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The Cenozoic alkaline magmatism in central-northern Madagascar: a brief overview

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Abstract. — The Cenozoic volcanic rocks of Madagascar were emplaced as lavas, pyroclastic rocks, dykes, and plugs, and range in composition from olivine melilitites, basanites and alkali basalts, to phonolites, trachytes and rhyolites. The ultrabasic-basic lithologies are dominant, in particular basanites and tephrites, with less abundant, mildly evolved, compositions. These rocks form at least three different magma lineages of broadly sodic affinity. Fractional crystallization of the observed phenocryst phases is the most reasonable petrogenetic model for the genesis of the more evolved compositions. The mantle-derived magmas were likely generated by variable degrees of partial melting of incompatible element-enriched mantle sources, possibly located in the deep lithosphere or in the asthenosphere.

Riassunto. — Le rocce vulcaniche Cenozoiche del Madagascar, a giorno come colate di lava, rocce piroclastiche e sciami di filoni, variano in composizione da termini ultrabasici (olivin melilititi) fino a basici (basaniti, tefriti, alcali basalti, hawaiiti) ed evoluti (trachiti, fonoliti, rioliti). Basaniti e tefriti sono dominanti. Queste rocce formano almeno tre serie magmatiche con diverso grado di sottosaturazione in silice e con affinità magmatica di tipo sodico o più raramente potassico. La cristallizzazione frazionata è il processo petrogenetico più probabile che ha portato alla formazione delle rocce evolute delle varie serie. I differenti magmi parentali sembrano essersi formati per variabili gradi di fusione parziale di sorgenti geochimicamente arricchite e probabilmente ricche in elementi volatili, questi ultimi localizzati in fasi quali anfiboli, flogopite e carbonati. Queste sorgenti sono probabilmente parti della litosfera continentale più profonda o dell'astenosfera.

Key Words: *Cenozoic magmatism, Madagascar, alkaline rocks, melilitites, basanites*

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Introduction and geological setting

The African continent has been the site of abundant within-plate volcanism in the Late Cenozoic, in response to tensional movements, and possibly due to thermal perturbations. Madagascar is not an exception to these processes. The central part of Madagascar was uplifted, with formation of horst-graben structures in the latest Cenozoic (de Wit, 2003). Many volcanic complexes were thus emplaced in rift-related settings (Ankaratra, Itasy, Alaotra, Takarindoha). The northern part of the island was also subject to rifting, with the formation

of a roughly linear zone, NW-SE-trending, of plutonic intrusions and volcanic complexes from the Nosy Be archipelago and the Ampasindava peninsula towards the Antongil Bay (Fig. 1). This linear zone has been sometimes interpreted as a rift (cf. de Wit, 2003). In the northernmost part of the island, the Massif d'Ambre and Bobaomby (Cap d'Ambre) are inferred to have been influenced by N-S trending extension (de Wit, 2003).

The chronology of the igneous events, which appear to have occurred from the Late Miocene (10 Ma ago) until very recent times (Emerick and Duncan, 1982, 1983), and the internal stratigraphy of intrusions and volcanic complexes are not known in detail. Several authors (Prior, 1901; Lacroix, 1923; Besairie *et al*., 1957; Besairie, 1964; Karche, 1973; Emerick and Duncan, 1982, 1983; Melluso and Morra, 2000; Buchwaldt *et al*., 2005; Melluso *et al*., 2007) presented petrography, age determinations and geochemical descriptions of the samples from central and northern Madagascar, but many large volcanic areas are still largely inaccessible (such as the intrusions of the Ampasindava peninsula and the very large Manongarivo intrusion, located SE of the Ampasindava peninsula), and for this

