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Key Points:

- Detrital zircon U-Pb and Hf isotope data from Madagascar indicate an extensive Paleoproterozoic basin defined as the Greater Itremo Basin
- Database of ∼15,000 zircon analyses from East Africa, Madagascar, and southern India support a Paleoproterozoic basin across these regions
- Plate tectonic configuration at c. 1,700 Ma show Madagascar, the Tanzania Craton, and the Southern Granulite Terrane of India are contiguous

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Proterozoic Basin Evolution and Tectonic Geography of Madagascar: Implications for an East Africa Connection During the Paleoproterozoic

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Abstract Madagascar hosts several Paleoproterozoic sedimentary sequences that are key to unraveling the geodynamic evolution of past supercontinents on Earth. New detrital zircon U–Pb and Hf data, and a substantial new database of ∼15,000 analyses are used here to compare and contrast sedimentary sequences in Madagascar, Africa, and India. The Itremo Group in central Madagascar, the Sahantaha Group in northern Madagascar, the Maha Group in eastern Madagascar, and the Ambatolampy Group in central Madagascar have indistinguishable age and isotopic characteristics. These samples have maximum depositional ages >1,700 Ma, with major zircon age peaks at c. 2,500 Ma, c. 2,000 Ma, and c. 1,850 Ma. We name this the Greater Itremo Basin, which covered a vast area of Madagascar in the late Paleoproterozoic. These samples are also compared with those from the Tanzania and the Congo cratons of Africa, and the Dharwar Craton and Southern Granulite Terrane of India. We show that the Greater Itremo Basin and sedimentary sequences in the Tanzania Craton of Africa are correlatives. These also tentatively correlate with sedimentary protoliths in the Southern Granulite Terrane of India, which together formed a major intra-Nuna/Columbia sedimentary basin that we name the Itremo-Muva-Pandyan Basin. A new Paleoproterozoic plate tectonic configuration is proposed where central Madagascar is contiguous with the Tanzania Craton to the west and the Southern Granulite Terrane to the east. This model strongly supports an ancient Proterozoic origin for central Madagascar and a position adjacent to the Tanzania Craton of East Africa.

1. Introduction

Reconstructing the geometry of the terranes of eastern Africa, Madagascar and India prior to the Neoproterozoic is challenging due to a scarcity of Mesoproterozoic magmatic rocks in some of these regions, limiting the use of zircon U–Pb dates in the correlation assessments. The Neoproterozoic to Cambrian amalgamation of central Gondwana, which formed the East African Orogen, has been extensively studied in recent years and provides important constraints on global plate reconstruction models (Merdith, Collins, et al., 2017; Merdith et al., 2020; Merdith, Williams, et al., 2017). The East African Orogen resulted from the collision of Africa, Madagascar and India (Collins & Pisarevsky, 2005; Fritz et al., 2013; Johnson et al., 2011; Merdith, Collins, et al., 2017; Schmitt et al., 2018). This provides a robust framework from which we can start to piece together continental fragments further back in time—the Paleoproterozoic to Mesoproterozoic being of particular interest across these regions.

Here we examine the provenance of the Paleoproterozoic Malagasy Itremo Group and compare it with other metasedimentary groups in Madagascar (Note that we use the term "Malagasy" to describe rocks/features originating from Madagascar, rather than the incorrect, but often used "Madagascan"; Voarintsoa et al., 2019) De Waele et al. (2011) proposed that the Itremo, Maha, and Sahantaha groups in Madagascar are equivalent metasedimentary sequences. Boger et al. (2014, 2019) linked the Anosyen Domain of southern Madagascar to the Itremo Group. The validity of these correlations, and likelihood that these represent

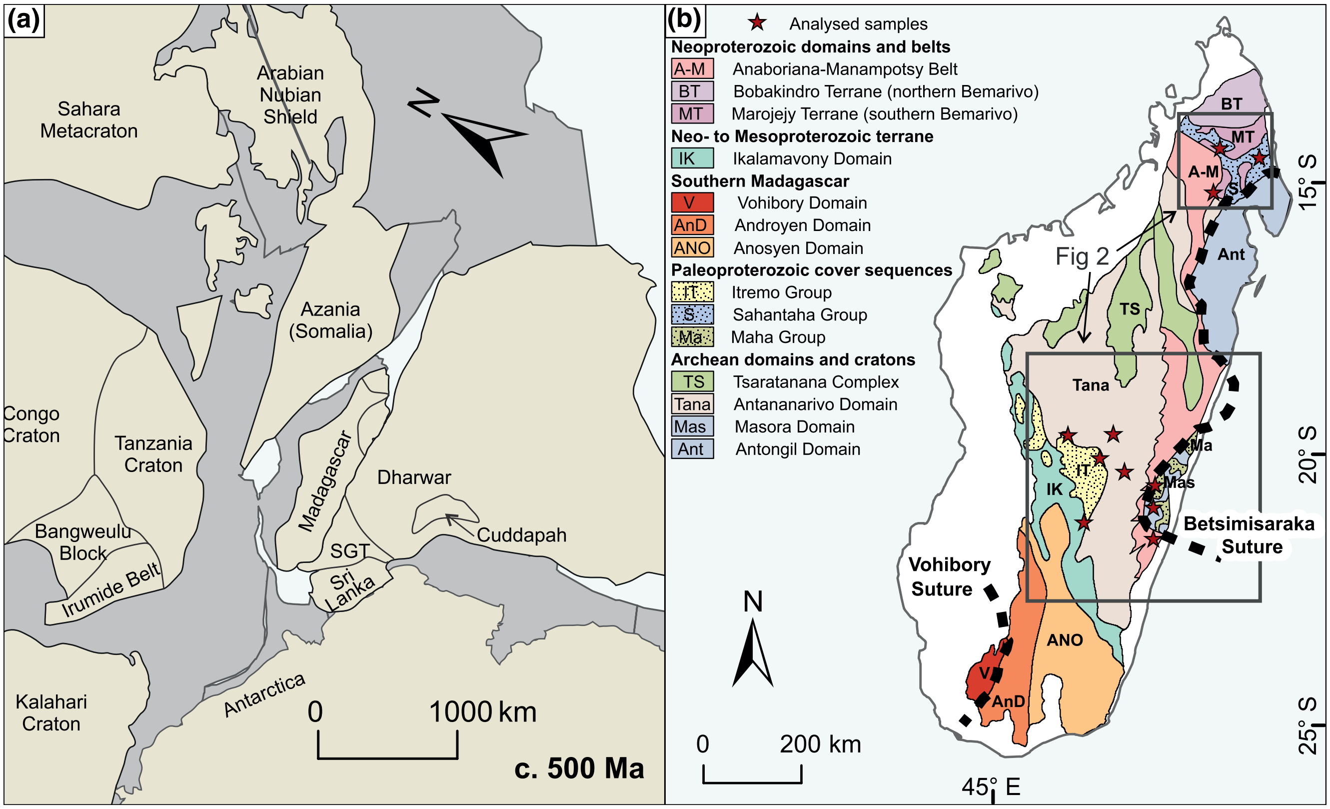

Figure 1. (a) Tectonic map of central Gondwana made using GPlates exported geometries from Merdith, Collins, et al. (2017) in ArcGIS; projected in Hotine Oblique Mercator with Madagascar in the center (reconstructed position, longitude = −75 and latitude = +40). SGT, Southern Granulite Terrane. (b) Present-day map of the geological domains of Madagascar after (De Waele et al., 2011). The two insets are the detailed maps shown in Figure 2.

contiguous Paleoproterozoic–Mesoproterozoic depositional systems, governs the paleogeographic reconstruction of this extensive part of Nuna and its tectono-geographic interpretation.

Similarities in Paleoproterozoic metasedimentary rocks of the Itremo Group in central Madagascar and the Muva Supergroup in the Tanzania Craton in Africa have been recognized for some time (Alessio et al., 2019; Cox et al., 1998, 2004; Fitzsimons & Hulscher, 2005). Similarities between the Itremo Group and the Cuddapah Basin of eastern India have also been proposed (Tucker, Roig, Delor, et al., 2011), as have similarities between the Itremo Group and the Southern Granulite Terrane of India (Collins et al., 2012; Collins, Santosh, et al., 2007; Plavsa et al., 2014). These potential correlations can be used as sedimentary piercing points that provide vital supercontinental links and important constraints on paleogeographic reconstructions of the Earth during the period of Nuna supercontinent formation and evolution (e.g., Evans & Mitchell, 2011; Pehrsson et al., 2016).

1.1. Regional Geology

Madagascar is made up of several domains with Archean to Neoproterozoic rocks, as constrained by U–Pb dating (Figure 1b). Central Madagascar consists of the Antananarivo Domain, which is composed of c. 2,500 Ma magmatic gneisses of the Betsiboka Suite (Collins & Windley, 2002; Kröner et al., 2000) and amphibolite–granulite facies metasedimentary rocks of the Ambatolampy Group (Archibald et al., 2015). To the east are the Antongil and Masora Domains, which contain c. 3,100 Ma rocks and are likely a continuation of the Dharwar Craton of India (Armistead et al., 2017; Schofield et al., 2010; Tucker et al., 1999; Tucker, Roig, Delor, et al., 2011). To the southwest of the Antananarivo Domain, and locally unconformable on it (Cox et al., 1998), is the Itremo Group, composed of quartzites, schists, and marbles with a maximum depositional age of c. 1,700 Ma (Cox et al., 1998, 2004; Fernandez et al., 2003). The Ikalamavony Domain lies southwest of the Itremo Group and is similarly made up of quartzites, schists, and marbles, but with notable volcanic and volcanoclastic horizons and a maximum depositional age of c. 1,000 Ma (Tucker, Roig, Macey, et al., 2011).

To the south of these metasedimentary domains are the Proterozoic Anosyen, Androyen, and Vohibory terranes (Boger et al., 2014; Collins et al., 2012; Emmel et al., 2008; Jöns & Schenk, 2008). The Anosyen and Androyen domains contain the Tranomaro, Tolanaro, and Mangoky groups (Figure 2), that, like the Itremo Group, also have c. 1,700 Ma maximum depositional ages (Boger et al., 2014).

A series of Neoproterozoic (meta)sedimentary sequences overlie, or are interleaved with these major domains, and a suite of Neoproterozoic magmatic rocks intrude the domains. The Molo Group is thrust within the Ikalamavony and Itremo domains. It has a maximum depositional age of c. 620 Ma and a minimum depositional age of c. 560 Ma defined by metamorphic overgrowths (Costa et al., 2021; Cox et al., 2004). The c. 1,080–980 Ma Dabolava Suite (Archibald, Collins, Foden, Payne, et al., 2017) is restricted to the Ikalamavony Domain while the c. 850–750 Ma Imorona-Itsindro Suite (Archibald et al., 2016) is widespread throughout much of central and eastern Madagascar. In the Vohibory Domain, the Linta Group contains sedimentary rocks with maximum depositional ages of c. 620 Ma that match the ages of the intrusive Marasavoa and Vohitany suites.

Because it is difficult to put absolute age constraints on sedimentary sequences, especially metasedimentary ones, there is some ambiguity over the classification and grouping of Neoproterozoic sedimentary rocks within the Antananarivo Domain. The Ambatolampy Group and Manampotsy Group were interpreted as Cryogenian sequences in the most recent mapping of Roig et al. (2012). However, in light of new published data (Archibald et al., 2015) and the data presented herein, these two groups have very different detrital zircon age spectra; and should therefore be considered as separate groups. Thomas et al. (2009) and BGS-USGS-GLW (2008) defined a new terrane—the Anaboriana Belt—which defines the boundary between the Antongil/Masora/Bemarivo domains and the Antananarivo Domain, and approximately marks the location of the Betsimisaraka Suture (Collins & Windley, 2002), thought to represent the amalgamation of Madagascar and the Dharwar Craton of India in the Neoproterozoic. This belt occupies most of what has traditionally been mapped as the Manampotsy Group (e.g., in Roig et al., 2012). We therefore refer to this as the Anaboriana-Manampotsy Belt herein and treat the Ambatolampy Group separately.

1.1.1. Sedimentology and Depositional Environment of the Itremo Group in Central Madagascar

The Itremo Group contains well-sorted quartzite, psammitic schist and gneiss, and dolomitic marbles. A detailed sedimentological study of the Itremo Group is given in Cox et al. (1998) and is summarized below. The Itremo Group quartzites contain well-sorted quartz arenites with flat laminations, wave ripples, cross-laminations, dune cross-bedding, and rare hummocky cross stratification (Cox et al., 1998). These sedimentary structures indicate deposition under shallow, subaqueous, conditions, and are consistent with a shallow subtidal depositional setting (Cox et al., 1998). Pelitic rocks of the Itremo Group are finely laminated siltstone and mudstone, with interbedded sandstones. They contain flat and cross-laminations, which indicate currents were periodically active (Cox et al., 1998). They were likely deposited in deeper water than the quartzites, with some deposited in a subtidal shelf environment (Cox et al., 1998). Carbonate rocks, which occur at the top of the Itremo Group, consist of dolomitic marble with stromatolites, and sandy marble. Some desiccation features indicate subaerial exposure in an intertidal setting, while the sandy marbles were likely deposited in a marginal marine environment (Cox et al., 1998). Overall, the Itremo Group is interpreted as a passive margin sequence, deposited on a shallow continental shelf or continental platform, with continental or cratonic sources (Cox et al., 1998; De Waele et al., 2011).

The Itremo Group is intruded by the c. 850–750 Ma Imorona-Itsindro Suite (Collins, Johnson, et al., 2003), which provides a minimum age of its deposition. The Itremo Group along with the Imorona-Itsindro Suite has been folded into polydeformed folds sometime between c. 650 Ma and c. 550 Ma (Armistead et al., 2020; Collins, Johnson, et al., 2003; Tucker et al., 2007). This deformation occurred as India, Azania (comprising the Archaean and Palaeoproterozoic crust of Madagascar, Somalia, Ethiopia, and Arabia) and Africa collided as central Gondwana amalgamated (Collins & Pisarevsky, 2005).

