Gondwana Research, V. 2, No. 3, pp. 363-367.
© 1999 International Association for Gondwana Research, Japan.
ISSN: 1342-937X

GR
Gondwana Research

Exhumation of Granulites Within a Transpressive Regime: an Example from Southern Madagascar

J. E. Martelat[1,2*], J.M. Lardeaux [1], C. Nicollet[2] and R. Rakotondrazafy[3]

[1] *Laboratoire de Pétrologie et Tectonique, Université Claude Bernard, UMR 5570, 43 Bd du 11 Novembre 69622 Villeurbanne, France*

[2] *Département de Géologie, Université Blaise Pascal, UMR 6224, 5 Rue Kessler, 63038 Clermont Ferrand, France*

[3] *Laboratoire de Pétrologie, Université d'Antananarivo, BP 906, 101 Madagasacar*

* *Present address: Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Albertov 6, 128 43 Prague, Czech Republic , e-mail jemartel@natur.cuni.cz*

(Manuscript received September 7, 1998; accepted February 24, 1999)

Introduction

In Madagascar, a preserved section of continental crust is exposed and offers an opportunity to study the thermomechanical behaviour of rocks metamorphosed under high-temperature and middle to deep crustal levels (Nicollet, 1990; Nédélec et al., 1995; Ashwal et al., 1997). We have established the bulk strain pattern and the P-T-t conditions over a significant area of more than 100 000 km^2 in the southern part of Madagascar (Fianarantsoa-Ihosy-Ampanihy-Fort Dauphin, Fig. 1).

Madagascar, a part of Gondwana, represents the eastern front of the Mozambique belt (Pallister, 1971; Shackleton, 1986). In the southern part of the island, the lithologies consist of post-Cambrian volcanics and sediments, but high-grade metamorphic rocks are dominant (Besairie, 1970a and b; Nicollet, 1990). These rocks are represented by orthogneisses, paragneisses, marbles, granitoids, migmatites and metabasites metamorphosed under granulite facies conditions. These granulites were highly strained during Pan-African time (580-530 Ma), but do not exhibit any record of the Archean age (Andriamarofahatra et al., 1990; Kröner et al., 1996; Montel et al., 1996; Paquette et al., 1994).

Strain Pattern

The finite strain pattern of southern Madagascar was derived from the study of satellite images (20 SPOT scenes) complemented by structural analysis in the field (foliation, stretching lineation trajectories and kinematics, Martelat et al., 1995; 1997; Lardeaux et al., 1997). On kilometre scale, the structural pattern is characterized by ductile and fragile structures. Huge faults and caldera in the south-east are well visible. Our studies were focussed on ductile structures. They are defined by intersection of lithological banding and flat topography, and show complex folded structures (dome-and-basin) bounded by huge ductile shear zones. Rounded fold geometries more or less elliptic in shape are considered a marker of strain intensity. The spacial evolution of these oval shapes shows axial ratios ranging from 1:1, 1:3 to 1: 20 underlining the regional strain gradients (Martelat et al., 1997). On satellite images, we have studied in detail and precised the limits of six major shear zones (MSZ) 15-25 kilometres wide by more than 100 kilometres long (Ejeda MSZ-1, Ampanihy MSZ-2, Beraketa MSZ-3, Bongolava-Ranotsara MSZ-4, Zazafotsy MSZ-5, Ifanadiana MSZ-6, Fig. 1) and numerous minor shear zones some 3-5 kilometres wide and less than 100 kilometres long (msz, Fig. 1).

