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Lithospheric shear zones and mantle–crust connections

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Abstract

A crustal-scale ductile shear zone network in the Precambrian granulite-facies crust of Madagascar is examined to determine the nature of the connections between the mantle and lower crust. Based on three independent data sets – field and satellite mapping, C- and O-isotope geochemistry and gravimetry – this crust is divided into three zones: (1) outside of shear zones; (2) minor shear zones that are <140 km long and 7 km wide; and (3) major shear zones that are >350 km long (up to 1000 km) and 20–35 km wide. The mantle is uplifted by about 10 km beneath the major shear zones. The major shear zones are rooted in and are inferred to be controlled by the mantle; they directly tapped mantle-derived CO_2. The small-scale minor shear zones were controlled by crustal processes and focused crustally derived H_2O-rich$\pm CO_2$ fluids. The regular distribution of the shear zones on a crustal scale is in agreement with models of buckling of the continental lithosphere in a compressional context. The propagation of these mechanical instabilities promoted and channelled fluid flow. These major Pan-African shear zones thinned the crust and were reactivated during the subsequent drifting of Madagascar and opening of the Indian Ocean during Jurassic to Cretaceous times. They also controlled many of the brittle fault zones in the overlying sedimentary basins. Mantle-rooted large-scale shear zones are inferred to be a general feature of cratonic areas reactivated by shear zone systems.

Keywords: lithosphere; shear zone; granulites; stable isotopes; gravimetry; fluid

1. Introduction

Deformation of the continental lithosphere is principally concentrated, at all scales, in networks of shear zones (Bak et al., 1975; Tapponier and Molnar, 1977; Carreras et al., 1980, and references therein; Caby et al., 1991). Brittle, brittle–ductile or ductile shear zones are known in various lithologies and structural levels (Ramsay, 1980) down to the upper mantle (Vissers et al., 1991). Shear zones are narrow, planar, sub-parallel-sided domains where strain was concentrated relative to their surrounding regions (Ramsay, 1980). Numerous investigations of their geometry and microstructures as well as finite and progressive shear strain and strain localization analyses have been carried out since the 1970s (e.g., Ramsay and Graham, 1970; Schmidt, 1982; Ramsay and Huber, 1983; Rutter and Brodie, 1988; Dutruge et al., 1995, and references therein). The termina-

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tion of shear zones, however, is poorly documented despite some efforts (Simpson, 1983; Ingles, 1986; Vauchez and Egydio da Silva, 1992). Also, little is known about the 3D geometry of shear zones and especially of the depth of their root zones. The root zone is considered to be deep when the outcrop length of vertical major shear zones is from a few hundred to a few thousand kilometres because of their narrow parallel-sided shape. Seismic reflection profiles offer a tool to investigate deep shear zones providing they are not too steeply dipping (Reston, 1990). However, proof is usually lacking that mantle reflectors detected under the seismic Moho in extensional basins are indeed shear zones, although mantle-hosted shear zones at the scale of 1 km have been studied in the field (Vissers et al., 1995).

The aim of this paper is to examine a large-scale outcropping shear zone network in the Madagascan Precambrian crust and to deduce whether it is probably rooted in the mantle. An attempt is made to give a 3D view of the geometry of these shear zones at the scale of the lithosphere. Integrated field investigations and satellite image analysis provide a surface view of the shear zones on a continental scale (Martelat et al., 1995). To address the problem of their vertical extent, we use two independent approaches:

(1) Stable isotope geochemistry is applied to infer the crustal or mantle source of the fluids from the root zone of these structures, since shear zones are known to act as preferred pathways for fluid circulation (Beach and Fyfe, 1972). Fluids in a shear zone with mantle roots should retain a mantle isotopic signature, at least for carbon.

(2) Gravimetric data provide an image of the shear zone geometry, and in particular around the level of the Moho, leading to a 3D picture of these structures at the scale of the lithosphere. Gravimetry can also reveal unmapped shear zones. This multidisciplinary approach illustrates the structural and geochemical connections between the mantle and the crust in major crustal shear zones that are rooted in the mantle, in contrast to minor shear zones which represent an internal crustally controlled deformation process.

