GEOCHRONOLOGY AND GEOCHEMISTRY OF CRETACEOUS AND CENOZOIC VOLCANIC ROCKS IN THE NORTHERN MADAGASCAR

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INTRODUCTION

The island of Madagascar is located in the Indian Ocean off the southeast coast of Africa opposite Mozambique. Paleogeographical reconstructions indicate that Madagascar was an integral part of the Gondwana supercontinent at the end of Proterozoic.

The central and eastern parts of Madagascar are mainly composed of Archean and Proterozoic rocks, which were partially reworked during the Pan-African orogeny. Based on lithotectonic and isotopic evidence, the central and northern part of island is subdivided into five distinct tectonic units (Collins *et al*., 2000; Fig. 1a): The Antongil Block (1) consists of a granitic and gneiss core, semi-encircled by a series of metasediments. The Antananarivo Block (2) is the dominant unit of central Madagascar. It consists of Late Archean granitoids, interlayered with Late Proterozoic granites, syenites and gabbros (Tucker *et al*., 1999). The Tsaratanana Unit (3) is composed of mafic gneiss, tonalites, podiform chromite-bearing ultrabasic rocks and pelites that have been metamorphosed to ultra-high temperatures (Nicollet, 1990). The Bemarivo Orogenic Belt (4) is composed of paragneiss, orthogneiss, granites, quarzites and schists (Collins *et al*., 2001). The Itremo Sheet (5) consists of a metasedimentary sequence (Cox *et al*., 1998) of dolomitic marble, quarzites, pelites and metasiltstones.

Extension and rifting between the East Gondwana (Madagascar, India/Seychelles Antarctica and Australia) and West Gondwana (Africa, Arabia and South America) started during the Permo-Triassic. Available geophysical data (Coffin *et al*., 1988) indicate that sea floor spreading between the conjugate-rifted margins of southern Somalia, Kenya and Tanzania (Western Somali basin) and northern Madagascar was initiated by Late Jurassic (~ 165 Ma). The opening of Somali basin and Mozambique channel was accompanied by the traslation of Madagascar along north-south trending transform fault (Davie Ridge). Crustal extension between Madagascar and Africa determined the formation of three sedimentary basins in western Madagascar: Morondava, Mahajanga and Diego basins.

During the Late Cretaceous, Madagascar was affected by widespread magmatic activity. The igneous rocks crop out along the rifted margin of eastern coast, in the Mahajanga and Morondava basins and directly above the Precambrian basement (Storey *et al*., 1995, 1997; Melluso *et al*., 1997, 2001, 2002, 2003, 2005, 2007, 2009; Mahoney *et al*., 1991, 2008; Fig. 1b). The Cretaceous igneous province of Madagascar consists of lava flows, dykes, sills and intrusive complexes. The chemical composition of igneous rocks is broadly bimodal, with predominant mafic and subordinate silicic rocks. Only in the Volcan de l'Androy complex (southern Madagascar) the silicic rocks are abundant and interbedded with basaltic flows (Mahoney *et al*., 2008). Extensive Late Cretaceous basaltic volcanism in Madagascar is probably linked to the Marion hotspot and the breakup of Madagascar and India (Storey *et al*., 1995; Torsvik *et al*., 1998).

From Late Eocene up to recent time, Madagascar was affected by a new magmatic activity in the northern and central part of the island, with a few outcrops in the southwest (Lacroix, 1923; Besairie, 1964). In northern Madagascar, the volcanic activity is mostly represented by the Massif d'Ambre

