Proterozoic basin evolution and tectonic geography of Madagascar during the Nuna/Columbia Supercontinent

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Abstract

Madagascar hosts several Paleoproterozoic sedimentary sequences that are key to unravelling 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 > 1700 Ma, with major zircon age peaks at c. 2500 Ma, c. 2000 Ma and c. 1850 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 against the Tanzania Craton of East Africa.

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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. 1700 Ma show Madagascar, the Tanzania Craton and the Southern Granulite Terrane of India are contiguous

ABSTRACT

Madagascar hosts several Paleoproterozoic sedimentary sequences that are key to unravelling 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 > 1700 Ma, with major zircon age peaks at c. 2500 Ma, c. 2000 Ma and c. 1850 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 against the Tanzania Craton of East Africa.

1. INTRODUCTION

Reconstructing 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 assessment of their correlation. The Neoproterozoic to Cambrian amalgamation of central Gondwana, which formed the East African Orogen, has been more extensively studied in recent years and provides important constraints on global plate reconstruction models (Merdith et al., 2017a; Merdith et al., 2017b). The East African Orogen resulted from the collision of Africa, Madagascar and India (Collins and Pisarevsky, 2005; Fritz et al., 2013; Johnson et al., 2011; Merdith et al., 2017a; 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 sedimentary groups in Madagascar. De Waele et al. (2011) proposed that the Itremo, Maha and Sahantaha groups in Madagascar are equivalent sedimentary sequences. Boger et al. (2014); Boger et al. (2019) linked the Anosyen Domain of southern Madagascar to the Itremo Group. The validity of these correlations, and likelihood that these represent contiguous Paleoproterozoic–Mesoproterozoic depositional systems, governs the paleogeographic reconstruction of this extensive part of Nuna and its tectono-geographic interpretation.

Similarities in Paleoproterozoic sedimentary rocks of the Itremo Group in central Madagascar and the Muva Supergroup in the Tanzania Craton in Africa have been recognised for some time (Alessio et al., 2019; Cox et al., 1998; Cox et al., 2004; Fitzsimons and Hulscher, 2005). Similarities between the Itremo Group and the Cuddapah Basin of eastern India have also been proposed (Tucker et al., 2011a), as have similarities between the Itremo Group and the Southern Granulite Terrane of India

(Collins et al., 2012; Collins et al., 2007b; 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 and Mitchell, 2011; Pehrsson et al., 2016).

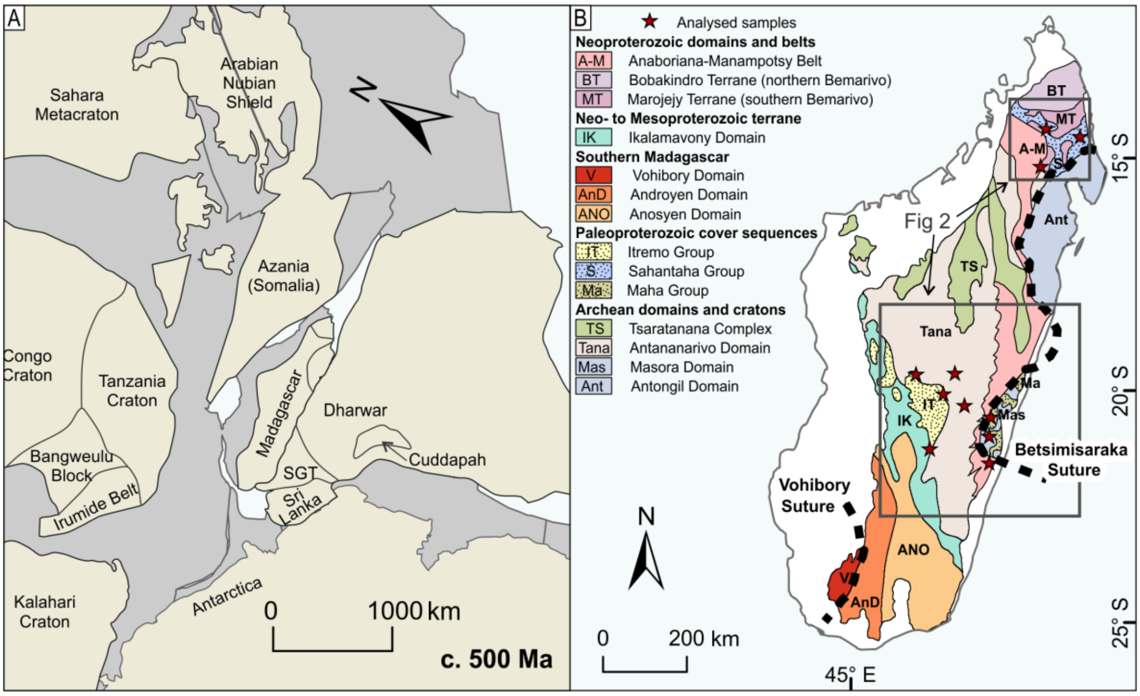

Figure 1 a) Tectonic map of central Gondwana made using GPlates exported geometries from Merdith et al. (2017a) in ArcGIS; projected in Hotine Oblique Mercator with Madagascar in the centre (reconstructed position, longitude=-75 and latitude=+40).; b) Present day map of the geological domains of Madagascar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

1.1. Regional geology

Madagascar is made up of several domains that contain rocks dated from Archean to Neoproterozoic (Figure 1b). Central Madagascar consists of the Antananarivo Domain, which is composed of c. 2500 Ma magmatic gneisses of the Betsiboka Suite (Collins and 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. 3100 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 et al., 2011a). 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. 1700 Ma (Cox et al., 1998; Cox et al., 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. 1000 Ma (Tucker et al., 2011b).

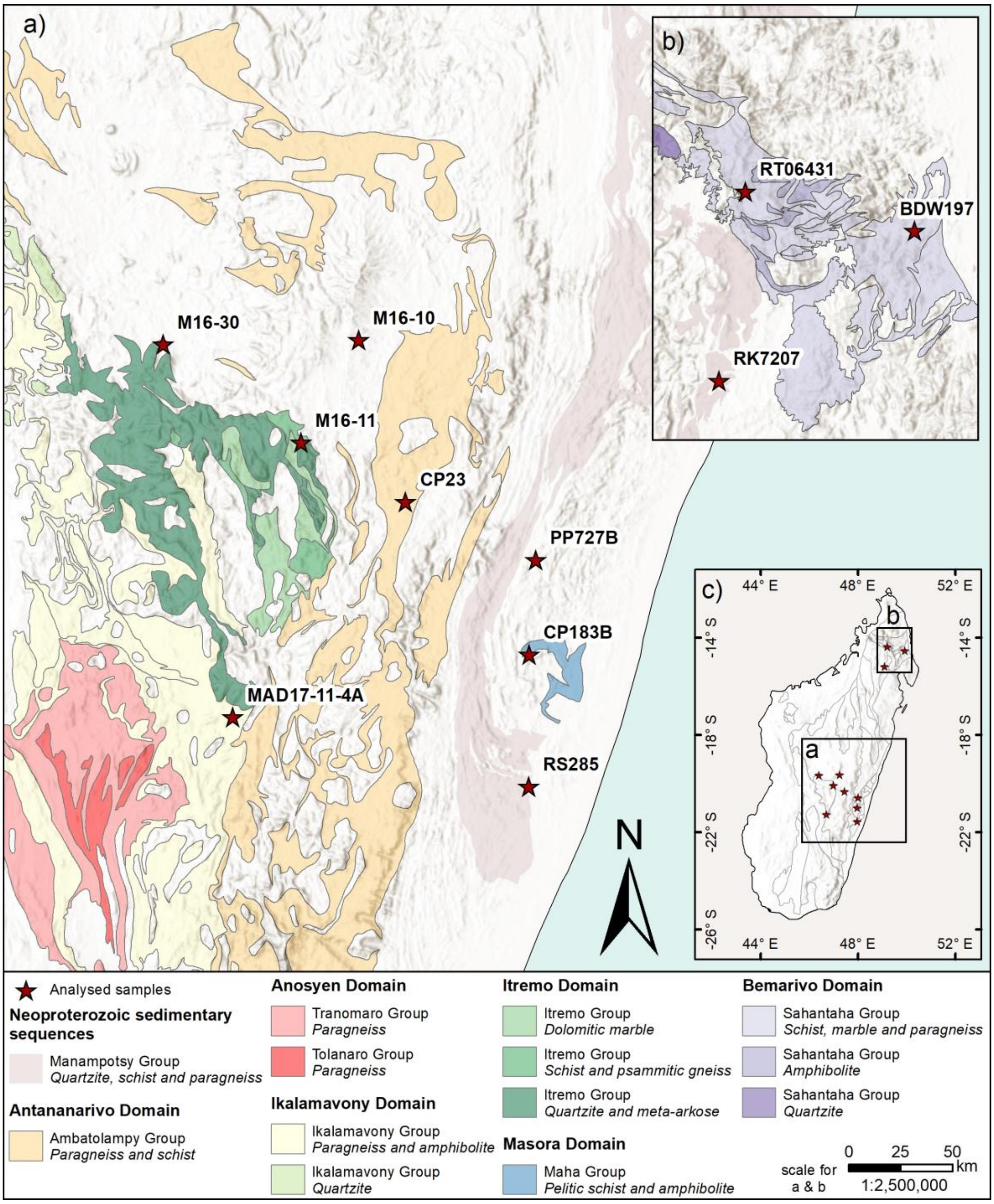

Figure 2 Geological map of Madagascar modified after Roig et al. (2012); a) central Madagascar showing major Proterozoic sedimentary groups; b) geological map of northern Madagascar including the Sahantaha Group; c) geological terranes of Madagascar showing insets for maps a and b.

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 and Schenk, 2008). The Anosyen and Androyen domains contain the Tranomaro, Tolanaro and Mangoky groups (Figure 2), that like the Itremo Group, also have c. 1700 Ma maximum depositional ages (Boger et al., 2014).

A series of Neoproterozoic 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 (Cox et al., 2004). The c. 1080–980 Ma Dabolava Suite (Archibald et al., 2017a) 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 closely reflect the ages of the intrusive Marasavoa and Vohitany suites.

Because it is difficult to put absolute age constraints on sedimentary sequences, there is some ambiguity over the nomenclature 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 spectra and ages; and should therefore be considered separately. 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 and Windley, 2002). 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 summarised 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 et al., 2003a), 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 et al., 2003a; 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 and 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; Cox et al., 2004; Fitzsimons and Hulscher, 2005). The age distribution of the Itremo Group closely matches the Tanzanian Craton but has little resemblance to sedimentary rocks in the dominantly Archean Dharwar Craton (see Collins et al., 2015). In subsequent years, this has been challenged and other datasets 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 known group. Here we address this with new data and compare detrital zircon spectra and their Hf isotope compositions for a range of sedimentary sequences in Madagascar, Africa and India.

2. ANALYTICAL 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 and REE/trace element geochronology was undertaken at the University of Adelaide using an Agilent 7900x ICP-MS with attached ASI Resolution excimer 193nm 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 and ^{238}U were measured. Each analysis comprised a 20s background and 30s ablation. GEMOC GJ-1 zircon (TIMS normalising 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. 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). U–Pb and REE data are provided in Supplementary A.

2.2. Zircon Lu–Hf

Near concordant U–Pb spots were additionally analysed 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. Zircons were ablated in a helium atmosphere that was then mixed with argon upstream of the ablation cell.

Zircon data reduction were carried out using the HfTRAX Excel macro (Payne et al., 2013). Data were normalised 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 analysed 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 (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 1.865x10^{-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)*10000) and are reported at the 2σ level. Isotopic data are provided in Supplementary A.

3. RESULTS

3.1. Sample descriptions

Three quartzite samples from the Itremo Group and one sample from the Ambatolampy Group (Figure 2) were collected and analysed for U–Pb, trace element geochemistry and Lu–Hf isotopes. The aim was to have 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 analysed for Lu–Hf isotopes in this study. Sample descriptions and location information are summarised in Table 1. 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).

