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Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal

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Abstract The Precambrian of Madagascar is divided into two sectors by the north-west trending sinistral Ranotsara shear zone, which continues in the Mozambique belt, probably as the Surma shear zone, and in Southern India as the Achankovil shear zone. South of Ranotsara six north–south trending tectonic belts are recognized that consist largely of granulite and high amphibolite facies paragneisses, phlogopite diopsidites, concordant granites and granulites. North of Ranotsara the central–northern segment is traversed by a north–trending axial 100–150 km wide dextral shear zone of probable Pan-African age, which was metamorphosed under granulite and high amphibolite facies conditions and which has reworked older basement. This shear zone continues across southern India as the Palghat-Cauvery shear zone. Major stratiform basic–ultrabasic complexes occur in the axial zone and in the basement to the west. Well preserved low grade continental margin-type sediments (quartzites, mica schists and stromatolitic marbles) of Kibaran age are present in western Madagascar. Two partly greenschist grade sedimentary groups lie unconformably on high grade basement in north-east Madagascar. Isotopic age data suggest the presence in Madagascar of Archaean, Early and Mid-Proterozoic crustal material that was extensively reworked in Pan-African times.

Key words Shear zones · Granulites · basic/ultrabasic · complexes · Paragneisses

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Introduction

The Precambrian rocks of Madagascar, which played a key part in the evolution of Gondwana, are overlain and intruded by Mesozoic–Cenozoic rocks related to the separation of Madagascar from Africa and India during the break-up of Gondwana.

Besairie studied the geology of Madagascar for nearly 50 years, and under his leadership the Geological Survey of Madagascar published geological maps of the Precambrian and other rocks on scales of 1:100000 and 1:200000 (each of many sheets published up to the 1970s), 1:500000 (Besairie, 1969–70), 1:1100000 (Besairie, 1964) and 1:2000000 (Besairie, 1973) and innumerable geological reports in four series: *Annales Géologiques* (1931–74), *Documentation du Bureau Géologique* (1949–73), *Travaux du Bureau Géologique* (1949–1974) and *Comptes Rendus des Semaines Géologiques* (1963–71). The Precambrian geology of Madagascar was synthesized by Besairie (1967; 1968–71) and Hottin (1976). Lacroix (1922–3) is a major source of mineralogical information.

Although there is considerable modern published information on the Precambrian of southern India, eastern Africa and Sri Lanka, very little has been published on the Precambrian of Madagascar. The aim of this paper is to review the main geological features of the Precambrian of Madagascar within a modern tectonic framework where possible, and to suggest some tectonic correlations with East Africa and South India (Shackleton, 1986a; Katz, 1989; Stern, 1994).

Geochronology

Reliable geochronological data on the Precambrian of Madagascar are sparse, but more than 56 whole-rock Rb/Sr isochron age determinations were published by Delbos (1965), Vachette (Caen-Vachette) (1977; 1979)

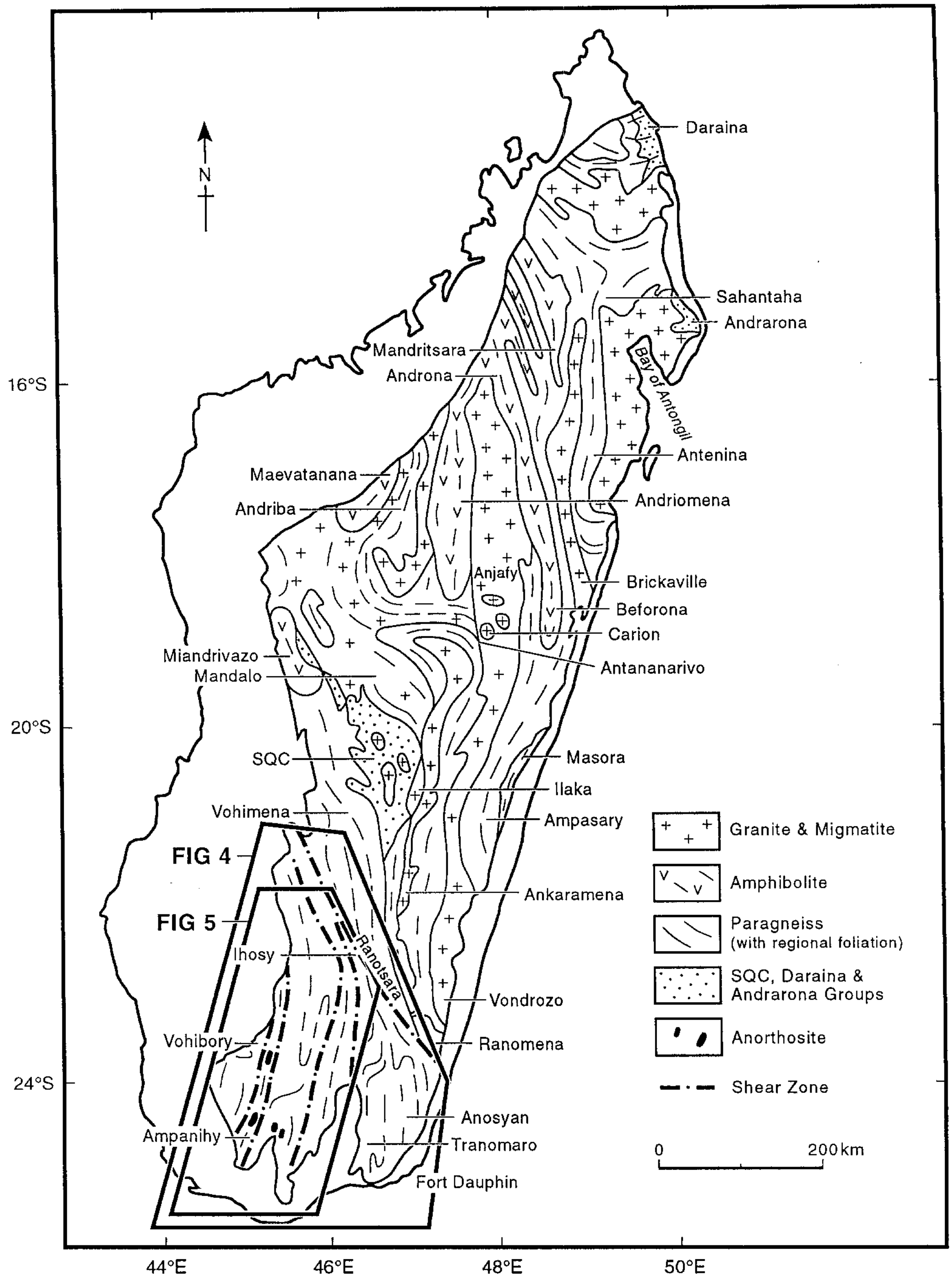


Fig. 1. Simplified and schematic geological map of the main elements of the Precambrian of Madagascar, compiled largely from Besairie (1973), Hottin (1976) and an unpublished (1980) geological map by Razafiniparany

and Vachette and Hottin (1974; 1975; 1977). Most of these were usefully summarized and critically evaluated by Cahen et al. (1984). Tables 2 and 4 list the most reliable of these dates together with more recent isotopic ages; these provide a comparative overview of the data. Because of the problems of Rb mobility, mixed ages in Rb/Sr dates, choice of samples and the lack of knowledge of isotopic systematics at the time, many of the older dates are geologically difficult to interpret. Many samples, particularly metamorphic types, cannot now be easily related to specific structures or texturally defined metamorphic events. However, dates on samples from late granitic intrusions are easier to evaluate. Besairie (1967) considered that the Precambrian consisted of a Late Archaean basement with a Pan-African overprint, but Hottin (1976) suggested that the southern part had a Early to Mid-Proterozoic age. Current isotopic studies confirm an important Pan-African event in the south (Table 2) and the north (Guerrot et al., 1993) and suggest the existence of an Early Proterozoic history in the south-east (Paquette et al., submitted).

In describing the geological units and tectonic framework it is not possible to differentiate as yet in most areas between Archaean, Early, Middle and Late