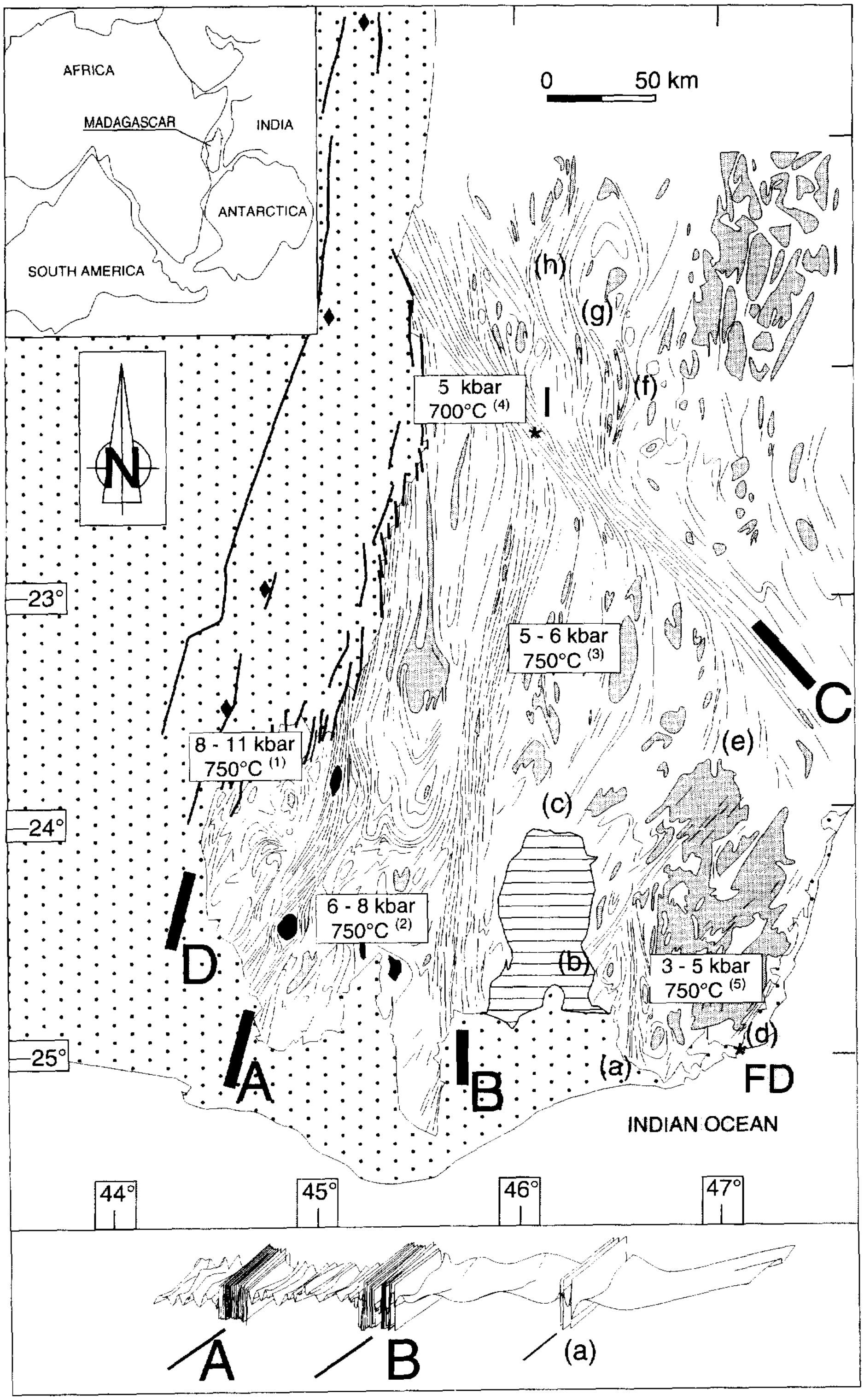
2. Geological setting

High-temperature and low-pressure granulites are well exposed throughout SE Madagascar (e.g., Nicollet, 1990). This granulite terrain is divided into a number of sub-terrains separated by shear zones that are hundreds of kilometres long by tens of kilometres wide, reflecting a crustal-scale strike-slip system (Martelat et al., 1995, 1997). The Madagascan Precambrian crust is considered to be the eastern front of the Mozambique belt (Kröner, 1977). It consists of Archaean and Proterozoic terranes reworked during the Pan-African event (530–630 Ma; Paquette et al., 1994). In southern Madagascar, various granulite-facies lithologies outcrop over 100,000 km^2. This metamorphism is related to post-orogenic extension with a general flat strain pattern (gently dipping foliation planes). Superimposed kilometre-scale folds and vertical ductile strike-slip shear zones have been mapped (Fig. 1) using remote sensing (Martelat et al., 1995), map compilation (Besairie, 1964, 1970) and detailed field studies. The transcurrent vertical shear zone network is superimposed upon the general granulite-facies flat strain pattern otherwise observed in Madagascar (see cross-section, Fig. 1). Shearing also occurred under granulitic conditions as marked by the sub-horizontal lineations of sapphirine, spinel–quartz and other characteristic mineral associations.

3. Shear zones network

Deformation is localized into both major (>350×20 km) and minor (50×5 up to 140×7 km) ductile shear zones. Fig. 1 presents the finite

Fig. 1. Simplified structural map and interpretative cross-section of SE Madagascar (modified after Martelat et al., 1995; and J.E. Martelat, pers commun., 1996). Light lines indicate the foliation plane directions. *A*, *B*, and *C* deformation corridors are three major shear zones. *D* is a poorly mapped shear zone that goes northward below the sedimentary basin as denoted by the distribution of the faults (heavy lines) and the location of the basement at the maximum depth −8000 m below the surface (grey diamonds; Besairie, 1964). Minor shear zones are referred to as (*a*) to (*h*). P–T data are compiled from *(1)* Nicollet (1990), *(2)* Martelat et al. (1997), *(3)* Ackermand et al. (1989), *(4)* Nicollet (1985), *(5)* Moine et al. (1985), A. Nédélec (pers. commun., 1996). Shaded areas, granites and charnockites; black areas, anorthosite bodies; dotted areas, sedimentary terranes; hatched areas, Androy Volcano. *I* = Ihosy; *FD* = Fort Dauphin.


AFRICA
MADAGASCAR
INDIA
ANTARCTICA
SOUTH AMERICA
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N
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(h)
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(f)
5 - 6 kbar
750°C (3)
C
8 - 11 kbar
750°C (1)
(e)
(c)
23°
24°
25°
6 - 8 kbar
750°C (2)
D
(b)
3 - 5 kbar
750°C (5)
(d)
(a)
FD
A
B
INDIAN OCEAN
44°
45°
46°
47°
A
B
(a)

strain pattern with the P–T data. Three major shear zones (A, B, C) and a dozen minor ones (a to h) can be recognized. The three major shear zones juxtapose blocks of different crustal levels due to their relative movements. This leads to an oblique cross-section through the lower to middle crust. At a rather constant temperature of around 750°C, pressure decreases from 11 to 8 kbar in the western compartment (Nicollet, 1990), to values as low as 5 to 3 kbar in the most southeastern part of the island (Moine et al., 1985; J.-E. Martelat, A. Nédélec, pers. commun., 1996). Granites are abundant in the relatively shallow eastern area whereas mantle-derived rocks such as anorthosites and metabasites are abundant in the deeper western area. The anorthositic bodies (black areas, Fig. 1) intruded the crust before or during the major strike-slip movements (Martelat et al., 1995). The shear zones are designated A for the Ampanihy shear zone, B for Beraketa, and C for Bongolova-Ranotsora shear zones. Shear zone A goes northward alongside a sedimentary basin and appears in this late structure through a fault network. D is a poorly mapped shear zone in a region of low satellite image recovery and basement outcrop but it goes northward below the sedimentary basin as shown by the distribution of the major faults and the deepest basement location points at −8000 m below surface (Besairie, 1964).

In the field, shear zones are characterized by nearly vertical (75–90°) foliation planes, sub-horizontal (0–15°) lineations and, in some cases, mylonitic textures. Direct control on the steeply dipping foliation planes in the major shear zones over a vertical scale of a few hundred metres was derived from observations of the topography, in quarries and in the phlogopite mines. Localization of strain in the shear zones cannot be explained by either lithologic heterogeneities between inside and outside of shear zones as inferred from the field and map observations or by temperature distribution heterogeneities (Fig. 1).

4. Geochemical evidence for fluid sources

Shear zones have long been shown as preferential fluid pathways (Beach and Fyfe, 1972). Fluids in a shear zone with mantle roots should retain a mantle isotopic signature, at least for carbon, because in contrast to oxygen, carbon is much less abundant in the crust and sparsely distributed. The isotopic signatures of carbonates from crustal and mantle reservoirs are well defined and contrasted. From a regional scale investigation of the C- and O-isotope compositions of carbonates from marbles and metabasites from both within and outside the shear zones, Pili et al. (1997) defined three distinct isotopic domains corresponding to contrasted composition and flow characteristics of fluids, which are summarized in Fig. 2. Outside both the major and minor shear zones, the isotopic compositions of marbles are indistinguishable from protolith values of the same age. These marbles, with no evidence for modification by externally derived circulating fluids and only minor isotopic variations caused by internal metamorphic devolatilization, were taken as the pre-shearing reference.

