

# Protracted mantle heat conduction after lithospheric foundering beneath the Malagasy orogen

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## ABSTRACT

Ultrahigh-temperature metamorphism (UHTM) is important for the evolution and long-term stability of continental crust. The Anosyen domain in southeastern Madagascar is a well-preserved UHTM terrane that formed during the amalgamation of Gondwana. The heat source(s) required to reach peak conditions is(are) a matter of debate. One potential cause of extreme crustal heating is the intrusion of mantle-derived melts into the crust. Foundering of the mantle lithosphere can also lead to increased heat flow. To assess the role of these heating mechanisms, we measured zircon  $\delta^{18}\text{O}$ ,  $\varepsilon_{\text{Hf}}(t)$  compositions, and U-Pb dates for plutonic rocks in the midcrustal UHTM domain. Our results indicate that pluton emplacement predated UHTM by as much as 40 m.y. and that all zircons have crustal O and Hf isotopic compositions. We propose that mantle lithosphere foundering caused melting in the lower crust, producing the magmas responsible for plutonism during the early stages of orogenesis. Prolonged conductive heating of the crust—combined with above-average radiogenic heating—may explain why UHTM occurred ~40 m.y. after foundering. This suggests that foundering of the mantle lithosphere can swiftly lead to partial melting in the lower crust, as well as protracted heating of the middle crust that culminates tens of millions of years later.

## INTRODUCTION

Crustal differentiation during ultrahigh-temperature metamorphism (UHTM;  $\geq 900^\circ\text{C}$ ; Harley, 1998) is important for the long-term stability of continental crust (Sawyer et al., 2011). UHTM terranes are common throughout Earth history and are often linked to the supercontinent cycle (Liu et al., 2022). In both orogens and rifts, temperatures may reach  $\geq 900^\circ\text{C}$  due to a combination of mechanical, radiogenic, and mantle heat conduction and mantle heat advection (Brown and Johnson, 2019; Jiao et al., 2023). Mechanical heating likely cannot produce regional UHTM alone, due to the inverse correlation between shear strength and temperature (Clark et al., 2011). Similarly, reaching UHTM conditions via radiogenic heating requires long

prograde heating (Clark et al., 2011). Therefore, the mantle may be a major source of heat in orogenic UHTM terranes.

Lithospheric foundering is a process that can introduce mantle heat into orogenic crust. For example, lithospheric removal has been invoked as a primary driver of (U)HTM in the Himalayas (e.g., Wang et al., 2021) and might be responsible for crust-derived melts across Gondwanan orogenic belts (e.g., Fritz et al., 2013; Fowler and Hamimi, 2023). The crustal geotherm can be perturbed by lithospheric foundering in two ways. First, upwelling asthenosphere might melt, producing magmas that transfer heat into the crust. Second, the removal of lithospheric mantle and subsequent upwelling asthenospheric mantle can increase the temperature at the base of the crust and therefore increase mantle heat flow into the crust. A series of granitoid plutons in southern Madagascar, which are part of the Ambalavao suite, may be the result of

lithospheric foundering during the amalgamation of Gondwana (Archibald et al., 2019). By using zircon O isotopes, Hf isotopes, and U-Pb ages, we evaluated the role and mechanisms of mantle heating in southern Madagascar, which have broad implications for mantle heating of orogens.

## GEOLOGIC CONTEXT

The basement of modern southeastern Madagascar was central to the Himalayan-style collisional orogeny that occurred during the amalgamation of Gondwana (e.g., Paquette et al., 1994). The collision of East Gondwana (India) and West Gondwana (Africa–South America), known as the East African orogeny (EAO), produced one of Earth's largest collisional orogens (Boger et al., 2015). Southern Madagascar was located along the axes of this orogen and experienced (U)HTM as a result (Boger et al., 2012; Holder et al., 2018b; Holder and Hacker, 2019; Horton et al., 2022).