This structural pattern results from the superposition of two distinct finite strain patterns D1 and D2. Outside the shear zones, the planar fabric (S1) is mainly horizontal with dominantly east-west stretching lineation (L1). Conjugate metric shear zones and F1 folds with horizontal axial planes are compatible with vertical shortening and subordinate westward displacement. Going towards the shear zones the early flat fabric (S1) becomes folded by kilometric folds (F2) with sub-horizontal hinge line. On a kilometre scale, these open folds progressively evolve to upright and unrooted folds into the shear zones. In the shear zones, the mean foliation is regularly vertical (S2) and the mineral lineation

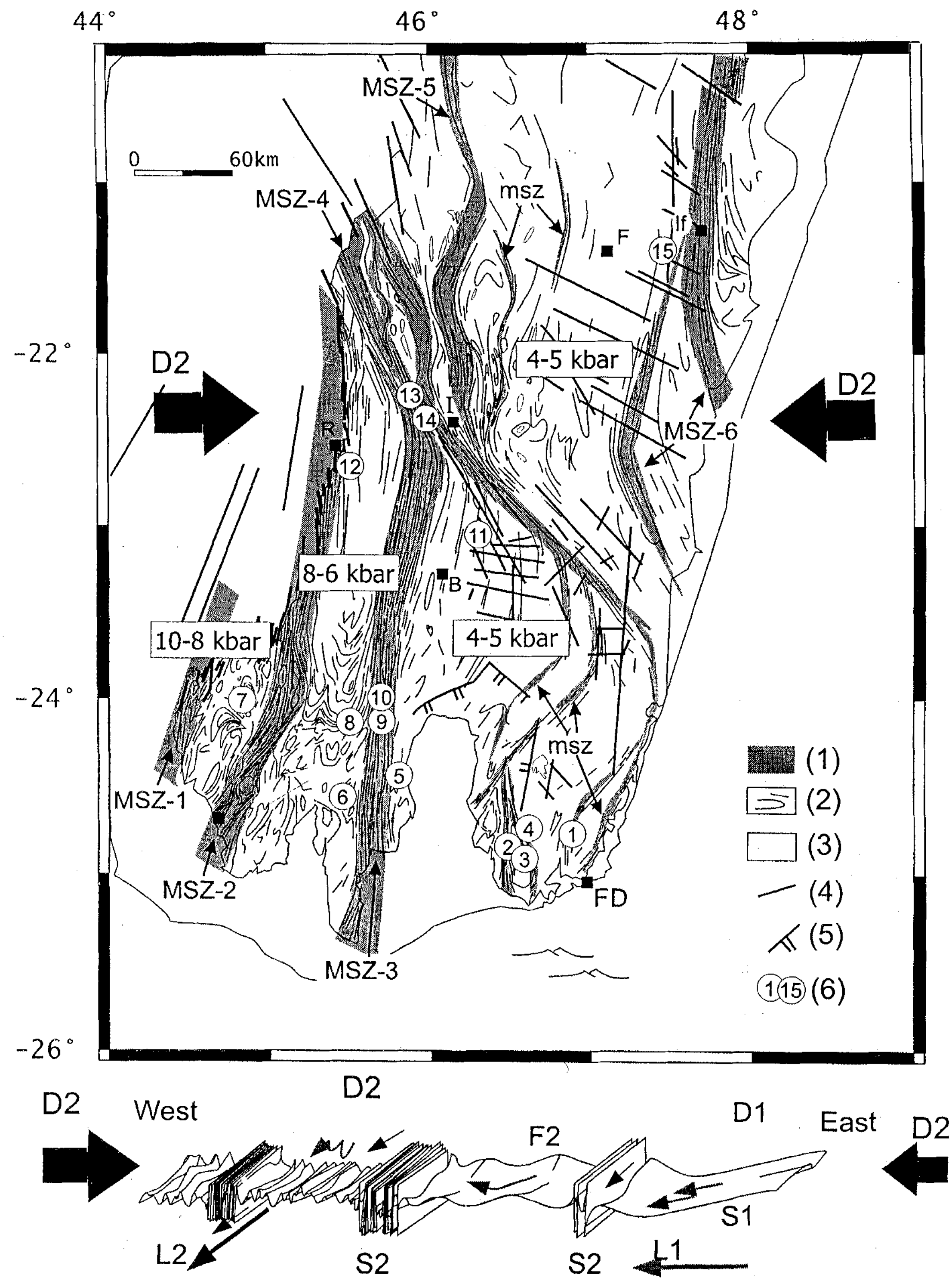

Fig. 1. Tectonic framework, P-T conditions and localization of geochronological data in the southern part of Madagascar. This tectonic map is based on satellite imaging and complemented by field studies (Martelat et al., 1997; Pili et al., 1997; Martelat, 1998) and correlated with published geological maps (Besairie, 1970a & b). The maximum pressure data are from Nicollet 1988, 1990; Nédélec et al., 1992 and pers. Communication; Martelat et al., 1997; Martelat, 1998. (1) Major shear zones (MSZ) of -1 Ejeda, -2 Ampanihy, -3 Beraketa, -4 Bongolava-Ranotsara, -5 Zazafotsy, -6 Ifanadiana and minor shear zones (msz), (2) major foliation trends developed in migmatites and rocks metamorphosed under granulite and high amphibolite facies, (3) post-Cambrian sediments and volcanic rocks, (4) major faults, (5) caldera, (6) numbered circles (1-15) indicate the position of the geochronological estimates on monazite (Tab. 1). Black squares : towns of Ampanihy A), Betroka B), Fort-Dauphin FD), Fianarantsoa F), Ifanadiana If), Ihosy I), Ranohira R). At the bottom a 3D schematic diagram of the structures shows the interference between D1 and D2 finite strain patterns.

is dominantly sub-horizontal (L2). This new fabric is marked by layered coarse grained rocks. In this spectacular mylonite, local macro to mesoscale shear criteria were observed. These structures are asymmetric and imply non-coaxial strain. At the outcrop, we also observed contrary shear sense indicators, symmetrical boudinage and syntectonic veins, in both the XZ and YZ sections of the finite strain ellipsoids compatible with coaxial strain. Consequently inside the shear zone we observed the competition between pure shear and simple shear strain regimes. The Bongolava-Ranotsara and the Beraketa shear zones are affected by simple shear dominant strain regime, whereas, farther to the west, the Ampanihy shear zone has undergone deformation with a strong component of pure shear.