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 analysed in this study. Age uncertainties are 2σ.*

Sample ID	Lithology	Geological unit	Latitude (WGS84)	Longitude (WGS84)	Maximum depositional age	U–Pb data source
M16-10	Quartzite	Ambatolampy Group	-19.62080	47.23781	1835 ± 86 Ma	This study
M16-11	Quartzite	Itremo Group	-20.06404	46.98979	1774 ± 90 Ma	This study
M16-30	Quartzite	Itremo Group	-19.64042	46.39433	1827 ± 91 Ma	This study
MAD-17-11-4A	Quartzite	Itremo Group	-21.21432	46.66460	1727 ± 89 Ma	This study
RK7207	Quartzite	Anaboriana-Manampotsy	-15.17330	49.08520	591 ± 17 Ma *	BGS et al. 2008
RS285	Quartzite	Anaboriana-Manampotsy	-21.55100	47.97240	765 ± 15 Ma *	BGS et al. 2008
CP23	Quartzite	Anaboriana-Manampotsy	-20.32070	47.44030	1001 ± 44 Ma	BGS et al. 2008
PP727B	Quartzite	Maha Group	-20.57110	48.00350	1742 ± 19 Ma	De Waele et al. 2011
CP183B	Quartzite	Maha Group	-20.98050	47.97490	1801 ± 18 Ma	De Waele et al. 2011
BDW197	Quartzite	Sahantaha Group	-14.52460	49.93010	1733 ± 18 Ma	BGS et al. 2008
RT06431	Quartzite	Sahantaha Group	-14.35410	49.19930	1728 ± 33 Ma	BGS et al. 2008

3.2. Zircon U–Pb and trace element geochemistry

The aim of analysing 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 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 profiles are provided in Supplementary A for completeness, however, we do not consider these data further.

Three quartzite samples analysed from the Itremo Group and one sample from the Ambatolampy Group contain near-concordant (<10%) detrital zircons ranging from c. 3485 to c. 1727 Ma (Figure 3). They contain similar age spectra with dominant peaks at c. 2500 Ma, c. 2200 Ma and c. 1800 Ma. Their maximum depositional ages are given in Table 1.

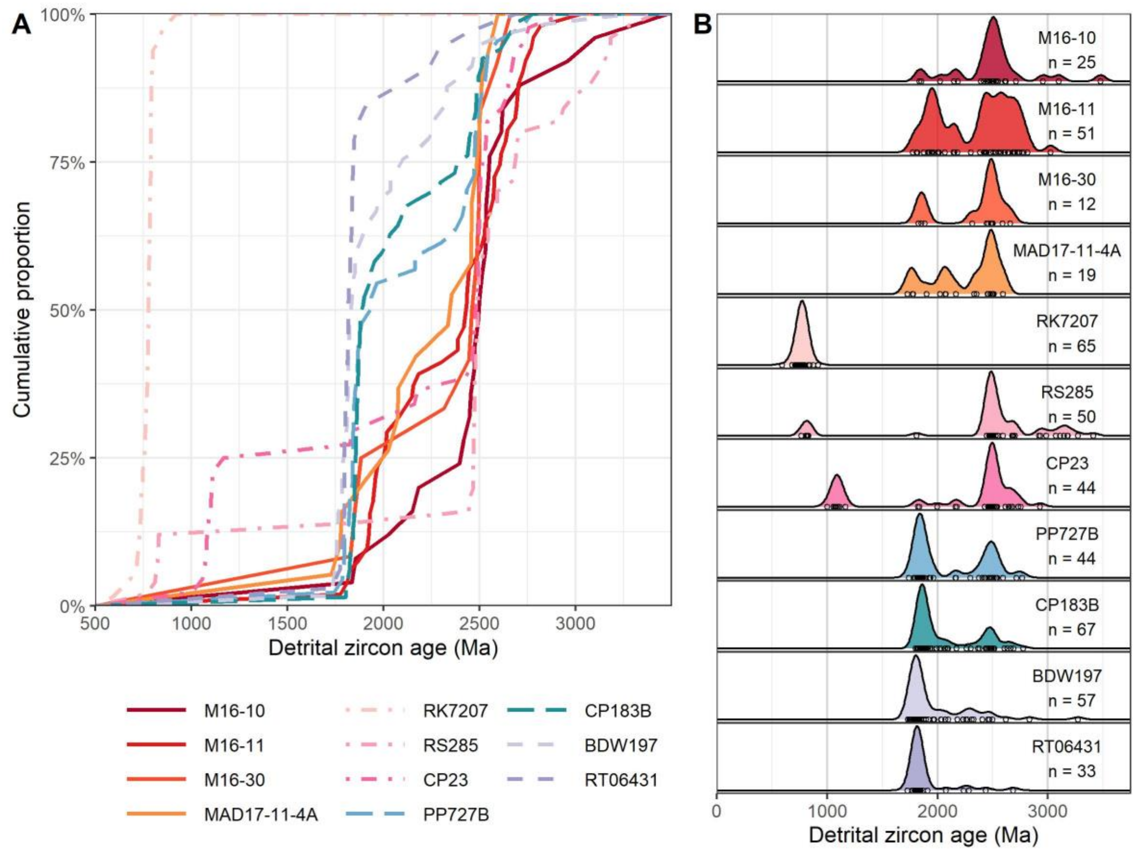

Figure 3 Zircon U–Pb data for metasedimentary units in Madagascar. Plots made in R using data that are within 10% concordance. A) data plotted on cumulative proportion plots showing subtle differences between the Itremo Group and the Sahantaha and Maha groups; b) kernel density estimate (KDE) plots of detrital zircon ages. have 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).

3.3. Zircon Lu–Hf analysis

Itremo Group and Ambatolampy Group samples with zircon ages of c. 2500 Ma are dominantly juvenile to moderately evolved; with $\varepsilon_{Hf}(t)$ values ranging from +5 to -14 (Figure 4a). Zircons with ages of c. 2200–1800 Ma are moderately evolved; with $\varepsilon_{Hf}(t)$ values ranging from +5 to -10. Zircon analyses with ages of c. 1800–1700 Ma are exclusively evolved, with $\varepsilon_{Hf}(t)$ ranging from 0 to -14.

Age equivalent analyses from the Maha Group have $\varepsilon_{Hf}(t)$ values ranging from +5 to -11 for c. 2500 Ma zircons, and +4 to -6 for c. 2200–1800 Ma zircons, and +2 to -10 for c. 1800–1700 Ma zircons (Figure 4). Age equivalent analyses from the Sahantaha Group have $\varepsilon_{Hf}(t)$ values ranging from +6 to -10 for c. 2500 Ma zircons, 0 to -4 for c. 2200–1800 Ma zircons, and -2 to -10 for c. 1800–1700 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. 3400–3000 Ma that have $\varepsilon_{Hf}(t)$ values ranging from +3 to -3. Zircons from this sample with ages of c. 2500 Ma have $\varepsilon_{Hf}(t)$ values ranging from +2 to -13. A single c. 1809 Ma zircon has an $\varepsilon_{Hf}(t)$ value of -2. Sample CP23 has c. 2500 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from +6 to -8, c. 2200–1800 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from -4 to -9, and c. 1100 Ma zircons with $\varepsilon_{Hf}(t)$ values ranging from +3 to -8.

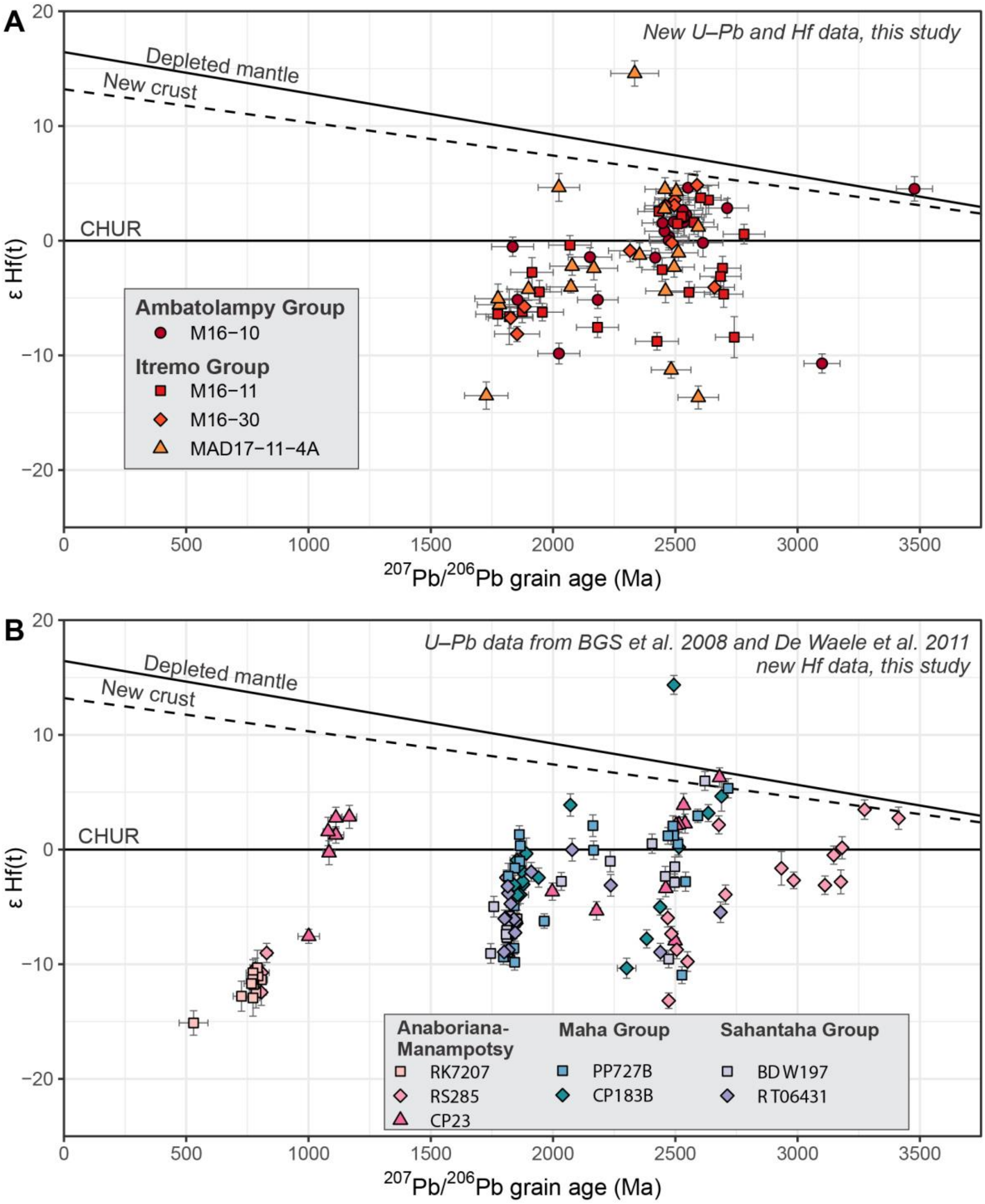

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Figure 4 New zircon Lu–Hf isotope data for metasedimentary units in Madagascar. A) New U–Pb and Hf data, and b) Samples with U–Pb data from BGS-USGS-GLW (2008) and De Waele et al. (2011), and new Hf data collected in this study. Depleted Mantle line calculated with εHf(t) = 16.44 at time 0 Ma and εHf(t) = 0 at 4560 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 εHf(t) = 13.2 at time 0 Ma and εHf(t) = 0 at time 4560 Ma (Dhuime et al., 2011).

4. DISCUSSION

We have compiled an extensive database of published data 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 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. References for the data used are tabulated in Table 2.

The database of detrital zircon data are filtered for data within 10% of concordance and analyses that have uncertainties of 10% or less. Only samples that contain 15 or more grains after filtering are included.

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 et al. (2003b); Cox et al. (1998); Cox et al. (2004); De Waele et al. (2011); Fitzsimons and Hulscher (2005); Tucker et al. (2011a); Tucker et al. (2011b).
Detrital	Africa	Alessio et al. (2019); Alessio et al. (2018); Batumike et al. (2009); Batumike et al. (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 et al. (2007a); 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); Armistead et al. (2020); Bauer et al. (2011); BGS-USGS-GLW (2008); Buchwaldt et al. (2003); Collins et al. (2012); Collins et al. (2003b); 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); Tucker et al. (2011a); Tucker et al. (2007); Tucker et al. (2011b);
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. (2020); Jayananda et al. (2015); Kröner et al. (2012); Kumar et al. (2017); Maibam et al. (2011); Mohan et al. (2014); Plavsa et al. (2015); Plavsa et al. (2012); Praveen et al. (2014); Wang et al. (2020); Yang and Santosh (2015)

4.1. Correlation of sedimentary 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. 1700 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 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. 2500 Ma peak compared to the younger peaks; the Maha Group has a smaller c. 2500 Ma peak and higher c. 1800 Ma peak; and the Sahantaha Group has a dominant c. 1800 Ma peak with minor older peaks (Figure 3). This is apparent on the cumulative proportion plots (Figure 3a and Figure 5c), where Itremo and Ambatolampy group samples consistently plot below the other samples, suggesting that they are sourced 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, therefore, that these samples were deposited within the same sedimentary system and sourced 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 samples deposited within the Greater Itremo Basin have maximum depositional ages between c. 1875 Ma and c. 1700 Ma (Figure 5). However, one sample from southern Madagascar has a maximum depositional age of 1593 ± 68 Ma (2σ), with an additional grain younger than c. 1700

Ma. The youngest significant cluster of dates within the database is at c. 1700 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 a late Paleoproterozoic basin. An alternative interpretation to this, is that the Greater Itremo Basin existed in the Mesoproterozoic and possibly even through to the early Neoproterozoic (e.g. Boger et al., 2014; Boger et al., 2019). However, for this to have occurred, sediments within the basin would have exclusively sourced zircons that formed hundreds of millions of years earlier than when they were deposited, with no near-contemporaneous sources. 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. In addition, stromatolite morphology and carbon isotope data from carbonates in the Itremo Group are consistent with them being deposited in the Paleoproterozoic (Cox et al., 2004). Based on these factors, a model whereby the Greater Itremo Basin was deposited shortly after their maximum depositional ages, during the late Paleoproterozoic, is most likely.

