When Was the Earth’s Conveyor Belt Set in Motion?

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Highlights and breakthroughs

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Abstract

The start of plate tectonics on Earth is one of the most controversial issues in modern geology, with proposed timings covering almost the entire history of our planet. On page ???? of this issue, Blichert-Toft and co-authors report Sm-Nd and Lu-Hf isotopic and lithophile trace element data for early Archean komatiites from the Barberton Greenstone Belt (GB) in South Africa, and argue for the onset of plate tectonics on Earth as early as 3.5 Ga. The studied komatiites show a large decoupling of the two isotopic systems and lithophile trace element signatures that are most consistent with deep-water, pelagic sediments being present in the lower-mantle source of these lavas. Their conclusions have far-reaching implications for advancing our understanding of how the Earth system operated in the distant geological past.
The first two billion years of Solar System history arguably constitute the most important period of Earth’s existence; processes acting on our planet during this period of time effectively determined how this initially hellish place became our life-accommodating world.

Terrestrial history is conventionally deciphered from the geological record. However, due to the dynamic nature of Earth and its violent, prolonged accretionary history, its surface has been continuously rejuvenated from the time the planet was born. As a result, the isotopic and chemical heterogeneities observed in modern mantle-derived rocks primarily reflect processes associated with the production and recycling of continental and oceanic crust through geological time. It is the early geological record from which information pertaining to the origin and early evolution of Earth that is most likely to be gleaned. Isotopic signatures created in early silicate reservoirs via radioactive decay of nuclides, such as $^{147}\text{Sm}$ and $^{176}\text{Lu}$, have been sampled by early magmas and preserved in early crustal rocks.

The $^{147}\text{Sm}-^{143}\text{Nd}$ and $^{176}\text{Lu}-^{176}\text{Hf}$ long-lived isotopic systems represent powerful tools for tracing the evolution of the mantle. All four elements are refractory and lithophile, and, as such, are unaffected by core segregation. Due to their incompatible nature during mantle melting and differentiation, these elements concentrate in partial melts and, ultimately, in the crust, and are depleted in mantle residues, albeit to different degrees. As a result, crustal reservoirs have lower Sm/Nd and Lu/Hf ratios than their respective depleted mantle sources, and, given enough time, evolve to distinct $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ isotopic signatures, which have been used to decipher the timing and mechanisms of mantle differentiation events (e.g., DePaolo and Wasserburg, 1976; 1979; Jacobsen and Wasserburg, 1979; Patchett et al., 1981; White and Patchett, 1984). Using a combination of Sm-Nd and Lu-Hf isotope systematics, it has also been possible to identify specific processes that may have controlled mantle differentiation, including fractionation of Mg- and Ca-perovskite during crystallization of a terrestrial magma ocean, and isolation of the differentiation products within mantle domains that survived mantle mixing for hundreds of millions of years (Caro et al., 2005; Hoffmann et al., 2011; Rizo et al., 2011; Puchtel et al., 2013).

One of the most important and controversial issues in modern geology is the timing of the onset of plate tectonics on Earth. Since the advent of the plate tectonics paradigm (Wilson, 1965), a large number of studies have been published on this subject, with proposed timings
covering almost the entire history of our planet. Most geologists, however, argue for the onset of plate tectonics sometime during the Archean, i.e., between 4.0 and 2.5 billion years ago (e.g., Komiya et al., 1999; Brown, 2006; Cawood et al., 2006; Condie and Kröner, 2008; Pease et al., 2008; Shirey et al., 2008; Van Kranendonk, 2008; Condie and O'Neill, 2010; Korenaga, 2011).

On page ??? of this issue, Blichert-Toft et al. (2015) report geochemical evidence, derived from their study of early Archean komatiites from the Barberton Greenstone Belt (GB) in South Africa, for the onset of plate tectonics on Earth as early as 3.5 Ga. Ever since komatiites were first described in the Barberton GB (Viljoen and Viljoen, 1969), these high-MgO lavas, that are mostly confined to the Archean terrains, have yielded important information bearing on the chemical and thermal evolution of the mantle (e.g., Nesbitt and Sun, 1976; Nisbet et al., 1993; Condie, 2003; Grove and Parman, 2004). Due to formation via generally high degrees of partial melting (Arndt, 1977) in deep mantle upwellings, or mantle plumes (Campbell et al., 1989), in many instances komatiites have compositions approaching those of mantle peridotites and, thus, may faithfully record the chemical and isotopic characteristics of their mantle sources.