Orogenesis resulted in high-temperature metamorphism throughout the Madagascar basement (GAF-BGR, 2008b) that reached ultrahigh-temperature (UHT) conditions in the Anosyen domain (Jöns and Schenk, 2011; Boger et al., 2012; Horton et al., 2016; Holder et al., 2018a). This domain is composed of metapelites, calc-silicates, and felsic paragneiss, and it has been interpreted as a Mesoproterozoic and Neoproterozoic passive-margin sequence intercalated with Paleoproterozoic crust (Tucker et al., 2014; Boger et al., 2014). Metamorphic U-Pb zircon and monazite dates range from ca. 630 Ma to 500 Ma (Paquette et al., 1994; Kröner et al., 1999; GAF-BGR, 2008b; Jöns and Schenk, 2011; Boger et al., 2014; Horton

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et al., 2016, 2022; Holder et al., 2018a; Holder and Hacker, 2019). Peak conditions in the Anosyen domain were  $>900^\circ\text{C}$  (Jöns and Schenk, 2011; Boger et al., 2012; Horton et al., 2016) at 0.65–0.8 GPa (Boger et al., 2012; Holder et al., 2018a) between ca. 550 and 525 Ma (Holder et al., 2018a; Horton et al., 2022).

There are several hypotheses for why the Anosyen domain reached UHT conditions while the adjacent domains in Madagascar did not, including: (1) focused radiogenic heating beneath a Tibet-like orogenic plateau (Horton et al., 2016); (2) incorporation of a thin, hot, precollisional back-arc or continental margin lithosphere into the orogen (Boger et al., 2012); (3) emplacement of high-temperature charnockite magmas into overthickened crust (Jöns and Schenk, 2011); and (4) a combination of radiogenic heating and mantle-heat advection (Holder et al., 2018a). The role of advective heating (Jöns and Schenk, 2011; Holder et al., 2018a) as a primary driver of metamorphism has not been rigorously tested to date.

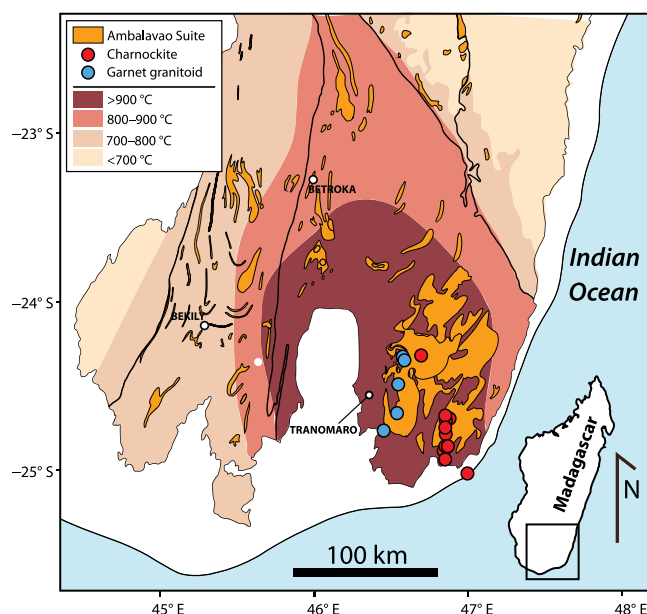
The Ambalavao suite, a series of granitoid plutons throughout Madagascar that are especially abundant in the UHTM domain, might be related to heat fluxes from the mantle (Holder et al., 2018a). For instance, the Ambalavao suite may represent evolved mantle melts that transferred mantle heat into the crust. Alternatively, the Ambalavao magmas within the Anosyen domain may have been derived from the lower crust. There is ambiguity about the timing and origin of Ambalavao magmatism with respect to UHTM. Whole-rock Sm–Nd model ages from the Ambalavao suite within the UHTM region suggest a protolith age of ca. 2.5–2.0 Ga (Paquette et al., 1994), consistent with the known basement of the Anosyen–Androyen domains (e.g., Tucker et al., 2014). Zircon U–Pb dates from the Ambalavao suite are limited and range from 580 to 510 Ma (Paquette et al., 1994; GAF-BGR, 2008b). Ambalavao suite rocks outside of the UHTM region have zircon O and Hf isotopes that allow for a significant crustal component and span a similar age range as those within the UHTM region (Archibald et al., 2019). However, it remains unclear whether the Ambalavao plutons within the UHTM domain and elsewhere have a common origin.

