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Metamorphism and Tectonics in Southern Madagascar : An Overview

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Abstract

The scope of this paper is to briefly summarize the general tectonic pattern and the metamorphic evolution of the continental crust from southern Madagascar. After a presentation of the main geophysical features of the Malagasy crust, the brittle and the ductile strain patterns are established at a crustal scale. The Pan-African metamorphic zonation is discussed and interpreted through a tectonic model related to a transpressive regime.

Key Words: Metamorphism, strain pattern, tectonics, southern Madagascar.

Introduction

Knowledge of the structure and the petrology of the continental crust is of a fundamental importance in the understanding of Earth dynamics. Together with geophysical investigations and experimental work, the study of deeply-eroded Precambrian terrains offers a unique opportunity to investigate significant volumes of middle to deep continental crust (see Dawson et al., 1986 , for a general discussion). The Precambrian belt of Madagascar offers a more or less continuous section in granulites and high-grade amphibolites with exceptionally diversified and preserved mineralogies (see general discussions in Nicollet ,1988, 1990). Moreover, crustal-scale syn-granulitic structures have been described (Besairie, 1967; Bazot,1974; Daso,1986;Rolin, 1991; Windley et al., 1994; Martelat et al., 1995,1997; Nédélec et al.,1994,1995; Pili et al.,1997a, b) showing that this area is a suitable target for the study of crustal dynamics. The aim of this paper is to present a brief synthesis of the recent advances obtained on the geology of southern Madagascar and to present an overview of its Pan-African (late-Precambrian) tectonic and metamorphic patterns.

Geological Outline

In its pre-drift position , before the end of Paleozoic times, Madagascar was adjacent to Kenya and Tanzania on the eastern front of the Mozambique belt (Fig.1).The Madagasy basement is therefore a part of the East-Gondwana, and was separated from the other segments during Jurassic-Cretaceous rifting and drifting.The Precambrian structures are related to the Mozambican continental collision zone (Pallister, 1971; Shackleton, 1986; Martelat, 1998; Paquette and Nédelec, 1998). In southern Madagascar, the salient tectono-metamorphic imprint is definitly Pan-African in age, and the entire structural evolution took place between 590 and 500 Ma (Caen-Vachette, 1979; Andriamarofahatra et al., 1990; Paquette et al.,1994; Montel et al., 1996; Kröner et al.,1996 ; Ashwal et al., 1997; Nicollet et al.,1997; Paquette and Nédélec 1998). Up to now,all the crustal-scale pictures of the Madagascan basement have been constructed on the basis of lithostratigraphic concepts and the division between different units (called "groups" after the impressive cartographic work of the Besairie team , see Besairie , 1968-1971) is clearly based on the spatial distribution of the contrasted lithologies . Because such an approach has clearly

