The Tectonic Evolution of Central and Northern Madagascar and Its Place in the Final Assembly of Gondwana — Source link ☒

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The Tectonic Evolution of Central and Northern Madagascar and Its Place in the Final Assembly of Gondwana

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ABSTRACT

Recent work in central and northern Madagascar has identified five tectonic units of the East African Orogen (EAO), a large collisional zone fundamental to the amalgamation of Gondwana. These five units are the Antongil block, the Antananarivo block, the Tsaratanana sheet, the Itremo sheet, and the Bemarivo belt. Geochronological, lithological, metamorphic, and geochemical characteristics of these units and their relationships to each other are used as a type area to compare and contrast with surrounding regions of Gondwana. The Antananarivo block of central Madagascar, part of a broad band of pre-1000-Ma continental crust that stretches from Yemen through Somalia and eastern Ethiopia into Madagascar, is sandwiched between two suture zones we interpret as marking strands of the Neoproterozoic Mozambique Ocean. The eastern suture connects the Al-Mukalla terrane (Yemen), the Maydh greenstone belt (northern Somalia), the Betsimisaraka suture (east Madagascar), and the Palghat-Cauvery shear zone system (south India). The western suture projects the Al-Bayda terrane (Yemen) through a change in crustal age in Ethiopia to the region west of Madagascar. Our new framework for the central EAO links the Mozambique belt with the Arabian/Nubian Shield and highlights the power of tectonic analysis in unraveling the complex tectonic collage of the EAO.

Introduction

The East African Orogen (EAO; Stern 1994) stretches from the Middle East southward through Arabia, Egypt, Eritrea, Ethiopia, East Africa, and Madagascar into southern India, Sri Lanka, and eastern Antarctica. The EAO is made up of crust that was deformed and metamorphosed during the final Neoproterozoic to Cambrian assembly of Gondwana (Powell et al. 1993; Shackleton 1996), which involved both the collision of cratonic blocks (e.g., the eastern Dharwar and Mawson cratons with the western Congo and Kalahari cratons) and accretion of material onto the active Gondwanan margin (e.g., much of the Arabian/Nubian Shield). Relics of the Mozambique Ocean, which separated East and West Gondwana (Dalziel 1991), are found within the EAO juxtaposed with island arc fragments and crustal blocks that were pervasively thermally and structurally reworked in Neo-
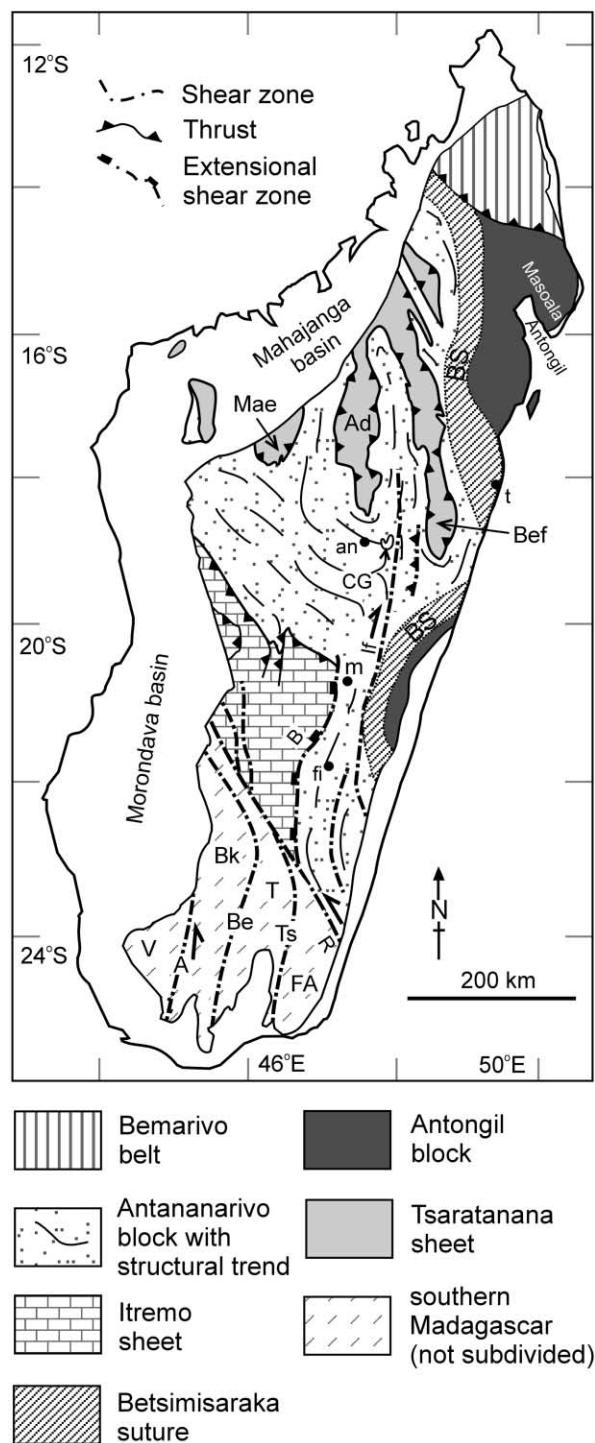
proterozoic times (Stern 1994; Shackleton 1996; Meert and Voo 1997; Kröner et al. 2000).

Madagascar is an ideal place to study the EAO; it is well exposed, accessible, and preserves a section from the hinterland of the EAO to the eastern foreland (Collins et al. 2001b, in press a). It also benefits from an excellent series of geological maps (for summary, see Besairie 1968–1971, 1969–1971, 1973; Hottin 1976). Recent work has identified three main periods of igneous activity in central and north Madagascar: 2600–2500, 820–740, and 630–530 Ma (Paquette and Nédélec 1998; Handke et al. 1999; Kröner et al. 1999, 2000; Tucker et al. 1999b). Recently, Collins et al. (2000a, 2000b) integrated these geochronological data with structural and lithological data to produce a tectonic model for the evolution of central and north Madagascar. In this article, we describe this tectonic model and compare it with the known geology of surrounding areas of Gondwana, locating the major tectonic units of the EAO and suggesting how the various components of the orogenic belt amalgamated.

