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New insights into the age, composition, and thermal history of the lower crust

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Introduction

Metamorphic crustal xenoliths provide information on the age, composition, and thermal history of the deeper portions of the continental crust. Our studies of such xenoliths address two motivating questions: 1) Can crustal heat production be determined by combining petrochronology of accessory phases from lower-crustal xenoliths and surface heat flow to allow determination of the mantle heat flux? 2) How and when were sediments emplaced into the lower crust? In particular, is there any evidence in the latter for relamination, i.e., the buoyant rise of subducted sedimentary rocks that might 'relaminate' the base of the crust (Hacker et al., 2011)?

Constraining crustal heat production from petrochronology of deep crustal xenoliths

Case study 1: Tanzanian Craton and Mozambique Belt

Petrochronology of lower-crustal granulite-facies and mid-crustal amphibolite-facies xenoliths, as well as surface exposures from the Archean Tanzanian Craton and adjacent Proterozoic Mozambique Belt, Tanzania, record the thermal history of these regions since their formation in the Archean (Apen et al., 2020). While the shallow crust of the Tanzanian craton preserves Archean cooling dates, accessory minerals in the lower crustal xenoliths (e.g., rutile, apatite) record re-heating during the East African Orogeny (EAO) and Quaternary rifting. By contrast, apatite, rutile and titanite in the entire crust of the Mozambique Belt record dates corresponding to the EAO (640–560 Ma) or younger, even though most of the crust here formed in the Archean, as recorded in zircon U-Pb dates. The present-day lower crust of the EAO resides above 650ºC (both rutile and apatite were open to Pb diffusion at the time of xenolith entrainment), whereas that of the craton is lower: 500-600ºC (both apatite and rutile record pre-eruptive dates) (Fig. 1). This suggests very low crustal heat production in both regions of ~0.5 $\mu W/m^3$ (cf. average continental crustal heat production of 0.8 to 1.0 $\mu W/m^3$, Jaupart and Mareschal, 2014). This low crustal heat production is similar, but slightly lower than that inferred for other Archean regions (0.56-0.73 $\mu W/m^3$, Jaupart and Mareshal, 2014) and is consistent with the ancient and heat-producing-element-depleted rocks observed at the surface in both the craton and Mozambique Belt. Higher Moho heat flow below the Mozambique Belt compared to the Tanzanian craton is likely due to a thicker lithosphere beneath the craton.

Case study 2: Udachnaya, Siberian Craton

In contrast to the Tanzanian results, lower-crustal granulite xenoliths from the 360 Ma Udachnaya kimberlite preserve Archean–Proterozoic events, indicating cool Moho temperatures of <400ºC at the time of kimberlite emplacement (Apen et al., 2022). Combining temperature constraints from the lower-crustal xenoliths with the P-T array of Udachnaya garnet peridotites yields an extremely low crustal heat production of ~0.3 $\mu W/m^3$ for this portion of the Siberian craton. Even with such low crustal heat production, the measured surface heat flow values of 19 mw/m^2 are impossibly low and suggest they are in error.

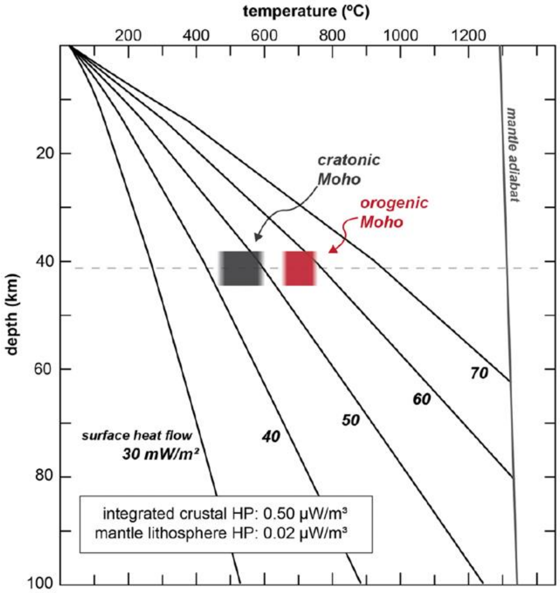

Figure 1. Present-day Moho temperature range based on thermochronology of accessory minerals in lower crustal xenoliths from the Tanznian craton (gray box, Labait) and the Mozambique Belt (red box, many localities). Apatite and rutile from granulite-facies xenloliths in the Mozamibque Belt all record zero-million-year ages (i.e., eruption ages), whereas titanite, monazite and zircon are all older. By contrast, From Apen et al. (2020).

How and when are sediments emplaced into the lower continental crust?

Case study 1: Potrillo Volcanic Field (PVF)

Metapelitic xenoliths from Kilbourne Hole and Potrillo Maar in the PVF derive from the present-day lower crust, which is currently undergoing ultra-high temperature (UHT) metamorphism (Cipar et al., 2020; Ringwood et al., 2023). Despite these extreme conditions, the metapelites record transportation to the lower crust during the ca. 1.4 Ga Picurus Orogeny, based on dates from metamorphic monazite and zircon (Fig. 2). A rare garnet core that likely formed during initial lower crustal emplacement records equilibration in the sillimanite stability field, thus documenting a higher dT/dP than expected for any subduction-zone processes (including relamination). Assuming the original history was not completely obliterated by subsequent metamorphic events, the petrochronology results suggest sediment transport to the lower crust during continental orogeny. The PVF lies on a Nd-isotope line demarcating older crust to the north, younger to the south, suggesting that this may mark a major crustal suture.