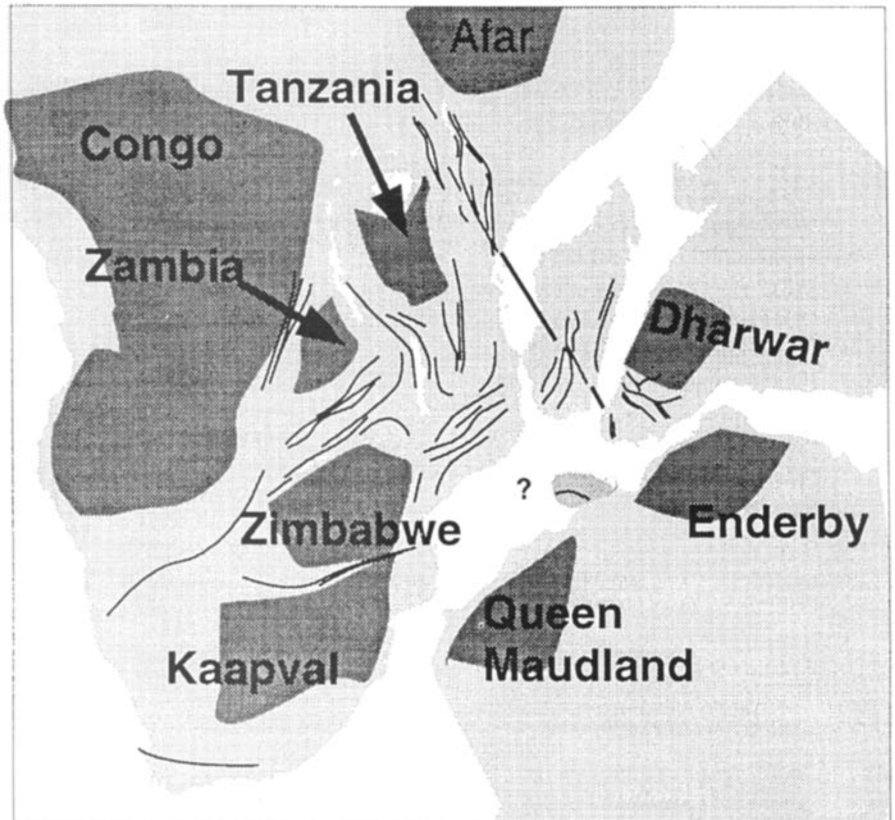

Fig.1. Madagascar in its pre-drift position showing the Pan-African structural trends of the Mozambique belt in between the main cratons.

shown its limits in the analysis of orogenic belts (see Burg and Ford,1997 for discussion), we attempt first to establish the distribution of the finite strain markers (brittle faults, foliation and lineation trajectories), of the strain gradients and of the kinematic indicators, and second to calculate the metamorphic P-T conditions at the regional scale in order to propose a rigorous structural scheme of southern Madagascar.

Finite Strain Pattern

The establishment of the late-Precambrian finite strain pattern in southern Madagascar requires first deciphering of the present-day crustal strucure of the island as well as the global distribution of the post Precambrian structures. We present this in the following crustal-scale geometries, brittle strain pattern and ductile strain pattern .

1) Crustal scale geometry

The thickness of the Madagascan continental crust can be determined using the available seismic and gravity data. Continuous seismic activity, characterized by low magnitude earthquakes (< 6), is registered since 1924 (Rakotondrainibe, 1977). All the available data (see discussions in Rakotondrainibe,1977; Rechenmann,1982; Fourno, 1987; Fourno and Roussel, 1990,1991; Pili,1997; Martelat, 1998) are coherent with a layered crust with P-waves velocities of about 5,9 Km.s^{-1} in between O and 16 Km and of about 6,7 Km.s^{-1} in between 16 and 36 Km. The general picture (Fig.2) is a 35-40 Km thick crust. The gravity data are in agreement with this interpretation (see discussions in Rechenmann,1982; Fourno and Roussel, 1993; Doin,1995, Pili et al., 1997b; Cardon, 1998). Important local variations of Bouguer anomalies can be observed near the Androy volcanic massif or near the Tuléar sedimentary basin , but the depth to the Moho is between 29 Km and 37

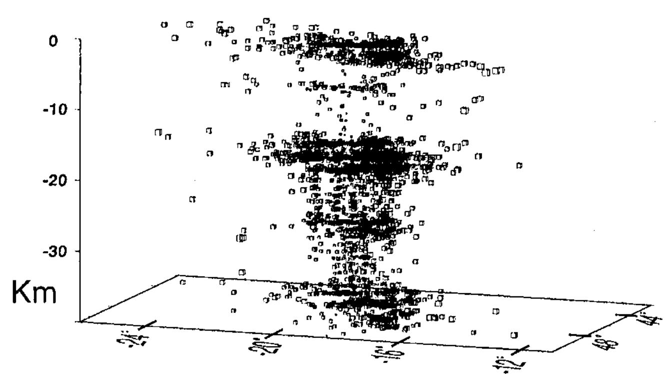

Fig. 2. Earthquake distribution with depth in central Madagascar (from Martelat,1998).

