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Gem corundum deposits of Madagascar: A review

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ABSTRACT

Madagascar is one of the most important gem-producing countries in the world, including ruby and sapphires. Gem corundum deposits formed at different stages in the geological evolution of the island and in contrasting environments. Four main settings are identified: (1) Gem corundum formed in the Precambrian basement within the Neoproterozoic terranes of southern Madagascar, and in the volcano-sedimentary series of Beforona, north of Antananarivo. In the south, high-temperature (700 to 800 °C) and low-pressure (4 to 5 kbar) granulites contain deposits formed during the Pan-African orogenesis between 565 and 490 Ma. They accompany mafic and ultramafic complexes (ruby deposits of the Vohibory group), skarns at the contact between Anosyan granites and the Proterozoic Tranomaro group (sapphire deposits of the Tranomaro–Andranondambo district), and shear-zone corridors cross-cutting feldspathic gneisses, cordieritites and clinopyroxenites in the Tranomaro, Vohimena and Androyan metamorphic series (biotite schist deposits of Sahambano and Zazafotsy, cordieritites of Iankaroka and Ambatomena). The circulation of fluids, especially along discontinuities, allowed *in-situ* alkaline metasomatism, forming corundum host rocks related to desilicified granites, biotitites, “sakenites” and “corundumites”. (2) Gem corundum also occurs in the Triassic detrital formations of the Isalo group, as giant palaeoplacers in the Ilakaka–Sakaraha area. Here, sapphires and rubies may come from the metamorphic granulitic terranes of southern Madagascar. (3) Gem corundum deposits occur within the Neogene-Quaternary alkali basalts from Ankaratra (Antsirabe–Antanifotsy area) and in the Ambohitra Province (Nosy Be, Ambato and Ambondromifehy districts). Primary deposits are rare, except at Soamiakatra where ruby in gabbroic and clinopyroxenite xenoliths within alkali-basalts probably derive from mantle garnet peridotites. The blue-green-yellow sapphires typical of basaltic fields are always recovered in palaeoplacer (in karst formed upon Jurassic limestones from the Montagne d'Ambre, Antsiranana Province) and alluvial and soil placers (Ankaratra volcanic massif). (4) Deposits occur within Quaternary eluvial, colluvial and alluvial concentrations, such as high-quality rubies from the Andilamena and Vatomandry deposits.

1. Introduction

Our knowledge of the mineralogy of Madagascar started at the beginning of the 20th Century during French colonisation (Lacroix, 1922a). Today, gemstones are of great economic importance to Madagascar, with ruby and sapphire (Schwarz et al., 1996; Mercier et al., 1999; Schwarz et al., 2000; Schwarz and Schmetzer, 2001; Razanatseheno et al., 2005) representing the main export of uncut and cut gems from the country. However, the low prices of the Madagascan rough gems and clandestine exportation, combined with the early good results obtained by Thai treatments, have lowered gem corundum values.

Corundums from different parts of the island of Madagascar (Lacroix, 1922a) were exploited as refractory material (Besairie,

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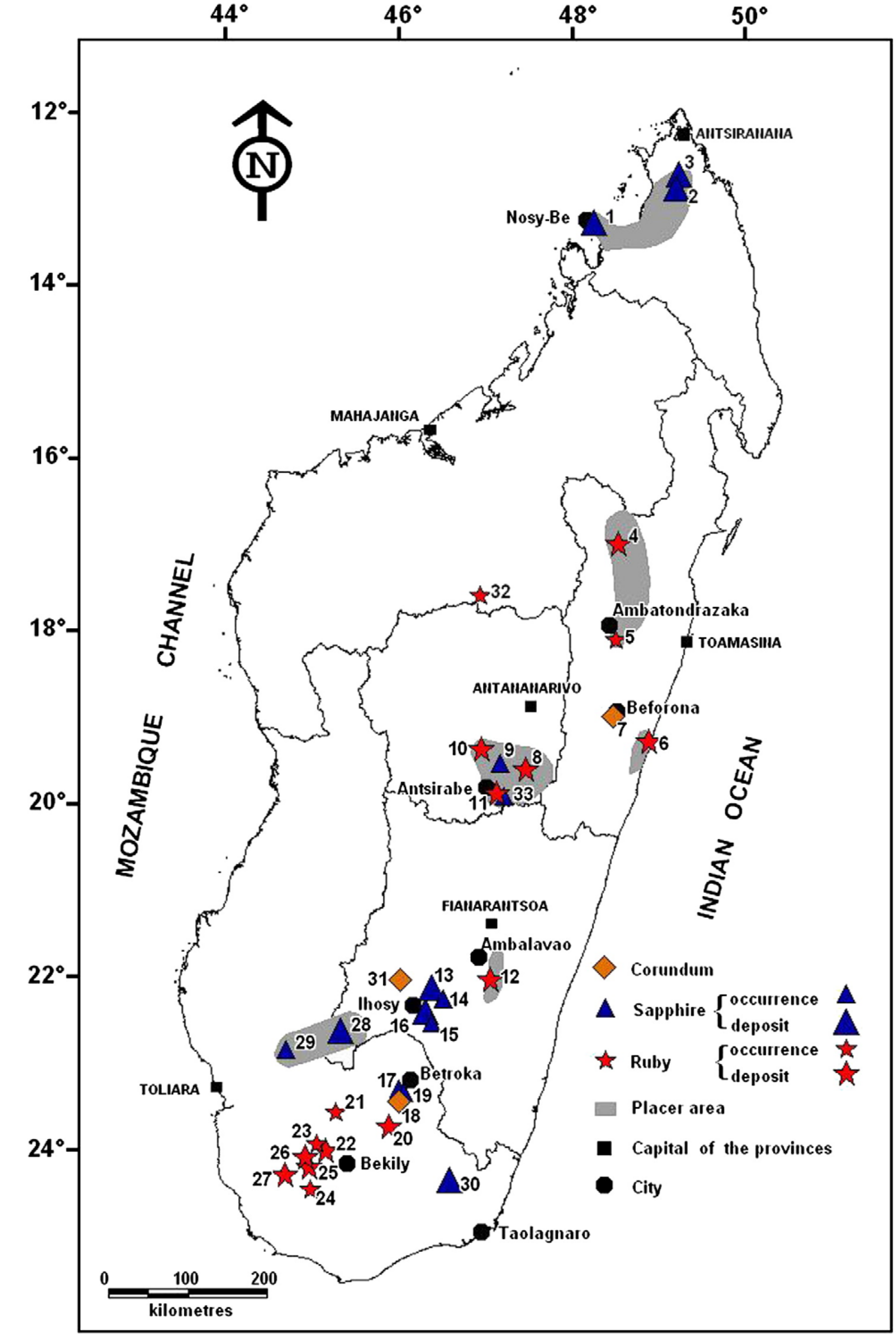

Fig. 1. The sapphire, ruby and corundum occurrences and deposits of Madagascar. 1: Nosy–Be, 2: Ambondromifehy, 3: Anivorano, 4: Andilamena, 5: Didy, 6: Vatomandry, 7: Ambohitranefitra (Beforona), 8: Antsahanandriana, 9: Mandrosohasina, 10: Faratsiho, 11: Soamiakatra, 12: Miarinarivo, 13: Zazafotsy, 14: Sakalalina, 15: Ambinda (Ihosy), 16: Sahambano, 17: Ambinda (Betroka), 18: Vohidava (Voronkafotra), 19: Iankaroka, 20: Ambatomena, 21: Ianapera, 22: Fotadrevo, 23: Anavoha, 24: Maniry, 25: Gogogogo, 26: Vohitany, 27: Ejeda, 28: Ilakaka, 29: Sakaraha, 30: Andranondambo, 31: Sakeny, 32: Andriba, 33: Anjomakely.

1966). Gem-quality corundum was rarely noted until 1986 when Schmetzer mentioned rubies from Vatomandry and Gogogogo, and later, Salerno (1992) described the polychrome sapphires from Iankaroka, in the southwest of Betroka, in the province of Tulear (see Fig. 1). Since 1993, large amounts of sapphires have been recovered from the Andranondambo metamorphic skarn-type deposit in southern Madagascar (Rakotondrazafy, 1995) and from alluvial deposits linked to basaltic rocks in the northern region (Schwarz et al., 2000). Most of the rubies on the market at the end of 2000 came from the secondary deposits of Andilamena and Vatomandry, in eastern Madagascar (Schwarz and Schmetzer, 2001). The discovery in late 1998 of the first giant alluvial sapphire and ruby deposits in the Ilakaka area foreshadowed the recovery of large quantities of fine gemstones from Madagascar. Since the classic three-volume book of Lacroix, “Minéralogie de Madagascar” which was published in 1922, most geological and/or gemmological studies focused only on specific

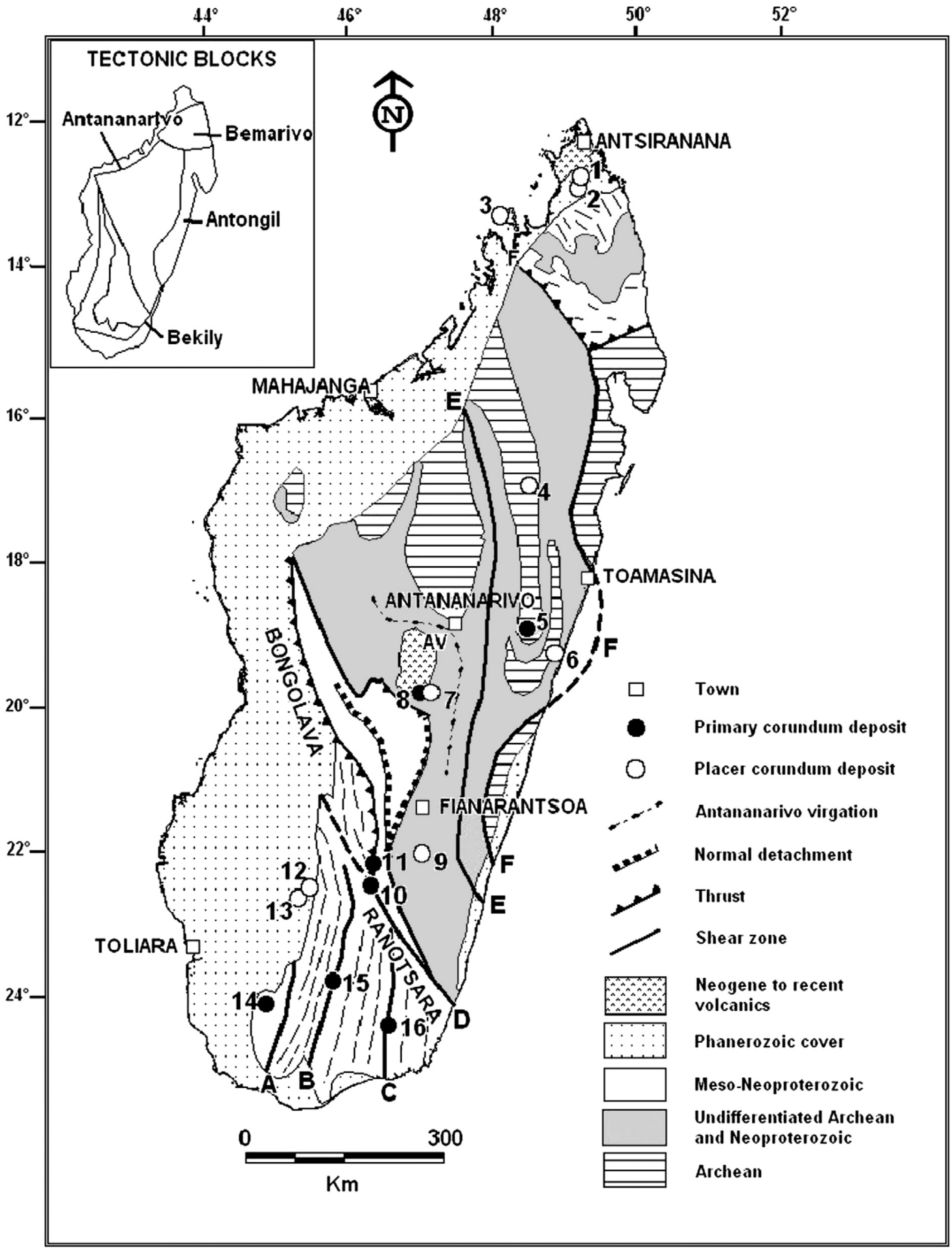

Fig. 2. Precambrian geology and main placers and primary deposits of Madagascar (modified from de Wit, 2003). Shear zones: A = Ampanihy, B = Vorokafotra, C = Tranomaro, D = Ranotsara–Bongolava, E = Ifondiana–Angavo, F = Betsimisaraka. Placer corundum deposits with 1 = Anivorano, 2 = Ambondromifehy, 3 = Nosy Be, 4 = Andilamena, 6 = Vatomandry, 7 = Kianjanakanga-Mandrosohasina; 9 = Miarinarivo, 12 = Ilakaka; 13 = Sakahara. Primary deposits with 5 = Ambohitranefitra (Beforona), 8 = Soamiakatra, 10 = Sahambano, 11 = Zazafotsy, 14 = Ejeda–Fotadrevo area, 15 = Ambatomena, 16 = Andranondambo.

deposits, especially the Andranondambo skarn-type deposit (Rakotondrazafy et al., 1996; Kiefert et al., 1996; Schwarz et al., 1996; Gübelin and Peretti, 1997), the Ejeda–Fotadrevo ruby district (Nicollet, 1986; Milisenda and Henn, 1996; Mercier et al., 1999) and the Ambondromifehy–Nosy Be basaltic sapphire type deposit (Schwarz et al., 2000; Rhamdhor and Milisenda, 2004). This present overview of corundum

Table 1
Synthesis of the main geologic and isotopic features of the different types of corundum deposits in Madagascar