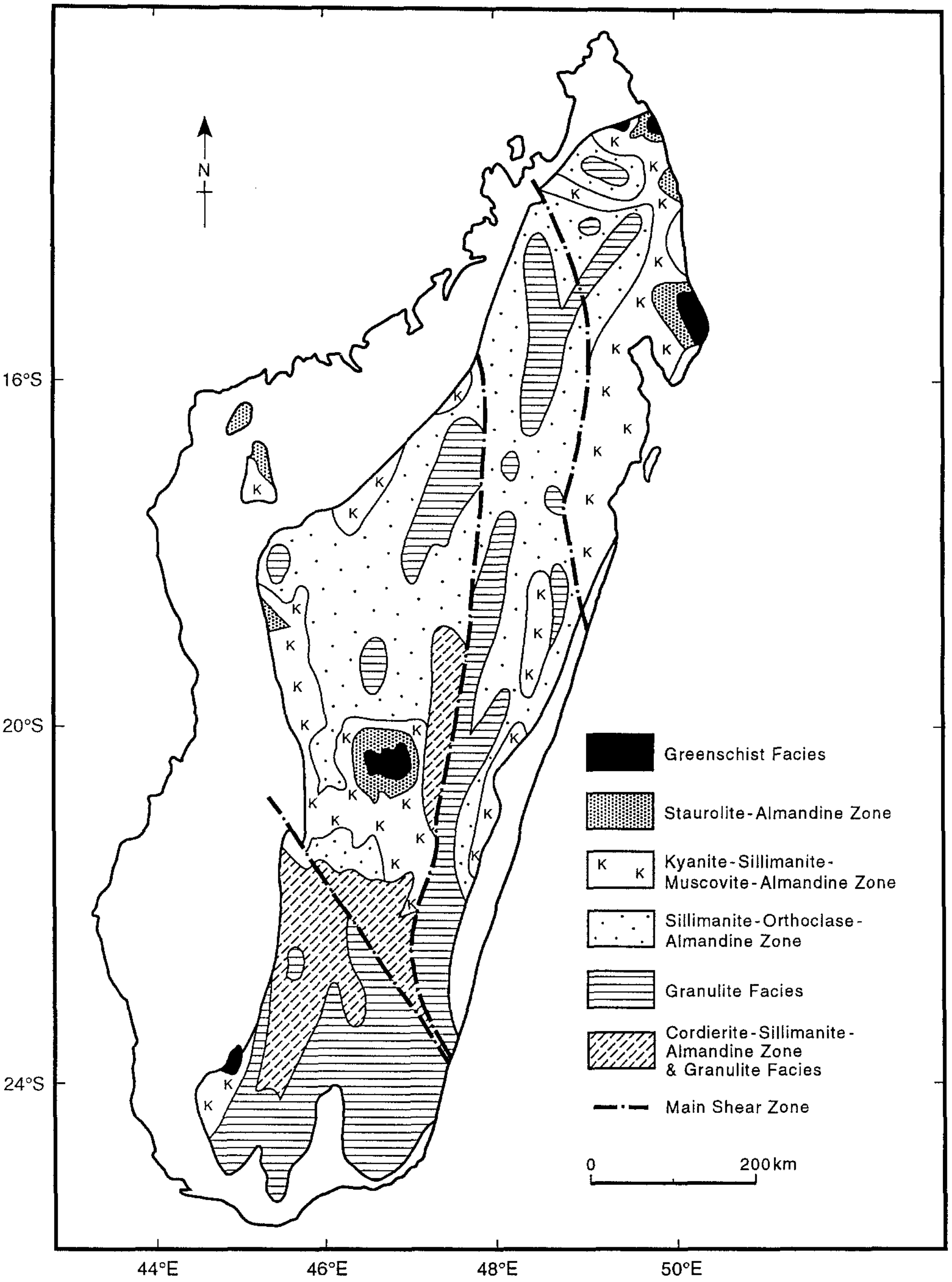


Fig. 2. Map of the metamorphic zones and facies of the Precambrian of Madagascar, modified after Hottin (1976)

Proterozoic metamorphic and deformational events; only more isotopic studies tied specifically to structural – metamorphic relations will make this possible.

Precambrian of Madagascar

The Precambrian of Madagascar (Fig. 1) can be subdivided on lithotectonic evidence into southern and central – northern sectors, each of which can be further subdivided into six belts and three zones, respectively.

The centre of Madagascar is traversed by a 100 km wide, north – south trending shear zone of probable Pan-African age which transects Proterozoic and Archaean basement. This is a high grade zone dominated by granulite and high amphibolite faces rocks, migmatites, conformable granite sheets and granite plutons. As the metamorphic map (Fig. 2) of Hottin (1976) shows, greenschist facies rocks occur in the tectonic zones on either side of the high grade zone. The dextral sense of displacement of the axial shear zone is defined by the regional drag of foliation on both sides, which is particularly prominent on the western side. The metamorphic facies correlate with the boundaries of the central shear zone. However, the problem today with Hottin's metamorphic map is that it does not take account of successive

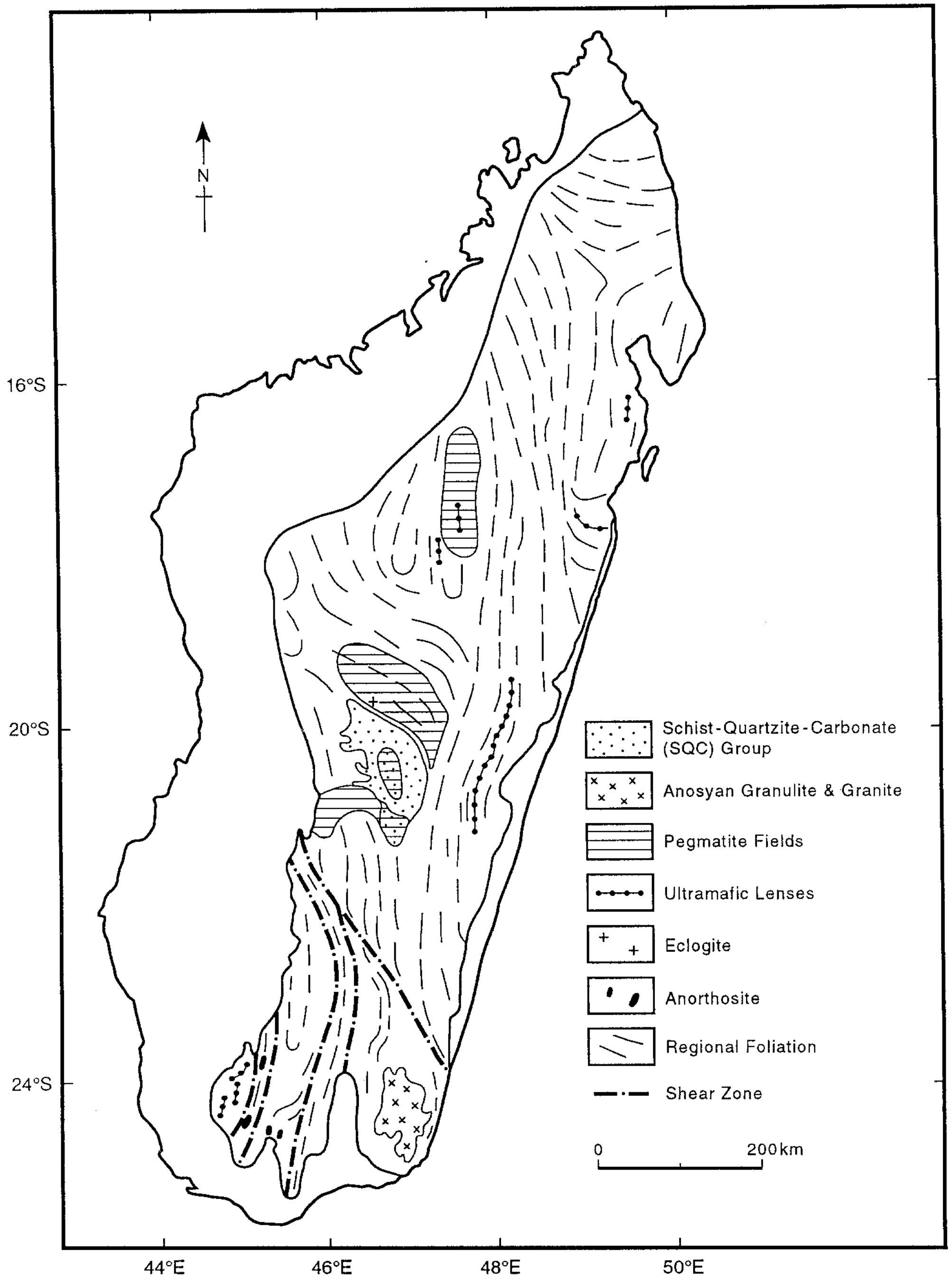


Fig. 3. Synoptic map of the main structural elements of the Malagasy Precambrian, plus the location of pegmatite fields, anorthosites and eclogite

metamorphic overprints; thus it only gives a statement of the current predominant metamorphic zones and facies.

The north-west trending, sinistral Ranotsara shear zone (Fig. 1) separates southern Madagascar, where paragneisses are predominant, from central – northern Madagascar dominated by granitic orthogneisses; the sinistral sense of movement is indicated by the virgation (drag) of the regional foliation on both sides (Fig. 3).

Southern Madagascar

Most rocks south of Ranotsara have been deformed and metamorphosed under granulite and high amphibolite facies conditions (Fig. 2), and as a result quartzo-feldspathic gneisses with or without hypersthene predominate. Particularly common are cordierite/sillimanite-bearing paragneisses, within which are layers of marble, quartzite and dioposidite of sedimentary parentage and amphibolite layers of presumed volcanic origin. Granitic rocks range from centimetre – metre size partial melt veins, typically concentrated in major migmatite belts, to many calc-alkaline and crustal melt bodies several kilometres across. Figure 4 shows six tectonic belts defined by us based on differences in lithostratigraphy and structure. Besairie (1973) and Hottin (1976) recognized the lithological character of these belts in terms of their different