On a regional scale, in the dome-and-basin domains, the folds are more tight in the western part of the studied area (i. e., west of Ampanihy MSZ-2), and to the south of the Bongolava-Ranotsara shear zone, the intensity of folding is compatible with the D2 strain gradient increasing from east to west.

The D2 finite strain pattern shows a strong strain marked by a horizontal east-west shortening, accommodated in a combination of coaxial and non-coaxial strain. This D2 finite strain pattern reflects a transpressive tectonic regime as defined by Sanderson and Marchini (1984), and Robin and Cruden (1994).

Both the D1 and D2 events occurred under granulite facies metamorphic conditions as demonstrated by the syntectonic migmatitization (Martelat et al., 1997). Typical mineral assemblages include two pyroxenes-plagioclase-quartz paragenesis in metabasites and spinel-quartz associations in metasediments (Nicollet, 1988; 1990; Martelat at al., 1997). We have more precisely defined the metamorphic conditions associated with the two finite strain fields. Estimates were done for various lithologies by using several methods (TWEEQU software and calibrations; Martelat, 1998). The results show that rather uniform high-temperature conditions (750-850°C) occured in the southern Madagascar. In contrast, concerning maximum pressure values, there is a regional trend from 12 kbar in the west to 5 kbar in the east. These differences in pressure are controlled by major shear zones, which in turn cause the differential vertical movements of the crustal blocks. Thus, the transpressive D2 strain field must have been responsible for exhumation of deep-seated rocks. Several pressure temperature evolutions can be recognized at such high-temperature conditions. The P-T-paths are in agreement with isothermal decompression from 12 kbar to 5 kbar in the western domain (between MSZ-1 and 2, Fig. 1). These results were obtained from studies of sapphirine-corrundum-bearing amphibolites and cordierite-bearing gneisses from the same outcrop. In the eastern domain, the decompression is weaker, marked by the breakdown of garnet to cordierite in sillimanite bearing metapelites (Nicollet, 1988, 1990; Martelat, 1998). These metamorphic evolutions are also compatible with similar decompression paths recorded by Ackermand et al., (1989).