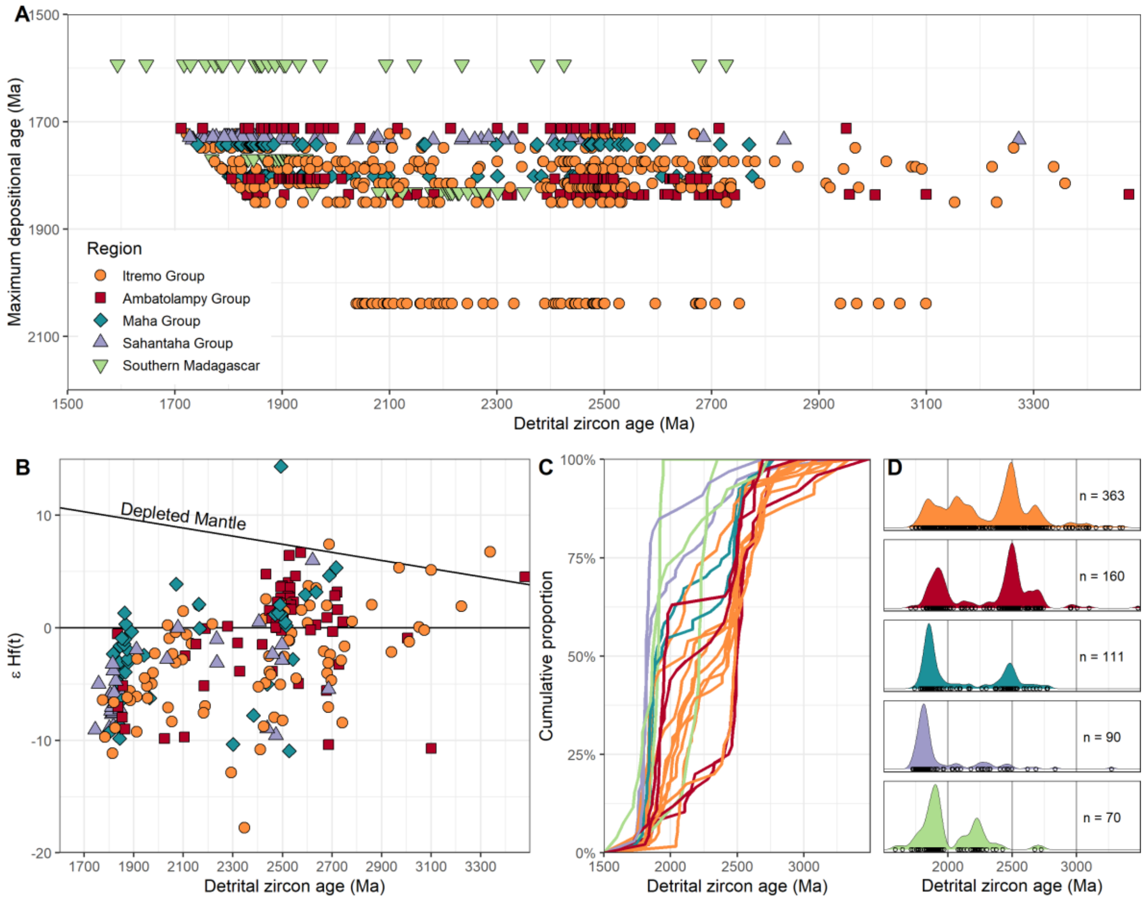

Figure 5 Comparison of Paleoproterozoic detrital zircon samples from Madagascar, symbolised by Group/Region. Data filtered to be within 10% of concordance and includes samples that contain at least 20 grain ages within 10% of concordance. a) Maximum depositional age vs. grain age, colour legend applies to all plots; b) εHf(t) vs. 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. Dataset includes new data from Figure 4 as well as data from Supplementary B.

4.1.2. Neoproterozoic sequences

Several sedimentary 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. The majority of samples from these interpreted Neoproterozoic sequences have maximum depositional ages between c. 790 Ma 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 sourced 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 et al., 2003b). The deposition of these groups therefore occurred during the Neoproterozoic, between c. 700 Ma and c. 600 Ma.

The Linta Group in the Vohibory Domain has detrital zircon dates between c. 1068 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 sources.

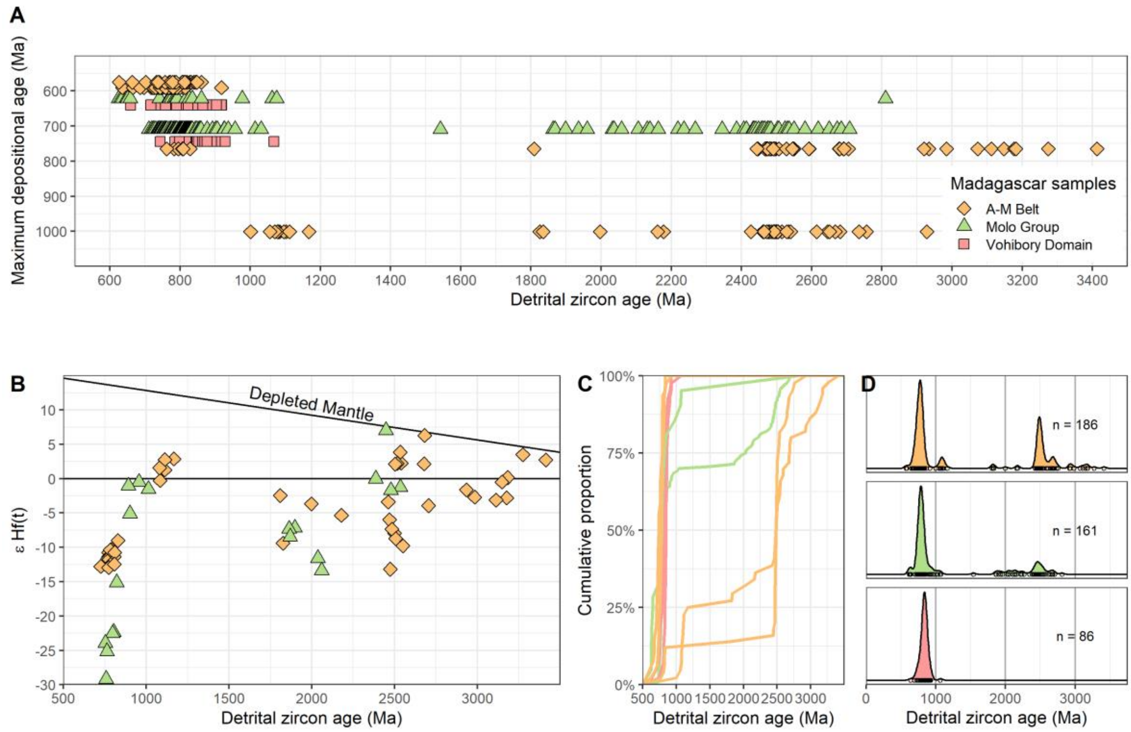

Figure 6 Comparison of Neoproterozoic detrital zircon samples from Madagascar, symbolised by Group/Region. Data filtered to be within 10% of concordance and includes samples that contain at least 20 grain ages within 10% of concordance. A-M Belt = Anaboriana-Manampotsy Belt. a) Maximum depositional age vs. grain age, colour legend applies to all plots; b) εHf(t) vs. 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. Dataset 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 spectra that share some similarities with those in East Africa, Cuddapah Basin of eastern India and the Southern Granulite Terrane of southern India (Figure 7; Figure 8a,b). 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 multi-dimensional scaling plots for detrital data with maximum depositional ages >1500 Ma (Figure 7). From Figure 7 and Figure 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. 1850–1750 Ma. The slight differences in age peak heights likely reflect the proximity of the depositional environment to the source rocks. For example, c. 2500 Ma magmatic rocks in Madagascar are likely a major source for c. 2500 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. 2500 Ma zircons. The abundance of c. 2020 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 sourced 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. 1880–1850 Ma, but with detrital zircon ages as young as c. 1800 Ma (De Waele and Fitzsimons, 2007). The Muva Supergroup is intruded by c. 1650–1550 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. 1900 Ma; older than those zircons in the Itremo Group and East Africa. These contain dominant zircon age peaks at c. 2650 Ma, 2425 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 multi-dimensional scaling plot (Figure 7) also indicates that samples from the Greater Itremo Basin, East Africa and Southern Granulite Terrane are similar (Figure 7).

The Cuddapah Basin samples are predominantly younger than c. 1850 Ma, with the majority of maximum depositional ages and zircon grain ages between c. 1850 and 1550 Ma (Figure 8b). The main detrital zircon peaks for the Cuddapah Basin are c. 1640 and c. 2520 Ma. The 1640 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 sedimentary 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 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.

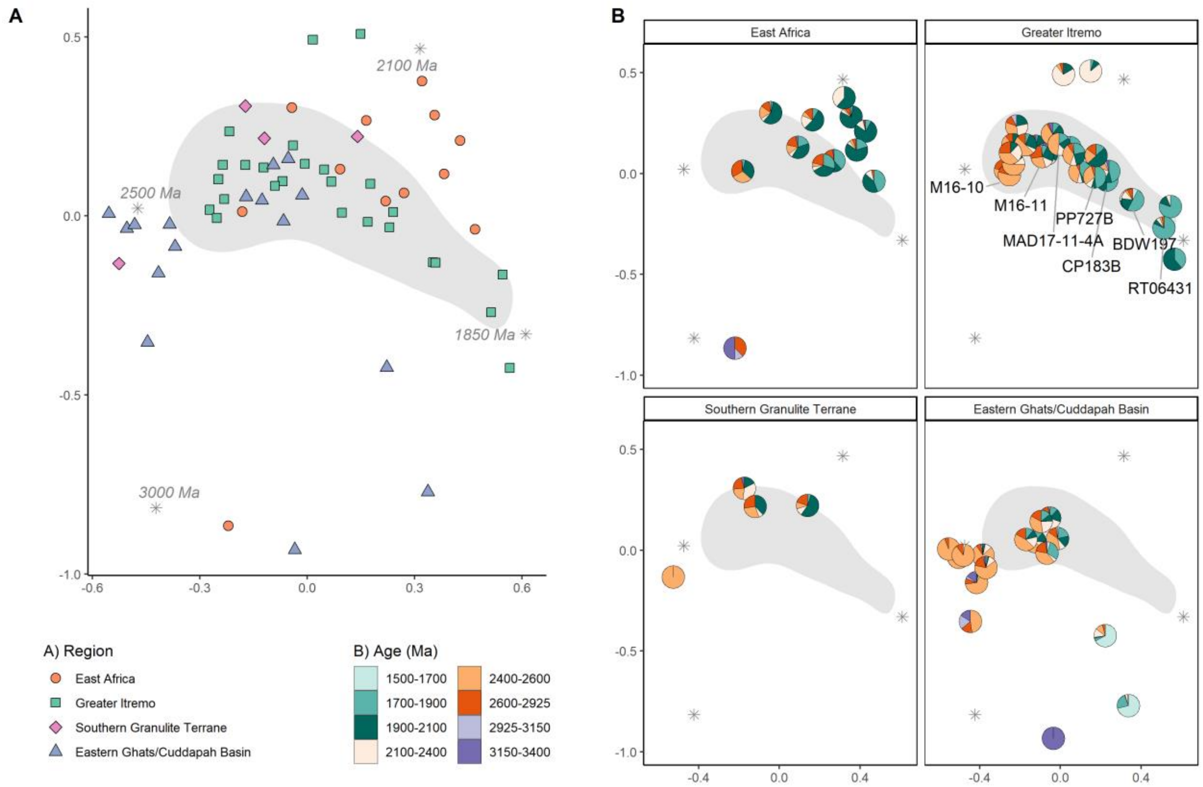

Figure 7 Multi-dimensional scaling (MDS) plots of detrital samples showing the dissimilarity between samples from different regions. Samples with maximum depositional ages > 1500 Ma and at least 15 grains within 10% of concordance are included. MDS calculated using the 'Provenance' package (Vermeesch et al., 2016) and pie charts plotted using the 'scatterpie' package (Yu and Yu, 2018). A) All MDS data plotted together for the four key regions assessed. Asterisk symbols indicate synthetic datasets (generated as multivariate normal random distributions of 1000 numbers simulated with mean age (1850 Ma, 2100 Ma, 2500 Ma and 3000 Ma) and variance of 50 Ma) for key ages to show the relative mixing between age groups. Grey 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 analysed in this study are labelled. Grey contour is the same as in A.