Pioneering detrital zircon U–Pb studies instigated the "out-of-Africa" model for the Itremo Group of central Madagascar (e.g., Cox et al., 1998, 2004; Fitzsimons & Hulscher, 2005). The age distribution of the Itremo Group closely matches the Tanzanian Craton but has little resemblance to metasedimentary rocks in the

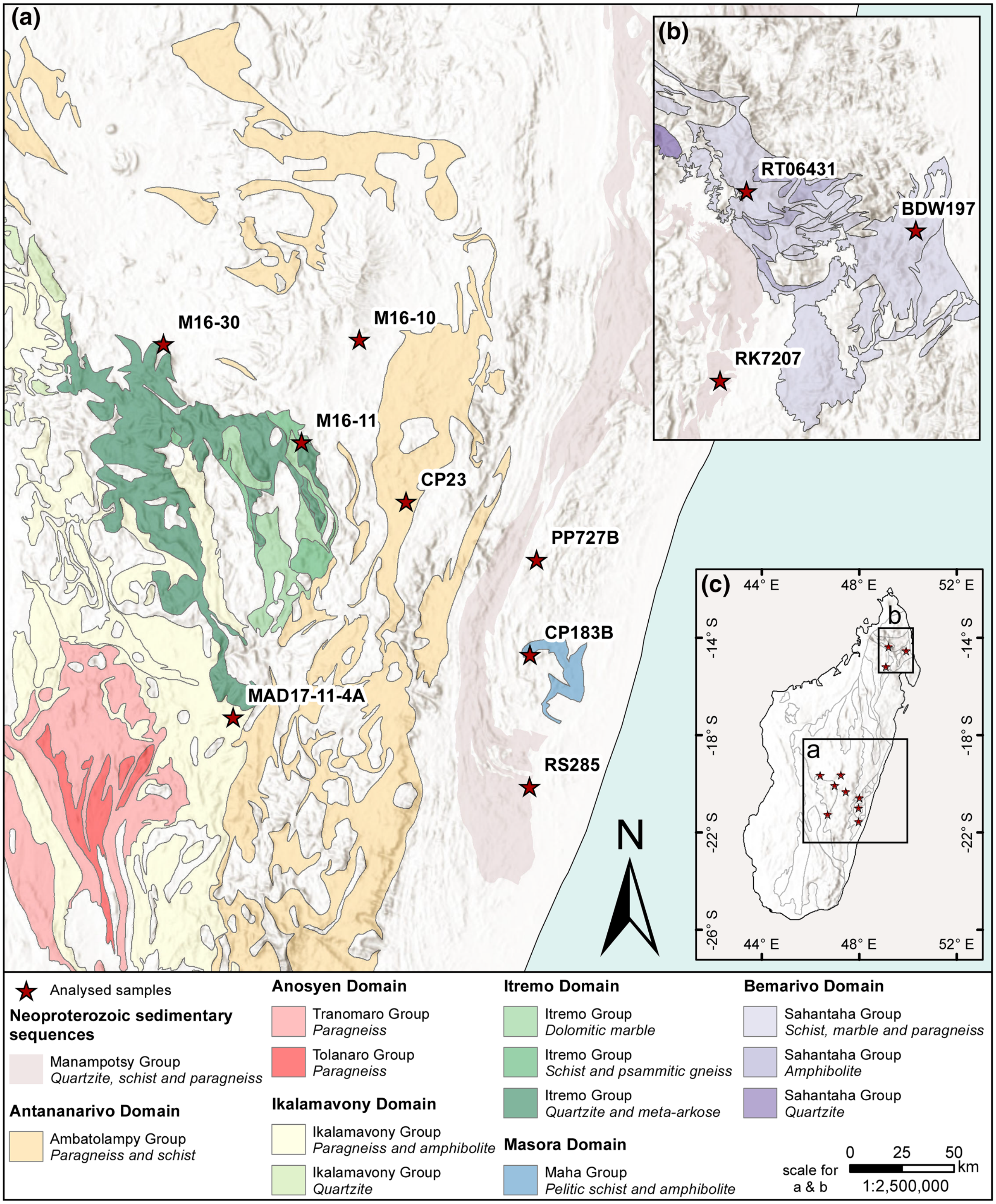

Figure 2. Geological map of Madagascar modified after Roig et al. (2012); (a) central Madagascar showing major Proterozoic metasedimentary groups; (b) geological map of northern Madagascar including the Sahantaha Group; (c) geological terranes of Madagascar showing insets for maps (a and b).

dominantly Archean Dharwar Craton (see Collins et al., 2015). In subsequent years, this has been challenged and other data sets complimentary to U–Pb ages, such as zircon Lu-Hf isotope data, have been collected on possible comparable sequences and source regions. This has left the Itremo Group as a relatively poorly characterized group. Here we address this with new data and compare detrital zircon spectra and their Hf isotope compositions for a range of metasedimentary sequences in Madagascar, Africa and India.

2. Methods

2.1. Zircon U–Pb and Trace Element Geochemistry

Rock samples were crushed and the zircon fraction (sieved 79–425 μm) was separated by panning. Zircons were hand-picked and mounted in epoxy resin. The zircon mounts were polished; carbon coated and imaged using a Gatan cathodoluminescence (CL) detector attached to Quanta 600 MLA Scanning Electron Microscope to identify suitable domains for analysis. Zircon U–Pb geochronology and trace element contents were measured at the University of Adelaide using an Agilent 7900x ICP-MS with attached ASI Resolution excimer 193 nm laser ablation system. A spot size of 29 μm and frequency of 5 Hz was used. Isotopes ^{90}Zr, ^{201}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{238}U were measured. Additional trace elements were measured and are provided in Supplementary A. Each analysis comprised a 20s background and 30s ablation. GEMOC GJ-1 zircon (TIMS normalizing ages ^{207}Pb/^{206}Pb = 607.7 ± 4.3 Ma, ^{206}Pb/^{238}U = 600.7 ± 1.1 Ma, and ^{207}Pb/^{235}U = 602.0 ± 1.0 Ma; Jackson et al., 2004) was used to correct for U–Pb fractionation and its variation over the analytical session. The Plešovice zircon standard (ID-TIMS ^{206}Pb/^{238}U = 337.13 ± 0.37 Ma; Sláma et al., 2008) was used to assess accuracy over the course of the laser session; 55 Plešovice standard analyses were made and yield a weighted average ^{206}Pb/^{238}U age of 339.2 ± 1.2 Ma (MSWD = 1.07; 95% confidence limits), which is within uncertainty of the ID-TIMS age for the uncertainties on individual analyses. Data were processed using Iolite (Paton et al., 2011), and propagated uncertainties are reported at 2σ. U–Pb and REE data are provided in Supplementary A.

2.2. Zircon Lu–Hf

Near concordant U–Pb spots were additionally analyzed for Lu–Hf isotopes. 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 length, and an intensity of ~4–5 J/cm^2.

Zircon data reduction were 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 by following the methodology of Woodhead et al. (2004).

Zircon standards were analyzed before, during and after 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 (2SD). This is within uncertainty of the published value of 0.282504 ± 0.000044 (2SD) 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 constant of 1.865×10^{-11} year^{-1} (Scherer et al., 2001). Values for the crustal model age (T_{DMC}) were calculated using a ^{176}Lu decay constant of 1.865×10^{-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. Isotopic data are provided in Supplementary A.

2.3. Database Methods

We have compiled an extensive database of published results from Madagascar, India, and Africa (Supplementary B) that builds on the database of Armistead et al. (2017). This database includes ~15,000 zircon U–Pb and Hf isotope analyses from East Africa, Madagascar, and India. Since we are focusing primarily on

Table 1
Summary of Sample Descriptions and Maximum Depositional Ages (Calculated as the Youngest $^{207}Pb/^{206}Pb$ Date Within 10% of Concordance, Except for Those Indicated With a "," Which are the Youngest $^{206}Pb/^{238}U$ Date Within 10% of Concordance) for Samples Analyzed in This study*

Sample ID	Lithology	Geological unit	Latitude (WGS84)	Longitude (WGS84)	Maximum depositional age (Ma)	U–Pb data source
M16-10	Quartzite	Ambatolampy Group	−19.62080	47.23781	1835 ± 86	This study
M16-11	Quartzite	Itremo Group	−20.06404	46.98979	1774 ± 90	This study
M16-30	Quartzite	Itremo Group	−19.64042	46.39433	1827 ± 91	This study
MAD-17-11-4A	Quartzite	Itremo Group	−21.21432	46.66460	1727 ± 89	This study
RK7207	Quartzite	Anaboriana-Manampotsy	−15.17330	49.08520	591 ± 17*	BGS et al. (2008)
RS285	Quartzite	Anaboriana-Manampotsy	−21.55100	47.97240	765 ± 15*	BGS et al. (2008)
CP23	Quartzite	Anaboriana-Manampotsy	−20.32070	47.44030	1,001 ± 44	BGS et al. (2008)
PP727B	Quartzite	Maha Group	−20.57110	48.00350	1742 ± 19	De Waele et al. (2011)
CP183B	Quartzite	Maha Group	−20.98050	47.97490	1801 ± 18	De Waele et al. (2011)
BDW197	Quartzite	Sahantaha Group	−14.52460	49.93010	1733 ± 18	BGS et al. (2008)
RT06431	Quartzite	Sahantaha Group	−14.35410	49.19930	1728 ± 33	BGS et al. (2008)

Note. Age uncertainties are 2σ.

Paleoproterozoic samples and correlations of zircons within the vicinity of Madagascar in Gondwana, we do not consider the substantial set of Neoproterozoic data in detail. Data sources are tabulated in Table 1.

The full database is included in Supplementary B before any filtering is applied. Data transformation and filtering was done using R. The R code is available from the corresponding author upon request. The database of detrital zircon data was filtered for data within 10% of concordance (between the $^{207}Pb/^{206}Pb$ and $^{238}U/^{206}Pb$ ages) and analyses that have $^{207}Pb/^{206}Pb$ age uncertainties of 10% or less. Metamorphic rim data were excluded. For analyses with $^{206}Pb/^{207}Pb$ ages of 900 Ma or older, the $^{206}Pb/^{207}Pb$ age was used, otherwise the $^{238}U/^{206}Pb$ age was used. The maximum depositional age was calculated as the youngest grain following the previous filtering. Only samples that contain 15 or more grains after these filtering techniques are included.

3. Results

3.1. Sample Descriptions

Three quartzite samples from the Itremo Group and one quartzite sample from the Ambatolampy Group (Figure 2) were collected and analyzed for U–Pb, trace element geochemistry and Lu–Hf isotopes. The aim was to have zircon data from a range of quartzite samples from a broad geographical region that are representative of the major metasedimentary groups in Madagascar, most notably the Itremo Group. A further three samples from the Anaboriana-Manampotsy Belt, two samples from the Maha Group and two samples from the Sahantaha Group (Figure 2) that were dated for U–Pb geochronology in BGS-USGS-GLW (2008) and De Waele et al. (2011) were analyzed for Lu–Hf isotopes in this study. Sample descriptions and location information are summarized in Table 2. Together, this collection of samples represents the main quartzite groups across the major geological domains of Madagascar, with the exception of the Anosyen, Androyen, and Vohibory domains of southern Madagascar (Figure 1).

Zircon from analyzed samples have variable morphologies and CL responses. Many contain concentric oscillatory zoning and most have rounded grain boundaries indicative of detrital zircon. Many zircons contain dark rims, indicating a metamorphic overprint. CL images of representative zircon analyzed in these samples are provided in Supplementary C.

3.2. Zircon U–Pb Geochronology and Trace Element Geochemistry

The aim of analyzing for trace elements was that it might distinguish different populations of zircons. However, the trace element signatures were not distinct for different age populations, so their usefulness

Table 2
References for Data Used in the Compilation, Data Provided in Supplementary B

Type	Continent	References
Detrital	Madagascar	Archibald et al. (2015); BGS-USGS-GLW (2008); Boger et al. (2014); Collins et al. (2012); Collins, Kröner, et al. (2003); Costa et al. (2021); Cox et al. (1998, 2004); De Waele et al. (2011); Fitzsimons and Hulscher (2005); Tucker, Roig, Delor, et al. (2011); Tucker, Roig, Macry, et al. (2011)
Detrital	Africa	Alessio et al. (2019); Alessio et al. (2018); Batumike et al. (2009, 2007); De Waele and Fitzsimons (2007); Foster et al. (2015); Kazimoto et al. (2014); Koegelenberg et al. (2015); Konopásek et al. (2014); Linol et al. (2016); Thomas et al. (2016)
Detrital	India	Armistead et al. (2017); Collins, Clark, et al. (2007); Collins et al. (2015); Henderson et al. (2014); Ishwar-Kumar et al. (2013); Joy et al. (2015); Kooijman et al. (2011); Lancaster et al. (2015); Li et al. (2017); Maibam et al. (2016); Maibam et al. (2011); Plavsa et al. (2014); Prakash and Sharma (2011); Raith et al. (2010); Sarma et al. (2012); Teale et al. (2011); Upadhyay et al. (2009)
Magmatic	Madagascar	Archibald et al. (2016); Armistead et al. (2017, 2020); Bauer et al. (2011); BGS-USGS-GLW (2008); Buchwaldt et al. (2003); Collins et al. (2012); Collins, Kröner, et al. (2003); de Wit et al. (2001); Goodenough et al. (2010); Handke et al. (1999); Kabete et al. (2006); Kröner et al. (2000); Paquette et al. (2004); Paquette and Nédélec (1998); Paquette et al. (1994); Schofield et al. (2010); Tucker et al. (1999, 2007); Tucker, Roig, Delor, et al. (2011); Tucker, Roig, Macry, et al. (2011)
Magmatic	Africa	Alessio (2019); Alessio et al. (2019); Ali et al. (2014); Blades et al. (2015); Bulambo et al. (2004); Cox et al. (2002); Daly (1986); De Waele et al. (2006); Dodson et al. (1975); Hanson et al. (1988); John (2001); Katongo et al. (2004); Key et al. (2001); Morag et al. (2011); Ngoyi et al. (1991); Nutman et al. (2013); Rainaud et al. (2005); Ring et al. (1999); Ring et al. (1997); Schenk and Appel (2001); Thomas et al. (2016); Vrána et al. (2004)
Magmatic	India	Clark et al. (2020); Clark et al. (2009); Ghosh et al. (2004); Glorie et al. (2014); Ishwar-Kumar et al. (2013); Jayananda et al. (2015, 2020); Kröner et al. (2012); Kumar et al. (2017); Maibam et al. (2011); Mohan et al. (2014); Plavsa et al. (2012, 2015); Praveen et al. (2014); Wang et al. (2020); Yang and Santosh (2015)

for distinguishing different populations is limited in this case. The trace element profiles were strongly correlated with discordance, with higher REE concentrations for discordant data, which adds additional uncertainty to their meaning. Trace element data are provided in Supplementary A and plotted trace element profiles are provided in Supplementary D for completeness, however, we do not consider these data further.

Three quartzite samples analyzed from the Itremo Group and one sample from the Ambatolampy Group contain near-concordant (<10%) detrital zircon ages ranging from c. 3,485 to c. 1,727 Ma (Figure 3). They contain similar age spectra with dominant peaks at c. 2,500, c. 2,200, and c. 1,800 Ma. Their maximum depositional ages are given in Table 2.

3.3. Zircon Lu–Hf Analysis

Itremo Group and Ambatolampy Group samples with zircon ages of c. 2,500 Ma are dominantly juvenile to moderately evolved; $\varepsilon_{Hf}(t)$ values range from +5 to −14 (Figure 4a). Zircons with ages of c. 2,200–1,800 Ma are moderately evolved and have $\varepsilon_{Hf}(t)$ values ranging from +5 to −10. Zircon analyses with ages of c. 1,800–1,700 Ma are exclusively evolved, with $\varepsilon_{Hf}(t)$ ranging from 0 to −14.

Analyses with the same U–Pb ages from the Maha Group have $\varepsilon_{Hf}(t)$ values ranging from +5 to −11 for c. 2,500 Ma zircons, and +4 to −6 for c. 2,200–1,800 Ma zircons, and +2 to −10 for c. 1,800–1,700 Ma zircons (Figure 4). Age-equivalent analyses from the Sahantaha Group have $\varepsilon_{Hf}(t)$ values ranging from +6 to −10 for c. 2,500 Ma zircons, 0 to −4 for c. 2,200–1,800 Ma zircons, and −2 to −10 for c. 1,800–1,700 Ma zircons (Figure 4b).

