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Genesis of the Tonian Imorona–Itsindro magmatic Suite in central Madagascar: Insights from U–Pb, oxygen and hafnium isotopes in zircon

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ABSTRACT

Madagascar occupies an important location within the East African Orogen (EAO). The EAO comprises an assemblage of Neoproterozoic microcontinents and arc terranes lodged between older cratonic blocks during the final assembly of the supercontinent Gondwana. The Imorona–Itsindro Suite of central Madagascar represents voluminous Tonian-aged (850–750 Ma) magmatism with controversial petrogenesis. Early work proposed arc magma generation coinciding with oceanic plate subduction during closure of the Mozambique Ocean along the 'Betsimisaraka Suture' in eastern Madagascar. Recently, others have questioned the existence of such a suture in Madagascar and rather suggest extension related emplacement into the middle and upper crust through a system of pre-existing structures. New U–Pb (zircon) geochronological data coupled with in-situ oxygen and hafnium isotopic analyses demonstrate that the Imorona–Itsindro Suite had several source components. Most of the Tonian-aged magmatic rocks were derived by mixing between ancient crust and mantle derived melts. $\delta^{18}O$ values show variation that indicates significant involvement of crustal material and hydrothermal fluids. Predominantly low negative $\varepsilon_{Hf}(t)$ values are also variable and indicate significant crustal involvement in the genesis of the Tonian magmas. A compilation of all available geochronological data shows magmatism was essentially continuous for ~100 Myr but with periods of increased activity at ~800 Ma, ~791 Ma and ~784 Ma. Temporal analysis shows magmatic cycles of enrichment and depletion on the scale of 15–40 Ma. Spatial variations in isotope compositions reflect the heterogeneity of probable crustal source rocks present in the Ikalamavony, Itremo, Antananarivo and Masora Domains. A tectonic model is proposed for the Imorona–Itsindro Suite as a long-lived Andean-like arc on the margin of the Mozambique Ocean. The longevity and temporal isotopic trends are interpreted as reflecting cycles of arc advance and retreat.

1. Introduction

The East African Orogen (EAO) is one of the largest of orogens formed during the Ediacaran/Cambrian amalgamation of Gondwana (Stern, 1994, 2002; Meert, 2003; Collins and Pisarevsky, 2005; Johnson et al., 2011; Fritz et al., 2013). This relationship is expressed in the Mozambique Belt (see Fritz et al., 2013 for a recent summary), where the EAO separates Neoproterozoic India from the African Congo-Tanzania-Bangweulu Block (Fig. 1a). To the north, in the Arabian–Nubian Shield, the EAO consists of fragments of pre-Neoproterozoic continental crust in Saudi Arabia, Yemen and the Horn of Africa (e.g. the Afif Terrane), interleaved with Neoproterozoic oceanic-arc like terranes (Johnson et al., 2011; Robinson et al., 2014; Blades et al., 2015) with final amalgamation in the Ediacaran (Doebrich et al., 2007; Cox et al., 2012). The pre-Gondwana ocean that separated these landmasses is referred to the Mozambique Ocean. Although the Arabian–Nubian Shield preserves many oceanic suture zones recording accretion of the shield but as the orogen is traced south, the identification of potential sutures becomes less clear. This led Shackleton (1996)

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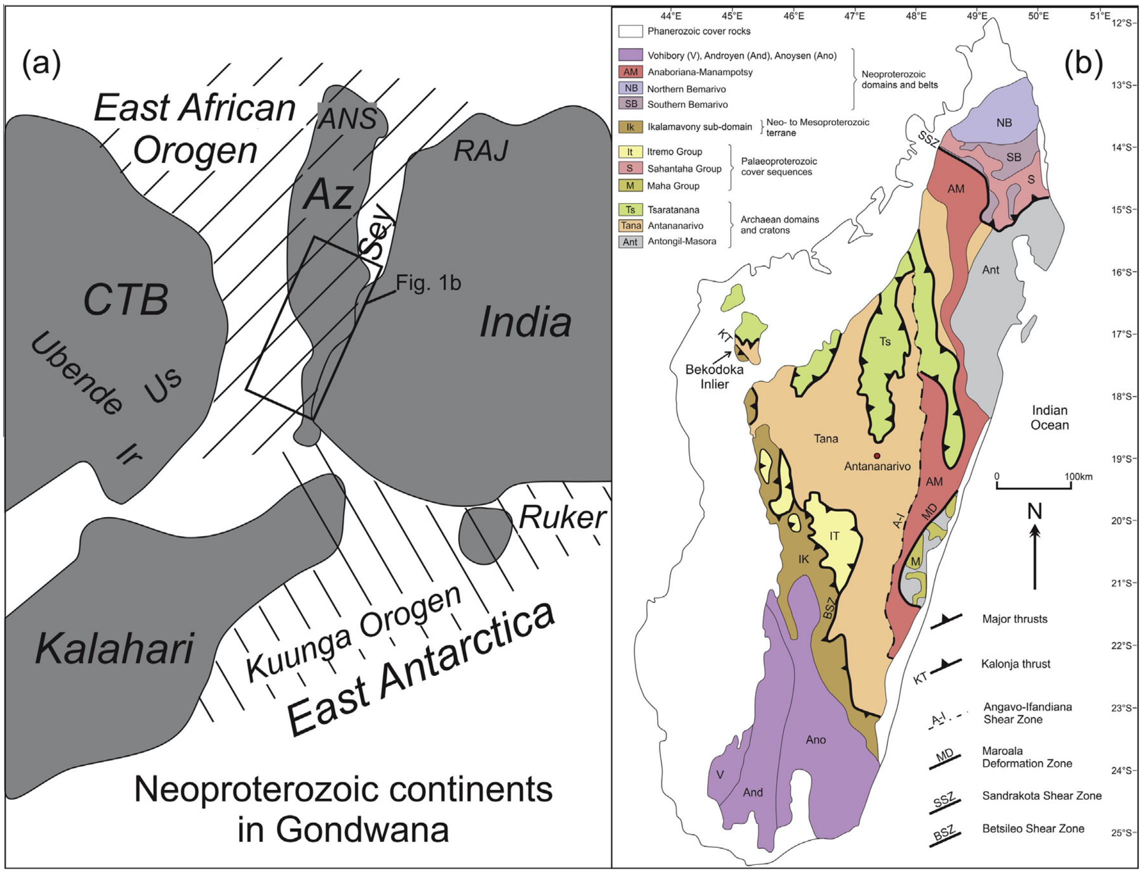

