Evolving Marginal Terranes During Neoproterozoic Supercontinent Reorganization: Constraints From the Bemarivo Domain in Northern Madagascar

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Special Section:
Collisional orogenic systems as recorders of collisions between arc and continents

Key Points:
- New model links northern Madagascar, Seychelles, NW India, Oman, south China at c. 750 Ma
- New zircon Hf and O isotope data from northern Madagascar indicate that the Bobakindro Terrane (northern Bemarivo Domain) is juvenile
- The Marojejy Terrane (southern Bemarivo Domain) has evolved Hf isotope signatures and likely links with central Madagascar magmatic suites

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Figure S1

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Evolving Marginal Terranes During Neoproterozoic Supercontinent Reorganization: Constraints From the Bemarivo Domain in Northern Madagascar

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Abstract Madagascar is a key area for unraveling the geodynamic evolution of the transition between the Rodinia and Gondwana supercontinents as it contains several suites of c. 850–700 Ma magmatic rocks that have been postulated to correlate with other Rodinian terranes. The Bemarivo Domain of northern Madagascar contains the youngest of these units that date to c. 750–700 Ma. We present zircon Hf and O isotope data to understand northern Madagascar's place in the Neoproterozoic plate tectonic reconfiguration. We demonstrate that the northern component of the Bemarivo Domain is distinct from the southern part of the Bemarivo Domain and have therefore assigned new names—the Bobakindro Terrane and Marojejy Terrane, respectively. Magmatic rocks of the Marojejy Terrane and Anaboriana Belt are characterized by evolved $\varepsilon_{Hf}(t)$ signatures and a range of $\delta^{18}O$ values, similar to the Imorona-Itsindro Suite of central Madagascar. These magmatic suites likely formed together in the same long-lived volcanic arc. In contrast, the Bobakindro Terrane contains juvenile $\varepsilon_{Hf}(t)$ and mantle-like $\delta^{18}O$ values, with no probable link to the rest of Madagascar. We propose that the Bobakindro Terrane formed in a juvenile arc system that included the Seychelles, the Malani Igneous Suite of northwest India, Oman, and the Yangtze Belt of south China, which at the time were all outboard from continental India and south China. The final assembly of northern Madagascar and amalgamation of the Bobakindro Terrane and Marojejy Terrane occurred along the Antsaba subduction zone, with collision occurring at c. 540 Ma.

1. Introduction

Reconstructing the tectonic geography of the ancient Earth and building a full-plate tectonic reconstruction for the globe in deep time is critically dependent on mapping the distribution of plate tectonic sensitive rocks, including juvenile and evolved arc-related suites, through time (e.g., Merdith et al., 2017). A key goal of characterizing these rocks is to better understand the supercontinent cycle, to determine whether it operates as a simple pulse (e.g., Nance et al., 2014) or as a two-stage process starting with supercontinent initiation, followed by progressive accretion (e.g., Condie, 2002). Distinguishing between differing models of the supercontinent cycle requires a detailed knowledge of the location and duration of the critical plate-margin geological events formed at either subduction zones or rifts (e.g., Mallard et al., 2016). The Neoproterozoic, in particular, is a critical period because it sees the major transition from the Nuna/Rodinia supercontinent cycle to the accretion and amalgamation of Gondwana/Pangaea (Merdith et al., 2017). Much of the evidence for this billion-year timescale plate reconfiguration is found in the East African Orogen that formed as the Mozambique Ocean closed and Neoproterozoic India collided with the Congo Craton to form central Gondwana (Armistead et al., 2017; Collins & Pisarevsky, 2005; Fritz et al., 2013). Madagascar was located in the center of the East African Orogen and thus provides an ideal location to study how the active margins consumed the Mozambique Ocean and the eventual formation of the Gondwana Supercontinent. Of particular interest and contention, is how and when the Archean nucleus of Madagascar amalgamated with the Dharwar Craton of India to the east, and East Africa to the west, as well as with smaller continental blocks of equivocal origin. One of these blocks—the Bemarivo Domain of northern Madagascar—is composed of

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Neoproterozoic rocks spanning c. 750–700 Ma. Its evolution and amalgamation with the rest of Madagascar is poorly understood and is the focus of this study.

Madagascar is made up of several terranes spanning from Archean to Neoproterozoic (Figure 1, inset). The center of Madagascar contains the Antananarivo Craton, which is composed of c. 2500 Ma magmatic gneisses (Collins & Windley, 2002; Kröner et al., 2000). To the east are the Antongil and Masora cratons, both of which contain rocks that are c. 3100 Ma and are likely a continuation of the Dharwar Craton of India (Armistead et al., 2017; Schofield et al., 2010; Tucker, Ashwal, Handke, et al., 1999). To the southwest of the Antananarivo Craton is the Itremo Group, composed of quartzites, schists, and marbles with a maximum depositional age of c. 1600 Ma (Cox et al., 1998; Fernandez et al., 2003). To the southwest of this, is the Ikalamavony Group, similarly made up of quartzites, schists, and marbles, but with a maximum depositional age of c. 1000 Ma. To the south of these metasedimentary sequences are the Proterozoic Anosyen, Androyen, and Vohibory terranes (Boger et al., 2014; Emmel et al., 2008; Jöns & Schenk, 2008).

North of the Antananarivo Craton is the Bemarivo Domain, made up of the Paleoproterozoic Sahantaha Group, and intruded by c. 750–700 Ma magmatic rocks with a range of geochemical compositions (Thomas et al., 2009). Separating the Antananarivo Craton from the Bemarivo Domain is the Anaboriana-Manampotsy belt—an interpreted late Neoproterozoic sequence of gneisses that represents the suture between Madagascar and the Dharwar Craton of India (Collins & Windley, 2002).

Northern Madagascar comprises the c. 3100 Ma Antongil Craton, the c. 2500 Ma Antananarivo Craton, and the c. 750–700 Ma Bemarivo Domain (Figure 1), all of which have debatable geological histories. It is well documented that the Antongil Craton of northern Madagascar shares many characteristics with the Dharwar Craton of India and that these two terranes were probably contiguous until the breakup of Gondwana (Armistead et al., 2017; Bauer et al., 2011; Collins & Windley, 2002; Schofield et al., 2010). The Dharwar Craton and Antongil Cratons both contain abundant c. 3100 and c. 2500 Ma magmatic rocks, and both cratons contain Archean metasedimentary rocks with indistinguishable detrital zircon U–Pb and Hf isotope signatures (Armistead et al., 2017). However, the timing of collision between the Antongil-Dharwar Craton of India and the rest of Madagascar is contentious. Two end-member models are generally evaluated for the amalgamation of Madagascar; (1) the Antongil (Dharwar)-Madagascar collision occurred in the late Archean, and central Madagascar and the Dharwar Craton have existed as "the Greater Dharwar Craton" from then until the breakup of Gondwana (Tucker et al., 2011), or (2) Antongil (Dharwar) and central Madagascar were separate terranes that were sutured during the major Ediacaran-Cambrian Malagasy Orogeny, marked by the Betsimisaraka Suture (Collins & Windley, 2002). The data presented in this manuscript provide considerable support for the second model described above, although the first model cannot be ruled out entirely.

We have collected Hf and O isotope data from zircon within the Bemarivo Domain of northern Madagascar to characterize the evolution of this terrane and compare it to terranes elsewhere in Madagascar and globally. Integrating this data set within a plate tectonic framework using GPlates reconstruction software allows us to assess tectonic models both temporally and spatially. The results of this study are important for supercontinent reconstructions of both Rodinia and Gondwana.