Geochronology

Geochronological estimates on monazite (electron microprobe dating monazite, U-Th-Pb Montel et al., 1996) were carried out to constrain the timing of deformation. This method, less precise than conventional isotopic techniques (one order of magnitude, Table 1), was applied to various leucocratic lithologies. Our results (Nicollet et al., 1997; Martelat, 1998) are consistent with the available age constrains carried out by other authors in the same kind of material but with different techniques (Andriamarofahatra et al., 1990; Kröner et al., 1996; Paquette et al., 1994; Tucker et al., 1997). These results have underlined the Pan-African ages. Moreover, the age values are systematically smaller in the shear zones (samples 9, 10, 13, 14). Consequently, we suggest that in the southern Madagascar, the tectono-metamorphic imprint developed between 590 and 500 Ma. More precisely, the D1 structures are dated between 590 and 530 Ma, and the D2 structures at 530-500 Ma. We chose 500 Ma as the lower limit as ages below 500 Ma are without tectono-thermal significance in the Mozambique belt (Stern, 1994).

The paleomagnetic constraints (Norton and Sclater, 1979; Powell et al., 1980) give the craton position corresponding to the end of the Pan-African geometry. This view complemented with the kinematic of the Pan-African shear zones framework in east Africa and southern India show

Table 1. Geochronological data obtained by electron microprobe dating of monazite (Montel et al., 1996 (a); Nicollet, 1997 (b); Martelat, 1998 (c)). Sample locations are indicated in Fig. 1. Samples 9, 10, 13, 14 are located inside the major shear zones, samples 2, 3, are from minor shear zones, other samples come from the dome-and-basin domains.

Rock type	Age in Million years	Locality Fig.1, circle n°	Source
Charnockite	558± 12	1	(b)
Charnockite	536±7	2	(b)
Charnockite	523±8	3	(b)
Mineral of monazite	550±20	4	(a)
Leucocratic gneiss	590±32	5	(c)
Paragneiss	529±21	6	(b)
Paragneiss	529±23	7	(b)
Paragneiss	539±20	8	(b)
Paragneiss	502±32	9	(b)
Paragneiss	488±24	10	(b)
Paragneiss	567±18	11	(b)
Leucocratic gneiss	534±23	12	(c)
Paragneiss	375±28	13	(b)
Charnockite	430±32	14	(b)
Leucocratic gneiss	515±20	15	(c)

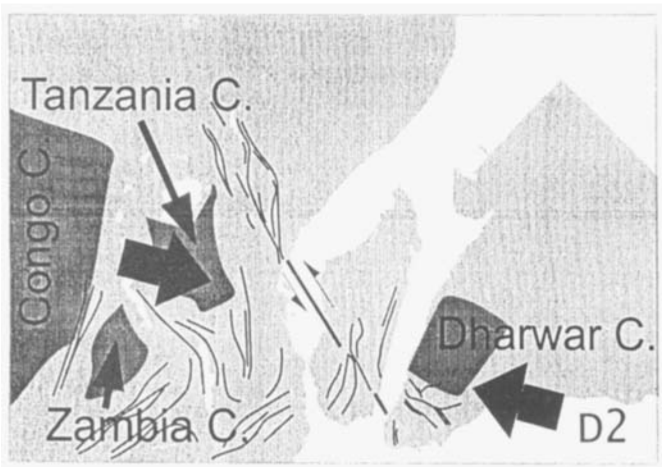

Fig. 2. Position of cratons (C.) and the proposed kinematic of the D2 event at the end of the Pan-African time. The Madagascar continental crust deformation resulted from the oblique convergence of crustal heterogeneities: the Tanzanian craton to the west and the Dharwar craton to the east, modified after Norton and Sclater, 1979; Drury and Holt, 1980; Powell et al. 1980; Daly, 1986; Schakleton, 1986; Kriegsman, 1993; Windley et al. 1994; Sacks et al. 1997; Martelat, 1998.

