Journal of African Earth Sciences 94 (2014) 156–170

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Chemical and oxygen isotopic compositions, age and origin of gem corundums in Madagascar alkali basalts

Saholy Rakotosamizanany [a,b,c], Gaston Giuliani [b,c,*], Daniel Ohnenstetter [c], Amos Fety Michel Rakotondrazafy [a], Anthony E. Fallick [d], Jean-Louis Paquette [e], Massimo Tiepolo [f]

[a] Université d'Antananarivo, Faculté des Sciences, Département des Sciences de La Terre, Ambohitsaina, BP 906, Antananarivo 101, Madagascar
[b] Université Paul Sabatier, GET/IRD, UMR CNRS-IRD-CNES 5563, 14 avenue Edouard Belin, F-31400 Toulouse, France
[c] Université de Lorraine, CRPG UMR 7358 CNRS-UL, 15 rue Notre-Dame-des-Pauvres, F-54501 Vandœuvre-lès-Nancy cedex, France
[d] Scottish Universities Environmental Research Centre, East Kilbride, Glasgow G75 0QF, Scotland, United Kingdom
[e] Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, BP 10448, F-63000 Clermont-Ferrand, France
[f] CNR, Istituto di Geoscienze e Georisorse, Unità di Pavia, via Ferrata 1, I-27100 Pavia, Italy

A R T I C L E I N F O

Article history:
Available online 13 July 2013

Keywords:
Madagascar
Placer in alkali-basalt
Gem corundum deposits
Chemical composition
Oxygen isotopes
Genetic model

A B S T R A C T

Madagascar is a large producer of gem corundum recovered from continental basaltic fields. The main mining areas are sapphire-bearing palaeoplacer deposits such as Ambondromifehy and Nosy Be in Antsiranana Province, northern Madagascar; Soamiakatra–Mandrosohasina in Antananarivo Province, central Madagascar; and Vatomandry district in Toamasina Province, eastern Madagascar. In Antananarivo Province, Soamiakatra is a primary deposit where ruby is found in metagabbro and pyroxenite xenoliths, brought-up to the upper crust by the Ankaratra volcanics. Petrographic studies indicate two different conditions of ruby formation, at the boundary of the eclogite domain ($T \sim 1100$ °C, $P \sim 20$ kb) and granulite facies ($T \sim 1100$ °C, $P < 15$ kb). In contrast, most of the sapphires in placer and paleoplacer have two origins: (i) differentiation of alkaline magma in chambers at the lower continental crust–mantle boundary (90% of the sapphires). They are related to syenite and anorthoclasite xenoliths in the basalts. These alkali-basalt hosts are linked with asthenosphere upwelling and E–W and N–S lithosphere thinning during Oligocene–Quaternary times. Zircons associated with the sapphires from Mandrosohasina and Ambatomainty sapphire deposits gave U–Pb ages at 7 Ma. The sapphires have low $\delta^{18}O$ values of 4.1 ± 0.4‰ ($n = 8$), within the range of sapphire in syenitic rocks. Chemical composition and mineral inclusions in sapphires, such as columbite-(Fe), tantalite-(Mn), pyrochlore group, samarksite group, uraninite and anorthoclase confirm their syenitic origin. (ii) metamorphic xenocrysts (10%) brought up by the same magma. Oxygen isotopic compositions of rubies from placer deposits, $\delta^{18}O$ = 3.1 ± 1.1‰ ($n = 6$) are typical of ruby in mafic and ultramafic rocks and 'plumasite' in mafic rocks (1.25 < $\delta^{18}O$ < 7.5‰, $n = 35$).

In Toamasina Province, the sapphires of Vatomandry are mainly of metamorphic origin (∼85%) and their $\delta^{18}O$ = 4.1 ± 0.4‰ ($n = 9$) are low and overlaps the range defined for metasomatic sapphires linked to 'plumasites' and biotite schists in shear zones; ∼15% of the sapphires are magmatic in origin with a low $\delta^{18}O$-isotopic range in the sapphire-bearing syenites field. In Antsiranana Province, there are no rubies and sapphires are either magmatic (∼40%) or metamorphic (∼60%) in origin. The $\delta^{18}O$ = 4.5 ± 0.5‰ ($n = 11$) values are similar to the mean $\delta^{18}O$ of sapphires from other two Provinces. Two U/Pb ages on zircons gave two contrasted ages at respectively 40.6 Ma for Ambondromifehy and 0.7 Ma for Nosy Be sapphire deposits. The characteristics of the corundum, their isotopic compositions as well as their ages demonstrate the existence of two distinct sources of corundum associated with alkali-basalts in Madagascar. On one hand, the rubies associated with metagabbros and garnet-bearing pyroxenites are linked to mafic and ultramafic complexes of eclogite facies at the boundary between lower crust and upper mantle, retrograded to granulite facies during the Pan-African event. On the other hand, the sapphires brought up during the Eocene to Quaternary are interpreted to be either magmatic and coeval with a volcanic event involving differentiated alkaline magma, or metamorphic and extracted from the pre-existing Precambrian basement during the extrusion of the magma.