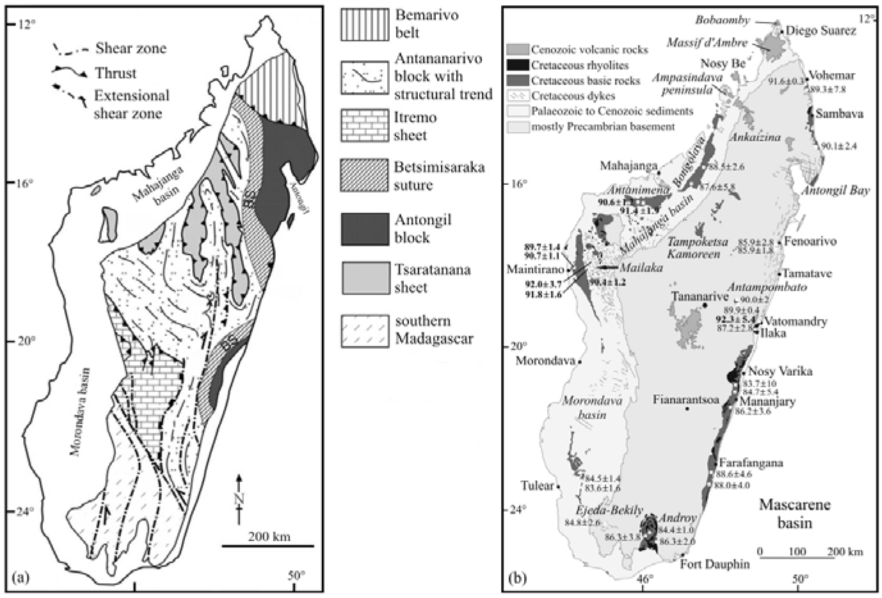

Fig. 1 - (a) Map of the tectonic units of Madagascar after Collins *et al*. (2000). (b) Geological sketch map of Madagascar. Outcrops of Cretaceous igneous rocks are in dark grey and black, whereas Cenozoic igneous rocks are indicated in grey. Previous Ar-Ar and U-Pb ages for Cretaceous igneous rocks are indicated (±2σ (black number). New Ar-Ar and U-Pb ages are indicated in bold.

stratovolcano, volcanic complexes in the Nosy Be archipelago, the Ankaizina district, and in the Ampasindava and Bobaomby (Cap d'Ambre) peninsula (Fig. 1b). The geochemical characteristics of the mafic volcanic rocks of the Nosy Be archipelago and Bobaomby peninsula have been studied by Melluso & Morra (2000) and Melluso *et al*. (2007). Karche (1973) made a major study of the volcanic rocks of the Massif d'Ambre. A tectonic study of the area is reported in Chorowicz *et al*. (1997). The Late Cenozoic alkaline volcanism in northernmost Madagascar is related to a roughly east-west extensional tectonic regime (Bertil & Regnoult, 1998; Rakotondraompiana *et al*., 1999; Piqué *et al*., 1999). The main geological structure produced by this regional extension is the Alaotra-Ankay rift, developed in the centre of Madagascar (de Wit, 2003; Kusky *et al*., 2007). A similar extensional tectonic regime is also observed in East Africa in recent times (Stamps *et al*., 2008). Emerick & Duncan (1982, 1983) proposed a plume origin for the volcanism in the Comore islands and in the northern coast of Madagascar, on the basis of progressive eastward increase of age of volcanism.

LATE CRETACEOUS MAGMATIC PROVINCE

Mailaka sector

The Mailaka lava succession covers a large area in central-western Madagascar, along the rifted margin of the Morondava basin and is characterized by basaltic to picritic basalt lava flows and minor evolved flows. *In situ* U-Pb dating of zircon in rhyodacites yields concordant ages of 89.7±1.4 Ma and 90.7±1.1 Ma (Fig. 2). Dykes and sills underlying basalt sequence have been analyzed by the $^{40}Ar/^{39}Ar$ method on plagioclase separates. The $^{40}Ar/^{39}Ar$ ages for three dykes and one sill range from 92 to 90 Ma.