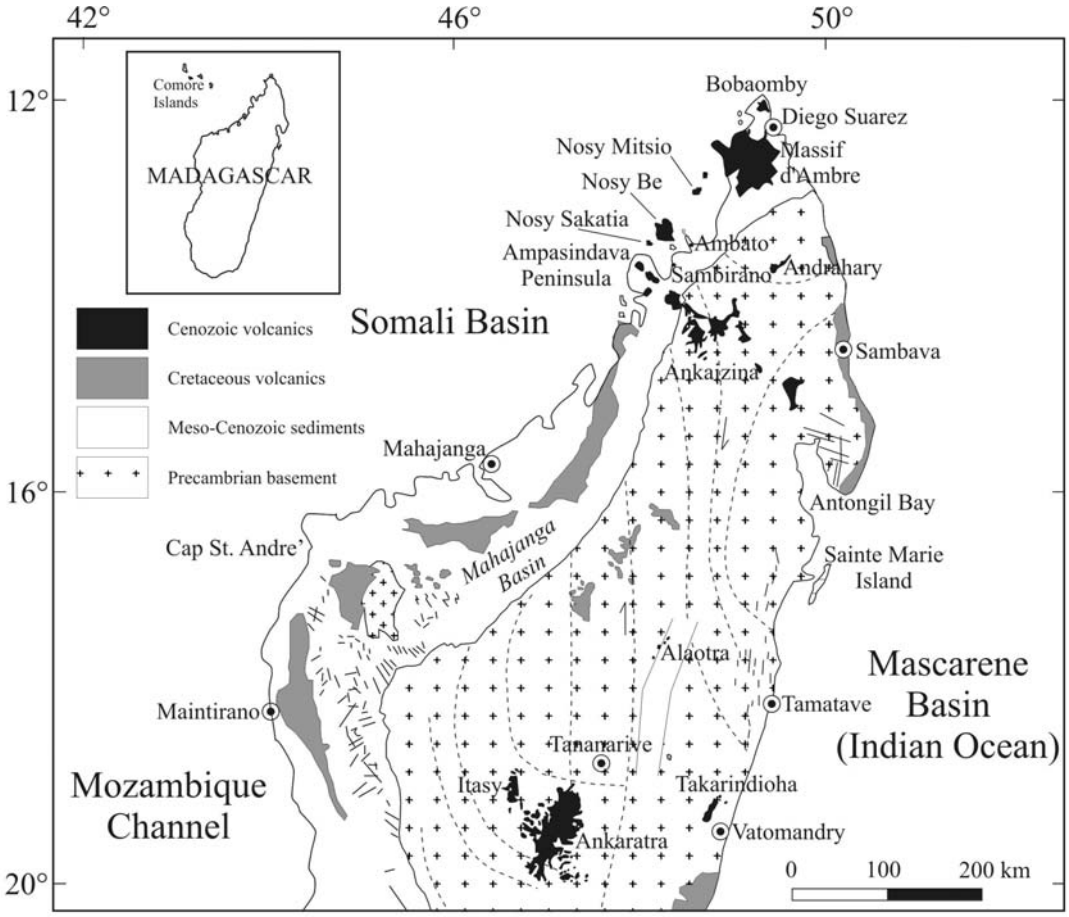

Fig. 1 — Geological sketch map of central-northern Madagascar with locations of the main volcanic complexes (after Besairie, 1964). Lineaments in the Precambrian are shear or thrust zones.

reason, a detailed petrological knowledge about the outcropping lithologies and their internal relationships is hampered. The Bobaomby (Cap d'Ambre) volcanic field is formed by scattered lava flows, huge spatter cones and by a significant dyke swarm with two normal orientations (broadly N-S and E-W), with rare, still well-preserved, tuff rings (Melluso *et al*., 2007). The Massif d'Ambre is a very large stratovolcano broadly elongated in a N-S direction. It is mostly formed by a wealth of lava flows, spatter cones, tuff rings, often occupied by lakes, and generally deeply altered pyroclastic flows and pyroclastic fall deposits. Rare acid rocks are found also in the form of plugs with well-developed columnar jointing, which were dissected by later basaltic (s.l.) lava flows. The Nosy Be archipelago is formed by several islets, of which Nosy Sakatia and Nosy Komba are the largest. Nosy Sakatia is formed by a rhyolitic lava flow cross-cut by a spatter cone and an eroded plug full of mantle xenoliths. Nosy Komba is a alkali gabbro-nepheline syenitic intrusion of roughly circular shape. The Nosy Be island is formed by Mesozoic sedimentary rocks which were intruded by syenitic stocks and after were covered by lava flows and tuff rings of basanitic to phonotephritic composition (Melluso and Morra, 2000). The Alaotra district is formed by a number of plugs and small lava flows mostly emplaced along the western shoulder of the Alaotra lake graben structure. The Takarindoha district, which is the only outcrop of Cenozoic volcanic rocks in the eastern coast, is a relatively small volcanic field mostly made up of lava flows, spatter cones and plugs, resting directly above the Precambrian (mostly Archean) basement of the area.

This paper, which is a review of our samples collected over the last decade in this very large alkaline province, provides basic petrographic and chemical features of the Cenozoic volcanics of Madagascar, with new information on the northernmost volcanic rocks and the melilitite lava fields of Alaotra and Takarindoha districts, which still need a detailed description (cf. Prior, 1901; Woolley, 2001), as well as for small, almost unknown outcrops (such as the Ambato granite intrusion and the Sambirano phonolite plugs). New petrographic, chemical and mineralogical information is given for rocks belonging to the volcanic complexes of Itasy and Ankaratra (whose chronology of the volcanic events and modern knowledge of the outcropping rocks are still completely lacking), Massif d'Ambre and Ampasindava-Nosy Be.

Classification and petrography of the samples

The volcanic rocks are classified according to the Total Alkali-Silica diagram (TAS; Le Bas *et al*., 1986; Fig. 2) and range from basic-ultrabasic types (olivine melilitites, olivine nephelinites, basanites, tephrites, alkali basalts, hawaiites) through intermediate (tephritic phonolites, phonolites) to acid (quartz trachytes and rhyolites) (Table 1). The chemical affinity of the Cenozoic Madagascan rocks is broadly sodic, excluding very few tephritic dyke rocks of Bobaomby and rocks from Itasy and Ankaratra with a slight potassic affinity (Melluso *et al*., 2007 and Table 1).

Olivine melilitites (the so-called *ankaratrites*, first named after Lacroix, 1923) and rare *olivine nephelinites* occur in the Ankaratra, Alaotra and Takarindoha districts; *basanites* are known from Ankaratra, Itasy, Nosy Be, Ankaizina and Massif d'Ambre-Bobaomby, whilst *alkali basalts* are present at Itasy, Ankaratra, Massif d'Ambre and Ampasindava. Intermediate and felsic rocks occur in almost all of the volcanic districts, excluding the melilitite lava fields of Alaotra and Takarindoha. Olivine melilitites and olivine nephelinites are olivine-phyric rocks, with subordinate clinopyroxene phenocrysts, often strongly zoned with purple, Ti-rich rims. The groundmass is made up of olivine, clinopyroxene, opaque oxides, perovskite, melilite, nepheline and biotite (Table 2; Figs. 3a, 3b). The basanites are also olivine- and clinopyroxene-phyric, with groundmasses rich in clinopyroxene, opaques and subordinate feldspar (Fig. 3c). *Alkali basalts* have olivine, plagioclase and titanaugite phenocrysts in a groundmass of the same phases together with opaque oxides (Fig. 3d). *Hawaiites* are plagioclase-phyric, with olivine, clinopyroxene and opaque microphenocrysts (Fig. 3e). *Tephrites and phonolitic tephrites* are characterized by clinopyroxene and, in the more evolved compositions, kaersutitic amphibole phenocrysts, with increasingly feldspar-rich matrices, and, sometimes, biotite; *tephritic phonolites* are characterized by amphibole and

feldspar phenocrysts, plus accessory magnetite and titanite, set in a trachytoid mesostasis (Fig. 3f). Intrusive equivalents of tephrites and tephritic phonolites are the *bekinkinites* (mafic nepheline monzonites) in the Ankaramy area. These subvolcanics are amphibole-bearing, with green-purple clinopyroxene, interstitial feldspars, feldspathoids, titanite and opaque oxides (Fig. 3g).

