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From hot oceanic ridges to cool cratons

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The fraction of radioactive heat production in Earth's mantle to convective heat loss has decreased with the aging of Earth, as more of its nuclear fuel became spent and more of its heat was lost to space. Earth was therefore hotter in its past, but there is no consensus as to how much higher the mantle's temperature was in early Earth compared to the present. This is an important problem to understand because it is expected to have imposed secular changes in the formation of oceanic lithosphere at ridges and its cycling at subduction zones (Herzberg and Rudnick, 2012; Foley, 2018). In a hotter early Earth, the ambient mantle melted more extensively, to make thicker basaltic oceanic crust and residual mantle peridotite, the latter of which was depleted in chemical elements that entered the magmas. Sometime later, the basaltic oceanic crust became hydrated by seawater, and it in turn melted to make silicic continental crust. As discussed in more detail below, this transformation led to the juxtaposition of continental crust on top of oceanic lithospheric mantle (Herzberg and Rudnick, 2012). The original "oceanic mantle lithosphere" is now called "continental mantle lithosphere" because it is located below continental crust in cratons. This hypothesis is explored by Servali and Korenaga (2018, p. 1047 in this issue of *Geology*), and is the reason why they entitle their paper an "oceanic origin of continental mantle lithosphere."

The residues of mantle melting that make up the oldest Archean continental mantle lithosphere are found as peridotite xenoliths in kimberlite. They differ from residues of modern oceanic crust production in being more highly depleted in FeO and enriched in MgO, and their olivines have higher forsterite (Fo) contents, as expressed as molar 100MgO/(MgO+FeO). For example, olivines in Archean continental mantle lithosphere typically have Fo contents of 92–94, whereas those below modern oceanic crust are more in the range of 89–91, a temporal dichotomy that has long been recognized in regional studies (Boyd, 1989). Servali and Korenaga have tested the hot mid-oceanic ridge hypothesis because it makes specific predictions about secular variations in whole rock and olivine 100MgO/(MgO+FeO) of the peridotite residues left behind by ambient mantle melting. These residue compositions were predicted by Herzberg and Rudnick (2012) from a mass balance model of secular variations in complementary non-arc basaltic compositions produced by ambient mantle melting (Herzberg et al., 2010). Servali and Korenaga compiled a global archive of peridotite samples below continents for which Re-Os model ages were determined, spanning most of Earth history. They discovered a smooth secular trend in mantle depletion that agrees with the prediction of Herzberg and Rudnick (2012). This result supports the model that non-arc basalts and peridotite xenoliths of Proterozoic and Archean ages originated by the melting of ambient mantle beneath hot mid-ocean ridges or similar tectonic environments (Herzberg, 2004; Rollinson, 2010; Herzberg et al., 2010; Herzberg and Rudnick, 2012; Pearson and Wittig, 2014; Su and Chen, 2018), and at high temperatures, predicted by Korenaga (2008, 2017). But is this a unique interpretation?

Servali and Korenaga contrast their hot early Earth ambient mantle temperatures with cooler models presented by Davies (2009) and Ganne and Feng (2017). They show that olivines in continental lithospheric mantle are too forsteritic to have formed in cool ambient mantle. This leads to the possibility that they formed as residues of hot mantle plumes, not hot ambient mantle, a model that is preferred in other studies (Arndt et al., 2009; Griffin et al., 2009; Aulbach, 2012). It seems unlikely that the smooth secular trend of olivines is a record of a smooth geodynamic change from early hot plumes to later cool ocean ridges; a more plausible interpretation might be that mantle plume products were preferentially preserved in the Archean. However, a critical flaw is that residues of hot mantle plumes have lower Cr_2O_3/Al_2O_3 compared with continental mantle lithosphere (Brey and Shu, 2018; Su and Chen, 2018).

Highly forsteritic olivines might also form by extensive fluid-assisted melting of cool ambient mantle peridotite in subduction zones (e.g., Carlson et al., 2005). However, there are many difficulties with this model (Herzberg and Rudnick, 2012), and analog peridotites as found in some ophiolites and forearcs generally have higher CaO/Al_2O_3 and Cr_2O_3/Al_2O_3 that than continental mantle lithosphere (Su and Chen, 2018). Nevertheless, this is important to examine more carefully because Archean/Proterozoic subduction is a topic of significant interest (Hawkesworth and Brown, 2018; Foley, 2018).