Tectonic Architecture of Central and Northern Madagascar

Collins et al. (2000a, 2000b) 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. The five tectonic units summarized below and in figure 2 are (1) the Antongil block: ~3.2-Ga gneiss intruded by Late Archean granite that has only experienced greenschist-facies metamorphism since ~2.5 Ga; (2) the Antananarivo block: ~2.5-Ga gneiss interlayered with 820–740-Ma granitoids and gabbros, pervasively deformed and metamorphosed to granulite-facies conditions between ~750 and 500 Ma; (3) the Itremo sheet containing Mesoproterozoic to Neoproterozoic metasedimentary rocks thrust over, and imbricated with, the Antananarivo block. Metasediments of the Itremo sheet nonconformably overlie Archean orthogneiss (Cox et al. 1998) of similar age as the protoliths of the Antananarivo block (Tucker et al. 1999b); (4) the Tsaratanana sheet: formed of 2.7–2.5-Ga mafic gneiss with Middle–Late Archean Sm/Nd ages and zircon xenocrysts (Tucker et al. 1999b; Collins et al. 2001a). This rock was deformed and metamorphosed at ~2.5 Ga (Goncalves et al. 2000) and cut by 800–760-Ma gabbro intrusions. Later, contractional deformation and metamorphism continued until ~500 Ma (Goncalves et al., in press); and (5) the Bemarivo belt: in the north of the island, which consists of east-west-striking metasediments, granites, and gneisses overlain by contractionally deformed metavolcanics. Young granulite-facies metamorphism in the Bemarivo belt is dated at 510–520 Ma (Tucker et al. 1999a).

Central and northern Madagascar are separated from southern Madagascar by the Ranotsara shear zone (Windley et al. 1994). Sinistral displacement of <100 km is implied by the regional drag of foliation to either side of the zone (Windley et al. 1994). This natural boundary forms the southern limit of this study. Southern Madagascar is treated
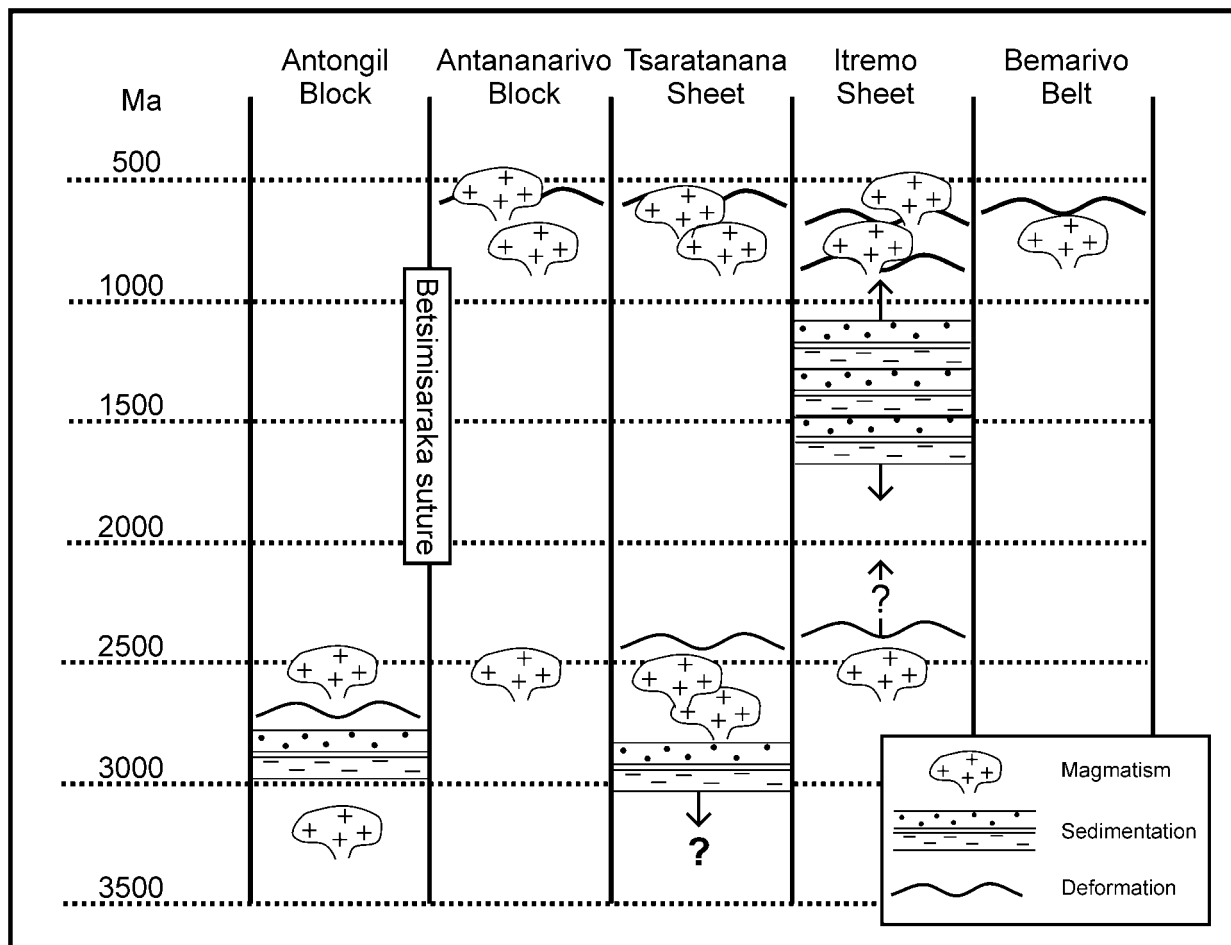
Figure 1. Central and northern Madagascar divided into the five tectonic units of Collins et al. (2000a, 2001b) based on original mapping by Besairie (1973) and the interpretations of Hottin (1976). an = Antananarivo; t = Toamasina; fi = Fianarantsoa; m = Manandona; Ad = Andriamena belt; B = Betsileo shear zone; Bef = Beforona belt; BS = Betsimisaraka suture zone; If = Ifanadriana shear zone; Mae = Maevatanana belt; R = Ranotsara shear zone; CG = Carion granite; Masoala = Masoala peninsula; Antongil = Bay of Antongil. Units south of the Ranotsara shear zone (after Windley et al. 1994; Martelat et al. 2000; de Wit et al. 2001): V = Vohibory belt; A = Ampanihy shear zone; Bk = Bekily belt; Be = Betroka shear zone; T = Tranomaro belt; Ts = Tranomaro shear zone; FA = Fort Dauphin/Anoysan belt.

Figure 2. Time/event chart for the five tectonic units of central and northern Madagascar. Note that the sedimentation periods marked are the time range during which sedimentation occurred and do not imply continuous sedimentation.

as part of surrounding Gondwana and is discussed in a later section.

