CRUSTAL EVOLUTION OF THE GRANULITES OF MADAGASCAR

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ABSTRACT. In its pre-drift position, before the end of the Paleozoic, Madagascar was adjacent to Kenya and Tanzania and was located on the eastern front of the Mozambican belt, juxtaposed against the Indian Craton. The crust of Archean age was reactivated during the Proterozoic (2.6 Ga, 1.1 Ga ?, 850-550 Ma). The metamorphic events were generally high grade and formed extensive granulite terrains. In the *north* of the island, granulites associated with belts of basic and ultrabasic magmatic rocks indicate high grade conditions : T≈1000°C and P≈6 kb. Aluminous rocks contained Q, Al-rich Opx, Ga, Sill, Rut and/or Ilm, Sp, Feld and probably osumilite and sapphirine. Primary Opx contain garnet lamellae and are aluminous-rich (7-10 wt % Al_2O_3). Near isobaric retrogression and hydration produced orthoamphibole-cordierite gneisses. In the *south* of Madagascar, the metamorphic grade increases from greenschist to granulite grade going from west to east. Supracrustal metabasites (sapphirine-corundum amphibolites, serendibite and clintonite clinopyroxenites, etc.) have undergone a prograde event. The synmetamorphic, anorogenic gabbro-anorthosite intrusive complex is related to an increased geothermal gradient going from W (high-P granulite facies) to E (intermediate-P granulite facies). Isobaric cooling was followed by decompression (P-T path concave towards the T-axis). Gneisses with Al-rich Opx, Ga, Cord, Sp+Q, are common in the SE and suggest high T. A widespread anatectic event produced Q-Kf-Pl-Ga-Cord-Sill-Bio gneisses and biotite rich residues which contain Sapph, Korn and grandidierite. It is proposed that the magmatic intraplating, the very high T metamorphism, the P-T path concave towards the T-axis and the variation in the geothermal gradient are the consequences of continental lithospheric thinning by extension followed by a compressive event.

Abbreviations in text and figures - Anth : anthophyllite, Bio : biotite, Clint : clintonite, Co : corundum, Cord : cordierite, Cpx : clinopyroxene, Feld : feldspar, Ga : garnet, Gd : gedrite, Grd : grandidierite, Hb : hornblende, Ilm : ilmenite, Kf : K feldspar, Ko, Korn : kornerupine, Oamph : orthoamphibole, Opx : orthopyroxene, Pl : plagioclase, Q : quartz, Rut : rutile, Sa, Sapph : sapphirine, Ser : serendibite, Si, Sill : sillimanite, Stl : staurolite, Sp : spinel, Tour : tourmaline, Zo : zoisite.

1. Introduction

Metamorphic terrains, showing a progressive transition from low grade to high grade rocks, can be interpreted as representing portions of the middle and lower crust. These regions are so diverse in composition, lithology, and tectonic style that no single model can adequately describe the nature of this portion of the crust (e.g. Harley, 1989). They provide evidence of varied geodynamic processes (e.g. calc-alkaline - granulite complexes in the lower crust in zones of tectonic convergence). They also represent zones of active crustal accretion and differentiation.

It is known that the lower crust is more basic than the upper crust. This intracrustal differentiation is produced in several different ways (e.g. Kay and Kay, 1986) : 1) by incorporation of slices of oceanic crust beneath continental crust, 2) by differentiation of a juvenile magma, 3) by

D. Vielzeuf and Ph. Vidal (eds.), Granulites and Crustal Evolution, 291–310.

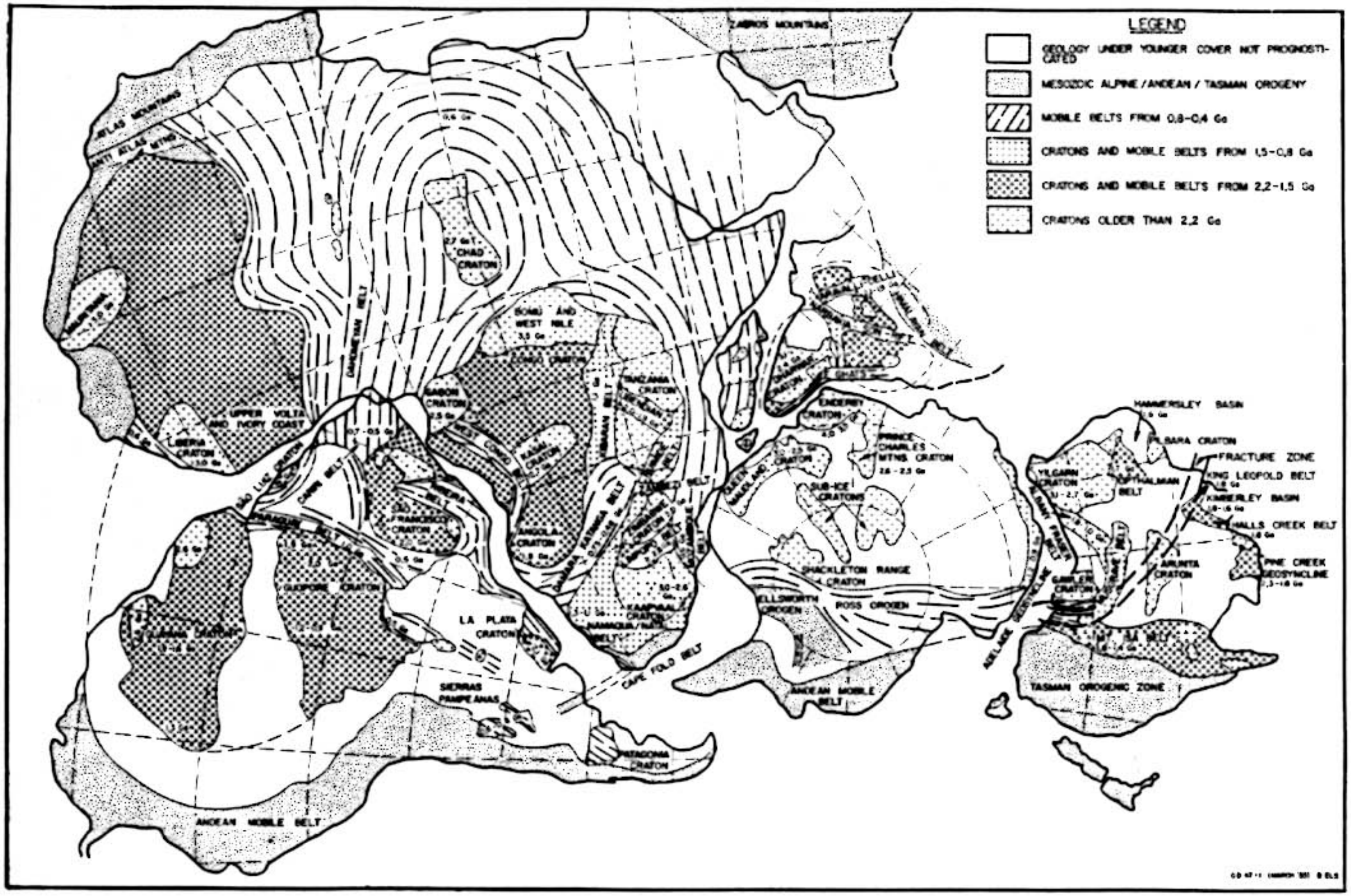

Figure 1. Madagascar in Gondwanaland (Toens and Andrews Speed, 1984 with permission).

density stratification of basic magmas, 4) by crustal fusion (restite model) : the necessary thermal transfer for fusion coming from mantle intrusions (see Clemens, this volume). Thus, basic magmatism has an important role in accretion and in the process of crustal differentiation.