## RESULTS

### Zircon Isotopic Analysis

The Ambalavao suite, as represented by our sample set (Fig. 1; Table S1 in the Supplemental Material<sup>1</sup>), has two distinct geochemical and

<sup>1</sup>Supplemental Material. Description of the analytical methods, thermal modeling, and geochemistry of our samples. Additionally, the supplemental material includes entire major and trace element data set and zircon U–Pb, Hf, and O isotope data. Please visit <https://doi.org/10.1130/G52316.1/7015608/g52316.pdf> to access the supplemental material; contact [editing@geosociety.org](mailto:editing@geosociety.org) with any questions.



**Figure 1. Simplified geologic map of southeastern Madagascar showing ultrahigh-temperature metamorphism isotherms and sample locations (after Horton et al., 2016).**

geochronological groups: garnet granitoids and charnockites. Dates from all garnet-bearing samples ( $n = 167$ ) fall on a common discordia; a subset of these dates ( $n = 33$ ) is within 5% uncertainty of the concordia (Fig. 2). The discordia has an upper intercept of  $2021 \pm 103$  Ma (2 standard deviations [s.d.]). The lower intercept is not discrete, and concordant dates are spread along the concordia from 612 Ma to 541 Ma. Concordant dates in the charnockites range from 623 to 494 Ma, and most of this range is observed in each sample. Dates in each charnockite sample are bimodally distributed.

Zircons from the charnockites have indistinguishable  $\delta^{18}\text{O}$  values with a weighted average of  $10.10\text{‰} \pm 0.54\text{‰}$  (2 s.d.,  $n = 56$ ). The garnet granitoids have  $\delta^{18}\text{O}$  of  $9.82\text{‰} \pm 0.83\text{‰}$  (2 s.d.,  $n = 17$ ), except two samples collected from the same locality. Those samples have distinctly lower zircon  $\delta^{18}\text{O}$  of  $8.18\text{‰} \pm 0.50\text{‰}$  (2 s.d.,  $n = 8$ ) and  $7.78\text{‰} \pm 0.70\text{‰}$  (2 s.d.,  $n = 4$ ), respectively. Despite slight zircon  $\delta^{18}\text{O}$  variability, our samples are universally heavier than the mantle average ( $5.3\text{‰} \pm 0.6\text{‰}$ ; Valley et al., 1998).

The zircon  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio varies significantly in this data set (Fig. 3). Age-corrected  $\epsilon_{\text{Hf}}(t)$  values vary from  $-40.49 \pm 0.05$  to  $-1.97 \pm 0.01$ , which correspond to Hf depleted mantle model ages ( $T_{\text{DM}}$ ) ages of 2.8 to 2.4 Ga, respectively. Charnockite zircons have indistinguishable  $\epsilon_{\text{Hf}}(t)$  values with an average  $\epsilon_{\text{Hf}}(t)$  of  $-28.17 \pm 3.92$  (2 s.d.,  $n = 449$ ). This corresponds to a depleted mantle model age of  $2.3 \pm 0.3$  Ga (2 s.d.,  $n = 449$ ).