Antongil Block. The Antongil block consists of a granitic and gneissic core semiencircled by metasediments. It is characterized by lower-temperature metamorphic assemblages (greenschist-lower amphibolite facies) as compared to those from the center of the island (Hottin 1976). The crystalline core of the Antongil block consists of ortho- and paragneisses that date back to 3127 Ma intruded by ∼2520–30-Ma granitic bodies (Tucker et al. 1999b; Collins et al. 2001a). Whole-rock Rb/Sr (Vachette and Hottin 1971) Archean ages 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 tectonothermal events so characteristic of the rest of Madagascar. Psammitic metasediments unconformably (Hottin 1976) overlie the crystalline core to the north and 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 podiform 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 was named the "Betsimisaraka" suture by Kröner et al. (2000).

Antananarivo Block. The Antananarivo block forms the largest pre-Paleozoic tectonic unit of

Madagascar (fig. 1). It consists of 2550–2500-Ma granitoids tectonically interlayered with voluminous 824–719-Ma granites, syenites, and gabbros (Tucker et al. 1999b; Kröner et al. 2000). The whole of the Antananarivo block was thermally and structurally reworked between ~750 and 500 Ma (Collins et al., in press a), with preexisting 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]) characteristic of this tectonic unit. These granites intruded at the same time as extensional deformation (Nédélec et al. 1995) associated with the crustal-scale Betsileo shear zone (Collins et al. 2000b; fig. 1). The eastern Antananarivo block was deformed by east-west contraction and top-to-the-east thrusts between 630 and ~515 Ma, which emplaced the then-amalgamated central Madagascar over the Antongil block. The 527–37-Ma Carion granite (Kröner et al. 2000; Meert et al. 2001a, 2001b) sealed this deformation.

Tsaratanana Sheet. The Tsaratanana sheet is composed of mafic gneiss, tonalites, podiform chromite-bearing ultramafic rocks, and metapelites, some of which were metamorphosed to ultra-high temperatures (Nicollet 1990) at ~2.5 Ga (Goncalves et al. 2000). This tectonic unit is formed of three main belts (the Maevatanana, Andriamena, and Beforona) of similar lithology, geochronology, and structural position (fig. 1). 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. 2001a) and Middle Archean Nd isotope signatures (Tucker et al. 1999b). Gabbros of 800–770-Ma age cut the earlier deformed older rocks (Guerrot et al. 1993; Tucker et al. 1999b) that, in the Andriamena belt, are themselves deformed into asymmetric folds and cut by east-directed thrusts. Top-to-the-east thrusting in the Beforona belt postdates intrusion of a granitoid at 637 Ma (Tucker et al. 1999b) 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. (in press) demonstrated that in the west, this mylonite zone has top-to-the-east kinematics, but as yet, the timing of this thrusting is uncertain.

Itremo Sheet. The Itremo sheet consists of a metasedimentary sequence (the Itremo Group of Cox et al. 1998; the massif schisto-quartzo-dolomitique of Moine 1968; Moine 1974) that nonconformably overlies amphibolite and gneiss correlatable with orthogneisses of the Antananarivo block

(Tucker et al. 1999b). The Itremo sheet increases in metamorphic grade from east to west with its lowest-grade rocks (lower greenschist facies) preserved directly west of Manandona (fig. 1; Moine 1968, 1974; Besairie 1973; Collins et al. 2000b). The Itremo Group consists of dolomitic marbles, quartzites, pelites, and metasiltstones deposited between 1855 and 804 Ma (Cox et al. 1998; Handke et al. 1999) and deformed into large (amplitudes of >20 km) recumbent isoclinal folds intruded by a set of gabbros and syenites (Hulscher et al. 2001) between 804 and 779 Ma (Handke et al. 1999). 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 779 Ma, the Itremo sheet was redeformed into open, upright folds, divergent reverse faults, and strike-slip faults (Collins et al., in press b) sealed by 570–539-Ma granitoid intrusions (Handke et al. 1997). A second sedimentary sequence, the Molo Group, has been discovered in the western Itremo sheet that contains many 1.1–1.0-Ga detrital grains and was deposited after 640 ± 20 Ma (Cox et al. 2001). The eastern margin of the Itremo sheet forms an extensive extensional detachment (the Betsileo shear zone; Collins et al. 2000b). The Itremo sheet itself was not extensively deformed during extensional deformation and appears to have passively slid on the Betsileo shear zone. The cooling history of the Itremo Group has been elucidated by Ar-Ar muscovite dating (492 ± 2 Ma; Fernandez et al. 2000).

Bemarivo Belt. The Bemarivo belt forms a tectonic region in the north of Madagascar, which map scale, crosscuts the Antananarivo block, the Antongil block, and the Betsimisaraka suture (fig. 1). 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 domelike massifs that intrude through migmatites and orthogneisses (Jourde et al. 1974). Tucker et al. (in Ashwal 1997, p. 9) dated one of these intrusions at 753.8 ± 1.7 Ma. Three major metavolcanosedimentary regions also occur in the 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. The southern region was deformed by top-to-the-south thrusting coeval with granulite-grade metamorphism. Tucker et al. (1999a) dated cooling after this metamorphic event by U-Pb in monazite and titanite as between 510 and 520 Ma. These ages are the youngest for high-temperature

metamorphic minerals so far discovered in Madagascar and indicate that the Bemarivo belt was thrust over the already amalgamated collage of central Madagascar in Cambrian times. After south-directed thrusting, this northern region was extended by a series of top-to-the-north shear zones (Collins et al. 2000a).

The broad, highly sheared region that separates the Antananarivo block from the Antongil block was interpreted to mark the remains of an oceanic suture zone by Kröner et al. (2000). This interpretation is supported by the thick succession of paragneisses with numerous entrained ultramafic and mafic rocks along the boundary. Voluminous 825–720-Ma arc-related intrusions are found within the hanging wall (the Antananarivo block), suggesting subduction of oceanic crust beneath central Madagascar at this time (Brewer et al. 2001). Both the general westward dip of foliation throughout east Madagascar and the provenance data, which suggests that the Itremo Group was derived from East Africa (Cox et al. 1998, 2000), indicate that this subduction zone lay to the east of the Antananarivo block along the line of its boundary with the Antongil block. Kröner et al. (2000) named this suture the "Betsimisaraka" suture after the region through which it passes.