The Anaboriana-Manampotsy Belt sample (RK7207) has a unimodal zircon peak at c. 780 Ma, with $\varepsilon_{Hf}(t)$ values ranging from −10 to −15. Sample RS285 contains zircons with ages of c. 3,400–3,000 Ma that have

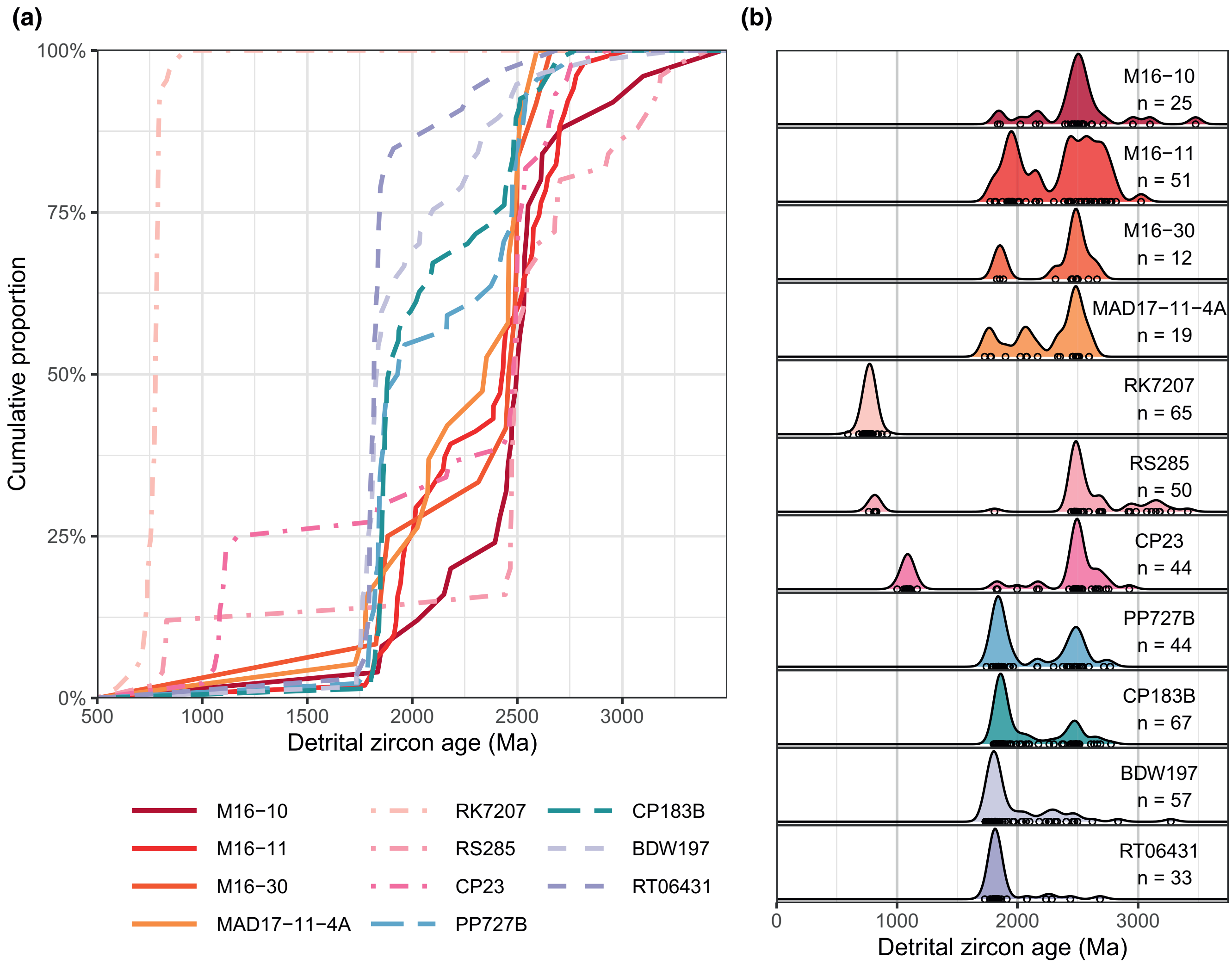

Figure 3. Zircon U–Pb data for metasedimentary units in Madagascar. Plots made in R using data that are within 10% concordance (concordance calculated between $^{206}Pb/^{207}Pb$ and $^{238}U/^{206}Pb$ ages). For analyses with $^{206}Pb/^{207}Pb$ ages of 900 Ma or older, the $^{206}Pb/^{207}Pb$ age was used, otherwise the $^{238}U/^{206}Pb$ age was used. (a) Data plotted on cumulative proportion plots showing subtle differences between the Itremo Group and the Sahantaha and Maha groups; (b) kernel density estimate (KDE) plots of detrital zircon ages using a bandwidth of 50 Ma. U–Pb data for the Maha Group and Sahantaha Group are from De Waele et al. (2011); U–Pb data for the Anaboriana-Manampotsy samples are from BGS-USGS-GLW (2008).

$\varepsilon_{Hf}(t)$ values ranging from +3 to −3. Zircons from this sample with ages of c. 2,500 Ma have $\varepsilon_{Hf}(t)$ values ranging from +2 to −13. A single c. 1,809 Ma zircon has an $\varepsilon_{Hf}(t)$ value of −2. Sample CP23 has c. 2,500 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from +6 to −8, c. 2,200–1,800 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from −4 to −9, and c. 1,100 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from +3 to −8.

4. Discussion

4.1. Correlation of Metasedimentary Sequences in Madagascar

4.1.1. Paleoproterozoic Sequences

New Hf isotope data support the interpretation made by De Waele et al. (2011) using U–Pb data, that the Itremo, Sahantaha, and Maha groups formed together as continental margin successions deposited no earlier than c. 1,700 Ma. The Ambatolampy Group and the Mangoky and Tolanaro groups of southern Madagascar also correlate and share a similar origin. Samples from the Itremo, Maha, Sahantaha, Ambatolampy, Mangoky, and Tolanaro groups have similar detrital zircon age spectra, maximum depositional ages within

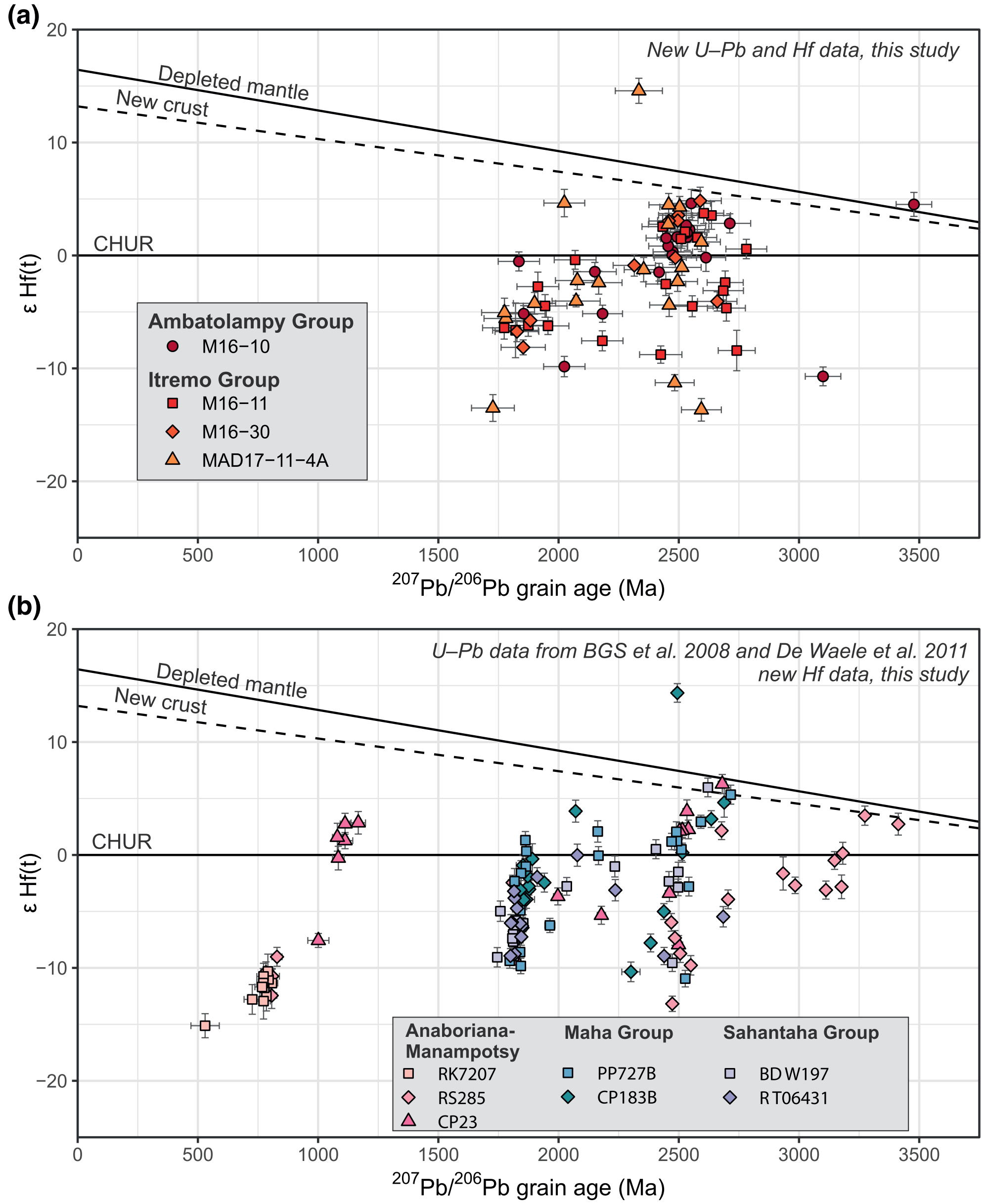

Figure 4. New zircon Lu–Hf isotope data for metasedimentary units in Madagascar. (a) New U–Pb and Hf data, and (b) samples with U–Pb data from BGS-USGS-GLW (2008) and De Waele et al. (2011), and new Hf data collected in this study. Depleted Mantle line calculated with $\varepsilon_{Hf}(t) = 16.44$ at time 0 Ma and $\varepsilon_{Hf}(t) = 0$ at 4,560 Ma using modern $^{176}Hf/^{177}Hf_{DM} = 0.28325$ (Griffin et al., 2000) and modern $^{176}Hf/^{177}Hf_{CHUR} = 0.282785$ (Bouvier et al., 2008). New Crust line calculated using $\varepsilon_{Hf}(t) = 13.2$ at time 0 Ma and $\varepsilon_{Hf}(t) = 0$ at time 4,560 Ma (Dhuime et al., 2011).

uncertainty of each other, and share similar $\varepsilon_{Hf}(t)$ values (Figure 5). There are subtle differences in the relative zircon age peak heights. For example, the Itremo Group has a stronger c. 2,500 Ma peak compared to the younger peaks; the Maha Group has a smaller c. 2,500 Ma peak and higher c. 1,800 Ma peak; and the Sahantaha Group has a dominant c. 1,800 Ma peak with minor older peaks (Figure 3). This is apparent on the cumulative proportion plots (Figures 3a and 5c), where Itremo and Ambatolampy group samples consistently plot below the other samples, suggesting that they are derived from more dissected, older cratonic terranes than rocks from the Maha, Sahantaha, or southern Malagasy groups (Cawood et al., 2012). We suggest these subtle differences reflect the proximity of these sample locations to particular sources across this broad region. Despite these minor differences, the major zircon components are present in all samples, maximum depositional ages are within uncertainty of each other and $\varepsilon_{Hf}(t)$ values are similar. We propose,

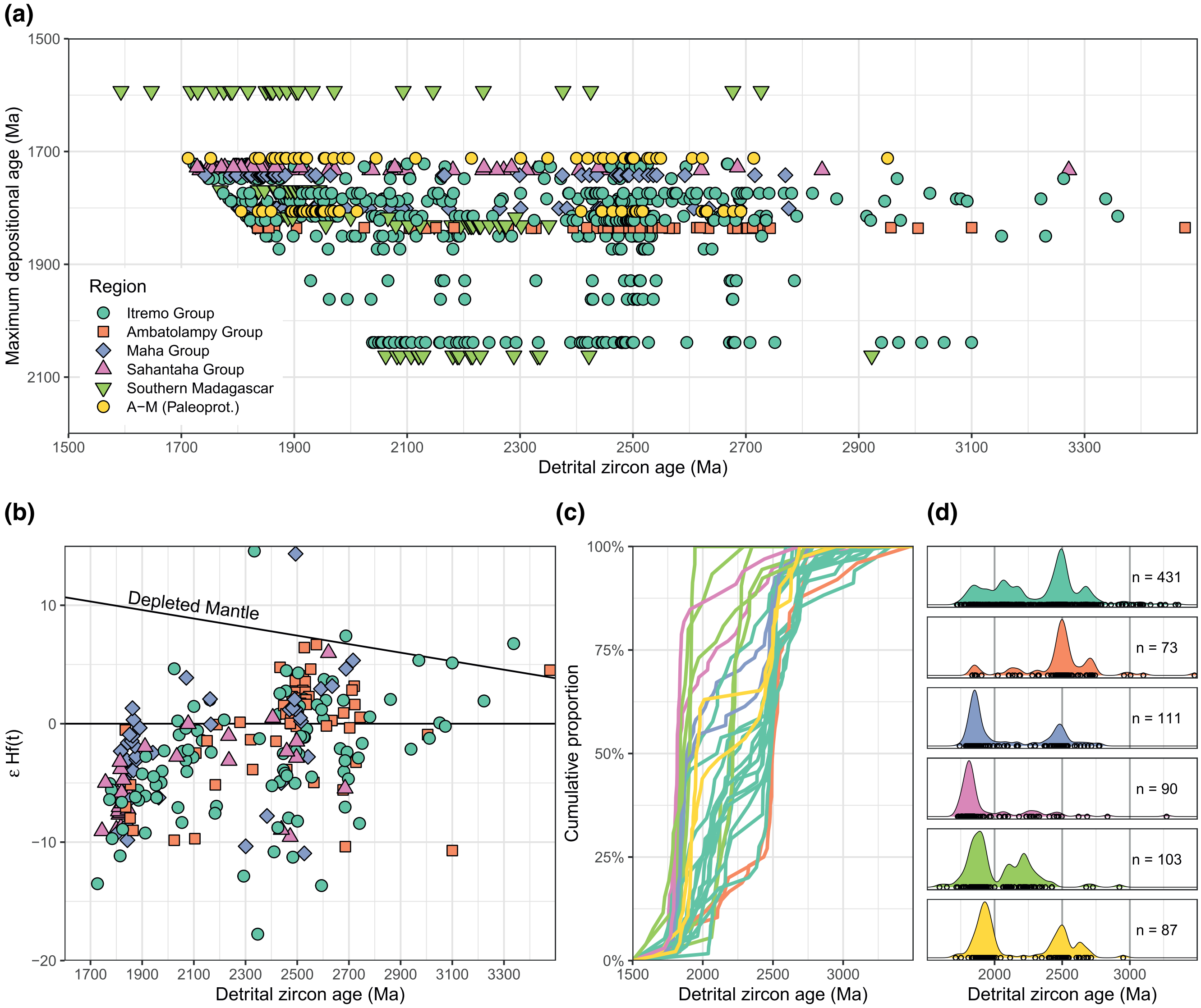

Figure 5. Comparison of Paleoproterozoic detrital zircon samples from Madagascar, symbolized by Group/Region. "A-M (Paleoprot.)" are the two samples from the Anaboriana-Manampotsy group that have Paleoproterozoic maximum depositional ages (Tucker, Roig, Delor, et al., 2011). Data filtered to be within 10% of concordance and includes samples that contain at least 20 grain ages within 10% of concordance. (a) Maximum depositional age versus grain age, color legend applies to all plots; (b) $\varepsilon_{Hf}(t)$ versus grain age; (c) cumulative proportion plot with each line representing an individual sample; and (d) kernel density estimate (KDE) plots of combined sample data for each region, bandwidth = 30. Data set includes new data from Figure 4 as well as data from Supplementary B.

therefore, that these samples were deposited within the same sedimentary system and derived their detritus from similar sources, consistent with interpretations by Boger et al. (2014) and De Waele et al. (2011).

