eds.), Supercontinents and Earth Evolution. Geological Society of Australia- Abstracts No. 81, pp. 121. Fremantle.

Cox, R., Armstrong, R.A., Ashwal, L.D., 1998. Sedimentology, geochronology and provenance of the Proterozoic Itremo Group, central Madagascar, and implications for pre-Gondwana palaeogeography. Journal of the Geological Society (London) 155, 1009–1024.

Cox, R., Coleman, D.S., Wooden, J.L., DeOreo, S.B., 2001. A newly recognised Late Neoproterozoic Metasedimentary Sequence in Central Madagascar suggests terrane juxtaposition at 560 ± 7 Ma during Gondwana assembly. Geological Society of America Abstracts with Programs, vol. 33, pp. A436.

Cox, R., Coleman, D.S., Chokel, C.B., DeOreo, S.B., Collins, A.S., Kröner, A., De Waele, B., 2004. Proterozoic tectonostratigraphy and paleogeography of central Madagascar derived from detrital zircon U–Pb age populations. Journal of Geology 112, 379–400.

de Wit, M., 2003. Madagascar: heads it's a continent, tails it's an island. Annual Review of Earth and Planetary Science 31, 213–248.

de Wit, M.J., Bowring, S.A., Ashwal, L.D., Randrianasolo, L.G., Morel, V.P.I., Rambeloson, R.A., 2001. Age and tectonic evolution of neoproterozoic ductile shear zones in southwestern Madagascar, with implications for Gondwana studies. Tectonics 20, 1–45.

Emberger, A., 1958. Les granites stratoïdes du Pays betsileo (Madagascar). Bulletin de la Société géologique de France VIII (6), 537–554.

Fernandez, A., Schreurs, G., 2003. Tectonic Evolution of the Proterozoic Itremo Group metasediments in central Madagascar. In: Yoshida, M., Windley, B., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, Special Publication of the Geological Society, London, pp. 381–399.

Fernandez, A., Schreurs, G., Villa, I.M., Huber, S., Rakotondrazafy, M., 2003. Age constraints on the tectonic evolution of the Itremo region in Central Madagascar. Precambrian Research 123, 87–110.

Fitzsimons, I.C.W., Hulscher, B., 2005. Out of Africa: detrital zircon provenance of central Madagascar and Neoproterozoic terrane transfer across the Mozambique Ocean. Terra Nova 17, 224–235.

Ghosh, J.G., de Wit, M.J., Zartman, R.E., 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies. Tectonics 23 (TC3006).

Goncalves, P., Nicollet, C., Lardeaux, J.-M., 2003. Finite strain patterns in Andriamena unit (north-central Madagascar): evidence for late Neoproterozoic–Cambrian thrusting during continental convergence. Precambrian Research 123, 135–157.

Goncalves, P., Nicollet, C., Montel, J.-M., 2004. Petrology and in situ U–Th–Pb monazite geochronology of ultrahigh-temperature metamorphism from the Andriamena mafic unit, north-central Madagascar. Significance of a petrographical P–T path in a polymetamorphic context. Journal of Petrology 45, 1923–1957.

Guérrot, C., Cocherie, A., Ohnenstetter, M., 1993. Origin and evolution of the west Andriamena Pan African mafic-ultramafic complexes in Madagascar as shown by U–Pb, Nd isotopes and trace elements constraints. Terra Abstracts 5, 387.

Handke, M.J., Tucker, R.D., Hamilton, M.A., 1997. Early Neoproterozoic (800–790 Ma) intrusive igneous rocks in central Madagascar; geochemistry and petrogenesis. Abstracts with Programs 29, 468.

Handke, M., Tucker, R.D., Ashwal, L.D., 1999. Neoproterozoic continental arc magmatism in west-central Madagascar. Geology 27, 351–354.

Hauzenberger, C.A., Bauernhofer, A.H., Hoinkes, G., Wallbrecher, E., Mathu, E.M., 2004. Pan-African high pressure granulites from SE-Kenya: Petrological and geothermobarometric evidence for a polycyclic evolution in the Mozambique belt. Journal of African Earth Sciences 40, 245–268.

Hottin, G., 1976. Présentation et essai d'interprétation du Précambrien de Madagascar. Bulletin du Bureau de Recherches Géologiques et Minières IV (2nd series), 117–153.

Huber, S., 2000. Geologie und Geochronologie der Itremo Sedimente im Gebiet des Mont Ibity (Zentral Madagaskar). MSc Thesis, Universität Bern, Bern, Switzerland. 97 pp.