1. Introduction

Madagascar is a major gem corundum-exporting country (Yager et al., 2008). In 1997, it was the second largest producer of

* Corresponding author. Address: CRPG/CNRS, 15 rue Notre-Dame-des-Pauvres, BP 20, F-54501 Vandœuvre-lès-Nancy, France. Tel.: +33 3 83 59 42 38; fax: +33 3 83 51 17 98.
E-mail address: giuliani@crpg.cnrs-nancy.fr (G. Giuliani).

1464-343X/$ - see front matter
http://dx.doi.org/10.1016/j.jafrearsci.2013.06.003

sapphires (4248 kg) following the discovery in 1996 of the Ambondromifehy placers, located in the basaltic Province of Antsiranana (Fig. 1; Schwarz et al., 2000). In 1999 after the discovery of giant placer deposits in the Ilakaka and Sakahara region, southern Madagascar (Garnier et al., 2004), the production of sapphires increased from 3810 to 9536 kg in 2000. Since 2004, the Malagasy production decreased to 4700 kg per year (Fig. 2A). The production of ruby wasnot significant before 2000, until the discovery of two deposits in the Province of Toamasina named Andilamena (Rakotondrazafy et al., 2008) and Vatomandry (Schwarz and Schmetzer, 2001). Since 2000, the mean annual production of ruby has remained at around 850 kg per year. In 2005, Madagascar was the third largest ruby-exporting country (Fig. 2B) after Kenya (5100 kg) and Tanzania (2800 kg). The deposits of Ambondromifehy and Vatomandry are placers related to basaltic environments (Giuliani et al., 2007a). These alluvial deposits are characterized by large volumes of gems extracted from detrital sediments, with a low grade of economic sapphires and/or ruby (circa 10–15% of the rough production; Schwarz et al., 2000). These sapphires called 'basaltic' or "BGY" blue–green–yellow sapphires (Sutherland et al., 1998a,b; Schwarz et al., 2000; Graham et al., 2008) are the main type of sapphires exported throughout the world (Fig. 1C and D) with the main producing-countries being Australia (5500 kg), China (3000 kg) and Cameroon (1000 kg).

In Madagascar, the main corundum deposits (Fig. 1) form sapphire-bearing palaeoplacers and placers of the Ambondromifehy district in the northern part of the country, Soamiakatra–Mandrosohasina and other deposits from Antsirabe region in the central part, and Vatomandry in the eastern part of the island. This paper aims to review geological and recent metallogenetic studies to classify ruby and sapphires in the different gem Provinces and to discuss the genetic model for their formation. Recent knowledge on these corundum deposits was obtained by the PhD thesis of Rakotosamizanany (2009) and fieldwork developed by the Institute of Research and Development (IRD) with the academics of the University of Antananarivo and the PGRM program from the Ministry of Energy and Mines of Madagascar (BGS-USGS-GLW, 2008).

The details of the geology of the deposits, mineralogy and chemistry of the gem-corundum and oxygen isotope data of ruby and sapphires are presented in the Electronic Supplement Material (see ESM text, tables and figures). The analytical procedures used for mineral chemistry, isotopic and radiometric data are compiled in the Appendix.