2. Regional Geology of the Bemarivo Domain

The Bemarivo Domain has loosely been divided into two terranes separated by the ~east-west trending Antsaba Shear Zone (Figure 1; Thomas et al., 2009). Following from the work of Thomas et al. (2009), in this manuscript we confirm the different origin of the northern and southern Bemarivo Domain. To avoid any confusion or implication that these terranes shared a geological history prior to their early Cambrian reworking into a mobile belt, we here refer to the northern part of the Bemarivo Domain as the Bobakindro Terrane and the southern part of the Bemarivo Domain as the Marojejy Terrane. The Marojejy Terrane contains the Sahantaha Group, a metasedimentary sequence derived from dominantly Paleoproterozoic sources, with a Paleoproterozoic maximum depositional age. This sequence has been interpreted as the passive margin sequence to the Antananarivo Craton. The Sahantaha Group contains detrital zircons with major age peaks at c. 1750 and c. 2500 Ma, similar to the Itremo Group of central Madagascar (BGS-USGS-GLW, 2008; Cox et al., 1998; Cox et al., 2004; De Waele et al., 2011; Fitzsimons & Hulscher, 2005). The Sahantaha Group is intruded by the c. 750 Ma Antsirabe Nord Suite, a plutonic suite that includes

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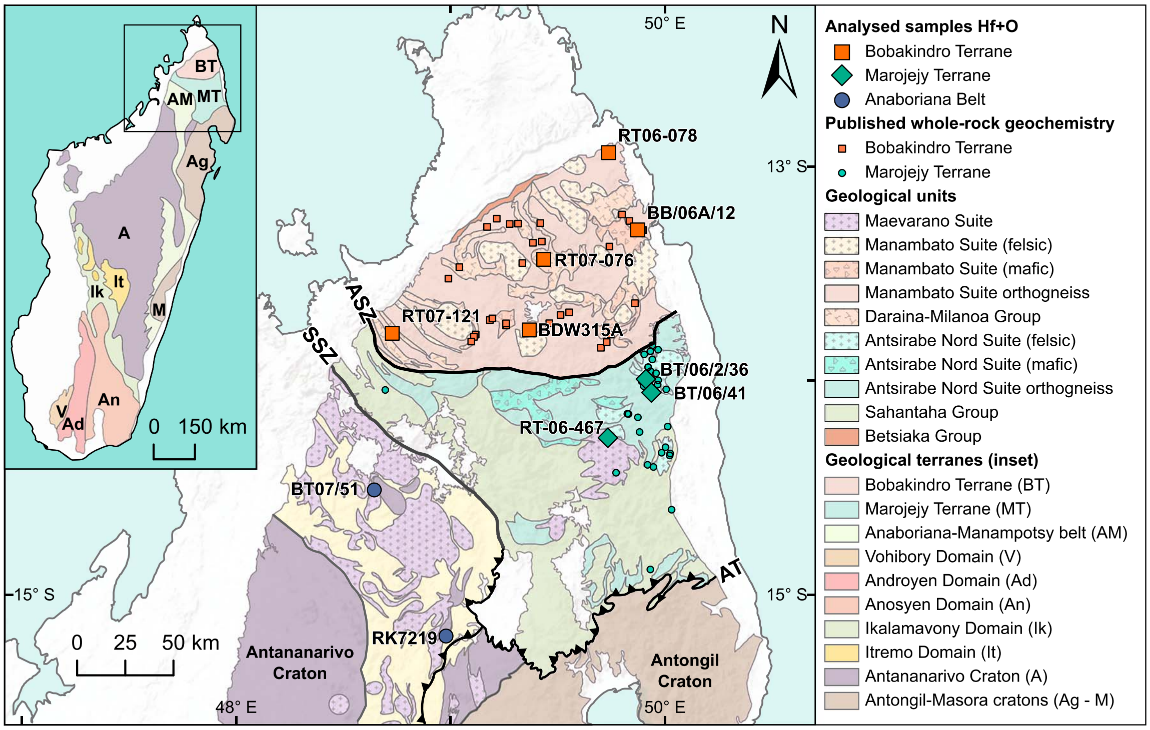

Figure 1. Geological map of northern Madagascar modified to reflect our interpretation of the region. ASZ=Antsaba Shear Zone, SSZ=Sandrakota Shear Zone, AT=Andaparaty Thrust. Geological map based on Roig et al. (2012) and Thomas et al. (2009), with the inset modified from De Waele et al. (2011).

gabbros through to granites (Thomas et al., 2009). Jöns et al. (2006) analyzed a magmatically zoned monazite using Electron Microprobe with four analyses producing an age of 737 ± 19 Ma, which they suggest represents the maximum depositional age of the Sahantaha Group. However, this technique is not able to distinguish lead-loss, and no other isotopic data indicate a maximum depositional age younger than c. 1730 Ma (BGS-USGS-GLW, 2008). We therefore prefer to consider the Sahantaha Group as an extension of the Itremo Group in central Madagascar, consistent with interpretations by De Waele et al. (2011) and Boger et al. (2014).

The Bobakindro Terrane contains a component of metamorphosed Archean schist and gneiss—the c. 2477 Ma Betsiaka Group, although outcrops of these rocks are scarce and restricted to the northwest margin of the Bemarivo Domain (Thomas et al., 2009). The Betsiaka Group is in fault-contact with the Bobakindro Terrane units and possibly represents a faulted block of the Antananarivo Domain. Two volcano-sedimentary groups were deposited in the Bobakindro Terrane at c. 750–720 Ma. The high-grade, amphibolite-facies volcano-sedimentary Milanoa Group has a maximum depositional age of c. 750 Ma, and the low-grade, greenschist to lower amphibolite facies, Daraina Group has an extrusive age of c. 740–730 Ma (Thomas et al., 2009). These groups are intruded by arc-related rocks of the Manambato Suite, which comprises c. 718–705 Ma magmatic rocks (Thomas et al., 2009).

Much of northern Madagascar is intruded by the c. 530 Ma Maevarano Suite, interpreted as post-tectonic granites that formed due to orogenic collapse of the East African Orogen (Goodenough et al., 2010). This suite has been used as a maximum age constraint on the final assembly of northern Madagascar, based on the interpretation that it is exposed in all terranes of northern Madagascar (Goodenough et al., 2010; Thomas et al., 2009).

When considered as a single coherent terrane, the Bobakindro Terrane and Marojejy Terrane have for some time been interpreted as a juvenile arc terrane that accreted to the Antananarivo Craton along a Neoproterozoic-Cambrian suture (Thomas et al., 2009). Juvenile Nd data were reported in abstract only (Tucker, Ashwal, Hamilton, et al., 1999) and have been used as evidence for the juvenile nature of both the Bobakindro Terrane and Marojejy Terrane. However, sample locations were not reported and it remains unclear whether these samples were collected from the Bobakindro Terrane or Marojejy Terrane. Extensive whole-rock geochemistry data collected through the World Bank Project (BGS-USGS-GLW, 2008; Thomas et al., 2009) indicate that much of the Bemarivo Domain formed from volcanic arc processes, with the majority of rocks being interpreted as juvenile, and derived from igneous protoliths. This interpretation was based on Y-Nb tectonic discrimination diagrams, and the calc-alkaline nature of the rocks preserved in the Bemarivo Domain. However, a lack of published isotopic data beyond zircon U–Pb geochronology for this region limits our ability to fully understand the magma processes and crustal assimilation involved in the evolution of the Bemarivo Domain. Understanding the isotopic nature of these magmatic suites in terms of their crustal versus mantle components is important for correlating them with other age-equivalent terranes. The c. 850–750 Ma Imorona-Itsindro magmatic suite is widespread in central Madagascar (Archibald et al., 2016; Archibald, Collins, Foden, & Razakamanana, 2017; Zhou et al., 2018), and may be an extension of the Bemarivo Domain. Likewise, there are age-equivalent terranes in the Seychelles, the Malani Igneous Suite of northwest India, Oman, and the Yangtze Belt of south China.

3. Methodology

A World Bank Project in Madagascar led to the collection of a substantial data set of geochemical, geochronological, and stratigraphic data from northern Madagascar (BGS-USGS-GLW, 2008). We were fortunate to have access to many of the zircon grain mounts analyzed for U–Pb through this project, some of which we have selected for further analysis. Ten samples that cover a broad area in northern Madagascar that were analyzed for U–Pb in BGS-USGS-GLW (2008) were selected for Hf and O analysis to characterize the isotopic nature of this region (Figure 1). Zircon U–Pb data were collected using the SHRIMP instrument at the John de Laeter Research Centre at Curtin University (BGS-USGS-GLW, 2008; Thomas et al., 2009). We have reinterpreted weighted averages from these data for consistency—which differ only slightly, if at all from the original interpreted ages—and these are summarized in Table 1. Isotopic data are provided in Supplementary File A in the supporting information.

3.1. O Isotopes

We selected near-concordant zircon grains with sufficient space for O and Hf isotopic analysis. Zircon mounts were repolished, and Aluminium coated prior to analysis using SHRIMP SI at the Research School of Earth Sciences, The Australian National University, in Canberra, Australia. A 10 kV, ~3-nA Cs + primary ion beam and a 30-μm spot size was used for analyses. Temora was used as the zircon standard, with two standard analyses approximately every five unknown analyses. Sample δ18O (zircon) values were determined by difference relative to the mean δ18O (zircon) measured on standards following normalization for long-term drift in its measured composition. The results of standard analyses are given in Table 1. Cathodoluminescence (CL) images were used to analyze as close as possible to the U–Pb analysis locations while remaining in the same CL zone. Details of the SHRIMP II method for oxygen isotope analysis are from Ickert et al. (2008).