Deposit	Sahambano (S) Zazafotsy (Z)	Iankaroka	Ambatomena	Vohitany (V) Ejeda (E) -Gogogogo (G)	Andranondambo	Beforona	Sakeny (Sk) Vohidava (Vo)	Soamiakatra
References	1, 2, 3	1, 4	1, 3	1, 5, 6, 7, 8	1, 9, 10, 11	12	12, 13	14
Genetic model	MM	M-MM	MM	M-MM	MG-HM	MG or MG-HM?	M-MM ?	M
Tectonic Unit	S: Southern Madagascar Z: Itremo sheet	Southern Madagascar	Southern Madagascar	Southern Madagascar	Southern Madagascar	Antananarivo Block	Southern Madagascar	Antananarivo Block
Formation and/or series	S: Tranomaro group Z: vohimena series	Androyan series	Androyan series	Vohibory series	Tranomaro group Anosyan granite	contact Manampotsy and Beforona groups	Androyan series	Ambatolampy series Ankaratra volcanism
Host rock	Metamorphic Feldspathic gneiss Intercalated with leptynite	Metamorphic Cordieritite intercalated With charnockite	Metamorphic Cordieritite (and pegmatite) In charnockites	Metamorphic *Amphibolite and pyroxenite Within M–UM (E–G–V) *Anorthosite layers (E–G) *Metasomatised Pegmatite in M–UM (V)	Skarn Fissural skarn	Magmatic Syenite	Metamorphic Sakenite vein	Volcanic Clinopyroxenite enclave In alkali basalt
Wall rocks	Biotitised gneisses Biotitite	Cordieritite Fissural Mg-biotitite	Metasomatised Cordieritite	*Amphibolite *Anorthosite *Biotitite and plagioclasite	Impure marble Pyroxenite Calc-silicate gneisses	Biotite gneiss Micaschist	Paragneiss, Amphibolite, Pyroxenite	Alkali basalt
Mineralization Control	Shear zone Fluid-rock interaction	Shear zone Fluid-rock interaction	Shear zone Fluid-rock interaction	Shear zone Fluid-rock interaction	Veinlet in skarn Fluid-rock interaction	Irregular vein Lens-like	Vein	Pyroxenite
Typical mineral Assemblage	Biotite–sapphire- Saphirine-plagioclase- K-feldspar-garnet-spinel	Phlogopite-cordierite- Sapphire-tourmaline- Spinel-saphirine	Cordierite-rutile-phlogopite Saphirine-plagioclase- Ruby	(V): Hornblende-ruby-plagioclase-spinel-phlogopite	K-feldspar-sapphire- F-apatite-calcite- Phlogopite	Biotite-sillimanite- Albite-sapphire- Microcline	Saphirine-sapphire Spinel-pyroxene- Plagioclase-edenite	Clinopyroxene-ruby- Amphibole-anorthite- Scapolite-garnet
Metamorphism	Granulite facies	Granulite facies	Granulite facies	Granulite facies	Granulite facies	Granulite facies	Granulite facies	Granulite facies
	T=700 °C P=5 kb (15)	T=750 °C P=5-6 kb (15)	T=750 °C P=5-6 kb (15)	T=730-870 °C P=9-11 kb (5, 7)	Tsaphir=500 °C Psaphir=2 kb (16)	T=? P=?	T=700 °C P=4-5 kb (12, 15)	T=1100 °C P=20 kb (14)
Age of the mineralization	Ar–Ar biotite (17) S: 492±5 Ma* Z: 494±5 Ma*	Ar–Ar biotite (17) No age (disturbed spectrum)	Ar–Ar biotite (17) 487±4 Ma*	Ar–Ar biotite Vohitany (17) No age (disturbed spectrum)	U/Pb zircon (18, 19) 565±15 Ma (18) 516±10 Ma (19)* 523±5 Ma (18)*	?	?	Alkali basalt (20) Miocene to Quaternary
Corundum	Multi-colored sapphire	Polychrome sapphire	Ruby	Ruby	Light to dark blue, pink sapphires	Red to purplish blue to grey sapphire	Grey-white to yellow sapphire	Ruby
$\delta^{18}O$ corundum (‰, V-SMOW)	S: 5.9±0.3 (n=5) Z: 8.9±0.1 (n=2)	2.05±0.5 (n=2)	2.9 (n=2)	V: $5.4<\delta^{18}O<6.1$ (n=2) E: 5.0; 5.9; G: 3.8	$10.1<\delta^{18}O<10.9$ (n=4) $14.0<\delta^{18}O<15.6$ (n=4)	8.1	Vo: 5.8 Sk: 4.9	$1.25<\delta^{18}O<4.7$ (n=2)

Abbrevations: M = Metamorphic, MM = Metamorphic metasomatism, MG = Magmatic, MG-HM = Magmatic-hydrothermal metasomatism, M-UM = Mafic-ultramafic rocks, * = sapphire mineralization.
References: 1 = Razanatseheno et al. (2005); 2 = Ralantoarison (2006); 3 = Andriamamonjy (2006); 4 = Koivula et al. (1992); 5 = Nicollet (1986); 6 = Nicollet (1990); 7 = Mercier et al. (1999); 8 = Pili (1997a,b); 9 = Rakotondrazafy et al. (1996); 10 = Rakotondrazafy (1995); 11 = Schwarz et al. (1996); 12 = Lacroix (1922a,b); 13 = Devouard et al. (2002); 14 = Rakotosamizanany (2003); 15 = Nicollet (1985); 16 = Ravolomiandrinarivo et al. (1997); 17 = Giuliani et al. (2007); 18 = Paquette et al. (1994); 19 = Andriamarofahatra and de La Boisse (1986); 20 = Besairie and Collignon (1972).

deposits in Madagascar is based on the currently known main deposits and occurrences (Rakotondrazafy et al., 2005) and is a synthesis of the literature published since the work of Lacroix.

2. The corundum deposits of Madagascar

Precambrian rocks are exposed in the eastern two thirds of Madagascar whereas the western third is composed of Late Palaeozoic to Recent sedimentary rocks and Late Cenozoic volcanic rocks (Fig. 2). Most corundum deposits occur in the areas of Precambrian exposure. Primary deposits can be grouped into three geological settings (Table 1). These are: (i) magmatic settings in syenite, granite and alkali basalt; (ii) metamorphic settings; and (iii) associated with alkaline metasomatism in the Precambrian rocks (gneiss, acidic and mafic to ultramafic granulites). The secondary deposits are detrital and include the palaeoplacers of the Triassic Isalo sediments in the southwestern part of Ihosy, volcanic-derived placers from Ankaratra in the central plateau and the Montagne d'Ambre provinces in the north, and those of unknown origin for the Andilamena and Vatomandry ruby placers.

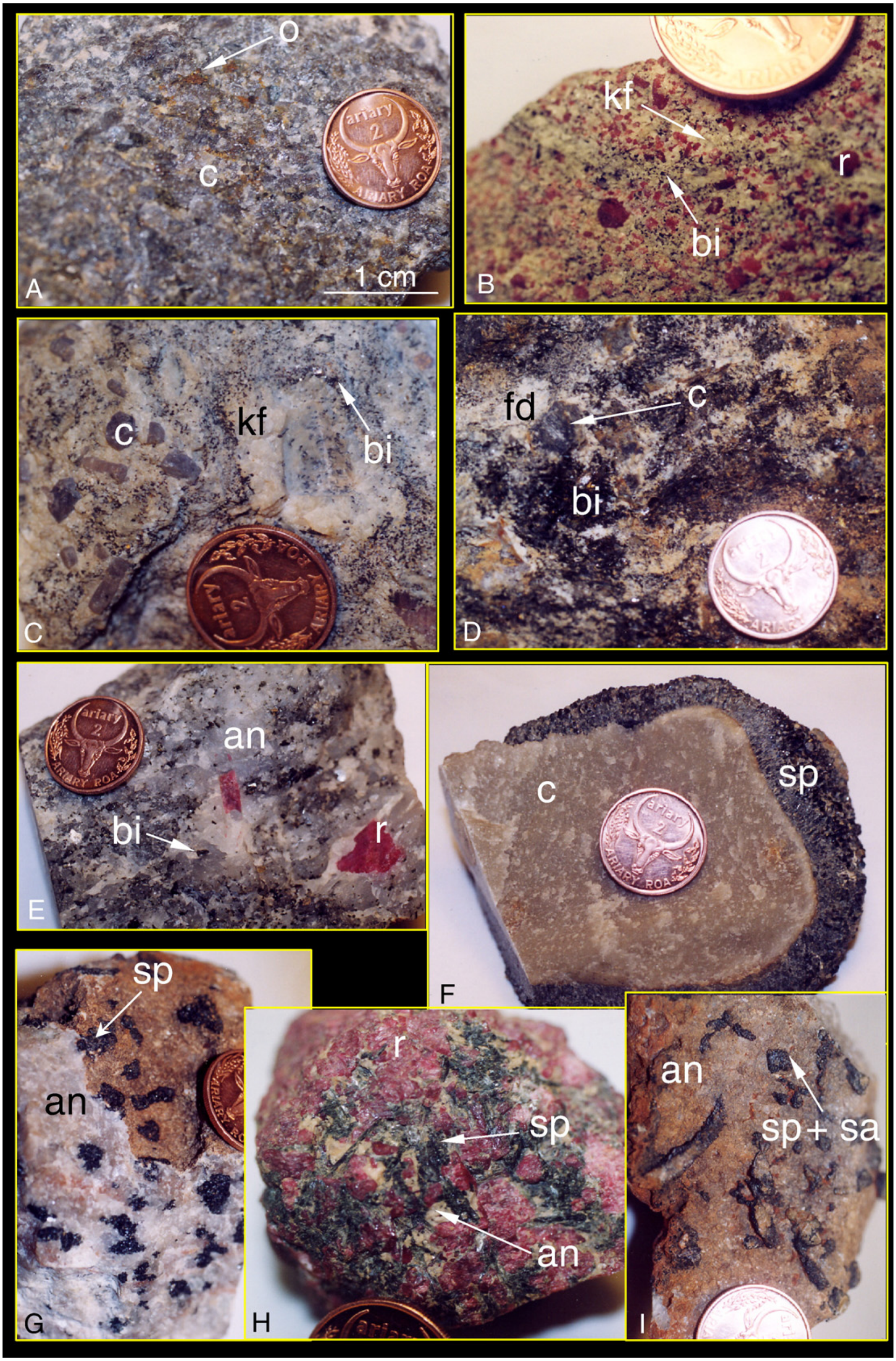

Fig. 3. The metamorphic corundum deposits of Madagascar. (A) The syenite from Antohidrano, near Sahomaloto (Beforana area). o: iron oxides; c: grey corundum. Lacroix MNHN collection (sample 1f). (B) Ruby-bearing "syenite" from the Ambohitranefitra (Ambafotsy, Beforona area). Ruby (r) is disseminated in a matrix of K-feldspar (kf) and biotite (bi). Lacroix MNHN collection (sample 6y). (C) The Ambohitranefitra deposit. Retromorphic textures with the formation of K-feldspar corona (kf) around corundum (c). The matrix is made of biotite (bi) and K-feldspar. Lacroix MNHN collection (sample S262). (D) The Anjomakely sapphire occurrence. Grey to pinkish sapphire (c) disseminated in a mica schist composed of biotite (bi) and K-feldspar (fd). Lacroix MNHN collection (sample 79φ). (E) The Anavoha "sakenite" in the Bekily area. Ruby (r) is disseminated in a matrix of anorthite (an) and biotite (bi). Lacroix MNHN collection (sample 199p). (F) The "corundumite" of Sakeny (Ihosy area). A corundum crystal (c) surrounded by a corona of spinel + sapphirine (sp). Lacroix MNHN collection (sample 87p). (G) A "sakenite" composed of anorthite (an) and spinel (sp). Lacroix MNHN collection (sample 88p). (H) "Corundumite" from the Ihosy area. The rock contains ruby (r), spinel (sp) and anorthite (an). Lacroix MNHN collection (sample 95f). (I) A "sakenite" from Sakeny (Ihosy area). The crystals of spinel and sapphirine (sp + sa) are disseminated in an anorthitic matrix (an). Lacroix MNHN collection (sample 88p). MNHN: Muséum National d'Histoire Naturelle (Paris).

Fig. 4. The primary gem-corundum deposits of Madagascar. (A) General view of the Soamiakatra ruby mine in 2003. The deposit is located in an alkali basalt plug intruding khondalite, biotite gneiss and quartzite (gn). The superficial weathered portion of the basalt was exploited (white soils, s) and remnants of fresh portion of the basalt are in the bottom part of the pit (b). (B) Typical ruby-bearing xenolith of the Soamiakatra basaltic plug composed of plagioclasite (pl, anorthite) and clinopyroxenite (clinopyroxene, amphibole, anorthite). The two-mm-sized pink ruby (r) is contained in the xenolith carried by the basalt (b). (C) Formation of the sapphire-bearing biotitites along fracture planes which affect feldspathic gneiss (Momo pit, Sahambano deposit, Ihosy). The biotite schist (b) is developed upon the garnet-bearing feldspathic gneiss (gn_1) and the sapphirine-bearing gneiss (s). A boudinaged-pegmatite (p) is cross-cut by the biotitite. The western border of the pit comprises a biotite–garnet–migmatic gneiss (gn_3). gn_1 = banded-garnet-bearing gneiss; gn_2 = sillimanite–biotite–garnet-bearing gneiss. (D) The ruby-bearing cordieritite of the Ambatomena deposit (south of Betroka). Ruby crystals are contained in a cordierite-sapphirine-anorthite ± phlogopite ± K-feldspar-bearing rock (c_2) at the contact of a cordierite-sapphirine-phlogopite rock (c_1). Ruby presents a coronitic texture made of spinel and sapphirine with sometimes a complete substitution of the corundum crystal (s). (E) Phlogopitites (phl) in the Ambatomena deposit that illustrate the circulation of fluids along the lithologic contact between the biotite–cordierite-bearing gneiss (gn), the pegmatite (p) and the cordieritites (c). The pegmatite is transformed into anorthitite (a) and the gneiss is highly phlogopitised (phlgn). (F) Pink sapphire contained in a biotitite (b) developed upon a feldspathic gneiss from the Zazafotsy deposit (NE of Ihosy). The size of the crystals is around 1 cm. (G) Aspect of the multi-coloured sapphire crystals from the Sahambano deposit. The size of the pink crystal in the centre of the photograph is around 8 mm. (H) A pink to fuchsia coloured sapphire in a garnet-bearing biotite schist (b) from the Zazafotsy deposit. The 2 cm-long crystal is embedded in a K-feldspar (f) and spinel (sp) coronitic zone. g = garnet.

2.1. Magmatic-hosted deposits

Syenite, “granite” and alkali-basalts host these deposits, which include sapphire-bearing syenites from the Ambohitranefitra deposit in the Beforona region; ruby and sapphire in desilicified granites and feldspathised host-rock from the Anjomakely areas; and ruby in alkali-basalts from the Soamiakatra deposit in the Antsirabe-Antanifotsy region (Fig. 1).

Table 2
Chemical composition of ruby and sapphires (in wt.%) from the Sahambano, Zazafotsy, Soamiakatra and Ilakaka deposits

Sahambano												
Colour	Red	Fuchsia	Purpley-pink	Pink	Dark pink	Pinky orange	Orange	Vert de gris	Brown to yellow-violet	Blue	Light blue	Colourless
Al_2O_3	99.2	99.67	99.08	99.8	99.6	99.28	99.9	98.67	99.38	99.35	99.41	97.99
MgO	0.01	0.01	0.01	0.01	0.01	0.01	0.007	0.01	0.010	0.01	0.009	0.01
TiO_2	bdl	bdl	0.01	0.01	bdl	bdl	bdl	0.01	0.01	0.013	0.01	0.01
V_2O_3	bdl	bdl	0.008	bdl	bdl	bdl	bdl	bdl	0.01	0.006	0.009	bdl
Cr_2O_3	0.21	0.25	0.140	0.1	0.07	0.1	0.047	0.04	0.094	0.059	0.096	0.027
FeO	0.27	0.29	0.33	0.28	0.27	0.24	0.28	0.29	0.32	0.301	0.293	0.25
Ga_2O_3	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.013	0.01	0.02
Total	99.71	100.24	99.60	100.21	99.97	99.65	100.25	99.04	99.83	99.75	99.84	98.31
Zazafotsy												
Colour	Fuchsia	Dark pink	Brown to violet	Purple	Pinky orange to violet	Orange to violet	Mauve to light pink	Light pink	Blue	Light blue	Greyish to light blue	
Al_2O_3	98.63	98.64	99.22	98.66	99.25	98.64	99.51	99	99.14	99.07	100.04	
MgO	0.01	0.01	bdl	0	0.01	0.01	0.01	0.01	0.01	bdl	0.01	
TiO_2	bdl	0.01	0.010	0.01	0.01	0.01	0.01	0	0.01	0.02	0.02	
V_2O_3	0.01	0	0.01	0.01	0.01	0	0	0.01	0.01	0.01	0.01	
Cr_2O_3	0.19	0.11	0.16	0.14	0.15	0.11	0.14	0.11	0.050	0.03	0.03	
FeO	0.3	0.31	0.29	0.29	0.31	0.31	0.310	0.31	0.31	0.31	0.21	
Ga_2O_3	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	
Total	99.14	99.08	99.71	99.12	99.75	99.09	100.00	99.44	99.54	99.44	100.33	
Soamiakatra										Ilakaka		
Ruby										Ruby		
Al_2O_3	98.27	99.61	97.55	97.73	96.64	98.16	97.70	97.80	97.18	97.85	97.66	97.39
MgO	na	na	na	na	na	na	na	na	na	na	na	na
TiO_2	0.09	0.01	0.02	0.03	0.04	0.03	0.04	0.05	0.03	0.01	bdl	bdl
V_2O_3	0.01	0.01	bdl	bdl	0.04	0.06	0.06	bdl	0.09	bdl	bdl	bdl
Cr_2O_3	0.38	0.04	0.630	0.730	0.99	0.86	0.93	0.8	0.830	0.22	0.33	0.56
FeO	0.56	0.33	0.5	0.52	0.51	0.52	0.53	0.53	0.51	0.26	0.2	0.27
Ga_2O_3	bdl	0.01	0.01	0.01	0	0.010	0.01	0.01	0.01	0.01	0.01	bdl
Total	99.32	99.99	98.72	99.03	98.22	1.48	99.27	99.19	98.64	98.35	98.20	98.22

bdl = below detection limit; detection limits for the trace elements (in ppm): Mg=34; Ti=22; V=22; Cr=26; Fe=24; Ga=43.
CAMECA SX100 electron microprobe (University Nancy I), with operating conditions of: accelerating voltage 15 kv, beam current 10 nA, collection time of 20 s for aluminium, and 25 kv, 150 nA, 120 s for trace elements.