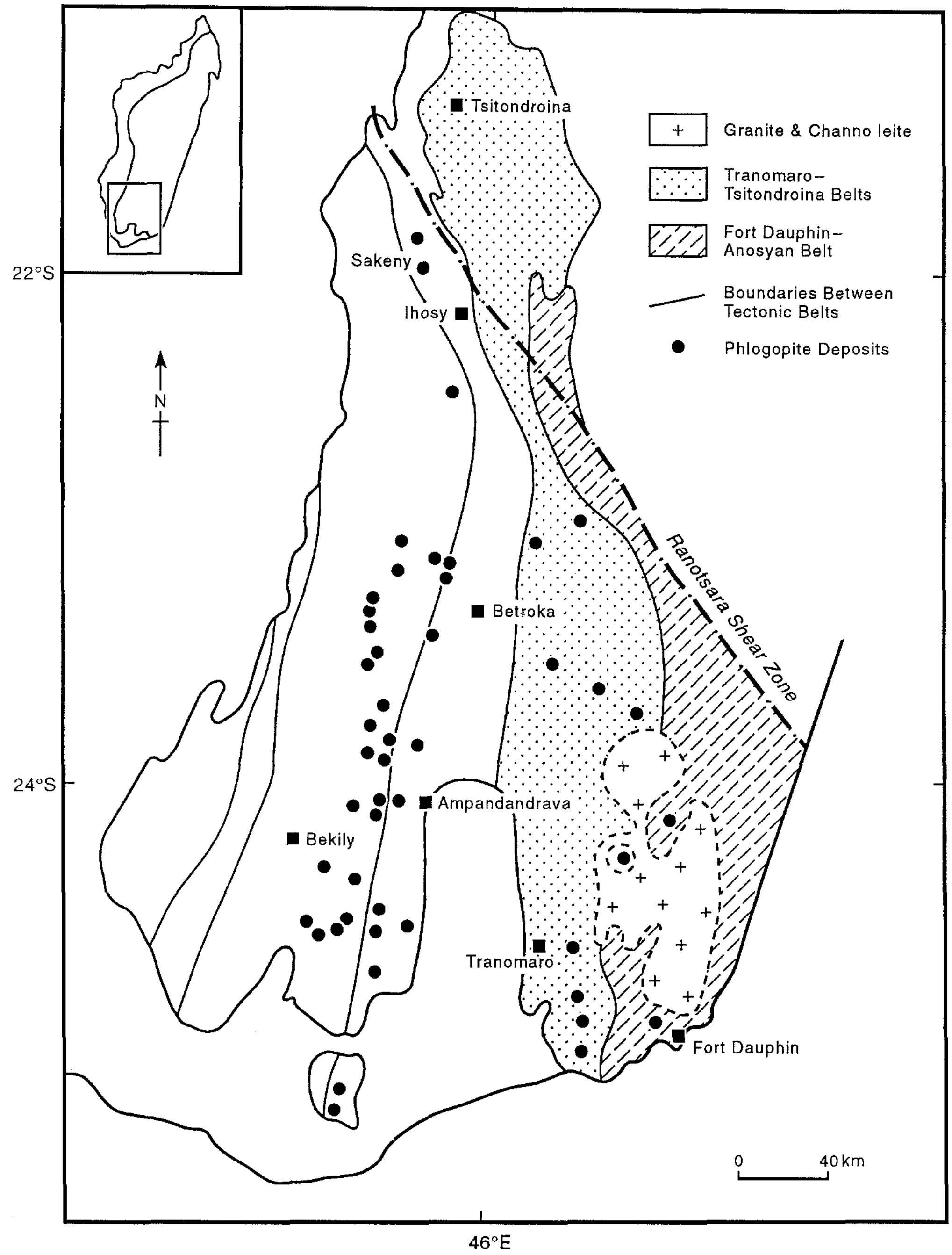


Fig. 4. Map showing the six tectonic belts of southern Madagascar, the Ranotsara shear zone and some correlated belts north of it. Compiled from many geological maps on different scales and our own observations

stratigraphic groups. The boundaries between the belts are marked by zones, up to several tens of metres wide, of finely banded gneisses, which we interpret as ductile shear zones. In particular, two linear belts (Ampanihy and Betroka) can be easily defined and serve to separate bordering belts that are characterized by complex fold interference patterns. The characteristic features of the belts are summarized in Table 1; additional interpretations and isotopic data are given here. From west to east these belts are:

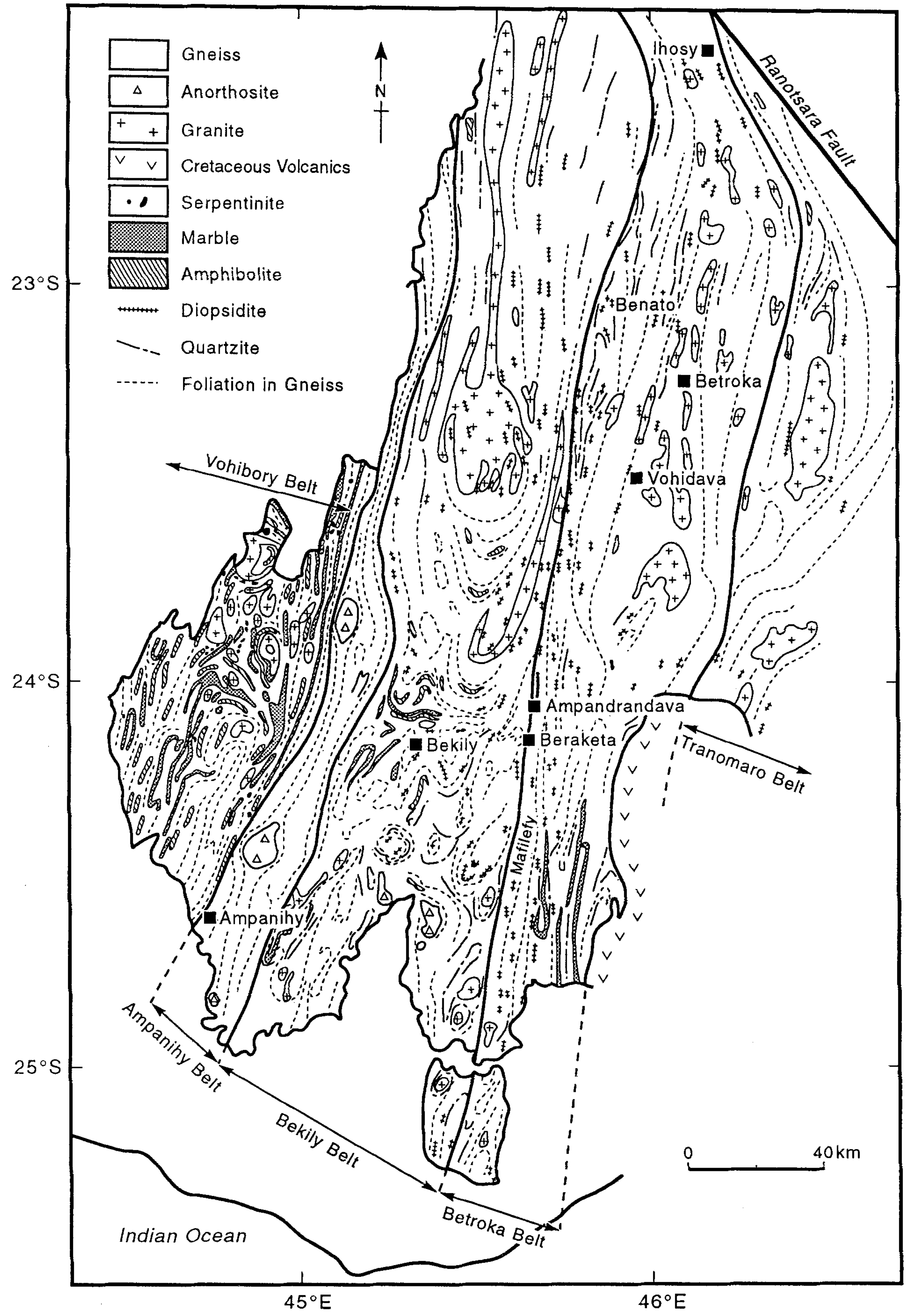
1. The Vohibory belt consists of orthogneisses and sillimanite—garnet and rare kyanite paragneisses, within which occur thick layers of marble and amphibolite. Trails of at least 55 lenses of chromite-layered serpentinized harzburgite and Iherzolite (Boulanger, 1956), associated with pillow-bearing amphibolite, metagabbro, metatroctolite and Mn, Fe, Au and Cu mineralization (Orloff, 1951) are possibly remnants of ophiolites. Basic rocks were converted during high pressure metamorphism (9—11.5 kbar) to garnet granulites (Nicollet, 1983; 1990a). This belt has a different lithostratigraphy from that in the belts to the east. According to Razakamanana (in prep.) the Vohibory supracrustal belt is a deformed and metamorphosed thin-skinned fold and thrust belt.

Table 1. Summary of the main features of the six tectonic belts of southern Madagascar