Tectonic Evolution of Central and Northern Madagascar

The five tectonic units that make up central and northern Madagascar were amalgamated during the Proterozoic and early Paleozoic. The Tsaratanana sheet was deformed before 825 Ma, at which time previously deformed Archean/Paleoproterozoic rocks were intruded by gabbroic and dioritic plutons (Guerrot et al. 1993; Tucker et al. 1999b). This deformation may have been coeval with large (>20 km) recumbent folding of the Itremo sheet bracketed between 1855 and 804 Ma (Cox et al. 1998; Hulscher et al. 2001; Collins et al., in press b). A younger constraint on both these deformations is provided by a 825–720-Ma magmatic suite that intrudes the Itremo sheet, the Tsaratanana sheet, and the Antananarivo block (Guerrot et al. 1993; Handke et al. 1999; Tucker et al. 1999b; Kröner et al. 2000). The occurrence of middle Neoproterozoic rocks throughout these three tectonic units suggests that much of central Madagascar had amalgamated by this time. These magmatic rocks are interpreted to have formed an Andean-type continental-margin arc above a westward-dipping sub-

duction zone that consumed a strand of the Mozambique Ocean (Brewer et al. 2001). This ocean, which would have separated the amalgamated tectonic units of central Madagascar from the Antongil block farther east, closed between 719 and 530 Ma, bracketed by the youngest age constraint on the now highly deformed arc-related magmatic rocks of the Antananarivo block (Kröner et al. 2000) and the age of the posttectonic Carion granite (Meert et al. 2001b). After 637 Ma (the youngest contractionally deformed intrusion in the Tsaratanana sheet; Tucker et al. 1999b), the eastern Antananarivo block and the eastern Tsaratanana sheet were intensely deformed and thrust eastward over the Antongil block. High-grade metamorphism in the central Antananarivo block occurred at ~550 Ma (Kröner et al. 2000) and was overprinted by extensional deformation (Collins et al. 2000b). Elsewhere in the Antananarivo block, synextensional magmatism as far back as 630 Ma (Paquette and Nédélec 1998) suggests that while the east of Madagascar was contractionally deformed, the center of the island was extending. This spatial segregation in structural style is seen in many modern orogenic belts (e.g., the Himalaya) where foreland regions are overthrust while more hinterland regions are extending.

The Bemarivo belt was thrust southward and metamorphosed after the remainder of the island was amalgamated. Tucker et al. (1999a) dated titanites and monazites that formed during this event at 510–520 Ma. After south-directed thrusting, this northern region was extended by a series of top-to-the-north shear zones (Collins et al. 2000a).

Postamalgamation Deformation

Early deformation in central and northern Madagascar created a gneissic fabric, low-angle ductile shear zones, and commonly, a well-developed mineral or mineral-aggregate lineation. Later deformation deformed the originally gently dipping gneissic fabric into open, upright folds and subvertical shear zones (fig. 1; Martelat et al. 2000; Nédélec et al. 2000). Collins et al. (2000b) described a crustal-scale extensional shear zone (the Betsileo shear zone) from the center of the island. This shear zone exhumed much of the central Antananarivo block and trends approximately parallel to the gneissic fabric of that unit. Collins et al. (2000b) suggested that the gneissic fabric, footwall granulite retrogression, A-type granitoid intrusion (Néd-

élec et al. 1994, 1995), and the Betsileo shear zone were consequences of postcollisional extensional deformation in central Madagascar. This deformation continued until after 551 Ma (Collins et al. 2000*b*). Farther east, the Ifanadriana shear zone identified by Martelat et al. (2000) may well correlate with the Angavo shear zone 200 km farther north (Windley et al. 1994; Nédélec et al. 2000). This shear zone was interpreted by Nédélec et al. (2000) to be active at approximately the same time as intrusion of the 530-Ma Carion granite (Meert et al. 2001*b*).

Relationship to Surrounding Gondwanan Terrains

Prior to the break up of Gondwana, Madagascar was located adjacent to East Africa with the Seychelles to the northeast (azimuth relative to present-day Africa), India and Sri Lanka to the east, and Mozambique to the south (fig. 3; Lawver et al. 1992, 1998). It has long been a problem how to accurately match up the Proterozoic structures across the intervening ocean basins (Katz and Premoli 1979; Berhe 1990; Stern 1994; Shackleton 1996; Kröner et al. 2000; Reeves and de Wit 2000). The following observations are not intended as a final answer, but sufficient data have recently been collected to firm up some of the matches and to highlight associated tectonic problems. Below and in table 1, we summarize the available geochronology and tectonic history of the regions of Gondwana that surrounded Madagascar, using a number of different features to correlate the remnants of Gondwana distributed around the western Indian Ocean. These include:

1. Shear zones: Since the groundbreaking work of Katz and Premoli (1979), matching up shear zones across post-Gondwana ocean basins has been the preferred method of many workers to correlate between adjacent Gondwanan fragments (e.g., Windley et al. 1994; Nédélec et al. 2000; de Wit et al. 2001). Although much success has been achieved by this method, linear shear zones often form late in the orogenic cycle and are therefore of limited use when trying to identify tectonic units involved in early stages of collision.

2. Thermal fronts (or fronts of isotopic disturbance): Radiogenic geochronometers date the time at which a daughter element was fixed in a mineral. Because this "fixing" is dominantly temperature controlled, it is possible to identify thermal fronts outside which a particular isotopic system was undisturbed by subsequent thermal effects.

3. Provenance (or derivation) domains: Sedimentary rocks caught up in an orogenic belt may preserve a provenance record indicating derivation from a particular block involved in the orogeny. In this way, domains of rocks sharing a similar derivation can be constructed. In a related method, Nd isotopes can be used to correlate bodies of rocks that share similar crustal residence histories.

4. Suture zones: Suture zones mark the sites of consumed oceanic crust and are broadly linear features that have a distinct lithological expression. These highly deformed zones are characterized by the presence of ocean crust lithologies including serpentinized peridotite, deep marine sediments, and basalt. Commonly, they also mark boundaries between provenance domains.