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 might not reflect the actual source rocks being eroded at the time. Source protoliths may not be magmatic in nature, indeed the maturity of the quartzites in the Greater Itremo Basin lend support to a multi-phase 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 crystallisation ages to compare with our detrital zircon dataset (Figure 8). Detrital zircon source regions for the Itremo Group outside of Madagascar have been proposed in east Africa (Cox et al., 1998; Cox et al., 2004; Fitzsimons and Hulscher, 2005) and India (Tucker et al., 2011a). These proposals are discussed in light of currently available data below.

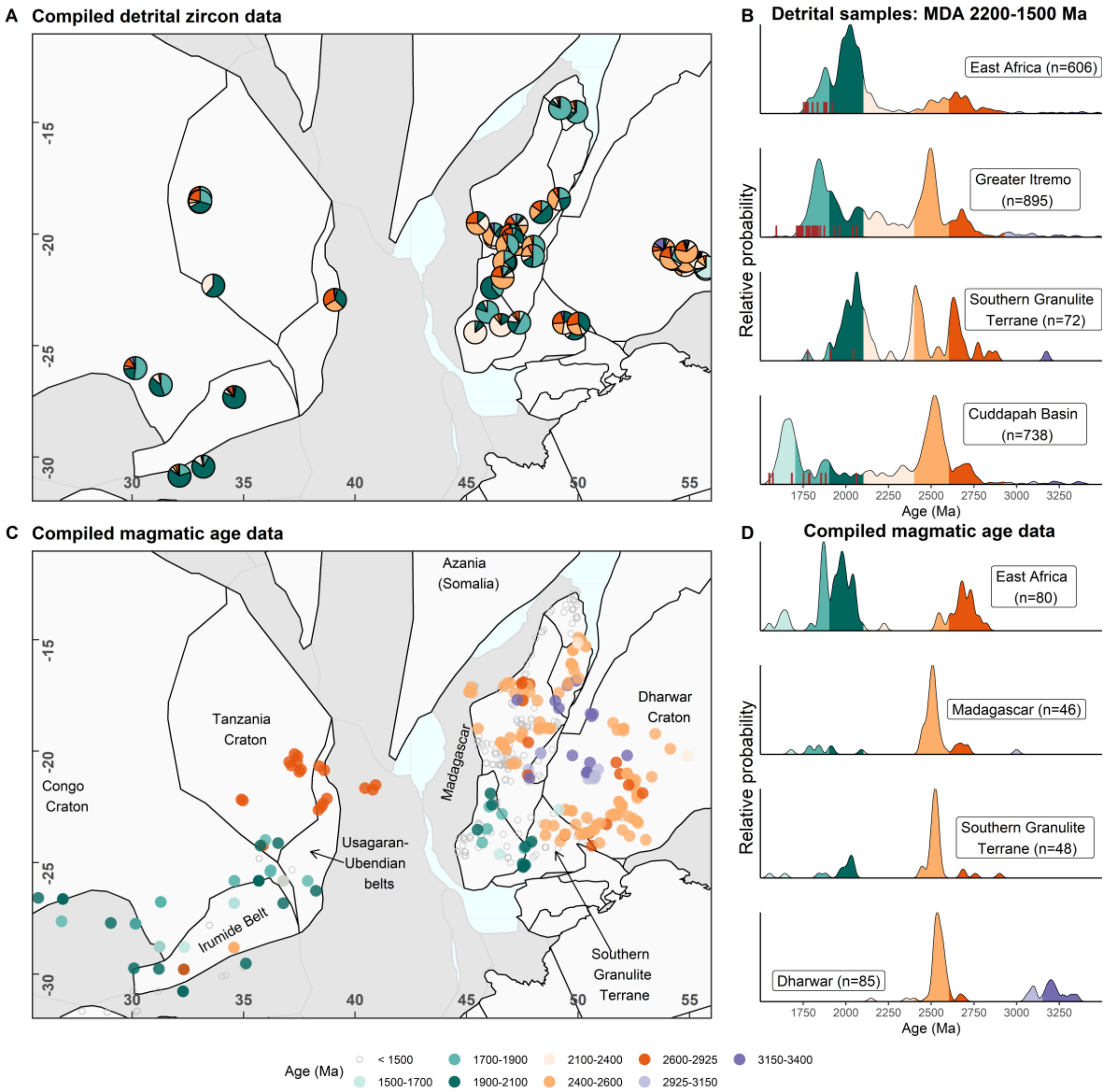

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Figure 8 Comparison of compiled detrital zircon and magmatic data for Africa, Madagascar and India. A) Map reconstructed to c. 500 Ma with pie charts representing detrital zircon age distributions. Pie charts plotted using the 'scatterpie' package in R (Yu and 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. 2200 and c. 1500 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, coloured by age. D) Kernel Density Estimate plots for compiled magmatic data. Tectonic reconstruction in A and C is from Merdith et al. (2017a).

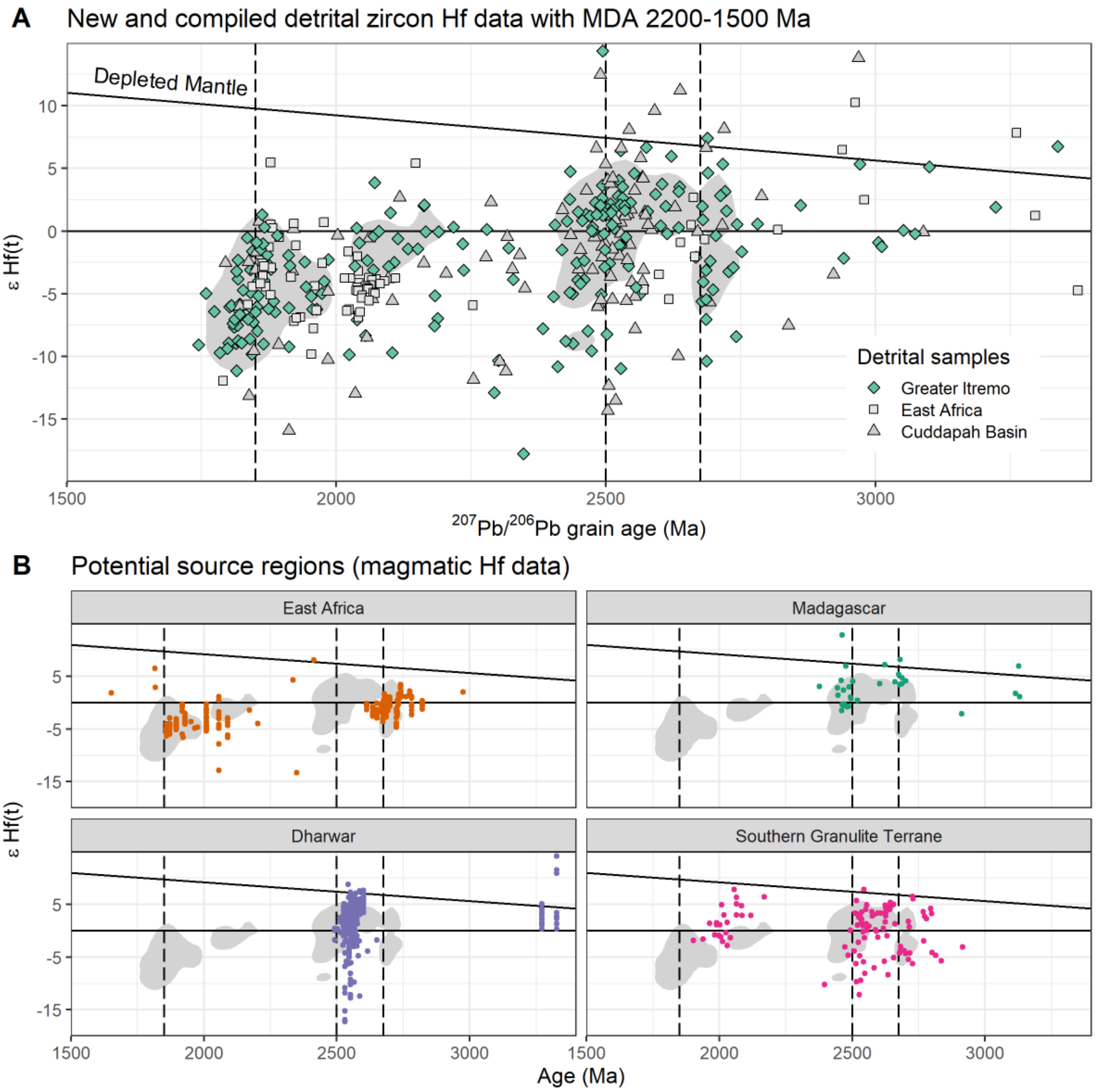

Figure 9 Comparison of detrital zircon Hf data with potential magmatic source regions; a) Detrital Hf isotopic data for samples with maximum depositional ages (MDA) between 2200 and 1500 Ma. Data for Greater Itremo Basin includes all data in Figure 5b. Grey contour is for Greater Itremo data only; b) Magmatic zircon Hf data from potential source regions, underlain with the grey contour from A.

The c. 2650 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. 2500 Ma is indistinguishable from the central Madagascar peak (Figure 8). It's 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. 2000–1750 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 sedimentary and magmatic rocks in Madagascar and East Africa suggest that these regions were juxtaposed during the Paleoproterozoic/early Mesoproterozoic. The abundant c. 2500 Ma detritus in East Africa sedimentary 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 with maximum depositional ages that are slightly older, has a significant c. 2100–1900 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). However, rocks of this age are not found in the adjacent Dharwar Craton. Given the similarities in both magmatic and detrital zircon 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 sedimentary sequences in East Africa and we suggest that they sourced 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 sedimentary 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 et al. (2017a) *GPlates* model; reconstructing the model based on our interpretation at c. 1700 Ma. Our georeferenced age database was reconstructed according to this modification and exported to ArcGIS where we then interpolated the data. We used natural neighbour interpolation of age data with a consistent legend for both plots for easy comparison.

Maximum depositional ages for sedimentary 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. Similar-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 sedimentary 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. Although 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 similar-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 can't rule this hypothesis out with the data here, yet 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 non-statistically tested pattern matching 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 and Pisarevsky, 2005; Collins and Windley, 2002; Cox et al., 2004; Fitzsimons and Hulscher, 2005). These correlations do not support the Greater Dharwar model (Tucker et al., 2011a; Tucker et al., 2011b) for the Paleoproterozoic and Mesoproterozoic. Furthermore, 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 and Pisarevsky, 2005). Madagascar later collided back against East Africa with Stenian–Cryogenian arc terranes marking the Vohibory suture (Archibald et al., 2017a; Archibald et al., 2017b; Jöns and Schenk, 2008). Shortly thereafter, Madagascar and India collided along the Ediacaran–Cambrian Betsimisaraka Suture (Armistead et al., 2019; Armistead et al., 2020; Collins, 2006; Fritz et al., 2013; Merdith et al., 2017a).