the convergence of the Tanzanian craton in the west and the Dharwar craton in the east (Fig. 2, Drury and Holt, 1980; Daly, 1986; Schakleton, 1986; Kriegsman, 1993; Windley et al., 1994; Sacks et al., 1997; Martelat, 1998). In this context, the superposition of the D1 and D2 strain patterns, in the range of 590-500 Ma, is clearly the result of an oblique convergence of cratons promoting the bulk shortening of the intracratonic lithosphere. Under very high-temperature metamorphism (max T > 850°C), we observe a strong strain partitioning on a regional scale and the D2 strain gradient increasing from the east to the west. Madagascar granulites were mainly exhumed (at least 20 kilometres of uplift) during a transpressive regime (D2 strain pattern). The vertical displacement was controlled by the D2 strain gradient, and was the largest in domains where the ratio of pure shear versus simple shear was the highest (Fig. 3), as predicted by thermomechanical modelling (Thompson et al., 1997). This hypothesis is supported by the regional distribution of lithologies, more granitic in the east and more mafic to the west. The basement of Madagascar, thus represents an example of deep seated rocks exhumed during an obliquely convergent (transpressive) orogen.

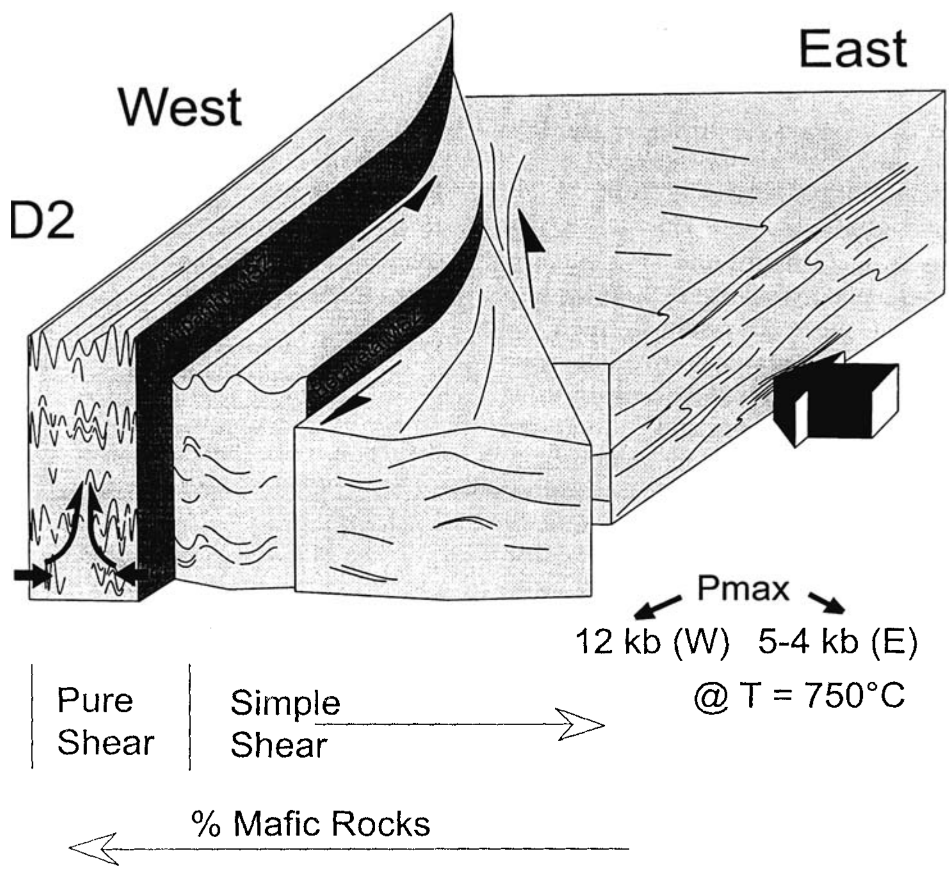

Fig. 3. Interpretative block diagram showing the D2 dynamic event in the southern part of Madagascar. The two vertical planes in dark grey represent vertical major shear zones of Ampanihy and Beraketa whereas the oblique shear zone corresponds to the Bongolava-Ranotsara structure. The zone where the exhumation of the lower crust is stronger is located to the west where the strain regime is pure shear dominated. The maximum pressure is given at a constant temperature of 800°C. Mafic lithologies increase from the east to the west.

References

Ackermand, D., Windley, B.F. and Razafiniparany, A. (1989) The Precambrian mobile belt of southern Madagascar. In: J.S. Daly, Cliff, R.A. and Yardleys, B.W.D. (Eds.), Evolution of metamorphic belts. Geol. Soc. Spec. Publ., v.43, pp. 293-296.

Andriamarofahatra, J., De La Boisse, H. and Nicollet, C. (1990) Datation U-Pb sur monazites et zircons du dernier épisode tectono-métamorphique granulitique majeur dans le Sud-Est de Madagascar. C. R. Acad. Sci. Paris, v.310, pp. 1643-1648.