Earlier Sm-Nd and Lu-Hf isotopic and lithophile trace element data reported for 3.5 and 3.3 billion year old Barberton komatiites by Puchtel et al. (2013) indicated decoupling of the two isotopic systems in the sources of these komatiites, i.e., the combined Nd and Hf isotopic data for these komatiites plotted well off the terrestrial Nd-Hf evolution curve. This decoupling was shown by these authors to be due to formation and long-term isolation of deep-seated mantle domains with fractionated Sm/Nd and Lu/Hf very early in Earth history, at ca. 4400 Ma, as a result of crystallization of a primordial magma ocean, with Mg-perovskite and minor Ca-perovskite acting as fractionating phases. Due to contrasting partitioning behavior of Sm, Nd, Lu, and Hf in these high-PT phases, the cumulates and residual liquids formed during crystallization of a magma ocean acquired very different Sm/Nd and Lu/Hf ratios compared to mantle residues and melts formed during shallow-mantle differentiation and crust-formation processes. By the time these deep-seated mantle reservoirs were sampled by the Barberton komatiites, they developed Nd and Hf isotopic compositions very different from those of upper mantle or crustal rocks.
In some of the 3.5 Ga Barberton komatiites, Blichert-Toft *et al.* (2015) found geochemical signatures similar to those reported by Puchtel *et al.* (2013). However, some of the 3.5 Ga komatiites they studied show much larger decoupling of the two isotopic systems that cannot be accounted for within the magma ocean scenario. Blichert-Toft and co-authors have done extensive modeling and have come up with an intriguing explanation – the Nd-Hf isotopic and lithophile trace element signatures found in these komatiites are most consistent with deep-water, pelagic sediments being present in the lower-mantle source of these komatiites.

One important question to ask is why pelagic sediments would have isotopic characteristics different from those of typical mantle and crustal rocks, thus causing the data to fall off the Nd-Hf terrestrial evolution curve? The Lu-Hf and Sm-Nd isotope systems are decoupled in clastic sediments because zircon, a very weathering-resistant mineral $(\text{Zr},\text{Hf})\text{SiO}_4$, is deposited in fluvial or coastal settings, while finer-grained, pelagic sediment, depleted in zircon and therefore characterized by high Lu/Hf, is deposited in deeper waters *(e.g., Patchett *et al.*, 1984; Vervoort *et al.*, 1999). Given enough time, this material would acquire unusual, highly positive initial $\varepsilon_{\text{Hf}}$ values and lower initial $\varepsilon_{\text{Nd}}$. Therefore, if such material were entrained in the source of Barberton komatiites, this could explain both the trace element patterns and the Nd and Hf isotope systematics observed by Blichert-Toft *et al.* (2015).

But how did the pelagic sediments end up deep in the mantle and in the source of the komatiites? One way of putting this material into the deep mantle is via subduction – the process that takes place at convergent boundaries by which one tectonic plate moves under another tectonic plate and sinks into the mantle as the plates converge; subduction is the driving force behind plate tectonics. It is at subduction zones that Earth's lithosphere, oceanic crust, and sedimentary layers are recycled into the deep mantle. The subducted material may age in the mantle for hundreds of millions of years until entrained in hot mantle upwellings, or mantle plumes, that originate at thermal boundary layers in the mantle, such as the 670 km discontinuity or even the 2900 km core-mantle boundary. The important observations reported by Blichert-Toft *et al.* (2015) require that some version of modern-style plate tectonics already operated as far back in Earth history as 3.5 billion years ago. Their conclusions are consistent with several lines of geochemical evidence for initiation of plate tectonics at 3.6 Ga put forward by Shirey *et
al. (2008), and have far-reaching implications for advancing our understanding of how the Earth system operated in the distant geological past.
References cited