3.2. Hf Isotopes

The same grains selected for O isotopes were also analyzed for Lu-Hf. Lu-Hf isotope analyses were undertaken on the Thermo-Scientific Neptune Multi-Collector ICP-MS with an attached New Wave UP-193 ArF excimer laser at the University of Adelaide following the methods of Payne et al. (2013). A beam diameter of 50 μm was used. Typical ablation times were ~82 s using a 5-Hz repetition rate, a 4-ns pulse rate, and an intensity of ~4.40 J/cm^2. Zircons were ablated in a helium atmosphere that was then mixed with argon upstream of the ablation cell. Zircon data reduction was carried out using the HfTRAX Excel macro (Payne et al., 2013). Data were normalized to ^{179}Hf/^{177}Hf=0.7325 using an exponential correction for mass bias. The Yb and Lu isobaric interferences on ^{176}Hf were corrected for following the methodology of Woodhead et al. (2004).

Zircon standards were analyzed before and during the analysis of unknowns to assess instrument performance and stability. The primary zircon standard Mud Tank was used and yielded a mean ^{176}Hf/^{177}Hf ratio of 0.282499 ± 0.000015 (2*SD*). This is within uncertainty of the published value of 0.282504 ± 0.000044 (2*SD*) by Woodhead and Hergt (2005). Values for ^{176}Hf/^{177}Hf$_{CHUR(t)}$ were calculated using modern ^{176}Hf/^{177}Hf=0.282785 (Bouvier et al., 2008), modern ^{176}Lu/^{177}Hf=0.0336 (Bouvier et al., 2008), and ^{176}Lu decay

Table 1
Summary of Samples and U–Pb Zircon Geochronology Used in This Study

Sample	Longitude (WGS 84)	Latitude (WGS 84)	Region	Stratigraphic unit or domain	Rock description	$^{238}U/^{206}Pb$ Age (Ma) ± 2σ	Calculation method
RK7219	48.9828	-15.1957	Anaboriana-Manampotsy belt	Groupe d'Androna-Manampotsy	Quartzofeldspathic gneiss	750 ± 4	Weighted average of oldest near-concordant analyses: *n*=8, MSWD=0.80
						*573 ± 13	*Youngest near-concordant (within 5%) zircon core analysis
						^514 ± 6	^Metamorphic age: *n*=4, MSWD=0.93
BT0751	48.6479	-14.5132	Anaboriana-Manampotsy belt	Group de Bealanana, Anaboriana belt	Charnockite gneiss	768 ± 8	Weighted average of oldest near-concordant analyses: *n*= 6, MSWD=1.4
						*561±8	*Youngest near-concordant (within 5%) zircon core analysis
						^518 ± 4	^Metamorphic age: *n*=7, MSWD=0.59
RT06467	49.7379	-14.2695	Marojejy Terrane	Bemarivo Domain	Granodioritic gneiss	756 ± 6	*n*=14, MSWD=0.60
BT0641	49.9411	-14.0582	Marojejy Terrane	Doany Arc, Bemarivo Domain	Tonalitic orthogneiss	746 ± 4	*n*=13, MSWD=1.5
BT0636	49.9153	-13.9953	Marojejy Terrane	Antsirabe-North Suite, Douany arc, Bemarivo Block	Diorite	754 ± 7	*n*=12, MSWD=0.69
RT0776	49.4385	-13.4362	Bobakindro Terrane	Bevoay Massif	Mica Granite	713 ± 6	*n*=5, MSWD=0.63
RT07121	48.7316	-13.7815	Bobakindro Terrane	Bemarivo Domain	Metagranodiorite gneiss	707 ± 5	*n*=6, MSWD=2.0
BDW315A	49.3712	-13.766	Bobakindro Terrane	Bemarivo Domain	Metagranodiorite	718 ± 7	*n*=6, MSWD=0.38
BB06A12	49.8762	-13.2988	Bobakindro Terrane	Daraina Group	Metarhyolite – flow banded	724 ± 7	*n*=9, MSWD=0.98
RT0678	49.741	-12.9375	Bobakindro Terrane	Daraina Group	Rhyolite	738 ± 7	*n*=5, MSWD=1.2

Note. All ages are interpreted as magmatic crystallization ages, except for those indicated by * which are interpreted as maximum depositional ages and ^ which are interpreted as metamorphic ages. Generally, for samples with lots of concordant analyses, we used a cutoff of ±5% concordance.
Abbreviation: MSWD, mean square weighted deviation.

constant of 1.865x10^{-11} year^{-1} (Scherer et al., 2001). Values for the crustal model age (T_{DMC}) were calculated using a ^{176}Lu decay constant of 1.865x10^{-11} year^{-1} (Scherer et al., 2001), modern $^{176}Hf/^{177}Hf$=0.28325, modern $^{176}Lu/^{177}Hf$=0.0384 (Griffin et al., 2000), and a bulk crust value of $^{176}Lu/^{177}Hf$=0.015 (Griffin et al., 2002). Uncertainties for $\varepsilon_{Hf}(t)$ are calculated as the $^{176}Hf/^{177}Hf_{Sample}$ uncertainty converted to epsilon notation (i.e., ($^{176}Hf/^{177}Hf_{2\sigma}$)/0.282785)*10,000) and are reported at the 2σ level.

4. Zircon U–Pb, Hf, and O Isotope Data

4.1. Anaboriana Belt

Two gneiss samples (BT0751 and RK7219) analyzed from the Anaboriana Belt have ambiguous protoliths, and it is unclear if they are derived from magmatic or sedimentary protoliths (BGS-USGS-GLW, 2008). U–Pb geochronology was unable to resolve this as there is considerable scatter on concordia plots for both samples, which could be either lead loss due to metamorphism or a detrital array. $^{176}Hf/^{177}Hf_i$ values obtained for these samples are consistent with lead loss and age resetting for the zircon grains as the values plot in a horizontal array (within uncertainty) across an age versus $^{176}Hf/^{177}Hf_i$ plot. Although the Hf isotope data are not conclusive, a magmatic protolith is also supported by the O isotope values. Analyses from the two samples have $\delta^{18}O$ values between +1.3‰ and +4.4‰. These values are lower than those normally expected for crustal or mantle values and are typically associated with the involvement of meteoric waters and hydrothermal alteration of volcanic/subvolcanic magma systems (e.g.Bindeman & Valley, 2001; Valley et al., 1998). It is highly unlikely that anomalous values such as these could be recorded in every single magma system that contributed detritus to a sedimentary rock, and hence, the samples are considered to have igneous protoliths—potentially volcanic or upper crustal intrusives.

Calculated magmatic crystallization ages for samples RK7219 and BT0751 are 750 ± 4 Ma and 768 ± 8 Ma (2σ), respectively (Table 1). When calculated at these ages (to remove the effects of Pb-loss), $\varepsilon_{Hf}(t)$ values for magmatic zircons are in the range -3.4 to -10.1. Four U–Pb rim analyses (see CL images in Supplementary File B) from sample RK7219 yield a calculated age of 514 ± 6 Ma and seven analyses from sample BT0751 yield an age of 518 ± 4 Ma, which we interpret as the age of metamorphism.

4.2. Marojejy Terrane

Three samples were analyzed from the Marojejy Terrane. These rocks include granodioritic gneiss, tonalitic gneiss, and diorite (Table 1). Interpreted magmatic crystallization ages for these rocks range from c. 756 to c. 746 Ma (Figure 2). Lu-Hf analyses from samples BT0636, BT0641, and RT06467 have negative $\varepsilon_{Hf}(t)$ values ranging from -15.0 to -1.5 (Figure 3). These analyses have two-stage depleted mantle model ages spanning c. 2.6–1.7 Ga.

Oxygen isotope data from the Marojejy Terrane show a wide range of $\delta^{18}O$ values. The majority of analyses from samples BT0641 and BT0636 are between +4.8‰ and +5.9‰, overlapping with the range of values expected for mantle-derived zircons, but extending to more positive values consistent with samples that have crystallized in equilibrium with surface-derived water (Valley et al., 1998). Four analyses from sample BT0641 and two analyses from sample BT0636 have $\delta^{18}O$ values lower than what is expected for mantle sources, ranging from +0.6 to +4.3‰. The majority of analyses from sample RT06467 are between +6.3‰ and +7.1‰, with two analyses of +5.8‰ that overlap with the mantle $\delta^{18}O$ field.

4.3. Bobakindro Terrane

Five samples from the Bobakindro Terrane were used for Hf and O isotopic analysis on zircon. These rocks include granites, granodioritic gneisses, and rhyolites (Table 1). Magmatic crystallization ages for these samples are younger than for the Marojejy Terrane and range from c. 740 to c. 705 Ma. Lu-Hf analyses from Bobakindro Terrane samples cluster to form a group of similar $\varepsilon_{Hf}(t)$ signature and age. These analyses have positive $\varepsilon_{Hf}(t)$ values between +4 and +11 and depleted mantle model ages spanning c. 1.4–1.0 Ga (Figure 3).

Samples from the Bobakindro Terrane record a restricted range of $\delta^{18}O$ values. Analyses from samples RT0776, RT07121, and BDW315A have $\delta^{18}O$ values ranging from +4.4 to +6.5‰ (Figure 3). These overlap with the range of values typical for mantle-derived zircons (5.3 ± 0.6‰; Valley et al. (1998)). Samples BB06A12 and RT06-78 have lower $\delta^{18}O$ values, with mean $\delta^{18}O$ values of +4.3‰ and +2.3‰ respectively.