To the East (***Southern India***).   Southern India consists of an Archean craton (Dharwar or Karnataka craton; Chadwick et al. 2000; Jayananda et al. 2000) separated by the Palghat-Cauvery shear zone system (made up of the Moyar, Bhavani, Palghat, Cauvery, and Attur shear zones; Chetty 1996; Meissner et al. 1999, 2002) from a Proterozoic metamorphic belt made up of the Madurai and Trivandrum blocks (fig. 3; Harris et al. 1994, 1996; Bartlett et al. 1998). The Dharwar craton is split into western and eastern domains by a north-south shear zone. In the western domain, a basement made of orthogneiss (the "Peninsular gneiss" with crystallization ages of 3.4–3.2 Ga; Peucat et al. 1993) and supracrustal rocks (the Sargur Group: deposited 3.13–2.96 Ga; Nutman et al. 1992) is overlain by later supracrustal rocks of the Dharwar Group (Swami Nath et al. 1976; Chadwick et al. 1989) that were deposited between 3.0 and 2.6 Ga (Nutman et al. 1996). Rare 2.55-Ga granitoid plutons cut the western domain (Rodgers 1988). The eastern domain is dominated by the Dharwar batholith (Chadwick et al. 2000), which consists of 2513–2552-Ma granitoid plutons (Jayananda et al. 2000). The well-known Closepet granite (Smeeth 1915) was identified as a part of the more extensive Dharwar batholith by Chadwick et al. (2000). Intercalated with these granitoids are schists that were deposited coeval with the Dharwar Group (Nutman et al. 1996; Chadwick et al. 2000).

Sm-Nd errorchrons indicate that significant crustal accretion occurred along the southern margin of the Dharwar craton at ~2.45 Ga (Harris et al. 1996), accompanied by metamorphism (Peucat et al. 1993) that ranged from granulite facies in the south to greenschist facies farther north (Raith et al. 1982). North of the Palghat-Cauvery shear zone, temperatures were <320°C by 2.2 Ga (Peucat et al. 1993) but south of this zone, the Archean Madurai and Trivandrum blocks (which had experienced separate tectonothermal histories in the Paleoproterozoic) were both meta-
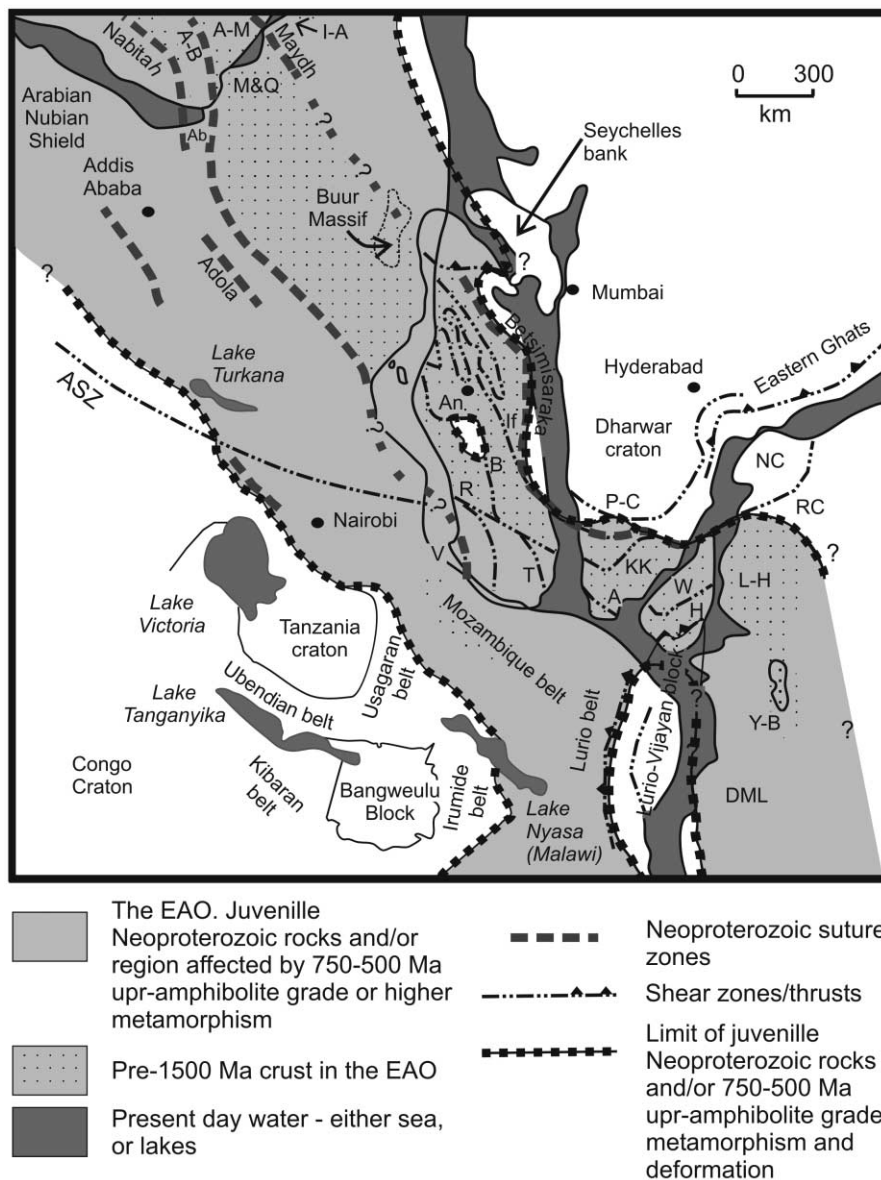
Figure 3. The relationships between Madagascar and surrounding regions of Gondwana. Tight-fit Gondwana reconstruction after Lawver et al. (1992, 1998). *Ab* = Abdulkadir terrane; *A* = Achankovil shear zone; *A-B* = Al-Bayda terrane; *A-M* = Al-Mahfid terrane; *An* = Antananarivo; *ASZ* = Aswa shear zone; *DML* = Dronning Maud Land; *H* = Highland Complex; *I-A* = Inda Ad Complex; *If* = Ifanadriana shear zone; *KK* = Karur-Kambam-Painavu-Trichur shear zone; *L-H* = Lützow-Holm Complex; *M&Q* = Mora and Qabri Bahar terrane; *NC* = Napier Complex; *P-C* = Palghat-Cauvery shear zone system; *R* = Ranotsara shear zone; *RC* = Rayner Complex; *T* = Tranomaro shear zone; *V* = Vohibory belt; *W* = Wanni Complex; *Y-B* = Yamato-Belgica complex; *Betsimisaraka* = Betsimisaraka suture. Data from Kröner and Williams 1993; Lenoir et al. 1994; Shiraishi et al. 1994; Kröner and Sassi 1996; Shackleton 1996; Kröner et al. 1997; Bartlett et al. 1998; Jacobs et al. 1998; Teklay et al. 1998; Tucker et al. 1999a, 1999b; de Wit et al. 2001; Muhongo et al. 2001; Whitehouse et al. 2001; Yibas et al., in press.

