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New insights into the origin of the Evate apatite-iron oxide-carbonate deposit, Northeastern Mozambique, constrained by mineralogy, textures, thermochronometry, and fluid inclusions

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ABSTRACT

The Evate deposit represents the largest resource of apatite in south-east Africa (155 Mt. ore grading 9.3 wt.% P_2O_5) accumulated in up to 100 m thick magnetite-carbonate-apatite horizons conformable to the granulitic gneiss of the Monapo Klippe. Baddeleyite and zircon from early iron-oxide (magnetite, geikielite, spinel), apatite- and forsterite-bearing rocks have been dated to 590 ± 6 Ma using the LA-ICPMS U-Pb method, whereas monazites from anhydrite-apatite-carbonate rocks show a concordant U-Pb-Th age corresponding to 449 ± 2 Ma. Temperatures inferred from calcite-dolomite solvus data and graphite structural ordering span the interval from ≥815 to 276 °C. Primary and secondary fluid inclusions in apatite document calciocarbonatite melts associated with early apatite, and CO_2-bearing sulfate-chloride brines progressively diluted with low-salinity, probably metoric waters, towards ultimate stages of the deposit formation. The calciocarbonatite melts have initially coexisted with liquid nitrogen and later with sulfate-chloride brines mixed with $N_2 \pm CO_2$ gas.

Crystallization of spinel around baddeleyite by the mechanism of Ostwald ripening, nucleation of graphite spherules along pyrrhotite-carbonate boundaries, the occurrence of molybdenite, baddeleyite-to-zircon transformation, and high crystallization temperatures inferred from graphite structural ordering and calcite-dolomite thermometry suggest a magmatic origin of the early mineral assemblages. In contrast, microthermometric characteristics of primary aqueous inclusions in the late apatite and the presence of zeolites (thomsonite-Ca, mezolite) is diagnostic of a low-temperature hydrothermal crystallization.

Formation of the early magnetite-apatite-forsterite assemblage is thought to be coeval with mafic alkalic intrusions of the Mazerapane Suite superimposed on the granulite facies metamorphism of the Monapo Klippe. The low-temperature, anhydrite-bearing mineralization was associated with the massive circulation of sulfate-rich brines along fractures activated during the Late Cambrian-Ordovician extension. Origin of the sulfate-rich brines may be genetically related either with the magmatic-hydrothermal differentiation, or with the remobilization of crustal evaporites.

1. Introduction

The origin of the Evate deposit of Mozambique – the largest apatite accumulation of south-east Africa – has been disputed. An intrusive magmatic origin and close genetic relationship with neighboring felsic and mafic plutons is indicated by fenite aureoles around some apatite-carbonate bodies (Macey et al., 2013). A hydrothermal-metasomatic origin is deduced from the preferential accumulation of apatite along N-S, W-E and NW-SE-trending fractures (Cílek, 1989). The deposit is also designated as metasomatized or metamorphosed marble (Karlsson, 2006; Ueda et al., 2012a; Macey et al., 2013), mainly owing to a 590 Ma old zircon in forsterite-magnetite rocks (Siegfried, 1999) coeval with the granulite-facies metamorphism. Hence, the principal problem

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to be solved is whether the deposit represents marble which has been metasomatized by fluids of carbonatitic affinity, being thus genetically similar to the Bayan Obo deposit of Inner Mongolia (e.g. Kynický et al., 2012), or it corresponds to carbonatite-phoscorite deposits associated with mafic-ultramafic intrusions such as those in the Kola Peninsula and other intra-plate tectonic settings (e.g. Wall and Zaitsev, 2004; Ivanyuk et al., 2016). Thirdly, it may belong to pseudo-carbonatites, i.e. sedimentary carbonates remelted by mafic intrusions in continent collision zones (e.g. Sklyarov et al., 2009).

This contribution presents new geochronological, mineralogical, textural, thermometric and fluid inclusion data which are essential for elucidating the origin of Evate deposit. Zircon, baddeleyite and monazite from different rock types were studied using electron probe microanalysis (EPMA) and U-Pb-Th isotopes were determined by in situ laser ablation inductively-coupled plasma mass spectrometry (LA-ICPMS). Fluid and solid inclusions were characterized in various apatite types. Graphite and calcite-dolomite thermometers were employed to constrain thermal history. Finally, new geochronological data are discussed within the framework of the tectonic evolution of Gondwana.

2. Geological setting

The Evate deposit occurs in the southeastern part of the Monapo Klippe, approximately 50 km east of the coastal region of the Nampula Province, Mozambique (Fig. 1). The Monapo Klippe is an oval structure, 40 × 35 km in size, interpreted as a relic of a Neoproterozoic nappe metamorphosed to granulite-facies conditions (Pinna et al., 1993; Grantham et al., 2008; Viola et al., 2008) thrusted over the Mesoproterozoic basement of the Nampula Block metamorphosed to amphibolite-facies conditions (Bingen et al., 2009; Macey et al., 2010).