Metabasites are ubiquitous in many granulite terrains. Did these rocks intrude the granulitic lower crust and then follow an isobaric cooling path (followed by adiabatic decompression : the P-T-t path being concave towards the T-axis) ? Or were these rocks emplaced in the upper crust and subsequently metamorphosed by a prograde event (following varied P-T-t trajectories) which may have then been followed by isobaric cooling ? In other words, are intrusion and granulitic metamorphism synchronous or not ? The principal difficulty is that the rocks preserve little mineralogical evidence of their prograde path.

Granulites comprise much of the Precambrian exposure of Madagascar. Metabasites are abundant and occur in belts several hundred kilometres long. The mineralogy of the granulites is exceptional and very diversified, permitting a detailed study of the metamorphic evolution of these rocks.

2. Geologic background

At the end of the Precambrian, Madagascar was located in the interior of the Gondwana supercontinent between India and Africa and marked the eastern limit of the Mozambican mobile belt against the Indian craton (Fig.1). The presence of E-W oriented magnetic anomalies in the southern portion of the Mozambique Channel and in the Somali Basin, plus the existence of thinned continental crust in the central portion of the Mozambique Channel, indicate that Madagascar adjoined Kenya and Tanzania (e.g. Mc Elhinny and Embleton, 1976 ; Ségoufin, 1978, Ségoufin and Patriat, 1980 ; Norton and Sclater, 1979). The exact position to the east between Madagascar and India and the Seychelles, and to the south with respect to Antarctica, is not as well constrained (Katz and Premoli, 1979 ; Powell et al., 1980).

Geophysical data are sparse. Study of natural seismisity (Rakotondrainibe, 1977) suggests that the Madagascan crust has a normal thickness below the base of the Precambrian in the center of the island (35-37km). There are two discontinuities. One separates an upper layer, which has a P-wave velocity of 5.9 km/s, from a lower layer ($V = 6.7$ km/s) at about 16 km ; the other discontinuity is between the lower layer (18 to 21 km thick) and the mantle ($V=8.0$ km/s). However, the recent work of Fourno (1987) and gravimetric study of Rechenmann (1982) suggest local variations in crustal thickness (between 24 and 37 Km), related to the breakup of Gondwana. The positive gravity anomalies can be correlated with basic and ultrabasic complexes.

Precambrian terrains occupy two thirds of the island (Fig. 2). They have been the subject of many studies by the Geological Survey of Madagascar, which have been compiled by Besairie (1967, 1968-71, 1973). South of the Bongolava - Ranotsara lineament (B.R. in Fig. 2), Besairie (1967, 1973) described an Archean age succession which he subdivided into three groups (based upon old Pb α data). Catazonal rocks of the *Androyan group* form the base of the succession. These are overlain by the *Graphite group*, which is composed of gneisses and leptynites with abundant graphite, and above that by the *Vohibory group* which is characterized by the occurrence of numerous amphibolites and marbles. Based upon petrography, Besairie (1973) correlated rocks from north of the Bongolava - Ranotsara (B.R.) fracture zone with the Graphite and Vohibory groups in the south. In the center of the island, rocks of the *Amborompotsy group* ("series of quartzites and marbles") crop out, which are a middle to upper Proterozoic in age.

More recent studies (Noizet, 1972 ; Bazot, 1976 ; Hottin, 1976) and the geochronologic data of Caen-Vachette (1977, 1979, see also Cahen and Snelling, 1984) lead to an interpretation of the Precambrian of Madagascar which requires important modification of Besairie's synthesis (1973). Caen-Vachette (1979) suggest that the Bongolava - Ranotsara lineament separates two chronologically distinct domains. The systematic re-orientation of nearly N-S trending structures to the

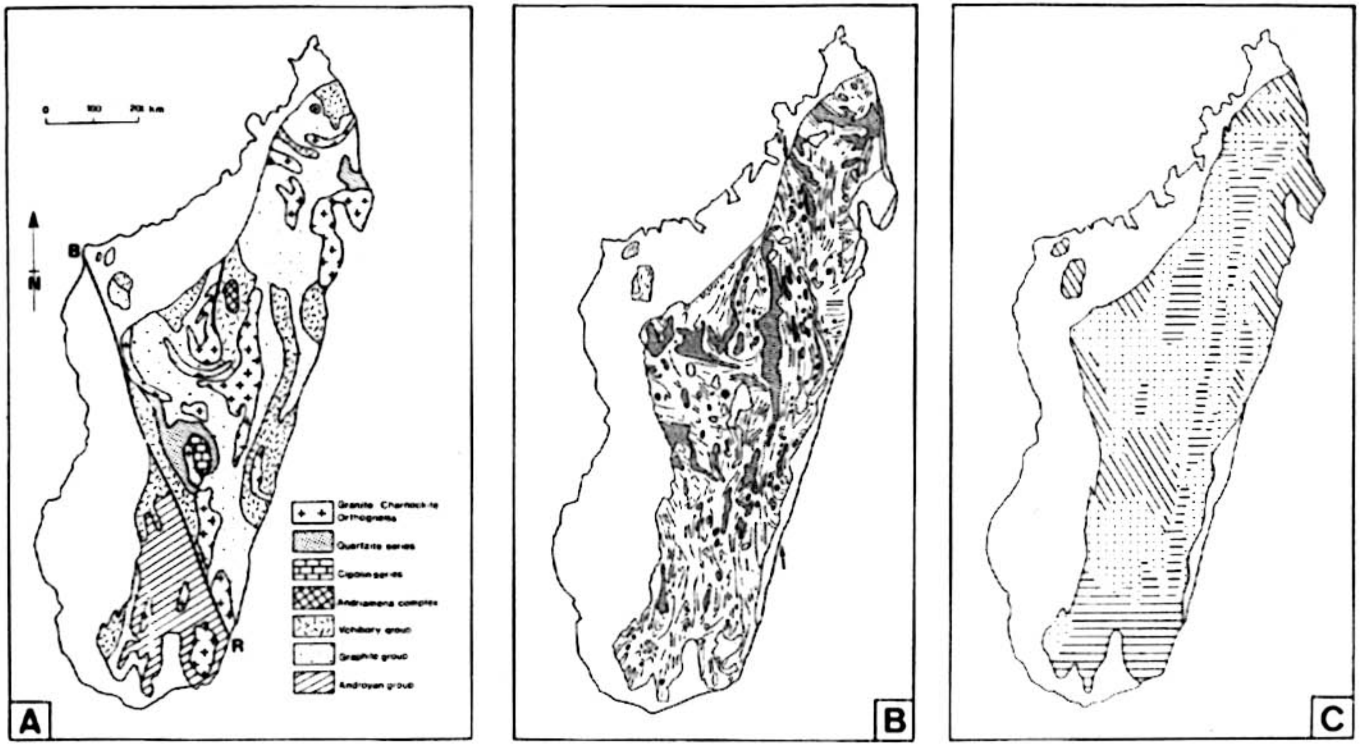

Figure 2.

A) - Simplified geological map of the Precambrian in Madagascar (Besairie, 1967) ; B.R.: Bongolava - Ranotsara lineament.

B) - Simplified structural map showing main structural trends. Unlabelled: Phanerozoic formations ; horizontal lines: Pan-African granites and migmatites (900-550 Ma) ; stippled: pre-Pan-African granites and charnockites ; black: precambrian metagabbros and ultrabasites ; between arrows: main basic-ultrabasic belt ; asterisk: low T eclogite from Faratsiho.

C) - Sketch map of the metamorphism (modified after Bazot et al, 1971). Oblique lines: epizone and mesozone ; stippled: upper amphibolite facies (above muscovite-out isograd) ; horizontal lines: granulite facies.