The *Ambohitranefitra deposit*, also known as the Beforana syenitic occurrence, is 20 km south of the city of Beforona. Corundum in the alluvium of the Sahamaloto, Marofody and Tsarafosa Rivers, was exploited for refractory material at the beginning of the 20th Century. The corundum was sorted by hand-picking directly in the river, or by pits in the banks. In 20 years, total production reached 3000 tons of corundum (Lacroix, 1922a) but only 20 tons per year were extracted until 1927, with a grade of 40 kg/m^3 (Duclos, 1927). The mineralised pebbles consisted of small cm-sized ruby, pink or grey to blue “corundumite” (Fig. 3A) composed of corundum and sillimanite with crystals of sapphires up to 150 mm, and syenite composed of disseminated red corundum (Fig. 3B) with K-feldspar, sillimanite and spinel (Razafimanantsoa, 1961). Today, exploitation has ceased.

The primary deposit, a syenitic vein injected concordantly into a migmatitic biotite–graphite-bearing gneiss (Lacroix, 1922b), became hidden by a landslide in the mid 20th century, but a nearby corundum-bearing pegmatite is also injected into the gneiss. The deposit lies at the contact zone between the Manampotsy and Beforona Groups; between migmatites and granitoids of the Brickaville and the Manampotsy Series, and the Beforana volcano-sedimentary series of amphibole-bearing gneiss, migmatites and amphibolites. The 1 to 2 km wide contact zone consists of migmatites, biotite–sillimanite gneisses and khondalites, following a N–S trend along a 40 km-long strike. Intercalations of graphite or sillimanite or garnet layers accompany the corundum-bearing syenitic injection into the mineralised zone (Lacroix, 1922b).

The above deposit is fine-grained and is composed of biotite and microcline (48%), sillimanite (42%), corundum (4%), zircon and magnetite. The proportion of sillimanite is highly variable, with some rocks composed of microcline, biotite and corundum (Fig. 3C). It is an “endomorphic syenite” which exhibit retromorphic textures characterized by the presence of K-feldspar coronas around corundum, suggesting a metasomatic transformation of the initial rock (Fig. 3C). Finally, disseminations of mm- to cm-sized rubies in the “endomorphic syenite” composed of feldspar and biotite (Fig. 3B) indicate that the quantity of chromium in the rock, or carried by the mineralising fluid, changed within the vein.

Crystals of euhedral corundum between 10 to 80 mm in size show either barrel-shaped habits with dominant hexagonal dipyramid ω combined with the basal pinacoid c and the rhombohedron r, or hexagonal dipyramid ω elongated following the c-axis or flattened following the pinacoid (Lacroix, 1922a).

South-east of Antsirabe, corundum-bearing desilicified granites and feldspathised micaschists form the *Anjomakely occurrence* (Lacroix, 1922a; Fig. 1). At the contact with the micaschists, the granite is desilicified. Quartz disappears while microcline, sillimanite, biotite, zircon and magnetite remain. Sapphire crystals of cm- to dm-size are dominantly grey, with variation to light pink. The schists are intensely metasomatised and composed of feldspar, biotite and corundum (Fig. 3D). The sapphire is rimmed by K-feldspar, in the Beforona syenite occurrence.

Other corundum-bearing micaschists unrelated to granites also occur nearby in Ankazondrano, Ambatomitety, Bilisy, Ambohimanarivo, Ambohimilemaka, Vatondrangy and Rafanjaka. These contain sillimanite and muscovite enveloped by large lamellae of biotite. Corundum forms porphyroblasts up to 10 cm in width. Lacroix noted that these micaschists form lenses within the garnet, tourmaline and sillimanite-bearing micaschist series. Similar occurrences also lie to the north (Tsinjoarivo), and to the west of Antsirabe city (Rafanjaka,

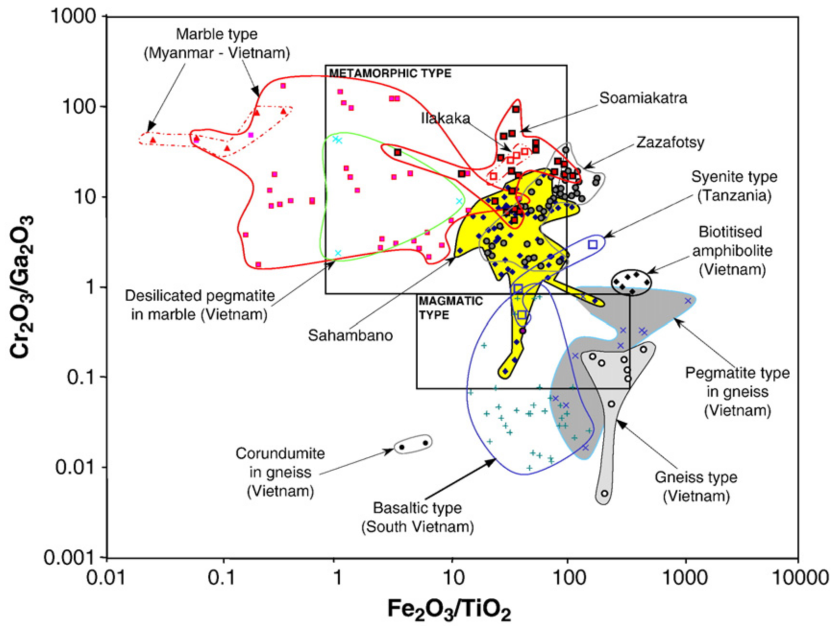

Fig. 5. Plot of the chemical composition of sapphires and rubies from Ilakaka, Soamiakatra, Zazafotsy and Sahambano in the Fe_2O_3/TiO_2 vs Cr_2O_3/Ga_2O_3 diagram. All the chemical data fit in the metamorphic field defined for corundum by Sutherland et al. (1998a, 2003). The geochemical fields of Sahambano and Zazafotsy sapphires overlap showing the similarity of these two deposits hosted by feldspathic gneisses. The reported geochemical fields of Vietnamese rubies and sapphires are from Pham Van et al. (2004) and the syenite field of the sapphires from Garba Tula in Tanzania is from Simonet et al. (2004).

Belanitra, Vohitrakanga and Antandrokomby), where they were the first source of industrial corundum in Madagascar (Lacroix, 1922a). A metasomatic origin is likely, but whether this is linked to granite or metamorphism requires further study.

The *Soamiakatra deposit* lies 35 km south of the Antanifotsy region in central Madagascar. Since 1997, corundum has been extracted by pans from alluvium and soils, but prospecting and mechanisation of operations has exposed the primary deposits (Fig. 4A). Ruby in Soamiakatra is found in clinopyroxenite xenoliths hosted by Cenozoic alkali basalts which intrude the graphitic gneisses and migmatites of the Ambatolampy and Tolongoina series (Rakotosamizanany et al., 2005). The clinopyroxenite contains Al-rich clinopyroxene, garnet (pyrope-almandine), plagioclase (bytownite–labradorite), scapolite, corundum and amphibole (Fig. 4B). Ruby crystals are euhedral to anhedral with globular or tabular habits, up to 20 mm in size, with pink to purplish blue to deep red colours. Mineral inclusions in ruby consist of Mg-rich phlogopite, rutile with some lamellar exolutions of ilmenite, zircon, albite, pyroxene, garnet, and Cr-bearing spinel. The trace element chemistry of ruby (Table 2) from this deposit is characterised by low Ga_2O_3 (between 70 and 110 ppm) and high Cr_2O_3/Ga_2O_3 ratios (Fig. 5). The vanadium content varies from less than 22 ppm up to 860 ppm. Titanium ranges between 60 to 940 ppm, and chromium between 350 to 3830 ppm. The Soamiakatra rubies fall into the metamorphic domain defined by Sutherland et al. (1998a, 2003) when plotted in the Fe_2O_3/TiO_2 vs Cr_2O_3/Ga_2O_3 diagram (Fig. 5).

The corundum-garnet-clinopyroxene assemblage in the clinopyroxenite gave a temperature of formation of ruby around 1100 °C at a pressure of ~20 kbar (Rakotosamizanany, 2003). We hypothesise that the ruby formed in mafic and ultramafic rocks at the base of the lower crust and was later transported to the surface by the alkali basalts. The oxygen isotopic composition of this ruby ($\delta^{18}O = 4.7‰$; Giuliani et al., 2005) falls within the isotopic range defined for ruby in mafic and ultramafic rocks ($3.2 < \delta^{18}O < 6.8‰$), confirming this origin.

2.2. Metamorphic-hosted deposits

Corundum deposits are hosted in the Precambrian granulitic domain of southern Madagascar (Fig. 6). This basement includes remnants of early crust (de Wit, 2003) which were intensely reworked between 950 and 450 Ma, during Pan-African tectonometamorphic events (Kröner, 1984). The collision processes between East and West Gondwana created Neoproterozoic (~650 Ma) mobile belts, mostly metamorphosed to high-grade granulite. These high and low pressure granulites are well-exposed throughout south-eastern Madagascar. They are divided into four major lithostratigraphic groups (Besairie, 1967; de Wit, 2003) corresponding to the juxtaposition of tectonic blocks of different crustal levels (Martelat et al., 1997, 2000; de Wit et al., 2001). This patchwork is due to the relative movements of major ductile shear zones reflecting a crustal-scale strike-slip system. Rocks in all blocks suffered metamorphism around 750 °C. The pressure shows an E–W increase from 3 to 5 kbar in the east to 8 to 11 kbar in the west (Nicollet, 1990). Granitoids are abundant in the eastern part whereas anorthosites and metabasites are abundant in the west.

Corundum deposits in the different tectonic blocks are strongly associated with major or minor shear zones (Fig. 6). These structures acted as preferential fluid pathways and the parental rocks of corundum have suffered intense fluid-rock interaction resulting in much metasomatic alteration. The parental host-rock varies from feldspathic gneisses (Zazafotsy and Sahambano deposits), cordieritites (Iankaroka and Ambatomena), amphibolites and anorthosites (Ejeda, Fotadrevo, Vohitany and Gogogogo) to impure marbles (Tranomaro). The "sakenites" described by Lacroix (1941) are found in paragneiss with intercalations of amphibolites, clinopyroxenites and impure marbles (Sakeny, Vohidava, Ejeda–Anavoha and Andranondambo occurrences) and consist of plagioclasite veins or segregations with ± spinel ± corundum ± phlogopite and ± hibonite.

2.2.1. Deposits in feldspathic gneisses

The *Sahambano deposit*, 30 km east of Ihosy town (Fig. 1), was discovered in 1999 and is exploited by the mining company Tany Hafa S.A. The sapphire crystals are multicoloured but rarely of gem-quality, and treatment is necessary to improve colour and transparency: 100 kg of corundum picked in the washed material contained 24 kg of coloured sapphires with 1 kg of translucent crystals, but only 50 g of gem-quality (Offant, 2005). The division of the colour is 15% brown to orange, 5%

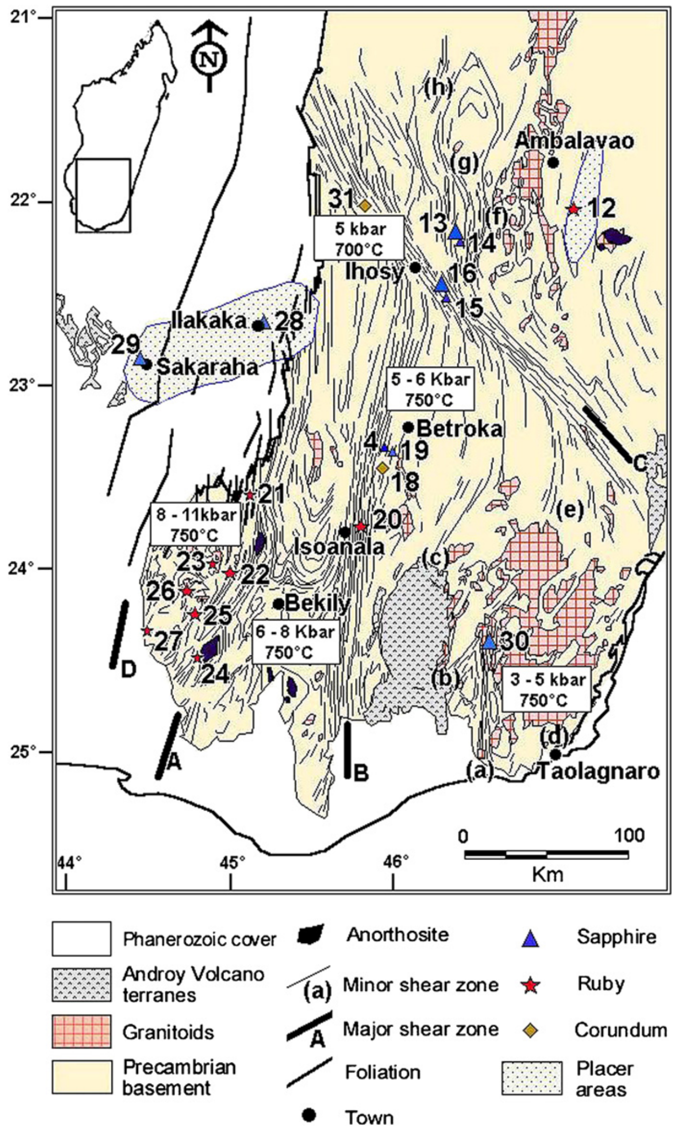

Fig. 6. Structural and lithological sketch map of southeast Madagascar with the location of the corundum deposits (modified from Martelat et al., 2000). Major shear zones: A = Ampanihy, B = Beraketa, C = Ranotsara, D = shear zone of the Phanerozoic cover. Minor shear zones referred as subpanels (a) to (h). The Pressures (kbar) and Temperatures (°C) are from Moine et al. (1985), Ackermand et al. (1989), and Nicollet (1990). The numbers of the individual corundum deposits are the same as in Fig. 1.

orange to pink, 40% pink to purple, 5% purple to fuchsia and 35% violet to blue.