Inside the minor shear zones (Fig. 2), the oxygen isotope compositions of the marbles are shifted down to 11‰, a granitic or other sialic rock end-member. The carbon shows only little ^{13}C depletion associated with an increase of silicate content, resulting from devolatilization reactions promoted by infiltration of crustal H_2O-dominated fluids. The crystallization of abundant syntectonic migmatitic granites is the most possible source for the fluid. In contrast, inside the major shear zones (Fig. 2), a strong ^{13}C-depletion ascribed to mantle-derived carbon infiltration is observed. An extreme depletion down to $\delta^{13}C = -4.5$‰ is recorded by one wollastonite-bearing mylonite. No major O-isotope shift is detectable for all the samples, except the wollastonite-bearing one. The formation of wollastonite in this setting requires the infiltration of an H_2O-rich+CO_2 fluid where the oxygen was buffered by the crust but the $\delta^{13}C$ values were controlled by the mantle.

The metabasites (Fig. 2) are not considered to be the immediate source of the carbon within the major shear zones. Mantle-derived magmas are only a minor constituent of the Madagascan crust and they are roughly equally distributed within and outside of shear zones. The metabasites were a source of CO_2 with a mantle ^{13}C-signature in the directly associated skarns (clinopyroxenites), whether inside or outside of shear zones. However, these are only locally developed on a metre scale. They cannot account for

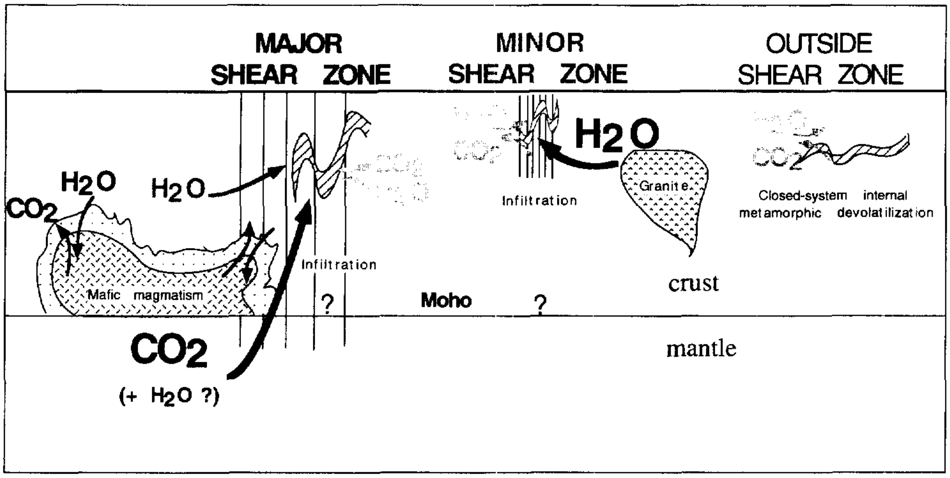

Fig. 2. Geochemical outline of the shear zones of Madagascar, after Pili et al. (1997). The wavy hatched structures represent a marble layer. Outside shear zones, marbles only record internal metamorphic devolatilization, which depends on the initial silicate-content of the limestone and hardly modifies their isotopic compositions. The minor shear zones only focus H_2O-rich and CO_2 fluids drained from the crust, from crystallizing synmetamorphic granites or internally produced by metamorphic reactions. Water infiltration enhances devolatilization of the marbles. In addition to crustal fluids, dominated by H_2O, the major shear zones focus $CO_2(\pm H_2O?)$ from the mantle. Mafic magmatism released CO_2 only locally and developed a corona of metasomatized rocks (clinopyroxenites) both outside and inside shear zones, and have been infiltrated by crustal H_2O. Metabasites are much more metasomatized inside than outside shear zones.

the continental-scale CO_2-bearing fluid focusing that occurred in the major shear zones. In the major shear zones, metabasites show isotope compositions slightly shifted towards those of the marbles. These shear zones define pathways where carbonate rocks and metabasites tends to homogenize via CO_2 circulation.

The mantle-like isotopic composition of calcite from hydrothermal veins associated with giant phlogopite deposits in major shear zones also emphasize that mantle-derived carbon circulated. There is no evidence for a regional pervasive CO_2 flux during granulite-facies metamorphism outside of the major shear zones in Madagascar. Large-scale C-isotope transfer into the crust is restricted to the major shear zones.

5. Gravimetric data

The gravimetric data have been selected in two different ways. About 20,000 gravity measurements have been obtained from the Bureau Gravimétrique International (BGI). Their distribution in space is shown in Fig. 3a. Over the ocean, free air anomalies derived from ERS1 satellite altimetry were computed on a 6×6 minute grid by Doin (1995). In order to emphasize the Moho structure below Madagascar, only Bouguer anomalies are considered. On land, the Bouguer reduction was performed by the BGI. On sea, the plateau correction with a density correction of (2.67–1.03) uses the topographic database ETOPO5 (NGDC, 1988). The complete data set is first averaged on a 15×15 minute grid, then interpolated with a 2D spline function. The computed map is in agreement with that published by Fourno and Roussel (1994) for the eastern part of Madagascar. As we are only interested in regional structures, we apply a bandpass filter that retains wavelengths in the range 80–200 km. To avoid side effects, wavelengths between 30–80 km and 200–600 km are cosine-tapered. Results are displayed in Fig. 3b.

Over the Mozambique Channel the major linear anomaly corresponds to the Davy Ridge along which Madagascar drifted away from Africa during the Jurassic (Coffin and Rabinowitz, 1988). Beyond the overall negative gravimetric anomalies of the Madagascan continental crust, some positive anomalies define more or less continuous bands trending roughly north–south. A large-amplitude positive anomaly crosses the continental margin along ca. 46°E longitude. This anomaly matches the location of the Androy Volcano and is part of the Marion

Fig. 3. (a) Gravity data distribution on land and location of the nine tracks used to stack the data. (b) Image of the Bouguer anomalies in mGal on the land of Madagascar (local measurements obtained from Bureau Gravimetrique International) and over the sea (corrected free air anomalies derived from satellite altimetry obtained from M.-P. Doin). The data are filtered in the range 80–200 km (see text). The dashed lines stand for the strike of the shear zones A, B and C (see Fig. 1). Dots are the anorthosite massifs.

hotspot track (Storey et al., 1995). The other striking anomaly is strictly restricted to the continental part of Madagascar. It matches the shear zone network defined from our structural map of southern Madagascar. In particular, shear zone A (Fig. 1) appears to coincide with a major gravimetric structure of the island. However, the gravity high seems to be continuous up to the northwest of the island which suggests that shear zone A extends across the whole island.