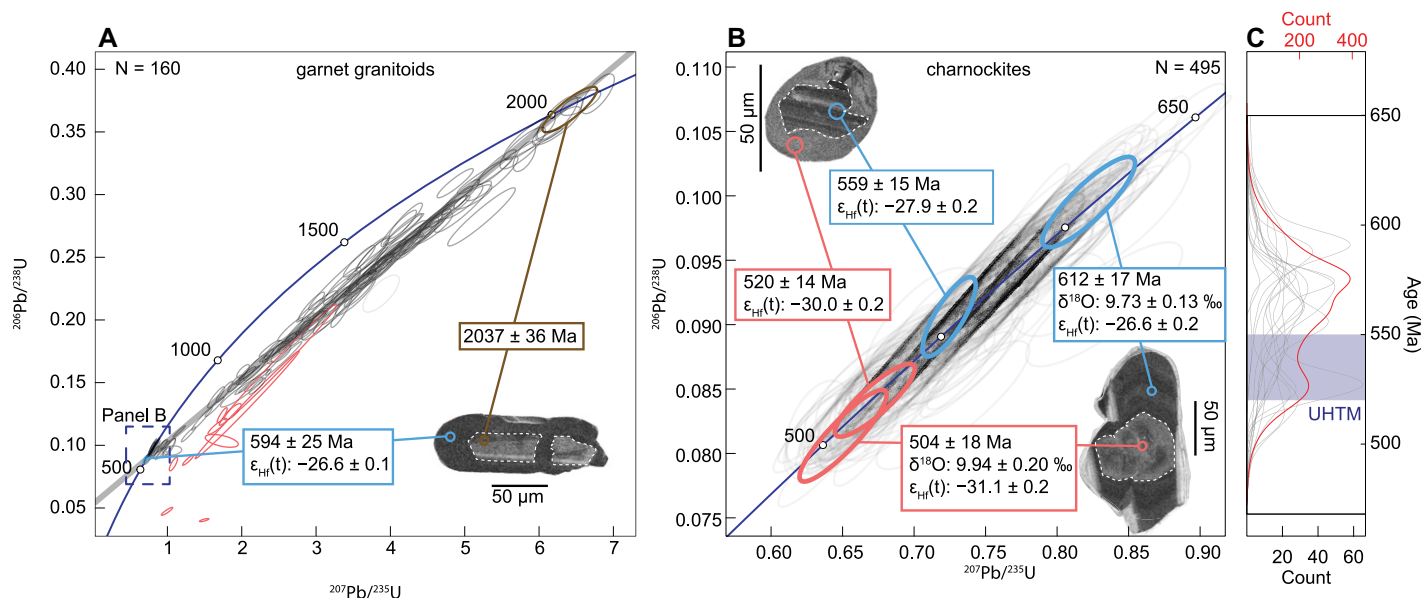
## DISCUSSION

Here, we discuss several lines of evidence that indicate that both the garnet granitoids and the charnockites were derived primarily from crustal melting.

In situ zircon  $\delta^{18}\text{O}$  and Hf isotopic compositions suggest the Ambalavao suite magmas had crustal protoliths. The  $\delta^{18}\text{O}$  values of both the garnet granitoid zircons ( $9.82\text{‰} \pm 0.31\text{‰}$ , 2 s.d.,  $n = 17$ ) and charnockite zircons ( $10.10\text{‰} \pm 0.54\text{‰}$ , 2 s.d.,  $n = 56$ ) are distinctly higher than the mantle ( $5.3\text{‰} \pm 0.6\text{‰}$ ; Valley et al., 1998). Similarly,  $\epsilon_{\text{Hf}}(t)$  values of both the garnet granitoids ( $-2.0$  to  $-40.4$ ) and charnockites ( $-19.1$  to  $-32.5$ ) are universally more negative than the depleted mantle (Fig. 3). Both sample suites have zircon  $T_{\text{DM}}$  between 3.7 and 2.0 Ga, suggesting a Paleoproterozoic or older crustal protolith, which broadly agrees with previous whole-rock Sm–Nd extraction ages (Paquette et al., 1994).

Zircon U–Pb ages also suggest a crustal protolith for the Ambalavao suite. Discordant dates from the garnet samples have an upper intercept ( $2021 \pm 103$  Ma) that overlaps with the regional basement (ca. 2.0 Ga; GAF-BGR, 2008a; Tucker et al., 2014). Discordia lower-intercept ages, which are corroborated by concordant dates, coincide with UHTM. This discordia suggests that zircons were inherited from the Paleoproterozoic basement and then partially to fully reset or newly crystallized during UHTM in the Anosyen domain (Jöns and Schenk, 2011; Horton et al., 2016; Holder et al., 2018a). Reverse-age zoned zircons—with cores that appear younger than the rims—in the Ambalavao suite provide further evidence that some zircons were inherited from the crust prior to peak metamorphism (Xu et al., 2012).