Rhyolites occur at several localities as lavas, plugs and pyroclastics, and tend to be early products in the stratigraphic successions. At Nosy Sakatia (Nosy Be archipelago) and Massif d'Ambre they are aphyric, with scarce feldspar and biotite microlites in a quartz-rich matrix. Intrusive equivalents are represented, among several examples, by the Ambato granite (Fig. 3h; Table 1), comprising granophyric intergrowths of quartz and alkali feldspar, with altered femic minerals. *Trachytes* occur as plugs and lavas in several complexes, in the Ampasindava peninsula and Itasy. These feldspar-phyric rocks can have either interstitial quartz or feldspathoids, together with alkali pyroxenes (Fig. 3i). *Phonolites* are found as dykes, plugs and lavas at several localities, including the northernmost tip of Madagascar (Sambirano, Massif d'Ambre, Bobaomby). They are porphyritic, with phenocrysts of sanidine, nepheline, sodalite, clinopyroxene, amphibole and accessory phases (titanite and magnetite). The groundmass is trachytoid, and has also deep green clinopyroxenes and amphiboles. Intrusive equivalents of the volcanic rocks (e.g., nepheline syenites, gabbros) are frequent in the Nosy Be archipelago (Melluso and Morra, 2000 and unpublished data). Further details about the rocks of the province, particularly about the plutonic complexes, can be found in the Woolley's compilation (2001).

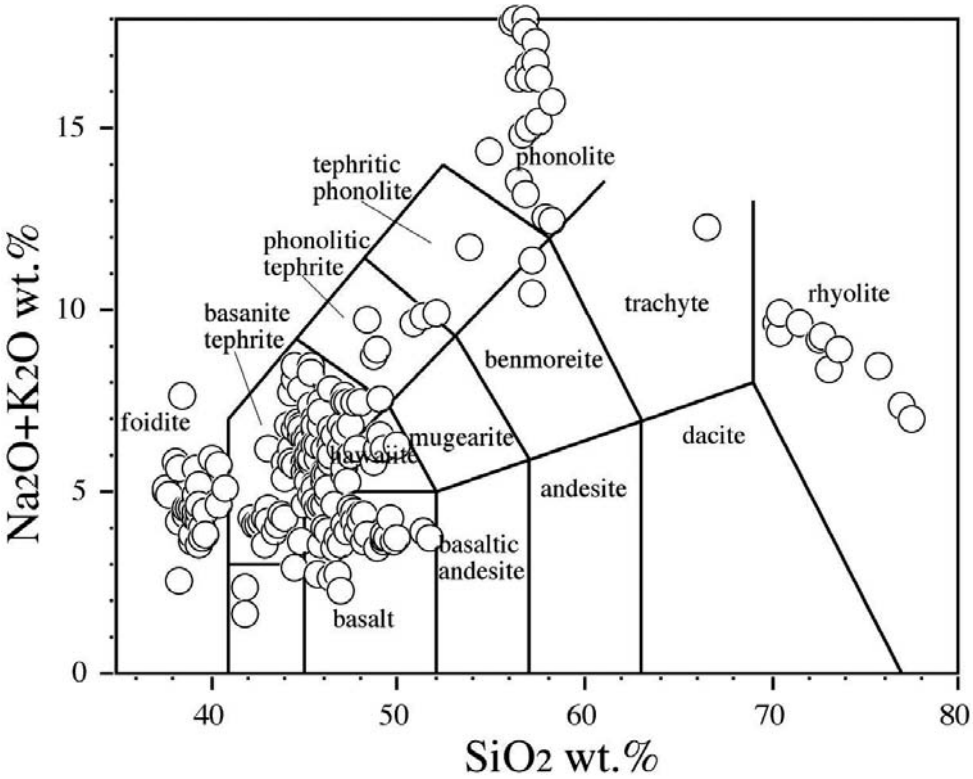

Fig. 2 — Classification of the Madagascan samples according to the Total Alkali-Silica diagram (Le Bas *et al.*, 1986).

TABLE 1 — *Representative major (wt.%) and trace element (ppm) compositions of the Cenozoic volcanic rocks of Madagascar*