Fig. 1. (a) Palaeogeographic reconstruction of the Neoproterozoic continents in Gondwana showing the location of the present study (after Collins and Pisarevsky, 2005). Abbreviations: Az = Azania; ANS = Arabian Nubian Shield; Sey = Seychelles; Ir = Irumide Belt; Ruker = Ruker Terrane, East Antarctica; CTB = Congo-Tanzania-Bangweulu Block; Ubende = Ubende Belt; and Us = Usagaran orogen. (b) Simplified basement geology of Madagascar (after Collins, 2006 and De Waele et al., 2011).

to review the various suggested traces of the Mozambique Ocean suture. He concluded that, unlike many Phanerozoic orogens that involve accretion of multiple terranes, the Mozambique Ocean closed as a single suture; and this lay within East Africa.

Collins and Windley (2002) proposed that this single-suture model was an over-simplification, and suggested a wide band of pelitic gneiss, with Neoproterozoic depositional ages (Collins et al., 2003b) and associated pod-like peridotite bodies, gabbro and emerald mineralisation represented another Mozambique Ocean suture zone (termed the 'Betsimisaraka Suture'), which separated central Madagascar from India. Several authors (Collins and Windley, 2002; Cox et al., 2004; Fitzsimons and Hulscher, 2005; Collins, 2006) have suggested that central Madagascar formed a Neoproterozoic microcontinent, which, along with parts of southern India (the Madurai Block, Plavsa et al., 2014; Collins et al., 2014), East Africa, Yemen and Saudi Arabia (Collins and Windley, 2002), was isolated from both Neoproterozoic India and the Congo-Tanzania-Bangweulu Block in East Africa by oceanic crust. Collins and Pisarevsky (2005) called this continent 'Azania' (Fig. 1a). The accretion of Azania to the Dharwar Craton along the Betsimisaraka Suture was accompanied by voluminous magmatism in central Madagascar (Collins, 2006) – interpreted to result from Andean-style subduction. Recently, the existence of Azania has been challenged, and an alternative 'Greater Dharwar' continent has been proposed (Tucker et al., 2011b, 2014; Boger et al., 2014) that incorporates all of eastern and most of central Madagascar on the margin of Neoproterozoic India – reverting to a single suture hypothesis for the Mozambique Ocean. According to Tucker et al. (2014), during Tonian times (recently redefined as ca. 1000–720 Ma; Cohen et al., 2015), to the west and north of central Madagascar lay an open ocean – the Mozambique Ocean – the subduction of which resulted in widespread magmatism in central Madagascar (Handke et al., 1999) implying a major magmatic event ~300–200 Myr prior to the final amalgamation of Gondwana.

Although the age of the Imorona–Itsindro Suite is well documented, (see Tucker et al., 2014 for a recent summary), the interpretation of the geochemistry of the suite as a whole is controversial. Traditionally, the suite was likened to a continental arc (Handke et al., 1997, 1999; Tucker et al., 1999b; Kröner et al., 2000). However, recent work proposed the suite may have formed during crustal extension, possibly involving a putative mantle plume (Tucker et al., 2014; Yang et al., 2014; Zhou et al., 2015b). This new model was based on: (1) the general bi-modal felsic-mafic nature of the suite (McMillan et al., 2003), (2) the nested geometry of the complexes and apparent emplacement of the suite into a series of pre-existing fractures (Moine, 1974), (3) the presence of similar lithologies with a common Proterozoic history on both sides of the Betsimisaraka Suture Zone (Tucker et al., 2011a) and (4) geochemical characteristics of some Tonian-aged rocks (Yang et al., 2014; Zhou, 2015; Zhou et al., 2015a). To try and clarify this conundrum, the current investigation presents an age and isotopic study of the entire Imorona–Itsindro Suite using isotopic information preserved in zircon. Zircon is a powerful tool in this context because of its durability and chemical stability over a wide range of lithospheric pressures, temperatures, and fluid/melt compositions (e.g. Cherniak et al., 1997). Analysis of individual zircon grains using micro-beam techniques is imperative because