These samples represent a large geographical area across Madagascar, with samples in the Sahantaha Group of northern Madagascar, the Itremo and Ambatolampy groups in central Madagascar, the Maha Group of eastern Madagascar and the Mangoky and Tolanaro groups of southern Madagascar. Published samples from southern Madagascar (Boger et al., 2014; Collins et al., 2012) that have similar detrital zircon age spectra, but no available Hf isotope data, are also likely part of this extensive sedimentary system. This suggests that a large basin existed over much of Madagascar at some point during or after the Paleoproterozoic—we herein refer to this as the "Greater Itremo Basin."

The majority of detritus deposited within the Greater Itremo Basin and analyzed, have maximum depositional ages between c. 1,875 and c. 1,700 Ma (Figure 5). However, one sample from southern Madagascar has a maximum depositional age of 1,593 ± 68 Ma (2σ), with an additional grain younger than c. 1,700 Ma. The youngest significant cluster of dates within the database is at c. 1,700 Ma, which is the best estimate for the maximum age of the Greater Itremo Basin.

Unfortunately, the minimum age constraint on the Greater Itremo Basin—the cross-cutting c. 850–750 Ma Imorona-Itsindro Suite—is almost a billion years younger than the maximum depositional ages. This leaves the age of deposition of sediments within the Greater Itremo Basin open to various interpretations. Based on the maximum depositional ages, and lack of any younger detrital zircons, the simplest interpretation is that the Greater Itremo Basin was actively accumulating sediments in the Paleoproterozoic. An alternative interpretation to this, is that the Greater Itremo Basin was accumulating sediments in the Mesoproterozoic and possibly even through to the early Neoproterozoic (e.g., Boger et al., 2014, 2019). However, if the second interpretation is correct, the zircons within the basin sediments must have been exclusively eroded from relatively ancient source rocks with no near-contemporaneous zircon sources eroded and preserved in the process. This is despite the exotic Ikalamavony Domain being thrust over the Itremo Domain in the Tonian and the early stages of the Imorona-Itsindro Suite being intruded at this time. Evidence against a younger depositional age for the Greater Itremo Basin include stromatolite morphology and carbon isotope data from carbonates in the Itremo Group that are consistent with them having a Paleoproterozoic depositional age (Cox et al., 2004). Additionally, André-Mayer et al. (2014) report Re–Os dating of gold veins within the Ikalamavony subdomain (which in their definition includes a portion of the Itremo Group), which yielded an age of 1,961 ± 79 Ma, suggesting a Paleoproterozoic depositional age for these sequences. Based on this information, our preferred model is for the Greater Itremo Basin deposition during the late Paleoproterozoic as approximated by zircon maximum depositional ages.

4.1.2. Neoproterozoic Sequences

Several metasedimentary rock groups have Neoproterozoic maximum depositional ages (Figure 6). These are located within the Anaboriana-Manampotsy Belt, the Ikalamavony Domain (Molo Group) and the Vohibory Domain, and the majority of these have maximum depositional ages between c. 790 and c. 625 Ma. Of these, the Anaboriana-Manampotsy Belt and Molo Group samples contain detrital zircons of similar age and Hf signature to the Greater Itremo Basin samples, with the addition of Neoproterozoic detritus. Therefore, these samples have likely derived a significant proportion of their detritus either from the same primary sources as the sediments within the Greater Itremo Basin, or from recycling the sedimentary rocks within the Itremo Group and its equivalents. The c. 850–750 Ma Imorona-Itsindro Group, which has relatively evolved $\varepsilon_{Hf}(t)$ values ranging from approximately 0 to −30 (Archibald et al., 2015), is a likely candidate for some of the younger detritus within these sequences. The c. 750 Ma southern Bemarivo Belt, which has evolved $\varepsilon_{Hf}(t)$ values ranging from approximately 0 to −15 (Armistead et al., 2019), is also a likely candidate for some of this younger detritus, particularly those samples located in northern Madagascar. Constraints on the minimum depositional age are given by zircon rim analyses that of c. 615–560 Ma for the Molo Group (Cox et al., 2004) and c. 520 Ma for the Anaboriana-Manampotsy Belt (Collins, Kröner, et al., 2003). The deposition of these groups therefore occurred during the Neoproterozoic, between c. 700 and c. 600 Ma.

We have included sample CP23 in the Anaboriana-Manampotsy belt samples due to its proximity to this belt and its Neoproterozoic maximum depositional age. This sample was originally ascribed to the Ambatolampy Group, and indeed, it does plot within the Ambatolampy Group on the large-scale geological map (Figure 2). However, all other zircon data from the Ambatolampy Group (Archibald et al., 2015; Tucker, Roig, Delor, et al., 2011; this study) are significantly older, with maximum depositional ages of c. 1,700 Ma. Since CP23 would be the only sample in the Ambatolampy Group that has any zircon younger than c. 1,700 Ma, we suggest this sample represents a different, younger group.

The Linta Group in the Vohibory Domain has detrital zircon dates between c. 1,068 and c. 555 Ma. These closely match ages from the Marasavoa Suite (c. 660–610 Ma) and the Vohitany Suite (c. 850 Ma), which are also in the Vohibory Domain (BGS-USGS-GLW, 2008). The sedimentary rocks in the Vohibory Domain appear to have exclusively derived material from local, roughly coeval, sources.

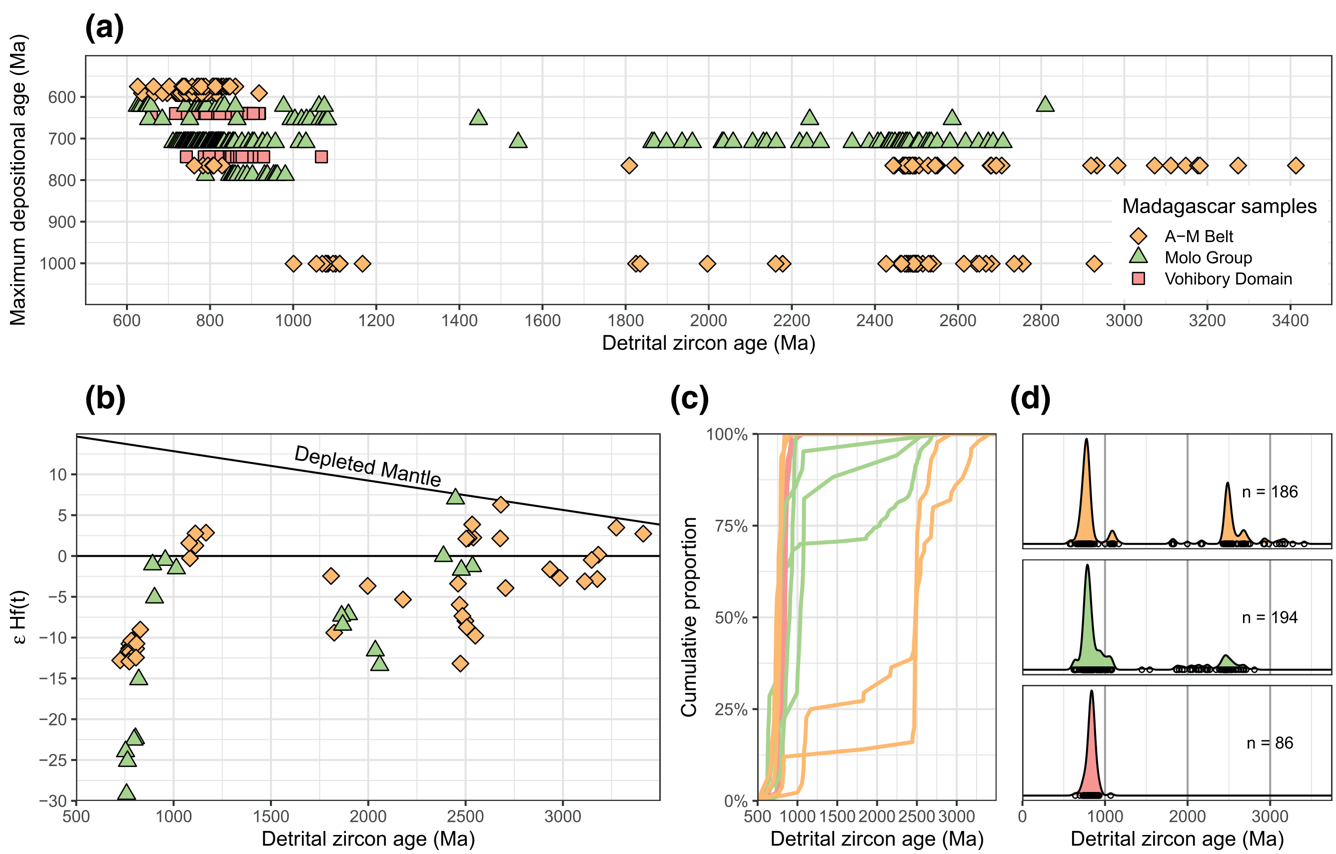

Figure 6. Comparison of Neoproterozoic detrital zircon samples from Madagascar, symbolized by Group/Region. Data filtered to be within 10% of concordance and includes samples that contain at least 20 grain ages within 10% of concordance. A-M Belt = Anaboriana-Manampotsy Belt. (a) Maximum depositional age versus grain age, color legend applies to all plots; (b) $\varepsilon_{Hf}(t)$ versus grain age for samples from Madagascar; (c) cumulative proportion plot with each line representing an individual sample; and (d) kernel density estimate (KDE) plots of Neoproterozoic samples, bandwidth = 30. Data set includes new data from Figure 4 as well as data from Supplementary B.

4.2. Correlation of the Greater Itremo Basin Formations With Other Regions

The Greater Itremo Basin contains formations with detrital zircon age spectra that share some similarities with those in East Africa, Cuddapah Basin of eastern India, and the Southern Granulite Terrane of southern India (Figures 7, 8a, and 8b). Herein we refer to “East Africa” as the region that includes the Tanzanian Craton, Irumide Belt, Usagaran-Ubendian belts, the Bangweulu Block, and the eastern Congo Craton shown in Figure 1a. To assess these similarities, we have produced multidimensional scaling plots for detrital data with maximum depositional ages >1,500 Ma (Figure 7). From Figures 7 and 8b, it is clear that the Greater Itremo Basin and East Africa both have detrital zircons that span the same ranges. Most notably, both regions have many samples with maximum depositional ages between c. 1,850–1,750 Ma. The slight differences in age peak heights likely reflect the proximity of the depositional environment to the source rocks. For example, c. 2,500 Ma magmatic rocks in Madagascar are likely a major source for c. 2,500 Ma detrital zircons in the Greater Itremo Basin, given similarities in their age and Hf isotope signature. This accounts for why the Greater Itremo Basin contains abundant c. 2,500 Ma zircons. The abundance of c. 2,020 Ma detrital zircons in East Africa indicates that it was closer to the sources of age-equivalent protoliths. However, we are wary of over interpreting the relative peaks of detrital zircon age spectra. The similarity in $\varepsilon_{Hf}(t)$ signatures of the Greater Itremo Basin formations and East Africa zircons (Figure 9) also suggests that these samples derived their detritus from similar protoliths.

The minimum age of the Muva Supergroup in East Africa are more tightly constrained than the Greater Itremo Group. The Muva Supergroup is interleaved with volcaniclastic units with ages of c. 1,880–1,850 Ma, but with detrital zircon ages as young as c. 1,800 Ma (De Waele & Fitzsimons, 2007). The Muva Supergroup

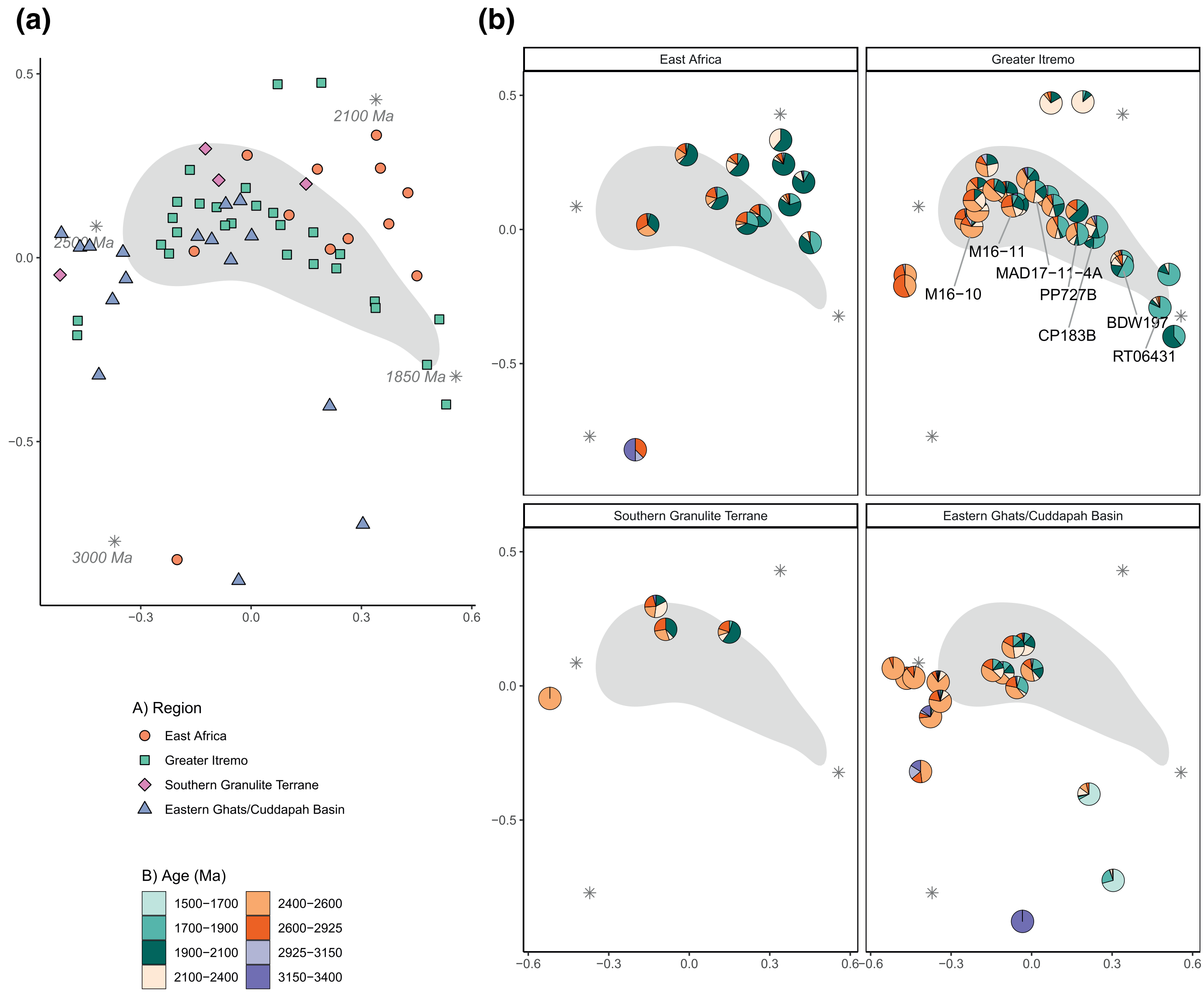

Figure 7. Multidimensional scaling (MDS) plots of detrital samples showing the dissimilarity between samples from different regions. Samples with maximum depositional ages > 1,500 Ma and at least 15 grains within 10% of concordance are included. MDS calculated using the "Provenance" package (Vermeesch et al., 2016) and pie charts plotted using the "scatterpie" package (Yu & Yu, 2018). (a) All MDS data plotted together for the four key regions assessed. Asterisk symbols indicate synthetic data sets (generated as multivariate normal random distributions of 1,000 numbers simulated with mean age (1,850 Ma, 2,100 Ma, 2,500 Ma, and 3,000 Ma) and variance of 50 Ma for key ages to show the relative mixing between age groups. Gray filled contour is for Greater Itremo data only; (b) the same data as (a) but separated for each region with pie charts showing the proportion of each age group. New samples analyzed in this study are labeled. Gray filled contour is the same as in (a).

is intruded by c. 1,650–1,550 Ma granitic gneisses, providing a minimum age constraint on its deposition (De Waele et al., 2003). If the Greater Itremo Group does correlate with the Muva Supergroup as we have interpreted here, then these magmatic rocks in East Africa provide further evidence that these sequences were deposited in the late Paleoproterozoic.