Tectonic Belts	Lithostratigraphy and structure	References	Comments
Vohibory	Migmatitic orthogneiss (hb, bi), paragneiss (bi, ga, hb, di), marble, pillow-bearing amphibolite with Au and Cu mineralization, many lenses of serpentinized chromite-layered peridotite, metagabbro, metabasic granulite and rodingitic clinopyroxenite. Tourmaline granite. Greenschist to high P granulite facies (9–11.5 kbar) metamorphism. Fold interference patterns	Orloff (1951), Boulanger (1956), Nicollet (1983); 1985; 1986; 1990a)	Shelf sequence interthrusted with orthogneisses and slices of ophiolitic complexes
Ampanihy	Flaggy hb-bi-graphite gneiss, paragneiss, leptynite, amphibolite, metabasic granulite, diopsidite, marble and quartzite. Mylonites. Lack of granites and migmatites. Two lenses (6 × 16 km) and (11 × 25 km) of anorthosite and leuconorite. Isoclinal and intrafolial folds, shallow mineral lineation	Boulanger (1959), De Wit et al. (in press), Ashwal et al. (in press), Rolin (1991), Martelat et al. (1993), Nicollet (1990a)	A steep, linear shear zone that separates belts of different types
Bekily	Paragneiss (bi, hb, hyp, sill, cd, ga), sill quartzite, di marble, di-hyp basic granulite, sa-cd-kornerupine rocks, diopsidite with much phlogopite mineralization. Rare migmatites. km wide folded layers of monzonite and granite. Two anorthosite lenses (50 and 25 km^2). Fold interference patterns	Aurouze (1953), Noizet (1966), Boulanger (1959)	Much meta-supracrustal material, prominent amphibolite. Granulite facies
Betroka	Paragneiss (bi, cd, sill, ga), orthogneiss, metre thick sillimanitite and cordieritite (lazulite), hyp. gneiss, marbles tens of m wide (sp, humite, phl, di), km wide quartzites (ga, mag, sill, graph), 50 m wide diopsidites with much phlogopite mineralization. Local hypersthenite and di-hyp basic granulite, 7 km wide folded gneiss–granite layers, sa-cd-phl and boron-bearing minerals, extensive 10 m wide mylonites and porphyroclastic augen gneiss. Subbelts separated by banded gneisses. Subhorizontal lineation. Isoclinal folds	Brenon (1953), Nicollet (1985; 1990), Joo' (1968), Noizet (1969), Razakamanana (1988), Moine et al. (1981)	Linear belt with late mylonite overprint. Many layers enriched in Mg, Al and B. Possible evaporitic material (lazulite)
Tranomaro	Paragneiss (bi, ga, cd, sill, di, hyp), orthogneiss (cores of homogeneous granite), 15 m wide marble (di, scap, fo, clinohumite, sp.), quartzite, 50 m wide diopsidite (scap, pl, woll), scapolitite. Boron-bearing layers contain grandidierite, serendibite and sinhalite. Lack of migmatites. Late undeformed granites. Much urano-thorianite mineralization in diopsidite, marble and orthogneiss (not in late granites), Fold interference patterns	Moine et al. (1985), Noizet (1969), Lacroix (1941), Paquette et al. (1993)	Sedimentary materials enriched in Mg, Al, Ca, B. U–Th minerals are distinctive
Fort-Dauphin/ Anosyan	Homogeneous paragneiss (ga, cd, sill, graph), minor quartzite and phl. diopsidite, few minor folds, only isoclines, hyp and ga isograds. Dark cd-ga veins. Shear zones with ga, bi. Mylonitic gneiss with granulitic fabric. Hyp. gneiss (granulite) and hyp-ga granite (charnockite)	Bazot (1974), Hottin (1976), Paquette et al. (1993)	Steep linear shear belt overlain by slab of charnockite and granite

Abbreviations: qu = quartz; bi = biotite; hb = hornblende; hyp = hypersthene; ga = garnet; cd = cordierite; ky = kyanite; sill = sillimanite; neph = nepheline; ph = phlogopite; sp = spinel; pl = plagioclase; graph = graphite; mag = magnetite; fo = forsterite; scap = scapolite; sa = sapphirine; Cu = copper; Ni = nickel; UB = ultrabasic.

2. The Ampanihy belt is a prominent 20 km wide, linear, steep, ductile shear belt (Fig. 5) which consists of graphite-bearing hornblende–biotite gneisses (Système du Graphite of earlier workers). A mineral lineation plunges shallowly to the north, interpreted by de Wit et al. (in press) as an intersection lineation, but by us as a stretching lineation. Two lenses of homogeneous labradorite–bytownite anorthosite–leuconorite up to 25 km across with well preserved igneous textures (Boulanger, 1959) have margins of recrystallized, refoliated anorthosite and leuconorite. Rolin (1991), Martelat et al. (1993) and ourselves interpret this belt as a (dextral) ductile strike-slip shear zone. In contrast, Ashwal et al. (in press) and de Witt et al. (in press) suggest the anorthosites were deformed in a pure shear zone of intense flattening deformation.
3. The 50 km wide Bekily belt consists of sillimanite–cordierite–garnet paragneisses, that encompass remarkably continuous layers of metasediments (Aurouze, 1953). Phlogopite mineralization is characteristic of the Bekily belt and the belts to the east (Lacroix, 1941; Noizet, 1963; 1969; Jourde, 1965; Joo', 1967; 1968). Figure 4 shows only the major occurrences of many hundreds of mineralization sites. For example, in the ≈ 1 320 km^2 Ampandrandava area there are about 90 prospects (Besson, 1953). This mineralization is an important feature of southern Madagascar; it is noticeably absent in the Vohibory belt and in the Precambrian block of central–northern Madagascar.


Gneiss
Anorthosite
Granite
Cretaceous Volcanics
Serpentinite
Marble
Amphibolite
Diopsidite
Quartzite
Foliation in Gneiss
N
Ihosy
Ranotsara Fault
23°S
Benato
Betroka
Vohidava
Vohibory Belt
24°S
Ampandrandava
Beraketa
Bekily
Tranomaro Belt
Mafilefy
Ampanihy
Ampanihy Belt
25°S
Bekily Belt
Betroka Belt
0
40km
Indian Ocean
45°E
46°E

◀ **Fig. 5.** Map illustrating the tectonic styles of the belts from Vohibory to Tranomaro in southern Madagascar. Compiled from a variety of geological maps and our observations

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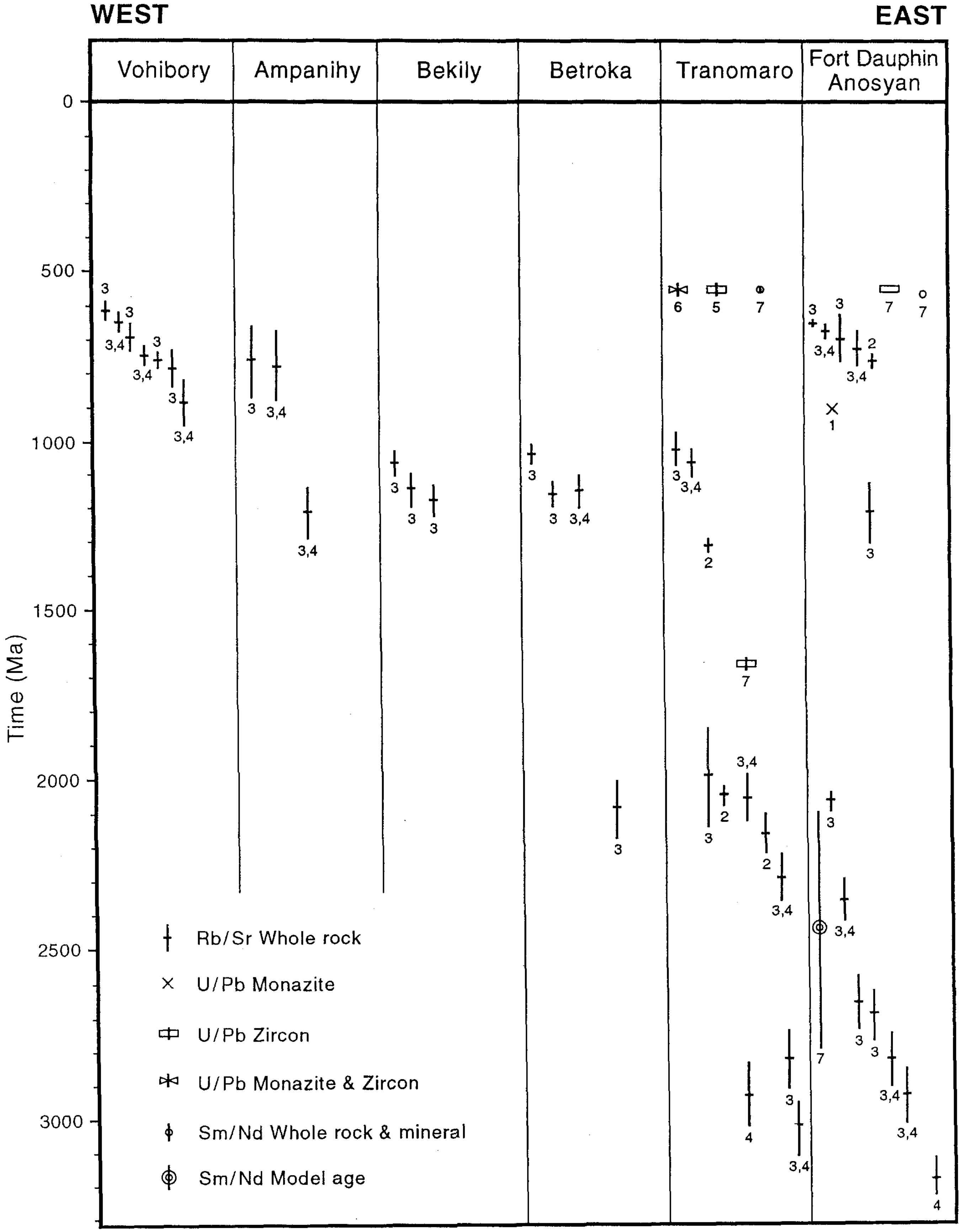
4. The 20 – 50 km wide linear (Fig. 5), steep Betroka belt (Brenon, 1953) consists of sillimanite (or orthopyroxene) – cordierite – garnet gneisses (Nicollet, 1985), which contain layers of metasediments and crustal melt granite. A belt of hypersthene gneisses occurs at Mafilefy (Fig. 5). At the northern part of this belt south of Beraketa we have observed abundant discordant, partly deformed amphibolite dykes in hypersthene gneiss; these relations point to an early granulite facies metamorphism followed by dyke intrusion and then by amphibolite facies metamorphism. Ackermand et al. (1989) reported a steep, nearly isothermal P – T trajectory from 10 to 4 kbar at 1 000 – 800 °C at Vohidava (Fig. 5); the reaction of enstatite + sillimanite to sapphirine + cordierite indicates early, very high temperature, granulite facies metamorphism above 9.5 kbar and 950 °C. Preliminary metamorphic studies near Ihosy suggest migmatization at 5 – 5.5 kbar and > 700 °C (Nicollet, 1985). In many parts of the belt 10 m wide mylonites are associated with porphyroclastic gneisses that contain lithic/crystal fragments, which indicate sinistral sense of movement.
5. The 40 – 60 km wide Tranomaro belt is characterized by paragneiss, orthogneiss and layers of metasediments that contain major urano-thorianite mineralization (Moine et al., 1985) and granitic sheets. High temperature borosilicates (grandidierite, serendibite, tourmaline) occur in paragneisses (Nicollet, 1990 b). Paquette et al. (1994) obtained a U – Pb single zircon inherited age of 1.71 Ga from the gneissic and locally migmatitic Vohimena granite that forms a conformable sheet in gneiss, and a Sm – Nd whole-rock and mineral age of 565 ± 7 Ma interpreted as the crystallization age of the granite. U – Pb data on monazites and zircons from a discordant 'non-deformed' garnet granodiorite dyke east of Ihosy (Fig. 4) yielded an age of 561 ± 12 Ma (Andriamorofahatra et al., 1990); these workers considered this age to date granulite facies metamorphism that was contemporaneous with the emplacement of the dykes of undeformed charnockite, leucogranite and granodiorite. Andriamarofahatra and de la Boisse (1986) obtained a 565 ± 15 Ma age on zircons from a pyroxenite in the southern Tranomaro belt. Zircon in calcite veins has a U – Pb age of 523 ± 5 Ma, which represents the latest Pan-African event in this belt (Paquette et al., 1994).
6. The linear Fort Dauphin – Anosyan belt contains steeply dipping, homogeneous garnet – cordierite gneisses (that include the so-called leptynites of rhyolitic origin in the French literature, e.g. Hottin, 1976; Nicollet, 1990 a), minor diopsidites, but relatively few other lithologies, few folds and mylonitic gneisses that have a granulitic fabric with elongate quartz (Hottin, 1976). Cordierite – garnet gneisses are traversed by networks of dark veins up to 40 cm wide that consist of K-feldspar, garnet and cordierite. The foliation – lineation structure of the host rocks is preserved within the veins. They were ascribed to 'recristallisation charnockitique' by Bazot (1974), were described as 'malgachites' by the French geologists and were widely regarded as a result of granulite facies metamorphism. They are probably similar in origin to the dark veins of incipient charnockite in southern India and Sri Lanka (Holt and Wightman, 1983; Hansen et al., 1987). An early high temperature association of hercynite and quartz (850 °C and 5 kbar) was overprinted by cordierite as a result of nearly isobasic cooling; Paquette et al. (1993; 1994) dated the high temperature metamorphism with a Sm – Nd whole-rock and mineral age of 588 ± 13 Ma.