Critically, the Ambalavao suite plutons investigated here were emplaced before UHTM. While reverse-age zoned zircons and discordant dates from the charnockites and garnet granitoids, respectively, imply that some zircons were inherited from the country rock, the age spectra of the surrounding metasedimentary units



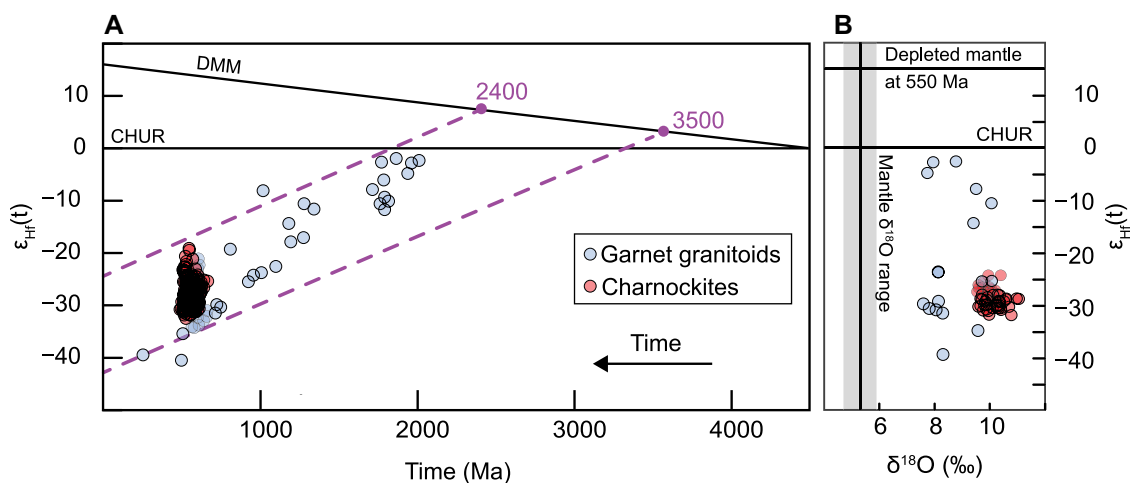
**Figure 2.** Full Ambalavao zircon U-Pb data set plotted on Wetherill projection. Ellipses represent 2 standard error. Red ellipses were disregarded for discordia calculations. (A) Garnet granitoid age data and cathodoluminescence image of representative normally zoned zircon with concordant rim and core spot analyses. (B) Charnockite date range (620–450 Ma). Representative zircons show normal and reverse age zonation. (C) Distribution of U-Pb dates shows two primary peaks at 574 Ma and 526 Ma for individual samples (gray) and full data set (red). Purple region depicts duration of ultrahigh-temperature metamorphism (UHTM).

and the Ambalavao suite do not match. Concordant dates older than ca. 560 Ma are rare in the metasedimentary basement and are only observed in metamorphic rim domains that lack oscillatory zoning (Boger et al., 2014). More than half of the dates from the Ambalavao suite are older than ca. 560 Ma, and many of these dates correspond to oscillatory-zoned cores (Fig. 2). Therefore, our results are consistent with Paleoproterozoic and minor ca. 620 Ma metamorphic zircon inheritance in Ambalavao suite zircons, which primarily crystallized during emplacement and underwent Pb loss or recrystallization during subsequent metamorphism.

For the bimodal U-Pb date distribution of each charnockite, the younger peaks correlate with the timing of UHTM (550–525 Ma; Holder et al., 2018a; Horton et al., 2022). We interpret the modes of the older peaks (594–564 Ma) as conservative minimum emplacement ages for each sample (Table S1). Of these, the oldest (ca. 590 Ma) may best represent the timing of the premetamorphic pulse of magmatism. This interpretation is consistent with published zircon U-Pb data from Ambalavao suite samples (Paquette et al., 1994; GAF-BGR, 2008b), which were previously interpreted as pre- and post-tectonic phases of magmatism at ca. 570 Ma and ca. 520 Ma, respectively.