The deposit occurs in the Tranomaro Group, characterized by a high-abundance of calcic and magnesian paragneiss and leptynite. It sits in the Ratnotsara shear zone, a 30 km wide and 300 km long steep structure, which has a long history of deformation and high-temperature metamorphism dated between 600 and 500 Ma (Martelat et al., 2000; de Wit et al., 2001; Collins and Windley, 2002). Ar–Ar dating of biotite from a sapphire-bearing biotitite gave a minimum age of formation at 492 ± 5 Ma (Table 1). Mylonitisation and dextral shears are common in the Sahambano area. The sapphires occur in feldspathic gneiss lenses intercalated within leptynite (pits of Dominique, Nono, Momo, Jeanne d'Arc and Ambinda Sud). Shearing opened fissures and fluid circulation resulted in the biotitisation of the host rock (Fig. 4C). Sapphire occurs in biotitites with sillimanite and spinel, and in gneiss composed of K-feldspar, biotite, sillimanite, spinel, sapphirine, garnet, and albite. The sapphires formed during prograde metamorphism at T ~ 650 °C and P ~ 5 kbar (Ralantoarison, 2006) according to the main reaction:

$$3\ \text{hercynite} + \text{K-feldspar} + H_2O \rightarrow 3\ \text{corundum} + \text{annite}$$

Euhedral crystals range from 1 to 50 mm in size and the sapphires display different colours according to their chromium and iron contents, including colourless, grey, greenish grey, orange, blue, dark pink, purple, brown, pink, and red to fuchsia (Fig. 4G). Crystals exhibit either short or long prismatic habits. They are often composed of a combination of rhombohedron, hexagonal prism and two basal pinacoids. Laminar and cylinder habits are composed of hexagonal dipyramids associated with pinacoids and/or hexagonal prisms. Mineral inclusions in sapphires are K-feldspar, zircon, barite, spinel, cheralite, sillimanite, diaspore, albite and pyrite.

Sapphires grew in metasomatic zones where the peraluminous gneisses supplied aluminium and the chromophore elements Cr, Fe, and Ti (Fig. 7). The colour of the sapphires is controlled by lithology: colourless to blue sapphires appear in the biotitite zone developed upon feldspathic gneiss, green to brown and “vert de gris” sapphires are in the sillimanite-bearing feldspathic gneiss, and finally red to fuchsia to pink and pinky orange crystals are located in the sapphirine-bearing feldspathic gneiss. The other coloured crystals are distributed randomly at the interface of biotitite and biotitised sapphirine-bearing feldspathic gneiss.

Major and trace element electron microprobe analyses (EMPA) from more than 17 different coloured sapphire crystals (Table 2) show significant substitutions of Fe, Cr, Mg, Ga and Ti. The FeO values average 2800 ppm and range up to 4000 ppm, Cr_2O_3 ranges between 300 and 2500 ppm. Ga_2O_3 and MgO are between 90 and 220 ppm and 70 and 130 ppm, respectively. TiO_2 is significant in green to brown and “vert de gris” crystals, and below detection limit (~22 ppm) for the other colours. Fig. 8A shows that colour is a function of the Fe/Cr ratio with a more less constant FeO content for a variable Cr_2O_3 content: high chromium for

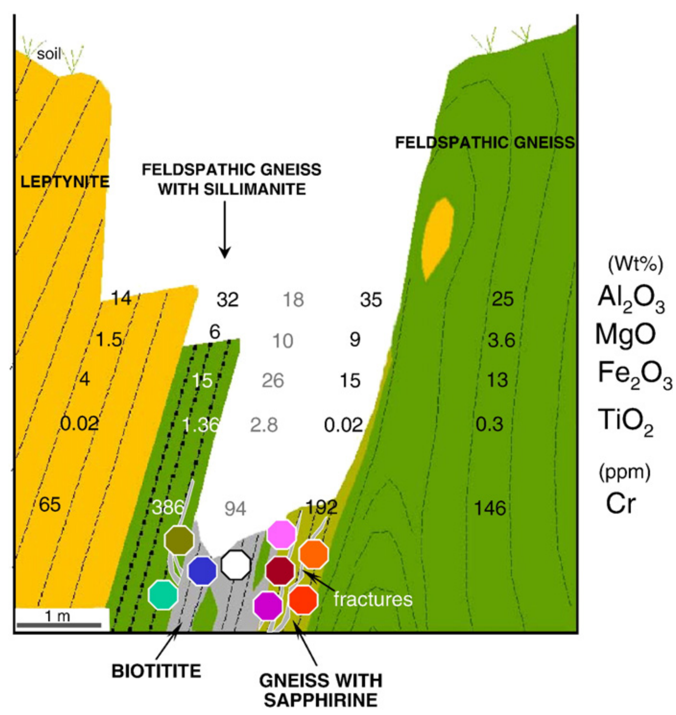

Fig. 7. Schematic geological section of the Momo trench in the Sahambano sapphire deposit (Ralantoarison, 2006). The respective contents in Al, Mg, Fe, Ti (in wt.%) and in Cr (in ppm) are reported for each different protolith and the metasomatite (biotitite). The coloured sapphire distribution is reported in the different zones. Major- and trace-element concentrations were determined by ICP-MS on representative whole rock samples at the SARM laboratory (CRPG/CNRS).

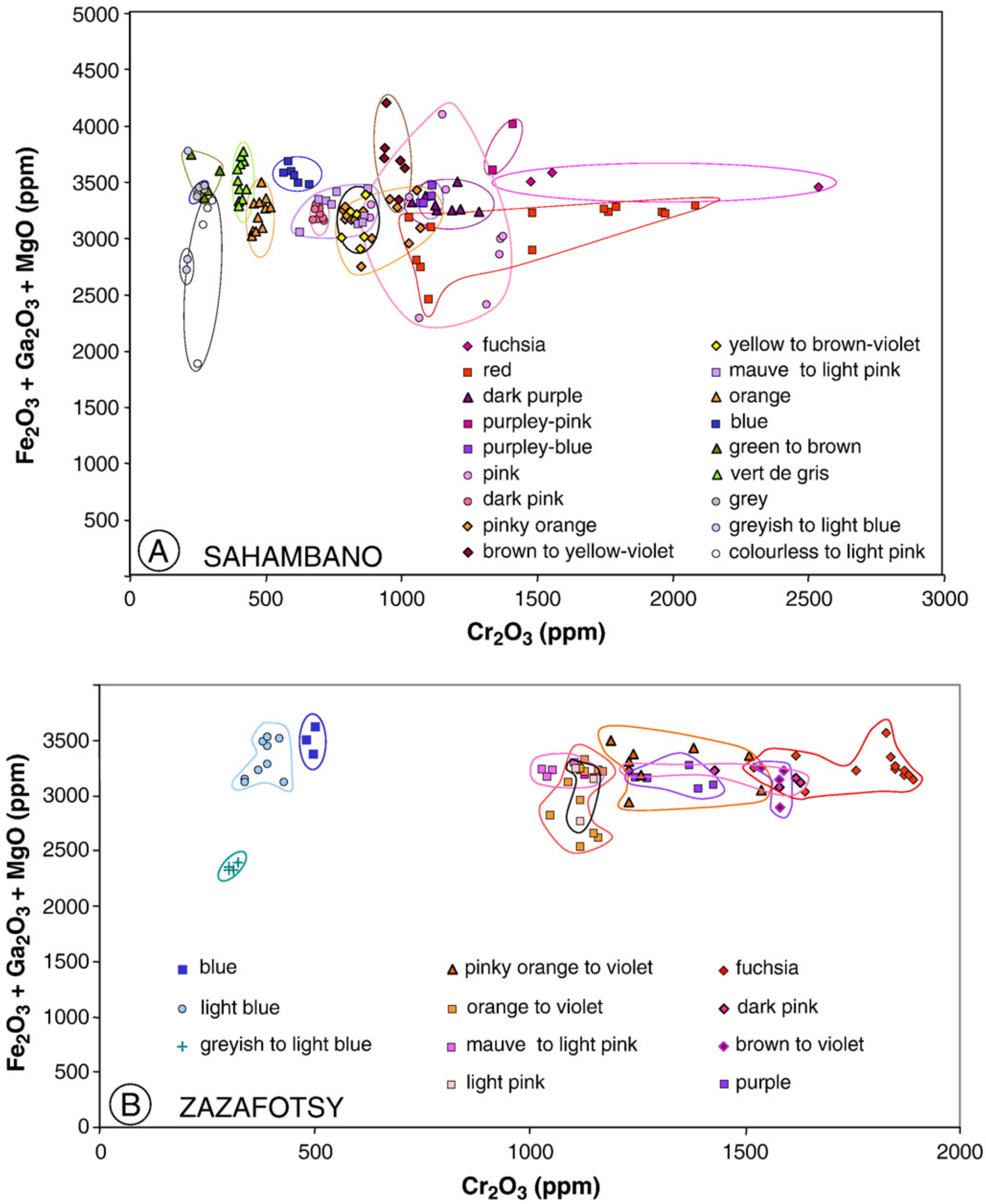

Fig. 8. Chemical variation diagrams Cr_2O_3 *vs.* $Fe_2O_3+Ga_2O_3+MgO$ showing ppm plots of trace-element contents of corundum from Sahambano (A) and Zazafotsy (B). Polished sections of coloured sapphires were analysed with a CAMECA SX100 electron microprobe (University Nancy I). The operating conditions were: acceleration voltage 15 kv, beam current 10 nA, collection time of 20 s for aluminium, and 25 kv, 150 nA, 120 s for trace elements. Natural and synthetic standards were used and the PAP program (Pouchou and Pichoir, 1991).

red to fuchsia and low chromium for colourless to blue sapphires. The chromium content is always lower than the iron content and the corundum is considered as a sapphire and not a ruby despite its fuchsia or pink colour. The pinky orange sapphire resembling “padparadscha” colour contains chromium between 780 and 1053 ppm.

Polychrome crystals are rare in the sapphire production. Such composite crystals are zoned and the contact between the different zones is either gradational or sharp. Some crystals are composite, made of a short blue to colourless hexagonal prism capped by a pinkish long hexagonal prism associated with rhombohedron faces and pinacoid. The contact between the two hexagonal prisms is sharp; the second prism has grown on a seed plate made by the first one which exhibits etching effects with dissolution zones on its surface.

Some crystals consist of a hexagonal prism with different coloured zones. Fig. 9 shows the section parallel to the *c*-axis of such a crystal. Chemically, across these zoned crystals there is a decrease in the FeO/Cr_2O_3 ratio versus the MgO content from a light pink (zone 1) to a cream to light mauve colour (zone 2). Between zones 2 and 3 (a purple-blue zone), the transition is sharp and characterised by a strong chemical front. The transition between zones 4 and 5, blue to colourless, marks a main chemical gap, where the chemical composition of the fluid reverted to a high FeO/Cr_2O_3 ratio and MgO content as for zone 1. This indicates a multi-stage fluid pulsation with the development of metasomatic chemical fronts, etching of the crystal and recrystallisation under the same *P*–*T* conditions but for different FeO/Cr_2O_3 ratio. In the infiltrating zones characterised by an intense micro-scale biotitisation in fissures and the formation of biotitites, the FeO/Cr_2O_3 ratio is high (between 3 and 5), and then in the infiltrated rocks it decreases to 1.15 (for fuchsia colour). The circulation of metasomatic fluids played a key role in the exchange and transfer of elements for the formation of sapphires in the biotite schist and in the biotite–sapphirine-bearing feldspathic gneiss.

In the correlation diagram Fe_2O_3/TiO_2 vs Cr_2O_3/Ga_2O_3 (Fig. 5), the sapphires plot in the metamorphic domain (Sutherland et al., 1998a,

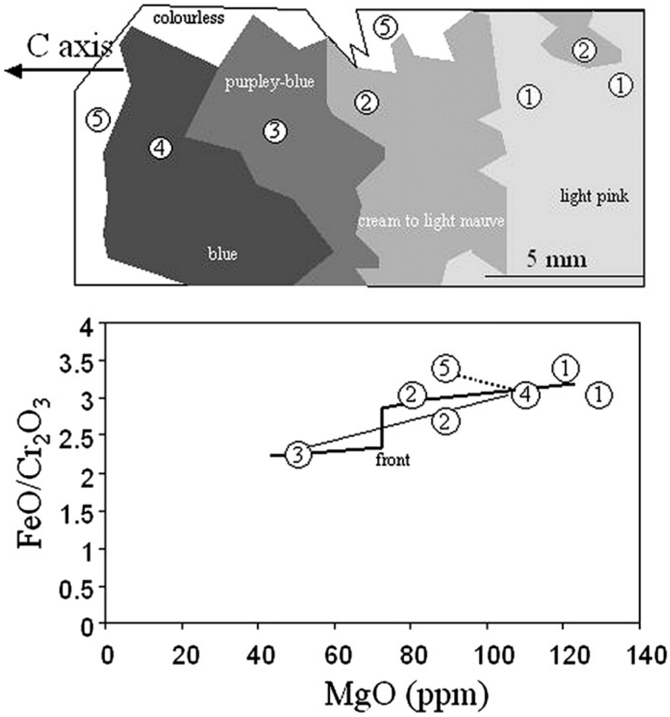

Fig. 9. Cross-section of a coloured sapphire from Zazafotsy showing the chemical variation from the inner to the outer zones of the crystal in the MgO (in ppm) *vs.* FeO/Cr_2O_3 diagram. Same caption as for Fig. 7 for the operating microprobe conditions.

2003), characterised by high Fe_2O_3/TiO_2 ratios (mostly between 10 and 100) and medium Cr_2O_3/Ga_2O_3 ratios (between 1 to 70).

The *Zazafotsy deposit*, also called "Amboarohy" (Pezzota, 2005), is 35 km north of Ihosy town on RN 7 to Ambalavao (Fig. 1). It was discovered in 1950 and first exploited by local miners in 1989. In 2003 it produced very beautiful euhedral sapphires in gangue (Fig. 4F). The majority were not of gem-quality and needed heat treatment to improve their transparency and colour. The deposit is located in the Itremo Group composed mostly of garnet–sillimanite–cordierite leptynites and amphibole-clinopyroxene gneiss with minor intercalations of quartzite and impure limestone. It lies in the Zazafotsy shear zone system also linked to the Pan-African tectono-metamorphic event (Martelat et al., 2000). The Ar–Ar age of 494±5 Ma for a biotite associated with sapphire (Table 1) confirmed that the mineralising episode is the latest Pan-African event in the area.

As in Sahambano, the mineralisation is found in several lenses of feldspathic gneisses intercalated within garnet-bearing leptynite, affected by fluid circulation in shear zone fractures (Andriamamonjy, 2006). The inner lens consists of crystals of garnet and sapphire up to 100 mm (Fig. 10), associated with biotite, plagioclase, spinel and K-feldspar formed around sapphire and garnet (Fig. 4H). The outer zone is a biotite schist with biotite, sapphire, spinel and very few crystals of grandidierite which pass into a biotitized feldspathic gneiss. In one lens, the outer zone consists of fine-grained metasomatic alternation of biotitite and black tourmalinite developed on a 0.2 m-wide scale.