	Alaotra	Ankar	Boba	NyBe	MdA	Takar	Itasy	Ampa	NyBe	MdA	Boba	Sakat	Boba	Itasy	Samb	Ambato	MdA	Ampa
	M707	M783	M574a	M236	M540	Vato1	M185	M513	M231	M533	M631	M226	M559	M187	M505	AMB-1	M602	M501
	a	a	b	b	b	a	b	b	b	b	b	b	b	b	b	a	b	b
class	mel	mel	bsn	bsn	bas	neph	bas	bek	tph	haw	tphph	rhy	pho	trach	pho	granite	rhy	trach
SiO_2	38.70	39.75	45.61	45.34	46.35	41.50	46.23	45.33	48.40	49.22	53.75	72.76	56.21	58.30	57.50	75.70	76.99	66.57
TiO_2	2.92	2.77	2.15	2.24	1.52	2.70	4.22	2.78	2.25	2.28	1.47	0.18	0.30	0.61	0.15	0.12	0.16	0.90
Al_2O_3	8.90	10.68	11.21	12.33	12.26	10.98	11.97	11.77	15.18	15.79	17.77	14.81	20.21	18.60	19.24	12.01	13.63	16.06
Fe_2O_{3t}	12.61	11.91	12.52	11.86	13.59	12.72	12.77	11.09	11.44	11.38	7.54	0.71	3.65	3.41	3.80	1.41	1.19	2.66
MnO	0.19	0.18	0.17	0.18	0.18	0.19	0.17	0.18	0.28	0.18	0.15	0.01	0.12	0.19	0.30	0.03	0.02	0.09
MgO	15.66	14.30	11.77	11.43	10.36	9.92	8.12	6.63	4.69	3.69	2.60	0.35	0.27	0.26	0.12	0.05	0.30	0.01
CaO	14.06	13.00	11.42	9.76	10.05	13.86	10.94	9.52	7.48	8.57	4.86	0.55	1.23	2.50	1.27	0.37	0.43	0.43
Na_2O	2.47	2.98	3.63	4.27	2.07	2.80	2.18	4.38	6.67	4.02	5.88	3.78	11.25	7.64	10.05	3.38	2.93	6.14
K_2O	1.67	2.23	1.06	1.93	0.52	0.73	2.69	2.96	3.06	2.12	5.78	5.45	6.73	4.77	5.07	5.08	4.33	6.09
P_2O_5	1.01	0.91	0.46	0.66	0.23	0.83	0.71	0.64	0.55	0.63	0.20	0.01	0.02	0.09	0.01	0.02	0.03	0.11
LOI	0.77	0.35	1.36	na	2.88	2.79	2.80	4.72	3.02	2.12	4.66	na	2.54	na	2.51	1.36	1.59	0.95
Sc	24	29	28	25	24	22	25	22	17	15	9	2	0.3	2	2		3	6
V	265	276	266	229	220	214	408	327	170	219	128	7	13	24	5		8	20
Cr	590	570	1020	551	598	220	173	49	73	10	3	2						
Ni	430	280	491	291	245	170	94	34	54	7	16	4	24		8			
Cu	80	70	96	54	61	80	63	56	47	10	80	39		11			43	
Zn	100	90	91	92	104	120	125	85	112	104	35	25	88	111	228	90	35	81
Rb	56	59	25	57	21	36	51	71	77	69	210	220	279	106	280	261	224	96
Sr	1247	1111	540	807	258	1032	1272	654	875	732	704	41	134	1729	8	15	60	8
Y	26	24	19	30	16	29	30	19	32	29	28	41	22	38	52	63	48	40
Zr	264	234	158	203	72	256	415	210	270	204	294	291	367	879	1553	176	134	469
Nb	87	98	48	72	23	75	86	77	100	58	94	69	102	168	157	67	46	102
Ba	1030	1200	546	760	198	706	784	821	970	651	1156		70	na	3	42	1008	9
A.I.	0.66	0.69	0.63	0.74	0.32	0.49	0.54	0.88	0.94	0.56	0.90	0.82	1.28	0.95	1.14	0.92	0.70	1.04
Mg#	0.74	0.73	0.68	0.68	0.63	0.64	0.59	0.57	0.48	0.42	0.44	0.52	0.14	0.15	0.06	0.07	0.36	0.01
Zr/Nb	3.0	2.4	3.3	2.8	3.1	3.4	4.8	2.7	2.7	3.5	3.1	4.2	3.6	5.2	9.9	2.6	2.9	4.6

Ankar, Ankaratra; Boba, Bobaomby; NyBe, Nosy Be; MdA, Massif d'Ambre; Takar, Takarindoha; Ampa, Ampasindava; Sakat, Nosy Sakatia; Samb, Sambirano mel, melilitite; bsn, basanite; neph, nephelinite; bas, alkali basalt; bek, bekinkinite (mafic nepheline monzonite); tph, tephrite; haw, hawaiite; rhy, rhyolite; trach, trachyte; pho, phonolite; phtph, tephritic phonolite; na, not analyzed; A.I.=molar (Na+K)/Al; Mg#=atomic $Mg/(Mg+Fe^{2+})$ with $Fe_2O_3/FeO=0.15$ Analyses performed at ACTLABS, Ontario, with ICP-MS (a) and Napoli with X-ray fluorescence (b). Full details of the analytical techniques are reported in Melluso et al. (2005, 2007)

Table 2 — *Representative mineral compositions in the Cenozoic volcanics of Madagascar*

	NosyBe	Boba	NosyBe	NosyBe	Boba	NosyBe	NosyBe	Alaotra	NosyBe
rock	bsn	bsn	bsn	bsn	pho	tph	bsn	mel	bsn
mineral	ol	ol	cpx	cpx	cpx	cpx	chr	chr	Ti-mt
type	core	gm	core	gm	gm	gm	gm	gm	gm
SiO_2	40.37	38.31	49.20	37.39	47.39	40.27			
TiO_2			1.97	6.25	1.65	5.40	2.82	1.91	21.47
Al_2O_3			5.55	7.73	5.20	11.72	22.10	26.64	3.67
FeO_t	12.20	25.24	5.47	18.23	14.34	7.80	33.43	24.16	69.29
MnO	0.35	0.60	0.08	0.33	0.60	0.08	0.42		0.89
MgO	46.82	35.39	14.06	9.10	7.66	10.47	9.29	14.44	1.48
CaO	0.22	0.37	22.85	19.03	21.91	22.41			
Na_2O			0.02	0.79	1.32	0.46			
Cr_2O_3			0.52	0.15		0.43	30.30	31.82	
NiO	0.35	0.19							
sum	100.31	100.09	99.72	99.00	100.05	99.04	98.36	98.97	96.80