NW at the contact of the fracture zone suggests left-lateral motion. Before the breakup of Gondwana, the Bongolava - Ranotsara lineament was an extension of the Assoua lineament in Africa. Ages are few and are essentially whole-rock Rb-Sr dates (there are some old, unreliable conventional mineral ages based on Pbα dating). Caen-Vachette (1979) shows that Madagascar is a portion of Archean crust that has been re-activated during the course of different tectono-metamorphic episodes which are poorly characterized. However, one event is well defined at 2.6 Ga (whole-rock Rb-Sr isochron on the Antongil granites : 2603 ± 93 Ma, Vachette and Hottin 1970). The nature of these rocks and the initial Sr ratio of 0.70491 shows that these granites are the product of fusion of older continental crust. A Kibaran episode is poorly defined (e.g. errorchron on the Brickaville granitoids of 1103 ± 31 Ma with Sr_i = 0.70495 ; Vachette and Hottin, 1975) and must be confirmed by other methods. It should be noted that the Kibaran event should be well represented in the southern portion of the Mozambican mobile belt (Jourde and Vialette, 1980 ; Sacchi et al., 1984) and in Sri Lanka and India (Grew and Manton, 1986 ; Kröner et al., 1987).

The Rb-Sr model ages on minerals (mostly biotite ; Delbos, 1965) indicate the existence of the Pan-African megacycle in Madagascar (500-750 Ma). This is confirmed by whole rock Rb-Sr dating (eg. Ankaramena granite 737 ± 15 Ma, Sr_i = 0.71261 : Vachette and Hottin, 1975 ; Carion granite 734 ± 15 Ma, Sr_i = 0.70383 : Vachette and Hottin, 1974) and Pb-U dating of the granulites in the SE (560-565 Ma); the 516 Ma age on zircons from a pegmatite, marks the end of the Pan-African event (Andriamarofahatra and de la Boisse, 1986 ; Andriamarofahatra et al., 1989).

A schematic map of the metamorphism was presented by Bazot et al (1971) (Fig. 2). This map shows the higher grade metamorphism independant of the influence of polymetamorphism or possible retrogression and does not take into account the ages of metamorphism. It shows also that low grade metamorphism was very localized and restricted to the "series of quartzites and marbles" in the center of the island, and on the NE coast. The amphibolite facies of intermediate pressure is well exposed north of the Bongolava - Ranotsara lineament and is also localized in the extreme SW of Madagascar. These are lower amphibolite grade rocks, containing sillimanite and lying above the muscovite-out isograd.

Granulite grade rocks crop out over a large area covering the majority of the southern Madagascar. To the North of the Bongolava - Ranotsara fracture zone, N-S oriented granulite belts, up to 800 km long, are coincident with basic - ultrabasic belts (Figs 2B and C). The granulites are extremely varied in mineralogy and chemical composition. Ubiquitous brown hornblende in the metabasites indicates variable a_{H2O} during metamorphism. Both anhydrous and biotite-bearing granulites occur in the metasediments. The abundance of charnockites has been noted by several authors (e.g. Razafiniparany, 1969), who often refer to them as "basic charnockites". This is a poor term for classifying basic granulites, because it is ambiguous and presents no benefits. The term "charnockite" should be only applied to rocks where potassium feldspar comprises at least 1/3 of the leucocratic minerals (Streckeisen, 1967, Winkler,1979). On Madagascar, such charnockites occur in thin horizons (several metres thick) or in massifs (scale of several tens of km) and are associated with basic granulites (2 pyroxenes granulites ; Razafiniparany, 1969). These two rock-types may be contemporaneous, but do not seem to be co-genetic. Charnockites could have formed by crustal anatexis induced by the intrusion of the gabbroic rocks.

3. Very high temperature (VHT) metamorphism (≈1000°C) associated with mafic-ultramafic belts

North of the Bongolava - Ranotsara lineament is a vast complex of gabbros and ultrabasites which have a N-S alignment parallel to the tectonic fabric and extends for 800 km (Fig.2). Further to the west, the Andriamena and Maevatanana formations form two short belts.These magmatic rocks, occurring as lenticular masses on the square hectometre to kilometre scale, were emplaced under

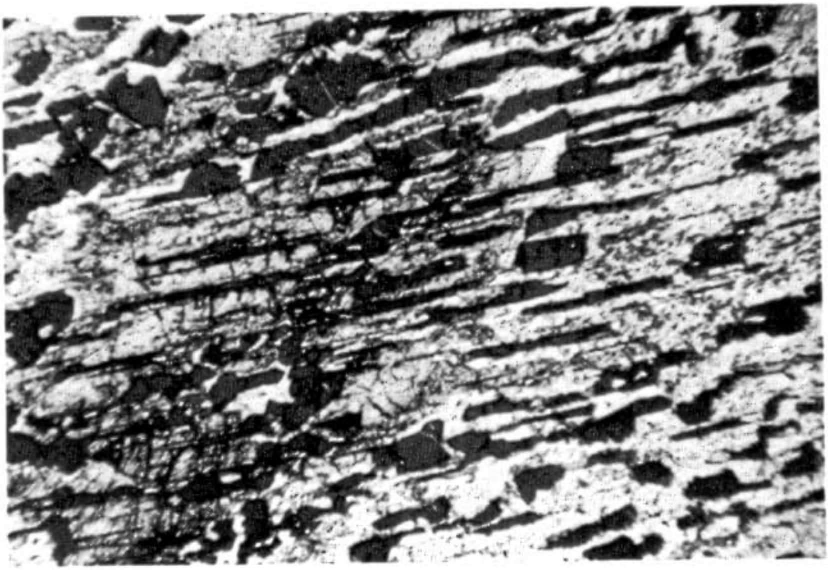

Figure 3. Garnet lamellae (dark) within primary Al-rich Opx. Nicols at an oblique angle ; field of view is approximately 2 mm.

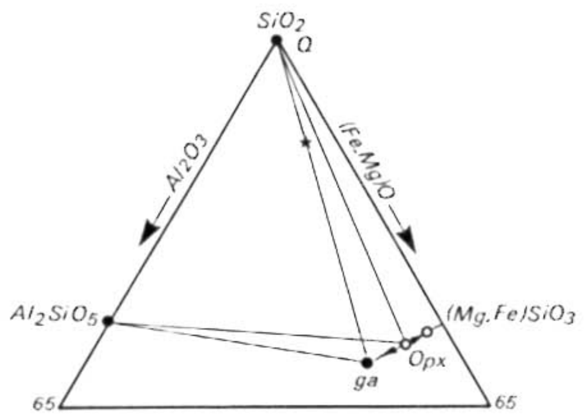

Figure 4. SiO_2 - Al_2O_3 - (Mg, Fe)O diagram showing the evolution of the composition of the Al-rich Opx according to the sliding reaction: Al-rich Opx = Al-poor Opx + Ga (lamellae). Tie lines connect the coexisting minerals of the primary paragenesis with Al-rich Opx - Ga - Q ± Sill. Tie lines cross because MgO and FeO are two independent components. Star: whole rock composition ; sample An4C.

upper amphibolite grade and intermediate granulite grade conditions (T ≈ 650°C, P ≈ 5.5 Kb). Despite these low temperatures, the metagabbros generally show granulite facies parageneses with two pyroxenes (± brown hornblende, ± biotite). Coronal garnet occurs in the most differentiated, Fe-rich rocks.

Ironstones, Opx-Sill granulites and orthoamphibole-cordierite granulites had sedimentary protoliths of late (?) Archean age. The iron formations are composed of quartz, magnetite, ferrohypersthene, ± grunerite, almandine-rich garnet. Opx-Sill granulites have unusual compositions which are neither like igneous rocks nor modern sediments : they are rich in Al and Si and poor in Ca and alkalis. They could represent ancient hydrothermally altered volcanics (e.g. Spear and Schumacher, 1982). On the other hand, as these rocks have undergone extreme metamorphism (see below), they could be residues after a high degree of partial fusion (40 - 50 % melting).