All sapphire crystals are euhedral and, as in Sahambano, exhibit either short or long prismatic habits associated with the hexagonal prism, the rhombohedron and terminated by two basal pinacoids. Mineral inclusions in the sapphires are zircon, K-feldspar, plagioclase, sillimanite, spinel and biotite. The sapphire colours include dark blue, light blue, grey blue, fuchsia, orange, pink, violet, mauve and brown, but lack colours such as yellow to brown, pinky orange, green to brown and "vert de gris" found in Sahambano sapphires. A total of 75 electron microprobe analyses of aluminium and trace elements from 11 sapphire crystals (Table 2) show element concentrations in the same range as those published by Caucia and Boiocchi (2005): sapphire has high iron content (2320 ppm<FeO<3300 ppm), variable chromium (300 ppm<Cr_2O_3<1890 ppm) and very low titanium, magnesium and gallium (less than 220 ppm combined total). Fig. 8B shows that colour varies with the Cr_2O_3 content of the crystal, as at Sahambano. Polychrome sapphires also resemble the Sahambano ones, with a chemical gap between a blue-dominant zone and a pink to red one, and traces of metasomatic-hydrothermal etching on the faces of the crystals resulting in corroded and brilliant zones. The correlation diagram Fe_2O_3/TiO_2 *vs.* Cr_2O_3/Ga_2O_3 (Fig. 5) shows that the sapphires fit in the metamorphic domain defined by Sutherland et al. (1998a, 2003) and overlaps the field for Sahambano sapphires. The high Fe_2O_3/TiO_2 (mostly between 10 and 100) and Cr_2O_3/Ga_2O_3 ratio exceed those of Sahambano.

2.2.2. Deposits in cordieritites

The *Iankaroka occurrence* was first reported in 1984–1985 and described by Salerno (1992). It is 35 km south of the city of Betroka (Fig. 1), in the province of Toliara. The deposit is characterized by polychrome sapphire displaying distinct colour bands. When observed in a plane parallel to the *c*-axis, the crystal is uniformly pinkish to purple and in a direction perpendicular to the *c*-axis thin layers of green, blue, orange, brown and pink are visible (Koivula et al., 1992). Crystals range between 1 to 10 mm in diameter and are elongated to tabular hexagonal prisms and bipyramids. The sapphires are found in a cordieritite lens, ~7 m long×4 m wide, intercalated concordantly within leptynitic biotite–cordierite-bearing gneiss of the Androyan

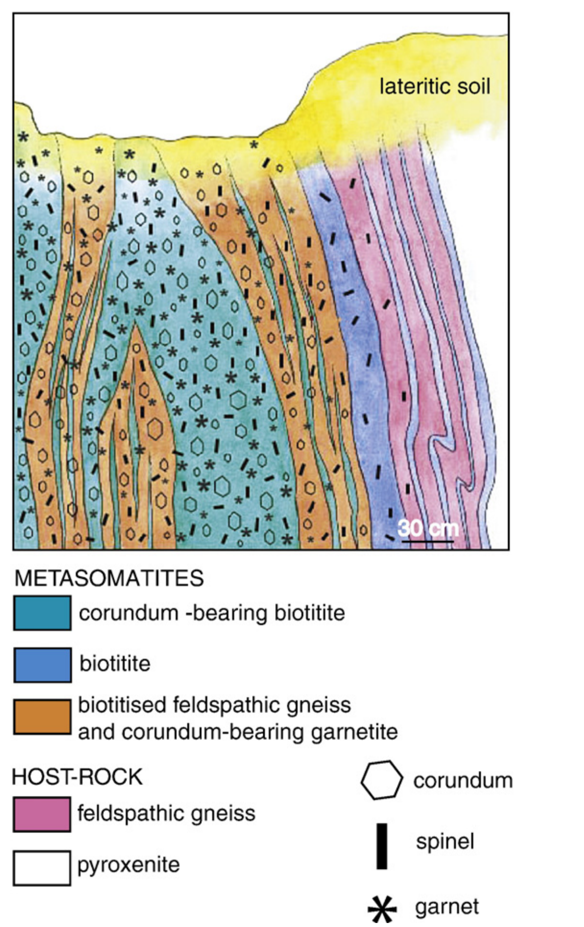

Fig. 10. Schematic geological cross-section of one pit of the Zazafotsy sapphire deposit (Andriamamonjy, 2006) showing the distribution of corundum, spinel and garnet in the biotitite and the biotitised feldspathic gneiss.

series. The cordieritite is composed of phlogopite, cordierite, plagioclase, green tourmaline, chlorite, pyrite, spinel and sillimanite. The cordieritite is affected by shearing; on its border this develops a biotitite on the gneiss, and sapphire-bearing fissures in the cordieritite.

The *Ambatomena ruby deposit*, 10 km NE of the city of Isoanala (Fig. 1), was exploited from 2000 to 2001 by a private company. Rubies were of good-quality consisting of euhedral prismatic crystals up to 30 mm long and 10 to 20 mm in diameter. The deposit occurs in the Androyan metamorphic series composed of paragneiss, orthogneiss, marble, granite, clinopyroxenite and quartzite (Windley et al., 1994). Ruby is contained in cordieritite layers or lenses intercalated within a biotite–cordierite–sillimanite-bearing charnockite. The mineralised zone has suffered an intense metasomatism characterised by a Mg-rich pervasive biotitisation transforming pegmatite veins in plagioclasite, and forming sapphire-free phlogopitites (Fig. 4E) and sapphirine–anorthite–phlogopite-bearing rocks (Fig. 4D). Ruby occurs in a cordieritite composed of cordierite, rutile, K-feldspar, sapphirine, phlogopite and ±pyroxene. Ruby crystals exhibit a spinel and sapphirine coronitic texture. Spinel results from the destabilisation of ruby during the retrograde phase and sometimes totally pseudomorphs the ruby.

2.2.3. Deposits in mafic-ultramafic rocks and anorthosites

The ruby deposits are found in the Vohibory unit, limited to the east by the Ampanihy shear zone (Fig. 6). This unit consists of amphibolitic gneiss intercalated with amphibolite, marble and orthogneiss (Besairie, 1967; Hottin, 1976). Mafic-ultramafic complexes of meta-peridotite, -gabbro and -troctolite were transformed into amphibolites and serpentinites with anorthosite veins. Ruby occurs north of Ampanihy city and between the villages of Ejeda and Fotadrevo (Mercier et al., 1999) in the deposits of Maniry, Gogogogo, Vohitany, Anavoha, Marolinta and Ianapera which are exploited sporadically by local farmers.

Ruby occurs in different host-rocks metamorphosed to granulite facies conditions at $P\sim 8$ to 11 kbar and $T\sim 750$ to 800 °C (Nicollet, 1986): (i) in amphibolites as elongated zones some tens of m in length and some tens of cm wide. Two main parageneses are described: 1) hornblende, plagioclase, ruby, spinel and phlogopite; 2) hornblende, plagioclase, ruby, ±sapphirine, gedrite, garnet and spinel. Ruby commonly combines the hexagonal prism *a* with the pinacoid *c*; the crystals are generally flat with a diameter reaching up to 100 mm and with a short prism; (ii) anorthosite as layers and/or veins with two main parageneses (Nicollet, 1986): 1) anorthite, ruby, ±garnet, ±hornblende, ±spinel; 2) anorthite, ruby, spinel, zoisite, ±clinopyroxene, ±hornblende; (iii) desilicified pegmatites in amphibolite (Vohitany occurrence). The pegmatite and the amphibolite are metasomatised by circulation of fluids at the contact of both rocks: the amphibolite is transformed into ruby-bearing phlogopite schist and the pegmatite is desilicified and composed of plagioclase with some crystals of phlogopite and ruby. Moreover, the metasomatic structure is affected by shearing and the formation of a stockwork made of stringers with anthophyllite and ruby.

2.2.4. Deposits in marbles

The sapphire deposits in the Tranomaro area occur in the high-grade granulite facies of the Proterozoic Tranomaro Group composed of metasedimentary rocks (metapelites, calc-silicates and marbles) interlayered with leucocratic gneisses (Rakotondrazafy et al., 1996; Fig. 11). During metamorphism, marbles and calc-silicate gneisses have been transformed into skarns in a calc-magnesian complex (Moine et al., 1985). Impure calcitic marbles (Fig. 12F), include diopsidites with variable amounts of scapolite, spinel, thorianite and pargasite, and peraluminous rocks made of plagioclase and/or scapolite with spinel, thorianite, hibonite ($CaAl_{12}O_{19}$) and/or blue to pink corundum (Fig. 12A, B and D). The diopsidite often occurs at the contact between marble and granitic or charnockitic intrusions from

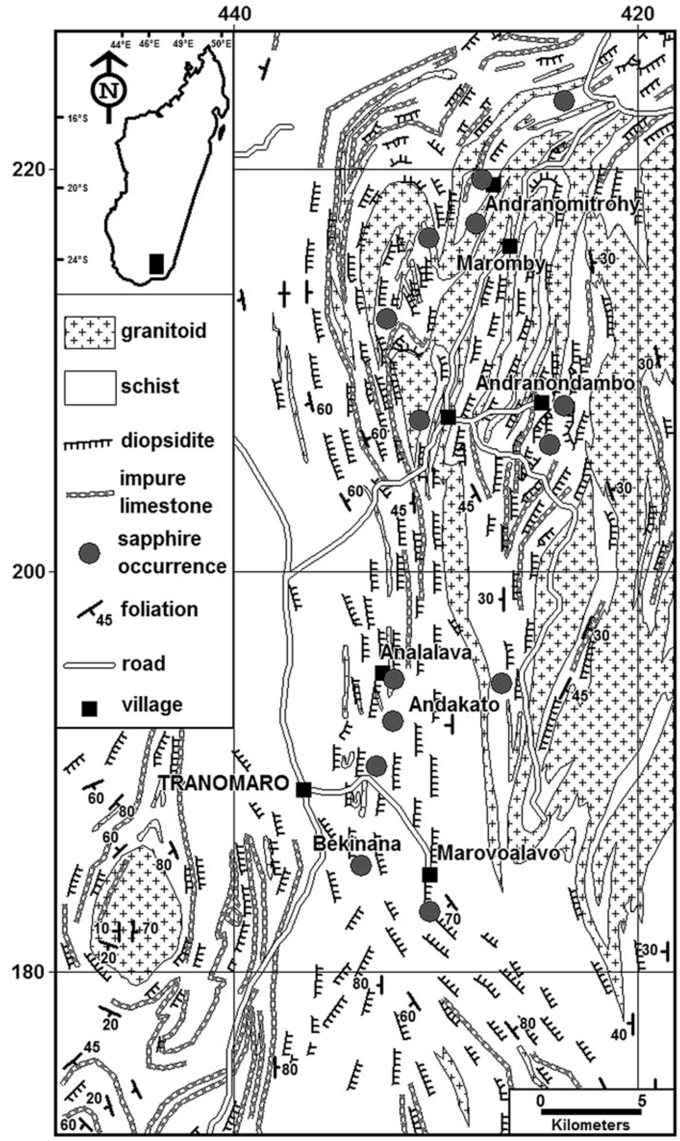

Fig. 11. Geological map of the Tranomaro area with the location of the corundum-hibonite skarn deposits (Rakotondrazafy, 1995).

the Anosyan magmatism (Fig. 11) and a metasomatic origin is proposed by Rakotondrazafy et al. (1996). Three stages of crystallisation have been defined in the skarns (Fig. 13):

stage 1 of metasomatism ($T\sim 850$ °C and $P\sim 5$ kbar). Ca-rich hyperaluminous segregations composed of meionite, spinel, thorianite and corundum are formed in a titanite-bearing matrix consisting of scapolite and aluminous diopside. U–Pb dating of zircon from a clinopyroxenite gave an age of 565±10 Ma (Andriamarofahatra and de La Boisse, 1986) in agreement with Pan-African ages (540 to 580 Ma) obtained for the granulite-facies metamorphism and the syn-metamorphic emplacement of the Anosyan charnockites and granites (Paquette et al., 1994);

stage 2 of metasomatism ($T\sim 800$ °C and $P\sim 3$ to 3.5 kbar). Diopside was partially transformed into fluorine-rich pargasite and most ca-scapolites were transformed into anorthite+calcite. Thorianite crystallized with fluorine-rich phlogopite, and hibonite crystallised at the expense of corundum and spinel (Fig. 12D);

stage 3 under retrograde granulite metamorphism. Lenses of phlogopite associated with calcite, diopside and anhydrite, and late stage REE-rich calcite veins with zircon, titanite and urano-thorianite

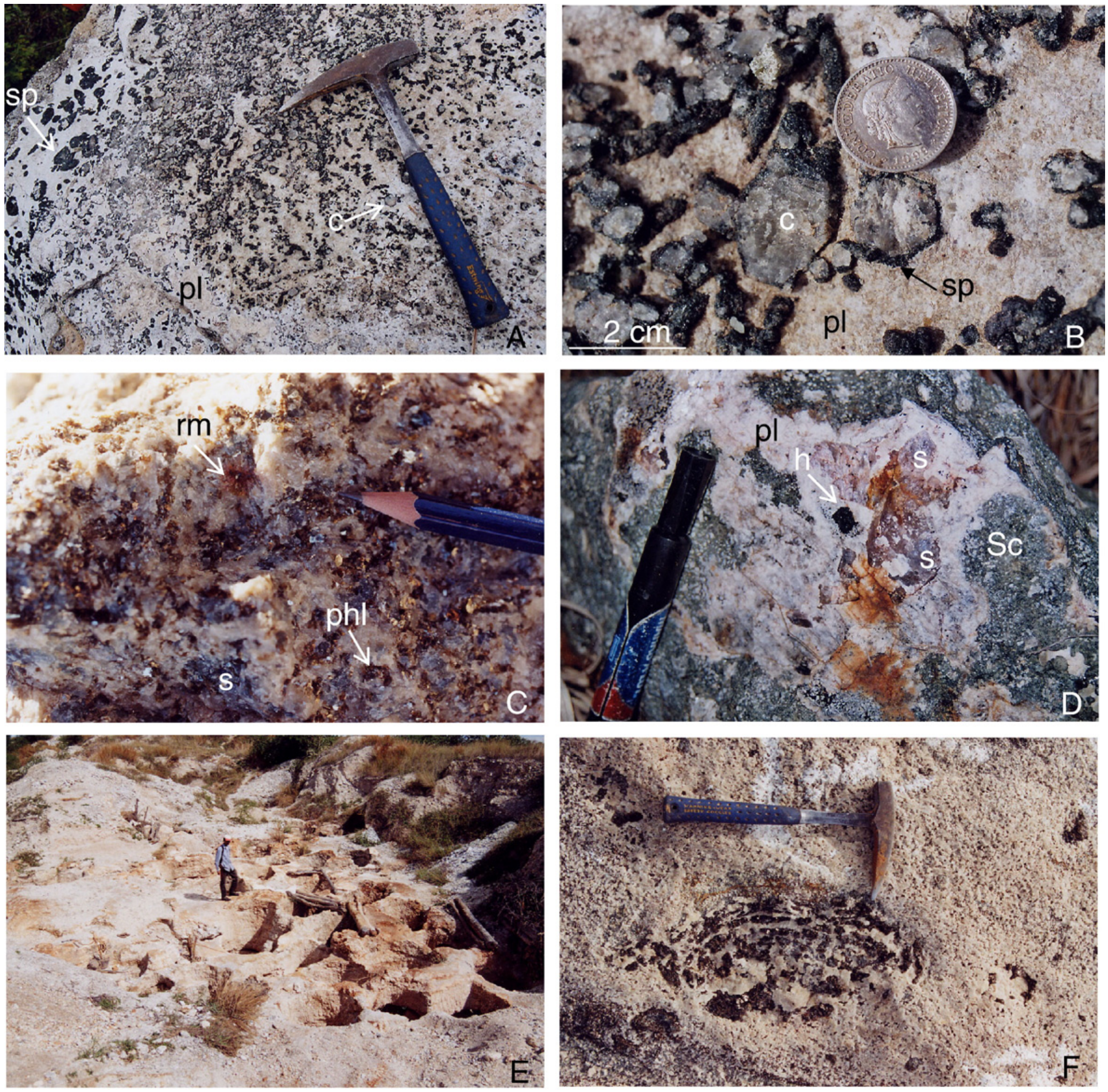

Fig. 12. Skarn deposits and "sakenite" occurrences of southeast Madagascar. (A) Corundum-spinel ± hibonite-bearing plagioclasite vein formed at the border of a phlogopite-bearing clinopyroxenite (Bekinana deposit, Tranomaro area). The size of the corundum crystals decreases from the border to the centre part of the vein. The crystals totally transformed into spinel (sp) at the edge of the vein are embedded in a plagioclasic matrix (pl). Hibonite crystallized at the expense of corundum (c) and spinel. (B) Detail of photograph (A) showing the spinel corona (sp) formed around the corundum (c). (C) The "sakenite" of the Vohidava occurrence. Association of sapphire (s), phlogopite (phl) and radioactive minerals (rm) in a plagioclasic matrix. (D) Scapolitite (Sc) with a plagioclasite segregation (pl) made of hibonite (h) and pink sapphire (s) at Analalava (skarns of the Tranomaro area). (E) Blue sapphire deposit excavations in the Andranoboaka mine. Gem sapphire is carried by K-feldspar veinlets that crosscut the hibonite-corundum-bearing skarn. (F) Aspect of a clinopyroxenite enclave in an impure limestone (Andranoboaka mine).

crosscut the calc-magnesian complex. U–Pb dating of zircon from a metasomatic calcite vein gave respectively ages of 516 ± 10 Ma (Andriamarofahatra and de La Boisse, 1986) and 523 ± 5 Ma (Paquette et al., 1994) which is the latest Pan-African event in the area.