### Implications for UHTM

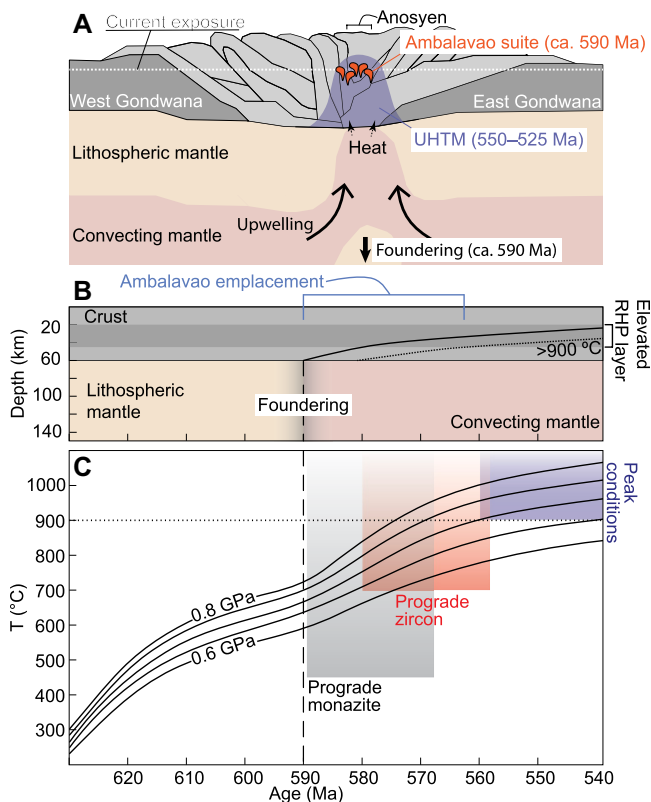
The Ambalavao plutons have crustal protoliths and predated UHTM by 20–40 m.y. Therefore, mantle magmatism was not a direct cause of UHTM. Furthermore, UHTM occurred at relatively low pressure (0.5–0.8 GPa; Boger et al., 2012; Holder and Hacker, 2019), with a prograde path of 30 m.y. (Holder et al., 2018a; Holder and Hacker, 2019). Our thermal modeling (see Supplemental Material) suggests that, at these pressures, radiogenic heat production would require longer prograde heating (~200 m.y.) to reach UHTM. Therefore, elevated radiogenic heat production alone cannot explain UHTM in the Anosyen domain.



**Figure 3.** (A) Chondritic uniform reservoir (CHUR)-normalized  $\epsilon_{\text{Hf}}(t)$  vs.  $^{206}\text{Pb}/^{238}\text{U}$  age. We assume modern  $^{176}\text{Hf}/^{177}\text{Hf}$  of  $0.282772 \pm 0.000029$  and  $^{176}\text{Lu}/^{177}\text{Hf}$  of  $0.279742 \pm 0.000029$  (Blichert-Toft and Albarede, 1997). Depleted mid-ocean-ridge basalt (MORB) mantle (DMM) assumes an extraction age of 4500 Ma and modern  $^{176}\text{Hf}/^{177}\text{Hf}$  of  $0.28325$  (Nowell et al., 1998) and  $^{176}\text{Lu}/^{177}\text{Hf}$  of  $0.0384$  (Griffin et al., 2000). We assume crustal  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of  $0.015$  (Griffin et al., 2002). (B) Oxygen isotopes vs.  $\epsilon_{\text{Hf}}(t)$ .

$\delta^{18}\text{O}$  mantle range ( $5.3\text{‰} \pm 0.6\text{‰}$ ) is from Valley et al. (1998). Average uncertainty is smaller than symbols.