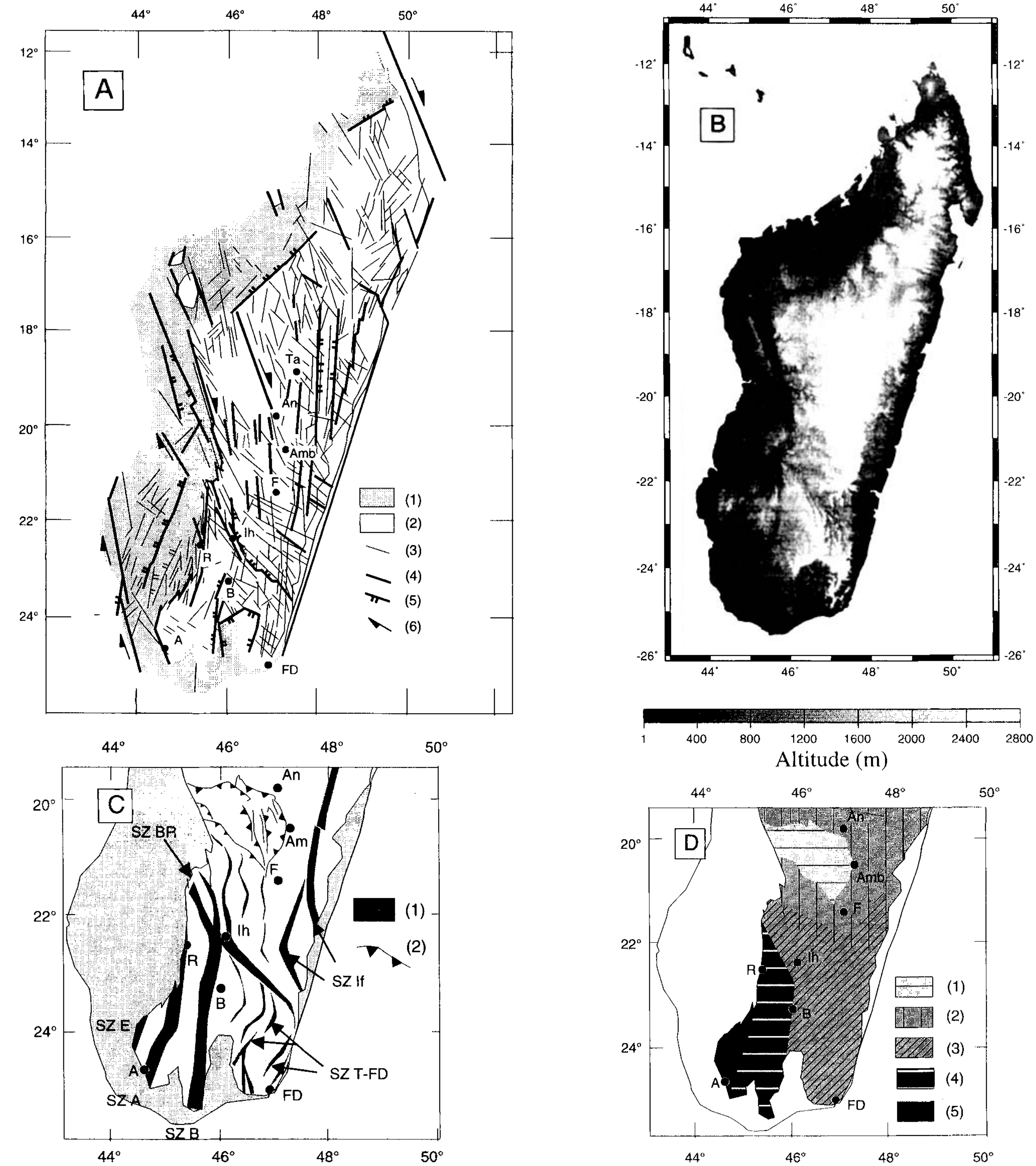

Fig. 3. Metamorphic and strain patterns in Madagascar. A : Map of brittle structures in Madagascar. (1) Sedimentary and volcanic rocks, (2) Precambrian basement, (3) Faults, (4) Main brittle structures, (5) Identified main normal faults, (6) Wrench faults.
B : Digital elevation model showing the main topography of the island obtained with GMT (Wessel and Smith, 1991, 1995).
C : Pan-African ductile strain pattern in southern Madagascar showing the network of shear zones (1) and the thrust planes (2) (folds in the basement are not represented ; SZ BR : Bongolova - Ranotsora shear zone; SZ If: Ifanadiana shear zone ; SZ T-FD : Tranomaro-Fort Dauphin shear zones; SZ B : Beraketa shear zone; SZ A : Ampanihy shear zone; SZ E : Ejeda shear zone; An: Antsirabe; Am: Ambositra; F: Fianarantsoa ; Ih : Ihosy ; R : Ranohira; B : Betroka ; FD: Fort Dauphin; A: Ampanihy).
D : Metamorphic zonation in southern Madagascar. (1) Greenschist facies zone, (2) Amphibolite facies zone, (3) Low-pressure granulite facies zone, (4) Intermediate-pressure granulite facies zone, (5) High-pressure granulite facies zone.

Km. Following Pili et al.(1997b), the crust-mantle boundary is uplifted by about 10 Km beneath the major Pan-African ductile shear zones, the latter being deeply rooted in the mantle .

2) Brittle tectonics and the present day geometry

The brittle strain pattern was established by the combination of previously published geological (Besairie, 1968-1971; 1973; Premoli 1977) or tectonic (Boulanger, 1957; Ségoufin, 1978; Ségoufin and Patriat, 1980; Montenat et al.,1993) maps with the analysis of 20 SPOT images (see details in Martelat, 1998), the analysis of a digitation elevation model established on the basis of topographic and bathymetric data from the " ETOPO 30" database (National Geophysical Data Center, USA, 1988) and finally with field observations. The resulting pattern is presented in Figure 3 in which it appears that the main topography as well as the actual coastal morphology of the island is controlled by the distribution of the brittle structures. The finite brittle pattern results from the superposition of three main fault populations oriented (in the present-day position of Madagascar) as :