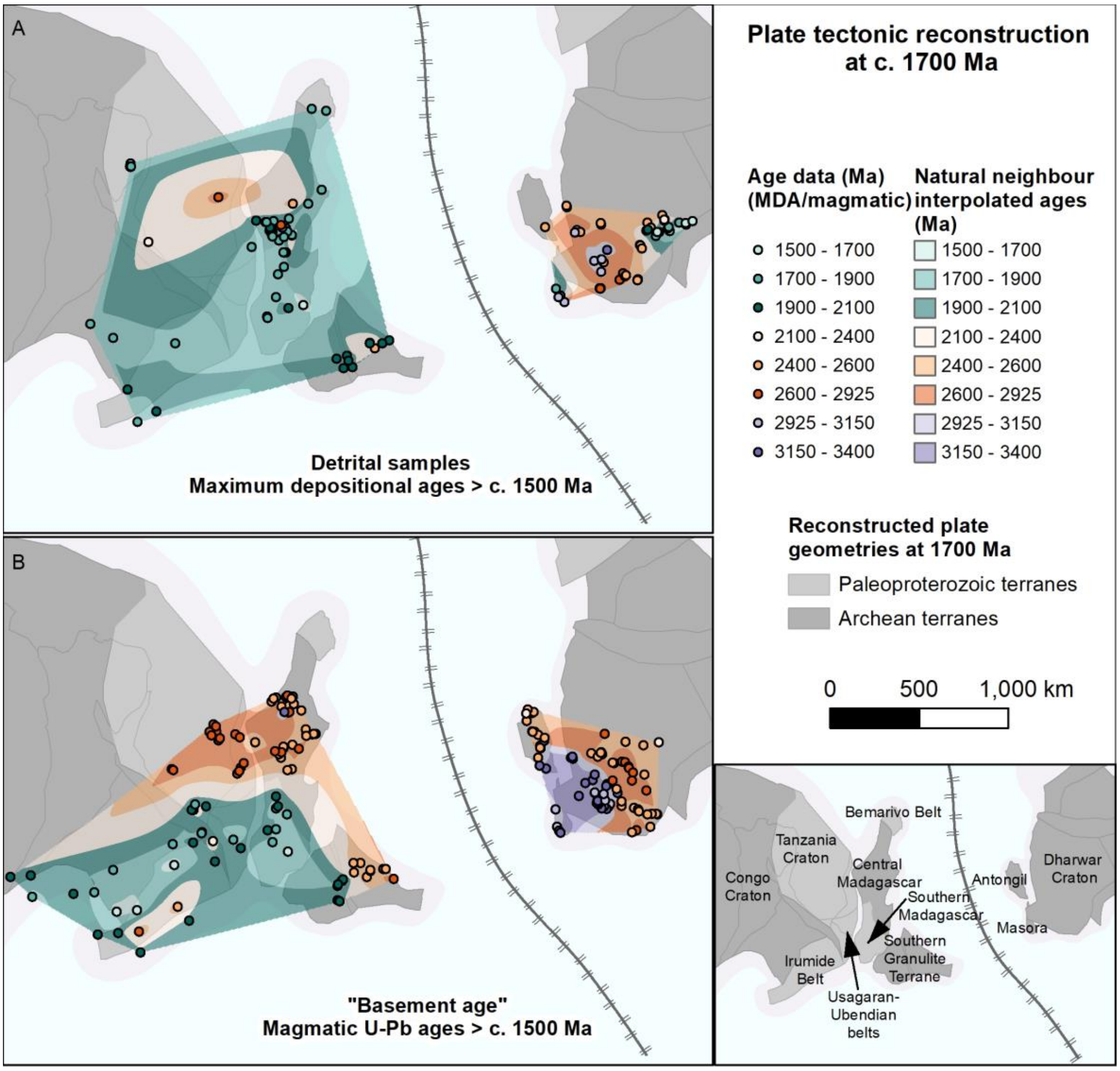

Figure 10 Interpreted reconstruction at 1700 Ma, with our U–Pb zircon magmatic and detrital database mapped and interpolated. All detrital samples with maximum depositional ages > c. 1500 Ma and magmatic samples with zircon U–Pb ages > c. 1500 Ma are included. The boundary separating the Africa-Madagascar-Southern India data and the Dharwar-Antongil-Masora data is arbitrary and simply indicates that we interpret these regions to be separate at this time.

The modelling highlights some regions where further data collection would be beneficial to increase the confidence of this reconstruction. More data from the Southern Granulite Terrane would be useful, particularly given the maximum depositional age differences. Further detrital studies of the Tanzania Craton, Usagaran-Ubendian belts and the Irumide Belt would also be useful for increasing the resolution of the interpolation in this region. Figure 9 also highlights regions where there are limited Hf isotope data. To our knowledge, there are no published Hf isotope data for detrital samples with c. 2000–1600 Ma maximum depositional ages in the Southern Granulite Terrane, southern Madagascar, and very few data for East Africa. Likewise, there are no Hf isotope data for c. 2000–1600 Ma magmatic samples from southern Madagascar, and very few Hf isotope data for magmatic rocks in East Africa and Dharwar Craton for all of the major age peaks discussed in this study. Further data collection will enable a more robust test of some of the ideas and the reconstruction we've presented in this manuscript.

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 localised sedimentary package, is here correlated with other sedimentary packages in Madagascar, including the Maha Group, Sahantaha Group, southern Madagascar, and the Ambatolampy Group. These are further correlated with Paleoproterozoic sedimentary 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 collided back with East Africa and India in the Neoproterozoic–Cambrian.

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Data availability statement: Datasets for this research are available from figshare. Supplementary A DOI: https://doi.org/10.6084/m9.figshare.12783869 and Supplementary B DOI: https://doi.org/10.6084/m9.figshare.12783887.

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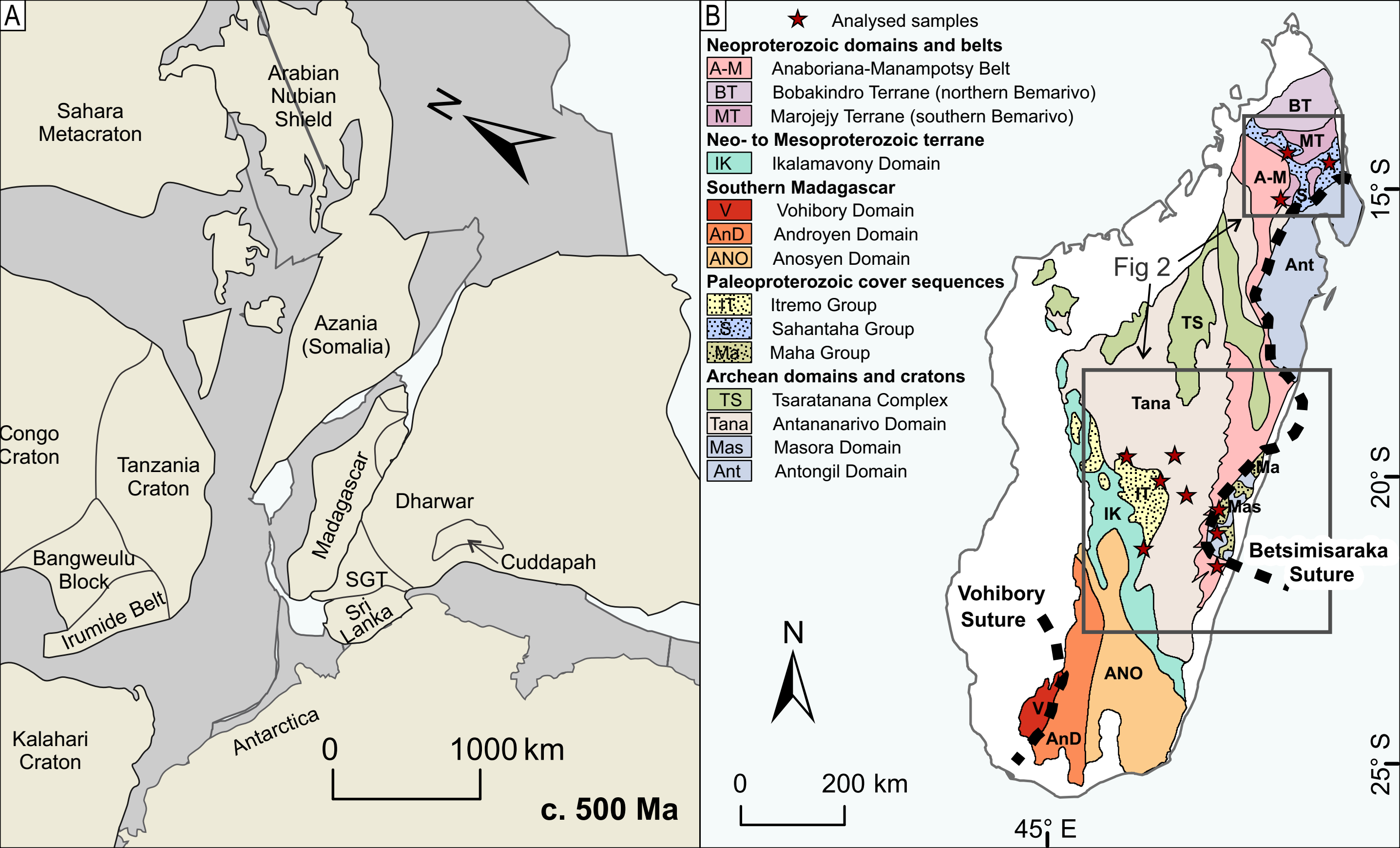
Figure 1.



A
Arabian Nubian Shield
Sahara Metacraton
Azania (Somalia)
Congo Craton
Tanzania Craton
Madagascar
Dharwar
Cuddapah
Bangweulu Block
Irumide Belt
SGT
Sri Lanka
Kalahari Craton
Antarctica
0 1000 km
c. 500 Ma
B
Analysed samples
Neoproterozoic domains and belts
A-M Anaboriana-Manampotsy Belt
BT Bobakindro Terrane (northern Bemarivo)
MT Marojejy Terrane (southern Bemarivo)
Neo- to Mesoproterozoic terrane
IK Ikalamavony Domain
Southern Madagascar
V Vohibory Domain
AnD Androyen Domain
ANO Anosyen Domain
Paleoproterozoic cover sequences
IT Itremo Group
S Sahantaha Group
Ma Maha Group
Archean domains and cratons
TS Tsaratanana Complex
Tana Antananarivo Domain
Mas Masora Domain
Ant Antongil Domain
Fig 2
BT
MT
A-M
S
Ant
TS
Tana
Ma
IT
Mas
IK
Betsimisaraka Suture
Vohibory Suture
ANO
V
AnD
N
0 200 km
15° S
20° S
25° S
45° E

Figure 2.