	NosyBe	Boba	Alaotra	NosyBe	Boba	Alaotra	Alaotra	Alaotra	Boba
rock	tph	pho	mel	tph	pho	mel	mel	mel	pho
mineral	amph	amph	bt	feld	neph	neph	melilite	pvk	sod
type	core	core	gm	gm	core	gm	gm	gm	core
SiO_2	39.23	36.14	27.95	53.22	46.18	40.75	41.82	0.03	38.06
TiO_2	5.23	4.06	11.31				0.13	54.33	
Al_2O_3	13.26	12.12	14.91	29.29	32.41	31.40	5.88	0.27	29.65
FeO_t	12.37	21.14	10.76	0.61	0.50	1.45	3.90	0.93	0.32
MnO	0.18	0.49	0.15				0.06	0.04	
MgO	11.65	5.20	11.61				8.53		
CaO	11.53	11.78	0.11	11.61	1.80	0.60	34.46	37.11	0.11
Na_2O	2.46	2.27	0.35	4.62	15.25	12.77	3.51	0.51	24.60
K_2O	1.23	1.78	3.64	0.43	3.63	10.89	0.17	0.05	0.22
BaO		0.14	16.31	0.35	0.01			0.78	0.04
Cr_2O_3			0.05						
SrO				0.44	0.05		0.29	0.35	
F	0.17	0.28	1.18					0.04	
Cl			0.02						7.38
sum	97.31	95.41	98.34	100.57	99.83	97.86	98.75	94.42	100.38

ol, olivine; cpx, clinopyroxene; chr, chrome spinel; Ti-mt, titanomagnetite; amph, amphibole; bt, biotite; feld, plagioclase; neph, nepheline; pvk, perovskite; sod, sodalite; gm, groundmas rock abbreviations as in Table 1.

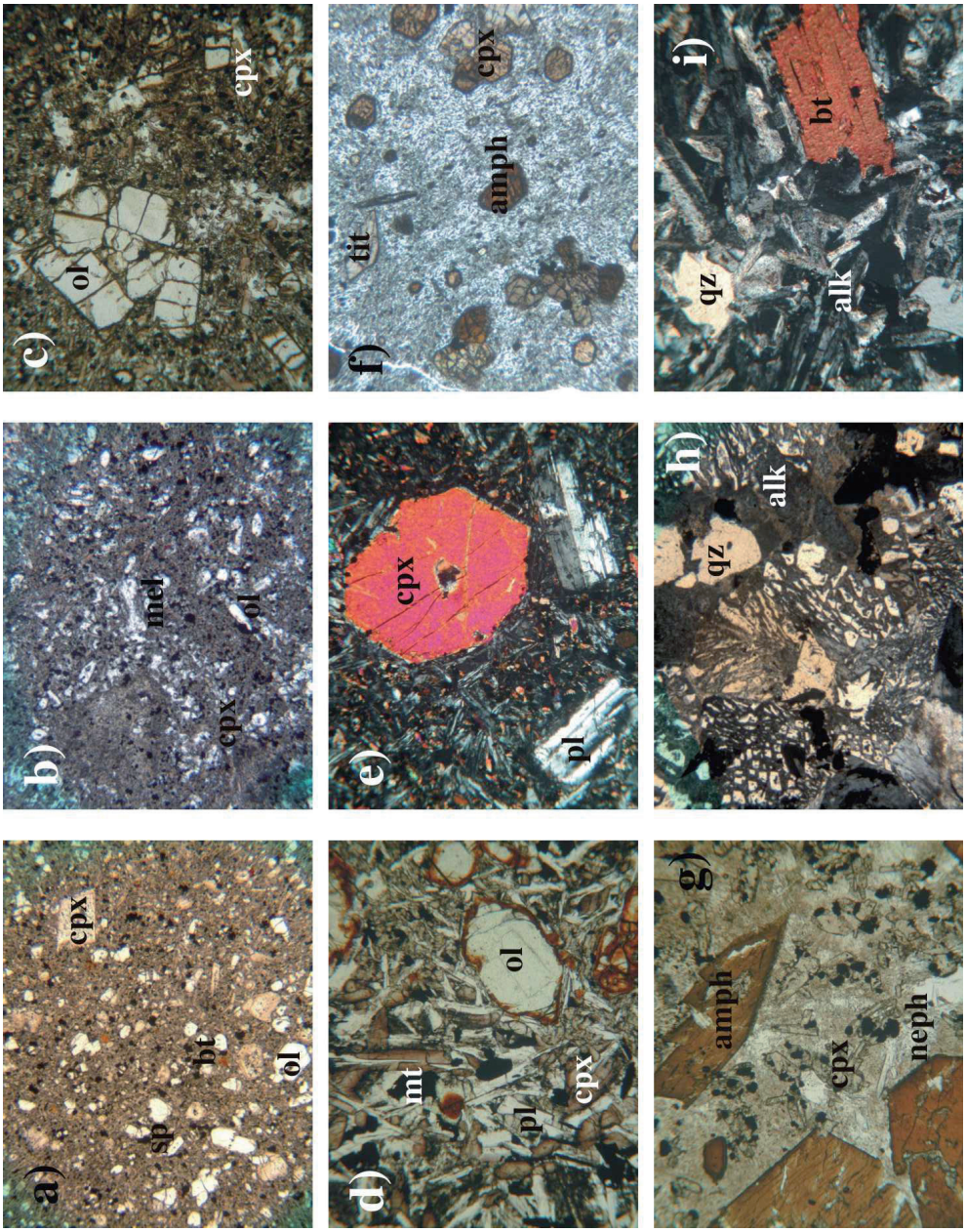

Fig. 3 — Microphotographs of Cenozoic Madagascan volcanic rocks: a) olivine melilitite, Amparafaravola, Alaotra district (plane polarized light); b) olivine melilitite, Tamboro, Takarindoha district (plane polarized light); c) basanite, eastern Massif d'Ambre (plane polarized light); d) alkali basalt, south of Massif d'Ambre (plane polarized light); e) hawaiite, north of Massif d'Ambre (crossed polarizers); f) tephritic phonolite, central Bobaomby peninsula (plane polarized light); g) "bekinkinite", Ampasindava peninsula (plane polarized light); h) granophyric alkali granite, Ambato intrusion (crossed polarizers); i) quartz trachyte, southern Ampasindava peninsula (crossed polarizers). Abbreviations: ol, olivine; cpx, clinopyroxene; pl, plagioclase; mel, melilite; mt, opaque oxides; amph, amphibole; alk, alkali feldspar; neph, nepheline; tit, titanite; qz, quartz. The horizontal side of the micrographs is ab. 2 mm. Other microphotographs of Madagascan Cenozoic volcanic rocks are found in Melluso *et al.* (2007).