The majority of Southern Granulite Terrane samples have maximum depositional ages greater that c. 1,900 Ma; older than those zircons in the Itremo Group and East Africa. These contain dominant zircon age peaks at c. 2,650 Ma, 2,425 Ma, and c. 2075 Ma, which overlap with analyses from the Greater Itremo Basin and East Africa, and may be derived from similar sources. If these are related, the Southern Granulite Terrane may represent an older depocenter, or separate basin, sourcing similar regions to the Greater Itremo Basin. The multidimensional scaling plot (Figure 7) also indicates that samples from the Greater Itremo Basin, East Africa, and Southern Granulite Terrane are similar (Figure 7).

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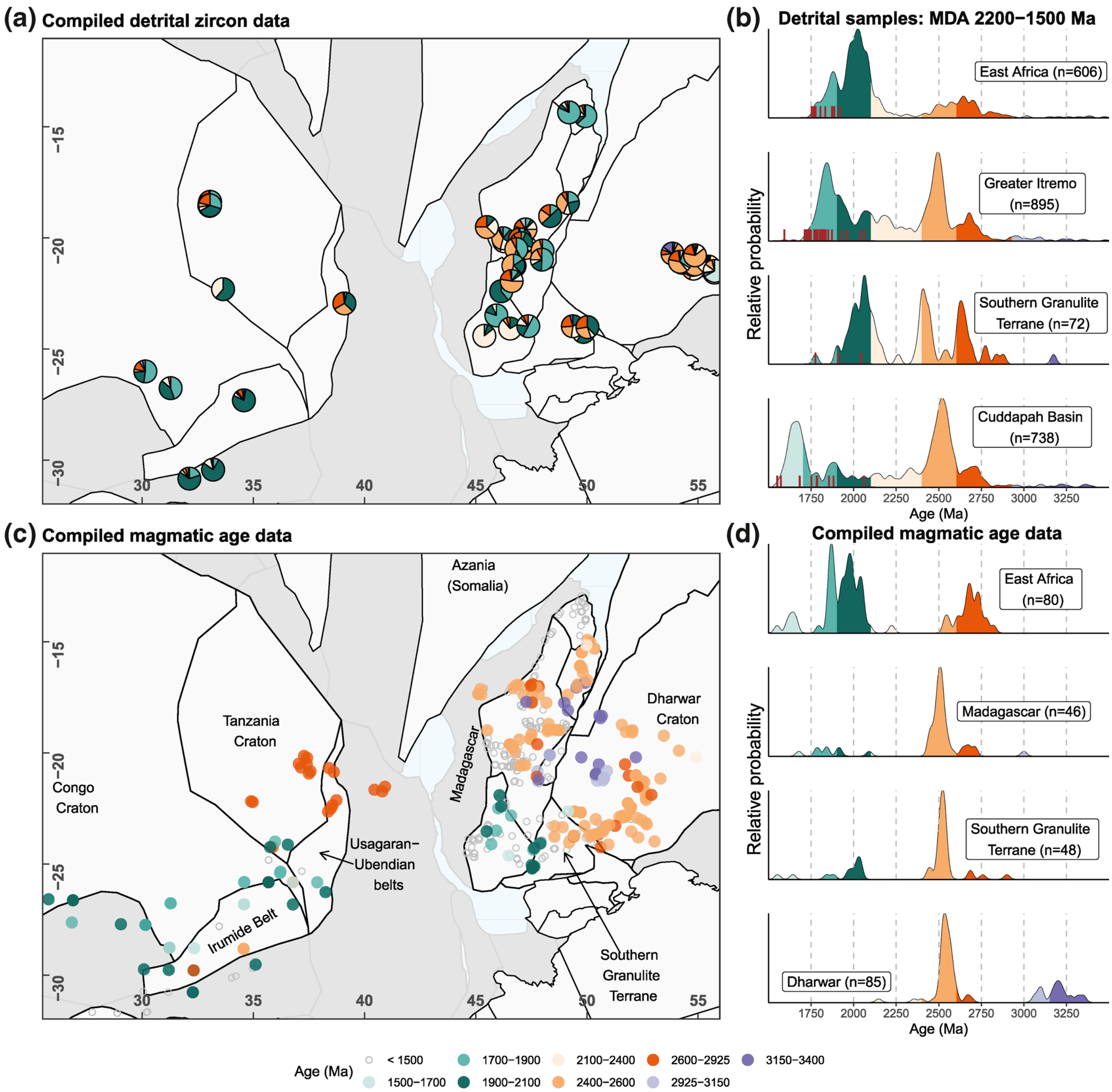

Figure 8. Comparison of compiled detrital zircon and magmatic data for Africa, Madagascar, and India. (a) Map reconstructed to c. 500 Ma with pie charts representing detrital zircon age distributions. Pie charts plotted using the "scatterpie" package in R (Yu & Yu, 2018), with colors representing the age bins represented in (b and d). (b) Kernel density estimate plots for compile detrital zircon data with maximum depositional ages between c. 2,200 and c. 1,500 Ma. Brown lines indicate the maximum depositional age for each sample. *N* refers to the number of grains included. (c) Map reconstructed to c. 500 Ma with magmatic sample locations, colored by age. (d) Kernel density estimate plots for compiled magmatic data. Tectonic reconstruction in (a and c) is from Merdith, Collins, et al. (2017).

The Cuddapah Basin samples are predominantly younger than c. 1,850 Ma, with the majority of maximum depositional ages and zircon grain ages between c. 1,850 and 1,550 Ma (Figure 8b). The main detrital zircon peaks for the Cuddapah Basin are c. 1,640 and c. 2,520 Ma. The 1,640 Ma peak is not represented in the other regions assessed. It is therefore unlikely that the Cuddapah Basin formed together with the Greater Itremo Basin or the metasedimentary rocks of East Africa. The Cuddapah Basin samples also have $\varepsilon_{Hf}(t)$ that extend to more negative values compared to the other terranes. This indicates that the Cuddapah Basin is

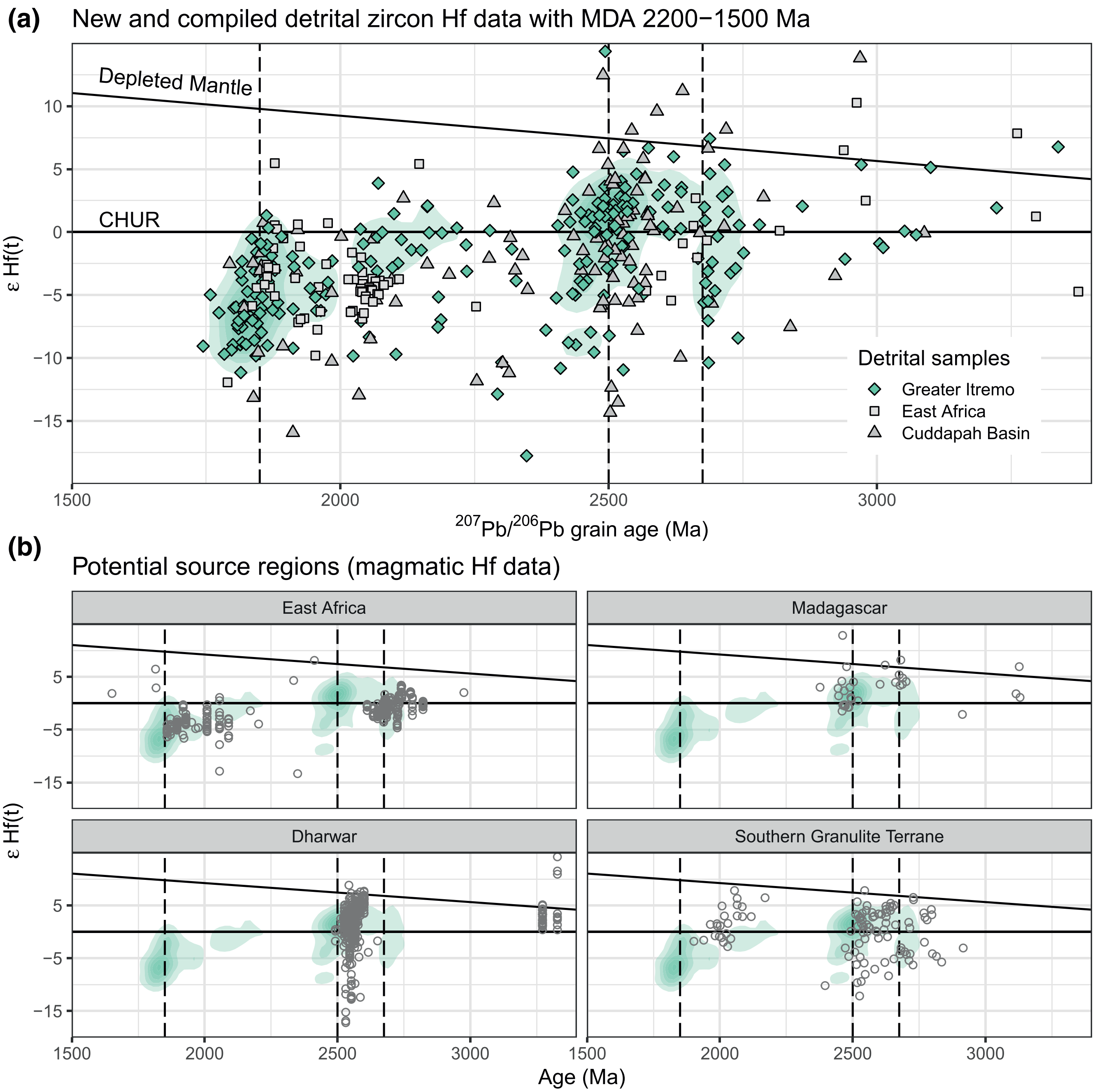

Figure 9. Comparison of detrital zircon Hf data with potential magmatic source regions; (a) detrital Hf isotopic data for samples with maximum depositional ages (MDA) between 2,200 and 1,500 Ma. Data for Greater Itremo Basin include all data in Figure 5b. Green filled contour is for Greater Itremo data only; (b) magmatic zircon Hf data from potential source regions, underlain with the green filled contour from (a). Dotted lines show the main detrital zircon age peaks in the Greater Itremo data set at 1,850 Ma, 2,500 Ma, and 2,675 Ma.

not related to the Greater Itremo Basin. Collins et al. (2015) suggested that sources for the Cuddapah Basin were identifiable within the southeast Indian Krishna Orogen and the eastern Dharwar Craton.

4.3. Provenance of the Greater Itremo Basin

Establishing the sources of detrital zircons far back in time is problematic for a range of reasons. The sources may no longer be exposed at the surface, and therefore our current databases of exposed rocks might not represent the sourced available for erosion during basin deposition. Source protoliths may not be magmatic in nature; indeed the maturity of the quartzites in the Greater Itremo Basin lend support to a multiphase sedimentary cycle for their final deposition, and many of the sources may be sedimentary rocks.

Despite these substantial limitations to establishing sources of detrital zircons, we have attempted to provide some preliminary assessment of potential source regions. To do this, we have only looked at magmatic protoliths and used the magmatic crystallization ages to compare with our detrital zircon data set (Figure 8). Hard rock source regions that could have provided the zircon sampled in the Itremo Group outside of Madagascar have been proposed in east Africa (Cox et al., 1998, 2004; Fitzsimons & Hulscher, 2005) and India (Tucker, Roig, Delor, et al., 2011). These proposals are discussed in light of currently available data below.

The c. 2,650 Ma peak in the Greater Itremo Basin data closely matches magmatic data from central Madagascar, the Southern Granulite Terrane and East Africa. This age is less common in the Dharwar Craton. Given that the Itremo Group overlies the Archean orthogneisses of central Madagascar, this source is unsurprising. The more significant detrital zircon age peak at c. 2,500 Ma is indistinguishable from the central Madagascar peak (Figure 8). It is worth noting here that the Dharwar Craton (including the Antongil-Masora domains of Madagascar) and the Southern Granulite Terrane peaks are slightly older. These observations support a local, central Malagasy origin for the majority of Archean detrital zircons in the Greater Itremo Basin.

The c. 2,000–1,750 Ma peak for the Greater Itremo Basin correlates with magmatic data from southern Madagascar, East Africa, and the Southern Granulite Terrane. Magmatic rocks of this age are unknown in the Dharwar Craton India. The age similarities in both metasedimentary and magmatic rocks in Madagascar and East Africa suggest that these regions were juxtaposed during the Paleoproterozoic/early Mesoproterozoic. The abundant c. 2,500 Ma detritus in East Africa metasedimentary rocks, with lack of age-equivalent magmatic rocks nearby, suggests that central Madagascar was a likely source for this component.

The Southern Granulite Terrane, although having maximum depositional ages that are slightly older, has a significant c. 2,100–1,900 Ma component of detrital zircons. Magmatic rocks of this age are also found in the Southern Granulite Terrane (e.g., Clark et al., 2020; Ghosh et al., 2004; Kumar et al., 2017) but are absent in the adjacent Dharwar Craton. Given the similarities in both magmatic and detrital zircon isotope data, it is likely that the Southern Granulite Terrane was contiguous with Madagascar at the time of deposition during the Paleoproterozoic.