Case study 2: Central Montana Alkalic Province, Great Falls Tectonic Zone

Both mafic granulites and rare metapelitic xenoliths carried in Eocene diatremes of the central Montana alkalic province derive from the lower crust/uppermost mantle of the Great Falls Tectonic Zone, which represents a major Paleoproterozoic continental collision between the Archean Wyoming Craton and the Archean Medicine Hat Block. Both were infiltrated near the time of entrainment by deep-seated fluids likely derived from the Farallon slab, as documented by Eocene titanite rimming rutile in mafic granulites that predates entrainment by up to 14 Myr (Apen et al., 2024) and ~60 Ma rims on Mesoproterozoic monazite in the metapelites (Ringwood et al., 2024). Rutile in the metapelites was open to Pb diffusion at the time of eruption, documenting relatively hot lower crust (>650°C) and providing a means of dating their host rocks (46.0 ± 1.5 Ma for the Big Slide diatreme and 51.3 ± 0.5 Ma for the Robinson Ranch diatreme). Zircon in the metapelites transitioned from detrital (dating back to 3.3 Ga) to metamorphic at 1.8 Ga, the age of the Great Falls Tectonic Zone. As for the PVF metapelites, sillimanite was the stable aluminosilicate at the time of transport to the deep crust, suggesting their transport to the lower crust during collisional orogeny between the Medicine Hat Block and the Wyoming craton. Mafic granulites have unusual mineralogy (grt-cpx-pl-ky-czo-scp) and textures and record equilibration pressures of 1.8 to 2.3 GPa. Based on their geochemistry, they likely formed as arc cumulates within the lithospheric mantle prior to the 1.8 Ga collision, though they contain no datable phases.

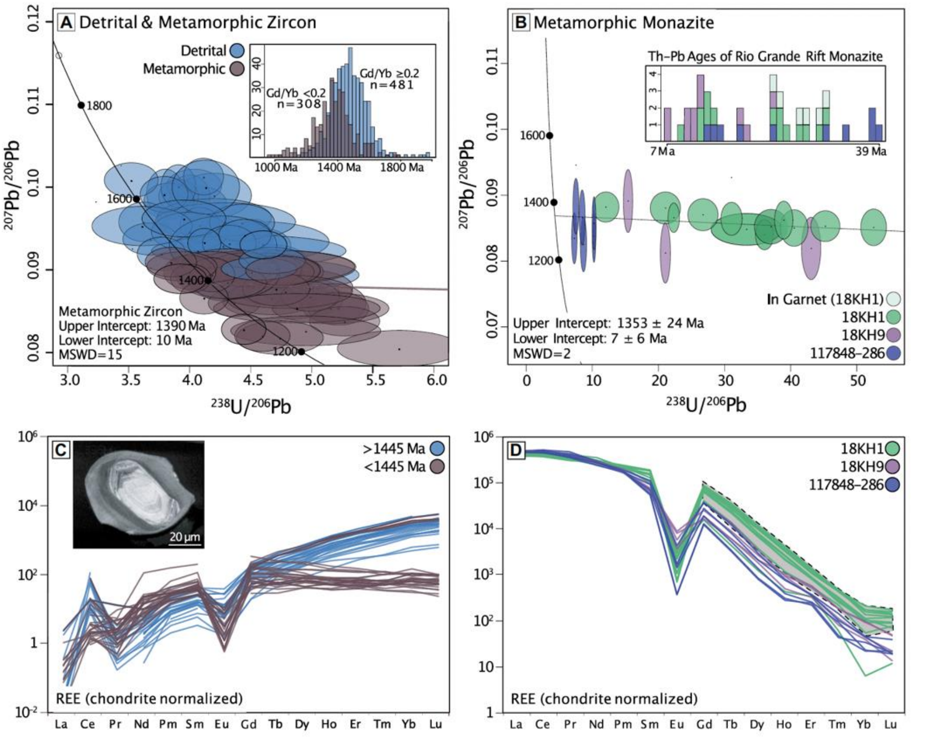

Figure 2. (A) Detrital zircon cores (n = 45) and metamorphic zircon (n = 33) that fall within 15% of concordia and have uncertainties less than 15% (2σ) for a Kilbourne Hole metapelite xenolith. Inset: upper intercept ages for individual zircon with a $^{238}U/^{206}Pb$ ratio <100 classified solely on Gd/Yb ratio. There is a clear transition from detrital to metamorphic zircon production during the ~1.4 Ga Picuris orogeny. (B) Metamorphic mnz from several PRV metapelite xenoliths. All dates are for matrix monazites except for the six pale green data points for sample 18KH1 in the histogram, which are inclusions in garnet; 2 σ error ellipses. (C) Rare earth element (REE) plot for concordant zircon sorted by age, showing a clear transition at 1450 Ma from steep to flat heavy (H)REE. Inset: cathodoluminescence image of zircon with an oscillatory-zoned detrital core surrounded by a metamorphic rim. (D) REE plot of metamorphic monazite. Gray field highlights the higher HREE of the Rio Grande rift-age monazite, indicating these younger grains are not simply the result of Pb loss from Proterozoic monazite and are instead a separate population. From Ringwood et al. (2023).

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