Geochemistry and petrogenesis

Some of the chemical analyses reported in Table 1 are the first to appear in the geological literature about the Cenozoic Madagascan rocks. The rocks have a very large span in SiO_2, MgO and CaO and consequently of most major oxides and trace elements. The mafic/ultramafic rocks range from nepheline- to larnite-normative; some trachytes and phonolites are peralkaline (A.I., molar (Na+K)/Al, up to 1.3; Table 1). No rhyolites at Nosy Be and Massif d'Ambre are found to be peralkaline. The rocks belong to at least three different magma series: 1) basanite-phonolite, probably most abundant in the lavas and dykes, 2) alkali basalt-trachyte-rhyolite, 3) melilitite series. The basanite-tephrite-phonolite magma series is known in several volcanic complexes, such as Massif d'Ambre, Bobaomby and Ankaratra (cf. Melluso *et al.*, 2007; Woolley, 2001). Melluso *et al.* (2007) pointed out that the evolution involved fractional crystallization of a) olivine and clinopyroxene from basanite to tephrite, b) clinopyroxene, amphibole and feldspar from tephrite to tephriphonolite and c) feldspar-dominated assemblages from tephriphonolite to the most evolved phonolites (Table 3).

The mildly alkaline rocks (alkali basalts, hawaiites) form significant parts of the Massif d'Ambre, Itasy and Ankaratra stratigraphy, do not form a clear differentiation trend towards trachytes and rhyolites, due to an apparent lack of the intermediate members (mugearites and benmoreites) (Fig. 2). The transition from alkali basalts to hawaiites at Massif d'Ambre took place through fractional crystallization of olivine gabbros (Table 3). Due to the lack of intermediate compositions, we did not attempt the transition between hawaiites and rhyolites, that may also be accompained by locally significant open-system evolution processes.

In the nepheline-kalsilite-silica diagram (Fig. 4), the evolved rocks plot within the thermal troughs connecting the three minimum melt compositions known in feldspar-bearing systems (Hamilton and MacKenzie, 1965).

As is well known worldwide, melilite-bearing volcanic rocks cannot be derived from, or be parental magmas of, feldspar-bearing rocks, particularly when Na-rich (see for instance Pan and Longhi, 1990), and for this reason we must considered them as a separate magma lineage. We did not find any trace of feldspar in the rocks with melilite. As yet, no evolved members of the olivine melilitite magma series are known in Madagascar. All the melilite-bearing samples have high MgO, generally much higher than the values found in basanites or alkali basalts (Fig. 5). Evolved, hence MgO-poor, melilite-bearing volcanic rocks are rare and restricted to very few localities in the world (Melluso *et al*., 1996).

The chemical composition of representative mineral phases in different lithotypes is given in Table 2. The mineral compositions of the felspar bearing-rocks are similar to those found in many other suites worldwide (cf. Aurisicchio *et al.*, 1983), with also peculiar mineral compositions, such as the groundmass Ti-Ba-rich biotites in the olivine melilitites, found also in other melilite-bearing volcanic rocks (Dunworth and Wilson, 1998).

Mg-rich rocks with different degrees of silica saturation can be considered having the composition of mantle-derived liquids (Table 1; Fig. 5). Among them, the olivine melilitites and olivine nephelinites have the most Mg-, Ti-, K- and Ca-rich, and Si- and Al-poor compositions (Table 1; Fig. 5). Particularly interesting is the jump in the MgO and SiO_2 contents

Table 3 — *Mass balance calculations for the transition from mafic to evolved lithotypes of different magmatic series of Madagascar*

from	**to**	ol	cpx	pl	mt	amph	alk	ap	tit	% subtracted solid	$\sum Res^2$
bsn	tph	-6.4	-34.5	-5.1	-1.3					-47.3	0.15
tph	tphph	-3.1	-13.5	-12.1	-6.3	-14.0		-1.9		-51.0	0.35
tphph	ph		-10.4	-1.6	-2.5	-11.2	-19.0		-0.01	-44.8	0.12
bas	haw	-15.5	-16.9	-10.1	-2.5					-44.9	0.34

bsn, basanite; bas, alkali basalt; tph, tephrite; haw, hawaiite; tphph, tephritic phonolite; ol, olivine; cpx, clinopyroxene; pl, plagioclase; mt, titanomagnetite; amph, amphibole; alk, alkali feldspar; ap, apatite; tit, titanite; $\sum Res^2$= sum of squares of residuals

of the melilitites (Fig. 5), which may indicate a significant change in the modal mineralogy of the sources.