Hypersthene gneisses (granulites) and hypersthene – garnet granites (charnockites) in the Anosyan mountains belong to a shallow dipping slab (Bazot, 1974; Paquette et al., 1993) that overlies the steeply dipping cordierite-garnet gneisses. Between the granulites – granites and the underlying gneisses a shallow dipping, 1 km wide zone consists of finely banded cordierite-garnet gneiss that contains a tectonic intercalation of isoclinally folded slices up to 80 m thick of granulites and gneisses; structural relations suggest to us that this is a ductile thrust zone (Razakamanana, in prep.). The Anosyan charnockites have Sm – Nd model ages of 2.1 – 2.8 Ga which led Paquette et al. (1994) to postulate the probable existence of a basement of at least early Proterozoic age. U – Pb dates on zircons in charnockites of 570 ± 3 Ma were interpreted by Paquette et al. (1993; 1994) as the crystallization age of the granite protolith under granulite facies conditions.

In summary, except for Vohibory, which is very different, the tectonic belts of southern Madagascar have similar sedimentary protolith material characterized by paragneisses including phlogopite diopsidites, marbles and quartzites and layers enriched in magnesium, aluminium and boron. Interference fold patterns of both domes and basins are common throughout many of the belts south of Ranotsara. Removal of the last north – south fold phase leaves flat-lying isoclines (see also de Wit et al., in press), the formation of which may be ascribed to compressional thrust tectonics. The extreme common attenuation of fold limbs and layers throughout these belts most probably resulted from extensional shear during collapse of the fold – thrust thickened crustal pile. In contrast, Martelat et al. (1993) interpreted the 'oval-shaped closed structures' as sheath folds in crustal-scale extrusion zones of subvertically stretched crust.

The Ampanihy shear belt is a significant terrane boundary. To the west the Vohibory belt contains diagnostic ophiolitic relics, no phlogopite-enriched diopsidites and has a greenschist to granulite facies

Table 2. Time chart of age determinations on rocks from the six tectonic belts of southern Madagascar.
References: 1 = Ahrens et al. (1959); 2 = Delbos (1965); 3 = Vachette (1977; 1979); 4 = Cahen et al. 1984); 5 and 6 = Andriamarofahatra et al. (1990)



metamorphic imprint. In contrast, all the belts to the east of Ampanihy have abundant, diagnostic phlogopite diopsidites, no basic – ultrabasic complexes and a metamorphic grade that varies between sillimanite – almandine – cordierite and hornblende granulite facies (Hottin, 1976). Table 2 suggests that, on passing eastwards across the tectonic belts of southern Madagascar, there is an increase in age of the crustal material; only better isotopic dating will confirm or refute this variation.

The Ampanihy, Betroka and Fort Dauphin-Anosyan belts underwent transpressive deformation and the formation of linear shear belts, on which were superimposed lower temperature mylonitic and cataclastic deformation. In contrast, the Vohibory belt consists of metasedimentary rocks with no phlogopite diopsidites, but with diagnostic metamorphosed ultramafic – gabbroic – basaltic complexes.

There is growing confusion about granulite facies metamorphism in southern Madagascar. The Betroka belt contains amphibolite dykes that post-date granulite facies gneisses, and also petrographic evidence of relict (undated), very early high temperature metamorphism with orthopyroxene above 950 °C and 9.5 kbar (Ackermand et al., 1989). The gneisses of the Tranomaro belt contain gneissic, migmatitic granite sheets that crystallized at 565 Ma contemporaneous with granulite facies metamorphism associated with the synmetamorphic emplacement of the 570 Ma Anosyan charnockites and granites in the nearby Fort Dauphin – Anosyan belt (Paquette et al., 1994). The Tranomaro gneisses are also transected by 'non-deformed' charnockitic and granitic dykes regarded by Andriamarofahatra et al. (1990) as sub-contemporaneous with granulite facies metamorphism, which they dated as 565 Ma. De Wit et al. (in press) state that all terrains in southern Madagascar 'have been involved in variable degrees of granulite metamorphism, which is almost certainly Pan-African in age, and probably synchronous with the tectonic activity of the Ranotsara shear zone'. These relations suggest more than one granulite facies event in southern Madagascar and to us a confusion among some workers of the relationships between deformation and metamorphism.

Vachette (1979) proposed that the Ranotsara shear zone separates two chronologically different terranes. If Besairie (1973) was correct, only the Tranomaro, and to a small extent the Fort Dauphin – Anosyan belts (Fig. 4), continue across the shear zone, but according to Hottin (1976) the belts on either side of the shear zone have different metamorphic grades (Fig. 2).

Central – northern Madagascar

North of the Ranotsara shear zone most Precambrian rocks (Tables 3 and 4) have a north – south strike. A high grade zone of granulites, gneisses, migmatites and granites along the axis of the island (Hottin, 1976) separates zones to the west and north-east which contain both high and low (greenschist) grade rocks.

Western Zone. In the north of this zone there are two belts with prominent metamorphosed basic and ultrabasic rocks (Table 3). The Maevatanana belt is of kyanite – sillimanite grade, whereas the Andriamena belt has been metamorphosed to hornblende granulite facies (Fig. 2). Andriamena contains important metavolcanic amphibolites and hornblende – two pyroxene – garnet basic granulites, many folded and boudinaged amphibolite and pyroxenite dykes and isoclinally folded, stratiform complexes (Giraud, 1960). Nicollet (1990 a) described very high temperature metasedimentary granulites with aluminous orthopyroxene – sillimanite – sapphirine – cordierite. The stratiform complexes are up to several hundred metres thick and commonly have the following stratigraphy (Bouladon et al., 1972):

Top	Thickness	
Norite	Minor	With phlogopite
Bronzitite	30 – 50 m	Layered norite at top; sporadic Cu – Ni
Pyroxenite	20 – 30 m	Bronzite – diallage (some anorthosite cumulate layers); increases upwards; main Cu – Ni mineralization
Norite	Few metres	Layered with pyroxenite, ilmenite-bearing
Peridotite	100 – 200 m	Alternating Iherzolite, wehrlite, harzburgite and allivalite; major chromite mineralization

The complex is bordered by magnetite quartzite. Retrogression has given rise to talc schists, chlorite schists and soapstones. Chromite deposits occur in talc and chlorite schists. These stratiform complexes have been compared with the Great Dyke of Zimbabwe (Bouladon et al., 1972; Hottin, 1976) and with the Messina complex in the Limpopo belt (Trottereau, 1971). Whole-rock Rb/Sr dating Vachette (1979) from rocks in the Maevatanana and Andriamena belts belong to a group of eight isochrons with an age of 2 600 ± 100 Ma (Cahen et al., 1984). Guerrot et al. (1993) reported a U – Pb zircon age of 787 ± 16 Ma from basic rocks and concluded that the basic – ultrabasic complexes were emplaced within an Archaean basement under granulite facies conditions in a Pan-African rift; no structural evidence was given to indicate a rift setting.