4.4. Implications for Proterozoic Paleogeography

The Greater Itremo Basin sequences are comparable to metasedimentary sequences in East Africa in terms of zircon age spectra and we suggest that they comprise detritus from the Archean basement rocks of Madagascar and the magmatic rocks of East Africa and southern Madagascar. This implies that East Africa—including the Tanzanian Craton, Usagaran-Ubendian belts, Irumide Belt, and Bangweulu Block—was contiguous with central Madagascar at the time of deposition, which we have interpreted here as latest Paleoproterozoic. This broadly supports the tectonic model of Cox et al. (2004) and Fitzsimons and Hulscher (2005). The connection with the Southern Granulite Terrane is less clear; some data correlate with the main grain age peaks of the Itremo/East Africa data, however, the Southern Granulite Terrane samples have older maximum depositional ages. We suggest that these terranes were contiguous, and that metasedimentary sequences of the Southern Granulite Terrane represent either an older part of the basin, or a separate, older basin sourcing the same regions. Further Hf isotope studies on Paleoproterozoic detrital zircons from the Southern Granulite Terrane would provide further evidence either for or against this model.

To test this model, we have incorporated our database into a continental reconstruction and interpolated the age data (Figure 10). We modified the model and used the plate geometries of the Merdith, Collins, et al. (2017) *GPlates* model, adapting the model based on our interpretation at c. 1,700 Ma. Our georeferenced

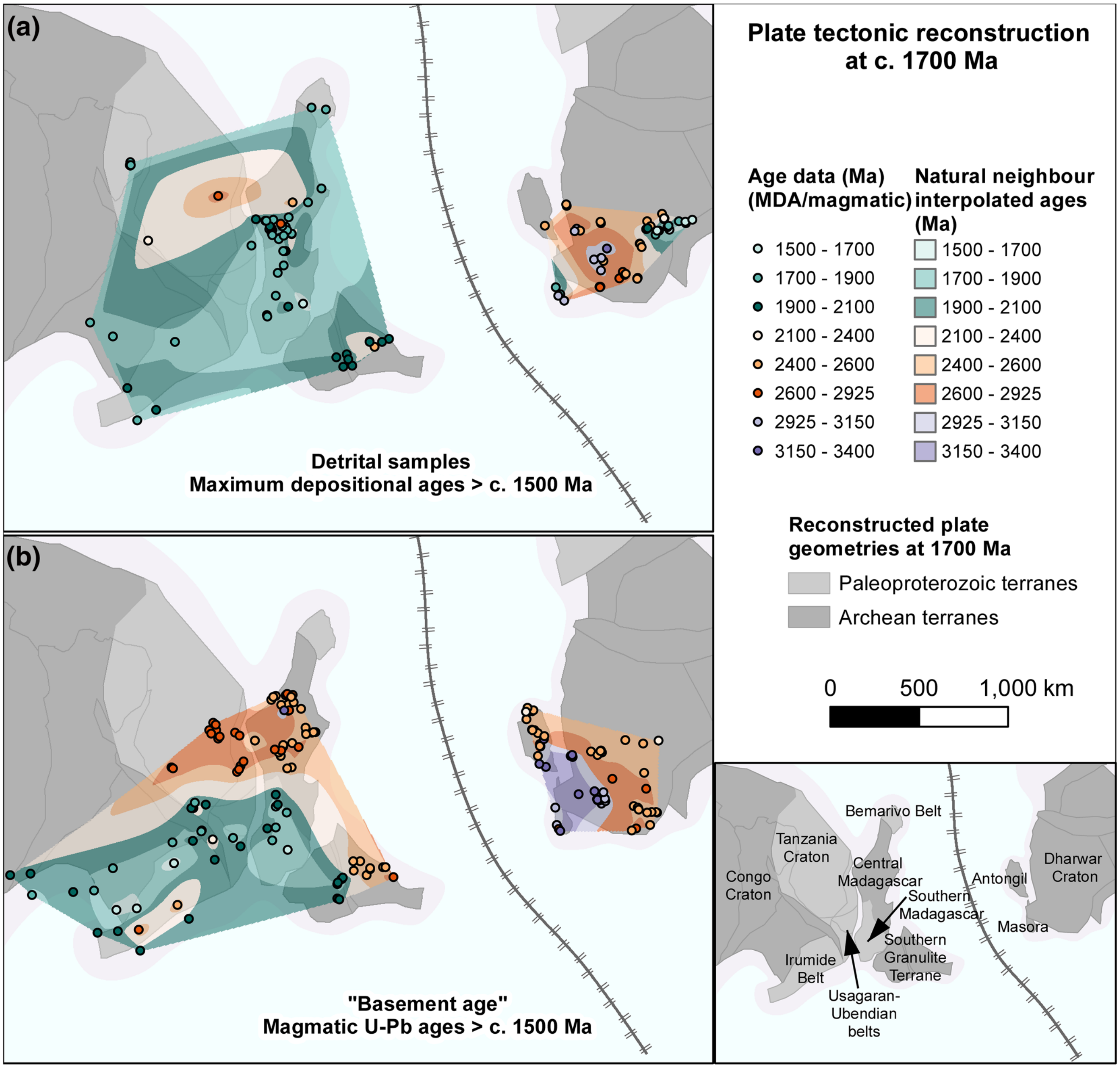

Figure 10. Interpreted reconstruction at 1,700 Ma, with our U–Pb zircon magmatic and detrital database mapped and interpolated. All detrital samples with maximum depositional ages > c. 1,500 Ma and magmatic samples with zircon U–Pb ages > c. 1,500 Ma are included. The hatched boundary separating the Africa-Madagascar-Southern India data and the Dharwar-Antongil-Masora data is arbitrary and simply indicates that we interpret these regions to be separate at this time.

age database was reconstructed according to this modification and exported to ArcGIS where we then interpolated the data using a natural neighbor interpolation of age data with a consistent legend for both plots for easy comparison.

Maximum depositional ages for metasedimentary rocks in Africa, Madagascar and the Southern Granulite Terrane are shown in Figure 10a, and the magmatic ages for these terranes are shown in Figure 10b. The magmatic age data are very consistent across the boundaries of East Africa and central Madagascar in the reconstruction. Notably, the progression from older Archean rocks in the north (reconstructed position) to Paleoproterozoic rocks in the south is consistent across both East Africa and central Madagascar. This is shown spatially in our interpreted link between the Irumide Belt, the Usagaran-Ubendian belts, and southern Madagascar. Similarly aged Archean rocks of the Tanzania Craton and central Madagascar also support a link. The Paleoproterozoic zone in the south of the map (green) as well as the Archean zone in the north of the map (orange), represent the two major source regions for detritus in the metasedimentary rocks of East Africa, Madagascar, and the Southern Granulite Terrane.

The correlation of samples with Paleoproterozoic maximum depositional ages is highlighted by the broad green zone in Figure 10a and further detrital zircon data from Africa would make this interpolation more robust. This highlights the broad geographical area over which these Paleoproterozoic rocks were deposited. It also crudely outlines the reconstructed, but presently exposed, margins of a wider late Paleoproterozoic basin. We call this basin the Itremo-Muva-Pandyan Basin after two of the most extensive sedimentary systems and the name for the "mobile belt" that encompasses the Southern Granulite Terrane of India.

Recently, Iaccheri and Bagas (2020) suggested that a similarly aged depositional system covered a huge region of Nuna/Columbia. They argued that detrital zircon ages and Hf isotopic values that are broadly comparable with those presented here, occur in Paleoproterozoic metasedimentary rocks in northern Australia. This suggests a depositional connection across the expanse of the supercontinent. We cannot rule this hypothesis out with our data, however we show here how subtle variation in age and isotopic composition are needed to distinguish between possible source areas, and therefore advise caution in the use of approximate and nonstatistically tested pattern matching of detrital isotopic data alone when making large paleogeographic interpretations.

The correlation of both basement terranes and sedimentary basins between central Madagascar and East Africa (as well as the Southern Granulite Terrane), and the dissimilarity of these systems with the Dharwar Craton, supports the "out-of-Africa" model of central Madagascar's origin (Collins, 2006; Collins & Pisarevsky, 2005; Collins & Windley, 2002; Cox et al., 2004; Fitzsimons & Hulscher, 2005). These correlations do not support the Greater Dharwar model (Tucker, Roig, Delor, et al., 2011; Tucker, Roig, Macey, et al., 2011) for the Paleoproterozoic and Mesoproterozoic.

We propose that to evolve from Nuna/Columbia to Gondwana, central Madagascar would have rifted off the Tanzania Craton to form an isolated late Mesoproterozoic–Neoproterozoic continent (named Azania by Collins & Pisarevsky, 2005). Madagascar later collided back against East Africa with Stenian–Cryogenian arc terranes marking the Vohibory suture (Archibald, Collins, Foden, Payne, et al., 2017; Archibald, Collins, Foden, & Razakamanana, 2017; Jöns & Schenk, 2008). Shortly thereafter, Madagascar and India collided along the Ediacaran–Cambrian Betsimisaraka Suture (Armistead et al., 2019, 2020; Collins, 2006; Fritz et al., 2013; Merdith, Collins, et al., 2017).

The modeling helps target areas for further data collection to support or refute this reconstruction. Further data collection in these key regions will enable a more robust test of some of the ideas and the reconstruction we've presented in this manuscript. It's also important to note that we have only evaluated data from Madagascar, East Africa and India in this study, with a focus on understanding the evolution of Madagascar's Paleoproterozoic metasedimentary rock packages. Regions with Paleoproterozoic rocks exist in many regions around the world including the North China Craton, North Australian Craton, and South Australian Craton. As more data is collected and compiled from these regions, we can work toward detrital zircon provenance studies at a larger, more global scale for the Paleoproterozoic.

5. Conclusions

New U–Pb and Lu–Hf zircon data together with a substantial database of magmatic and detrital U–Pb and Lu–Hf data have been used to show the similarities and differences of terranes in Africa, Madagascar, and India. The Itremo Group, which has traditionally been mapped as a relatively localized metasedimentary package, is here correlated with other metasedimentary packages in Madagascar, including the Maha Group, Sahantaha Group, southern Madagascar, and the Ambatolampy Group. These are further correlated with Paleoproterozoic metasedimentary rocks of the Tanzania Craton in East Africa and tentatively with metasedimentary rocks in the Southern Granulite Terrane of India to form a major intra-Nuna/Columbia sedimentary basin that we name the Itremo-Muva-Pandyan Basin. We propose a plate tectonic configuration for the Paleoproterozoic where central Madagascar is contiguous with East Africa to the west (relative to present-day positions) and the Southern Granulite Terrane to the east. This model strongly supports an ancient Proterozoic origin for central Madagascar against the Tanzania Craton of East Africa, and the isolation of central Madagascar as the late Mesoproterozoic microcontinent Azania that recollided back with East Africa and India in the Neoproterozoic–Cambrian.

Data Availability Statement

Data sets for this research are available from figshare. Supplementary A DOI: https://doi.org/10.6084/m9.figshare.12783869. Supplementary B DOI: https://doi.org/10.6084/m9.figshare.12783887. Supplementary C DOI: https://doi.org/10.6084/m9.figshare.13379831. Supplementary D DOI: https://doi.org/10.6084/m9.figshare.13379849.

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References

Alessio, B. L. (2019). *The tectonic evolution of the southern Congo Craton* (PhD Thesis).

Alessio, B. L., Collins, A. S., Clark, C., Glorie, S., Siegfried, P. R., & Taylor, R. (2019). Age, origin and palaeogeography of the Southern Irumide Belt, Zambia. *Journal of the Geological Society*, *176*, 505–516.

Alessio, B. L., Collins, A. S., Siegfried, P., Glorie, S., De Waele, B., Payne, J., & Archibald, D. B. (2018). Neoproterozoic tectonic geography of the south-east Congo Craton in Zambia as deduced from the age and composition of detrital zircons. *Geoscience Frontiers*, *10*, 2045–2061.

Ali, K. A., Jeon, H., Andresen, A., Li, S.-Q., Harbi, H. M., & Hegner, E. (2014). U–Pb zircon geochronology and Nd–Hf–O isotopic systematics of the Neoproterozoic Hadb adh Dayheen ring complex, Central Arabian Shield, Saudi Arabia. *Lithos*, *206–207*, 348–360.

André-Mayer, A. S., Ramiandrisoa, N., Vanderhaeghe, O., Reisberg, L., Rabeandrasana, S., & Zimmermann, C. (2014). Re–Os geochronological constraints on the Dabolava mesothermal gold occurence, Madagascar: Implications for the Ikalamavony sub-domain deposition age. *Journal of African Earth Sciences*, *94*, 119–127.

Archibald, D. B., Collins, A. S., Foden, J. D., Payne, J. L., Holden, P., Razakamanana, T., et al. (2016). Genesis of the Tonian Imorona–Itsindro magmatic Suite in central Madagascar: Insights from U–Pb, oxygen and hafnium isotopes in zircon. *Precambrian Research*, *281*, 312–337.

Archibald, D. B., Collins, A. S., Foden, J. D., Payne, J. L., Macey, P. H., Holden, P., & Razakamanana, T. (2017). Stenian–Tonian arc magmatism in west–central Madagascar: The genesis of the Dabolava Suite. *Journal of the Geological Society*, *175*, 111–129.

Archibald, D. B., Collins, A. S., Foden, J. D., Payne, J. L., Taylor, R., Holden, P., et al. (2015). Towards unravelling the Mozambique Ocean conundrum using a triumvirate of zircon isotopic proxies on the Ambatolampy Group, central Madagascar. *Tectonophysics*, *662*, 167–182.

Archibald, D. B., Collins, A. S., Foden, J. D., & Razakamanana, T. (2017). Tonian arc magmatism in central Madagascar: The petrogenesis of the Imorona-Itsindro Suite. *The Journal of Geology*, *125*(3), 271–297.

Armistead, S. E., Collins, A., Merdith, A. S., Payne, J. L., Cox, G. M., Foden, J. D., et al. (2019). Evolving marginal terranes during Neoproterozoic supercontinent reorganisation: Constraints from the Bemarivo Domain in northern Madagascar. *Tectonics*, *38*(6), 2019–2035. https://doi.org/10.1029/2018TC005384

Armistead, S. E., Collins, A. S., Payne, J. L., Foden, J. D., De Waele, B., Shaji, E., & Santosh, M. (2017). A re-evaluation of the Kumta Suture in western peninsular India and its extension into Madagascar. *Journal of Asian Earth Sciences*, *157*, 317–328.

Armistead, S. E., Collins, A. S., Redaa, A., Jepson, G., Gillespie, J., Gilbert, S., et al. (2020). Structural evolution and medium-temperature thermochronology of central Madagascar: Implications for Gondwana amalgamation. *Journal of the Geological Society*, *177*, 784–798.

Batumike, J. M., Griffin, W. L., O'Reilly, S. Y., Belousova, E. A., & Pawlitschek, M. (2009). Crustal evolution in the central Congo-Kasai Craton, Luebo, D.R. Congo: Insights from zircon U–Pb ages, Hf-isotope and trace-element data. *Precambrian Research*, *170*(1–2), 107–115.

Batumike, J. M., O'Reilly, S. Y., Griffin, W. L., & Belousova, E. A. (2007). U–Pb and Hf-isotope analyses of zircon from the Kundelungu Kimberlites, D.R. Congo: Implications for crustal evolution. *Precambrian Research*, *156*(3–4), 195–225.

Bauer, W., Walsh, G. J., de Waele, B., Thomas, R. J., Horstwood, M. S. A., Bracciali, L., et al. (2011). Cover sequences at the northern margin of the Antongil Craton, NE Madagascar. *Precambrian Research*, *189*(3–4), 292–312.