Ito, M., Suzuki, K., Yogo, S., 1997. Cambrian granulite to upper amphibolite facies metamorphism of post-797 Ma sediments in Madagascar. Journal of Earth and Planetary Sciences, Nagoya University 44, 89–102. Japan.

Jayananda, M., Moyen, J.-F., Martin, H., Peucat, J.-J., Auvray, B., Mahabaleswar, B., 2000. Late Archaean (2550–2520 Ma) juvenile magmatism in the Eastern Dharwar craton, southern India: constraints from geochronology, Nd–Sr isotopes and whole rock geochemistry. Precambrian Research 99, 225–254.

Johnson, P.R., Woldehaimanot, B., 2003. Development of the Arabian–Nubian Shield: perspectives on accretion and deformation in the northern East African Orogen and the assembly of Gondwana. In: Yoshida, M., Windley, B.F., Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup, Geological Society, London, Special Publication, vol. 206, pp. 289–325.

Jöns, N., Schenk, V., Appel, P., Razakamanana, T., 2005a. P–T evolution of the Bemarivo Belt (nothern Madagascar): the final assembly of Gondwana. In: Wingate, M.T.D., Pisarevsky, S.A. (Eds.), Supercontinents and Earth Evolution, Geological Society of Australia, Abstracts, vol. 81, pp. 103. Fremantle.

Jöns, N., Schenk, V., John, T., Razakamanana, T., 2005b. Relics of the Mozambique Ocean: geochemistry of the Vohibory Block (Madagascar). In: Wingate, M.T.D., Pisarevsky, S.A. (Eds.), Supercontinents and Earth Evolution, Geological Society of Australia, Abstracts, vol. 81, pp. 133. Fremantle.

Jourde, G., 1971. Essai de synthèse structurale et stratigraphique du Précambrien malagache. Compte Rendu Sociète Géologique France, 59–70.

Jourde, G., Rasamoelina, D., Raveloson, S.A., Razanakolona, J., 1974. Geological map of the Milanoa–Vohemar area, W33-X33, 1:100000. Service Géologique de Madagasikara, Antananarivo.

Kabete, J.K., Groves, D.I., McNaughton, N.J., Dunphy, J.M., in press. The geology, SHRIMP U–Pb geochronology and metallogenic significance of the Ankisatra–Besakay District, Andriamena Belt, northern Madagascar. Journal of African Earth Sciences.

Kröner, A., Braun, I., Jaeckel, P., 1996. Zircon geochronology of anatectic melts and residues from a high-grade pelitic assemblage at Ihosy, southern Madagascar: evidence for Pan-African granulite metamorphism. Geological Magazine 133, 311–323.

Kröner, A., Windley, B.F., Jaeckel, P., Brewer, T.S., Razakamanana, T., 1999. Precambrian granites, gneisses and granulites from Madagascar: new zircon ages and regional significance for the evolution of the Pan-African orogen. Journal of the Geological Society (London) 156, 1125–1135.

Kröner, A., Hegner, E., Collins, A.S., Windley, B.F., Brewer, T.S., Razakamanana, T., Pidgeon, R.T., 2000. Age and Magmatic history of the Antananarivo Block, Central Madagascar, as derived from zircon geochronology and Nd isotopic systematics. American Journal of Science 300, 251–288.

Lacroix, A., 1921–23. Minéralogie de Madagascar, Paris. 1755 pp.

Markl, G., Bäuerle, J., Grujic, D., 2000. Metamorphic evolution of Pan-African granulite facies metapelites from Southern Madagascar. Precambrian Research 102, 47–68.

Martelat, J.E., Nicollet, C., Lardeaux, J.M., Vidal, G., Rakotondrazafy, R., 1997. Lithospheric tectonic structures developed under high-grade metamorphism in the southern part of Madagascar. Geodinamica Acta 10, 94–114.

Martelat, J.-E., Lardeaux, J.-M., Nicollet, C., Rakotondrazafy, R., 2000. Strain pattern and late Precambrian deformation history in southern Madagascar. Precambrian Research 102, 1–20.

Meert, J.G., Nédélec, A., Hall, C., Wingate, M.T.D., Rakotondrazafy, M., 2001. Paleomagnetism, geochronology and tectonic implications of the Cambrian–age Carion Granite, central Madagascar. Tectonophysics 340, 1–21.

Meert, J.G., Nédélec, A., Hall, C., 2003. The stratoid granites of central Madagascar: paleomagnetism and further age constraints on Neoproterozoic deformation. Precambrian Research 120, 101–129.

Moine, B., 1968a. Carte du Massif Schisto–Quartzo–Dolomitique. 1\200000. Service Géologique de Madagasikara, Antananarivo.

