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Ampandrandava and similar phlogopite deposits in southern Madagascar: Derivation from a silicocarbonatitic melt of crustal origin

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ABSTRACT

The Ampandrandava phlogopite deposit, located near Beraketa in southern Madagascar, and others like it in the region, in both the Androyen and Anosyen domains, were created by the crystallization of pods and dikes of crustally derived silicocarbonatitic melt. The anatectic reaction seems to have involved regional marble with C and O isotopes shifted toward mantle values and, at Ampandrandava, in particular, input from an evaporitic sequence. This hypothesis accounts for the importance of magmatic anhydrite in the pegmatitic pods and the presence of chlorine in the fluorapatite and phlogopite. The pods and dikes were emplaced in phlogopite-bearing clinopyroxenite; the aggressive carbonate–sulfate melt digested the host locally, and the diopside, phlogopite and fluorapatite crystallized quickly owing to a vapor pressure quench rather than a thermal quench. The high-temperature anatectic event occurred after the final episode of regional metamorphism, at a time of exhumation of deep crust, tectonic quiescence accompanying post-orogenic collapse, and anorogenic magmatism once collision and deformation had ceased.

1. Introduction

The southern sector of Madagascar offers a glimpse into the deep crust in an area strongly deformed before, during and after a series of continent–continent collisions associated with the Pan-African orogeny (Windley et al., 1994; Martelat et al., 1997). The area has been a major focus of attraction recently in connection with Gondwana-related research. In the realm of mineral deposits, the area attracted the attention of Alfred Lacroix, who in 1941 published a landmark memoir on phlogopite deposits and the pyroxenite bodies that are their exclusive host. At that time, the exploitation of phlogopite deposits was in full swing, as there was a great demand for phlogopite, and Madagascar was the world's major supplier. There are dozens of such deposits in southern Madagascar. We focus here on Ampandrandava, the most important of the deposits, but also present information on a handful of smaller deposits. At Ampandrandava, the euhedral crystals of phlogopite, up to a meter across in a calcite + anhydrite matrix, are undeformed. The matrix in the other deposits sampled consists mostly of calcite. Ampandrandava is located in the Beraketa high-strain zone (Fig. 1), which cuts the Imaloto Group of granulite-facies rocks in the Androyen domain (Tucker et al., 2011). The deposit was still in production in 1997, but closed soon thereafter. In this study, we explore the implications of undeformed books of phlogopite that attain metric dimensions in a syngranulitic high-strain zone. We provide information on the texture, chemical and isotopic compositions and age of the main minerals. We examine the genetic aspects of the association with pyroxenite, syenite and granite, draw on similarities with similar deposits in eastern Canada, as did Lacroix (1941), and evaluate the possibility that a crustal silicocarbonatitic melt was the cause, rather than a mixed H_2O–CO_2 fluid.

2. The geological context

There is an unusually complete database concerning the Ampandrandava mine (Fig. 1, #3), owing to its relative accessibility, including underground accessibility on up to four levels, and its importance as a supplier of phlogopite. Pierdzig (1992) and Rakotondrazafy (1992) both sought to define the *P–T* conditions attained during high-grade metamorphism at Ampandrandava. The deposit consists of a series of dikes and pods emplaced within tabular bodies of clinopyroxenite over an area of about 2 × 0.5 km. It is located close to 20°5′ S, 45°42′ E, roughly 10 km northeast of Beraketa in Tulear Province, southern Madagascar. In fact, most of the phlogopite deposits are located in the eastern Androyen domain (Tucker et al., 2011), along the Beraketa high-strain zone, aligned 250 km north–south and about 25 km in width (Fig. 1). High-grade granulite-facies rocks exposed in the Androyen domain show the

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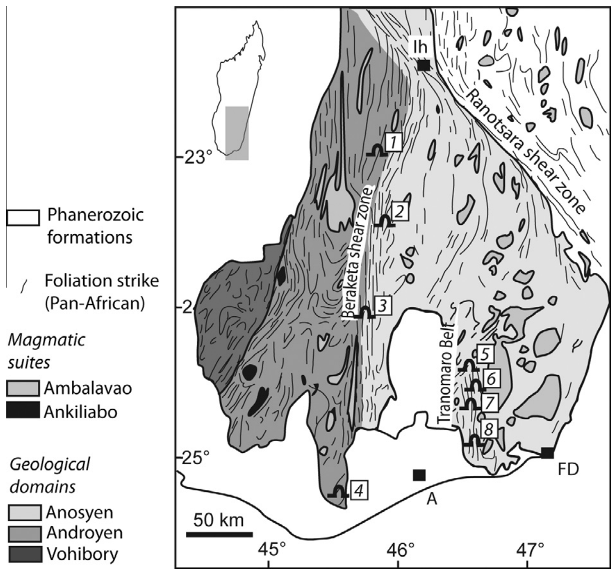

Fig. 1. Map of southeastern Madagascar showing the major shear zones and the distribution of the phlogopite deposits sampled. Sample locations: Beraketa belt: (1) Benato, (2) NO Isoanala, (3) Ampandrandava, (4) Sakamasy; Tranomaro belt: (5) Marosohy Sud, (6) M74 Amboanevo, (7) Analalava, (8) Sakaravy. Localities: Ih Ihosy, A Ambovombe, FD Fort Dauphin (now Tôlanaro). Magmatic suites and geological domains are simplified from Tucker et al. (2011). The Ankiliabo anorthositic suites are dated at 930–910 Ma, whereas the Ambalavao suites are granitic and syenitic, and range in age from 545 to 510 Ma. The inset shows the area of interest in southeastern Madagascar.

effects of two orogenic pulses. The M_1 event resulted from a collision at about 630 Ma, and the mineral assemblages developed in the supracrustal rocks record high temperatures, in the range 750–800 °C (Jöns and Schenk, 2011). Tucker et al. (2011) placed the timing of the M_1 event at 620–600 Ma, and proposed conditions of 835 ± 20 °C and 7.0 ± 0.5 kbar. At Ampandrandava, Rakotondrazafy et al. (1997) and Martelat et al. (1997) had established a maximum pressure in the range 7–8 kbar and a minimum temperature of 850 °C for M_1. The second event, M_2, involved the east-directed translation to the Androyen domain and "orogenic convergence" with the Anosyen domain in Ediacaran time (~560–530 Ma); conditions in the Androyen domain are considered to have been 550–600 °C and 4–5 kbar (Tucker et al., 2011).