- N0 to N20 trending faults,
- N140 to N160 trending faults,
- N100 to N110 trending faults.

Detailed tectono-sedimentary studies are now available in western Madagascar as well as in the Mozambique channel (Premoli, 1977; Segoufin, 1981; Malod et al., 1991; Rajaomazava,1992; Ramahavory, 1993; Montenat et al., 1993) showing that the NNE-SSW and NNW-SSE faults are related to Triassic to Jurassic extension (Karoo rifting). During late Jurassic-upper Cretaceous times, the N140-N160 faults show a significant dextral wrench component coherent with the development of the Davie Ridge. In the Morondava basin, some NNE-SSW and NNW-SSE faults are clearly sealed by late Cretaceous deposits (Montenat et al.,1993), while in other places , these faults are associated to an extensive upper Cretaceous volcanism (olivine or quartz-tholeiites and associated rhyolites, Nicollet,1984; Mahoney et al., 1991) related to the Indo-Madagascar rifting or the action of the Marion hotspot. The N100-N110 trending faults are commonly underlain by numerous Cretaceous doleritic dykes (mainly alkaline rocks, Boulanger,1957; Nicollet, 1988). During the Tertiary and Quaternary, in central Madagascar, some of these faults are strongly reactivated and are still active today.

Finally it is important to emphasize that the brittle structures are in part inherited from the main Pan-African structural discontinuities (i.e. ductile shear zones, Fig.3) reactivated during Cenozoic rifting.

3) Ductile tectonics and Pan-African strain pattern

In the last five years , we have established the finite strain pattern in the southern part of the Malagasy basement (see details in Martelat et al., 1995,1997; Lardeaux et al.,1997; Pili, 1997; Pili et al., 1997 a,b; Martelat, 1998) by a multiscale tectonic analysis including SPOT image studies and field investigations.