BGS-USGS-GLW. (2008). *Republique de Madagascar Ministère de L'engergie et des Mines (MEM/SG/DG/UCP/PGRM)*: British Geological Survey Research Report.

Blades, M. L., Collins, A. S., Foden, J., Payne, J. L., Xu, X., Alemu, T., et al. (2015). Age and hafnium isotopic evolution of the Didesa and Kemashi Domains, western Ethiopia. *Precambrian Research*, *270*, 267–284.

Boger, S. D., Hirdes, W., Ferreira, C. A. M., Schulte, B., Jenett, T., & Fanning, C. M. (2014). From passive margin to volcano–sedimentary forearc: The Tonian to Cryogenian evolution of the Anosyen Domain of southeastern Madagascar. *Precambrian Research*, *247*, 159–186.

Boger, S. D., Maas, R., Pastuhov, M., Macey, P. H., Hirdes, W., Schulte, B., et al. (2019). The tectonic domains of southern and western Madagascar. *Precambrian Research*, *327*, 144–175.

Bouvier, A., Vervoort, J. D., & Patchett, P. J. (2008). The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters*, *273*(1), 48–57.

Buchwaldt, R., Tucker, R. D., & Dymek, R. F. (2003). Geothermobarometry and U-Pb Geochronology of metapelitic granulites and pelitic migmatites from the Lokoho region, Northern Madagascar. *American Mineralogist*, *88*(11–12), 1753–1768.

Bulambo, M., De Waele, B., Kampunzu, A., & Tembo, F. (2004). *SHRIMP U–Pb geochronology of the Choma–Kalomo block (Zambia) and geological implications* (p. 96). Proceedings 20th Colloquium of African Geology, Orléans, France.

Cawood, P. A., Hawkesworth, C. J., & Dhuime, B. (2012). Detrital zircon record and tectonic setting. *Geology*, *40*(10), 875–878.

Clark, C., Collins, A. S., Taylor, R. J., & Hand, M. (2020). Isotopic systematics of zircon indicate an African affinity for the rocks of southernmost India. *Scientific Reports*, *10*(1), 1–12.

Clark, C., Collins, A. S., Timms, N. E., Kinny, P. D., Chetty, T., & Santosh, M. (2009). SHRIMP U–Pb age constraints on magmatism and high-grade metamorphism in the Salem Block, southern India. *Gondwana Research*, *16*(1), 27–36.

Collins, A. S. (2006). Madagascar and the amalgamation of Central Gondwana. *Gondwana Research*, *9*(1–2), 3–16.

Collins, A. S., Clark, C., Sajeev, K., Santosh, M., Kelsey, D. E., & Hand, M. (2007). Passage through India: The Mozambique Ocean suture, high-pressure granulites and the Palghat-Cauvery shear zone system. *Terra Nova*, *19*(2), 141–147.

Collins, A. S., Johnson, S., Fitzsimons, I. C., Powell, C. M., Hulscher, B., Abello, J., & Razakamanana, T. (2003). Neoproterozoic deformation in central Madagascar: A structural section through part of the East African Orogen. *Geological Society, London, Special Publications*, *206*(1), 363–379.

Collins, A. S., Kinny, P. D., & Razakamanana, T. (2012). Depositional age, provenance and metamorphic age of metasedimentary rocks from southern Madagascar. *Gondwana Research*, *21*(2–3), 353–361.

Collins, A. S., Kröner, A., Fitzsimons, I. C. W., & Razakamanana, T. (2003). Detrital footprint of the Mozambique ocean: U–Pb SHRIMP and Pb evaporation zircon geochronology of metasedimentary gneisses in eastern Madagascar. *Tectonophysics*, *375*(1–4), 77–99.

Collins, A. S., Patranabis-Deb, S., Alexander, E., Bertram, C. N., Falster, G. M., Gore, R. J., et al. (2015). Detrital mineral age, radiogenic isotopic stratigraphy and tectonic significance of the Cuddapah Basin, India. *Gondwana Research*, *28*(4), 1294–1309.

Collins, A. S., & Pisarevsky, S. A. (2005). Amalgamating eastern Gondwana: The evolution of the Circum-Indian Orogens. *Earth-Science Reviews*, *71*(3–4), 229–270.

Collins, A. S., Santosh, M., Braun, I., & Clark, C. (2007). Age and sedimentary provenance of the Southern Granulites, South India: U-Th-Pb SHRIMP secondary ion mass spectrometry. *Precambrian Research*, *155*(1–2), 125–138.

Collins, A. S., & Windley, B. F. (2002). The tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana. *The Journal of Geology*, *110*(3), 325–339.

Costa, R. L., Schmitt, R. S., Collins, A., Armistead, S. E., Gomez, I. V., Archibald, D., & Razakamanana, T. (2021). *Tectonic evolution of an Early Cryogenian late-magmatic basin in central Madagascar*: EarthArXiv.

Cox, R., Armstrong, R. A., & Ashwal, L. D. (1998). Sedimentology, geochronology and provenance of the Proterozoic Itremo Group, central Madagascar, and implications for pre-Gondwana palaeogeography. *Journal of the Geological Society*, *155*(6), 1009–1024.

Cox, R., Coleman, D. S., Chokel, C. B., DeOreo, S. B., Wooden, J. L., Collins, A. S., et al. (2004). Proterozoic tectonostratigraphy and paleogeography of central Madagascar derived from detrital zircon U-Pb age populations. *The Journal of Geology*, *112*(4), 379–399.

Cox, R., Rivers, T., Mapani, B., Tembo, D., & De Waele, B. (2002). *New U-Pb data for the Irumide belt: LAM-ICP-MS results for Luangwa Terrane* (Vol. 10). Proceedings Abstracts, 11th IAGOD Quadrennial Symposium and Geocongress Windhoek.

Daly, M. (1986). *The tectonic and thermal evolution of the Irumide belt*. Zambia: University of Leeds.

De Waele, B., & Fitzsimons, I. C. W. (2007). The nature and timing of Palaeoproterozoic sedimentation at the southeastern margin of the Congo Craton; zircon U–Pb geochronology of plutonic, volcanic and clastic units in northern Zambia. *Precambrian Research*, *159*(1–2), 95–116.

De Waele, B., Liégeois, J.-P., Nemchin, A. A., & Tembo, F. (2006). Isotopic and geochemical evidence of proterozoic episodic crustal reworking within the irumide belt of south-central Africa, the southern metacratonic boundary of an Archaean Bangweulu Craton. *Precambrian Research*, *148*(3–4), 225–256.

De Waele, B., Thomas, R. J., Macey, P. H., Horstwood, M. S. A., Tucker, R. D., Pitfield, P. E. J., et al. (2011). Provenance and tectonic significance of the Palaeoproterozoic metasedimentary successions of central and northern Madagascar. *Precambrian Research*, *189*(1–2), 18–42.

De Waele, B., Wingate, M. T., Fitzsimons, I. C., & Mapani, B. S. (2003). Untying the Kibaran knot: A reassessment of Mesoproterozoic correlations in southern Africa based on SHRIMP U-Pb data from the Irumide belt. *Geology*, *31*(6), 509–512.

de Wit, M. J., Bowring, S. A., Ashwal, L. D., Randrianasolo, L. G., Morel, V. P. I., & Rambeloson, R. A. (2001). Age and tectonic evolution of Neoproterozoic ductile shear zones in southwestern Madagascar, with implications for Gondwana studies. *Tectonics*, *20*(1), 1–45.

Dhuime, B., Hawkesworth, C., & Cawood, P. (2011). When continents formed. *Science*, *331*(6014), 154–155.

Dodson, M., Cavanagh, B., Thatcher, E., & Aftalion, M. (1975). Age limits for the Ubendian metamorphic episode in northern Malawi. *Geological Magazine*, *112*(4), 403–410.

Emmel, B., Jons, N., Kroner, A., Jacobs, J., Wartho, J. A., Schenk, V., et al. (2008). From closure of the Mozambique Ocean to Gondwana breakup: New evidence from geochronological data of the Vohibory Terrane, Southwest Madagascar. *The Journal of Geology*, *116*(1), 21–38.

Evans, D. A., & Mitchell, R. N. (2011). Assembly and breakup of the core of Paleoproterozoic–Mesoproterozoic supercontinent Nuna. *Geology*, *39*(5), 443–446.

Fernandez, A., Schreurs, G., Villa, I. M., Huber, S., & Rakotondrazafy, M. (2003). Age constraints on the tectonic evolution of the Itremo region in Central Madagascar. *Precambrian Research*, *123*(2–4), 87–110.

Fitzsimons, I. C. W., & Hulscher, B. (2005). Out of Africa: Detrital zircon provenance of central Madagascar and Neoproterozoic terrane transfer across the Mozambique Ocean. *Terra Nova*, *17*(3), 224–235.

Foster, D. A., Goscombe, B. D., Newstead, B., Mapani, B., Mueller, P. A., Gregory, L. C., & Muvangua, E. (2015). U–Pb age and Lu–Hf isotopic data of detrital zircons from the Neoproterozoic Damara Sequence: Implications for Congo and Kalahari before Gondwana. *Gondwana Research*, *28*(1), 179–190.

Fritz, H., Abdelsalam, M., Ali, K. A., Bingen, B., Collins, A. S., Fowler, A. R., et al. (2013). Orogen styles in the East African Orogen: A review of the Neoproterozoic to Cambrian tectonic evolution. *Journal of African Earth Sciences*, *86*, 65–106.

Ghosh, J. G., de Wit, M. J., & Zartman, R. (2004). Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies. *Tectonics*, *23*(3), TC3006. https://doi.org/10.1029/2002TC001444

Glorie, S., De Grave, J., Singh, T., Payne, J. L., & Collins, A. S. (2014). Crustal root of the Eastern Dharwar Craton: Zircon U–Pb age and Lu–Hf isotopic evolution of the East Salem Block southeast India. *Precambrian Research*, *249*, 229–246.

Goodenough, K. M., Thomas, R. J., De Waele, B., Key, R. M., Schofield, D. I., Bauer, W., et al. (2010). Post-collisional magmatism in the central East African Orogen: The Maevarano Suite of north Madagascar. *Lithos*, *116*(1–2), 18–34.

Griffin, W., Pearson, N., Belousova, E., Jackson, S., Van Achterbergh, E., O'Reilly, S. Y., & Shee, S. (2000). The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta*, *64*(1), 133–147.

Griffin, W., Wang, X., Jackson, S., Pearson, N., O'Reilly, S. Y., Xu, X., & Zhou, X. (2002). Zircon chemistry and magma mixing, SE China: In-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos*, *61*(3), 237–269.

Handke, M. J., Tucker, R. D., & Ashwal, L. D. (1999). Neoproterozoic continental arc magmatism in west-central Madagascar. *Geology*, *27*(4), 351–354.

Hanson, R. E., Wilson, T. J., Brueckner, H. K., Onstott, T. C., Wardlaw, M. S., Johns, C. C., & Hardcastle, K. C. (1988). Reconnaissance geochronology, tectonothermal evolution, and regional significance of the Middle Proterozoic Choma-Kalomo block, southern Zambia. *Precambrian Research*, *42*(1–2), 39–61.

Henderson, B., Collins, A. S., Payne, J., Forbes, C., & Saha, D. (2014). Geologically constraining India in Columbia: The age, isotopic provenance and geochemistry of the protoliths of the Ongole Domain, Southern Eastern Ghats, India. *Gondwana Research*, *26*(3–4), 888–906.

Iaccheri, L. M., & Bagas, L. (2020). Zircon provenances provide paleogeographic constraints on models reconstructing the Paleoproterozoic Columbia Supercontinent. *Gondwana Research*, *82*, 254–266.

Ishwar-Kumar, C., Windley, B., Horie, K., Kato, T., Hokada, T., Itaya, T., et al. (2013). A Rodinian suture in western India: New insights on India-Madagascar correlations. *Precambrian Research*, *236*, 227–251.

Jayananda, M., Aadhiseshan, K., Kusiak, M. A., Wilde, S. A., Sekhamo, K.-u., Guitreau, M., et al. (2020). Multi-stage crustal growth and Neoarchean geodynamics in the Eastern Dharwar Craton, southern India. *Gondwana Research*, *78*, 228–260.

Jayananda, M., Chardon, D., Peucat, J.-J., & Fanning, C. M. (2015). Paleo-to Mesoarchean TTG accretion and continental growth in the western Dharwar craton, Southern India: Constraints from SHRIMP U–Pb zircon geochronology, whole-rock geochemistry and Nd–Sr isotopes. *Precambrian Research*, *268*, 295–322.

John, T. (2001). *Subduction and continental collision in the Lufilian Arc-Zambesi Belt orogen: A petrological, geochemical, and geochronological study of eclogites and whiteschists (Zambia)*: Christian-Albrechts Universität Kiel.

Johnson, P. R., Andresen, A., Collins, A. S., Fowler, A. R., Fritz, H., Ghebreab, W., et al. (2011). Late Cryogenian–Ediacaran history of the Arabian–Nubian Shield: A review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. *Journal of African Earth Sciences*, *61*(3), 167–232.

Jöns, N., & Schenk, V. (2008). Relics of the Mozambique Ocean in the central East African Orogen: Evidence from the Vohibory Block of southern Madagascar. *Journal of Metamorphic Geology*, *26*(1), 17–28.

Joy, S., Jelsma, H., Tappe, S., & Armstrong, R. (2015). SHRIMP U–Pb zircon provenance of the Sullavai Group of Pranhita–Godavari Basin and Bairenkonda Quartzite of Cuddapah Basin, with implications for the Southern Indian Proterozoic tectonic architecture. *Journal of Asian Earth Sciences*, *111*, 827–839.

Kabete, J., Groves, D., McNaughton, N., & Dunphy, J. (2006). The geology, SHRIMP U–Pb geochronology and metallogenic significance of the Ankisatra-Besakay District, Andriamena belt, northern Madagascar. *Journal of African Earth Sciences*, *45*(1), 87–122.

Katongo, C., Koller, F., Kloetzli, U., Koeberl, C., Tembo, F., & De Waele, B. (2004). Petrography, geochemistry, and geochronology of granitoid rocks in the Neoproterozoic-Paleozoic Lufilian–Zambezi belt, Zambia: Implications for tectonic setting and regional correlation. *Journal of African Earth Sciences*, *40*(5), 219–244.

Kazimoto, E. O., Schenk, V., & Berndt, J. (2014). Neoarchean and Paleoproterozoic crust formation in the Ubendian Belt of Tanzania: Insights from zircon geochronology and geochemistry. *Precambrian Research*, *252*, 119–144.

Key, R., Liyungu, A., Njamu, F. M., Somwe, V., Banda, J., Mosley, P., & Armstrong, R. (2001). The western arm of the Lufilian Arc in NW Zambia and its potential for copper mineralization. *Journal of African Earth Sciences*, *33*(3–4), 503–528.

Koegelenberg, C., Kisters, A., Kramers, J., & Frei, D. (2015). U–Pb detrital zircon and 39Ar–40Ar muscovite ages from the eastern parts of the Karagwe-Ankole Belt: Tracking Paleoproterozoic basin formation and Mesoproterozoic crustal amalgamation along the western margin of the Tanzania Craton. *Precambrian Research*, *269*, 147–161.