Although the data distribution on land is heterogeneous, we defined nine cross-sections perpendicular to the strike of the 'shear-zone-like' anomaly A where the data distribution is dense (Fig. 3a). Along each track we projected the data located within 0.5° apart and average them by means of a moving window with a resolution of 8 km (Fig. 4) Each track includes from 600 to 1600 data points. The nine tracks are depicted in Fig. 4a. They are centred across shear zone A so that point-to-point correlations can be made. Fig. 4b displays the same tracks as Fig. 4a on top of a geographical map of Madagascar. In addition to the gravimetric map (Fig. 3) which shows filtered data, Fig. 4 displays vertical cross-sections of rough data.

As the solution of the inverse gravimetric problem does not yield a unique solution we do not try to define a best-fit model of the shape of the Moho. We simply attempt to give a qualitative image of the Moho in relation to the shear zone distribution.

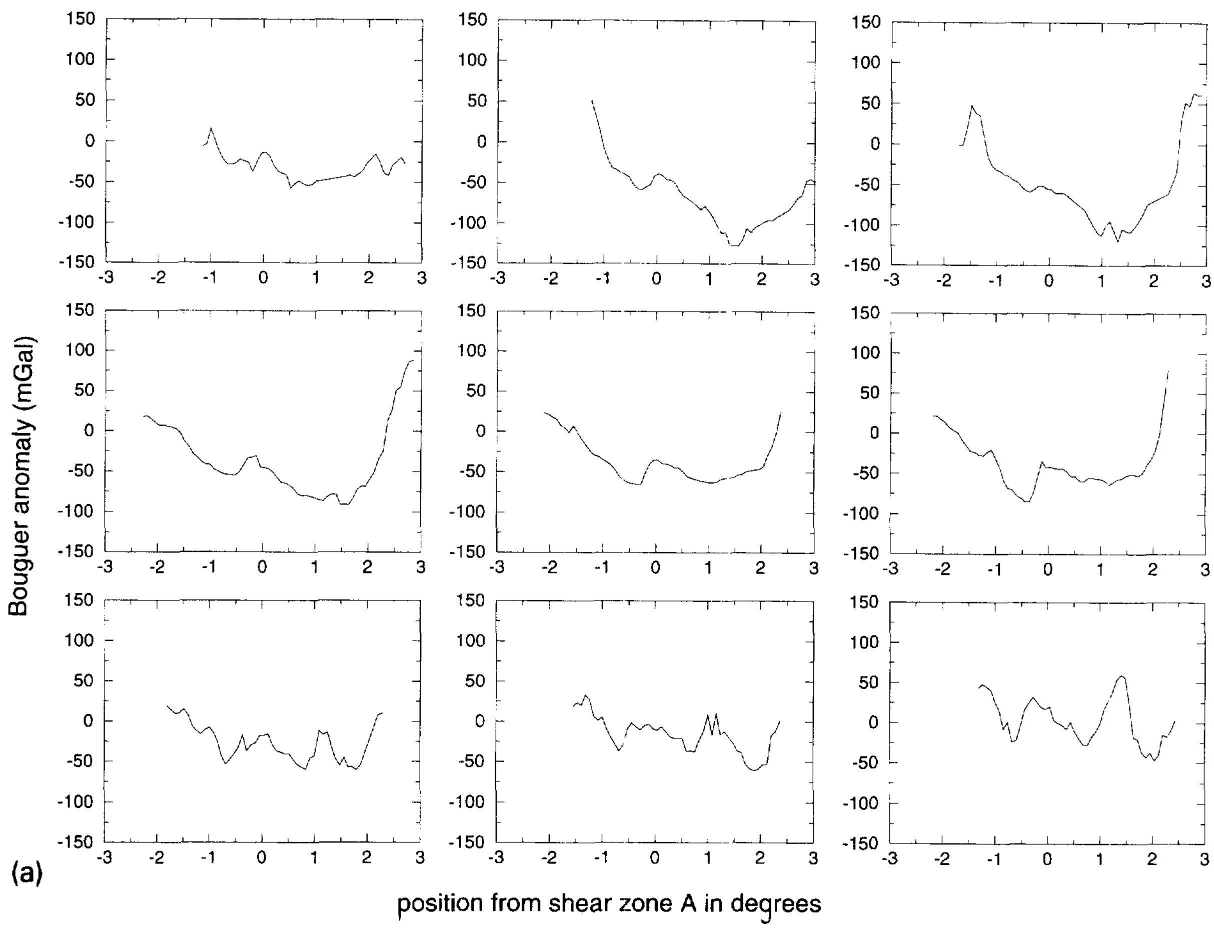

Fig. 4. (a) Stacks along nine tracks chosen to be perpendicular to the strike of the shear zone A from north to south (see Fig. 3a). Horizontal axis is the position along the track in degrees (1° ≈ 100 km). The origin is centred on the position of shear zone A. Vertical axis is the Bouguer anomaly amplitude in mGal.

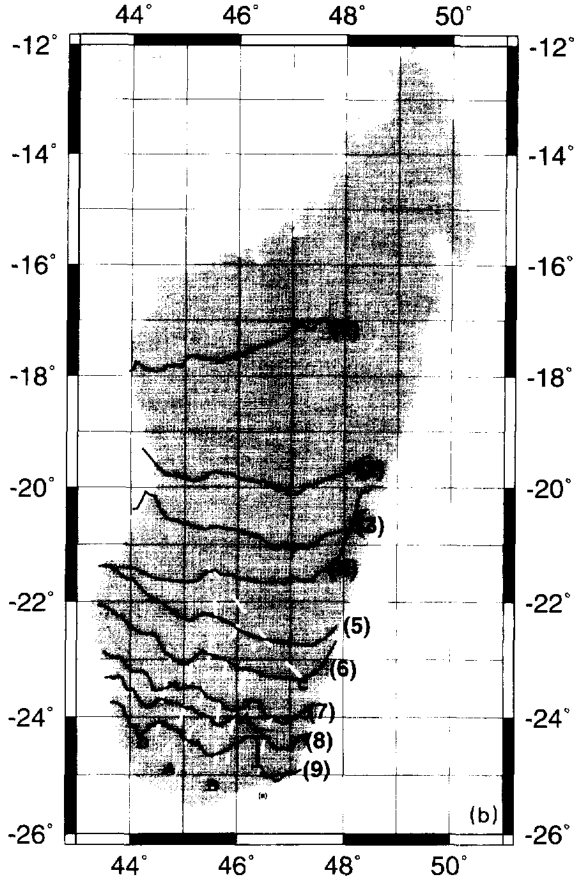

Fig. 4 continued. (b) Outline of the geographical distribution of the anomalies along the tracks and superimposition of the shear zone network.