The Monapo Klippe is composed of variegated, strongly deformed granulite-facies rocks of the Metachéria Complex intruded by weakly deformed, silica-oversaturated alkaline felsic igneous rocks of the Ramiane Suite and silica-undersaturated, alkaline, mafic to ultramafic rocks of the Mazerapane Suite. Intrusion of the Ramiane granite pluton is nearly synchronous with the granulite-facies metamorphism of the Metachéria Complex, as documented by almost identical U-Pb zircon ages in both suites ranging from 626 to 642 Ma. Absence of a contact metamorphic aureole indicates that the mafic/ultramafic Mazerapane suite intruded the country rocks during peak temperature metamorphic conditions. Ages of exhumation and hydration events have been deduced from 568 to 590 Ma and 591–601 Ma old zircon rims in the Metachéria granulites and the Ramiane pluton, respectively (Grantham et al., 2013; Macey et al., 2013). The apparent shift of zircon ages in both units has been interpreted as diachronic metamorphic response caused by contrasting lithologies and prolonged zircon growth at lower temperatures (Macey et al., 2013). Minimum age of latest tectonic deformations within the Monapo Klippe has been constrained by a 551–569 Ma old undeformed aplite vein in the Ramiane pluton (Jamal, 2005), although ~550 Ma old collisional fabrics have also been recognized in other places (Ueda et al., 2012b). The late collisional fabrics have been attributed to the N-S collision between northern and southern Gondwana which started at ~590 Ma (Grantham et al., 2013). The Monapo Klippe was emplaced in its recent position atop the Nampula Block within the time interval from 530 to 490 Ma, as inferred from kinematic indicators in the marginal mylonite zone (Miller et al., 2013) and from SHRIMP U-Pb ages of detrital zircons in para-authochtonous

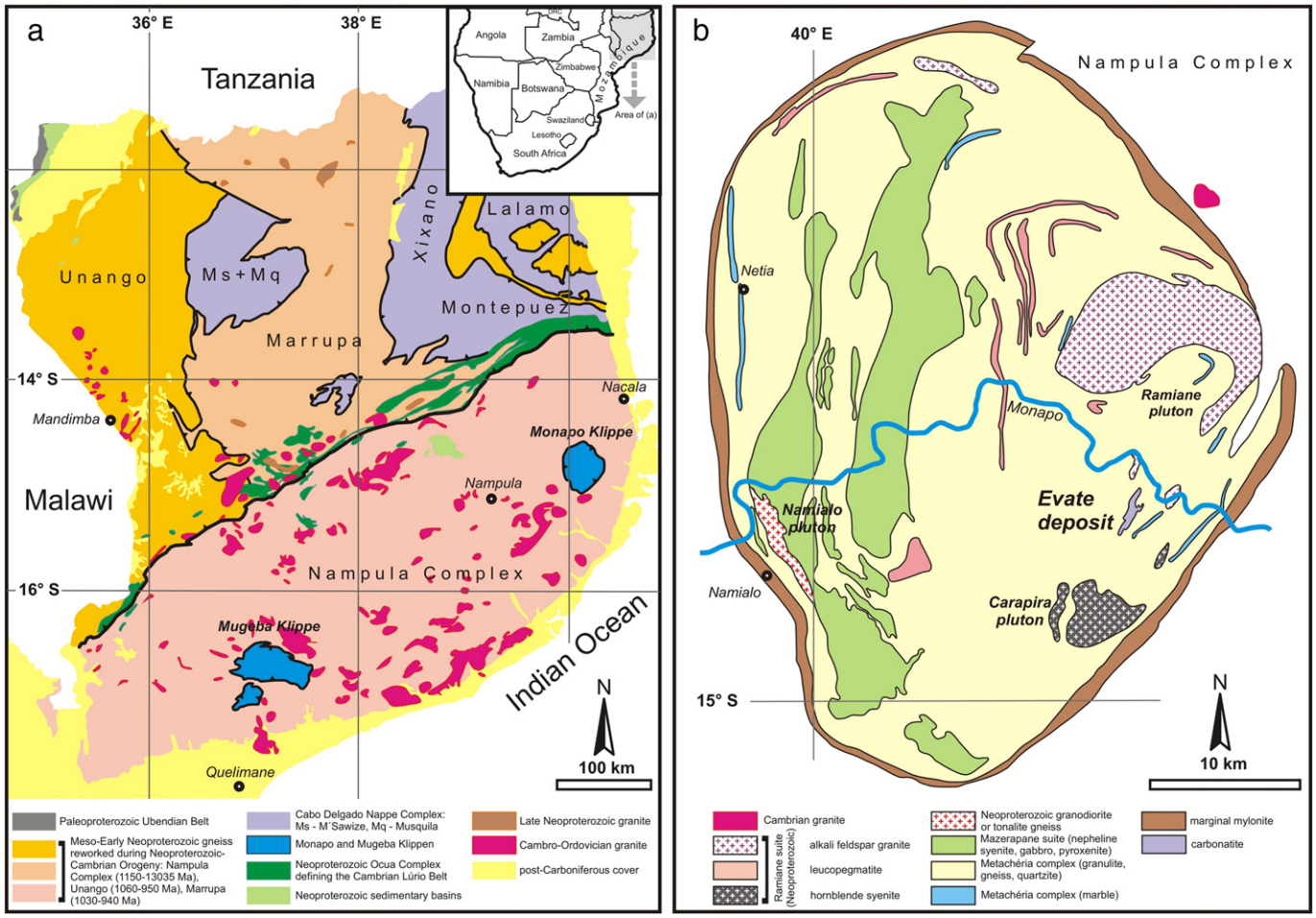

Fig. 1. Simplified geological maps of the northern Mozambique (a) and the Monapo Klippe (b) adapted from Macey et al. (2013) and references therein.