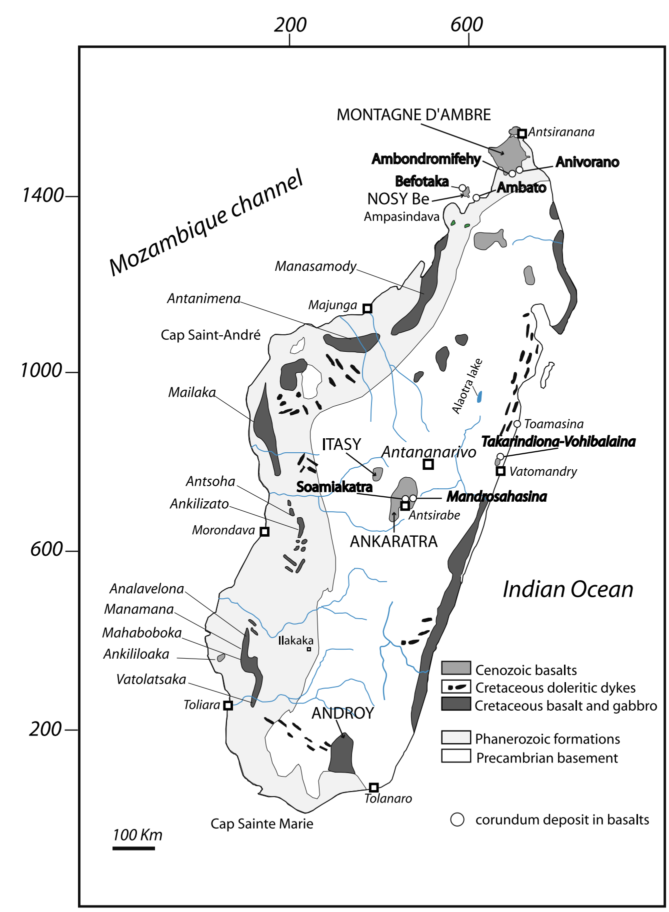

Fig. 1. The volcanic Provinces of Madagascar and localities of the 'basaltic' corundum deposits related to the Cenozoic basalts in the Provinces of Antsiranana, Antananarivo and Toamasina (modified from Rasimanana, 1996). The deposits of gem corundum: north in the Antsiranana Province, the mining districts of Ambondromifehy and Anivorano in the Montagne d'Ambre, Ambato peninsula and Befotaka in Nosy Be island; in central Madagascar in Antananarivo Province, the mines of Soamiakatra, Mandrosohasina–Kianjanakanga (Antsirabe area) in the volcanic Ankaratra massif; and in east Toamasina Province, with the deposits of Vatomandry in the Takarindiona and Vohibalaina basaltic areas. The geographic coordinates are related to the Laborde projection.

2. Mesozoic and Cenozoic magmatism in Madagascar

Madagascar experienced several significant magmatic episodes during the break-up of the Gondwana super-continent and continuous continental drift between Africa and Madagascar, India and Sri Lanka, and Antarctica (de Wit, 2003). The first was an Upper Cretaceous episode at the Turonian–Coniacian (87 Ma). The two other episodes are Cenozoic in age, with volcanic flows in the Paleocene and Eocene (65–34 Ma), and in the Upper Miocene (circa 10 Ma), and finally in the Quaternary (Karche, 1973; Melluso et al., 1997; Melluso and Morra, 2000; Mottet, 1981; Tucker et al., 2008; Bardintzeff et al., 2010; Cucciniello et al., 2011).

The Upper Cretaceous magmatic episode produced tholeiitic basaltic flows and doleritic dykes (Fig. 1; Besairie et al., 1957). It formed widespread stratified flows on the sedimentary units in the western and southern coastal regions in the Morondava and Majunga, and Androy areas (Fig. 1). The Androy massif sequence, 1500 m thick, contains tholeiitic basalts associated with alkali-basalts and rhyolites. The Cretaceous flows are also found on the eastern border of Madagascar in the Provinces of Antsiranana, Toamasina and Fianarantsoa (Besairie et al., 1957; Nicollet, 1984).

The Paleogene–Neogene and Quaternary magmatic episodes north of Toliara (Ankililoaka flows), south and north of Antsiranana (Montagne d'Ambre, Nosy Be, Ambato peninsula, Ampasindava), around Antsirabe (Massifs of Itasy and Ankaratra; Besairie, 1971), and close to Vatomandry (Fig. 1), form a sequence of alkali-basalts, ignimbrites, rhyolites, trachytes, phonolites, and basaltic and basanitic tuffs (Karche, 1973). The gem corundum deposits in basaltic areas are only related to these two Cenozoic episodes, in Antsiranana, Antananarivo and Toamasina Provinces (see ESM text). The deposits from Antsiranana Province are located 70 km south of Antsiranana city, in the areas of Anivorano and Ambondromifehy on the southern border of the Montagne d'Ambre (Fig. 1), and in the Ambato peninsula and Nosy Be Island. The sapphires and/or ruby deposits from Antananarivo Province are located within the Ankaratra volcanic massif. Two types of deposits are recognized: (i) a primary ruby deposit associated with a basaltic dyke at Soamiakatra (Antanifotsy region); and (ii) secondary deposits (i.e. alluvial placer and paleoplacer), located to the north and east of Antsirabe city (Mandrosohasina, Kianjanakanga, Ambatomainty, Antsabotraka). The rubies and sapphires of Toamasina