The nort-west trending Mandalo belt is situated in the major sinusoidal flexure (virgation) on the western side of the axial shear zone. The predominant banded migmatitic gneisses encompass mica schists, graphitic gneisses, leptynites and quartzites, as well as conformable granitic sheets and several charnockite bodies up to 25 km across. From an alpine-type eclogite at Faratsiho (Fig 3) that consists of omphacite, garnet, amphiboles and paragonite, Nicollet (1989) estimated P – T conditions of 11 kbar at 500 °C (rims) and 9 kbar at 420 °C (cores). The tectonic relationships of this eclogite occurrence are unknown. A major pegmatite field extends across the eastern Mandalo belt (Fig. 3) in which there are two

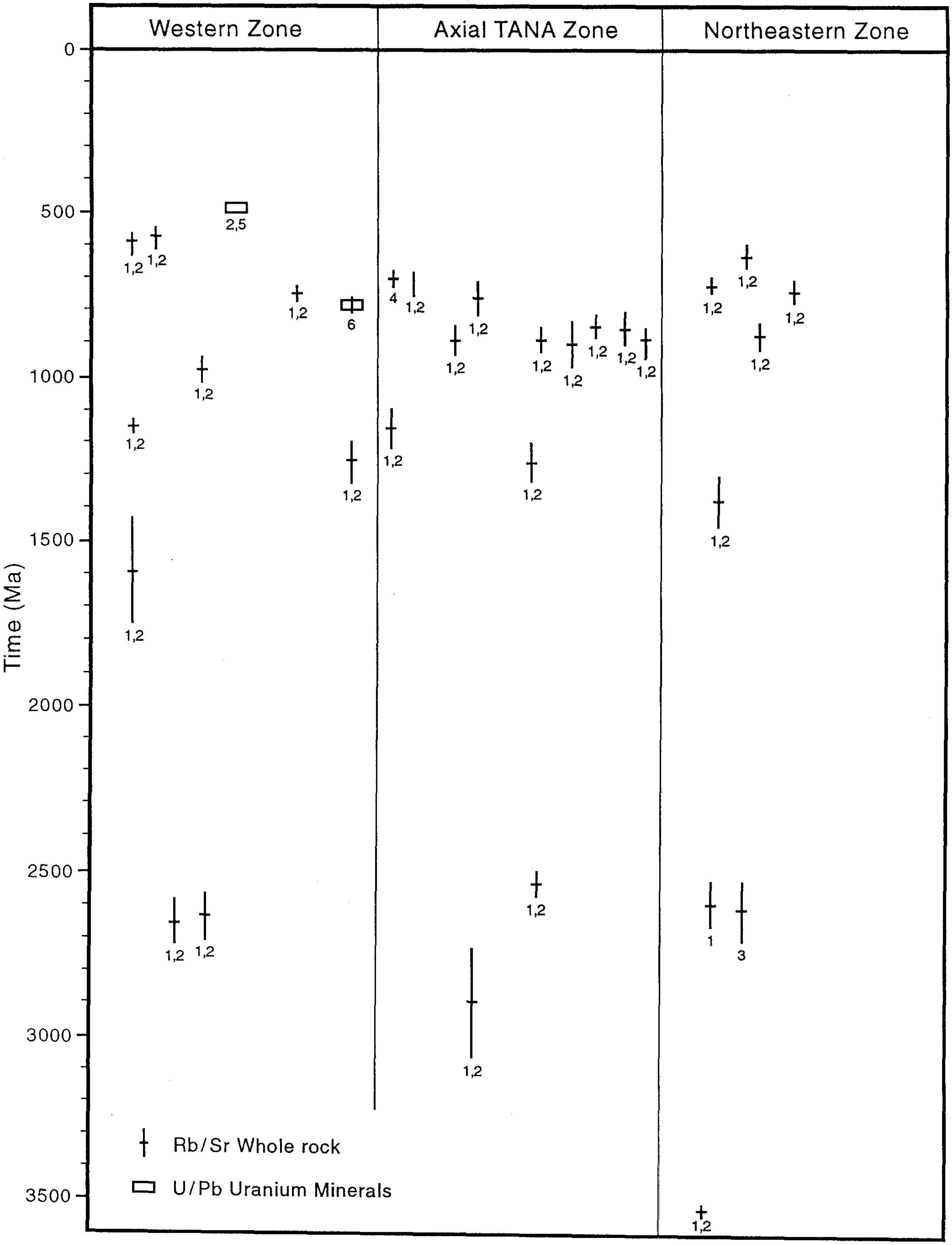
Table 3. Summary of the characteristic features of the three tectonic zones of the Precambrian of central–northern Madagascar. Abbreviations as in Table 1

Western Zone	Axial Shear Zone	North-eastern Zone
Maevatanana Hb gneiss, quartzite, mica schist, hornblendite, Hb schist, tonalitic orthogneiss, meta-gabbro and -UB rocks (tremolitite and soapstone)	Androna to Beforona and Mandritsara Ga-sill gneiss, quartzite, amphibolite, lenses of pyroxenite, dunite, peridotite, noritic gabbro, Ni, Cr mineralization	Daraina Sedimentary-volcanic Group unconformable on basement. Basal conglomerate (often undeformed), quartzite, flows, tuffs and breccias of rhyolite, dacite, andesite and basalt, Cu mineralization. Greenschist to sill-ky grade
Andriba Ga-di gneiss, sill-ga migmatite, sill quartzite, mica schist, conformable granites	Anjafy–Vondrozo Major belt of migmatite and conformable granites	Andrarona Unconformable sedimentary Group. Basal arkosic conglomerate and phyllite, quartzite and sericite schist. Greenschist grade
Andriamena Leuco-qu-gneiss (leptynite), cd-sill and hyp-sa paragneiss, amphibolite, quartzite, metabasic and -UB complexes (gabbro, peridotite, Pyroxenite, tremolitite, soapstone), major Cr mineralization, Pt–Pd in peridotites	Carion One of several discordant intrusive plutons of homogeneous, undeformed granite	Antongil Calc-alkaline granite, monzonitic granodiorite, minor quartzite, mica schist and amphibolite, metabasic and UB lenses (amphibolite, peridotite, pyroxenite, soapstone, Cr and Ni mineralization)
Mandalo Gneiss, graphitic schist, minor quartzite, charnockite bodies, basic granulite	Masora Orthogneiss, ky-sill schist, fuchsite quartzite, amphibolite, harzburgitic UB and soapstone	Sahantaha Quartzite, gneiss, mica schist, amphibolite, marble. Westward increase in grade from ky-sill through ga-sill to charnockite
SQC Quartzite, mica schist, stromatolitic dolomitic marble, plutons of alkaline granite, gabbro-diorite, norite and alkaline and neph syenite, thrusts and folds verge to E, inverted isograds dip W, pegmatite field (rose beryl, kunzite)	Ranomena Granulite facies gneiss, green charnockitic granites	Antenina Gneiss, basic complexes of meta-gabbro, ga pyroxenite, and amphibolite. Metamorphism increases from ky-sill in E to sill in W
Vohimena Mica schist, quartzite, marble, amphibolite, pyroxenite, cd-ga-sill leptynite, beryl-columbite pegmatites		

pegmatite types, containing either columbium, tantalum and uranium minerals, or beryl and muscovite (Bourret, 1988).

So far in the Western Zone tectonic belts have been discussed; now we come to a supracrustal group. SQC (schisto–quartzo–calcaire) is the largest well preserved Precambrian sedimentary group in Madagascar (Moine, 1974). The upward sedimentary sequence is quartzite, mica schist and dolomitic marble. The quartzites are up to 1 500 m thick and contain ripple marks and cross-bedding; the mica schists include slates, sericite schists and are biotite-bearing; and the marbles contain stromatolites and diopsidite beds. There is an overall general dip to the west and south, and folds and thrusts verge to the east. Metamorphism increases via four inverted isograds (tremolite–calcite, diopside, sillimanite–muscovite and sillimanite–K-feldspar) to the west. The basal unconformity is not preserved. In the east the original succession is preserved, but thrusts have imbricated and reversed the stratigraphic order in most of the belt so that quartzites are predominant in the west. In the middle of the belt folds and thrusts have exposed a block of gneissic basement. The western border of the SQC is difficult to define because of the high metamorphic grade and large-scale fold interference patterns. However, the lithologies sugggest common pelites and greywackes interbedded with amphibolitic metavolcanics. Thus overall there is a passage from east to west from a shelf succession to deeper water sediments and volcanic rocks derived from a continental margin/rise. If this relationship is combined with the fact that the thrusts dip to the west, it suggests that a possible suture zone might be situated on the western side of the SQC. To the north-west the Miandrivazo belt (Fig. 1) consists of gneisses that contain metavolcanic amphibolites and several complexes, up to 25 km across, of gabbro, leuconorite, anorthosite and minor peridotite and pyroxenite. About 40 km to the east of the northern end of the Miandrivazo belt nepheline gneisses are associated with many mylonites (Welter, 1964). The sediments of the SQC are intruded by post-tectonic bodies of ophitic olivine gabbro, gabbro-diorite, potassic granite, syenite and nepheline syenite. Gem pegmatites

Table 4. Time chart of age determionations from the three tectonic zones of central–northern Madagascar.
References: 1 = Vachette (1977; 1979) and Vachette and Hottin (1979); 2 = Cahen et al. (1984); 3 = Vachette and Hottin (1970); 4 = Vachette and Hottin (1974); 5 = Ahrens et al. (1959) an Besairie and Burger (1968)



carry ruby, beryl, kunzite and spessartine. From the RB/Sr data of Vachette (1979), Cahen et al. (1984) suggested that the SQC was most probably deposited between 1602 ± 168 Ma (the poorly constrained age of the Ilaka granite in the basement to the east; Fig. 1) and 1148 ± 13 Ma, in which instance we have a well preserved Kibaran age continental margin in Madagascar.