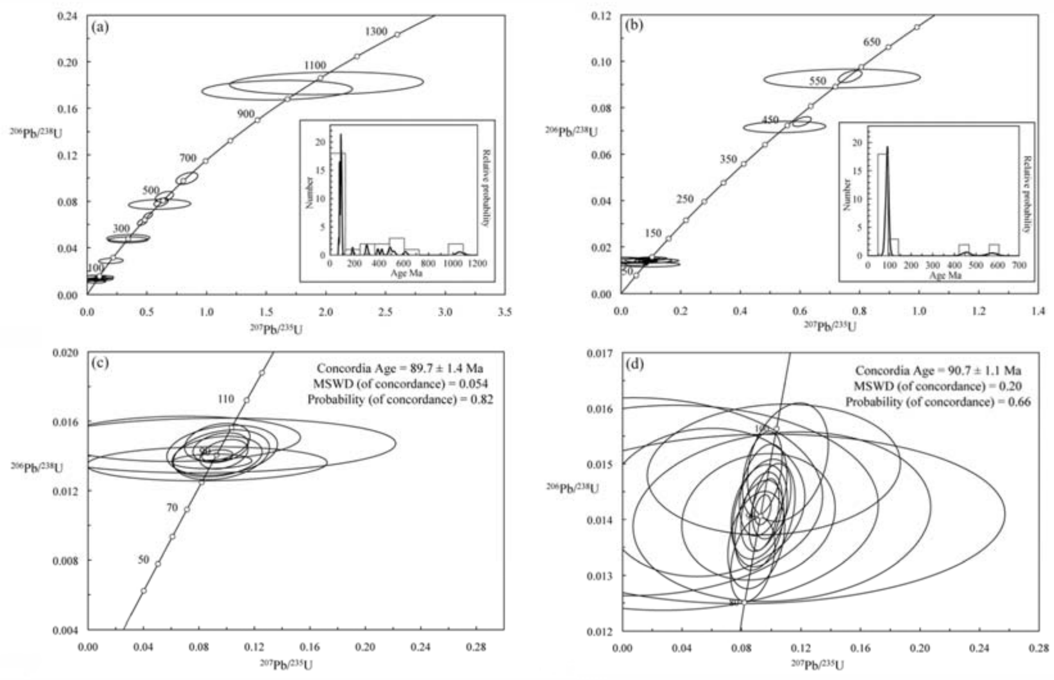

Fig. 2 - U-Pb ages of zircons from two rhyodacites. $^{206}Pb/^{238}U$ *vs.* $^{207}Pb/^{235}U$ Concordia diagram for concordant ages. In panel (a-b), the cumulative Gaussian distribution curves are also shown. Error ellipses are 2s.

The U-Pb and $^{40}Ar/^{39}Ar$ ages indicate that the igneous rocks of Mailaka succession were emplaced during a period of ~2 milion years.

Two geochemically different lava series are present. A transitional series ranging from picritic basalts to basalts has incompatible element abundances and Pb, Os and Nd isotope ratios within the range of MORB (mid-ocean ridge basalts). In addition, the concentrations of platinum group elements (Ir < 0.35 ppb, Ru < 0.17 ppb, Pd = 1.0-1.6 ppb) in the transitional basalts are generally lower than in basaltic lavas from oceanic plateaus (*e.g.* Ontong Java and Kerguelen) and other continental flood basalt provinces (*e.g.* Deccan and Etendeka).

A tholeiitic series ranges from picritic basalts to rhyodacites, and has relatively high concentrations of trace elements (*e.g.* Rb, Ba, Th and light lanthanides) and the Pb-Sr-Nd and Os isotopic characteristic of magmas that have assimilated continental crust. The Pb isotope ratios of tholeiitic andesites indicate the involvement of a component highly depleted in radiogenic Pb, very likely old lower crust.

Energy-constrained-assimilation-fractional-crystallization (EC-AFC; Spera & Bohrson, 2001) modeling indicates that the rhyodacites may be the result of ~ 25% assimilation of upper continental crust with a ratio between assimilated mass and subtracted solid of ~ 0.35. An andesite with low Pb isotope ratios may be the result of ~ 8% assimilation of lower continental crust with a mass assimilated/mass accumulated ratio of ~ 0.1. Interaction of mantle-derived magmas with crustal lithologies of different age and evolutionary history thus occurred in this sector of the flood basalt province. Contamination of mantle-derived rocks by material of different crustal domains is a process also observed in other large igneous provinces, such as the Deccan Traps.

Mahajanga basin and Tampoketsa Kamoreen

The basaltic rocks exposed in the Mahajanga basin (Antanimena and Bongolava-Manasamody plateau) represent one of the most important lava sequences of the Madagascar province. Two tholeiitic basalt flows from the Antanimena plateau gave $^{40}Ar/^{39}Ar$ ages of 90.6±1.2 Ma and 91.3±1.9 Ma, respectively, statistically indistinguishable from age determinations of the Mailaka lava succession.