The Opx-Sill granulites show an extraordinary range in mineralogy which reflects the various stages of retrogression ; orthoamphibole - cordierite bearing rocks being the final stage which is also the most widespread. The initial paragenesis was : Q + Al-rich Opx + Ga + Sill + rutile and/or ilmenite + green spinel ± feldspar, ± graphite ± pyrite. According to the observations of Schreyer and Seifert (1967) in Norway, and Grew (1982) in Antarctica, fine complex aggregates of Opx_{II} + $Sill_{II}$ + Cord + Feld ± Bio and fine Kf + Cord + Q symplectites suggest that the primary paragenesis contained osumilite and/or sapphirine and/or cordierite (Nicollet, 1988). Centimetre size orthopyroxene with exsolution lamellae of garnet (Figure 3) is aluminum-rich, up to 10 wt % Al_2O_3 (Table I). The Al content of the re-composed primary pyroxene, using garnet exsolutions and host mineral compositions, reaches 13 wt%. The exsolution lamellae in pyroxene imply the following reaction :

$$RAl_2SiO_6 \,.\, 2\,R_2SiO_6 \leftrightarrow R_3Al_2Si_3O_{12} + R_2Si_2O_6 \qquad (1)$$
$$\text{Al-rich } Opx_{ss} \leftrightarrow Ga + Opx_{II}$$

where $R = Mg^{++}, Fe^{++}$ (Fig.4).

Application of the geothermobarometer based on this reaction (Harley and Green, 1982) indicates temperatures near 1000°C at a pressure of about 6 Kb (Nicollet, 1988). The fluid pressure was very low. The garnet lamellae are related to the decrease in temperature during isobaric retrogression, while the presence of only incipient reaction of garnet and quartz by :

$$Ga + Q \leftrightarrow \text{Al-poor } Opx + Cord \qquad (2)$$

indicates that only minor reduction in pressure occurred by the end of cooling (P,T,t path concave towards the T-axis). Element redistribution during isobaric cooling was such that conventional geothermometers and geobarometers only indicate final conditions, which are identical to those computed from the metabasites. However, the validity of these calibrations is questionable (Lasaga, 1983 ; Perkins, this volume). Evaluation of such high grade conditions at the peak of metamorphism is not possible by these geothermo-barometers, because of rapid cation diffusion at very high temperatures.

The degree of preservation of the highest grade parageneses is a function of the presence of water as dictated by the following retrograde reactions :

$$Opx + Q + H_2O \leftrightarrow Anth \qquad (3)$$
$$Ga + Q\ (\pm Feld) + H_2O \leftrightarrow Oamph + Cord\ (\pm Biot) \qquad (4)$$
$$Ga + Kf\ (+ Cord) + H_2O \leftrightarrow Sill + Bio + Q \qquad (5)$$

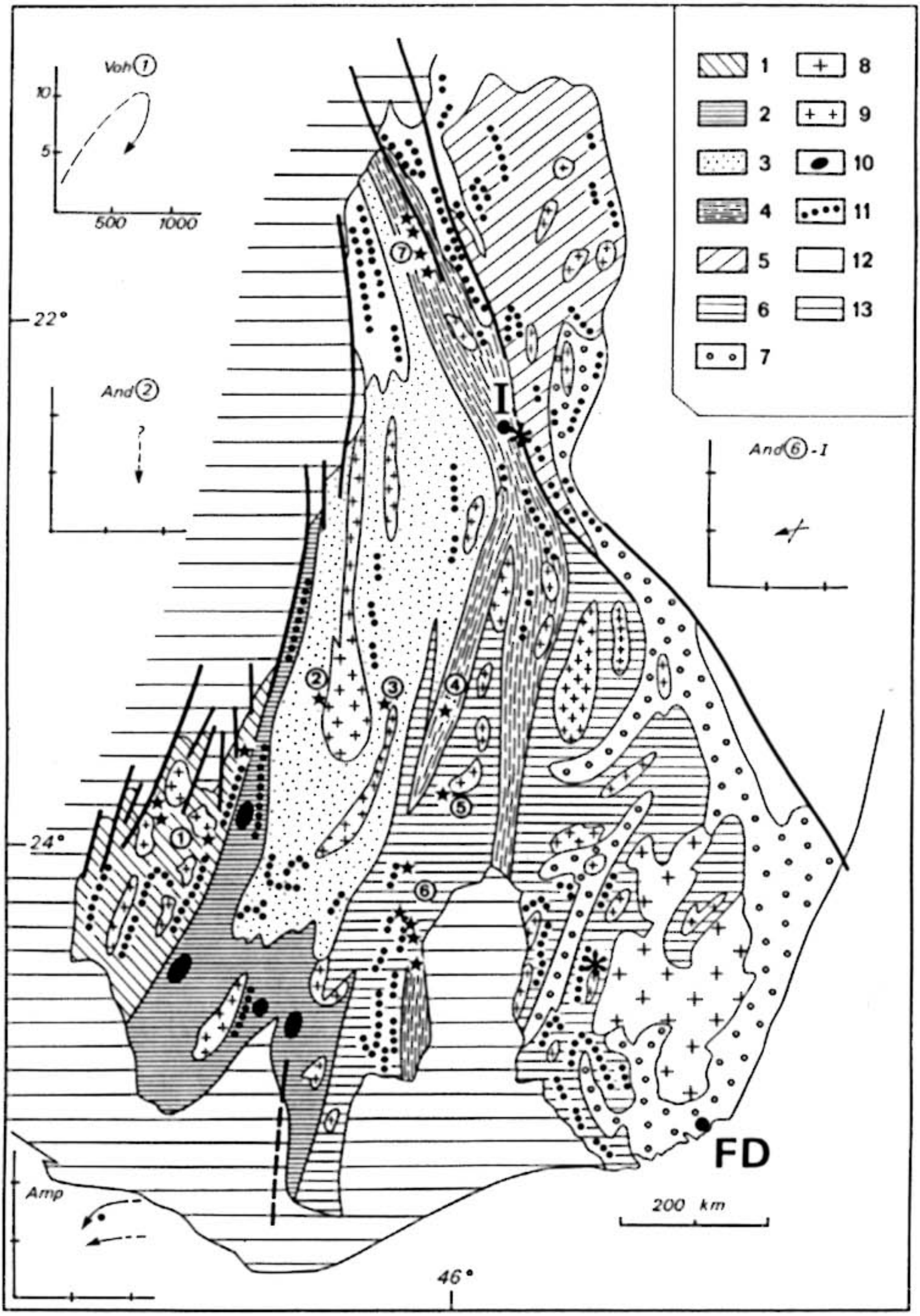

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Figure 5. Simplified geological map of the southern part of Madagascar and main petrographic types. **Vohibory group**: 1 - Vohibory formation: amphibolitic gneisses, amphibolites, marbles ; **Graphite group**: 2 - Ampanihy formation: graphite gneisses ; garnet - sillimanite leptynites, metabasic granulites ; **Androyan group**: 3 - Horombe formation: garnet leptynites (± cord and Sill) ; rare pyroxenites ; 4 - Ihosy formation: seven phase anatectic gneisses ; cordierite leptynites ; 5 - Tsitondroina formation: migmatites and leptynites ; 6 - Tranomaro formation: leptynites, banded cordierite bearing gneisses, marbles, scapolitic pyroxenites, scapolitites, charnockites ; 7 - Fort Dauphin formation: Cord and Ga leptynites and gneisses ; 8 - charnockites and granites ; 9 - granites and orthogneisses ; 10 - anorthosites ; 11 - marbles ; 12 - undifferentiated Precambrian ; 13 - Phanerozoic. I, FD: Towns of Ihosy and Fort Dauphin. **Stars: Sapph bearing rocks.** (1) Sapph - Co amphibolites of the Vohibory formation (Nicollet, 1986, 1988). (2) Korn - Sapph - gneisses from Ianakafy (Mégerlin, 1968 ; Von Knorring et al., 1969 ; Nicollet 1988) and (3) Itrongay (Lacroix, 1912) ; (4) "Sakénite" (= plagioclasite) and Sapph bearing schists from Vohidava (Brenon, 1953) ; (5) Cord - Sp - Sapph gneisses ; (6) idem around the locality of Ampandrandava (Brenon, 1953) ; (7) "Sakénite" and Sapph amphibolite in Sakény (Lacroix, 1929). (*): U-Pb data on granulites (560-565 Ma).