The Vohimena belt (Fig. 1), extending from the southwest side of the SQC to the Ranotsara shear zone, consists largely of metasedimentary rocks (Table 1) and contains an important gem pegmatite field (Fig. 3) with beryl and columbite. It includes the Tsitondroina subbelt that consists of migmatitic gneisses, leptynites and metasediments which Besairie (1973) and Nicollet (1990 a) correlated with the Tranomaro belt south of Ranotsara (Fig. 4). If this correlation is correct, it serves to define the approximate displacement of 120 km on the Ranotsara shear zone. The Ankaramena granite towards the border of the axial zone (Fig. 1) has a Rb/Sr whole-rock age of 726 ± 18 Ma, $Sr_i = 0.7121$ (Vachette and Hottin, 1975).

Axial Shear Zone. This high grade zone forms a central north – south axis to the Precambrian of Madagascar (the axial zone of Hottin, 1976). It is dominated by granulite and high amphibolite facies gneisses that commonly contain graphite (the système du graphite), abundant partial melt migmatites and many conformable granites (Anjafy-Vondrozo). Minor metasediments include quartzite and garnet – sillimanite mica schist. In the Androna – Beforona belt (Fig. 1) the metasedimentary rocks enclose major folded stratiform complexes of basic and ultramafic rocks similar to those in the Andriamena belt (Bouladon et al., 1972). In the graphitic gneisses extending south to Ampasary (Fig. 1) there are many smaller aligned lenses of basic – ultramafic rocks. Prominent are serpentinized harzburgite and dunite, gabbro and noritic gabbro, pyroxenite, tremolitite and soapstone. Ultramafic rocks contain prominent chromite and nickel mineralization. The 1 : 500 000 map (Besairie, 1969 – 70) of the southern part of this zone indicates six localities of eclogites. However, Nicollet (1990 a) showed that that these are not eclogites, but low pressure granultes ($P < 6.5$ kbar).

In the far south of this zone the Ranomena belt (Fig. 1) consists of intercalated leptynite, gneisses with sillimanite, garnet or diopside, quartzite, feldspathic orthopyroxenite, green charnockite of granitic – granodioritic composition and potassic granite (Razafiniparany, 1966).

East of Antananarivo (Fig. 1) several intrusive plutons consists of undeformed homogeneous granite. The main Carion granite is 25 km across and has Rb/Sr whole-rock isochron ages of 682 ± 26 Ma, $Sr_i = 0.7048$ and 734 ± 15 Ma, $Sr_i = 0.70383$ (Vachette and Hottin, 1974) and 706 ± 22 Ma, $Sr_i = 0.7048$ (Vachette, 1979; Cahen et al., 1984).

North-Eastern Zone. In the far north two partly greenschist grade sedimentary groups lie unconformably on high grade basement:

1. The Daraina Group consists of two sequences. The lower has a major basal conglomerate, often undeformed, with boulders of quartz, granite, leptynite, volcanic rocks and gneiss. It is succeeded by paragneiss, leptynite, sillimanite – kyanite mica schist and intercalations of quartzite or conglomerate with locally preserved cross-bedding. The upper volcanic sequence, which lies unconformably on the eroded lower sequence, consists of alternating acid-basic extrusions of lavas, tuffs and breccias of rhyolitic, dacitic, andesitic and basaltic compositions. The volcanic rocks are reported to range from a completely intact sequence to amphibolites, basic orthogneisses, feldsphatic amphibolites and epidotites. Copper mineralization is disseminated through basic orthogneisses. The isotopic age of this sedimentary – volcanic group is unknown (Cahen et al., 1984). The structural relations of this group are not clear, but appear to indicate a thrust pile.
2. The Andrarona Group consists of schist and sericite quartzite, with arkose, locally conglomeratic, and phyllite at the base. These greenschist grade metasediments rest subhorizontally on Antongil granites. Two Rb/Sr whole-rock isochrons by Vachette and Bousteyek (1974) yielded ages of 594 ± 65 to 594 ± 56 Ma. The age of this Group is problematic because a sample of lepidodendron of Devonian age was discovered in 1972 in a borehole in the vicinity of Andrarona. However, its location is poorly known, and it is not certain that it comes from the sediments of the Andrarona Group. In our opinion it is possible that it comes from Devonian sediments in a fault zone in Andrarona basement, the Devonian cover having been eroded.

The above two groups formed on a basement of intercalated paragneiss, graphitic gneiss, mica schist, quartzite, marble and migmatite, which were metamorphosed under high amphibolite or granulite facies conditions (Fig. 2). The rocks have a general north-westerly strike, having been bent by drag against the eastern dextral boundary of the axial shear zone to the west.

The Antongil belt around the bay of the same name (Fig. 1) is dominated by granites and migmatites with minor intercalations of quartzite, mica schist, hornblende gneiss and amphibolite. Granitic rocks range from granodiorites to potassic calc-alkaline granites with predominant granodiorites and monzonites containing biotite and epidote. Many granites and migmatites form domal massifs between hornblende – biotite gneisses intercalated with quartzite, amphibolite and kyanite, sillimanite or staurolite gneiss. Within these gneisses, aligned meta-ultramafic lenses, which consist of peridotite, pyroxenite, tremolite – actinolite amphibolite and soapstone, contain chrome and nickel mineralization. There is a northward increase in metamorphic grade from kyanite – staurolite, through garnet – sillimanite to hornblende granulite and a westward increase in metamorphism through north – south trending, metamorphic zones that pass from staurolite – kyanite in the east, through kyanite – sillimanite to garnet – sillimanite in the migmatitic gneiss belt in the west (Hottin, 1976). Rb/Sr whole rock data of Vachette and Hottin (1970) gave an age of 2603 ± 93 Ma on Antongil granites. Further data by Vachette (1979) yielded an isochron of 3190 ± 244 Ma, which, being affected by a 2600 Ma event, Cahen et al. (1984) recalculated to 3480 Ma, but using only two points. Thus the Antongil rocks have long been regarded as the oldest rocks in Madagascar.

The Sahantaha – Antenina belt (Fig. 1) is situated between the Antongil belt and the eastern boundary of the high grade axial zone. In the north near Sahantaha thick quartzites on the east pass westwards to two mica schists and kyanite – sillimanite gneisses, and further west to gneisses with numerous intercalated amphibolites and marbles. Metamorphism increases westwards from kyanite – sillimanite mica schists through garnet – sillimanite gneisses and migmatites, to charnockitic gneisses. Further south, near Antenina, there is a similar increase in metamorphic grade from kyanite – sillimanite in the east to sillimanite in banded migmatites in the west. In gneisses near Antenina several folded and metamorphosed basic complexes, up to 30 km across, consist of gabbro, noritic gabbro, orthoamphibolite, garnet pyroxenite and minor peridotite. At the southern end of this belt near the coast the rocks strike east – west, and bend westwards in a major drag to a north – south strike parallel to the eastern boundary of the axial zone.

Discussion of the Precambrian of Madagascar

A combination of the geological and isotopic data suggests that the Malagasy Precambrian contains rock material of Archaean and Early Proterozoic age that has been extensively reworked and added to in Pan-African times.

The Precambrian of central – northern Madagascar has a dominant north – south strike, which is largely caused by the axial high grade shear belt. Table 4 suggests that Archaean material is present in all the three tectonic zones. Very similar and diagnostic stratiform mafic – ultramafic complexes occur within the axial zone (Androna – Beforona and Mandritsara) and outside it (Andriamena and Maevatanana). It still has to be confirmed whether all these complexes are Pan-African in age (Guerrot et al., 1993), and whether or not some are ophiolites. A combination of geological and isotopic data suggests that the axial shear zone formed in Pan-African times by the deformation of earlier Precambrian rocks. The evidence for the axial high grade zone being a shear belt is as follows:

1. The prominent drag of regional foliation on either side of the axial zone indicates a dextral sense of movement.
2. The western and north-eastern zones contain well preserved prograde greenschist facies belts and have both been metamorphosed extensively in the Barrovian-type kyanite – sillimanite – muscovite – almandine and to a lesser extent the staurolite – almandine facies. The western one also contains sillimanite – orthoclase – almandine zones of Barrovian type and minor hornblende granulite facies rocks. In contrast, the high grade axial zone has been metamorphosed in the granulite facies and sillimanite – almandine – orthoclase facies. In many places the boundaries of the shear belt indicated by structural criteria coincide with the major metamorphic boundaries (Hottin, 1976). Existing geochronology is insufficient to place an age on most of these periods of metamorphism.

Gondwana connections

The pre-Jurassic juxtaposition of Madagascar against East Africa is tightly constrained by ocean floor geophysical data (Coffin and Rabinowitz, 1987; 1988) and the relative positions of Africa, Madagascar and India at 150 Ma are well constrained by the continental margin reconstructions of de Wit et al. (1988). The position of Sri Lanka is controversial; geological relationships are more consistent with the suggested position of Lawver and Scotese (1987), Kröner (1991), Yoshida et al. (1992) and Kriegsman (1993), as shown in Fig. 6, than with that of de Wit et al. (1988). With these reconstructions correlations of certain structures are possible.