Phlogopite deposits also occur in the Anosyen domain, juxtaposed to the east. The oldest supracrustal rocks there are Paleoproterozoic, and there is no record of M_1. The collisions led to regional conditions close to 900 °C and 9–10 kbar (Tucker et al., 2011) in the interval 560–530 Ma, and possibly as high as 950–1000 °C and 11 kbar (Jöns and Schenk, 2011). Anorogenic granitic rocks, locally charnockitic, were emplaced in Early Cambrian time (545–510 Ma), in a period of regional relaxation following repeated collisions (e.g., de Wit et al., 2001). Four of the deposits mentioned in this paper are from the Anosyen domain, in the Tranomaro belt (Fig. 1).

As Tucker et al. (2011) pointed out, the Androyen and Anosyen domains contain a newly recognized suite of Paleoproterozoic igneous rocks (2.1–1.8 Ga), and the stratified supracrustal rocks contain detrital grains of zircon that give ages in the interval 2.3–1.8 Ga. Meta-evaporites have not been encountered, and there is no sign of Archean crust in this region, except for the unradiogenic Nd isotope composition of granites and metasedimentary units [ε_{Nd} (565 Ma) = −22: Boulvais et al. (2000)], which points to the reworking of an Archean basement.

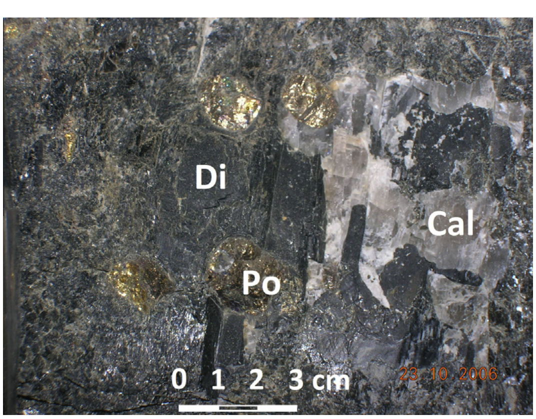

Fig. 2. Diopside-rich border of a small pod, showing globules of pyrrhotite trapped in diopside and a "finger" of diopside projecting into the carbonate matrix. Note the presence of bits of the carbonate matrix in the diopside.

3. The phlogopite-bearing pods

Mineralization is associated with vertically disposed planar bodies of clinopyroxenite in a tightly isoclinally folded sequence. Lacroix (1941, p. 42) described the phlogopite as filling dikes ("*filons*") and pods ("*poches qui ne peuvent présenter aucun vide*") of calcite, associated with anhydrite at Ampandrandava. The borders of these cross-cutting bodies typically are lined ("*leurs contours sont hérissés*") with euhedral crystals of diopside or phlogopite that advance into the carbonate + sulfate matrix (Figs. 2, 3a and b; see also Morteani et al., 2013, Fig. 2) in what can be described as a mega-scale cellular interface leading to a comb texture. Other primary minerals in the pods and dikes include apatite, titanite, spinel, and globules of pyrrhotite (Fig. 2). The phlogopite-bearing pods are restricted to the clinopyroxenite bodies, and bear no relationship to planar bodies of K-rich syenite that also strike north–south, conformably with all other units (Fig. 4). The pods are found at the intersection of orthogonal faults cutting the pyroxenite, and developed in openings caused by late minor transtensional or "en relais" adjustments. The minerals in these pegmatite-textured pods and dikes show no sign of deformation (Fig. 3c).

4. Petrographic and mineralogical details

The clinopyroxenite in the steeply dipping planar bodies has a granoblastic texture and a grain size of 1–3 mm; it is mineralogically not completely uniform along strike with respect to the accessory minerals that it contains. Lacroix (1941) mentioned the variable presence of minor amounts of phlogopite, calcite, anorthite and meionitic scapolite in the pyroxenite, and the absence of quartz, garnet, amphibole and titanium-bearing minerals. The euhedral diopside, phlogopite and apatite crystals in the pods and dikes are not restricted to the walls, but also occur completely surrounded by the calcite + anhydrite matrix (Fig. 5). All three minerals have grown *in situ* within this composite matrix, and are commonly embedded partly in calcite, partly in anhydrite (Pierdzig, 1992, Figs. 75 and 76). The diopside, phlogopite and apatite crystals, attaining tens of centimeters, contain roundish to elongate inclusions of the calcite or anhydrite matrix. In addition, films of orange calcite or of purplish anhydrite are positioned between adjacent mineral grains and line open cleavages in phlogopite.

The crystals of diopside (Table 1) depart from the ideal 2.00 *apfu* Si composition by incorporating up to 4.3 wt.% Al_2O_3, most of which is present as ^{IV}Al filling the *Si* site. The Mg# is 0.89, and in three samples of four, one can infer more Fe^{3+} than Fe^{2+} on the basis of charge-balance considerations, a characteristic also present in the material analyzed by Lacroix (1941). The books of phlogopite