Figs. 3 and 4 suggest that the Moho depth varies a lot below Madagascar. The positive Bouguer anomalies satisfactorily fit the shear zones network location and the volcanic area (Androy Volcano). The large north–south-trending anomaly seen in Fig. 3b fits shear zone A in southern Madagascar (Fig. 1, and Fig. 4a at 0° position in all tracks). Shear zone C is associated with a less conspicuous NW–SE anomaly that cuts the island from one coast to the other. Although not observed in Fig. 3b because of the filtering of shorter wavelengths, shear zone B is recorded by the data along tracks (Fig. 4a at 0.5° position). The poorly mapped shear zone D clearly appears in the westernmost positive anomaly (Fig. 3b, and Fig. 4a at $-1°$ position, especially in the southern tracks). The minor shear zones (a to h) do not provoke any reasonably detectable uplift of the Moho.

The Moho uplift under shear zones A and B (Fig. 1) is easily modelled either by a parallelepipedic volume or by two parallel cylinders of density $\rho_M - \rho_C$. These density anomalies are located at the average Moho depth, 35 km, (Fourno and Roussel, 1994) and are infinitely long along the shear zone strike. The computed anomalies are shown in Fig. 5. For the observed Bouguer anomaly variation of about 65 mGal under shear zones A and B, our simple model implies a Moho uplift of ca. 10 km (110 km wide box-model) or ca. 14 km (two cylinders 70 km apart).

The effects of a shear zone derived from our gravity analysis are summarized in Fig. 6. Areas of volcanic rock emplacement (e.g., Androy Volcano) are outside the scope of this paper. Positive Bouguer anomalies are due to an uplift of the Moho as illustrated in Fig. 6a, because mantle uplift represents an excess of mass in the crust. In contrast, a sedimentary basin represents a mass deficit and should be associated with negative anomalies unless isostatic compensation fully operates (McKenzie, 1978). The existence of positive Bouguer anomalies under the sedimentary basins thus may also result from a 'shear zone' effect that pulls the Moho up (Fig. 6b).

6. Discussion

6.1. Structural, geochemical and geophysical correlations

Three independent data sets — (1) *structural*, the field and satellite mapping of the shear and fault zone network (Fig. 1), (2) *geochemical*, the C- and O-isotope compositions of the marbles (Fig. 2), and (3) *geophysical*, the distribution of gravimetric anomalies (Fig. 3) — are all coherent with the division of the Madagascan crust into three zones: outside of shear zones, minor shear zones, and major shear zones. The major shear zones are geophysically and geochemically distinct from the minor shear zones.

The gravimetric anomalies that have been characterized are restricted to the continental limits of Madagascar. This means that they describe *pre-drift* continental tectonic features. They are not related to the Marion hotspot that ran alongside the eastern

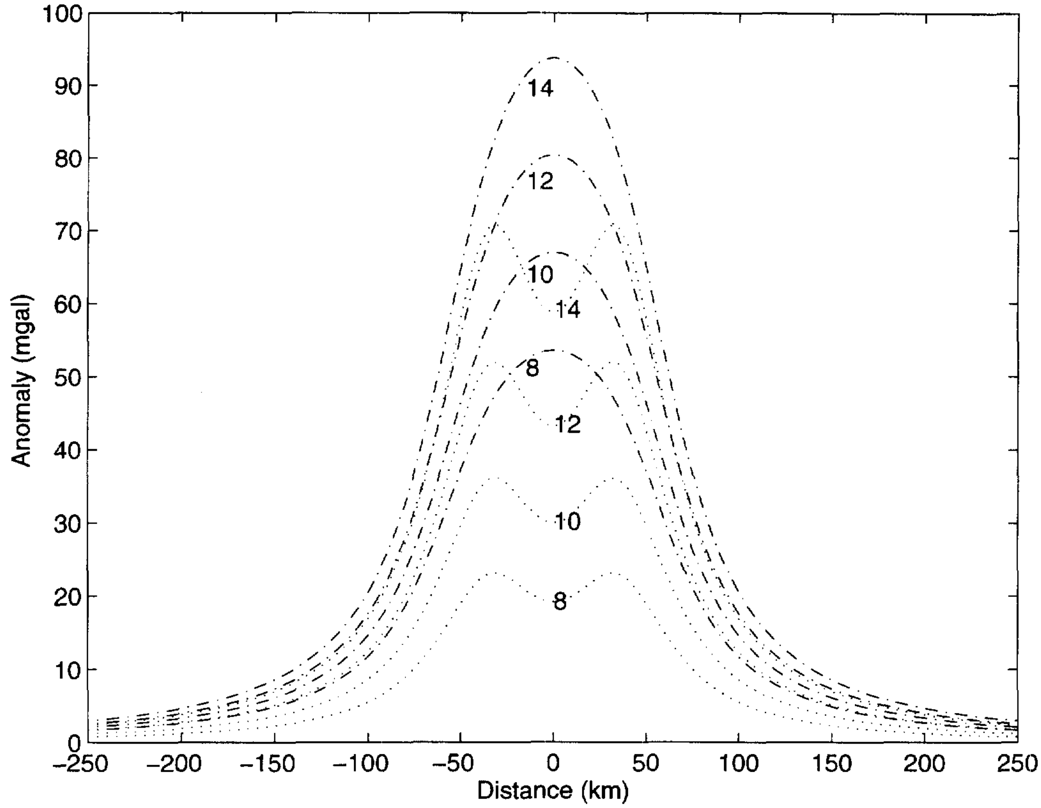

Fig. 5. A simple model of the two shear zones A and B (Figs. 1 and 4). Calculated anomalies (mGal) yield a Moho uplift with the shape of either two parallel infinitely long cylinders (dotted curve) or a parallelepipedic volume (dash–dotted curve). The Moho depth is 35 km, the diameter of the two cylinders as well as the height of the box-like anomaly varies from 8 to 14 km. The two cylinders are 70 km apart, the box width is 110 km.

coast of the island from 120 to 88 Ma (Storey et al., 1995) and yielded anomalies that cross the continent–ocean boundary (Fig. 4). The cartographically defined major shear or fault zones A, B, C and D, match the positive Bouguer anomalies (Figs. 3 and 4). The calculated uplifts of the Moho under the two shear zones A and B are of about 10 km (Fig. 5). Correlations between a large-scale shear zone network and the distribution of Bouguer anomalies have been previously described in the literature (Lambeck, 1983), but they were interpreted in terms of lithospheric buckling and not as reflecting mantle-rooted shear zones (Lambeck et al., 1988).