The mafic/ultramafic rocks have similar incompatible element patterns, decreasing in the abundance of the most incompatible elements from olivine melilitites to alkali basalts (Figs 5 and 6), a marked trough at K, which is present in all the mafic rocks regardless for their degree of silica undersaturation, and a peak at Nb. Ti may or may not have a small trough. This feature is observed throughout central-northern Madagascar, suggesting that similar mantle source compositions were involved in the melting regime at various degrees of partial melting and pressures of formation. The low Zr/Nb of all the mafic/ultramafic samples (Zr/Nb<5; see also Table 1) is evidence of small-degree melting of an enriched source (e.g., le Roex *et al.*, 1985). The overall geochemical patterns of the Madagascan alkaline rocks are broadly similar to typical OIB (Ocean Island Basalts; cf. Sun and McDonough, 1989; Fig. 6). Melluso and Morra (2000) estimated a degree of partial melting between 3% and 5% for the Nosy Be basanites. A similar range of degrees of partial melting was estimated by Melluso *et al*. (2007) for the Bobaomby basanites, located about 170 km NE of Nosy Be. The alkali basalt and basanite magmas may have been generated from decreasing amounts of melt from amphibole-bearing spinel lherzolites (cf. Melluso and Morra, 2000; Melluso *et al*., 2007). These lherzolites are actually recorded in the mantle xenolith suite of Massif d'Ambre (M. Coltorti, unpublished data), or postulated in the sources of the nearby active Comores archipelago, NW of Madagascar (Späth *et al*., 1996; Class and Goldstein, 1997), even though Coltorti *et al.* (1999) did not find amphibole in the mantle xenolith suites of Comores. Nevertheless, the presence of *residual* amphibole is not evident from the lava geochemistry (Melluso and Morra, 2000; Melluso *et al*., 2007). In our opinion, the genesis of such low-silica magmas as olivine melilitites is to be linked to melting mantle rocks without orthopyroxene (and possibly without amphibole) and with significant H_2O+CO_2, possibly hosted in phlogopite- and carbonate-bearing garnet wehrlites

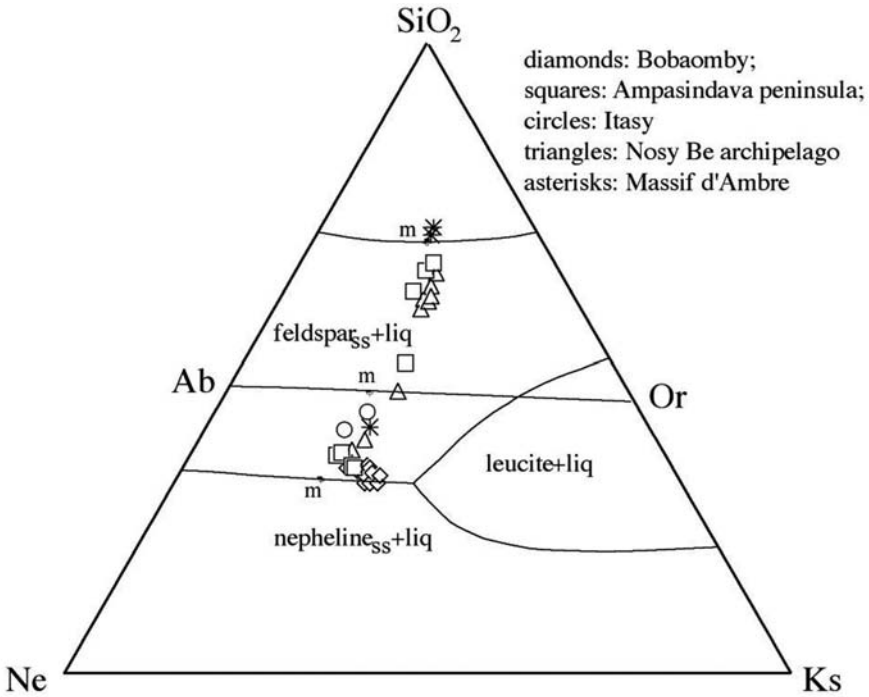

Fig. 4 — Nepheline-kalsilite-silica diagram at 1 kbar P_{H2O} (Hamilton and MacKenzie, 1965) for the evolved rocks of Madagascar.