Moine, B., 1968b. Relations stratigraphiques entre la série <<Schisto–Quartzo–Calcaire>> et les gneiss environnants (centre ouest de Madagascar): donées d'une première étude géochimique. Comptes Rendus de la Semaine Géologique 1967, Madagascar, 1967, 49–53.

Moine, B., 1974. Caractères de sédimentation et de métamorphisme des séries précambriennes épizonales à catazonales du centre de Madagascar (Région d'Ambatofinandrahana). Sciences de la Terre, Mémoire, pp. 293. Nancy.

Moine, B., Chan Peng, C., Mercier, A., 2004. Rôle du fluor dans la formation des gisements d'émeraude de Mananjary (Est de Madagascar). Comptes Rendus Geoscience 336, 513–522.

Nédélec, A., Paquette, J.-L., Bouchez, J.L., Olivier, P., Ralison, B., 1994. Stratoid granites of Madagascar: structure and position in the Panafrican orogeny. Geodinamica Acta (Paris) 7, 48–56.

Nédélec, A., Stephens, W.E., Fallick, A.E., 1995. The Panafrican stratoid granites of Madagascar: alkaline magmatism in a post-collisional extensional setting. Journal of Petrology 36, 1367–1391.

Nédélec, A., Leterrier, J., Poitrasson, F., 1999. Sr–Nd geochemistry of the Panafrican A-type stratoid granites from central Madagascar. American Geophysical Union, Abstract vol. V31A-01.

Nédélec, A., Ralison, B., Bouchez, J.-L., Grégoire, V., 2000. Structure and metamorphism of the granitic basement around Antananarivo: a key to the Pan-African history of central Madagascar and its Gondwana connections. Tectonics 19, 997–1020.

Nédélec, A., Bouchez, J.-L., Grégoire, V., 2003. Quartz fabric evidence for early Pan-African penetrative east-directed shearing in the Itremo Supracrustal Group of central Madagascar. Terra Nova 15, 20–28.

Nicollet, C., 1990. Crustal evolution of the granulites of Madagascar. In: Vielzeuf, D., Vidal, P. (Eds.), Granulites and Crustal Evolution. Kluwer Academic Publishers, Dordrecht, pp. 291–310.