In the southernmost part of the studied area (South of Fianarantsoa, Fig.3), two major Pan-African deformation events have been recognized :

- The first one (D1) is represented by a flat-lying granulitic foliation coeval with isoclinal folds and bearing E-W stretching lineations,
- The second one (D2) corresponds to the development of vertical shear zones, the major ones being rooted in the mantle, and steep refolding of D1 fabrics. In these shear zones a gently dipping stretching lineation is well developed.

As shown in Figure 3, the Pan-African ductile strain pattern is a crustal-scale shear zones network and the main structural trend is between N0 and N20 in the actual position of the island. In the shear zones the ratio of simple shear to pure shear is highly variable , but the Beraketa and the Bongolava-Ranotsora shear zones show a significant component of strike-slip.The shear zones separate regions of weaker deformation characterized by folding of earlier fabrics . The folds have sub-vertical axial planes and mainly sub-horizontal axes. A strain gradient (corresponding to the D2 event) is evidenced by folding and tectonic transposition intensities increasing westwards (Martelat et al., 1997; Martelat, 1998). This D2 finite strain pattern reflects first crustal-scale strain partitioning under a transpressive regime and second an E-W bulk horizontal shortening of the Precambrian crust .

In the northernmost part of the studied area (North of Fianarantsoa, Fig.3), the Pan-African deformation is characterized by thrust tectonics involving the so- called "SQC "metasedimentary serie (or "Itremo group" see Moine, 1968,1971). The latter is metamorphosed to greenschist up to amphibolite facies conditions, but even if the bedding has been transposed in many areas, sedimentary markers are preserved, such as rippled surfaces, cross-bedding or stromatolite morphologies (Ashwal et al.,1997; Cox and Armstrong, 1997). The tectonic pattern is characterized by the regional folding of the metasedimentary sequence and the associated development of thrust sheets or reverse faults. Opposite directions of thrusting can be locally depicted (Daso,1986 , Fig. 4) and basement rocks, such as orthogneisses and granites are involved in the thrust sheets. The dominant folds at the regional scale have in general sub-vertical axial planes and gently dipping axes with a general NW-SE trending(Noizet, 1963; Moine, 1971; Daso,1986). The regional stretching lineations are E-W or NE-SW trending, and in some cases the axial planes of the folds are parallel to sub-vertical ductile shear zones. In such a case a mylonitic foliation plane is