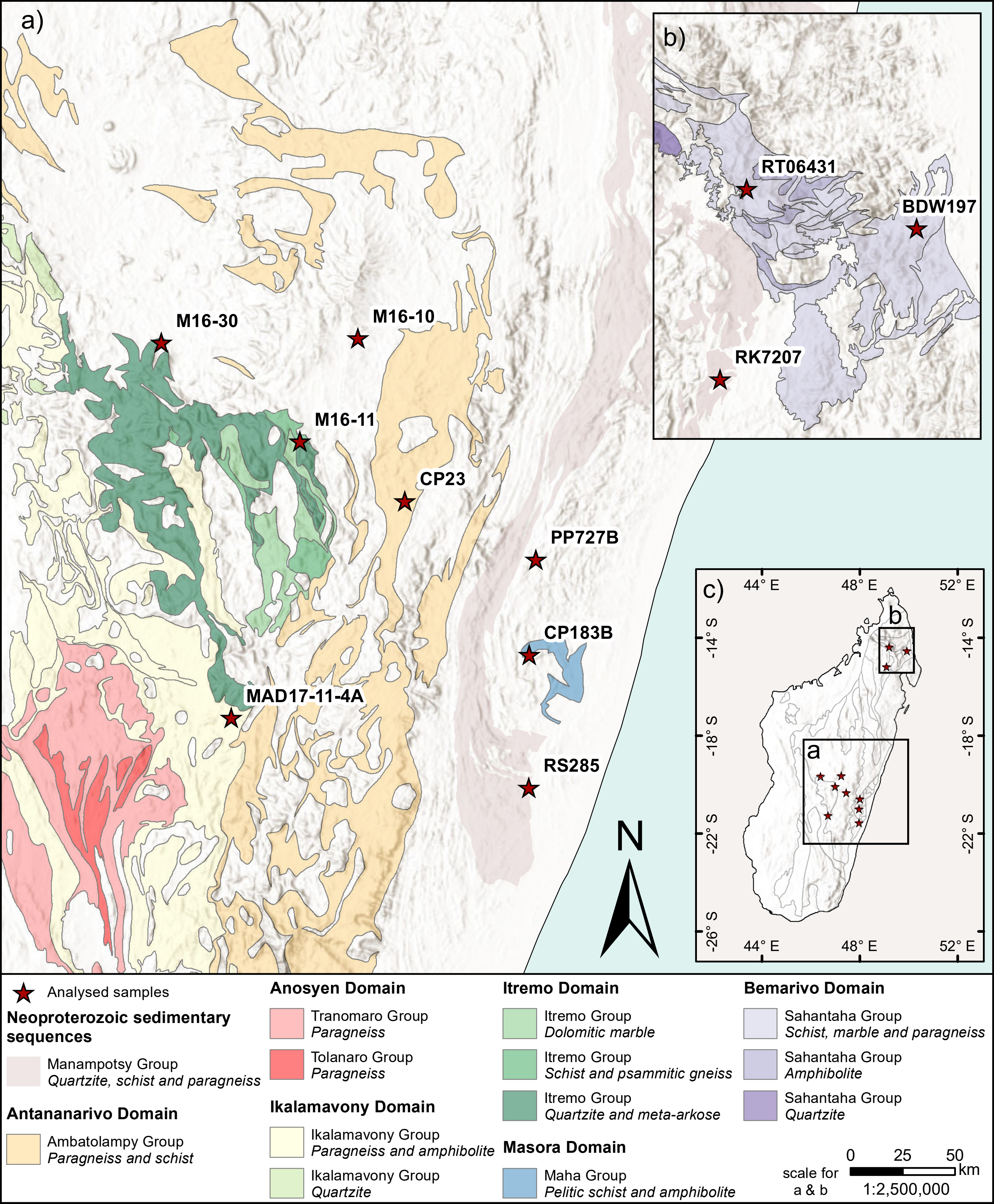
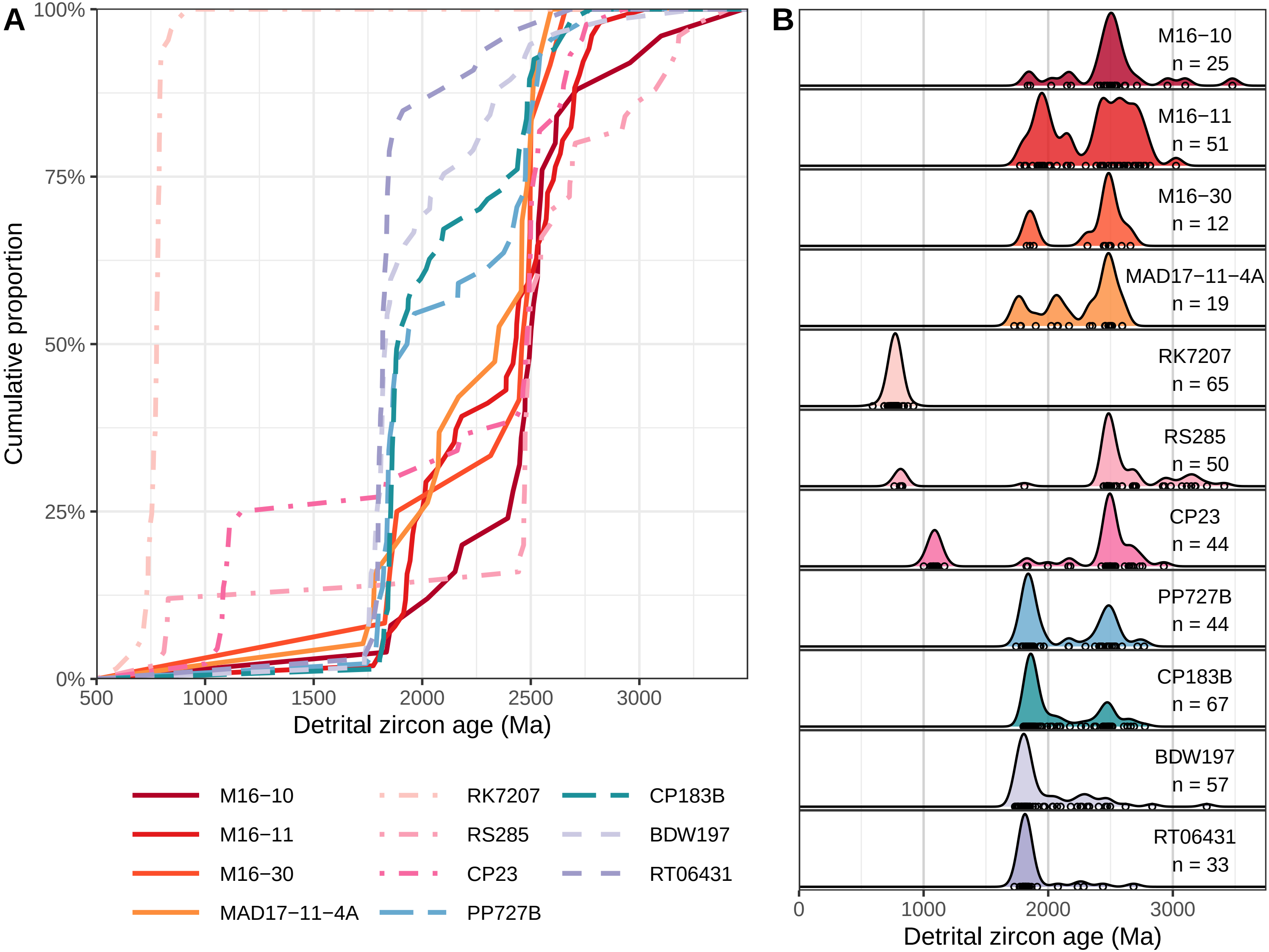

a)
b)
c)
M16-30
M16-10
M16-11
CP23
PP727B
CP183B
MAD17-11-4A
RS285
RT06431
BDW197
RK7207
N
44° E
48° E
52° E
-14° S
-18° S
-22° S
-26° S
a
b
Analysed samples
Neoproterozoic sedimentary sequences
Manampotsy Group
Quartzite, schist and paragneiss
Antananarivo Domain
Ambatolampy Group
Paragneiss and schist
Anosyen Domain
Tranomaro Group
Paragneiss
Tolanaro Group
Paragneiss
Ikalamavony Domain
Ikalamavony Group
Paragneiss and amphibolite
Ikalamavony Group
Quartzite
Itremo Domain
Itremo Group
Dolomitic marble
Itremo Group
Schist and psammitic gneiss
Itremo Group
Quartzite and meta-arkose
Masora Domain
Maha Group
Pelitic schist and amphibolite
Bemarivo Domain
Sahantaha Group
Schist, marble and paragneiss
Sahantaha Group
Amphibolite
Sahantaha Group
Quartzite
0 25 50 km
scale for a & b
1:2,500,000

Figure 3.



A
B
Cumulative proportion
0%
25%
50%
75%
100%
500
1000
1500
2000
2500
3000
Detrital zircon age (Ma)
M16−10
M16−11
M16−30
MAD17−11−4A
RK7207
RS285
CP23
PP727B
CP183B
BDW197
RT06431
M16−10
n = 25
M16−11
n = 51
M16−30
n = 12
MAD17−11−4A
n = 19
RK7207
n = 65
RS285
n = 50
CP23
n = 44
PP727B
n = 44
CP183B
n = 67
BDW197
n = 57
RT06431
n = 33
0
1000
2000
3000
Detrital zircon age (Ma)

Figure 4.

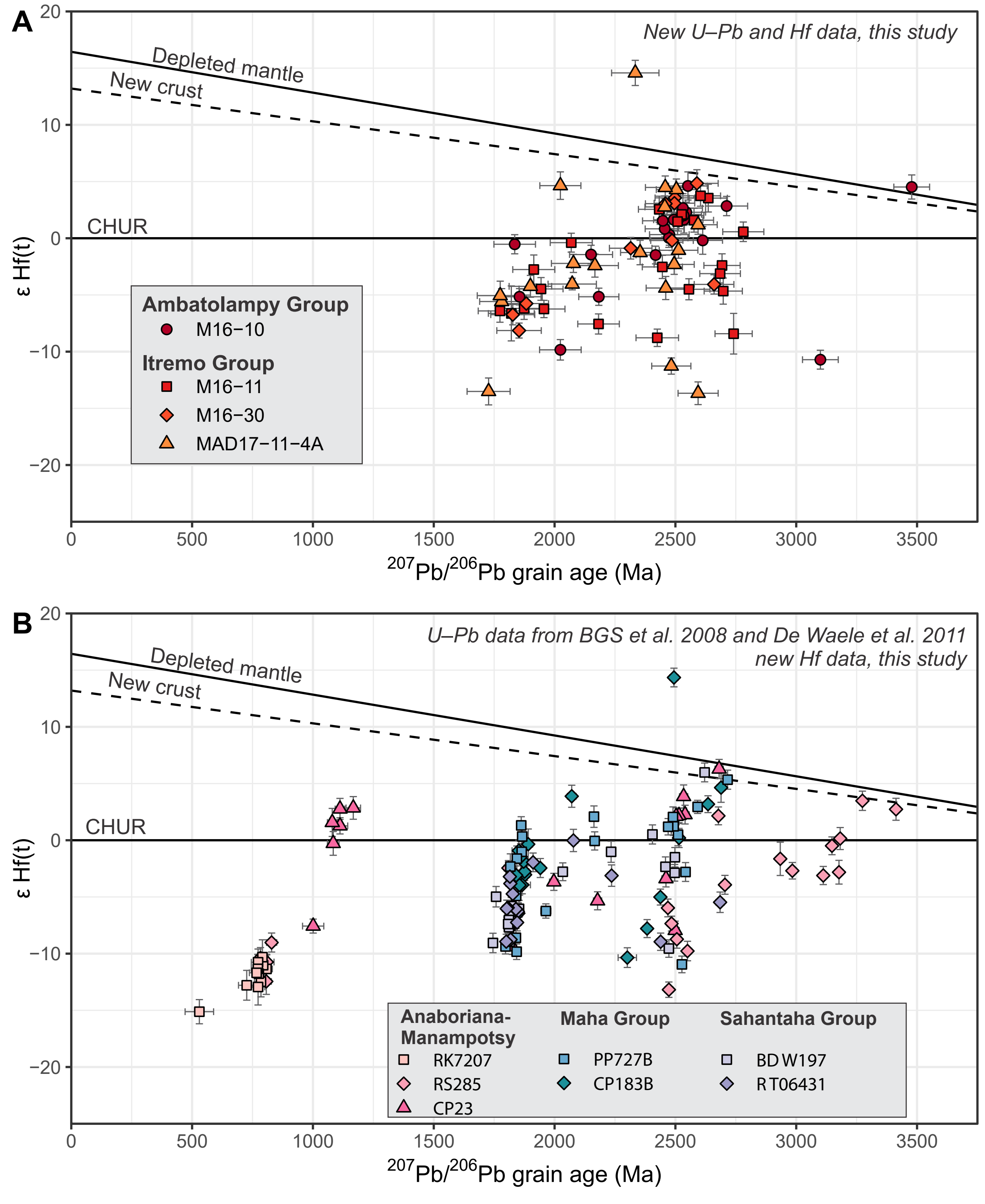

A
New U–Pb and Hf data, this study
Depleted mantle
New crust
CHUR
ε Hf(t)
Ambatolampy Group
M16−10
Itremo Group
M16−11
M16−30
MAD17−11−4A
$^{207}Pb/^{206}Pb$ grain age (Ma)
B
U–Pb data from BGS et al. 2008 and De Waele et al. 2011
new Hf data, this study
Depleted mantle
New crust
CHUR
ε Hf(t)
Anaboriana-Manampotsy
RK7207
RS285
CP23
Maha Group
PP727B
CP183B
Sahantaha Group
BDW197
RT06431
$^{207}Pb/^{206}Pb$ grain age (Ma)

Figure 5.