Konopásek, J., Košler, J., Sláma, J., & Janoušek, V. (2014). Timing and sources of pre-collisional Neoproterozoic sedimentation along the SW margin of the Congo Craton (Kaoko Belt, NW Namibia). *Gondwana Research*, *26*(1), 386–401.

Kooijman, E., Upadhyay, D., Mezger, K., Raith, M. M., Berndt, J., & Srikantappa, C. (2011). Response of the U–Pb chronometer and trace elements in zircon to ultrahigh-temperature metamorphism: The Kadavur anorthosite complex, southern India. *Chemical Geology*, *290*(3–4), 177–188.

Kröner, A., Hegner, E., Collins, A. S., Windley, B. F., Brewer, T. S., Razakamanana, T., & Pidgeon, R. T. (2000). Age and magmatic history of the Antananarivo Block, central Madagascar, as derived from zircon geochronology and Nd isotopic systematics. *American Journal of Science*, *300*(4), 251–288.

Kröner, A., Santosh, M., & Wong, J. (2012). Zircon ages and Hf isotopic systematics reveal vestiges of Mesoproterozoic to Archaean crust within the late Neoproterozoic–Cambrian high-grade terrain of southernmost India. *Gondwana Research*, *21*(4), 876–886.

Kumar, T. V., Rao, Y. B., Plavsa, D., Collins, A. S., Tomson, J., Gopal, B. V., & Babu, E. (2017). Zircon U-Pb ages and Hf isotopic systematics of charnockite gneisses from the Ediacaran–Cambrian high-grade metamorphic terranes, southern India: Constraints on crust formation, recycling, and Gondwana correlations. *Bulletin*, *129*(5–6). 625–648.

Lancaster, P. J., Dey, S., Storey, C. D., Mitra, A., & Bhunia, R. K. (2015). Contrasting crustal evolution processes in the Dharwar craton: Insights from detrital zircon U–Pb and Hf isotopes. *Gondwana Research*, *28*(4), 1361–1372.

Linol, B., de Wit, M. J., Barton, E., de Wit, M. M. J., & Guillocheau, F. (2016). U–Pb detrital zircon dates and source provenance analysis of Phanerozoic sequences of the Congo Basin, central Gondwana. *Gondwana Research*, *29*(1), 208–219.

Li, S.-S., Santosh, M., Indu, G., Shaji, E., & Tsunogae, T. (2017). Detrital zircon geochronology of quartzites from the southern Madurai Block, India: Implications for Gondwana reconstruction. *Geoscience Frontiers*, *8*(4), 851–867.

Maibam, B., Gerdes, A., & Goswami, J. (2016). U–Pb and Hf isotope records in detrital and magmatic zircon from eastern and western Dharwar craton, southern India: Evidence for coeval Archaean crustal evolution. *Precambrian Research*, *275*, 496–512.

Maibam, B., Goswami, J., & Srinivasan, R. (2011). Pb–Pb zircon ages of Archaean metasediments and gneisses from the Dharwar craton, southern India: Implications for the antiquity of the eastern Dharwar craton. *Journal of earth system science*, *120*(4), 643–661.

Merdith, A. S., Collins, A. S., Williams, S. E., Pisarevsky, S., Foden, J. D., Archibald, D. B., et al. (2017). A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research*, *50*, 84–134.

Merdith, A. S., Williams, S. E., Collins, A. S., Tetley, M. G., Mulder, J. A., Blades, M. L., Young, A., et al. (2020). Extending full-plate tectonic models into deep time: Linking the neoproterozoic and the phanerozoic. *Earth-Science Reviews*, *214*, 103477.

Merdith, A. S., Williams, S. E., Müller, R. D., & Collins, A. S. (2017). Kinematic constraints on the Rodinia to Gondwana transition. *Precambrian Research*, *299*, 132–150.

Mohan, M. R., Sarma, D. S., McNaughton, N. J., Fletcher, I. R., Wilde, S. A., Siddiqui, M. A., et al. (2014). SHRIMP zircon and titanite U-Pb ages, Lu-Hf isotope signatures and geochemical constraints for~ 2.56 Ga granitic magmatism in Western Dharwar Craton, Southern India: Evidence for short-lived Neoarchean episodic crustal growth? *Precambrian Research*, *243*, 197–220.

Morag, N., Avigad, D., Gerdes, A., Belousova, E., & Harlavan, Y. (2011). Crustal evolution and recycling in the northern Arabian-Nubian Shield: New perspectives from zircon Lu–Hf and U–Pb systematics. *Precambrian Research*, *186*(1–4), 101–116.

Ngoyi, L. K. K., Liégeois, J.-P., Demaiffe, D., & Dumont, P. (1991). Age tardi-ubendien (Protérozoïque inférieur) des dômes granitiques de l'arc cuprifère zaïro-zambien. *Comptes rendus de l'Académie des sciences. Série 2, Mécanique, physique, chimie, sciences de l'univers, sciences de la terre*, *313*(1), 83–89.

Nutman, A. P., Mohajjel, M., Bennett, V. C., & Fergusson, C. L. (2013). Gondwanan Eoarchean–Neoproterozoic ancient crustal material in Iran and Turkey: Zircon U–Pb–Hf isotopic evidence. *Canadian Journal of Earth Sciences*, *51*(3), 272–285.

Paquette, J.-L., Goncalves, P., Devouard, B., & Nicollet, C. (2004). Micro-drilling ID-TIMS U-Pb dating of single monazites: A new method to unravel complex poly-metamorphic evolutions. Application to the UHT granulites of Andriamena (North-Central Madagascar). *Contributions to Mineralogy and Petrology*, *147*(1), 110–122.

Paquette, J.-L., & Nédélec, A. (1998). A new insight into Pan-African tectonics in the East–West Gondwana collision zone by U–Pb zircon dating of granites from central Madagascar. *Earth and Planetary Science Letters*, *155*(1–2), 45–56.

Paquette, J.-L., Nédélec, A., Moine, B., & Rakotondrazafy, M. (1994). U-Pb, single zircon Pb-evaporation, and Sm-Nd isotopic study of a granulite domain in SE Madagascar. *The Journal of Geology*, *102*(5), 523–538.

Paton, C., Hellstrom, J., Paul, B., Woodhead, J., & Hergt, J. (2011). Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, *26*(12), 2508–2518.

Payne, J. L., Pearson, N. J., Grant, K. J., & Halverson, G. P. (2013). Reassessment of relative oxide formation rates and molecular interferences on in situ lutetium–hafnium analysis with laser ablation MC-ICP-MS. *Journal of Analytical Atomic Spectrometry*, *28*(7), 1068–1079.

Pehrsson, S. J., Eglington, B. M., Evans, D. A., Huston, D., & Reddy, S. M. (2016). Metallogeny and its link to orogenic style during the Nuna supercontinent cycle. *Geological Society, London, Special Publications*, *424*(1), 83–94.

Plavsa, D., Collins, A. S., Foden, J. D., & Clark, C. (2015). The evolution of a Gondwanan collisional orogen: A structural and geochronological appraisal from the Southern Granulite Terrane, South India. *Tectonics*, *34*(5), 820–857. https://doi.org/10.1002/2014TC003706

Plavsa, D., Collins, A. S., Foden, J. F., Kropinski, L., Santosh, M., Chetty, T. R. K., & Clark, C. (2012). Delineating crustal domains in Peninsular India: Age and chemistry of orthopyroxene-bearing felsic gneisses in the Madurai Block. *Precambrian Research*, *198–199*, 77–93.

Plavsa, D., Collins, A. S., Payne, J. L., Foden, J. D., Clark, C., & Santosh, M. (2014). Detrital zircons in basement metasedimentary protoliths unveil the origins of southern India. *Geological Society of America Bulletin*, *126*(5–6), 791–811.

Prakash, D., & Sharma, I. (2011). Metamorphic evolution of the Karimnagar granulite terrane, Eastern Dharwar Craton, south India. *Geological Magazine*, *148*(1), 112–132.

Praveen, M., Santosh, M., Yang, Q., Zhang, Z., Huang, H., Singanenjam, S., & Sajinkumar, K. (2014). Zircon U–Pb geochronology and Hf isotope of felsic volcanics from Attappadi, southern India: Implications for Neoarchean convergent margin tectonics. *Gondwana Research*, *26*(3), 907–924.

Rainaud, C., Master, S., Armstrong, R., & Robb, L. (2005). Geochronology and nature of the Palaeoproterozoic basement in the Central African Copperbelt (Zambia and the Democratic Republic of Congo), with regional implications. *Journal of African Earth Sciences*, *42*(1–5), 1–31.

Raith, M. M., Sengupta, P., Kooijman, E., Upadhyay, D., & Srikantappa, C. (2010). Corundum–leucosome-bearing aluminous gneiss from Ayyarmalai, Southern Granulite Terrain, India: A textbook example of vapor phase-absent muscovite-melting in silica-undersaturated aluminous rocks. *American Mineralogist*, *95*(7), 897–907.

Ring, U., Kröner, A., Layer, P., Buchwaldt, R., & Toulkeridis, T. (1999). Deformed A-type granites in northern Malawi, east-central Africa: Pre-or syntectonic? *Journal of the Geological Society*, *156*(4), 695–714.

Ring, U., Kröner, A., & Toulkeridis, T. (1997). Palaeoproterozoic granulite-facies metamorphism and granitoid intrusions in the Ubendian-Usagaran Orogen of northern Malawi, east-central Africa. *Precambrian Research*, *85*(1–2), 27–51.

Roig, J., Tucker, R., Delor, C., Peters, S., & Théveniaut, H. (2012). *Carte géologique de la République de Madagascar à 1/1 000 000, scale 1:1,000,000*.

Sarma, D. S., McNaughton, N. J., Belusova, E., Ram Mohan, M., & Fletcher, I. R. (2012). Detrital zircon U–Pb ages and Hf-isotope systematics from the Gadag Greenstone Belt: Archean crustal growth in the western Dharwar Craton, India. *Gondwana Research*, *22*(3–4), 843–854.

Schenk, V., & Appel, P. (2001). Anti-clockwise P–T path during ultrahigh-temperature (UHT) metamorphism at ca. 1050 Ma in the Irumide Belt of Eastern Zambia: Berichte der Deutschen Mineralogischen Gesellschaft. *Beihefte zum European Journal of Mineralogy*, *13*(161), 99–121.

Scherer, E., Münker, C., & Mezger, K. (2001). Calibration of the lutetium-hafnium clock. *Science*, *293*(5530), 683–687.

Schmitt, R. S., de Araújo Fragoso, R., & Collins, A. S. (2018). Suturing Gondwana in the Cambrian: The orogenic events of the final amalgamation. In *Geology of Southwest Gondwana* (pp. 411–432): Springer.

Schofield, D. I., Thomas, R. J., Goodenough, K. M., De Waele, B., Pitfield, P. E. J., Key, R. M., et al. (2010). Geological evolution of the Antongil Craton, NE Madagascar. *Precambrian Research*, *182*(3), 187–203.

Sláma, J., Košler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., et al. (2008). Plešovice zircon—a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, *249*(1), 1–35.

Teale, W., Collins, A. S., Foden, J., Payne, J. L., Plavsa, D., Chetty, T. R. K., et al. (2011). Cryogenian (~830Ma) mafic magmatism and metamorphism in the northern Madurai Block, southern India: A magmatic link between Sri Lanka and Madagascar? *Journal of Asian Earth Sciences*, *42*(3), 223–233.

Thomas, R. J., De Waele, B., Schofield, D. I., Goodenough, K. M., Horstwood, M., Tucker, R., et al. (2009). Geological evolution of the Neoproterozoic Bemarivo Belt, northern Madagascar. *Precambrian Research*, *172*(3–4), 279–300.

Thomas, R. J., Spencer, C., Bushi, A. M., Baglow, N., Boniface, N., de Kock, G., et al. (2016). Geochronology of the central Tanzania Craton and its southern and eastern orogenic margins. *Precambrian Research*, *277*, 47–67.

Tucker, R., Ashwal, L., Handke, M., Hamilton, M., Le Grange, M., & Rambeloson, R. (1999). U-Pb geochronology and isotope geochemistry of the Archean and Proterozoic rocks of north-central Madagascar. *The Journal of Geology*, *107*(2), 135–153.

Tucker, R. D., Kusky, T. M., Buchwaldt, R., & Handke, M. J. (2007). Neoproterozoic nappes and superposed folding of the Itremo Group, west-central Madagascar. *Gondwana Research*, *12*(4), 356–379.

Tucker, R. D., Roig, J.-Y., Delor, C., Amelin, Y., Goncalves, P., Rabarimanana, M., et al. (2011). Neoproterozoic extension in the Greater Dharwar Craton: A reevaluation of the "Betsimisaraka suture" in Madagascar. *Canadian Journal of Earth Sciences*, *48*(2), 389–417.

Tucker, R. D., Roig, J. Y., Macey, P. H., Delor, C., Amelin, Y., Armstrong, R. A., et al. (2011). A new geological framework for south-central Madagascar, and its relevance to the "out-of-Africa" hypothesis. *Precambrian Research*, *185*(3–4), 109–130.

Upadhyay, D., Gerdes, A., & Raith, M. M. (2009). Unraveling sedimentary provenance and tectonothermal history of high-temperature metapelites, using zircon and monazite chemistry: A case study from the Eastern Ghats Belt, India. *The Journal of Geology*, *117*(6), 665–683.

10.1029/2020TC006498

Vermeesch, P., Resentini, A., & Garzanti, E. (2016). An R package for statistical provenance analysis. *Sedimentary Geology*, *336*, 14–25.

Voarintsoa, N. R. G., Raveloson, A., Barimalala, R., & Razafindratsima, O. H. (2019). Malagasy' or 'Madagascan'? Which English term best reflects the people, the culture, and other things from Madagascar? *Scientific African*, *4*, e00091.

Vrána, S., Kachlık, V., Kröner, A., Marheine, D., Seifert, A., Žáček, V., & Babůrek, J. (2004). Ubendian basement and its late Mesoproterozoic and early Neoproterozoic structural and metamorphic overprint in northeastern Zambia. *Journal of African Earth Sciences*, *38*(1), 1–21.

Wang, J.-Y., Santosh, M., Jayananda, M., & Aadhiseshan, K. (2020). Bimodal magmatism in the Eastern Dharwar Craton, southern India: Implications for Neoarchean crustal evolution. *Lithos*, *354*, 105336.

Woodhead, J. D., & Hergt, J. M. (2005). A preliminary appraisal of seven natural zircon reference materials for in situ Hf isotope determination. *Geostandards and Geoanalytical Research*, *29*(2), 183–195.

Woodhead, J. D., Hergt, J., Shelley, M., Eggins, S., & Kemp, R. (2004). Zircon Hf-isotope analysis with an excimer laser, depth profiling, ablation of complex geometries, and concomitant age estimation. *Chemical Geology*, *209*(1–2), 121–135.

Yang, Q.-Y., & Santosh, M. (2015). Zircon U–Pb geochronology and Lu–Hf isotopes from the Kolar greenstone belt, Dharwar Craton, India: Implications for crustal evolution in an ocean-trench-continent transect. *Journal of Asian Earth Sciences*, *113*, 797–811.

Yu, G., & Yu, M. G. (2018). *Package 'scatterpie'*: R Package Version 1.2.