A central question is whether weak lithospheric plate boundaries could have formed at high mantle temperatures, as inferred from Archean non-arc basalts (Herzberg et al., 2010) and their complementary depleted peridotite residues (Servali and Korenaga, 2018). If the lithosphere deformed by pseudoplasticity, plate failure would not have occurred, and Earth's mantle would have convected in a stagnant lid regime, where subduction and plate motions were absent (Foley, 2018). However, if the lithosphere responded to stress by grain-size reduction in shear zones, formation of weak plate boundaries would not have been impeded by early Earth thermal conditions; in this case, high mantle temperatures led to a more-sluggish, drip-like style of subduction (Foley, 2018). These theoretical considerations are backed up by geological evidence that supports subduction in the Archean (e.g., van Hunen and Moyen, 2012; Arndt, 2013).

The following two points are more specifically relevant to craton formation: (1) petrological pressure estimates (Herzberg et al., 2010; Su and Chen, 2018) indicate there were ~85–135 km of lithospheric mantle peridotite residues produced below hot oceanic ridges during the Archean, considerably less than ~250 km below present-day Archean cratons; this thickness paradox can be resolved by tectonic thickening associated with convergent boundary underthrusting (Jordan, 1988), although other mechanisms might be possible (Lee and Chin, 2014); and (2) the lithosphere

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must have thickened and cooled significantly in the Archean to foster diamond formation (Stachel and Harris, 2008).

We need to understand how hot oceanic ridges transformed to cool cratons, and it did not happen in a single stage; rather, it required three stages, the first two of which were magmatic, and the third tectonic. Stage 1 began with mantle melting below hot oceanic ridge–type environments to form thick basaltic crust overlying complementary depleted residual peridotite mantle. In stage 2, some of the basaltic oceanic crust was hydrated and partially melted to make tonalite–trondhjemite–granodiorite (TTG) in continental crust and complementary residues such as amphibolite, garnet amphibolite/pyroxenite, and rutile/quartz/coesite eclogite (e.g., Rollinson, 2010; Moyen and Martin, 2012; Arndt, 2013). Cratons formed in stage 3 with the tectonic juxtaposition of stage 2 continental crust on top of stage 1 oceanic residual peridotite mantle. What is notably missing within cratons are the large amounts of stage 1 oceanic crust and its stage 2 eclogitic residues (Herzberg and Rudnick, 2012; Pearson and Wittig, 2014). This is a craton mass imbalance problem.

In modern subduction zones, the descending oceanic lithosphere consists of basaltic oceanic crust that is mechanically coupled to the underlying peridotite residual mantle; the basalt transforms at high pressures to dense eclogite, a significant driver of plate tectonics (Ringwood and Green, 1966). In the Archean, subduction might have broken the lithosphere at the crust-mantle boundary, imposing grain damage and shear zone localization. The high-density eclogite basaltic crust might have delaminated into the deep mantle, and the more buoyant peridotite rose to underplate the continental crust. This is a possible solution to the craton mass imbalance problem (Herzberg and Rudnick, 2012). Crust-mantle mechanical decoupling and density inversion can be simulated for thick basaltic oceanic crust away from plate boundaries, owing to the stabilization of dense garnet amphibolite/pyroxenite at the base (Johnson et al., 2014; Sizova et al., 2015). It is crust recycling by dripping, and it features in some models of Archean tectonics (e.g., Bédard, 2006). However, dripping and subduction might have occurred concurrently (Sizova et al., 2015). It is not difficult to imagine Archean cratons nucleating above sluggish drippy subduction zones wherein the lithospheric plates broke up internally on their way down. Buoyant depleted mantle peridotite, untethered from its descending crustal eclogite anchor, would rise and collect under continental crust to make thickened continental mantle lithosphere. Future work should examine this possibility because it might help to understand how the style of subduction responded to the cooling of Earth (Foley, 2018).

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