5. Insights From Published Whole-Rock Geochemistry Data

Whole-rock geochemistry from the Bobakindro Terrane and Marojejy Terrane was published in Thomas et al. (2009). We have used these data to further compare and contrast the Bobakindro Terrane and Marojejy Terrane. We have shown that magmatic rocks from the Marojejy Terrane have evolved $\varepsilon_{Hf}(t)$ signatures, so the geochemistry is potentially reflective of the crust that is being incorporated rather than the processes that generated the mantle melts. Although there are only three samples that have both Hf isotope and whole-rock geochemistry data for the Marojejy Terrane, there does appear to be a trend between these two data sets. The more evolved sample has a ferroan signature compared to the less evolved sample, which has a magnesian signature (Figure 4a). There is an increase in alkalinity for increasing $\varepsilon_{Hf}(t)$ values (Figure 4b). The Sr anomalies and trace elements are also higher for the evolved samples (Figures 4c and 4d). Together, this indicates that crustal assimilation was the dominant cause for changing ε_{Hf}(t).

In contrast, samples from the Bobakindro Terrane are dominantly magnesian (Figure 4a), calc-alkalic (Figure 4b), and are not as enriched in trace elements (Figure 4d). Combined with the juvenile nature of these rocks, they most likely formed in an arc environment, consistent with the interpretation of Thomas et al. (2009). Although there are only two samples with both Hf isotope and geochemistry data from the Bobakindro Terrane, the younger, marginally more evolved sample has a higher Sr anomaly and higher values for the majority of the trace elements (Figures 4c and 4d). Low degrees of fractionation and crustal assimilation may have been involved in the evolution of the Bobakindro Terrane, which accounts for the trend of decreasing ε_{Hf}(t) values with time (Figure 3).

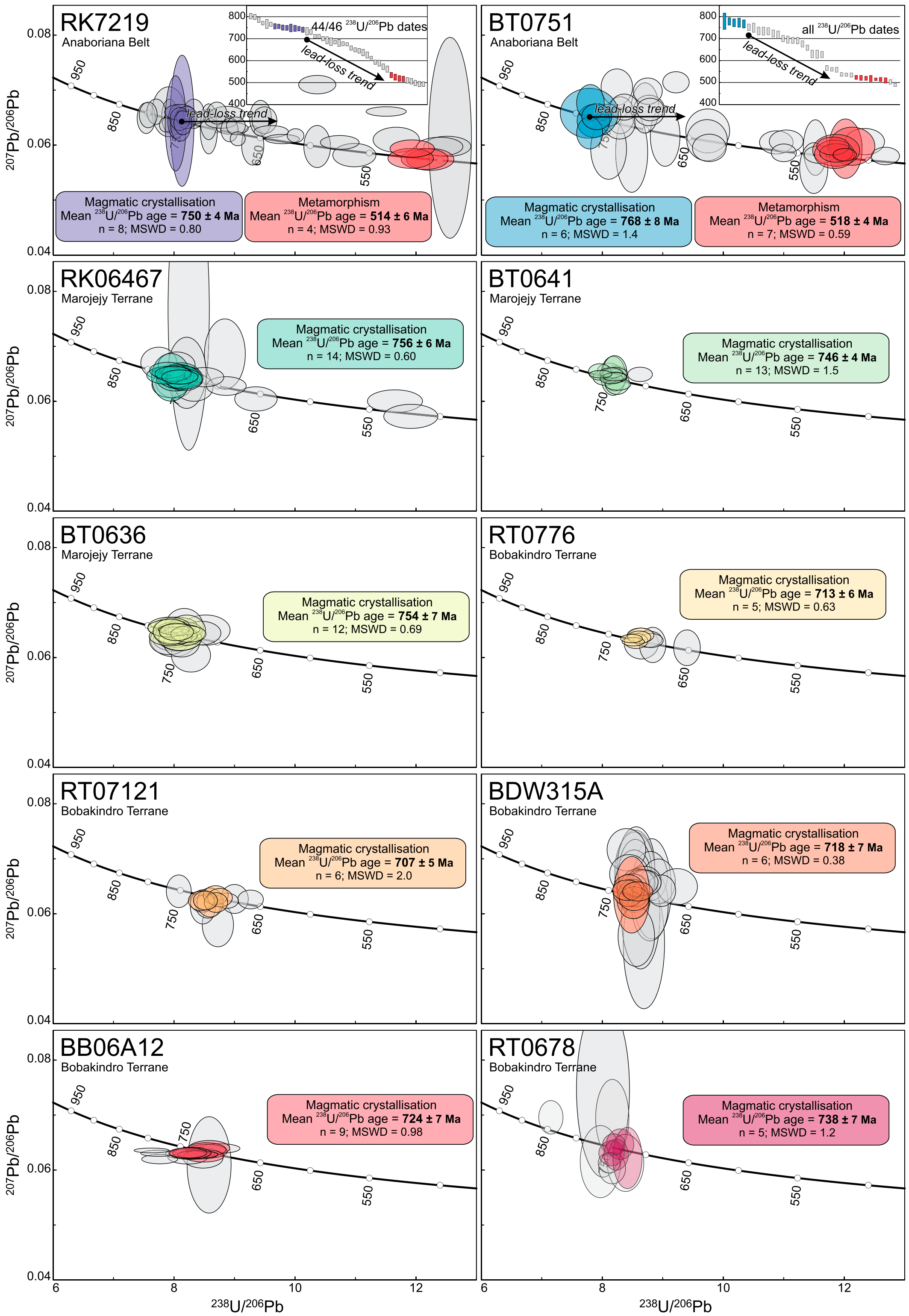

Figure 2. Concordia plots with reinterpreted ages using data from Thomas et al. (2009). Axes are the same range for all plots. The colored ellipses were used to calculate the ages provided; the grey ellipses show remaining data that were excluded from calculations. Several analyses were excluded from the calculated ages, as many appear to have undergone lead-loss or resetting—as indicated by the apparent shift to the right of many of the ellipses from the main population. Some samples also have analyses that appear to have undergone "lead-gain," where analyses are negatively discordant and appear to shift to the left of the main population on the concordia plots (e.g., BB06A12 and RT0678). We therefore generally only included analyses that were within 5% concordance.

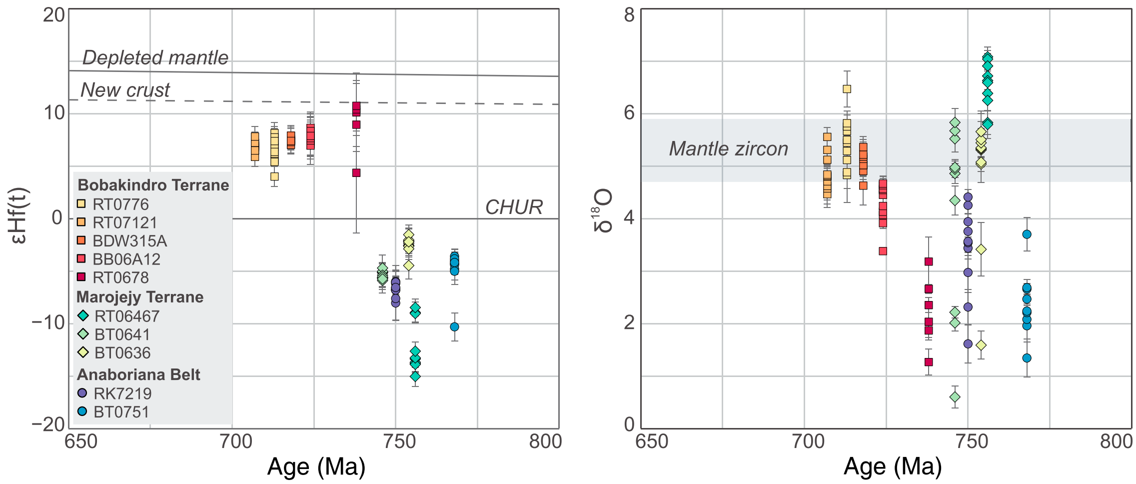

Figure 3. $\varepsilon_{Hf}(t)$ versus age and $\delta^{18}O$ versus age (calculated $^{238}U/^{206}Pb$ magmatic crystallization ages) for samples analyzed from northern Madagascar. $\varepsilon_{Hf}(t)$ for each analysis was calculated using the magmatic crystallization age, data given in Supplementary File A. Plots produced in R, code written to produce plots is documented in Supplementary File C.