Paquette, J.-L., Nédélec, A., 1998. A new insight into Pan-African tectonics in the East–West Gondwana collision zone by U–Pb zircon dating of granites from central Madagascar. Earth and Planetary Science Letters 155, 45–56.
Paquette, J.L., Nédélec, A., Moine, B., Rakotondrazafy, M., 1994. U–Pb, single zircon Pb-evaporation, and Sm–Nd isotopic study of a granulite domain in SE Madagascar. Journal of Geology 102, 523–538.
Paquette, J.-L., Moine, B., Rakotondrazafy, M., 2003. ID-TIMS using the step-wise dissolution technique versus ion microprobe U–Pb dating of metamict Archean zircons from NE Madagascar. Precambrian Research 121, 73–84.
Paquette, J.-L., Goncalves, P., Devouard, B., Nicollet, C., 2004. Micro-drilling ID-TIMS U–Pb dating of single monazites: A new method to unravel complex poly-metamorphic evolutions. Application to the UHT granulites of Andriamena (North-Central Madagascar). Contributions to Mineralogy and Petrology 147, 110–122.
Peucat, J.J., Mahabaleshwar, B., Jayananda, M., 1993. Age of younger tonalitic magmatism and granulitic metamorphism in the South India transition zone (Krishnagiri area): comparison with older Peninsular gneisses from the Gorur-Hassan area. Journal of Metamorphic Geology 11, 879–888.
Phillips, G., Boger, S.D., Wilson, C.J.L., Campbell, I.H., Allen, C.M., 2005. Relics of a ca. 1100–1000 Ma mobile belt within Neoproterozoic passive margins attributed to the break-up of Rodinia: evidence from the Ruker Province, East Antarctic Sheld. In: Wingate, M.T.D., Pisarevsky, S.A. (Eds.), Supercontinents and Earth Evolution, Geological Society of Australia — Abstracts, vol. 81, pp. 89. Fremantle.
Raharimimahefa, T., Kusky, T.M., in press. Structural and remote sensing studies of the southern Betsimisaraka suture, Madagascar. Gondwana Research.
Raval, U., Veeraswamy, K., 2003. India–Madagascar separation: breakup along a pre-existing mobile belt and chipping of the craton. Gondwana Research 6, 467–485.
Reeves, C., de Wit, M.J., 2000. Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova 12, 272–280.
Rolin, P., 1991. Présence de déchrochements précambriens dans le bouclier méridional de Madagascar: implications structurales et géodynamiques. Comptes Rendus de l'Académie des Sciences de Paris 312, 625–629.
Schenk, V., Wegner, H., Appel, P., Schumann, A., 2004. Pan-African granulite-facies reworking of Archaean granulites in the West Nile region (Congo Craton; Uganda). 20th Colloquium of African Geology. BRGM, Orleans, France, pp. 364.
Sommer, H., Kröner, A., Hauzenberger, Muhongo, S., 2003. Metamorphic petrology and zircon geochronology of high-grade rocks from the central Mozambique belt of Tanzania. Journal of Metamorphic Geology 21, 915–934.
Torsvik, T.H., Carter, L.M., Ashwal, L.D., Bhushan, S.K., Pandit, M.K., Jamtveit, B., 2001. Rodinia refined or obscured: palaeomagnetism of the Malani igneous suite (NW India). Precambrian Research 108, 319–333.
Tucker, R.D., Ashwal, L.D., Hamilton, M.A., Torsvik, T.H., Carter, L.M., 1999a. Neoproterozoic silicic magmatism of northern Madagascar, Seychelles, and NW India: clues to Rodinia's assembly and dispersal. Geological Society of America, Abstracts with Programs, vol. 31, pp. 317.
Tucker, R.D., Ashwal, L.D., Handke, M.J., Hamilton, M.A., Le Grange, M., Rambeloson, R.A., 1999b. U–Pb geochronology and isotope geochemistry of the Archean and Proterozoic rocks of north-central Madagascar. Journal of Geology 107, 135–153.
Tucker, R.D., Ashwal, L.D., Torsvik, T.H., 2001. U–Pb geochronology of Seychelles granitoids: a Neoproterozoic continental arc fragment. Earth and Planetary Science Letters 187, 27–38.
Tucker, R.D., Kusky, T.M., Buchwaldt, R., Handke, M.J., in press. Neoproterozoic nappes and superposed folding of the Itremo Group, west-central Madagascar. Precambrian Research.
Vachette, M., 1979. Radiochronologie du Precambrien de Madagascar, Colloque de Geologie Africaine. Resumes, 25–27.
Vachette, M., Hottin, A.M., 1974. Ages de 682 et de 527 Ma dans le massif granitique de Carion (centre de Madagascar). Comptes Rendus Hebdomadaires des Seances de l'Academie des Sciences, Serie D: Sciences Naturelles 278, 1669–1671.
Vachette, M., Hottin, G., 1971. Ages du strontium des granites d'Antongil et de l'Androna (nord-est et centre-nord de Madagascar). Comptes Rendus de la Semaine Géologique Madagascar 1970, 73–76.
Vachette, M., Hottin, G., 1975. Ages de 726 millions d'années déterminé au strontium ajusté par isochrone sur roches totales des granites d'Ankaramena (Centre Sud de Madagascar). Comptes Rendus de l'Académie des Sciences de Paris 281, 1975–1977.
Vachette, M., Hottin, G., 1977. Age de 1066 M.A. au strontium ajusté par isochrone sur roches totales des formations granitoïdes de Brickaville (est de Madagascar). Comptes Rendus de l'Académie des Sciences de Paris 284, 1135–1138.
Vachette, M., Hottin, G., 1979. The Precambrian of Madagascar through whole-rock Rb/Sr isochron data. Histoire du Gondwana vue de Madagascar, Antananarivo.
Vachette, M., Razafiniparany, A., Roques, M., 1969. Ages au strontium de 2700 millions d'années et de 1000 millions d'années, pour deux massifs charnockitiques de Madagascar. Comptes Rendus de l'Académie des Sciences de Paris 269, 1471–1473.
Windley, B.F., Razafiniparany, A., Razakamanana, T., Ackermand, D., 1994. Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. Geologische Rundschau 83, 642–659.

Alan Collins is a Senior Lecturer in the School of Earth and Environmental Sciences at the University of Adelaide, Australia, and a member of the Continental Evolution Research Group. He is an Associate Editor of Gondwana Research, a proud member of the International Association for Gondwana Research and the Secretary for the International Geological Correlation Programme project 509, Palaeoproterozoic Supercontinents and Global Evolution. He graduated with a BSc Hons (1993) from Imperial College, London and a PhD (1997) from Edinburgh University and did post-docs at the University of Leicester, Curtin University of Technology and the University of Western Australia. He is a broad based tectonic geologist with particular interests in applying structural, sedimentological and geochronological techniques to solving tectonic problems. Particular research areas include: Neoproterozoic palaeogeography and tectonics; Palaeoproterozoic tectonic processes; and, the evolution of Tethys.