morphosed to upper amphibolite to granulite facies at 560–510 Ma (Bartlett et al. 1998). The Moyar, Bhavani, and Palghat-Cauvery shear zones were active in late Neoproterozoic times (Meissner et al. 2002). Thus, the Palghat-Cauvery shear zone

system is an important divide between rocks that experienced a Neoproterozoic to Cambrian tecton-othermal event in the south and rocks to the north that did not (Raith 1999). The Betsimisaraka suture zone marks a correlatable thermal boundary in

Table 1. Summary of the Available Geochronology of the Regions Adjacent to Madagascar in a Tight-Fit Reconstruction of Gondwana

Location	Geochronological description	References
South India:		
Dharwar craton	3.4–3.0-Ga ortho- and paragneisses, overlain by 3.0–2.6-Ga sediments; 2.55–2.51-Ga granite intrusion; 2.5–2.3-Ga metamorphism and accretion in south	1–5
Madurai block	3.2–2.2-Ga crustal growth; 700–500-Ma metamorphism	6, 21
Trivandrum block	3.0–2.0-Ga crustal growth; ~1.8-Ga metamorphism; 700–500-Ma metamorphism	6
North Mozambique	615-Ma granulites of the Lurio belt thrust eastward over the 1.2–1.0-Ga Lurio foreland that has not experienced high-grade metamorphism in Neoproterozoic times.	7–9
South Madagascar	Tectonic slices of orthogneiss older than 2.9 Ga; sedimentation post–720 Ma derived from Mesoproterozoic and Neoproterozoic source; contractional deformation and intrusion 650–607 Ma; extended period of high-temperature metamorphism 605 to ~520 Ma	10–13
South Somalia	~2.5-Ga granite protoliths; 600–535-Ma granulite metamorphism, deformation and intrusion; ~470-Ma postkinematic granites	14, 15
Seychelles	808–703-Ma granitoid intrusions	16, 17, 23
South and East Ethiopia:		
Southwest	884–526-Ma granitoid gneiss with Nd mean crustal residence ages of 0.96–1.26 Ga	18, 22
Northeast	2489–781-Ma S-type granites with Nd mean crustal residence ages of 2.88–1.62 Ga	18
North Somalia:		
Abdulkadir Complex	700–640-Ma basalts	19
Mora and Qabri Bahar Complex	840–720-Ma granite gneiss with 1820–1400-Ma xenocrysts	20
Maydh Complex	Mid-ocean ridge basalt–like basalts suggested to be 700–640	19
Inda Ad Group	Intruded by 630-Ma granites with pre-900-Ma xenocrysts	15

Sources.   1, Peucat et al. 1993; 2, Nutman et al. 1992; 3, Nutman et al. 1996; 4, Jayananda et al. 2000; 5, Harris et al. 1996; 6, Bartlett et al. 1998; 7, Kröner et al. 1997; 8, Sacchi et al. 1984; 9, Costa et al. 1992; 10, de Wit et al. 2001; 11, Kröner et al. 1996; 12, Paquette et al. 1994; 13, Ashwal et al. 1999; 14, Küster et al. 1990; 15, Lenoir et al. 1994; 16, Tucker et al. 1999*a*; 17, Suwa et al. 1994; 18, Teklay et al. 1998; 19, Sassi et al. 1993; 20, Kröner and Sassi 1996; 21, Meissner et al. 2002; 22, Yibas et al., in press; 23, Tucker et al. 2001.
Note.   For tight-fit reconstruction of Gondwana, see figure 3.

eastern Madagascar because it is broadly coincident with the eastern (i.e., forelandward) limit of Neoproterozoic disturbance of the whole-rock Rb/Sr isotopic system (Vachette 1979; Cahen et al. 1984). It also marks a provenance boundary separating the Antongil block where Nd model ages (T_{DM}) date back to 3.2 Ga (Tucker et al. 1999*b*) from the Antananarivo block where Nd model ages only pass back to 2.7 Ga (Tucker et al. 1999*b*; Kröner et al. 2000).

As well as marking a provenance boundary and a thermal boundary, the Betsimisaraka suture is interpreted as an oceanic suture zone because it consists of highly deformed metapelites and is beaded by many podlike ultramafic bodies (see above). The same features are present along the Palghat-Cauvery shear zone system, and a number of workers have suggested that this too marks an ancient suture zone (see Chetty 1996). Thus, the Betsimisaraka suture and the Palghat-Cauvery shear zone system are cor-

related both on metamorphic grounds as thermal fronts and on lithological grounds as suture zones.

A number of large, subvertical shear zones cut southern India and Madagascar (figs. 1, 3). Madagascar is split in two by the sinistral Ranotsara shear zone. Eastern Madagascar is cut by the north-south Ifanadiana shear zone (Martelat et al. 2000; correlated here with the more northern Angavo shear zone of Nédélec et al. 2000), which is subparallel to the Betsimisaraka suture in the south but diverges away from it northward. Southern India is crossed by a number of shear zones including (from north to south) the anastomosing Moyar, Bhavani, and Palghat-Cauvery shear zones (together forming the Palghat-Cauvery shear system), the Karur-Kambam-Painavu-Trichur shear zone (KKPT; Ghosh et al. 1998; de Wit et al. 2001), and the Achankovil shear zone. As discussed above, the Palghat-Cauvery shear zone system and the Betsimisaraka suture are linked as suture zones and

thermal fronts (see above). In southeastern Madagascar, the Ifanadiana shear zone cuts rocks of the Betsimisaraka suture (fig. 1). This is similar to the situation in southern India where suture zone rocks are deformed by the Palghat-Cauvery shear zone system. This reconstruction agrees well with that of de Wit et al. (2001) because it aligns the Ranotsara shear zone with the KKPT and the Achankovil shear zone with the Tranomaro shear zone.

To the Northeast (Seychelles). Prior to opening of the Indian Ocean, the Seychelles lay off northeastern Madagascar adjacent to the Bemarivo belt (fig. 3). This continental fragment consists of a set of granodiorite/tonalite gneisses intruded by later granites (Suwa et al. 1994; Plummer 1995). The early orthogneisses are calc-alkaline I-type granitoids (Suwa et al. 1994), whereas the later granites have strongly depleted $\delta^{18}O$ signatures and A-type characteristics (Stephens et al. 1997). Ashwal et al. (2002) has recently interpreted these granitoids as the root of a continental arc. Conventional U-Pb zircon dating on the granites has produced ages between 809 and 703 Ma (Stephens et al. 1997; Tucker et al. 1999a, 2001), a similar age range to that of felsic volcanism in northwestern India (870–748 Ma, Malani rhyolites; Tucker et al. 1999a; Torsvik et al. 2001) and granitoid magmatism in the Bemarivo belt (Tucker et al. 1999a).