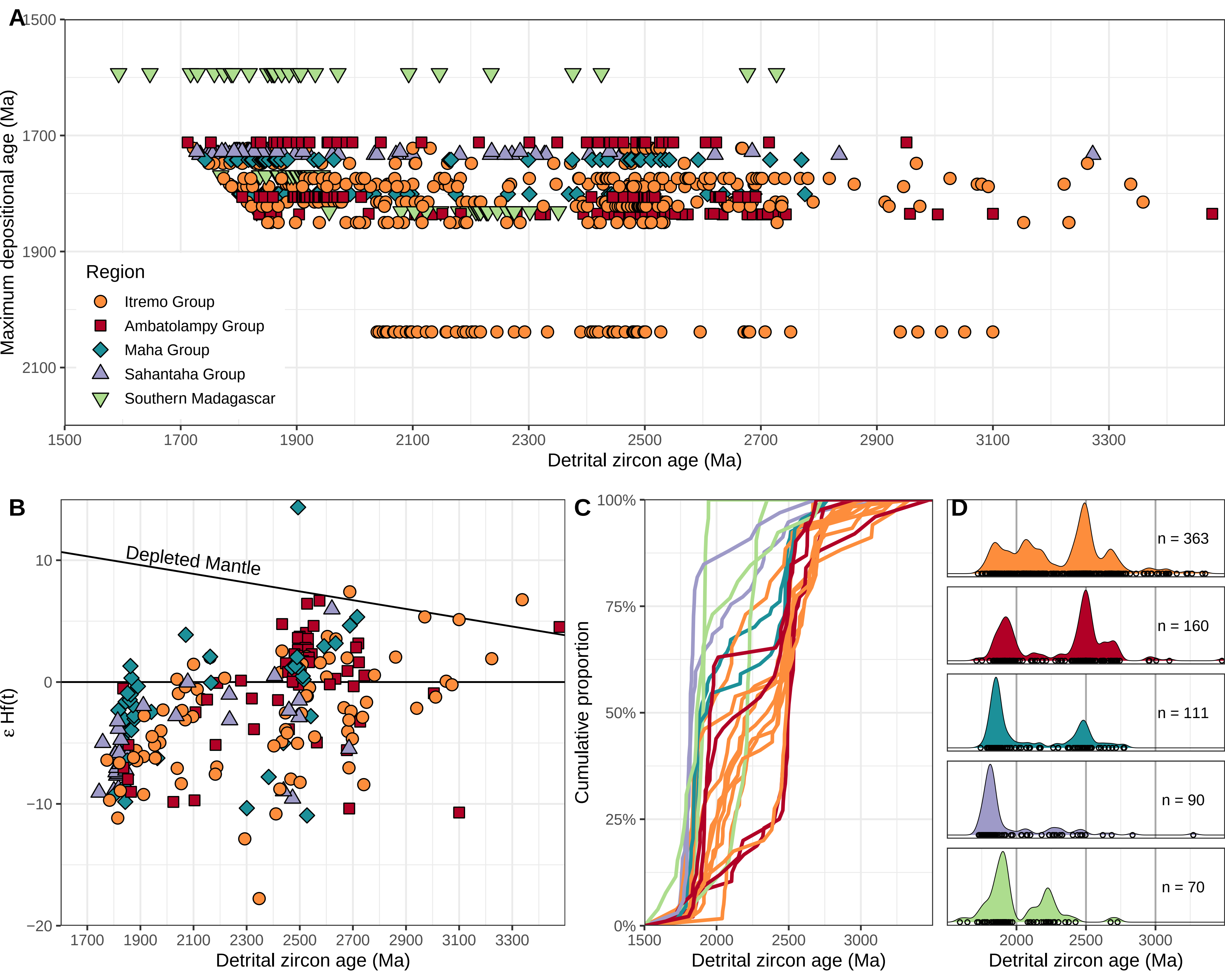
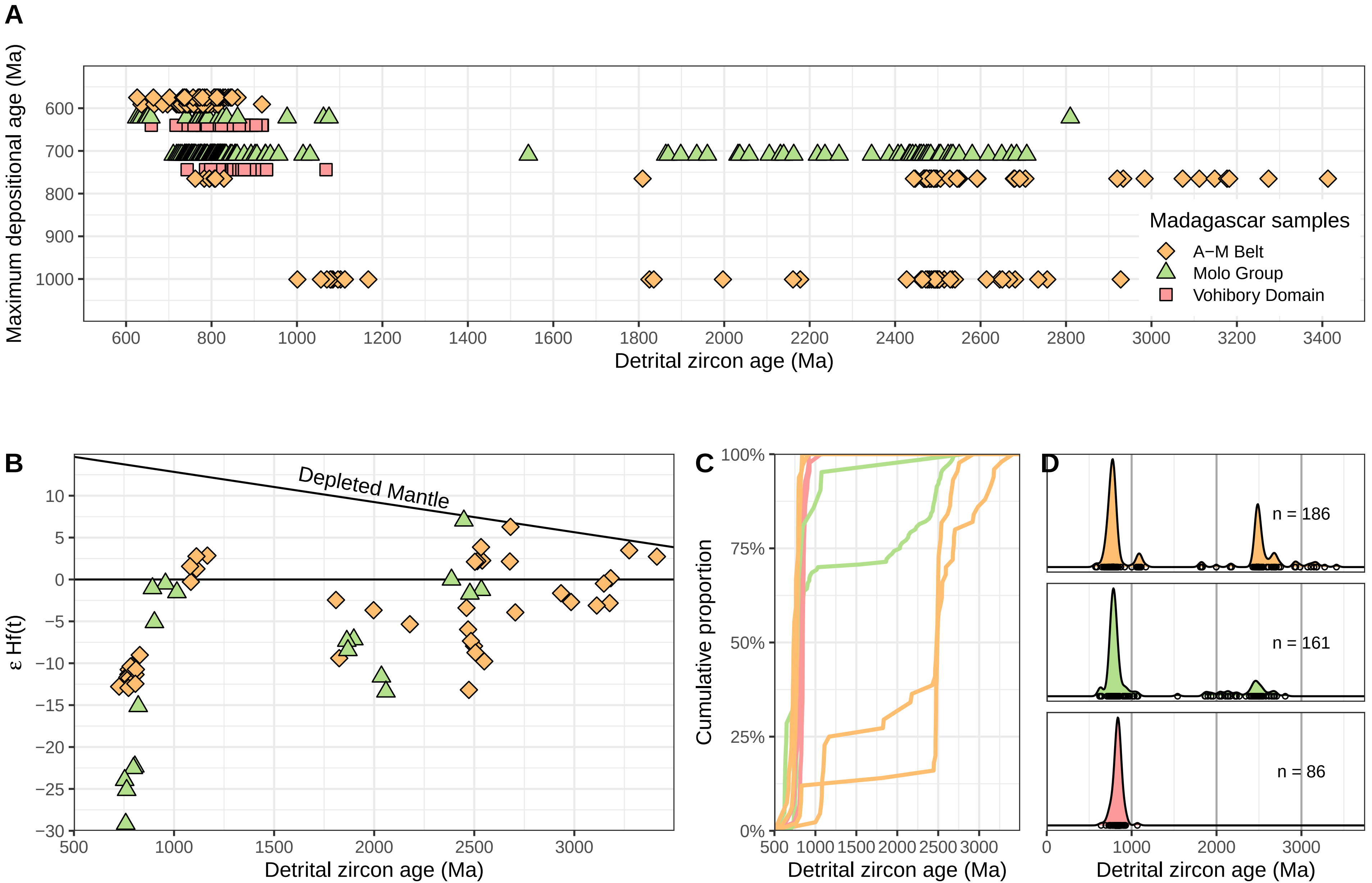
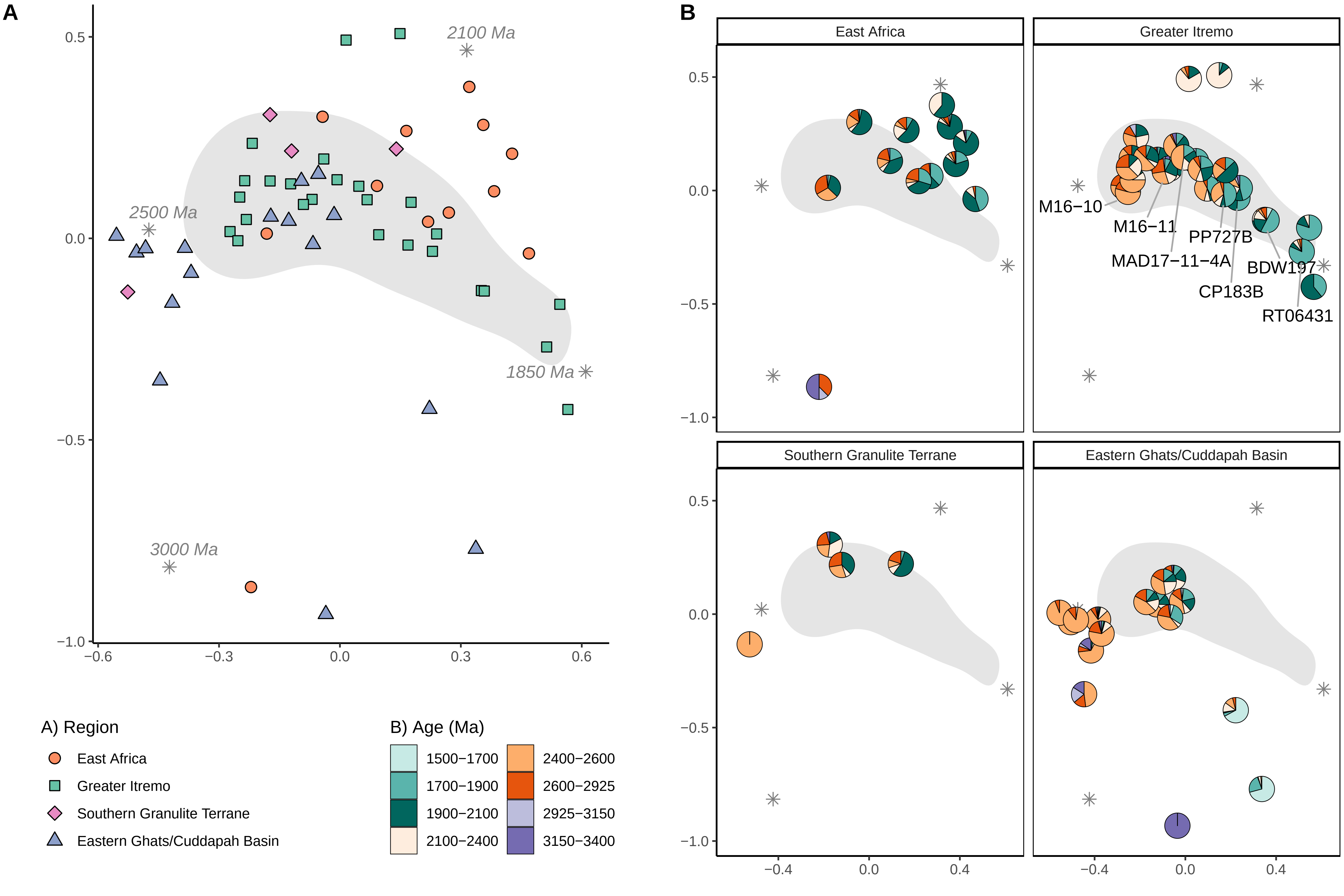

A
B
C
D
Maximum depositional age (Ma)
Detrital zircon age (Ma)
Region
Itremo Group
Ambatolampy Group
Maha Group
Sahantaha Group
Southern Madagascar
Depleted Mantle
ε Hf(t)
Cumulative proportion
n = 363
n = 160
n = 111
n = 90
n = 70

Figure 6.