Ashwal, L. D., Cox, R., Le Grange, M., Müller, B. G. J., Rambeloson, R. A. and Tucker, R. D. (1997) Guidebook to Field Excursions : North- and South-Central Madagascar. In: Ashwal, L.D. (Ed.), UNESCO-IUGS-IGCP 348/368. Internal Symposium and field workshop on proterozoic geology of Madagascar, p. 53 .

Besairie, H. (1970a) Carte géol., Fianarantsoa, Antananarivo. Service géol. Madagascar, échelle 1 : 500 000.

Besairie, H. (1970b) Carte géol., Ampanihy, Antananarivo. Service géol. Madagascar, échelle 1 : 500 000.

Daly, M. C. (1986) The intracratonic Irumide Belt of Zambia and its bearing on collision orogeny during the Proterozoic of Africa. In: Coward, M.P. and Ries, A.C. (Eds.), Collision Tectonics. Geol. Soc. Spec. Publ., v. 19, pp. 329-349.

Drury, S. A. and Holt, R. W. (1980) The tectonic framework of the South Indian craton: a reconnaissance involving LANDSAT imagery. Tectonophys., v. 65, pp. T1-T15.

Kriegsman, L. M. (1993) Geodynamic evolution of the Pan-African lower crust in Sri-Lanka. Structural and petrological investigations into high-grade gneiss terrain. Thesis Univ. Utrecht, v. 114, 208 p.

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

Lardeaux, J.M., Martelat, J.E., Nicollet, C., Pili, E., Rakotondrazafy, R., Ricard, Y., Sheppard, S. and Vidal, G. (1997) The deep continental crust in southern Madagascar : Strain pattern and related fluid and heat transfers. Jour. African Earth Sci., v. 23, pp. R3-R6.

Martelat, J.E. (1998) Evolution thermomécanique de la croûte inférieure du Sud de Madagascar. PhD Thesis Univ. B. P. Clermont-Ferrand II, 232p.

Martelat, J.E., Nicollet, C., Lardeaux, J.M., Vidal, G. and Rakotondrazafy, R. (1997) Lithospheric tectonic structures developed under high-grade metamorphism in the southern part of Madagascar. Geod. Acta., 10, v. 3, pp. 94-114.

Martelat, J.E., Vidal, G., Lardeaux, J.M., Nicollet, C. and Rakotondrazafy, R. (1995) Satellite images and tectonics of the lower continental crust : The example of South-Western Madagascar. C. R. Acad. Sci. Paris, 321, série II a, pp. 325-332.

Montel, J.M., Foret, S., Veschambre, M., Nicollet, C. and Provost, A. (1996) Electron microprobe dating of monazite. Chem. Geol., v. 131, pp. 37-53.