Hypothetical P-T paths of the granulites. Vohibory group (Voh 1): the conditions of the peak of metamorphism are obtained by the Sapph - amphibolites and Ser -, Clint - clinopyroxenites (outcrops: stars 1) using univariant curves ; the retrograde portion of the P-T path is estimated from Sill - Ga - Cord - Kf gneisses (thermometry: Ga - Biot, Ga - Cord ; barometry: Ga - Sill - Cord - Q) ; Graphite group - Ampanihy formation (Amp): near isobaric cooling of the anorthositic complex from high pressure (W of the formation) to intermediate pressure (E of the formation) , followed by decompression (see text for the thermo-barometric methods) ; point: graphite gneisses (thermometry: Ga - Biot ; barometry: Ga - Pl - Sill - Q) ; Androyan group - And 2: Korn-Sapph-Cord gneisses from Ianakafy (outcrop: star 2) using univariant curves ; And 6-I: arrow: Cord-Ga-Opx, Sp-Cord leptynites from the locality of Ampandrandava (stars 6) and segment: seven phase gneisses from Ihosy (I) (thermometry: Ga - Biot, Ga - Cord, Ga-Opx, Sp-Cord ; barometry: Ga - Pl - Sill - Q, Ga - Sill - Cord - Q, Sp - Ga - Sill - Q, Opx - Ga - Pl - Q)

The soda content of the orthoamphibole produced by reaction (4) is low, with less than 1%. The mineral is variable in composition from the Al-rich to the Al-poor end-members. According to Robinson et al (1971), this should be interpreted as exsolution (optically undetectable) of an end-member into the other.

The final stage of retrogression is represented by gneisses containing orthoamphiboles of variable composition , biotite, cordierite and garnet or quartz.

4. South of Madagascar : contrasting HP and IP granulitic belts

As noted previously, the south of Madagascar is divided into three groups : from west to east, these are the Vohibory, Graphite and Androyan groups. The lithologies of these groups are given in Figure 5. The granulites of the Androyan group have been the subject of many studies (Lacroix, 1922-1923, De la Roche, 1963 ; Noizet, 1969 ; Rakotondratsima, 1983). In fact, granulites occur in all three groups (Nicollet, 1983, 1986, 1988).

In the south of Madagascar, there is a continuous succession in metamorphic grade from lower greenschist and Barrovian type amphibolite facies in the Vohibory group to High Pressure (HP) and Intermediate Pressure (IP) granulite facies in the Graphite (Ampanihy formation) and Androyan groups, respectively. The granulites have a very large surface exposure. In this region, there are two distinct types of metabasites which are not co-genetic : green hornblende amphibolites and brown hornblende granulites. The amphibolites are magnesium-rich and are associated with serpentinites and metavolcanics. The granulites have $X_{MgO} \leq 70$ and are associated with anorthosite massifs (Nicollet, 1988).

4.1. SUPRACRUSTAL METABASIC GRANULITES AND RELATED ROCKS

4.1.1. Sapphirine and corundum bearing amphibolites

Amphibolites are characteristic of the Vohibory group. A supracrustal origin is indicated by the volcano-sedimentary character of some rocks (Besairie, 1970) and by the occurrence of pillow lavas (Raith, pers. com.). The amphibolites may contain green hornblende, anorthite, corundum, sapphirine or gedrite, green spinel, and sometimes garnet. The hornblende + corundum assemblage precludes gedrite + sapphirine in plagioclase-bearing rocks according to the reaction :

$$Hb + Co \leftrightarrow Gd + Sapph + Pl + H_2O \qquad (6)$$

The protoliths were leucotroctolites (Nicollet, 1985b, 1986). Metre size anorthosite veins associated with these rocks contain anorthite, corundum, garnet, sapphirine, Mg- and Cr-rich staurolite (X_{Mg} = 52, Cr_2O_3 = 0.8 - 2.2 wt % ; see Table I) ± hornblende and ± gedrite. The unusual occurrence of staurolite and sapphirine instead of gedrite + hornblende + corundum is due to the very low Na content of these rocks. The calculated P-T conditions of 9-11.5 Kb and 750-800°C, at the amphibolite-granulite facies transition, represent the peak of a Barrovian type event (Figs. 5 - Voh 1 and 9).

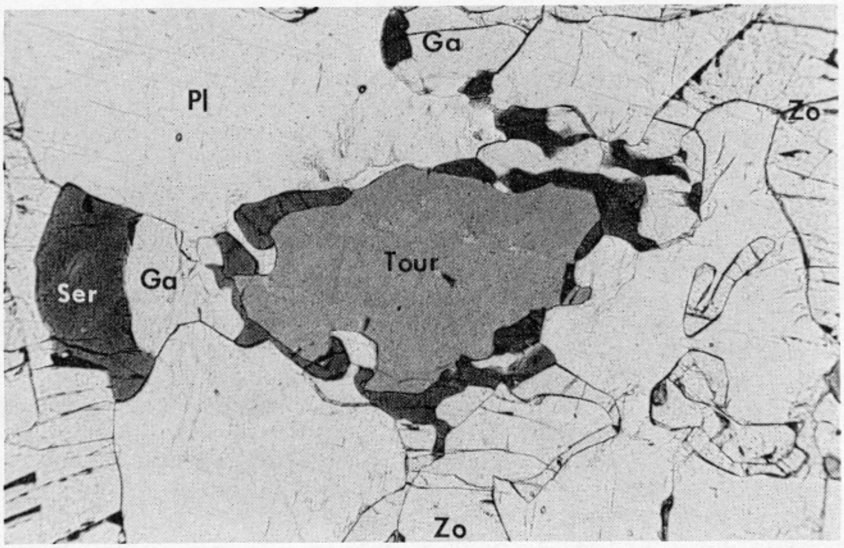


Figure 6. Serendibite around uvite-rich tourmaline in an anorthite, fassaite, Al-rich clinoamphibole, grossular-almandine, zoisite, clinozoisite calcsilicate gneiss interpreted as a metarodingite. Plane polarized light ; field of view is approximately 1 mm.

4.1.2. Gneisses with clintonite and serendibite

Calcsilicate gneisses are abundant in the South of Madagascar. In the SE, uranothorianite-bearing pyroxenites are interpreted as the products of the metamorphism of Mg-rich marls within an evaporitic series (Moine et al., 1985). In the Vohibory formation, clinopyroxenites containing fassaite, zoisite, green and brown spinel, Al-rich amphibole (up to 20 wt % Al_2O_3), ± grossular, ± anorthite, and ± carbonates are associated with the sapphirine-bearing amphibolites and the metatroctolites. The rare borosilicate, serendibite, which is associated with uvite-rich tourmaline (Fig. 6), and the brittle mica clintonite occur in these rocks (Table I). Source of boron is unknown. However, the low variance of the serendibite gneiss (see Fig.6) suggests isochemical metamorphism of a protolith metasomatized prior to the high grade metamorphism. These clinopyroxenites show strong Ca and variable Al enrichment and Na and Si depletion relative to their metatroctolite precursors. Their chemical composition is similar to that of rodingites. At the periphery of a serpentinite massif is a peridotite with abundant green spinel and an Al content too high for this body to have a magmatic origin. It may be a metamorphosed "chloritic blackwall" which typically occurs in between rodingites and serpentinites.