At this late stage, blue gem sapphire from the Andronandambo area crystallized in late K-feldspar veins cross-cutting marbles at $T \sim 500$ °C and $P \sim 2$ kbar (Ravolomiandrinarivo et al., 1997). The CO_2-rich mineralising fluid phase was in equilibrium with the granulite mineral paragenesis of the skarn (Ramambazafy et al., 1998). The veins are vertical with cm- to dm-scale width. Sapphire is associated with K-feldspar, fluorapatite, calcite and phlogopite. At the border of the veins, marbles are feldspathized. The stability of the K-feldspar-corundum-calcite is controlled by the equilibria: muscovite ⇔ K-feldspar + corundum + water and anorthite + CO_2 ⇔ calcite + corundum + H_2O.

In early 1952, the French geologist Hibon reported small eluvial sapphire associated with hibonite south of Andranondambo village. The first deposit was discovered at Esiva in 1991 (Fig. 10). News of the discovery of a rich sapphire deposit spread quickly and in 1995 thousands of miners rushed to the area. In 1996 around 10,000 miners were estimated to be working in pits (Fig. 12E). Prospectors dug pits up to 15 m deep and 50 to 80 cm wide, at Andranondambo, Antirimena, Analalava and Andranomitrohy (Fig. 11) in an area of more than 7000 km^2.

2.2.5. Deposits in "sakenites"

The term "sakenite" was defined by Lacroix (1941), for a rock at Sakeny, north of Ihosy (Fig. 1). It is a high-grade granulitic metamorphic white- to greenish rock composed of anorthite ± corundum ± spinel ± sapphirine ± phlogopite ± amphibole (edenite) ± clinopyroxene ± zircon (Fig. 12C). Other occurrences were discovered in southern Madagascar including Vohidava, Anavoha (Fig. 3E), and in the hibonite-thorianite-

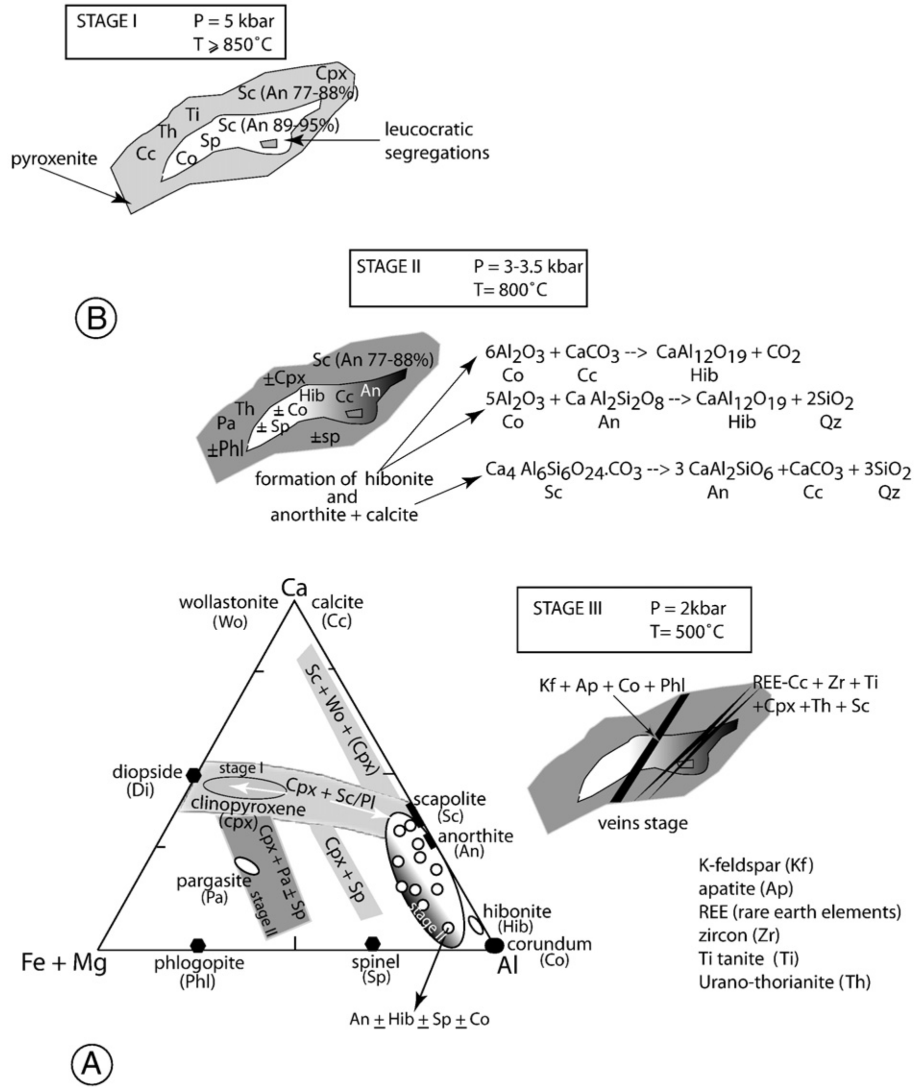

Fig. 13. The U–Th-corundum-bearing skarn deposits from the Tranomaro area (Rakotondrazafy et al., 1996). (A) Al–(Fe+Mg)–Ca diagram showing the distribution of the different assemblages of the calc-magnesian and skarn rocks from stages I and II of skarn metasomatism. (B) The three stages of skarn formation with stage I metasomatism (leucocratic segregation in clinopyroxenite), stage II (formation of hibonite and anorthite+calcite assemblages) and stage III (retrograde and fracturing stage with REE-bearing calcite veins and gem sapphire-K-feldspar bearing veins).

bearing skarns at Tranomaro (Bekinana occurrence, Fig. 12A). These rocks are plagioclasite, with nearly pure anorthite and often a coronitic texture due to the partial or complete replacement of corundum porphyroblasts by spinel (Figs. 3F and 12B), or spinel+hibonite, spinel+sapphirine, K-feldspar+spinel, anorthite+sapphirine. At Sakeny, Devouard et al. (2002) identified platelets of musgravite ($BeMg_2Al_6O_{12}$) in the spinel-sapphirine corona surrounding corundum. Nearby, “sakenites” are intercalated with Al-rich paragneisses, amphibolites and clinopyroxenites. The main bench is 10 m in width and 5 km long. At Vohidava, the “sakenite” level is contained in a series of impure marble, clinopyroxenite and paragneiss; the contact of the “sakenite” with the surrounding rock is diffuse and the level is 1 m wide and several meters long. At Bekinana in the Tranomaro area, the plagioclasite containing corundum, spinel and hibonite is injected into a clinopyroxenite; the contact is diffuse and crosscuts the metamorphic foliation. The size of the injection varies from only 10 mm to several metres.

At Sakeny, “sakenites” display petrographic variations within a single bench, with local predominance of one mineral species. Lacroix (1941) distinguished sapphirine, spinel, spinel+sapphirine-bearing “sakenites” (Fig. 3G, I) and sometimes “anorthitic corundumite” (anorthite+corundum) and “corundumite” (Fig. 3H). Lacroix considered “sakenites” as a product of high-grade metamorphism of clay-rich marls. Devouard et al. (2002) favoured metamorphism/metasomatism of clay-rich limestones. However, such plagioclase-corundum associations are also described for plumasite, i.e., desilicified pegmatites as in northern Transvaal (Robb and Robb, 1986). The chemical composition of “anorthitic corundumite” (Lacroix, 1941) i.e., 12.3 wt.% SiO_2 and 73.6 wt.% Al_2O_3, implies a loss of silica with drastic enrichment of alumina from the host rock, whether a marl, a clay-rich limestone or a mafic rock with a pegmatite. Nevertheless, residual quartz in the “sakenites” is not reported unlike pegmatite-related corundum deposits. The process of desilication resulted in the formation of plagioclase and corundum from an aluminium-bearing rock. The calcium content of up to 19 wt.% for a plagioclasite from Sakeny (Lacroix, 1941) is the result of a process of calcification whereby calcium was extracted from the host rock (marl, clay-rich limestone or mafic rock) and the surrounding rocks (amphibolite, clinopyroxenite and paragneiss). The redistribution of Si, Ca and Al characterised alkali metasomatism at high temperature in the granulite facies.

“Corundumites” are generally found as pebbles and rounded blocks in rivers and appear in the Beforona region within the Sahamoloto, Tsarafosa, Ivoloina and Marorofy rivers, and in the Vatomandry and Saka

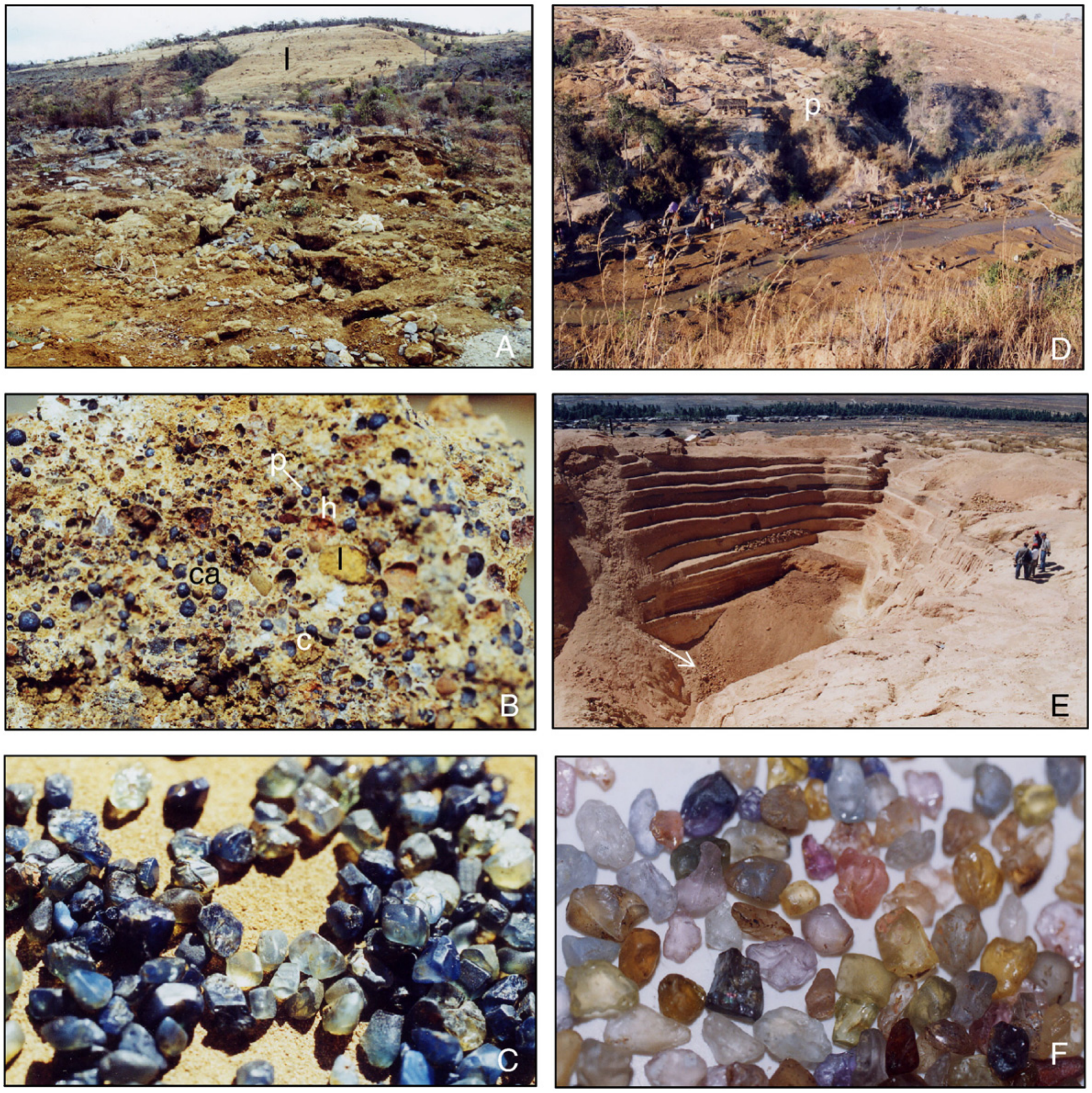

Fig. 14. Placer deposits in Madagascar. (A) General view of the Maromikatra prospecting pits (Ambondromifehy area, northern Madagascar). The sapphire deposit comprises a succession of superficial pits up to 5 m deep, dug within soil and karst structures within the Jurassic limestones (l). (B) Aspect of the mineralised paleoplacer facies made of ferruginous pisoliths (p), limonite nodules (l), hematite (h), calcareous fragments (c) which are cemented by carbonates (ca). Size of the limonitic nodule is ca. 2 cm. (C) The "Blue-Green-Yellow" sapphires from the Maventibao prospecting pits (Ambondromifehy area). The crystals have an average size of 5 to 10 mm. (D) The sapphire placer deposit of Manumbo Vaovao in August 2003, 30 km South of Ilakaka town, and discovered in February 2003. View of the pits in an old alluvial terrace (p) and the washing of the extracted material in the Andondoza river. (E) Vertical view of the Ilakaka placer at the site called "La Banque Suisse". The gem-gravel levels are reached by a succession of banks which keep the mining site in good condition. The position of the gem-gravel levels are indicated by the arrow. (F) The multicoloured sapphires from the Ilakaka placers. The size of the crystals is between 6 to 10 mm.

regions (Lacroix, 1922a). They are composed of grey to pinkish crystals or masses of corundum which sometimes contain spinel (Fig. 3H), muscovite, tourmaline and sillimanite. "Corundumite" was described at Sakeny with masses of anorthitite. The crystals of corundum are whitish to yellowish with inclusions of clinopyroxene (Fig. 3F).