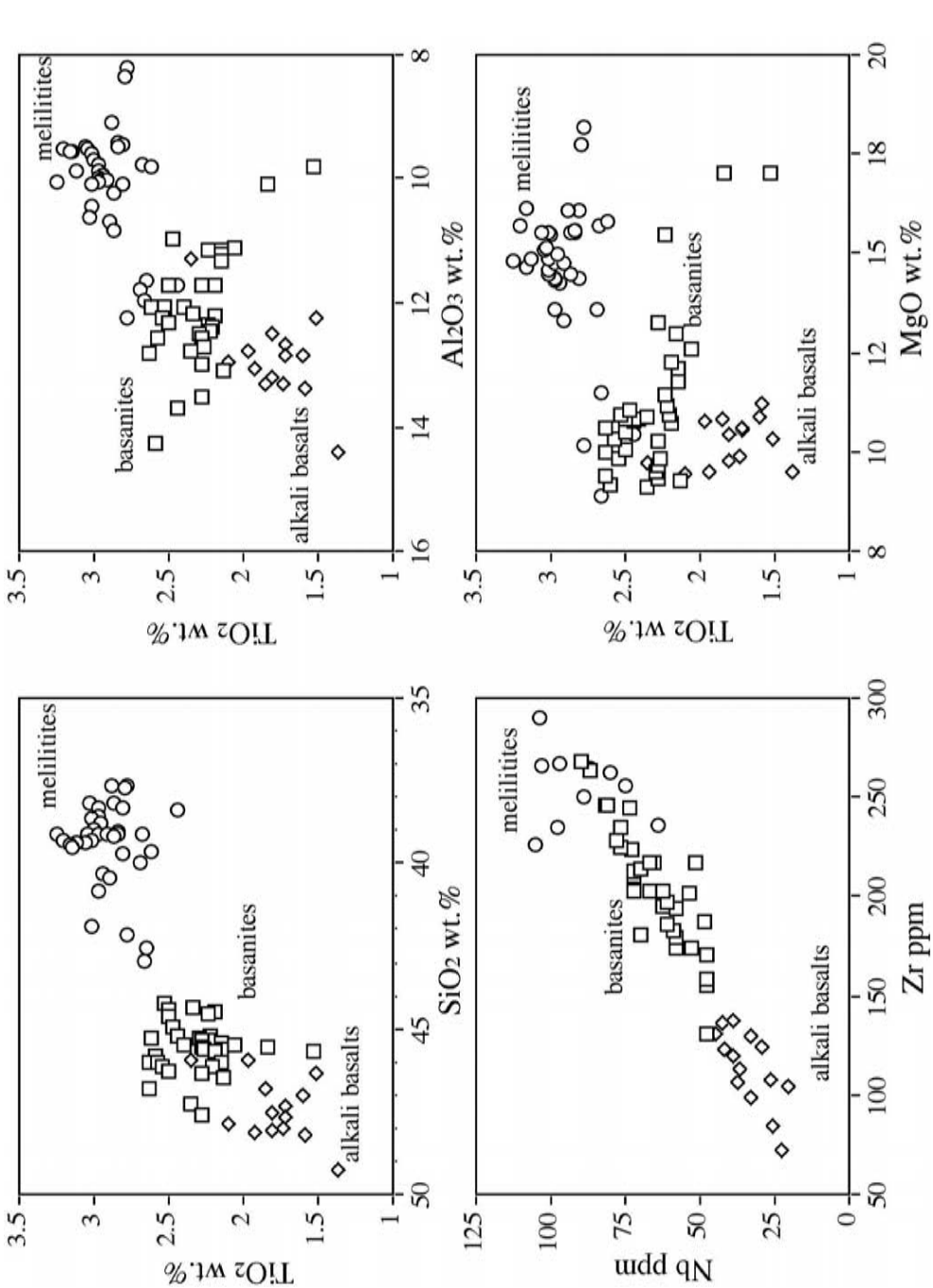

Fig. 5 — TiO_2-SiO_2, TiO_2-Al_2O_3, TiO_2-MgO and Zr-Nb diagrams (oxides in wt.%, trace elements in ppm) of the Cenozoic primitive mafic rocks (MgO>9 wt.%) of Madagascar. Note the broad overlap of incompatible trace element contents of basanites and olivine melilitites, but the sharp differences of major oxide contents, a likely result of change of the mineralogy of the sources, other than differing degrees of partial melting.

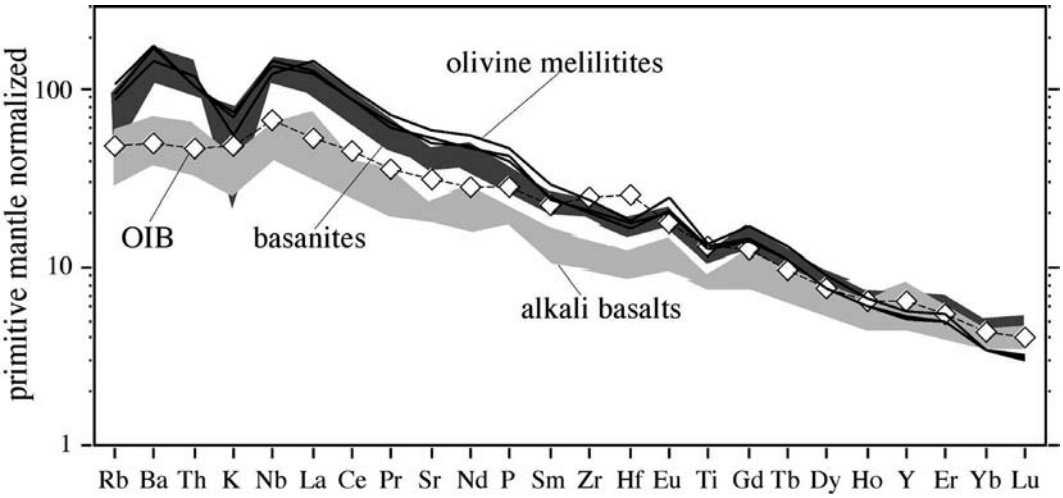

Fig. 6 — Primitive mantle-normalized incompatible element patterns of the Madagascan mafic volcanic rocks. The estimated primitive mantle values and the Ocean Island Basalt (OIB) composition are taken from Sun and McDonough (1989). The data of basanites are reported in Melluso and Morra (2000) and Melluso *et al.* (2007), the other data are unpublished.

(see also the experimental work of Brey and Green, 1977). These source rocks may be locally found in the deeper parts of the Madagascar lithosphere, or as "exotic" blobs in the asthenosphere (for instance, see Fig. 12 of Dunworth and Wilson, 1998), and melted during the Late Cenozoic rifting events which affected Madagascar.

Conclusions

The wide compositional range of the mafic, mantle derived, compositions, and of the associated evolved igneous rocks in the northern part of the Cenozoic igneous sequence of Madagascar has some interesting implications: not less than three different liquid lines of descent have been found, sometimes in the same volcanic complex, with production of late felsic derivatives ranging from phonolite to rhyolite. The mantle-derived magma compositions are represented by alkali basalts, basanites and olivine melilitites (±olivine nephelinites). The sources of alkali basalts and basanites may have suffered metasomatism, with formation of small quantities of mantle amphibole, and melted at various degrees, forming the feldspar-normative rocks after the complete exhaustion of the hydrous phase. The source of the olivine melilitites, though certainly formed after metasomatic events, may not be a typical lherzolite, due to the larnite-normative magma compositions that were generated, and could possibly be a CO_2-H_2O-rich wehrlite.

Further geochronological, petrological and geochemical work on the rocks of this province will clarify the relationships with tectonic activity, lithospheric thickness, postulated existence of Cenozoic mantle plumes beneath Madagascar, and internal evolution of volcanic/plutonic complexes.

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