To the West (East Africa). The EAO passes through Kenya and eastern Tanzania, where at its western margin, it abuts against the Archean Tanzanian craton and truncates the ~2.0-Ga Usagarian belt (fig. 3). In western Kenya, Neoproterozoic deformation includes westward thrusting of the Pokat ophiolite over the Tanzania craton (Vearncombe 1983; Key et al. 1989). Protoliths of orthogneisses in the Tanzanian EAO indicate the presence of 2.6–2.75-Ga crust, rare Paleoproterozoic and Mesoproterozoic intrusions followed by an extensive phase of magmatism and basin formation between 665 and 843 Ma (Muhongo et al. 2001). Metamorphic zircons have been used to date near-peak granulite-grade metamorphism at ~640 Ma (Coolen et al. 1982; Muhongo and Lenoir 1994; Appel et al. 1998; Muhongo et al. 2001). Granulite-facies metamorphism is significantly older here than in central Madagascar (~640 Ma in Tanzania as opposed to 550 Ma in central Madagascar; Kröner et al. 2000); however, it is coeval with the older end of the range of ages obtained for high-grade metamorphism in southern Madagascar (see below; Ashwal et al. 1999; de Wit et al. 2001).

To the Northwest (Somalia and Ethiopia). The Buur massif of southern Somalia lay directly northwest of north Madagascar in Gondwana (fig. 3). Although poorly exposed, paragneisses, migmatites, quartzites, ironstones, and marbles occur in this region and are crosscut by two granitoid suites (Dal Piaz and Sassi 1986; Küster et al. 1990). An early foliated suite contains zircons that define a discordia line that has been interpreted to indicate the presence of ~2.5-Ga crust in the region, with anatexis occurring at 536 ± 18 Ma (the lower intercept with the concordia curve; Küster et al. 1990). Younger, A-type potassic granitoids (Lenoir et al. 1994) contain zircons that indicate posttectonic emplacement at 474 ± 9 Ma (Küster et al. 1990). The inferred 2.5-Ga protoliths correlate well with the age of the Antananarivo block.

A western major boundary between this thermally and structurally reworked pre-1000-Ma tectonic unit (similar to the Antananarivo block) and the post-1000-Ma, juvenile, Arabian-Nubian Shield occurs between the Buur Massif and southern Ethiopia (fig. 3). The Arabian-Nubian Shield consists of a collage of Neoproterozoic ophiolite-decorated suture zones and island arc fragments that cover large areas of western Ethiopia, Eritrea, northeastern Sudan, Yemen, eastern Egypt, and western Saudi Arabia (Stern 1994; Shackleton 1996; Johnson and Kattan 2001). In southern Ethiopia, a far-traveled nappe of oceanic crust has been thrust toward the east (de Wit and Senbeto 1981) over 884–716-Ma granitoid gneiss (Teklay et al. 1998). That ophiolite, dated by Teklay et al. (1998) at 700.5 ± 1.3 Ma, is intruded by 657-Ma I-type trondjemites. Volcanism in an associated arc sequence (Beraki et al. 1989) occurred at ~605 Ma. Deformation in the underlying orthogneiss occurred after ~560 Ma (Teklay et al. 1998).

The western boundary of the pre-1000-Ma crust is then traced north, with eastern Ethiopia and northwest Somalia (Mora and Qabri Bahar terranes) lying to the east of it (fig. 3). These regions consist of paragneisses and orthogneisses overlying and derived from Paleoproterozoic and Mesoproterozoic crust. Deformed 710–845-Ma granitoids, gabbros, and syenites intrude these rocks (Kröner and Sassi 1996; Teklay et al. 1998). In eastern Ethiopia, this deformation is concentrated in the west of the outcrop and occurred after intrusion of the protolith of a biotite gneiss at 649.3 ± 0.6 Ma (Teklay et al. 1998). In the far northwest of Somalia, the Abdulkadir Complex represents juvenile arc-related extrusive rocks (Sassi et al. 1993) that mark the limit of the ancient terrane caught up in the EAO.

The eastern margin of this pre-1000-Ma tectonic unit is exposed in central north Somalia where it abuts against the Maydh greenstone belt along a mylonite zone (Utke et al. 1990). The Maydh green-

stone belt consists of metasediments, microgabbros, and pillow basalts metamorphosed to greenschist facies. The basic igneous rocks are chemically similar to mid-ocean ridge basalts (Utke et al. 1990). The nature of the boundary between the Maydh greenstone belt and the overlying Inda Ad Group is poorly known. It may be either a thrust contact (Lenoir et al. 1994) or a gradational sedimentary contact (Utke et al. 1990). Turbidites of the Inda Ad Group contain the remains of enigmatic fossils (Abbate et al. 1981) and are intruded by ~630-Ma postkinematic granites that contain evidence of interaction with pre-1000-Ma crust at depth (Lenoir et al. 1994). Isolated outcrops of high-grade gneiss and granite near the Horn of Africa and in the archipelago continuing eastward to the island of Socotra are likely to be this basement to the Inda Ad Group. Farther north, and outside the scope of this article, similar tectonic units to those of northern Somalia have been identified in Yemen and Saudi Arabia (Whitehouse et al. 2001).

Somalia and eastern Ethiopia preserve evidence of a broad north-south belt of pre-1000-Ma crust thermally reworked during the Neoproterozoic. Neoproterozoic rocks that formed on or within oceanic crust as island arcs or ocean-floor rocks delineate this belt in both the east and west. A similar situation is preserved in central Madagascar. Here, the Archean Antananarivo block (and overlying Mesoproterozoic–early Neoproterozoic Itremo sheet) was thermally and structurally reworked between 750 and 520 Ma. These tectonic units are bound in the east by the Betsimisaraka suture that is correlated with the Maydh greenstone belt of northern Somalia (fig. 3). Deformation and metamorphic grade increase westward in the Itremo sheet (Moine 1966, 1968), but a western suture is not preserved in central Madagascar and is presumed to be buried beneath the Phanerozoic Morondava basin (figs. 1, 3). Pillow basalts, ultramafics, and basic gneisses that crop out in Vohibory complex of southern Madagascar (see below; Windley et al. 1994) are interpreted to represent this suture displaced eastward by the Ranotsara shear zone (figs. 1, 3).