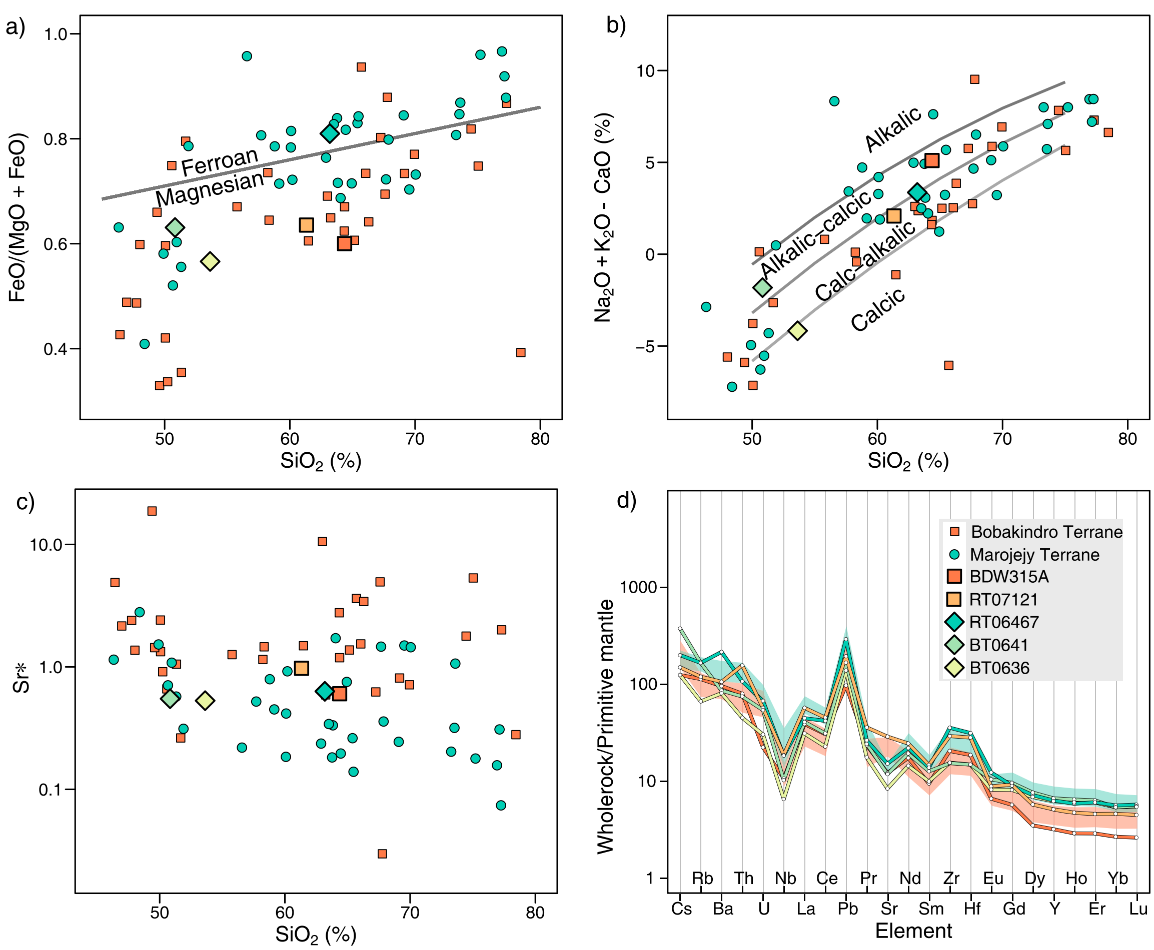

Figure 4. (a) Fields for ferroan and magnesian rocks after Frost and Frost (2008); (b) fields for alkali, alkali-calcic, calc-alkaline, and calcic after Frost and Frost (2008); (c) Sr anomaly (Sr*) calculated as $Sr_N/\mathrm{sqrt}\,(Pr_N{*}Nd_N)$, where N is the chondrite normalized values after Sun and McDonough (1989); and (d) Spider plot for samples with Hf and O isotope data. The shaded bands behind these lines are the bootstrapped mean and 95% confidence intervals of Primitive Mantle normalized elemental data for all samples from the Bobakindro Terrane and Marojejy Terrane; normalizing values from Sun and McDonough (1989). Bootstrapping was performed with replacement for 50000 repetitions. R scripts to produce plots are provided in Supplementary File C. Data from Thomas et al. (2009).

6. Regional Evolution of the Bemarivo Domain

The Bemarivo Domain of northern Madagascar has previously been interpreted as a juvenile Neoproterozoic arc-related terrane that amalgamated with central Madagascar in the late Neoproterozoic to early Cambrian (Collins, 2006; Kröner et al., 2000; Tucker, Ashwal, Hamilton, et al., 1999). Possible links between Madagascar and the Seychelles, Malani Igneous Suite of northwest India and south China have been proposed (Ashwal et al., 2002; Tucker, Ashwal, Hamilton, et al., 1999; Wang et al., 2017). Similarly, in a reconstruction presented in Cox et al. (2004), the Bemarivo Domain links up with the Seychelles and northwest India at c. 750 Ma. New Hf and O isotope data collected in this study allow us to interpret the tectonic evolution of the Bemarivo Domain and assess possible paleogeographical links. Differences between these terranes indicate that they have undergone separate tectonic histories at discrete times during the Neoproterozoic.

6.1. Anaboriana Belt

Zircons analyzed from the two Anaboriana Belt samples have evolved $\varepsilon_{Hf}(t)$ signatures that overlap with values from the Marojejy Terrane samples, but are generally less evolved than those from the slightly older Imorona-Itsindro Suite (Archibald et al., 2016; Zhou et al., 2018). We interpret this evolved signature as the result of incorporation of crustal material during magma genesis. $\delta^{18}O$ values for the Anaboriana Belt samples are lower than most analyses from the Marojejy Terrane. Low $\delta^{18}O$ values are typically the result of hydrothermal cycling of meteoric water during magma generation (Bindeman & Valley, 2001; Valley et al., 1998). These are often correlated with extensional environments where rifting may have occurred that facilitated hydrothermal circulation in near-surface or volcanic settings (Bindeman & Valley, 2001; Valley et al., 1998). We therefore suggest that the Anaboriana Belt samples were generated from magmas that contained a component of older crustal material, but likely underwent hydrothermal alteration in an extensional environment.

6.2. Marojejy Terrane

The Marojejy Terrane samples contain zircons with negative $\varepsilon_{Hf}(t)$ signatures that indicate a contribution of continental crust during magma generation. $\varepsilon_{Hf}(t)$ model ages for these analyses range between c. 2.56 and 1.73 Ga. The majority of $\delta^{18}O$ analyses from sample BT06467 are above the mantle range, indicating that supracrustal rock assimilation and melting were involved in magma generation. The majority of zircon analyses from samples BT0641 and BT0636 have $\delta^{18}O$ values in the mantle range. Several analyses from the aforementioned samples, as well as analyses from the Anaboriana Belt samples RK7219 and BT0751, have very low $\delta^{18}O$ values that indicate the involvement of meteoric fluids and hydrothermal alteration in a similar way to that envisaged for similar values from the Tonian Imorona-Itsindro Suite in central Madagascar by Archibald et al. (2016).

The Sahantaha Group, in which these magmatic rocks intrude, have major detrital zircon components of c. 2500–1700 Ma (De Waele et al., 2011), broadly overlapping with the range of depleted mantle model ages for the analyzed samples. The Antananarivo Domain, which may underlie the Sahantaha Group, is dominantly composed of c. 2500 Ma gneisses. The data presented here support the interpretation of Thomas et al. (2009) that subduction was taking place beneath the Sahantaha Group (and underlying Antananarivo Domain) at c. 750 Ma, which produced melts that incorporated crustal material from surrounding rocks. Notably, this interpretation is consistent with previous models for the Marojejy Terrane (Thomas et al., 2009). Low $\delta^{18}O$ samples from the Anaboriana Belt likely formed in a back-arc extensional environment to the main Marojejy Terrane volcanic arc.

6.3. Bobakindro Terrane

Samples analyzed from the Bobakindro Terrane are dominated by juvenile $\varepsilon_{Hf}(t)$ signatures, and $\delta^{18}O$ values that indicate a mantle source and relatively little assimilation of supracrustal material. The majority of analyses from samples RT0776, RT07121, and BDW315A have $\delta^{18}O$ values in the mantle range, but samples BDW315A and RT0678 have $\delta^{18}O$ values that are significantly lower than those from the mantle. Given the similar $\varepsilon_{Hf}(t)$ values of these samples and the other Bobakindro Terrane samples, we propose that they were also generated from a juvenile depleted mantle source but involved hydrothermal fluids during magma generation. This relates to their generation in an extensional environment (Bindeman & Valley, 2001; Valley et al., 1998). The felsic nature of the Bobakindro Terrane indicates that the original magmas were likely to have fractionated in thickened crust. The juvenile Hf signatures of these samples, and mantle-like $\delta^{18}O$ values, imply that they formed in an arc environment, with little involvement of any significantly older, or supracrustal material.