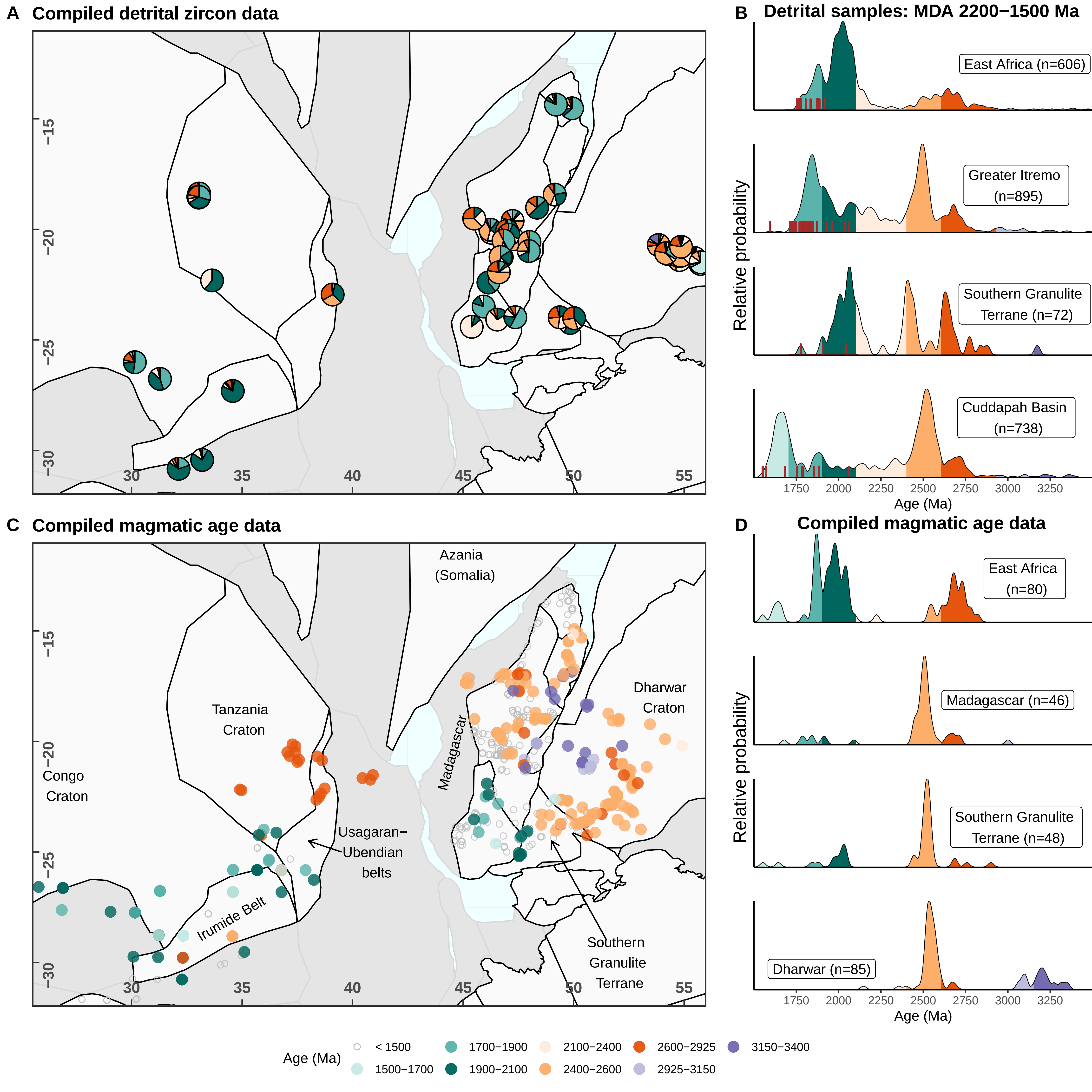
A
Maximum depositional age (Ma)
Detrital zircon age (Ma)
Madagascar samples
A−M Belt
Molo Group
Vohibory Domain
B
Depleted Mantle
ε Hf(t)
Detrital zircon age (Ma)
C
Cumulative proportion
Detrital zircon age (Ma)
D
n = 186
n = 161
n = 86
Detrital zircon age (Ma)

Figure 7.



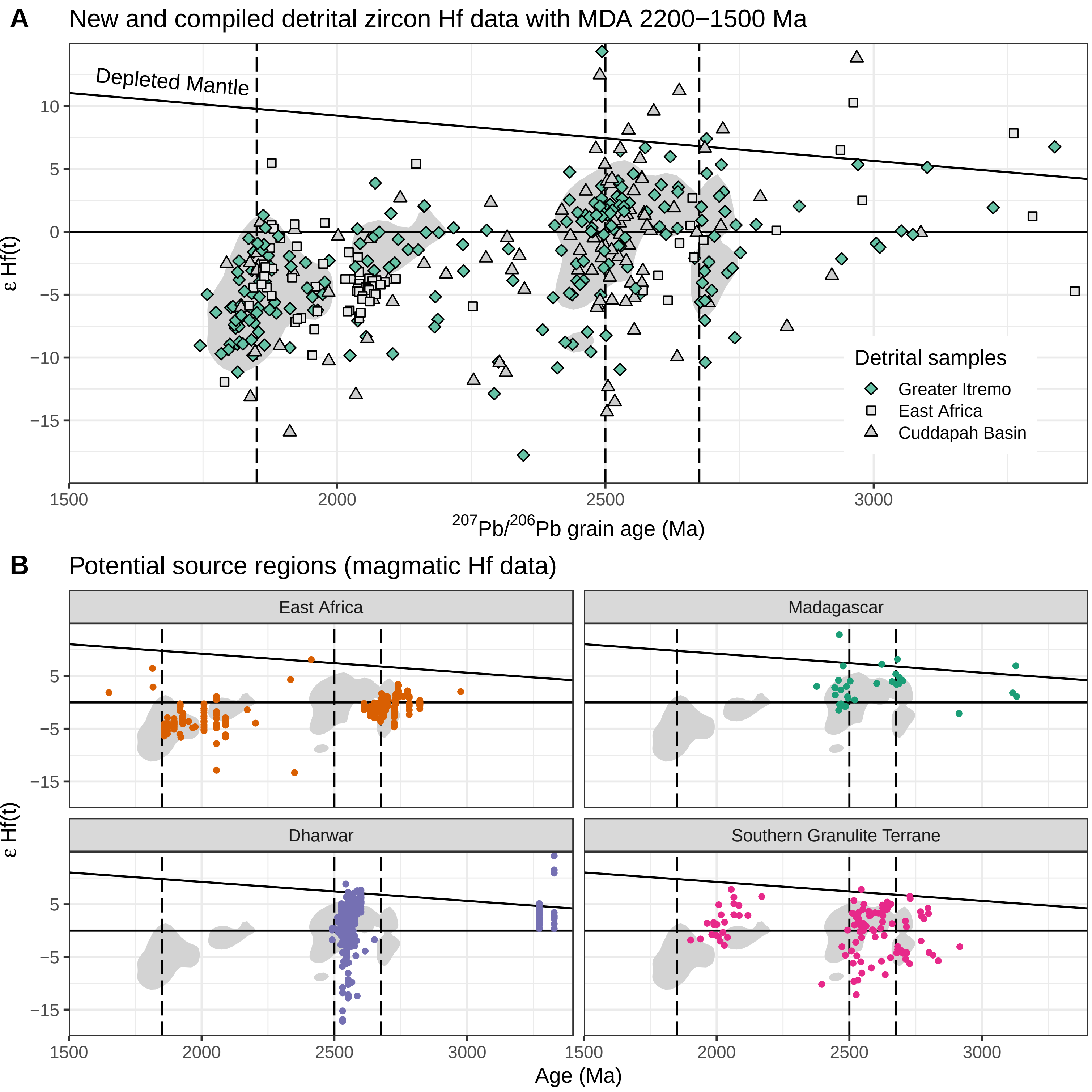
A
B
2100 Ma
2500 Ma
1850 Ma
3000 Ma
East Africa
Greater Itremo
Southern Granulite Terrane
Eastern Ghats/Cuddapah Basin
M16−10
M16−11
PP727B
MAD17−11−4A
BDW197
CP183B
RT06431
A) Region
East Africa
Greater Itremo
Southern Granulite Terrane
Eastern Ghats/Cuddapah Basin
B) Age (Ma)
1500−1700
1700−1900
1900−2100
2100−2400
2400−2600
2600−2925
2925−3150
3150−3400

Figure 8.



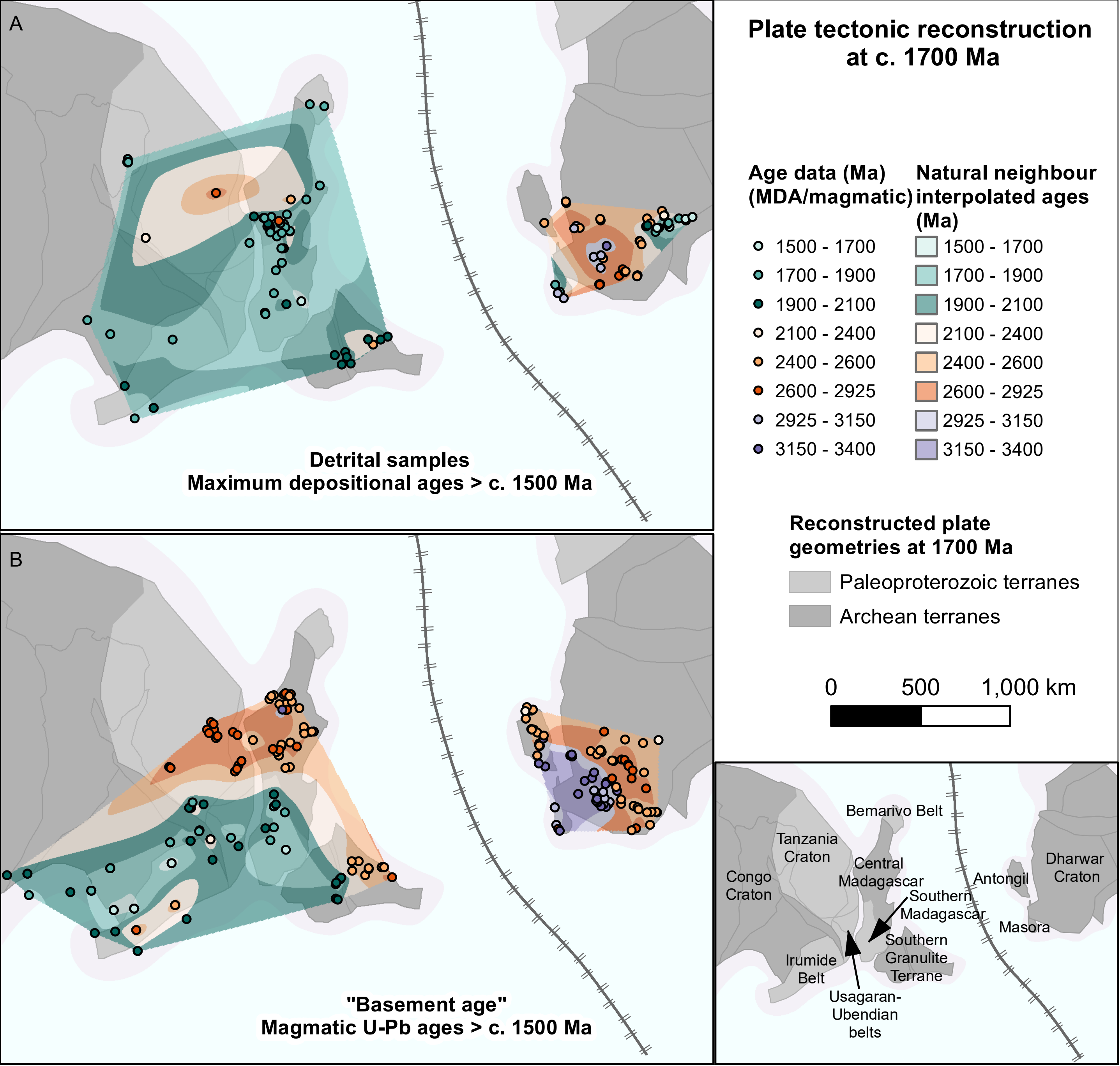
A Compiled detrital zircon data
B Detrital samples: MDA 2200−1500 Ma
East Africa (n=606)
Greater Itremo (n=895)
Southern Granulite Terrane (n=72)
Cuddapah Basin (n=738)
Relative probability
Age (Ma)
C Compiled magmatic age data
D Compiled magmatic age data
East Africa (n=80)
Madagascar (n=46)
Southern Granulite Terrane (n=48)
Dharwar (n=85)
Azania (Somalia)
Tanzania Craton
Congo Craton
Usagaran−Ubendian belts
Irumide Belt
Madagascar
Dharwar Craton
Southern Granulite Terrane
−15
−20
−25
−30
30
35
40
45
50
55
1750
2000
2250
2500
2750
3000
3250
Age (Ma)
< 1500
1500−1700
1700−1900
1900−2100
2100−2400
2400−2600
2600−2925
2925−3150
3150−3400

Figure 9.



A
New and compiled detrital zircon Hf data with MDA 2200−1500 Ma
Depleted Mantle
ε Hf(t)
$^{207}Pb/^{206}Pb$ grain age (Ma)
Detrital samples
Greater Itremo
East Africa
Cuddapah Basin
B
Potential source regions (magmatic Hf data)
East Africa
Madagascar
Dharwar
Southern Granulite Terrane
ε Hf(t)
Age (Ma)

Figure 10.


A
Detrital samples
Maximum depositional ages > c. 1500 Ma
B
"Basement age"
Magmatic U-Pb ages > c. 1500 Ma
Plate tectonic reconstruction at c. 1700 Ma
Age data (Ma) (MDA/magmatic)
Natural neighbour interpolated ages (Ma)
1500 - 1700
1700 - 1900
1900 - 2100
2100 - 2400
2400 - 2600
2600 - 2925
2925 - 3150
3150 - 3400
Reconstructed plate geometries at 1700 Ma
Paleoproterozoic terranes
Archean terranes
0
500
1,000 km
Bemarivo Belt
Tanzania Craton
Central Madagascar
Congo Craton
Antongil
Dharwar Craton
Southern Madagascar
Masora
Southern Granulite Terrane
Irumide Belt
Usagaran-Ubendian belts