To the South (Southern Madagascar and Northern Mozambique). In southern Madagascar, south of the Ranotsara shear zone, a number of tectonic units have been identified. From west to east these are the Vohibory belt, the Ampanihy belt, the Bekily belt, the Betroka belt, the Tranomaro belt, and the Fort Dauphin/Anosyan belt (fig. 1; Windley et al. 1994). The belts reflect rock packages that preserve different structural styles; the Ampanihy and the Betroka belts are subvertical shear zones (the latter called the "Vorokafotra" shear zone by de Wit et al. [2001] and the "Beraketa" shear zone by Martelat et al. [2000]). Subsequently, Martelat et al. (2000) identified the Tranomaro shear zone separating the Tranomaro belt from the Fort Dauphin/Anosyan belt (fig. 1). With the exception of the Vohibory belt, these belts are derived from mainly sedimentary protoliths and consist of granulite- and upper amphibolite-grade gneisses. Detrital zircons from paragneisses range in age from 1.8 to 0.72 Ga (Kröner et al. 1996; de Wit et al. 2001) suggesting a similar provenance to the Itremo and Molo Groups of central Madagascar (see above). Apart from tectonic slivers of Archean orthogneiss (de Wit et al. 2001) in the Anosyan belt, the majority of rocks in this region formed during the Neoproterozoic (Paquette et al. 1994; Kröner et al. 1996, 1999; de Wit et al. 2001). Southern Madagascar was metamorphosed to peak conditions of 7–11.5 kbar and 750°–900°C (Nicollet 1986, 1990; Markl et al. 2000) at between 650 and 630 Ma (de Wit et al. 2001). Elevated temperatures were maintained between 605 and 520 Ma, with accelerated exhumation of ~10°C/Ma between 520 and 490 Ma (Ashwal et al. 1999; de Wit et al. 2001). The Bekily and Betroka belts form north-south lithosphere-scale shear zones (Martelat et al. 1997; Pili et al. 1997) correlated by de Wit et al. (2001) and Reeves and de Wit (2000) with shear zones in India and Mozambique.

The EAO continues into north Mozambique where the east-directed Lurio belt thrusts 615-Ma granulites over a 1.0–1.2-Ma foreland region (Sacchi et al. 1984; Costa et al. 1992; Kröner et al. 1997) that preserves no evidence of high-grade metamorphism in Neoproterozoic times (Kröner et al. 1997). The thrust base of the Lurio belt contains siliceous metasedimentsand basic and ultrabasic rocks that have been interpreted as fragments of an ophiolite (Sacchi et al. 1984).

A similar relationship with Neoproterozoic granulites thrust over a 1.0–1.2-Ga unit is found in southeastern Sri Lanka where the Highland and Wanni Complexes are thrust east over the Vijayan Complex (Kriegsman 1995). Because of their proximity in the tight-fit reconstruction of Lawver et al. (1998), we have linked the Vijayan Complex of Sri Lanka and the Lurio foreland to form a poorly known Mesoproterozoic tectonic block caught up in the EAO (fig. 3).

Discussion

The EAO is formed of a series of crustal blocks separated by oceanic sutures and is similar in ap-

pearance to Phanerozoic sites of oceanic closure (e.g., the Anatolide-Tauride system of Turkey; Şengör and Yilmaz 1981). Central Madagascar consists of a 2.5-Ga crustal fragment (Antananarivo block) that was caught up in the closure of the Mozambique Ocean. This crustal unit can be traced northward through Somalia and east Ethiopia, where it is bound both east and west by Neoproterozoic juvenile material. This Archean tectonic unit continues north into the Yemen, where it is known as the "Al-Mahfid" gneiss terrane (Whitehouse et al. 2001). West of the Al-Mahfid gneiss terrane is the Al-Bayda terrane, an arc-related terrane of ophiolitic fragments and arclike volcanics that, following Whitehouse (2001), is linked with Abdulkadir Complex in northern Somalia; the change in crustal age seen in eastern Ethiopia (Teklay et al. 1998). This suture is projected south from Ethiopia toward the west of Madagascar (fig. 3), where deformation along it may relate to the extreme deformation seen in the western Itremo sheet of central Madagascar (Moine 1968).

The east margin of this Archean unit in Somalia is the Maydh greenstone belt. This suture is correlated north with the Al-Mukalla terrane of the Yemen (Whitehouse et al. 2001) and south with the Betsimisaraka suture of east Madagascar and the Palghat-Cauvery shear zone of south India. Rocks east of the Maydh greenstone belt were metamorphosed to greenschist facies in Neoproterozoic times. This contrasts with eastern Madagascar and southern India where the Betsimisaraka suture and Palghat-Cauvery shear zones are approximately coincident with the east limit of Neoproterozoic thermal reworking. However, because most geochronological studies east of the Betsimisaraka suture and north of the Palghat-Cauvery shear zone have used phases with relatively high blocking temperatures, greenschist-facies Neoproterozoic metamorphism is not ruled out.

We identify a large region of pre-1000-Ma crust (~1 million km^2) extending from Yemen to southern India, caught up in the EAO and bound in both the east and west by juvenile post-1000-Ma arc-derived rocks and oceanic suture zones. On a broad scale, the EAO has similarities with the Phanerozoic accretion of Asia (Şengör and Natal'in 1996). In both regions, microcontinental blocks are caught up in the orogenic belt, forming more ancient fragments within the broad orogenic melange.

Conclusions

By linking the deformational, geochronological, and metamorphic history of a region into a tectonic framework, disparate regions can be compared and contrasted with each other to produce a more holistic model for the tectonic evolution of an orogenic belt. By using this approach on the EAO, strands of the Mozambique Ocean suture are located, one connecting the Al-Bayda terrane of Yemen with the change in crustal age seen in east Ethiopia and passing directly west of central Madagascar. Another more eastern suture links the Al-Mukalla terrane of Yemen with the Maydh greenstone belt of north Somalia, the Betsimisaraka suture of east Madagascar, and the Palghat-Cauvery shear zone of south India. Between these sutures, there is an extensive terrane of pre-1000-Ma crust that dates back to ~2.5 Ga and has been extensively reworked in the Neoproterozoic.

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