Four geochemically distinct magma types (group A, B, C and D) are recognized in within the flood basalt sequence of Mahajanga. The groups are defined on the basis of whole-rock TiO_2, Nb and Zr contents and Sr-Nd-Pb and Os isotopic data.

Group A and C basaltic rocks (Antanimena plateau) have low to moderate TiO_2, Nb and Zr contents, are enriched in light lanthanides (LREE; La_n/Yb_n = 1.4-4.5) and show large variations in εNd_i (+0.1 to –10.5) and γOs (+11.4 to +7378). They have low Pb isotopic composition with, $^{206}Pb/^{204}Pb$ varying from 15.283 to 16.325. The extreme isotopic variations, particularly in Nd-Pb and Os isotopic compositions, are probably due to crustal assimilation with an unradiogenic Pb component.

Group B and D basaltic rocks (Bongolava-Manasamody plateau and Tampoketsa Kamoreen) have moderate to high TiO_2 and Nb contents and are enriched in LREE with La_n/Yb_n ranging between 2.9 to 7.8. Age corrected Nd and Os isotope ratios of the basaltic lavas of group B and D show a small range in εNd_i (+1.0 to +4.0) and a wide range in γOs (+128 to +1182). Their $^{207}Pb/^{204}Pb$ value is within the group A and C basaltic rocks range, but their $^{207}Pb/^{204}Pb$ (16.518-17.355) and $^{208}Pb/^{204}Pb$ (37.511-38.009) values are higher.

The role of crustal contamination combined with fractional crystallization (AFC) has played an important role in the petrogenesis of Bongolava-Manasamody basaltic rocks, involving lower crustal contaminant. The marked differences in the trace element and isotopic characteristics of the four magma types cannot be explained by considering only AFC processes. The different trace element enrichment of Bongolava-Manasamody basalts, relative to Antanimena basalts, suggests the presence of heterogeneous mantle sources in northern Madagascar. However, the distinctive geochemical signature of Marion plume is not evident in the compositions of Mahajanga basalts.

Antampombato-Ambatovy complex

The Antampombato-Ambatovy complex (central-eastern Madagascar) is composed by two core of ultramafic rocks (dunite, wehrlite and clinopyroxenite), surrounded by gabbroic rocks. The gabbros and ultramafic rocks and the Precambrian basement near to the intrusion are cross-cut by picritic basalt to mugearite to alkali-rhyolite dyke swarm.

The Precambrian basement close to the intrusion is composed by orthogneisses, migmatites, amphibolites, magnetite quartzites and rare marbles (Melluso *et al*. 2005).

The Antampombato-Ambatovy mafic dykes are weakly alkaline (nepheline normative or slightly hyperstene normative) and are characterized by wide range of MgO (24-6 wt.%), Nb (3.8-16.2 ppm), Zr (52-135 ppm) and Ba (46-382 ppm) contents. The REE patterns show moderate LREE enrichment (La_n/Yb_n = 4.3-5.2). The isotopic compositions of Antampombato basalts are most similar to those MORB (initial $^{87}Sr/^{86}Sr \sim 0.7033$, $\varepsilon Nd_i > 7.3$, $^{206}Pb/^{204}Pb \sim 18.3$). Trace element and isotopic variations observed in the Antampombato basalts are compatible with melting of incompatible element-enriched mantle source. The influence of crustal contamination in the petrogenesis of Antampombato basalts is negligible.

CENOZOIC IGNEOUS PROVINCE

Massif d'Ambre

The Massif d'Ambre is the largest stratovolcano (*ca.* 2500 km^2) in the Cenozoic igneous province of northern Madagascar. It is broadly elongated in a N-S direction and is formed by hundreds of lava flows, plugs, spatter cones, tuff rings, pyroclastic flows and pyroclastic fall deposits.