Nédélec, A., Moine, B. and Rakotondrazafy, M. (1992) Granulites du Sud-Est de Madagascar : thermobarométrie des leptynites de Fort-Dauphin. 14ème Réunion des Sciences de la Terre, Toulouse, p. 113.

Nédélec, A., Stephens, W.E. and Fallick, A.E. (1995) The Pan African stratoid granites of Madagascar: alkaline magmatism in a post-collisional extensional setting. Jour. Petrol., v. 36, pp. 1367-1391.

Nicollet, C. (1988) Métabasites granulitiques, anorthosites et roches associées de la croûte inférieure. Exemple pris à Madagascar et dans le Massif Central Français. Arguments en faveur d'un métamorphisme associé à l'extension lithosphérique. Thèse d'Etat, Univ. Clermont-Ferrand. 315 p.

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

Nicollet, C., Montel, J.M., Foret, S., Martelat, J.E., Rakotondrazafy, R. and Lardeaux, J.M. (1997) E-Probe monazite dating in Madagascar : a good example of the usefulness of the in-situ dating method. In: Ashwal, L.D. and Cox, R. (Eds.), UNESCO-IUGS-IGCP 348/368. Internal Symposium and field workshop on proterozoic geology of Madagascar. Abst. Vol., p. 65.

Norton, I.O. and Sclater, J.G. (1979) A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. Jour. Geophys. Res., 84, B12, pp. 6803-6830.

Paquette, J.-L., Nédélec, A., Moine, B. and Rakotondrazafy, M. (1994) U-Pb, Single Zircon Pb-Evaporation, and Sm-Nd Isotopic Study of a granulite Domain in SE Madagascar. Jour. Geol., v. 102, pp. 523-538.

Pallister, J.W. (1971) The tectonics of East Africa. In. UNESCO, The tectonics of Africa, v. 6, pp. 511-543.

Pili, E., Sheppard, S.M.F., Lardeaux, J.M., Martelat, J.E. and Nicollet, C. (1997) Fluid flow vs. scale of shear zones in the lower continental crust and the granulite paradox. Geology, v. 25, pp. 15-18.

Powell, C.McA., Johnson, B.D. and Veevers, J.J. (1980) A revised fit of east and west Gondwanaland. Tectonophys., v. 63, pp. 13-29.

Robin, P.Y.F. and Cruden, A.R. (1994) Strain vorticity patterns in ideally ductile transpression zones. Jour. Str. Geol., v. 16, pp. 447-466.

Sanderson, D.J. and Marchini, W.R.D. (1984) Transpression. Jour. Str. Geol., v. 6, pp. 449-458.

Sacks, P.E., Nambiar, C.G. and Walters, L.J. (1997) Dextral Pan-African shear along the southwestern edge of the Achankovil shear belt, South India : constraints on Gondwana Reconstructions. Jour. Geol., v. 105, pp. 275-284.

Shackleton, R.M. (1986) Precambrian collision tectonic in Africa. In: Coward, M.P. and Ries A.C. (Eds.), Collision Tectonics. Geol. Soc. Spec. Publ., v. 19, pp. 329-349.

Stern, R. J. (1994) Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for the consolidation of Gondwana, Annu. Rev. Earth Planet. Sci. Lett., v. 22, pp. 319-351

Thompson, A.B., Schulmann, K. and Jezek, J. (1997) Thermal evolution and exhumation in obliquely convergent (transpressive) orogens. Tectonophys., v. 280, pp. 171-184.

Tucker, R. D. et al. (1997) Guidebook to Field Excursions: Map of U-Pb zircon ages. In: Ashwal, L.D. (Ed.), UNESCO-IUGS-IGCP 348/368. International symposium and field workshop on proterozoic geology of Madagascar, p. 9.

Windley, B.F., Razafiniparany, A., Razakamanana, T. and Ackermand, D. (1994). Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. Geol. Rundsch., v. 83, pp. 642-659.