Our new Hf and O data from northern Madagascar indicate that the Bobakindro Terrane and the Marojejy Terrane have distinct isotopic evolutions, and we therefore conclude that they were not contiguous at the time of their formation (c. 750 Ma). The Antsaba Shear Zone that marks the boundary between the Bobakindro Terrane and Marojejy Terrane (Thomas et al., 2009) also marks a boundary between samples of a juvenile signature in the north and an evolved signature in the south. The only detailed descriptions of the Antsaba Shear Zone are presented in Thomas et al. (2009) and are summarized here. The Antasaba Shear Zone is best exposed in the western part of the Bemarivo Domain where it is ~15 km wide, and becomes less exposed toward the east where it is <1 km wide. It contains intense strike-slip deformation with zones of steeply inclined planar fabrics, with prominent shallowly plunging, strike parallel, mineral stretching lineations. Because this zone has been intensely sheared, we suspect that the identification of typical suture zone rock assemblages would be difficult to identify; however, further research is needed to properly characterize this structure. Given the evidence presented in our study as well as the contrast in rock types either side of the Antsaba Shear Zone, this structure marks a major tectonic boundary in northern Madagascar and likely represents a cryptic suture zone.

7. Assembly of North Malagasy Gondwana

The terranes of northern Madagascar form a tectonically unresolved triple-junction (Figure 1), with the Marojejy Terrane (including the Sahantaha Group), Anaboriana Belt, and Antongil Domain all in contact with each other (Figure 1). We have shown here that rocks from the Anaboriana Belt and Marojejy Terrane are isotopically similar and that they were part of the same continental-margin volcanic arc system at c. 750 Ma. The relationship between these two terranes and the Antongil Domain is less straightforward. Understanding the nature and timing of contacts between these three terranes is essential for understanding the evolution of northern Madagascar.

7.1. The Amalgamation of the Dharwar Craton With Madagascar

The assembly of northern Madagascar is a contentious topic with different models proposed for the nature and timing of amalgamation (e.g., Armistead et al., 2017; Boger et al., 2014; Collins & Windley, 2002; Tucker et al., 2011). The relationship between the Sahantaha Group (maximum depositional age c. 1730 Ma, minimum depositional age c. 800 Ma) and the Antongil Craton provides clues as to the relative timing of these tectonic events. Despite the current fault contact being marked by the major Andaparaty Thrust between the Sahantaha Group and Antongil Domain (Figure 1), several authors have suggested that the Sahantaha Group stratigraphically overlies the Antongil Domain (Bauer et al., 2011; De Waele et al., 2011), implying that the Antongil Domain was adjacent to central Madagascar at the time of deposition. Against this interpretation are the paucity of c. 3100 Ma detrital zircons in the Sahantaha Group (De Waele et al., 2008; Thomas et al., 2009), despite the Antongil Craton being rich in zircon-bearing protoliths of this age (Tucker, Ashwal, Handke, et al., 1999) and the lack of any depositional contact mapped between the terranes. These observations support that the Sahantaha Group is allochthonous with respect to the Antongil Craton and that the two were juxtaposed by the major Andaparaty Thrust.

If these two terranes formed separately from one another, when did they come together? Widespread metamorphism throughout much of northern Madagascar is recorded at c. 560–510 Ma (Buchwaldt et al., 2003; Jöns et al., 2006; Jöns et al., 2009), and we propose that this time period records the amalgamation of the Antongil Craton with the rest of Madagascar (including the Sahantaha Group and Anaboriana Belt), along the Betsimisaraka Suture of Collins and Windley (2002).

7.2. What Does the Anaboriana Belt Represent?

The Anaboriana-Manampotsy belt (Figure 1) has been interpreted to mark the approximate location of the Betsimisaraka Suture that has been interpreted as the site of amalgamation of the Antananarivo Craton with the Dharwar Craton (at the time including the Antongil-Masora domains) during the Ediacaran to early Cambrian (Armistead et al., 2017; Collins et al., 2003; Collins & Windley, 2002). The Anaboriana Belt is

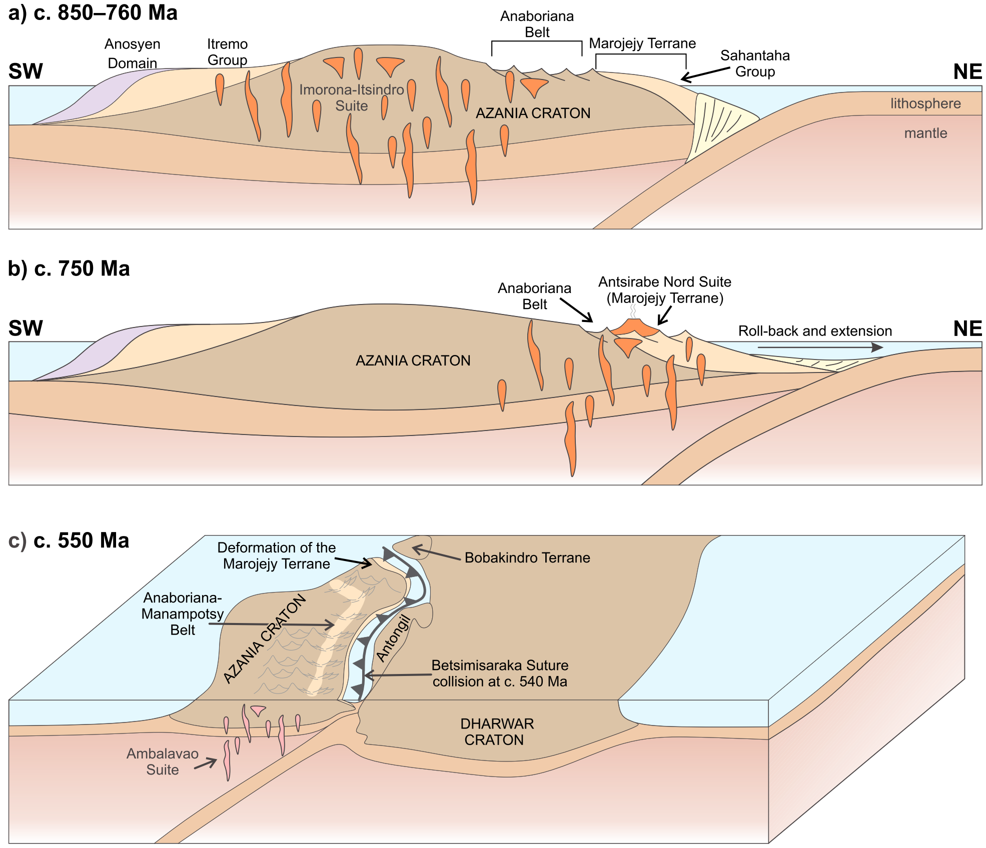

Figure 5. Schematic diagram of the Neoproterozoic arc evolution of Madagascar. (a) Intrusion of the Imorona-Itsindro Suite in central Madagascar at c. 850–750 Ma, (b) roll-back and extension of the subduction zone and subsequent intrusive and extrusive rocks associated with the Antsirabe Nord Suite, and (c) collision of the Dharwar Craton and Bobakindro Terrane with the Azania Craton.

the northern part of this extensive belt and separates the Sahantaha Group from the Antananarivo Craton. Above, we have argued that the Sahantaha Group formed stratigraphically above the Antananarivo Craton, which implies that the Anaboriana Belt is not a suture, or at least would only have been a minor marginal Neoproterozoic ocean basin suture. An alternative interpretation for the Anaboriana-Manampotsy belt is that it does not represent a suture zone but was an elongated sedimentary basin that formed due to Tonian rifting (Tucker et al., 2011).

As we have described in our interpretation of samples from the Anaboriana Belt, due to pervasive high-grade metamorphism, it can be difficult to recognize sample protoliths as either sedimentary or magmatic in origin. It is therefore unclear whether the Anaboriana Belt represents a sedimentary sequence at all, or whether it should really be considered as a zone of major high-strain shearing (or both). To date, samples from the entire length of the Anaboriana Belt have been interpreted with protolith ages ranging from c. 850 to c. 750 Ma, with metamorphism interpreted from zircon rims at c. 550–520 Ma. The Anaboriana-Manampotsy Belt is therefore best considered as a forearc basin that formed in response to subduction at c. 750 Ma. At c. 550 Ma this belt was significantly reworked during the Betsimisaraka Suture event and approximately marks the location of the Gondwana suture in Madagascar. As it trends north, the suture is represented by the Andaparaty Thrust, which separates the Antongil Craton from the Marojejy Terrane (Figure 1). The Betsimisaraka Suture then strikes north-easterly into sea and continues back on land as the east-west striking Antsaba Shear Zone (Figures 1 and 5).