New ^{40}Ar-^{39}Ar age determinations for lavas of Massif d'Ambre and Bobaomby peninsula (the northernmost tip of Madagascar) yielded ages of 12.1±0.2 Ma and 10.56±0.09 Ma. These ages indicate that at least part of the volcanic activity of the Bobaomby peninsula is later than the beginning of the activity of the Massif d'Ambre.

The volcanic products of Massif d'Ambre are mildly to strongly alkaline (with sodic affinity) to tholeiitic with very limited amounts of evolved magmas. The mafic rocks have compositions similar to those of primitive mantle-derived magmas (MgO >10 wt.%, Cr and Ni > 400 and > 200 ppm, respectively).

The strongly alkaline suite shows a liquid line of descent from basanite to phonolite, dominated by fractional crystallization of clinopyroxene and olivine.

The mafic rocks (basanites, alkali basalts, transitional and tholeiitic basalts) have values of Zr/Nb (2.4-5.8), Ba/Nb (7-24) and La/Nb (0.7-1.1) ratios typical of incompatible element-rich within-plate basalts. The primitive mantle-normalized incompatible element patterns (Fig. 3) of the Massif d'Ambre mafic rocks are characterized by peaks at niobium and troughs at potassium, and are identical in shape and absolute abundances to those of the Nosy Be and Bobaomby (Cap d'Ambre) basanites.

The range of La_n/Yb_n ratios (9-24) indicates that the Massif d'Ambre primitive compositions are the product of variable degrees of partial melting (4-12%) of a broadly similar and slightly incompatible element-enriched mantle source.

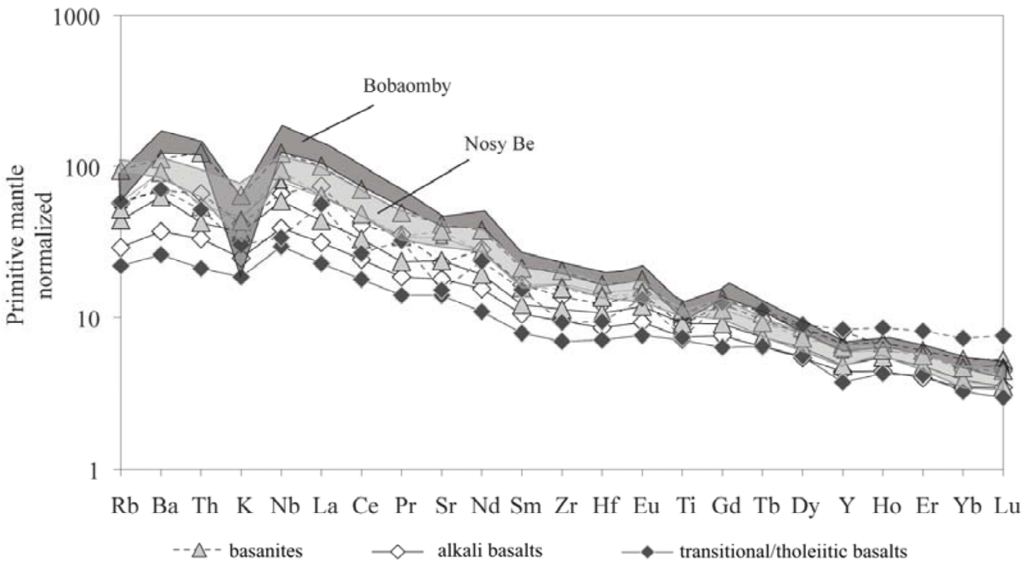

Fig. 3 - Primitive mantle normalized incompatible element diagram for mafic rocks of Massif d'Ambre. Bobaomby and Nosy Be basanites are reported for comparison. Normalization values are taken from Sun & McDonough (1989).

Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of alkali basalts and basanites vary from 0.70326 to 0.70359 and 0.51279 to 0.51286, respectively. Alkali basalts and basanites have little variation in $^{206}Pb/^{204}Pb$ (19.073-19.369), $^{207}Pb/^{204}Pb$ (15.613-15.616) and $^{208}Pb/^{204}Pb$ (39.046-39.257). This range is well within the range of Sr-Nd-Pb isotope values of the basanites of the Nosy Be archipelago, thus again confirming substantially similar source compositions throughout northern Madagascar.

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