	Opx	GaL	Stl	Ser	Tour	Clint	Korn	Grd
SiO_2	48.46	39.24	27.90	19.83	34.28	16.01	30.54	20.56
TiO_2	0.05	0.03	1.00	0.38	0.75	0.20	0.24	0.02
Al_2O_3	9.63	22.28	53.80	37.18	33.92	45.94	42.27	51.96
FeO	20.66	30.30	9.10	14.75	6.51	1.37	3.77	7.17
MnO	-	0.25	-	0.06	0.05	0.02	-	0.15
MgO	20.15	8.85	5.40	7.65	8.21	18.92	18.03	9.81
CaO	0.07	0.30	-	15.38	3.77	12.99	0.06	-
Na_2O	-	0.02	-	0.15	0.92	0.01	0.07	-
K_2O	-	0.030	-	-	0.04	0.01	0.03	0.02
Total	99.02	101.29	99.40	95.39	88.45	95.99	95.00	89.69
Ox. Nb.	6	24	46	18.5	24.5	11	21.5	15
Si	1.801	5.997	7.531	2.506	5.511	1.118	3.947	2.006
Ti	0.001	0.003	0.020	0.036	0.091	0.011	0.023	0.002
Al	0.422	4.014	17.080	5.539	6.429	3.783	6.440	5.975
Fe^{2+}	0.642	3.873	2.040	1.559	0.875	0.080	0.408	0.585
Mn	-	0.032	-	0.006	0.015	0.001	-	0.012
Mg	1.117	2.016	2.190	1.441	1.967	1.970	3.473	1.426
Ca	0.003	0.049	-	2.083	0.649	0.972	0.008	-
Na	-	0.005	-	0.037	0.287	0.001	0.018	-
K	-	0.007	-	-	0.008	0.001	0.005	0.006
XMg	63	34	52	48	69	96	90	71

Table I. Selected analyses of unusual minerals in granulites from Madagascar. Opx: Al-rich orthopyroxene within an Opx-Sill-bearing aluminous granulite (Andriamena complex, Fig. 2 A) ; GaL: garnet lamella within the previous Opx ; Stl: Mg-Cr rich staurolite (Cr_2O_3 = 2,20 %) within a Co - Sapph - Stl - Gd - Sp anorthosite (Vohibory formation, see Fig. 5) ; Ser, Tour, Clint: Serendibite around tourmaline, clintonite (Cr_2O_3 = 0,52 %) within clinopyroxenites associated with Sapph - Co amphibolites. (Vohibory formation) ; Korn: Korn - Sapph - Cord - biotite gneisses (Ianakafy, Fig. 5) ; Grd: grandidierite in seven phase anatectic gneisses from Ihosy (Fig. 5). All iron as FeO.

4.2. THE GABBRO-ANORTHOSITIC COMPLEX

Granulitic metabasites are common components of the granulite terrain in the south of Madagascar. They contain Opx, Cpx, Pl, Ga, Hb (generally brown), Q, Bio, ilmenite and rarely graphite. Large massifs of anorthosites (from 25 km^2 to 100 km^2 ; Fig.5) in the Ampanihy formation consist of labradorite, Opx (with plagioclase lamellae), inverted pigeonite, olivine (in the Volovolo massif), ± Cpx, ± Hb, ± Ilm and ± Ga. Metatroctolites are orthocumulates with olivine (X_{Mg} = 40-75), labradorite, ilmenite, and green spinel as cumulus phases. Post cumulus Cpx, Opx, Hb, and Bio developed at a late stage, partially from subsolidus reactions. Sometimes olivine and plagioclase are separated by spectacular coronae of garnet with or without pyroxene symplectites (Nicollet, 1988).

Thirty different parageneses are apparent with 17 representative of the high (HP) and intermediate (IP) pressure hornblende granulite facies. The IP parageneses have a regional distribution while the HP parageneses are localized in the south-western part of the island. Many parageneses of both types are observable at the scale of several hectares due to the wide compositional range of these rocks (X_{MgO} from 9 to 73 and X_{Ab} from 6 to 64) and the multivariance of the isograd reactions. The diverse mineralogy permits the application of many geothermometers and geobarometers. A pressure range of 7 to 9 Kb is obtained (with a good intersection of the Ga-Cpx Fe-Mg exchange reaction and the Fe and Mg end-members of the Opx-Pl-Ga-Q geobarometer) for the granulites, anorthosites, and metatroctolites in the HP granulite facies zone. To the east, in the IP granulites, the pressure is estimated to be on the order of 5 Kb (Figs. 5 - Amp and 9). The P_{H2O} was roughly a third of total pressure and the f_{O2} was between the WM and QFM buffers. The rarity of graphite suggests that P_{CO2} was also very low (e.g. Lamb and Valley, 1984). However, these estimates are all very approximate to the extent that it is not known whether P_{fluid} was equal to or less than P_{total} (Nicollet, 1988).

The Cpx-Ga thermometer of Ellis and Green (1979) indicates temperatures of 710°-890°C (from mineral cores). This large temperature range is attributable to the appearance of garnet during cooling, in rocks of variable composition, at a pressure of 7 to 9 Kb. These are probably diffusion closure temperatures which explains the rarity of high calculated temperatures. In the presence of ilmenite, the Ti content of amphibole can be used to make a crude temperature estimate (Otten, 1984). Values between 1000° and 700°C trace the retrograde evolution of these rocks from late magmatic temperatures. This suggests that the gabbro-anorthosite complex was emplaced and cooled at between 15 km (in the east) and 30 km (in the west) where it acquired granulite parageneses. As noted by Percival (this volume), metamorphism is an integral component of crustal accretion and is impossible to separate from magmatic intraplating and underplating. Preliminary isotopic data (Rb-Sr, Nd-Sm) suggest that the anorthosite complex originated from partial melting of depleted mantle after 1.5 Ga (model ages of 1.0 Ga : Nicollet, 1988).

4.3. METASEDIMENTS

The parageneses of the metasediments (marbles, calcsilicate gneisses, leptynites, metapelites, etc.) indicate an increase in grade from west to east. Epizonal rocks and those with kyanite and muscovite are restricted to the extreme NW portion of the region, whereas sillimanite bearing rocks occur elsewhere. In the eastern portion of the Ampanihy formation and in the Androyan formations, ubiquitous cordierite confirms the elevated geothermal gradient that was suggested from the metabasites (Fig.9).

In the Ampanihy formation, the abundant gneisses and leptynites contain Q, Pl, Bio, Sill, Ga, and graphite. In the Ihosy formation (Androyan group, Figure 5), a widespread anatectic event produced migmatic gneisses with seven phases : Q, Kf, Pl, Ga, Cord, Sill, and Bio (with Sp included in the cordierite) and aluminous residues rich in biotite and sometimes containing sapphirine, kornerupine (Fig. 7), or grandidierite (Nicollet, 1985a, 1988, 1990). Monazite from a granodiorite vein produced by the anatectic event yielded a U-Pb age of 561 ± 12 Ma (Andriamarofahatra et al., 1989). This is identical to that obtained from a parapyroxenite (Figure 5 ; 565 ± 15 Ma ; Andriamarofahatra and de la Boisse, 1986). In the SE, the leptynites can contain

Figure 7. Corundum armoured by Sapph, and Sapph by kornerupine in a Pl (± Sill) matrix ; leucocratic lens in a phlogopite rich gneiss. Plane polarized light ; same scale as Fig. 3.