2.3. Placer deposits in basaltic provinces

The sapphire placer deposits in the Antsiranana province are about 70 km south of Antsiranana city, in the Anivorano and Ambondromifehy area, and in Nosy–Be Island (Fig. 1). In 1996, blue-violet, blue, greenish blue, greenish yellow and yellow (BGY) sapphires were discovered near Ambondromifehy. Local miners dug around the roots of trees or pits up to 10 m deep to reach sapphire in consolidated sediments (Fig. 14A). The deposit soon became a prolific source of commercial quality stones, but between 1996 and 2000, only two mining companies set up operations. The IMA group/Suzannah company recovered 350 kg of corundum of which 15% were faceteable (Schwarz et al., 2000).

Sapphire-bearing alluvial materials filled voids and cracks in a shallow karst developed on Jurassic Ankaratra limestone and arenites south of the volcanic massif of the Montagne d'Ambre (Fig. 15). All gem-bearing sediments are cemented by secondary carbonates (the Maromikotra, Sanaderikely and Ambohangimamy deposits are contained in limestones) or quartz (the Maventibao deposit is contained in arenites) within palaeoplacers. The conglomerates are composed of fragments of red to orange zircon (hyacinthe variety), sapphire, angular carbonate, rounded iron oxide and ferruginous pisolith as well as products originating from the stripping of a ferruginous cuirasse (Fig. 14B). The orange to red zircon crystals are generally rounded but with sub-euhedral habits and up to 20 mm in size. The sapphire crystals are elongated, barrel-shaped and most are rounded, corroded and broken at both ends. The hexagonal dipyramid ω or z is the dominant

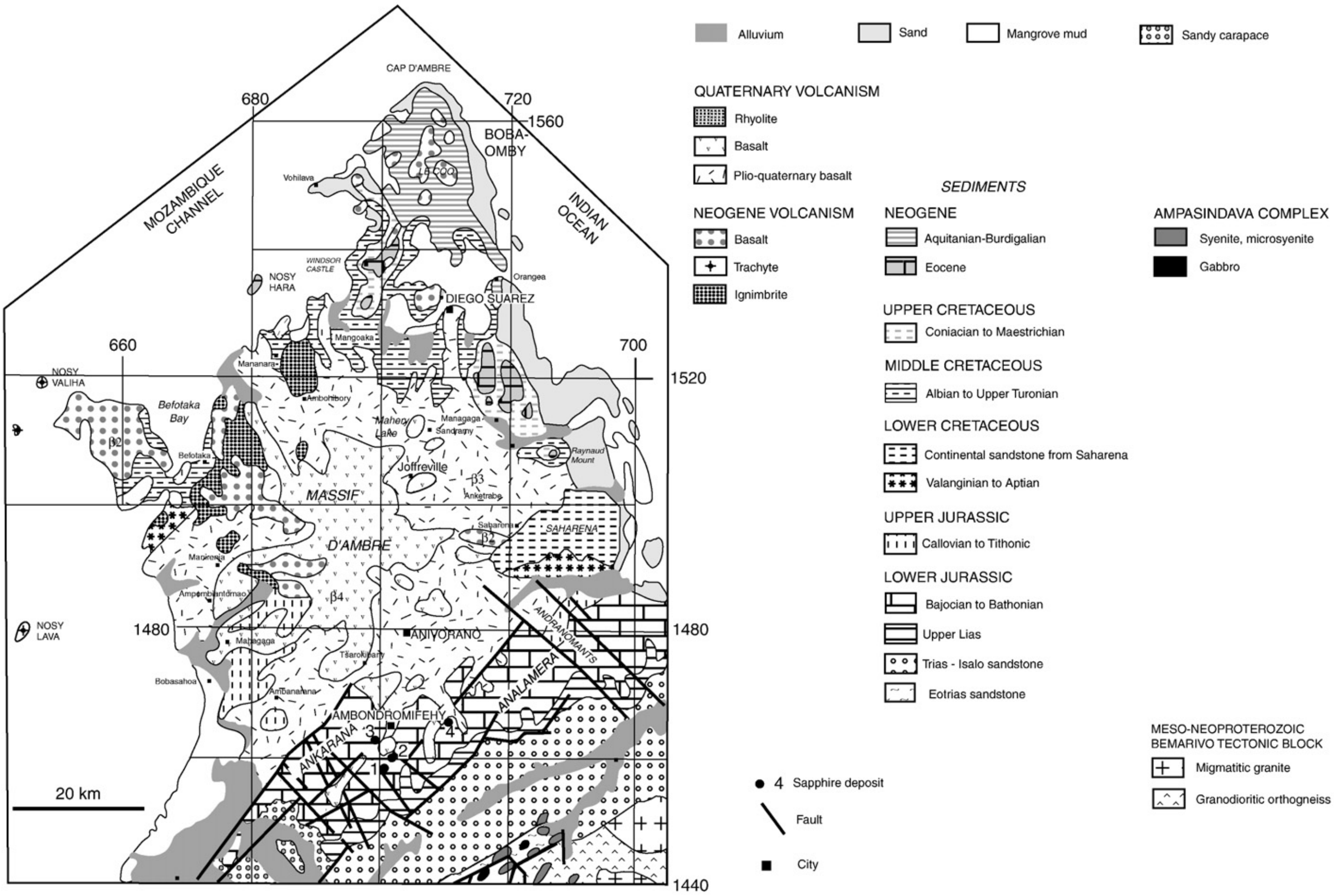

Fig. 15. Geological map of the Montagne d'Ambre massif with the location of the main placer deposits of the Ambondromifehy area (map of Diego Suarez 1, scale of 1: 200,000 modified from Besairie, 1971). 1: Maventibao, 2: Maromikatra, 3: Sanaderikely, 4: Ambohangimamy.

form combined with the basal pinacoid *c*. Smaller faces of the rhombohedron *r* and of additional hexagonal dipyramid *n* are common (Schwarz et al., 2000). Rough sapphires show distinct colour zoning within crystals (polychrome sapphire) and many have milky white or blue areas and some are translucent (Fig. 14C). The mechanized operation from the ABFG mine at Anivorano nord, between 1998 to mid-2000, permitted the definition of the colour distribution and the average weight of the ore (Schwarz et al., 2000): dark blue to bluish green sapphires represented 88% of the rough, and the range 0.1 to 0.5 grams yielded 70% of the weight production; crystals weighing more than 1 g corresponded to 11% of the production. The mine extracted 3 to 5 kg of gem-quality corundums in a 10-hour shift, but only 17% of the rough was suitable for heat treatment and cutting. About 5 kg of rough sapphire from the ABFG mine would be expected to yield 900 carats of faceted stones, that is to say 3.6% of the rough.

The crystal morphology, colour distribution, internal growth patterns and mineral inclusions of these sapphires are reminiscent of Australian "BGY sapphire" and the alkali basalts are thought to have transported the corundum to the surface (Superchi et al., 1997; Schwarz et al., 2000). The area contains 3500 km^2 of Cenozoic volcanic rocks. The 35-km wide volcanic flows include basalts, tuffs, pozzolanas and pyroclastites which contain xenoliths, mainly of dunite and lherzolite. Recent prospecting and field work failed to locate any sapphire-bearing basalt flows in the Montagne d'Ambre volcanics. Nevertheless, Lacroix (1922a) noted the presence of a big crystal of sapphire, zircon and spinel associated with hornblende and syenitic xenoliths in basaltic scoria at Lake Mahery from the Montagne d'Ambre, and one crystal from the island of Nosy Mitsio which is constituted of basanite, phonolite and trachyte.

Two new sapphire deposits found in 2001, occur in Nosy–Be Island and the Andovokonko area on the Ambato Peninsula (Fig. 16). Nosy–Be sapphires were discovered by local villagers mainly in the alluvium of small creeks in the Befotaka area and are now exploited by the CanaAlta Gems company (Rhamdhor and Milisenda, 2004). The "BGY-sapphires" are found in alluvial loess in a pebble level formed of basalt, sapphire and zircon located 1 m above the granitic bedrock. At the Andovokonko deposit, sapphire is found on the basalt surface covered by calcrete crust, and in tidal flats.

Alluvial corundum deposits in the southeastern part of the Ankaratra volcanic massif in the Antsirabe area (Fig. 1) were described by Lacroix (1922a). Ruby was exploited at Andranomadio, ruby and sapphire at Andriankely but blue, green and yellow sapphire at different localities (Ampitatafika, Vohimena, Ambatotsipihana, Maroparasy, Sambaina, Ambohimandroso, Iankiana, Vontovorona, Mahanoro, Faratsiho, Vakinakaratra and Belambo). Nowadays, recent alluvial placers are always recovered by locals in river and soil. The BGY sapphire deposits of Kianjanakanga–Mandrosohasina and the ruby deposit of Antsabotraka are mined from sedimentary deposits made of basaltic and phonolitic pebbles cemented by lateritic soils. The "BGY sapphires" have barrel-shaped crystals, often somewhat broken, rounded and corroded.

2.4. Placer deposits of unknown origin

New deposits found in 2000 in the area of Vatomandry and Andilamena (Fig. 1) drastically changed ruby production in Madagascar. Vatomandry is about 140 km south of the town of Toamasina. The mining area, which comprises alluvial deposits, is mostly a private concession not accessible to foreigners. Preliminary investigations of

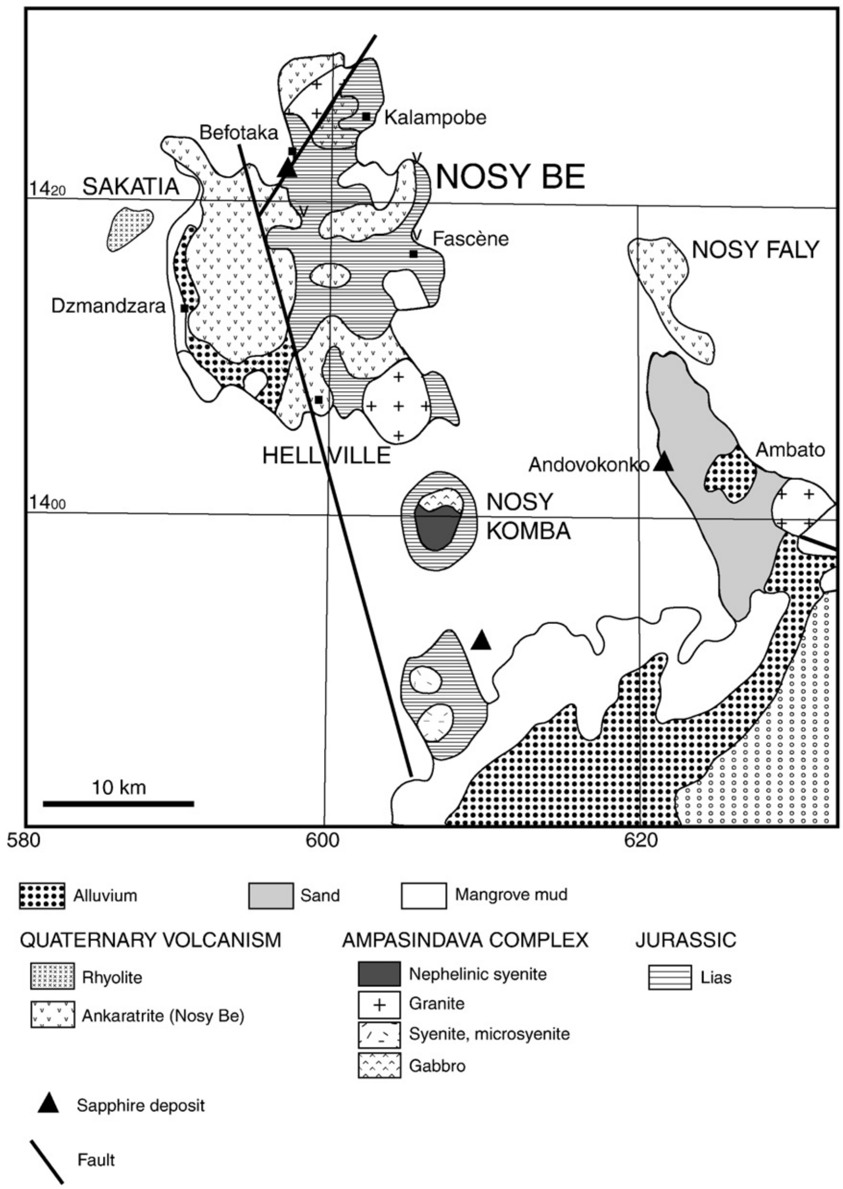

Fig. 16. Geological map of the Nosy–Be Island and the Ambato Peninsula with the location of the placer deposits of Befotaka and Andovokonk (Map of Diego Suarez 1, scale of 1: 500,000 modified from Besairie, 1971).

ruby from Vatomandry by Schwarz and Schmetzer (2001) showed no growth structures, the presence of rutile needles and numerous zircon crystals, and high iron contents comparable to those of "basaltic ruby" from Thailand.

Andilamena, ca. 240 km NE of Antananarivo, hosts alluvium and primary deposits in a tropical forest. Up to now, geological information was lacking, but the recent visit to the mining district by V. Pardieu (Gübelin Gem Lab) has permitted us to clarify the following points: i) ruby and sapphires were first found in alluvial deposits, ii) ruby and sapphires are found in deep holes dug into primary deposits that represent the main economic production. Although the corundum host rocks are highly weathered, they comprise fuchsite-bearing mafic rocks, biotite schists and kaolinite-bearing rocks. Rubies are found in mafic rocks and/or biotite schists developed upon them. Sapphires are restricted to veins of quartz-free kaolinite-bearing rocks that crosscut the mafic rocks. The oxygen isotopic composition of ruby from Andilamena ($0.5<\delta^{18}O<4‰$; Giuliani et al., 2007), which overlaps the range of mafic rocks ($1.25<\delta^{18}O<4‰$), confirms the preliminary field observation.

The Miarinarivo placer 30 km south of Ambalavao city (Fig. 6) contains pinkish to brownish corundum in a large volume of alluvium. The crystals are largely preserved with their hexagonal habit during alluvial transport. The primary source is unknown; and regionally the Precambrian basement comprises gneiss, quartzite and amphibolite intruded by syenite, gabbro and anorthosite.

2.5. The giant Ilakaka placer deposit in a sedimentary basin

The Ilakaka mining district is located in the Isalo massif, between the cities of Sakaraha and Ilakaka (Fig. 6). Other districts lie north of Ilakaka and near Bezaha, 120 km SW of Ilakaka. The giant alluvial deposit was discovered in late 1998 at the side of the RN 7 highway. The ensuing rush of locals and immigrants opened up several mining zones between Ilakaka and Sakaraha, including Sakalama, Ampasimamitaka, Vohimena, Bekily and Manombo Vaovao (Fig. 14D). The deposits are generally exploited by illegal miners using 1-m diameter shafts reaching up to 20 m in depth, with windlass systems, washing gravels in pans and removing the stones from the sieves by hand.

