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

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Highlights and breakthroughs

Submitted to *American Mineralogist*

June 18, 2015

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}Sm and ^{176}Lu, have been sampled by early magmas and preserved in early crustal rocks.

The ^{147}Sm-^{143}Nd and ^{176}Lu-^{176}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}Nd/^{144}Nd and ^{176}Hf/^{177}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 billio 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 $(Zr,Hf)SiO_4$, 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 εHf values and lower initial εNd. 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

Arndt, N.T., 1977. Ultrabasic magmas and high-degree melting of the mantle. Contributions to Mineralogy and Petrology **64**(2): 205-221.

Brown, M., 2006. Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean. Geology **34**(11): 961-964.

Campbell, I.H., Griffiths, R.W., and Hill, R.I., 1989. Melting in an Archaean mantle plume: head it's basalts, tails it's komatiites. Nature **339**(6227): 697-699.

Caro, G., Bourdon, B., Wood, B.J., and Corgne, A., 2005. Trace-element fractionation in Hadean mantle generated by melt segregation from a magma ocean. Nature **436**(7048): 246-249.

Cawood, P.A., Kröner, A., and Pisarevsky, S., 2006. Precambrian plate tectonics: Criteria and evidence. GSA Today **16**: 4-11.

Condie, K.C., 2003. Incompatible element ratios in oceanic basalts and komatiites: Tracking deep mantle sources and continental growth rates with time. Geochem. Geophys. Geosys. **4**: 1005-1033.

Condie, K.C., and Kröner, A., 2008. When did plate tectonics begin? Evidence from the geologic record. Geological Society of America Special Papers **440**: 281-294.

Condie, K.C., and O'Neill, C., 2010. The Archean-Proterozoic Boundary: 500 My of Tectonic Transition in Earth History. American Journal of Science **310**(9): 775-790.

DePaolo, D.J., and Wasserburg, G.J., 1976. Nd Isotopic Variations and Petrogenetic Models. Geophysical Research Letters **3**(5): 249-252.

DePaolo, D.J., and Wasserburg, G.J., 1979. Sm-Nd age of the Stillwater Complex and the mantle evolution curve for neodimium. Geochimica et Cosmochimica Acta **43**(7): 999-1008.

Grove, T.L., and Parman, S.W., 2004. Thermal evolution of the Earth as recorded by komatiites. Earth and Planetary Science Letters **219**(3-4): 173-187.

Hoffmann, J.E., Münker, C., Polat, A., Rosing, M.T., and Schulz, T., 2011. The origin of decoupled Hf-Nd isotope compositions in Eoarchean rocks from southern West Greenland. Geochimica et Cosmochimica Acta **75**(21): 6610-6628.

Jacobsen, S.B., and Wasserburg, G.J., 1979. Mean Age of Mantle and Crustal Reservoirs. Journal of Geophysical Research **84**(NB13): 7411-7427.

Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M., and Okamoto, K., 1999. Plate tectonics at 3.8-3.7 Ga: Field evidence from the Isua accretionary complex, Southern West Greenland. Journal of Geology **107**(5): 515-554.

Korenaga, J., 2011. Thermal evolution with a hydrating mantle and the initiation of plate tectonics in the early Earth. Journal of Geophysical Research: Solid Earth **116**(B12): B12403.

Nesbitt, R.W., and Sun, S.S., 1976. Geochemistry of Archaean spinifex-textured peridotites and magnesian and low-magnesian tholeiites. Earth and Planetary Science Letters **31**(3): 433-453.

Nisbet, E.G., Cheadle, M.J., Arndt, N.T., and Bickle, M.J., 1993. Constraining the potential temperature of the Archaean mantle: A review of the evidence from komatiites. Lithos **30**(3-4): 291-307.

Patchett, P.J., Kauvo, O., Hedge, C.E., and Tatsumoto, M., 1981. Evolution of continental crust and mantle heterogeneity: evidence from Hf isotopes. Contributions to Mineralogy and Petrology **78**(3): 279-297.

Patchett, P.J., White, W.M., Feldmann, H., Kielinczuk, S., and Hofmann, A.W., 1984. Hafnium/rare earth element fractionation in the sedimentary system and crustal recycling into the Earth's mantle. Earth and Planetary Science Letters **69**(2): 365-378.

Pease, V., Percival, J., Smithies, H., Stevens, G., and Van Kranendonk, M., 2008. When did plate tectonics begin? Evidence from the orogenic record. Geological Society of America Special Papers **440**: 199-228.

Puchtel, I.S., Blichert-Toft, J., Touboul, M., Walker, R.J., Byerly, G., Nisbet, E.G., and Anhaeusser, C.R., 2013. Insights into early Earth from Barberton komatiites: Evidence from lithophile isotope and trace element systematics. Geochimica et Cosmochimica Acta **108**: 63-90.

Rizo, H., Boyet, M., Blichert-Toft, J., and Rosing, M., 2011. Combined Nd and Hf isotope evidence for deep-seated source of Isua lavas. Earth and Planetary Science Letters **312**(3-4): 267-279.

Shirey, S.B., Kamber, B.S., Whitehouse, M.J., Mueller, P.A., and Basu, A.R. (2008). A review of the isotopic and trace element evidence for mantle and crustal processes in the Hadean and Archean: Implications for the onset of plate tectonic subduction. Geological Society of America Spec. Paper 440: When Did Plate Tectonics Begin on Planet Earth?**:** 1-29.

Van Kranendonk, M.J., 2008. Two types of Archean continental crust: Plume and plate tectonics on early Earth. American Journal of Science **310**(10): 1187-1209.

Vervoort, J.D., Patchett, P.J., Blichert-Toft, J., and Albarède, F., 1999. Relationships between Lu-Hf and Sm-Nd isotopic systems in the global sedimentary system. Earth and Planetary Science Letters **168**(1-2): 79-99.

Viljoen, M.J., and Viljoen, R.P., 1969. Evidence for the existence of a mobile extrusive peridotitic magma from the Komati formation of the Onverwacht Group. Geological Society of South Africa Special Publication **2**: 87-112.

White, W.M., and Patchett, J., 1984. Hf-Nd-Sr isotopes and incompatible element abundances in island arcs: implications for magma origins and crust-mantle evolution. Earth and Planetary Science Letters **67**(2): 167-185.

Wilson, J.T., 1965. A New Class of Faults and their Bearing on Continental Drift. Nature **207**(4995): 343-347.