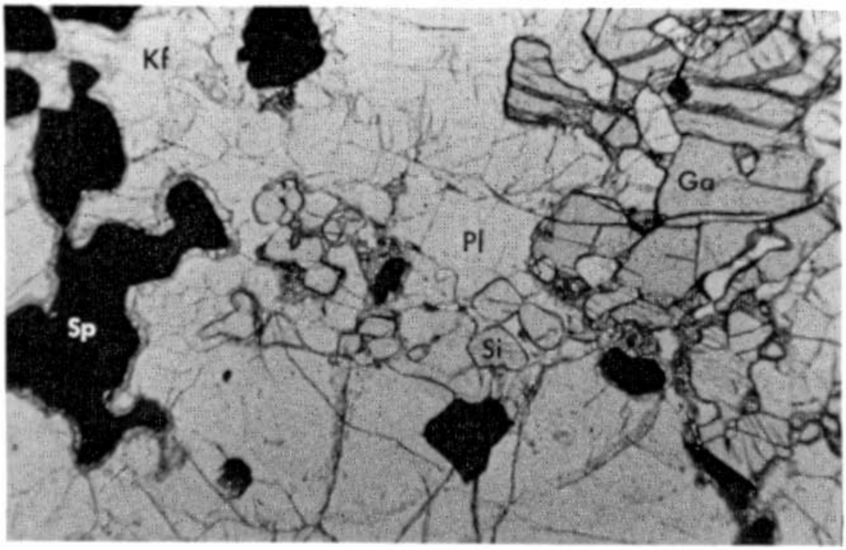
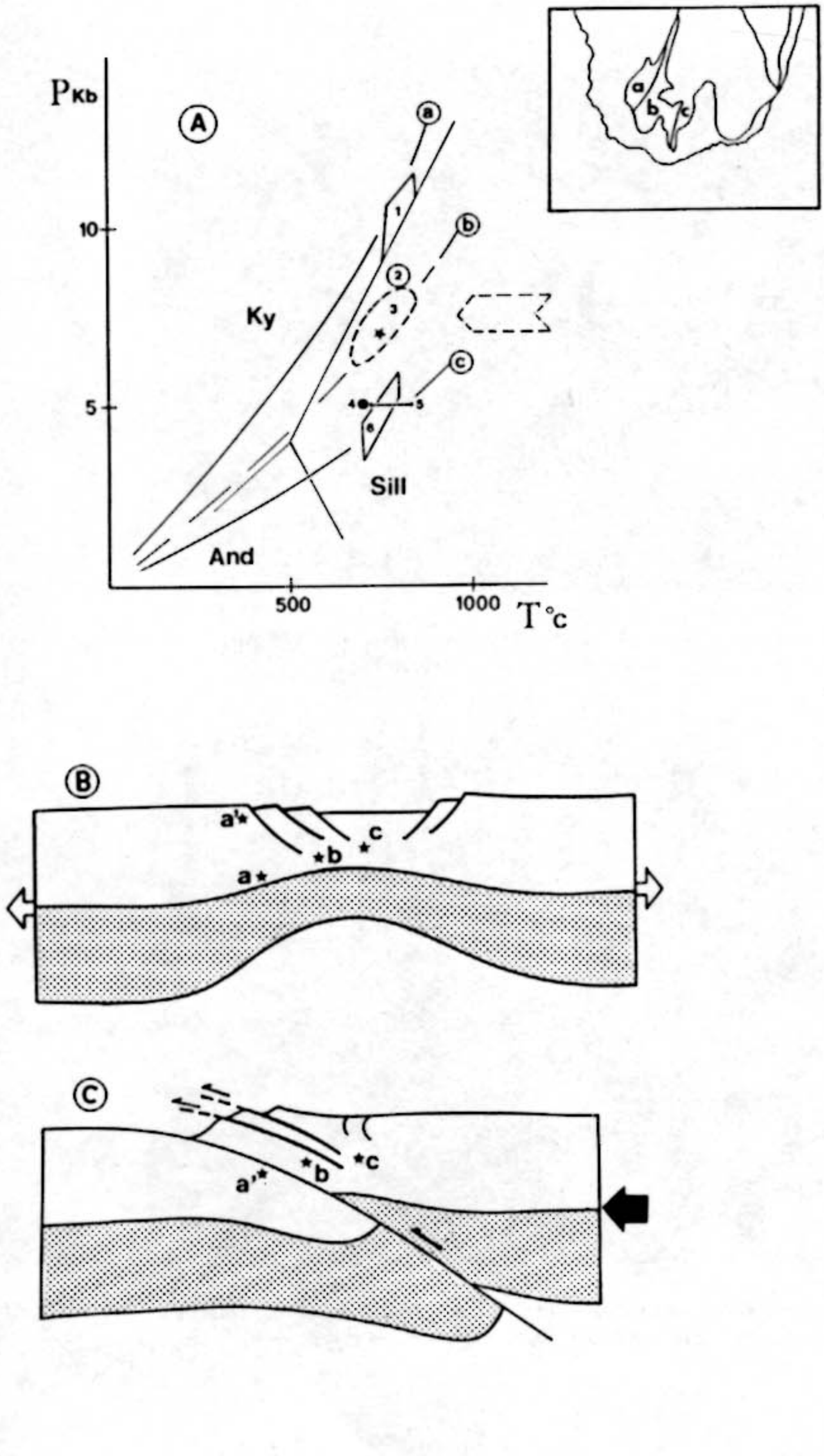


Figure 8. Green gahnite-poor spinel (black) rimmed by anhydrous Cord at the contact with Q. Sill, Ga, Kf, Pl are also visible ; leptynite. Plane polarized light ; same scale as Fig. 3.



P Kb
A
a
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1
2
3
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5
6
10
5
Ky
Sill
And
500
1000
T °c
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a'
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c

Figure 9. Crustal evolution model for the granulites in the Southern part of Madagascar:
• A - Review of the P - T estimates (see individual PT diagrams and thermo-barometric methods in Fig. 5): **a - Vohibory formation**: (1) - Sapph - Co bearing amphibolites and (2) serendibite or clintonite clinopyroxénites (conditions attained after a prograde clockwise PT path: Fig. 5 - Voh 1) ; **b - Ampanihy formation**: (3 and 4) - anorthosite complex (after isobaric cooling: arrow and Fig. 5 - Amp) and star: graphite bearing gneisses ; **c - Androyan formations**: (5) - Cord-Ga-Opx-, Sp-Q gneisses and leptynites ; (6): seven phase anatectic gneisses from Ihosy. a,b,c: geothermal gradients in the Vohibory, Ampanihy and Androyan formations. Kyanite-sillimanite transition after Holdaway (1971).
• B - Location of the three formations in the lower levels (a,b,c) or in the upper levels (a') of continental crust undergoing extension. The lower line separates lithosphere from asthenosphere. Upwelling of hotter asthenosphere causes the intrusion of the anorthosite complex and the high T granulitic metamorphism.
• C - Compressional stage bringing the upper level Vohibory formation (a' in B) under catazonal conditions. Granulites of the three formations may be exhumed at the end of this tectonic cycle.

quartz, mesoperthite, plagioclase, cordierite, garnet, sillimanite or Al-rich orthopyroxene (≈ 7 wt % Al_2O_3), green spinel, hibonite, rutile, and a little biotite. The high temperature gahnite-poor spinel - quartz (Fig.8) association is widely distributed in SE Madagascar. In fact, these rocks were mentioned by de la Roche (1963), Noizet (1969), Rakotondratsima (1983), Rakotondrazafy (1985) and Nicollet (1988). These leptynites occur in layers many metres thick and are intercalated with two pyroxene-Hb-Bio basic granulites and banded charnockites. The Sp-Q and the Al-rich Opx-Ga-Cord assemblages indicate temperatures of at least 850°C (at P ≈ 4-6 Kb), which are significantly above those calculated from conventional thermometry (≈ 700°C). A few mineralogical associations provide evidence of adiabatic decompression (Figs. 5 - Voh 1 and And 2 ; Ackermand et al., 1986 ; Nicollet, 1988) after the isobaric cooling of the gabbro-anorthosite complex.