7.3. Final Assembly of Northern Madagascar

Two stages of metamorphism have been identified in the Bemarivo Domain that represents collision of the Bemarivo Domain with the rest of Madagascar (Jöns et al., 2006). M1 monazite cores range from c. 563 to c.

532 Ma, which represent the collisional event, and M2 monazite rims represent peak metamorphic temperatures and record ages of c. 521 to c. 513 Ma (Jöns et al., 2006). These authors concluded that collision led to the burial of much of the Marojejy Terrane to a depth of >25 km, and approximately 25–30 Ma later, the terrane underwent magmatic underplating and ultrahigh-temperature metamorphism. They suggested that the northern part of the Bemarivo Domain (the Bobakindro Terrane) was also affected by this event but was buried to lower depths and therefore metamorphosed to lower grades. We propose that this is why c. 560–510 Ma metamorphic evidence is much more apparent in the Marojejy Terrane compared to the Bobakindro Terrane in the north. Jöns et al. (2006) suggested that these metamorphic events represent the entire Bemarivo Domain docking with the rest of Madagascar. In light of new evidence presented in our study whereby the two terranes of the Bemarivo Domain are separate and that the Marojejy Terrane was likely contiguous with the Antananarivo Craton—we instead propose that these metamorphic events represent the suturing the Bobakindro and Marjojejy terranes along the Antsaba Shear Zone to form the Bemarivo mobile belt. This accounts for the different metamorphic assemblages and conditions described in either terrane by Jöns et al. (2006). The c. 537–522 Ma post-tectonic Maevarano Suite that crops out in the Marojejy Terrane, Anaboriana Belt, and the Antananarivo Craton also provides a constraint on the final assembly of northern Madagascar (Goodenough et al., 2010). This magmatic suite is the likely driver of the age-equivalent ultrahigh-temperatures recorded in the Marojejy Terrane by Jöns et al. (2006) .

8. Links to Rodinia

In an attempt to link the Bobakindro Terrane with other potential c. 720 Ma arc terranes, we have compared our new isotopic data with several regions containing age equivalent rocks. We compared the Bobakindro Terrane with South China, northwest India, central Madagascar, the Seychelles, Oman, and the Arabian Nubian Shield (Figure 6). We also integrated this data set with the *GPlates* (www.gplates.org) Neoproterozoic tectonic model (Merdith et al., 2017) to assess correlations temporally and spatially.

We have used a revised version of the Merdith et al. (2017) full-plate model of the Neoproterozoic, which provides a kinematic framework that models plate boundaries and the evolution of continental crust from 1000 to 520 Ma. Using such a model allows us to account for paleogeographic and paleotectonic constraints from other regions, as the model integrates key data sets such as paleomagnetism, geochronology, and geophysics to form a full-plate tectonic framework. We calculated an average age and average $\varepsilon_{Hf}(t)$ for each sample compiled in our database. This data set was then added to GPlates as a shapefile, and a start and end time for each data point was assigned ±30 Ma (i.e., each point will show up 30 Ma before the average age and disappear 30 Ma after). Data points are colored according to their average $\varepsilon_{Hf}(t)$ value.

It has been suggested that the Imorona-Itsindro Suite of central Madagascar is analogous to the Seychelles and the Malani Igneous Suite granitoids based on age correlations (Tucker et al., 2001; Tucker et al., 2014). Tectonic models by Wang et al. (2017) and Ashwal et al. (2013) proposed a continuous juvenile Andean-type arc between south China, the Malani Igneous Suite of northwest India, and Seychelles. Wang et al. (2017) further included the Imorona-Itsindro suite along with this magmatic arc. However, available $\varepsilon_{Hf}(t)$ data from the Imorona-Itsindro Suite of central Madagascar (Archibald et al., 2016; Zhou et al., 2018) are predominantly evolved (Figure 6), implying that it does not correlate with this juvenile arc system. Oman has also been interpreted as a series of arcs that accreted to Rajasthan in northwest India (which includes the Malani Igneous Suite) during the period c. 850–720 Ma (Blades et al., in review). We have shown here that age-equivalent rocks from the Bobakindro Terrane have juvenile $\varepsilon_{Hf}(t)$ signatures, which correlate well with $\varepsilon_{Hf}(t)$ data from the proposed south China-Malani-Seychelles arc system of Wang et al. (2017) as well as new data from Oman (Blades et al., in review; Figure 6). These correlations are highlighted in the full-plate tectonic model in GPlates, where juvenile analyses (data points with shades of red; Figure 7) all form an elongated “arc” along the western (reconstructed orientation) margin of India and China.

The period of magmatism in this proposed arc was long-lived, beginning at around c. 850 Ma and ending at around c. 700 Ma. There is a general southward younging trend (reconstructed orientation; Figure 7), with the oldest record coming from China, and progressing to younger rocks through Oman, Malani, Seychelles, and the Bobakindro Terrane. It is possible that this period of juvenile arc magmatism represents a single long-lived arc; however, we argue that a complex history of accretionary terranes that formed along the edge of Rodinia is more likely.

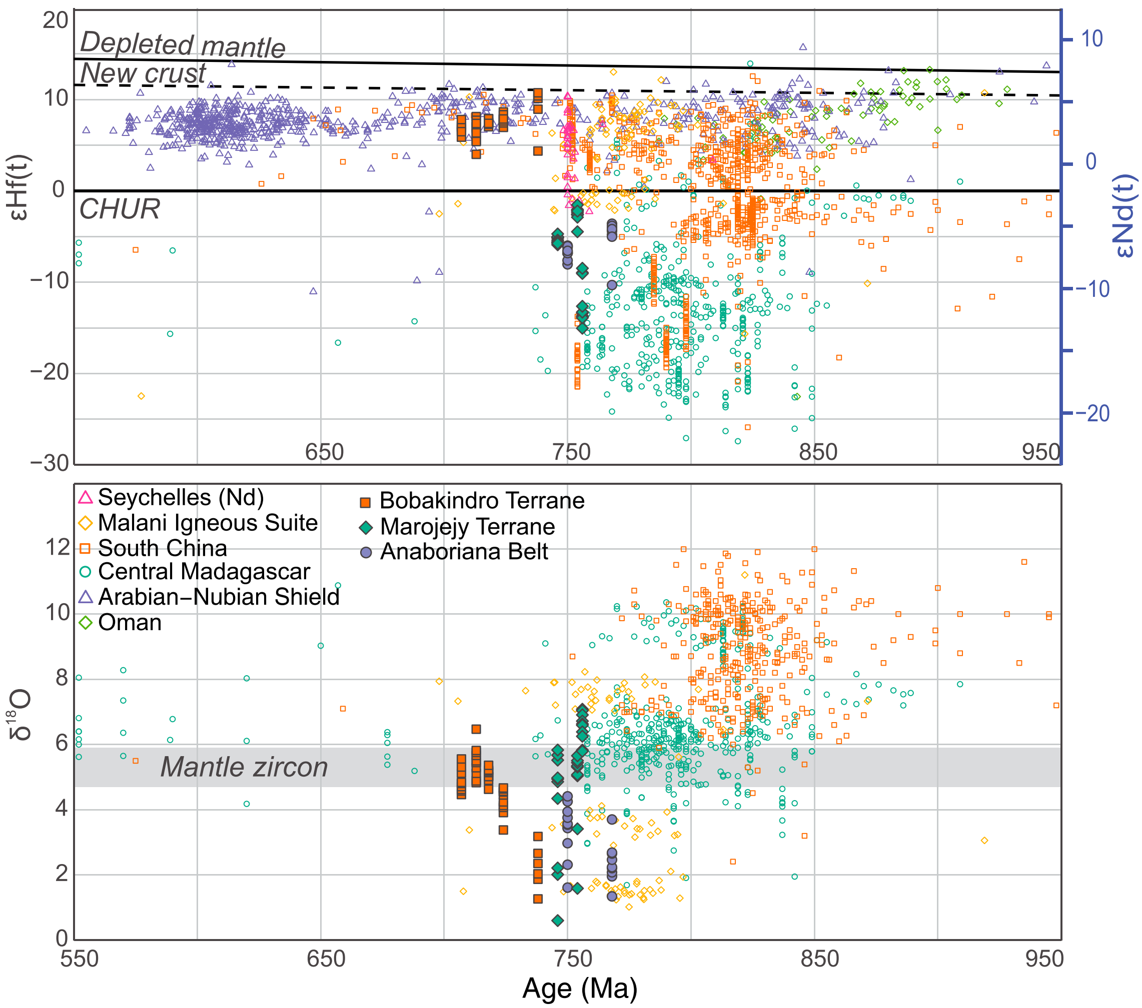

Figure 6. $\varepsilon_{Hf}(t)$ versus age and $\delta^{18}O$ versus age for other regions compared to northern Madagascar; Seychelles data are converted from $\varepsilon_{Nd}(t)$ to $\varepsilon_{Hf}(t)$ using the equation $\varepsilon_{Hf}(t) = 1.34\varepsilon Nd(t) + 2.95$ for "terrestrial array" (Vervoort et al., 1999) and scale is shown to the right of the plot. R scripts to produce plots are provided in Supplementary File C. Data sourced from the following: Alessio et al. (2018), Archibald et al. (2016), Ashwal et al. (2002), Blades et al. (2015), Huang et al. (2008), Long et al. (2011), Morag et al. (2011), Qi et al. (2012), Robinson et al. (2014), Wang et al. (2017), Wang et al. (2013), Zhao et al. (2013), Zheng et al. (2008), Zheng et al. (2007), and Zhou et al. (2018).