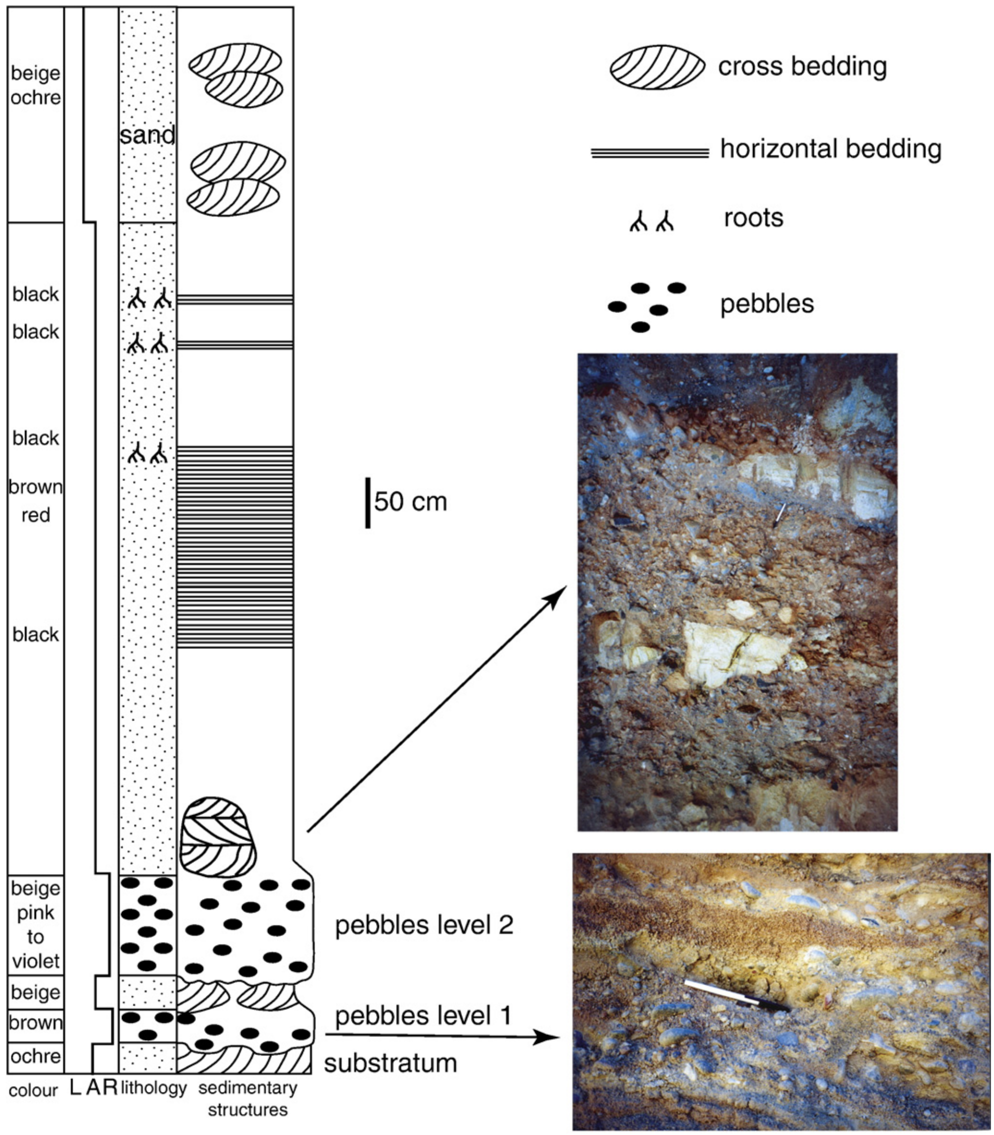

Fig. 17. Lithological section of the gem-bearing terraces exploited in the Vohimena Talo placer, Ilakaka district. L: lutite, A: arenite, R: rudite.

Some deposits are exploited in open pits following benches to reach the mineralized zones (Fig. 14E). In summer 2000, only two legal operators were working with classical washing plants (Garnier et al., 2004).

The deposits produce very fine blue, pink, blue-violet, violet, purple, orange, yellow and translucent sapphires (Fig. 14F), along with zircon, alexandrite, topaz, garnet, spinel, andalusite and tourmaline. Test mining during 38 days of production (Gem Mining Resources, 2002) realised approximately 43 kg of gemstones, comprising 4% of other gemstones, volcanic glasses, and rubies, and 96% of sapphires with 58% of pink sapphires, 30% of blue sapphires, and 8% of other coloured sapphires (yellow, padparadscha, green). The operators exploit the alluvial terraces of the Ilakaka and Benahy rivers which lie on and are derived from the Triassic Isalo sandstones. These poorly consolidated quartziferous sands contain pebbles of ferruginous sandstone (laterite), rounded blocks of Isalo sandstone and quartz, quartzite and schist pebbles (Garnier et al., 2004). On the Benahy river, three levels of gemmiferous terraces locally called “lalambato” are found (Fig. 17). In the bottom terrace gemstone concentrations reach up to 5 to 7 g/m^3 for the mechanized exploitations. The concentration in some terraces exploited by washing and hand-recovery reached about 10 g/m^3. They correspond to deep potholes or sinuous meanders which are not accessible for mechanical exploitation. River sands, sampled in the stream bed, contain between 0.2 and 2.1 g/m^3 of sapphire. This alluvial concentration results from the erosion of old terraces.

3. Discussion

The primary gem corundum deposits form two distinct groups, magmatic and metamorphic. Magmatic deposits consist of syenite and alkali-basalt types. Ruby in the gabbroic and clinopyroxenite xenoliths of the Soamiakatra alkaline basalt sheds light on rubies in basaltic-derived placers found worldwide. Such xenocrysts originally formed in mafic metamorphic rocks under mantle conditions (Sutthirat et al., 2001; Garnier et al., 2005). The oxygen isotope compositions of rubies including those of Soamiakatra confirmed this hypothesis (Giuliani et al., 2005; Yui et al., 2006). The Soamiakatra deposit demonstrates that one source of ruby is mantle garnet clinopyroxenites (Rakotosamizanany, 2003). The blue, green and yellow sapphires as mingled in Madagascar placers are common worldwide (Sutherland et al., 1998b), and their origin is in debate (Giuliani et al., 2007). In the Montagne d'Ambre massif, the palaeoplacers are contained in Jurassic limestone karsts and the conglomerates apparently lack fragments of basalts. In the Ankaratra region, the deposits are mined in rivers and lateritic soils which contain basaltic and phonolitic pebbles.

The sapphire-bearing syenite deposit of Beforona includes sillimanite and is an "endomorphic syenite" (Lacroix, 1922a); the magmatic character of the mineral assemblage is not proven. Retromorphic textures especially feldspathic coronas suggest a metasomatic origin for the sapphire.

Nearly all the types of corundum metamorphic deposits described worldwide (Garnier et al., 2004) are found in Madagascar, except for rubies hosted in marbles as found in the Himalayan and Tanzanian metamorphic belts (Hänni and Schmetzer, 1991). The control of such deposits is lithological (Garnier et al., 2004) and dependent of the presence of evaporite intercalation in pure and impure limestone horizons from a carbonate platform. Spinels and sapphires are found in marble and "cipolin" in Madagascar (Lacroix, 1922a), so that studies of the origin and chemistry of marbles in Neoproterozoic metasedimentary series from southern Madagascar will aid prospecting targeting such types of deposit.

The sapphire deposits associated with desilicified granite or pegmatite occur in the central and southern parts of Madagascar, in mica schist in the Anjomakely area (Lacroix, 1922a) and in amphibolite in the Vohitany district (Andriamamonjy, 2006). In both deposits, corundum is hosted by biotite schists and feldspar rocks such as plagioclasite or microclinite, and fluid circulation is recorded through cm- to dm-wide conduits and intense fluid-rock K- and Ca-metasomatism. All the corundum-bearing biotite–sillimanite mica schists described by Lacroix in the Antsirabe and Vatomandry areas result from metasomatic transformation of schists. In the southern Neoproterozoic metamorphic belt of Madagascar, all these sites are systematically located in a shear-zone corridor. The importance of shearing and fluid flow was stressed by Pili et al. (1997a,b) who proposed a mantle fluid circulation into the major shear zones and a crustal fluid contribution in minor ones.

The nature of the percolated host-rock will define new types of corundum deposits. Two new types of Madagascan metamorphic gem corundum deposits are described here: sapphire in biotite schists developed upon feldspathic gneisses (Sahambano and Zazafotsy deposits) and ruby and polychrome sapphire in cordieritites intercalated within charnockites (Ambatomena and Iankaroka deposits). These deposits lie within shear zones and corundum is linked to fluid circulation through channels along fractures, foliation planes and lithological contacts. Similar deposits also occur in the Neoproterozoic Karur–Kangayam gemstone belt in southern India (Santosh and Collins, 2003), but differ in that the cordieritites are associated with pegmatites.

Infiltrational metasomatism, whether from crustal or mantle fluids, is important in the granulitic domain of southern Madagascar (Pili et al., 1997a,b). Phlogopite deposits hosted by clinopyroxenites, phlogopite occurrences in marbles and "sakenites" illustrate perfectly the fluid-rock interactions in the metamorphic formations. Previously, phlogopite-rich clinopyroxenites were attributed to metasomatism of marls (Lacroix, 1941; de La Roche, 1958; Joo, 1972) but C- and O-isotopic studies of carbonates and pyroxene from clinopyroxenites and metabasites show that the initial protolith was metabasite (Pili, 1997). Outside the shear zones, marbles have isotopic compositions similar to their protolith values, and metabasites have mantle-$\delta^{13}C$ signatures. In major shear zones, the input of mantle CO_2 suggests that the structures are deep-rooted. In minor shear zones, marbles and their related skarns were affected by CO_2-devolatilisation and water-rich infiltration. However, large isotopic variations at the metre scale in the shear zones reflect the heterogenous distribution of fluid flow (Pili, 1997). Significant phlogopite deposition in a major shear zone also suggests considerable input of H_2O into the conduit. "Sakenites" also represent infiltrational metasomatism but the original protolith was suggested to be a marl or clay-rich limestone (Lacroix, 1941; Devouard et al., 2002). The oxygen isotopic composition of corundum in "sakenites" from Sakeny, Vohidava and Ejeda (Table 1), however are within the $\delta^{18}O$ range ($4.9<\delta^{18}O<5.8$‰) which overlaps the $\delta^{18}O$ worldwide range of corundum hosted by mafic and ultramafic rocks ($3.2<\delta^{18}O<6.8$‰; Giuliani et al., 2007). This supports observations in the Tranomaro area, where the "sakenite" occurrence of Bekinana is formed at the expense of clinopyroxenite, and the Vohidava locality where clinopyroxenites are close to the "sakenite".

"Corundumites" are generally found as pebbles in rivers, but occur *in situ* only in the "sakenite" of Sakeny in association with anorthosites (Lacroix, 1941). Crystals of corundum with a size up to 10 to 20 dm appear in the desilicified granites and feldspathised mica schists from the Antsirabe region, and in the Anjomakely, Vatondrangy, Vohitrakanga and Antandrokomby areas (Lacroix, 1922a). The $\delta^{18}O$ values of corundums from the Lacroix collection "corundumites" from Anjomakely, Antohidrano and Ihosy are respectively 4.9, 3.95 and 5.4‰ (Giuliani et al., 2007). This again overlaps the $\delta^{18}O$ range of mafic-ultramafic rocks indicating that such huge crystals are developed in mafic and ultramafic rocks affected by intense Ca-metasomatism (anorthitite).

The Andranondambo sapphire deposit in south-eastern Madagascar is related to skarn mineralisation (Rakotondrazafy, 1995). It has produced variable amounts of medium to top gem-quality blue sapphires since 1994. In the Tranomaro area, extensive sapphire occurrences formed at the two main stages of skarn formation (Fig. 13). However, the economic gem-sapphire is linked to the third stage of crystallisation formed during retrograde metamorphism (Rakotondrazafy et al., 1996). The K-feldspar veins cut the marbles and associated diopside-bearing calc-silicate rocks. In the rim of the vein, K-feldspar clearly crystallised at the expense of calcite and diopside which implies a high mobility of aluminium in addition to potassium and silica. Fluid inclusions in different minerals from gneisses, skarns and sapphire-bearing veins are CO_2-rich (Ramambazafy et al., 1998). Fluids with high PCO_2 ($XCO_2>0.8$ mol.%) and PO_2 and low PH_2O are in equilibrium with the mineral assemblages. The C-and O- isotopic composition of the Tranomaro marbles have shown the crustal origin of these fluids and their probable relation with granitic magmatism (Boulvais et al., 1998). The infiltrated marbles and metasomatic clinopyroxenites do not record any contribution from a crustal C-source and the contribution of fluid infiltration is insignificant. The formation of the skarn in marble, however, results from the transport of Si, Mg, Th, U, Zr and REE by the metasomatic fluid. CO_2-rich fluids are not a good candidate for the mobilisation and transport of such elements which are rather immobile. At high PCO_2, the solubility of silica is low and a H_2O–NaCl-rich fluid may possibly transport the metals (Ramambazafy et al., 1998). Unmixing would produce a CO_2-rich phase in equilibrium with a H_2O–NaCl brine (Gibert et al., 1998). With such a high CO_2 concentration in the fluid, the CO_2-rich phase ($XCO_2>0.8$ mol.%; $P=5$ kbat and $T=600$ °C) would have to coexist with NaCl salt (Shmulovich and Graham, 1999).

The placers of Ilakaka represent an extreme mingling of ruby and sapphires from probably different origins. Pink and blue sapphires form over 88‰ of the production of gemstones but coloured sapphires and ruby of high-quality are also recovered. The possible origins of these gem corundums are discussed from geological considerations.

From the Upper Carboniferous to Mid-Jurassic (300 to 180 Ma), Madagascar was adjacent to East Africa with the Seychelles to the northeast (Lawler et al., 1992), and basins formed in connection with terrestrial rifts in Africa. Sedimentation covers about one third of Madagascar along its western extensional margin (de Wit, 2003), in sequences divided into the Sakoa, Sakamena and Isalo Groups. The Isalo Group represents the upper part of the active rift depositional sequences, 1 to 6 km thick, made up of conglomerates and white sandstones, capped by Lower Triassic red-bed sequences. Giant gem palaeoplacers formed in the Isalo sandstones, so that corundum sources are older than 200 Ma and a Late Cenozoic alkali-basalt contribution can be excluded.

The Phanerozoic sedimentary sequences and the Isalo Group cover the Precambrian basement which was intensely reworked between 950 and 450 Ma, during Pan-African tectonometamorphic events (Kröner, 1984). The Ar–Ar ages obtained on the corundum host- rocks are between 487 and 494 Ma (Table 1) and the U/Pb age obtained on zircon from stage 3 of skarn metasomatism of Andranondambo (Fig. 13), contemporaneous with gem sapphire deposition, is between 510 and 523 Ma (Paquette et al., 1994). The proximal location of the Ilakaka gem corundum district to the sapphire-bearing Precambrian terranes (Fig. 6) and ages of primary corundum deposits, make the Neoproterozoic metamorphic rocks a good candidate for the detrital corundums. Primary ruby and pink sapphire deposits occur in mafic and ultramafic rocks of the Vohibory unit and in cordieritites of the Androyan series. Trace elements in Ilakaka rubies plotted in the Fe_2O_3/TiO_2 *vs.* Cr_2O_3/Ga_2O_3 diagram fall into one group, within the metamorphic domain defined by Sutherland et al. (1998a, 2003) and overlap the domain defined by the metamorphic rubies of Soamiakatra.

Yellow and green sapphires are not yet known from the granulitic metamorphic rocks of Madagascar. The origin of the possible protoliths is still debatable from worldwide natural occurrences. Green and yellow sapphire of xenocryst origin are described in placers from alkali basalts (Sutherland et al., 1998b), the Garba Tula syenitic dyke (Simonet et al., 2004), the desilicified pegmatites in serpentinites from the Eastern African Neoproterozoic belt (Seifert and Hyrsl, 1999) and in amphibolitised gabbro associated with iolite at Malapatty in southern India (Santosh and Collins, 2003). An alkali basalt source is unlikely here but the three other origins are highly possible considering that pegmatites and mafic to ultramafic rocks are present in the Precambrian terranes of southern Madagascar.

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