**Figure 4. (A) Schematic of East African orogen in cross section. Current exposure is drawn in white dashed line. East and West Gondwana cratonic bodies and other outboard units associated with basement of East Africa, India, and Madagascar are in gray. Our model envisions removal of lithospheric keel beneath Anosyen domain and resulting production of Ambalavao suite at ca. 590 Ma, followed by continued conduction of mantle heat over next 20+ m.y., leading to midcrustal ultrahigh-temperature metamorphism (UHTM). (B) In model, 60-km-thick crust has band of higher radiogenic heat production (RHP) between 20 and 45 km depth. Lithospheric mantle, which founders at ca. 590 Ma, is replaced by hotter convecting upper mantle. (C) Modeled temperature-time paths at five different depths (0.6–0.8 GPa). Gray, red, and blue boxes show pressure-temperature-time (P-T-t) conditions inferred from prograde monazite (e.g., Holder et al., 2018a), prograde zircon (Horton et al., 2022), and peak metamorphic mineral assemblages (Horton et al., 2022). Model parameters are given in Supplemental Material (see text footnote 1).**

and blue boxes show pressure-temperature-time (P-T-t) conditions inferred from prograde monazite (e.g., Holder et al., 2018a), prograde zircon (Horton et al., 2022), and peak metamorphic mineral assemblages (Horton et al., 2022). Model parameters are given in Supplemental Material (see text footnote 1).

Foundering of the mantle lithosphere is an alternative mechanism for heating the middle crust. The removal of the mantle lithosphere and upwelling of the asthenosphere to the base of the crust can steepen the geotherm. Foundering has been invoked in orogenic settings to explain the thin mantle lithosphere below the central Tibetan Plateau (Harrison et al., 1992) and crustal melts throughout the EAO (Fritz et al., 2013; Fowler and Hamimi, 2023).

Our models suggest that an abrupt increase in mantle heat conduction associated with a foundering event can explain the 20–40 m.y. lag between the Ambalavao suite emplacement and UHTM. We infer that the onset of crustal thickening and metamorphism occurred around 620–600 Ma, based on the oldest metamorphic zircon dates in the Anosyen-Androyen domains (Jöns and Schenk, 2011; Horton et al., 2016, 2022). Foundering may have caused magmatism ca. 590 Ma by increasing mantle heat flow into the lower crust and thereby driving crustal melting, which led to Ambalavao magmatism in the southern Anosyen domain. This pulse of mantle heat could have conducted through the crust, resulting in UHTM in the now-exposed middle crust of the Anosyen domain 20–40 m.y. later.

In this scenario, the combined effects of elevated radiogenic heat production and litho-

spheric foundering could have produced UHT conditions in the Anosyen domain (Fig. 4). Using a moderately radiogenic midcrustal layer ( $1.7\text{--}3.5\text{ }\mu\text{W m}^{-3}$ ) and a crustal thickness of 55–65 km, the thermal model can produce UHTM at the peak pressures preserved in the Anosyen domain (0.6–0.8 GPa; Boger et al., 2012; Holder et al., 2018a). This result occurs over a range of crustal thicknesses (75–50 km) and radiogenic heat production rates ( $>2\text{ }\mu\text{W m}^{-3}$ ). The implication is that mantle lithosphere foundering increased mantle heat conduction into the crust, which first melted the lower crust to produce the Ambalavao magmas and culminated tens of millions of years later with peak metamorphism in the middle crust.

## CONCLUSIONS

UHTM in southern Madagascar was most likely caused by a combination of elevated radiogenic heat production and conductive heating following the foundering of the mantle lithosphere. Ambalavao suite zircons have Paleoproterozoic cores, crust-like  $\delta^{18}\text{O}$ , negative  $\varepsilon_{\text{Hf}}(t)$  values, and domains that experienced Pb loss during metamorphism. These results imply that the Ambalavao suite within the southern Anosyen domain predated UHTM and has crustal origins. We conclude that the mantle lithosphere

foundered at ca. 590 Ma, resulting in conductive heating of the lower crust, which melted to produce the Ambalavao suite magmas. Sustained mantle heat conduction associated with this foundering event could have caused UHTM in the middle crust 20–40 m.y. later. This tectonic model implies that the removal of mantle lithosphere can have immediate and protracted thermal consequences in orogens.

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