Samples analyzed from the Bobakindro Terrane are slightly younger than rocks from south China and Malani, although they have similar juvenile $\varepsilon_{Hf}(t)$ signatures. The Bobakindro Terrane therefore formed during the late stages of this juvenile arc system. The whole-rock geochemistry data (Figure 4) indicate that the Bobakindro Terrane underwent a degree of crustal assimilation and fractionation (see section 4). However, the $\varepsilon_{Hf}(t)$ data show that the Bobakindro Terrane is dominantly juvenile, with little input of significantly older crustal material. Together this implies that the crustal assimilate incorporated into magmatic rocks of the Bobakindro Terrane was not significantly older than c. 720 Ma. This supports a model where the Bobakindro Terrane formed on a rolled-back crustal remnant of slightly older crust, possibly from south China, Malani or Oman (Alessio et al., 2018).

The integration of $\varepsilon_{Hf}(t)$ data with the full-plate tectonic model of (Merdith et al., 2017) broadly supports the south China-Malani-Seychelles linkage proposed by Wang et al. (2017) and Ashwal et al. (2013), and the links between Oman and northwest India proposed by Blades et al. (in review). We further extend this model to include the Bobakindro Terrane of northern Madagascar as a younger, more outboard component of this arc system. There is no significant overlap between the highly evolved data from the Imorona-Itsindro Suite and that of this proposed juvenile Neoproterozoic arc system. The lack of juvenile Hf data from the Imorona-Itsindro Suite indicates that this terrane was not part of the south China-Malani-Seychelles-Bemarivo arc.

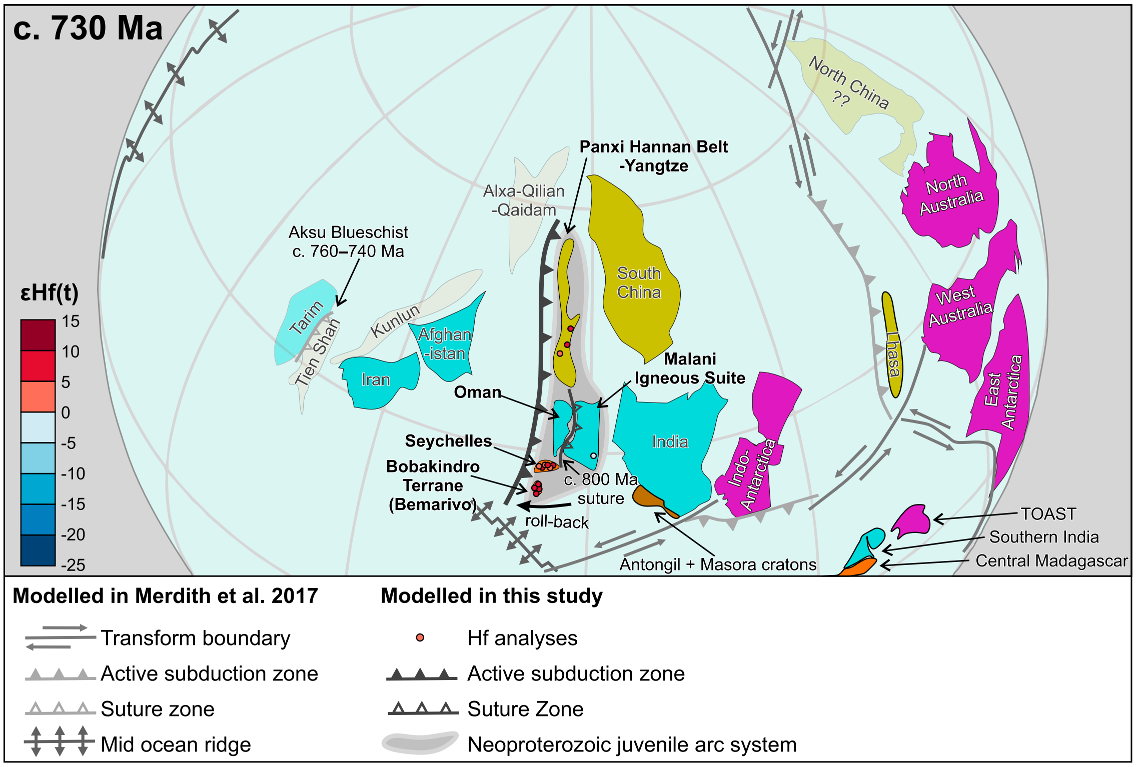

Figure 7. GPlates reconstruction at 730 Ma showing the location of compiled Hf and Nd isotope data (see Figure 6 for the conversion calculation used). Transparent polygons are uncertain in the model but are included as suggestions based on their positions post-Gondwana amalgamation. Lhasa is linked to Australia after Zhu et al. (2011), addition of the TOAST terrane to Azania after Jacobs et al. (2015) and Archibald, Collins, Foden, Payne, et al. (2017).

Our proposal to link these previously discrete volcanic arcs into a long-lived subduction zone would elucidate long-term trends in plate boundary length and, when compared to the connectedness of continental lithosphere, assist with quantitatively understanding the supercontinent cycle for pre-Pangea supercontinents (e.g., Merdith et al., 2019).

Distinguishing between different arc systems for India-south China as we have in this study suggest a far more nuanced and intricate subduction system than has previously been captured in tectonic models for the Neoproterozoic (e.g., Li et al., 2008; Merdith et al., 2017). Plate modeling necessitates some simplifications in the geometrical representation of real-world tectonic systems (e.g., rifts, arcs); however, this should result in more conservative estimates of their lengths (Merdith et al., 2019). Consequently, plate modeling can reveal pertinent implications in understanding whole Earth systems such as the supercontinent cycle.

Here our preferred tectonic reconstruction at 730 Ma suggests nearly 4,000 km of continuous subduction occurring from the Panxi-Hanaan belt in south China (Cawood et al., 2018) through to southern India occurring over 250 million years. The size and longevity of this subduction system, in addition to the size of the combined south China-India continent (Figure 7), suggest a considerable portion of continental lithosphere (roughly equivalent to present-day Australia) with an active subduction zone was removed from Rodinia. This raises questions about the nature of the supercontinent cycle and what classifies as a “supercontinent,” beyond that of whether all continental crust must be present for a supercontinent to exist (e.g., Pastor-Galán et al., 2018). In particular, we highlight that processes typically associated with supercontinents such as slab roll-back leading to intracratonic rifting (e.g., Nanhua rift system in south China; Wang & Li, 2003) and the continental amalgamation of juvenile crust and evolved continental ribbons to continental masses occurred away from the established Rodinian supercontinent. This is not irreconcilable with some geodynamic modeling, which suggests that the sizable separate pieces of continental crust can also induce changes in mantle flow and structure (e.g., Flament et al., 2017). Further study could analyze the impact of such a subduction system as described here on mantle flow and the surface expression of the flow.

9. Conclusions

We have presented new zircon Hf and O isotope data that help unravel the subduction history of the Mozambique Ocean during the critical time of supercontinent cycle transition—from the Nuna/Rodinia cycle to the amalgamation of Gondwana. We have compared these Madagascar data to other age-equivalent terranes globally. The key outcomes of this research are as follows:

1. The Bobakindro Terrane and Marojejy Terrane in the Bemarivo Domain of northern Madagascar are different terranes that have separate tectonic evolutions until the Cambrian, based on zircon $\varepsilon_{Hf}(t)$ and $\delta^{18}O$ data.
2. The c. 750 Ma Marojejy Terrane and Anaboriana Belt are isotopically evolved terranes that likely represent a younger component of the retreating volcanic arc represented in central Madagascar by the Imorona-Itsindro Suite.
3. The c. 720 Ma Bobakindro Terrane is a juvenile terrane that likely formed in a juvenile arc environment related to the Seychelles, the Malani Igneous Suite of northwest India, Oman, and the Yangtze Belt of South China. The Bobakindro Terrane is interpreted as forming above an aging, retreating, subduction zone.
4. The Bobakindro Terrane collided with Madagascar at c. 540 Ma along the Antsaba Shear Zone/Betsimisaraka Suture, which marks final closure of the Mozambique Ocean and assembly of supercontinent Gondwana.

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