6.2. Madagascan shear zone network

Starting from the initial cartographic, field and remote sensing image of the shear zones (Fig. 1), the analysis of the gravimetric data has advanced our knowledge of the shear zone network in three important ways. Firstly, the real present-day lengths of the major shear zones are longer than the classic measurements from a structural map. Secondly, certain shear zones are shown to be major ones. For example, although shear zone D is poorly defined from both satellite images and basement outcrop, it must be an additional major shear zone, 25 km wide by 350 km long with its strike parallel to A and B. Its northern end is also covered by the deep western sedimentary basin of Madagascar. Thirdly, certain surface features are probably related to deep shear zone structures. The striking linearity of the east coast of Madagascar is probably controlled by a major shear zone. This coastline is parallel to shear zones A, B and D (Fig. 1). By itself, the gravimetric signature associated with a shear zone cannot be

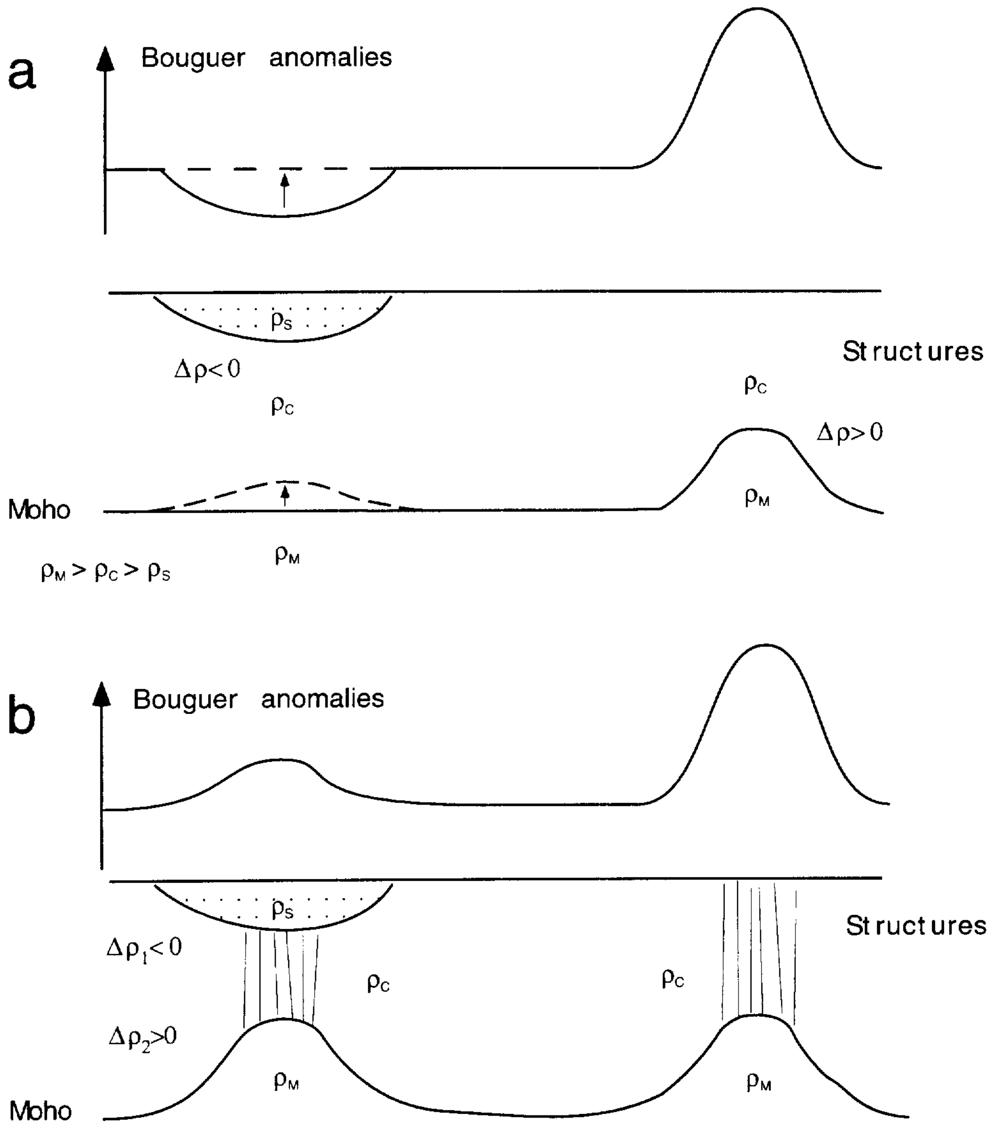

Fig. 6. Gravimetric 'shear zone effect' and shape of the Bouguer anomalies along a synthetic lithospheric cross-section: (a) positive Bouguer anomaly due to uplift of the Moho and normal negative anomaly over a sedimentary basin (dotted area); (b) positive Bouguer anomaly over a sedimentary basin that conceals a major shear zone. ρ_M, ρ_C and ρ_S stand for the densities of the mantle, crust and sediments, respectively. The vertical lines illustrate a shear zone. See text for discussion.

readily separated from that related to the thinning of the crust towards the ocean and presence of basalts. However, the distribution of the Cretaceous basalts on both the western and eastern sides of Madagascar, that are related to the Marion hotspot (see fig. 1 in Mahoney and Nicollet, 1991; Storey et al., 1995) does not fit the positive Bouguer anomalies on the western coast but it does on the eastern one. This suggests that the Bouguer anomaly along the eastern coast reflects, at least in part, the major shear zone structure. This also implies that the western coast which is not rectilinear and does not display 'shear-zone-like' gravimetric anomalies despite the presence of similar volcanic rocks as on the eastern coast is unrelated to a hidden shear zone. The Madagascar–India breakup was initiated with strike-slip faulting (Dyment, 1991), which is consistent with the dynamics of the shear zone network. The linear east coast major shear zone that was a thinner and thus a weaker zone in the lithosphere, was more easily cut when passing over the Marion hotspot. This pre-existing lithospheric weakness probably controlled the breakup of Madagascar from India (Dunbar and Sawyer, 1989; Vissers et al., 1995).

The post-Jurassic tectonics of Madagascar reactivated the major Pan-African structures. The faults related to shear zones A and D cut Jurassic to Cretaceous sediments in the western sedimentary basin, and the opening of the Indian Ocean reactivated the presumed coastal shear zone.