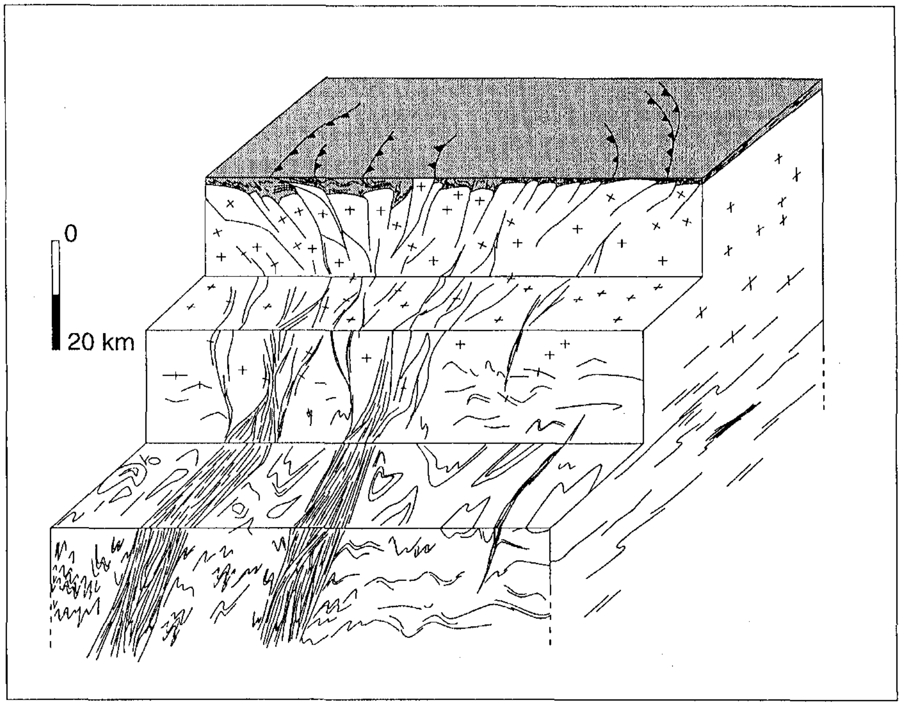

Fig.4. Schematic block diagram of a flower -like structure showing the possible relationships between the main crustal levels now exposed in Madagascar. Under transpression the thrusts developed in the upper crust are connected with vertical ductile shear zones in the lowermost structural levels. In the deepest part of the thickened crust strain is partitioned between shear zones and folded domains.

well developed and the transposition of the sedimentary sequence is complete . This finite strain pattern is clearly compatible with a main E-W or ENE-WSW bulk horizontal shortening of the crust.

Metamorphic Zonation in Southern Madagascar

In this paper we propose a metamorphic zonation of southern Madagascar at a given reference time, here the Pan-African period (590-500Ma).The metamorphic map was established using typomorphic mineral assemblages, classical exchange thermo-barometry and thermodynamic softwares (see details in Nicollet, 1990; Martelat et al., 1997; Martelat,1998). The results were compared with the available P-T estimates at the regional scale (Hottin,1976; Nicollet, 1983;1985 a,b; 1986; Rakotondrasima, 1983; Moine et al., 1985; Daso, 1986; Ackermand et al.,1991; Rakotondrazafy,1992; Rakotondrazafy,1995) to produce the map presented in Figure 3. The metamorphic conditions evolve from greenschist facies (P=3-5Kbar, SQC serie, north of Fianarantsoa) up to high-pressure granulite facies (P=10-12Kbar west of Ampanihy). The transition between the different metamorphic zones is either progressive (amphibolite facies near Fianarantsoa up to low pressure granulite facies near Ihosy) or controlled by the major ductile shear zones (high pressure, intermediate pressure and low pressure granulite facies domains tectonically juxtaposed south of Ihosy).

Taking into account the present -day thickness of the crust (35-40 Km) , the calculated P-T metamorphic conditions (P Max. = 10-12 Kbar) suggest a thickening of the crust up to 60-70 Km during Pan- African times.

Discussion

The Pan-African metamorphic and tectonic patterns of southern Madagascar can be explained through a simple and coherent model of crustal thickening under a transpressive regime. The crustal-scale geometry is compatible with bulk horizontal shortening (mainly E-W in the present position of the island) giving rise to a positive flower-like structure (Fig. 4). At upper crustal levels (SQC series), thrusts and folds are developed under greenschist facies conditions, while at deeper levels the strain is strongly partitioned between ductile shear zones (sometimes with a strong strike-slip component) and folded domains contemporaneous with granulite facies conditions . South of Ihosy and as a consequence of the high temperature conditions (T=750-800°C) reached during the Pan-African metamorphism , all the obtained ages are late-Precambrian. On the other hand, at upper crustal levels, in the greenschist facies zone, older ages are well preserved in the basement involved in the thin-skinned thrust tectonics .

In the proposed tectonic setting, the main structural trends are mostly N-S and clear strain gradients can be depicted, E-W oriented in the granulite facies zone (south of Ihosy). In this case, the strain is mainly concentrated in the N0-N20 oriented shear zones and the sinistral Bongalava -Ranotsora shear zone is only an accommodation structure. The latter cannot be regarded as a "major suture zone" during the Pan-African orogeny. It must be underlined that the BR shear zone has been strongly reactivated during the opening of the Mozambique channel and now represents a major topographic boundary (normal fault) between southern and central Madagascar.

The juxtaposition of contrasted metamorphic domains is related to different exhumation rates during progressive Pan-African transpression and subsequent Cenozoic brittle extension (or transtension). As a consequence, southern Madagascar offers an exceptional natural cross- section of a shortened orogenic root.

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