The left-lateral Ranotsara shear zone is probably an extension of the major Surma sinistral shear zone in East Africa (Bonavia and Chorowicz, 1992) or the parallel Ashwa (or Asswa) shear zone (Chorowicz et al., 1987). The Achankovil shear zone crosses the southern tip of India (Fig. 6). Drury et al. (1984) stated that its sense of movement was not known, but that similar $P-T$ determinations on either side suggested a dominantly strike-slip displacement. However, the southward swing of regional foliation on the northern side of the fault (Fig. 3 of Drury et al., 1984) may well suggest a sinistral movement. The region immediately south of the Achankovil shear zone underwent granulite facies metamorphism at about 558 Ma (Choudhary et al., 1992); this is close to the 560 – 580 Ma age of the granulite facies metamorphism immediately south of the Ranotsara shear zone (Andriamarofahatra and de la Boisse, 1986; Andriamorofahatra et al., 1990; Paquette et al., 1994). In the India – Sri Lanka fit of Fig. 6 the Achankovil shear zone passes just south of Sri Lanka following Kriegsman (1993). There is only a vague relationship between the geological data presented here and the speculative correlations of Agrawal et al. (1992) between Madagascar and southern India based largely on magnetic and gravity data.

Kriegsman (1993) made an alternative correlation of southern Madagascar with the Mozambique belt. He suggested that the whole sector of Madagascar south of the Ranotsara shear zone continues as a 200 km wide

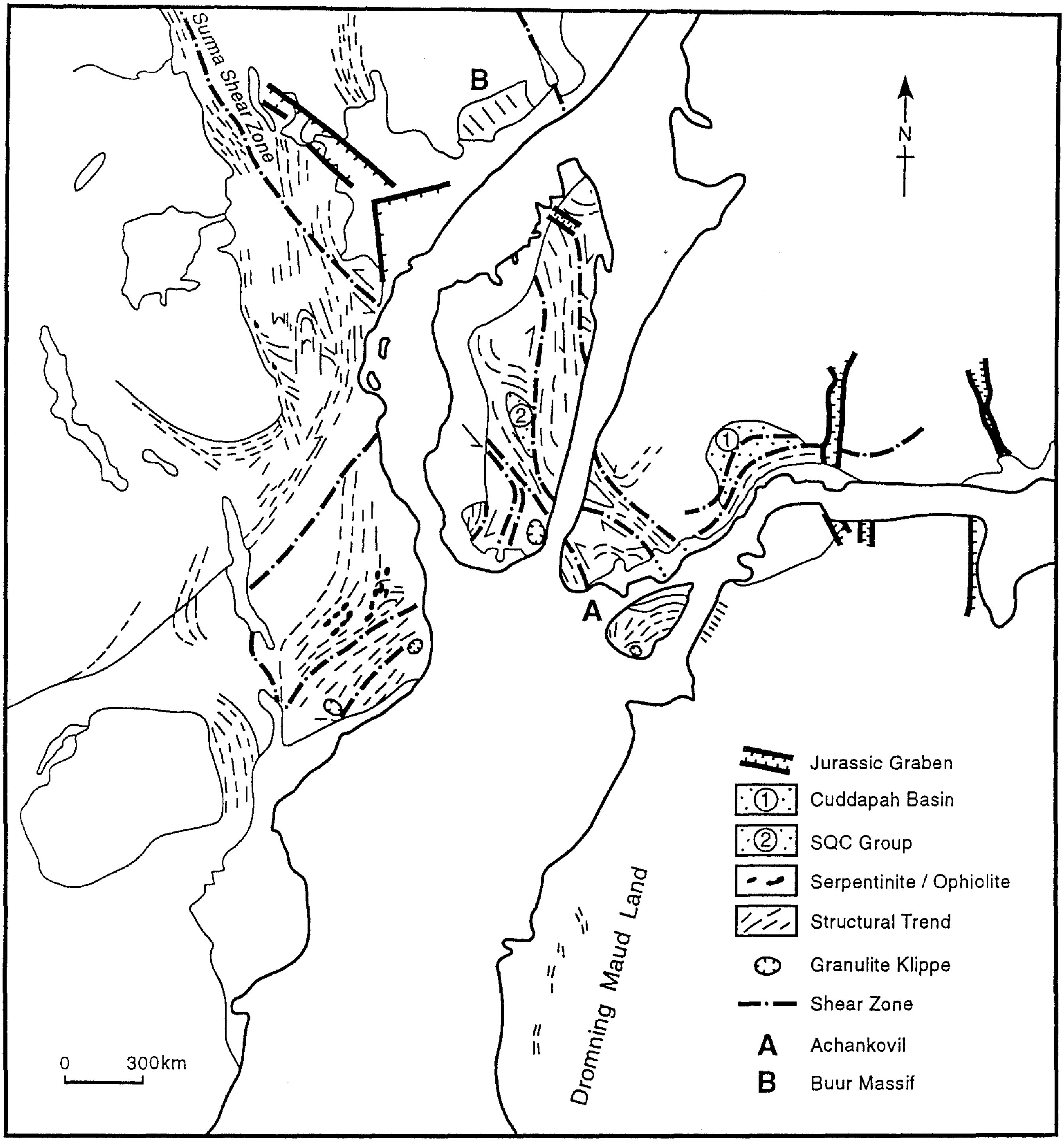


Fig. 6. Schmatic compilation map of the main Precambrian structures of eastern Africa, Madagascar, southern India and Sri Lanka. Based on reconstruction maps of Lawver and Scotese (1987), Coffin and Rabinowitz (1987; 1988), de Wit et al. (1988) and Kriegsman (1993)

strike-slip zone in Kenya as indicated by Shackleton (1986b). However, Shackleton (1993) showed that this zone bends southwestwards into Tanzania, in which case it cannot be correlated with southern Madagascar to its south-east.

The Ranotsara shear zone was apparently reactivated in the Phanerozoic. Along its strike to the north-west the Mesozoic—Cenozoic sediments in the north-west trending 'fosse de Myanabe' reach more than 7000 m in thickness, and movement on this major fault structure may have controlled the formation of the aligned NNW trending coastline during Gondwana breakup. Arthaud et al. (1990) showed that Precambrian structure controlled many Neotectonic structures and morphology.

The 100—150 km wide right-lateral axial high grade shear zone of Madagascar continues in the Buur massif of southern Somalia (Küster et al., 1990) and as the 100–150 km wide right-lateral high grade Palghat–Cauvery shear zone across southern India (Fig. 6) (Drury et al., 1984). Isotopic data indicate that the latter shear zone represents a boundary between two blocks with strongly contrasting geological histories (Choudhary et al., 1992). These shear zones share major similarities. They both enclose granulite facies belts of Archaean age (e.g. in India the Nilgiri massif). The Palghat–Cauvery shear zone and the Archaean craton to the north contain many folded stratiform ultrabasic–basic complexes (Weaver, 1990); these are similar to the stratiform ultrabasic–basic complexes in the Androna–Beforona belt and in the Andriamena belt in the Archaean 'craton' to the west.

In southern India a Late Archaean (ca. 2600 Ma) metamorphic isograd (southward increase from amphibolite to granulite facies) is situated just north of the northern boundary of the Palghat–Cauvery shear zone; the distance varies from 100 km to only a few kilometres (Drury et al., 1984). This metamorphic increase may be similar in age and type to that in north-east Madagascar, passing westwards from the Antongil to the Sahantaha–Antenina belt.

The Vohibory belt contains abundant mafic–ultramafic lenses of probable ophiolitic origin, but unknown age. In so far as the Ranotsara shear zone has a sinistral displacement, the Vohibory belt belongs tectonically to the eastern side of the Mozambique belt. Comparable mafic–ultramafic bodies, also thought to be dismembered ophiolite complexes, occur in Ethiopia, Kenya and Tanzania (Vearncombe, 1983; Shackleton, 1986 b; Berhe, 1990). Other possible equivalent rocks occur in the Tanzanian coastal region (Maboko and Basu, 1987), and, most importantly for along-strike correlation with the Vohibory rocks, in Mozambique (Andreoli, 1984; Pinna et al., 1993). However, a lack of isotopic data on almost all of these most important rocks prevents any reasonable assessment or correlation of sutures which may be Early to Late Proterozoic in age.

Although many of the isotopic data presented in Tables 2 and 4 are old (Vachette, 1977; 1979), the presence of a major Pan-African event in Madagascar is confirmed by the zircon and monazite ages of 561–565 Ma of Andriamarofahatra et al. (1990), the 787 Ma zircon ages of Guerrot et al. (1993) and the 580–570 Ma single zircon and Sm–Nd data of Paquette et al. (1994). Part of the terrane south of the Ranotsara shear zone was probably affected by at least early Proterozoic activity (Paquette et al., 1994). In central–northern Madagascar the axial zone developed in Pan-African times as a high grade shear belt as advocated by Hottin (1976), which was superimposed on an Archaean to Mid-Proterozoic basement.

It is not intended here to discuss in any detail tectonic models. Suffice to say that plate collision was no doubt the most likely mechanism for Pan-African crustal development (Key et al., 1989; Shackleton, 1986 b). Models range from the indentation of East Gondwana into West Gondwana (Abdelsalam and Stern, 1991) or vice versa (Bonavia and Chorowicz, 1992). Whichever the case, the Precambrian of Madagascar represents the deep section of an exhumed thrust-thickened crust. Nicollet (1990 a), Mosley (1993) and de Wit et al. (in press) suggested that Madagascar represents the eastern edge/foreland of the Mozambique belt. This would be confirmed if the SQC Group (of whatever age) had been thrust eastwards in Pan-African times towards the Archaean Dharwar craton, which lies on the eastern boundary of the orogen.

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