6.3. Shear zones geometry

Little is known about the relationships between length, width and depth of shear zones in general, although width–time (Means, 1984) and width–displacement (Hull, 1988) relations have been established. In Fig. 7 the width of the shear zones is plotted against their length in km. Measurements were made from SPOT satellite images and the structural, geological, and gravimetric maps. The directly observed lengths of the major shear zones are minimum values as the 'ends' of these structures may be either covered by sedimentary deposits or truncated by the subsequently formed Indian Ocean and Mozambique Channel during Cretaceous and Jurassic times, respectively (Coffin and Rabinowitz, 1988; Scotese et al., 1988). Although the gravimetrically determined shear zone lengths are longer, these may also be truncated by the continental boundaries. Two sets of length data have been determined for the major shear zones. One contains the apparent lengths measured from our structural maps, and is biased because of the lack of outcrop. The other contains the gravimetrically determined lengths and may be biased because of the oceans. The strong elongation of rocks and parallelism of the foliation planes within the shear zones allow their widths to be directly measured on the satellite images with some certainty (Martelat et al., 1995). The minor shear zones, which are not detected by the gravimetry, provide only one set of length measurements. The width of the shear zones is reported versus their length in Fig. 7. The revised lengths of the major shear zones derived from the gravimetric data are larger and appears clearly. The minor shear zones do not exceed 150 km long and 7 km wide, whereas the four major shear zones are more than 350 km long and 20 km wide. The mi-

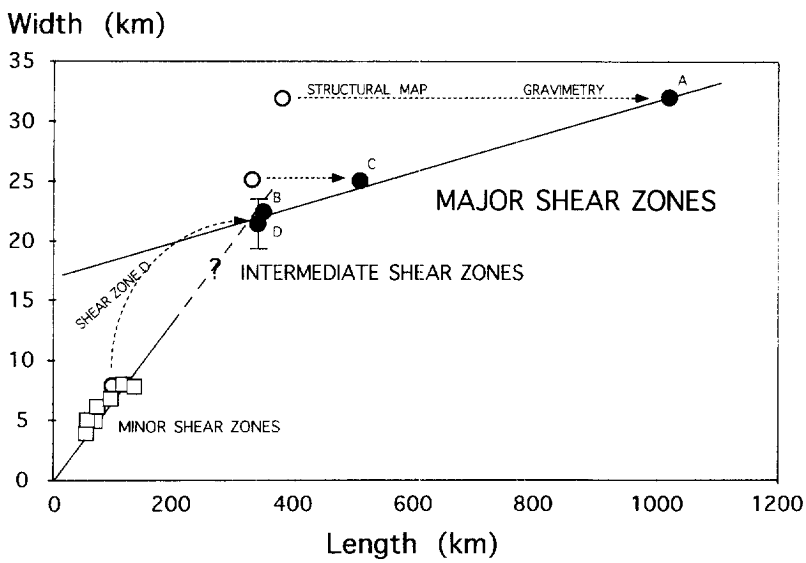

Fig. 7. Plot of the width of the shear zones versus their length (both in km). Length is only apparent, in particular for the major shear zones, insofar as these structures may be covered by sedimentary deposits or truncated by the coast. Note one group for major shear zones – circles are derived from the structural map (Fig. 1) and dots from the gravimetric analysis – and another for minor shear zones (squares). See text for discussion of intermediate shear zones.

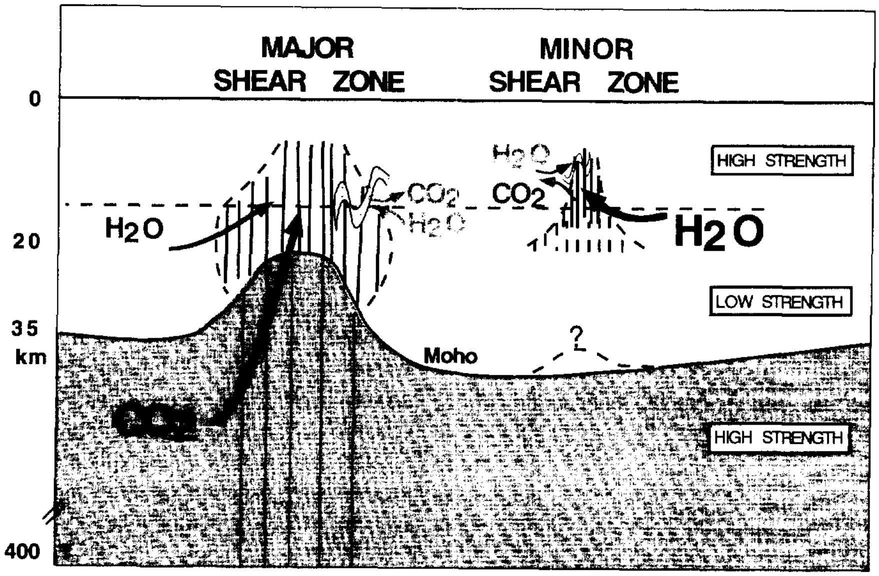

Fig. 8. Tectonic setting, structural and geochemical outlines of the shear zones of Madagascar. The major shear zones are rooted in the high-strength upper mantle, raise the depth of the Moho, probably widen in the low-strength lower crust and narrow in the high-strength upper crust. These major shear zones focus $CO_2 \pm H_2O$ from the mantle, and H_2O from the crust $\pm CO_2$ from marbles. The minor shear zones are solely rooted in the crust and only focus H_2O-rich and CO_2 fluids drained from the crust or produced internally. See Fig. 2 for details.

nor shear zones have a length/width ratio of about 17 that passes through the origin; the less well defined length/width ratio for the major shear zones is about 60 (for a width of about 20 km at zero). The major shear zones A and C may be even longer (1000 km or more?) because they coincide with equivalent structures in Kenya, which was close to Madagascar before it drifted. Thus, their L/W ratio may be much higher. In contrast, shear zones C and D do not seem to be much longer and may be named 'intermediate shear zones'. They have an equivalent L/W ratio to that of the minor shear zones (Fig. 7).

Distinct L/W ratios for the major and minor shear zones (Fig. 7) argues for different deformation processes. Thus we infer that the major shear zones were not derived from the minor ones as the simple result of a single growth process. In contrast, the intermediate shear zones may result from the growth of the minor ones. As depicted in Fig. 8, the minor shear zones, up to 150 km long and 7 km wide, collected only crustal H_2O-dominated fluids (Fig. 2) and do not affect the depth of the Moho (Figs. 3 and 4). We infer that these structures are rooted solely and entirely within the crust. In the case of major (and intermediate) shear zones, whose dimensions are more than 350×20 km, two independent sets of data indicate that they reach the Moho. First, they collected CO_2 directly derived from the mantle. Second, they decreased the depth of the Moho. This implies that the major shear zones are rooted in the mantle and represent lithospheric-scale structures (Fig. 8).