5. Crustal thinning - magmatic intraplating - VHT metamorphism

In Madagascar, the granulites are intimately associated with the synmetamorphic emplacement of the magmatic complexes : anorthosite complexes in the south and basic-ultrabasic belts in the north. Isobaric cooling from very high temperatures followed by decompression (P-T-t path concave towards the T-axis) represents the final retrograde stage of metamorphism. Retrograde cooling can occur from a variety of tectonic conditions and processes (Bohlen, 1987; Ellis, 1987 ; Harley, 1989 ; Sandiford and Powell, 1986) : 1) at the end of a clockwise P-T-t path of lower crust thickened by continental collision ; 2) at the end of a counter-clockwise path of lower crust heated magmatically before and during tectonic loading , such as below a calk-alkaline arc ; 3) at the base of the crust during continental extension. The prograde portion of the trajectories is rarely preserved, but this part is essential for understanding the metamorphism. Also, the exhumation of granulites formed in these ways requires an additional tectonic event (indicated by decompression after isobaric cooling).

The absence of evidence for the prograde trajectory in the basic-ultrabasic belts of northern Madagascar precludes the choice of a particular hypothesis. However, at the estimated pressure of 6 Kb, the temperatures are too high for the granulites to have formed during isostatic uplift of a portion of lower crust thickened by continental collision. In addition, the basic-ultrabasic complex does not have the chemical character of a deep seated magma chamber related to a calc-alkaline arc, but it rather has an affinity with a continental stratiform complex (Nicollet, 1984 ; Bouladon, 1986). The very high-temperature, moderate-pressure metamorphism and the magmatism are probably the result of continental extension. Here, upwelling of hot asthenosphere is responsible for altering the geothermal gradient and provides the source of the intraplating or underplating intrusions. While these intrusions are not directly responsible for the VHT metamorphism, they probably facilitate the transfer of heat from the mantle to the crust. The decompression at the end of cooling coincides with the uplift which brought the granulites near to the surface. The overthrusting event associated with the formation of the low temperature Faratsiho eclogite (Nicollet, 1988, 1989) could have caused the exhumation.

An important conclusion that can be drawn from the rocks in southern Madagascar is that the two types of metabasites had different histories. The supracrustal amphibolites of the Vohibory formation certainly attained catazonal conditions during a prograde event that followed a clockwise trajectory in P-T space (Fig. 5 - Voh 1). In the Ampanihy formation, the gabbro-anorthosite complex was synmetamorphic and has a P-T-t path concave towards the T-axis with isobaric cooling followed by decompression (Fig. 5 - Amp). The emplacement of the anorthosite complex coincides with the increased geothermal gradient from west (where the gradient is normal) to the east (Fig. 9). Lithospheric extension is a possible explanation for the modified geotherm and crustal thinning. The anorogenic character of Proterozoic anorthosites is generally acknowledged (e.g. Morse, 1982 ; Emslie, 1985). The complexes would be associated with failed rifts during a period of slow plate motion (Windley, 1983).

A perpendicular traverse across a rift will show a similar variation in the geothermal gradient to that observed in southern Madagascar (Fig. 9). In the lower crust, the Vohibory formation (star a in Fig. 9B) would have been at or near the border of a distensive structure (with a normal or near normal geothermal gradient). The Androyan group would have been near the rift axis and the Ampanihy formation at an intermediate position (c and b respectively in Fig. 9B). The thermal anomaly related to lithospheric thinning would correspond to the formation of the anorthosite complex and its emplacement under granulite facies conditions. Uplift and exposure of these catazonal parts of the lower crust requires an additional tectonic event after the episode of distension.

This scenario assumes that the supracrustal rocks (in particular the sapphirine-bearing amphibolites and clinopyroxenites of the Vohibory group) were emplaced in the lower crust during an earlier event. However, it is equally possible that the rocks of the Vohibory group were situated in the upper crust at the edge of a distensive structure (a' in Fig. 9B). At the same time, the anorthosite complex was emplaced in the lower part of the crust, under granulite facies conditions, in the Ampanihy and Androyan formations (b and c in Fig. 9B). A subsequent compressive event led to thrusting along pre-existing fractures (Fig. 9C). While the anorthosite complex and the associated Ampanihy and Androyan formations cooled (PT diagrams : Amp and And 6-I in Fig. 5), the Vohiborian supracrustal rocks were transported to lower crustal depths where they were metamorphosed (Fig. 5 - Voh 1). Isostatic uplift of the thickened crust exposed these rocks in the same tectonic cycle and was responsible for the rare parageneses which provide evidence for the decompression (Fig. 5 - Voh 1 and And 2).

According to Shackleton (1986), the Mozambican mobile belt resulted from a succession of late Proterozoic continental plate collisions. The sutures, marked by ophiolites, should dip to the east. In such a tectonic environment, the distensive structures of Madagascar could represent basins formed by intracontinental back-arc extension which subsequently experienced compressive deformation during continental collision.

6. Conclusions

The following is a model of the tectonic evolution of the Malagasy portion of the Mozambican belt. Madagascar is composed of a core of Archean age rocks. Late Proterozoic tectono-metamorphic events largely obliterated any evidence of the Archean and early Proterozoic history of these rocks. Nevertheless, it is known that a metamorphic event at 2600 Ma probably reached granulite facies conditions. The Precambrian rocks and structures of Madagascar are essentially attributable to the Kibaran (?) - Pan-African megacycle. An episode of continental lithospheric extension accompanied the emplacement of the anorthosite complex in the south and the basic-ultrabasic magmatism in the north. The magmatism was associated with very high temperature metamorphism. This was followed by continental collision.

This model is a simplified view of the geological history of the Precambrian of Madagascar. As a matter of fact, it shows that there are many problems yet to be resolved in Madagascar where detailed studies are only just beginning. Madagascar is an excellent location for the study of very high temperature metamorphism which is undoubtedly one of the keys to understanding the mechanisms of intracrustal differentiation and also the origin of the lower crust (cf. Vielzeuf et al., this volume). To this end, a careful inventory and detailed studies must be made of large domains containing aluminous granulites. Geothermobarometric conventional approaches are incapable of properly assessing these extreme conditions. Osumilite- and sapphirine + quartz - bearing assemblages have not yet been found in Madagascar, but they are very likely to be present. How are these rocks able to reach such high temperatures without melting ? Are these essentially refractory residues ? What is the nature and exact origin of the associated basic complexes ? A firm understanding of the regional geology is necessary. There have been no structural studies and the geodynamic significance of the numerous granitoids remains uncertain. Chronologic data are sparse (Vachette, 1979 ; Andriamarofahatra and de la Boisse, 1986; Andriamarofahatra et al., 1989) : a geochronologic study is a top priority for future work.

The principal goal of this article is to report what is presently known about the granulites of Madagascar. The article also emphasizes that unresolved problems remain, and it is hoped that it will stimulate further work in Madagascar.

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