Since the thickness of the crust is inferred to be around 33 km in the southeast of Madagascar (Fourno and Roussel, 1994), the vertical dimension of the mantle-rooted major shear zones is at least of that magnitude. Their length and width dimensions are at least 1000 km long by 30 km wide. Since shear zones are planar structures, and because it seems legitimate to extrapolate these observations to lithospheric shear zones (Tsalenko, 1970), the real vertical dimension is probably much greater, around one order of magnitude greater than their width. Pavlenkova (1995), based on tomographic results, suggests that the main features of the continents have roots down to a depth of about 400 km.

6.4. *Organization of the shear zone network*

The proposed shear zone network shows four major shear zones (A, B, C, D) parallel to the rectilinear

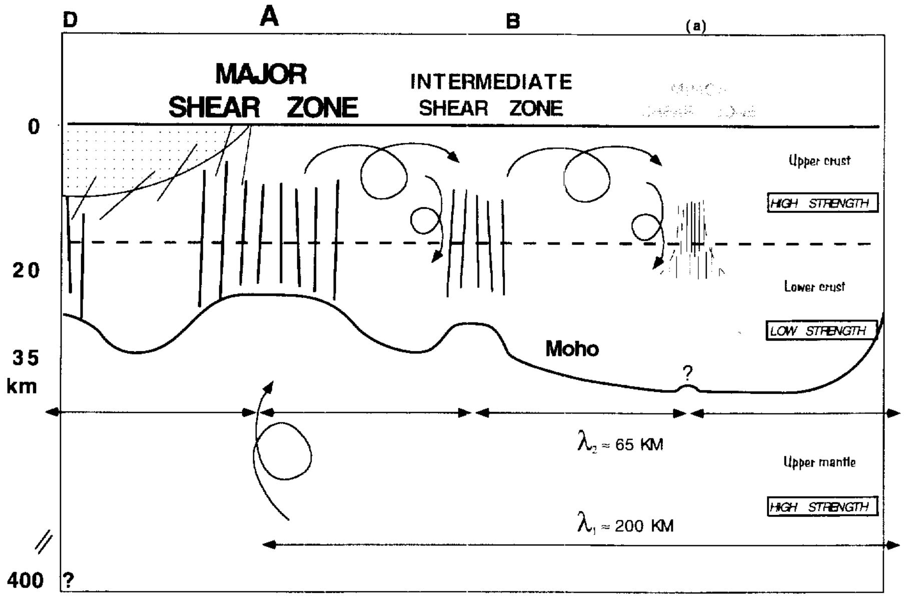

Fig. 9. Proposed mechanical distribution and evolution of the shear zones of Madagascar. Curved arrows stand for mechanical instabilities that give rise to the shear zones, with a wavelength of $\lambda_1 \approx 200$ km for those controlled by the upper mantle (major shear zones) and $\lambda_2 \approx 65$ km for those intrinsically developed within the upper crust (intermediate and minor shear zones). The propagating instabilities probably promote fluid transfer (see Fig. 8). The dotted area represents a sedimentary basin and the vertical lines the shear zones.

eastern coast that probably reflects another shear zone. The distance between shear zones D and A, and A and B (Fig. 1) is about 70 km. This inter-distance is also observed between the shear zones B and (a), and (a) and the eastern coast. Shear zone (a) is a minor shear zone, according to our structural and geochemical definitions and no significant variation of the Moho depth has been detected below it. However, this striking regularity of the shear zone distribution in space is reminiscent of the periodicity of some lithospheric extensional (boudinage) (Ricard and Froidevaux, 1986) or compressional (buckling) (Martinod, 1991) deformation models of the lithosphere. In the latter case, which is appropriate for our strike-slip system, two deformation mechanisms compete with long wavelengths (150–300 km), caused by a mantle plastic layer, and short ones (40–60 km) due to the intrinsic buckling of the upper crust (Martinod, 1991). The fact that the strain localization in the shear zones cannot be explained by either lithologic or thermal heterogeneities between inside and outside shear zones implies that the shearing process is controlled by the mantle. We propose a model (Fig. 9) of the evolution of the shear zones from a mechanical point of view. A major shear zone (e.g., shear zone A) initiated in the mantle and controlled the large-scale deformation of the crust with a wavelength $\lambda_1 = 200$ km. The instability is propagated in the upper crust, which reacts with its own wavelength ($\lambda_2 = 60$ km), and is responsible for the nucleation of minor shear zones (e.g., minor shear zone (a)), that initially are entirely located in the crust. These widen and grow downward until they pull up the Moho (i.e. intermediate shear zones B and D). Shear zone C is thought to be equivalent to shear zone A. The propagation of the mechanical instabilities is inferred to promote the transfer of fluids from the mantle to the crust and within the crust (compare Figs. 8 and 9).

7. Conclusion

This paper attempts to characterize the third dimension of an observed large-scale crustal shear zones network. Lithospheric structures have been defined in Madagascar by combining the results of structural geology, stable isotope geochemistry and gravimetry. These Pan-African thinned zones have been reactivated during the subsequent major tectonic events.

The differences in scales between shear zones in Madagascar are associated with both differences in shearing process and fluid flow. The large-scale deformation of the crust results from the development of mantle-rooted shear zones. This deformation is controlled by the probably high-strength upper mantle and is associated with mantle-derived $CO_2 \pm H_2O$ plus crustal H_2O drained into the major shear zones. The small-scale internally controlled deformation of the crust is associated with internally derived H_2O-rich$\pm CO_2$ fluids in the minor shear zones. Mantle-rooted large-scale shear zones may be a rather general feature insofar as correlations of gravimetric anomalies with well known shear zones network have been reported in the literature from other continents. These authors have only interpreted the larger wavelengths of such variations which do not resolve the mantle–crust connections (e.g., Lambeck, 1983; Lambeck et al., 1988; Collins and Teyssier, 1989, for the granulitic crustal-scale Arunta Inlier in Central Australia; Poudjom Djomani et al., 1995, for the 2000-km-long Central African Shear Zone).

The combined effects of H_2O and CO_2 on deformation mechanisms are still unknown. At the lithospheric scale, the fact that deformation precedes and triggers infiltration that sustains in turn deformation is the most plausible scenario. The propagation of mechanical instabilities probably promotes fluid transfer (Figs. 8 and 9).

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