Forum Reply

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Kimberlites and the start of plate tectonics

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We thank Gary Ernst for his interest in and Comments (Ernst, 2017) about our recent Geology paper (Stern et al., 2016), which highlighted the temporal distribution of kimberlites. We considered what are the possible reasons for the young kimberlite phenomenon and the implications regarding the onset of plate tectonics and conclude that the best explanation is that there has been a recent increase in deep mantle hydration and carbonation caused by the recent (<1 Ga) onset of deep subduction and plate tectonics. We agree with many of Ernst's points, including "Initial mantle circulation might have been chiefly bottom up (plume-driven), but as Earth cooled, top-down overturn (plate subduction) began to dominate its thermal evolution", but we disagree about when this change in tectonic style occurred.

Ernst's closing sentence "Lithospheric subduction (plate tectonics) apparently has operated episodically or continuously (?) since consolidation of the Hadean magma ocean" nicely captures the main point of disagreement. This statement implies that there is no other way to deform rocks and generate melts except plate tectonics. We define plate tectonics as a style of silicate body convection where lid fragment (plate) motions are mostly due to sinking of dense lithosphere in subduction zones, causing upwelling of asthenosphere at divergent plate boundaries and seafloor spreading accompanied by focused upwellings (mantle plumes). With this definition, the key geodynamic question is when did Earth's lithosphere become dense enough to begin to sink beneath underlying asthenosphere? We are impressed by the evidence that sufficient lithospheric densification required sufficient cooling and so is likely to have happened late in Earth history (Korenaga, 2013).

Here we use two lines of evidence to refute Ernst's uniformitarianist assumption that plate tectonics has dominated Earth's tectonic history. The first line of evidence comes from comparative planetology. Humanity finished taking a look at all the large bodies in the solar system in 2015 with the NASA Dawn mission to Ceres and the New Horizons mission to Pluto and Charon, and now know that Earth is alone in the solar system in having plate tectonics. Venus, Mars, and Io are tectonically and magmatically active, but none have plate tectonics. Io is the most active of the three because it is Jupiter's innermost satellite and is kept hot by tidal flexing. Io is characterized by heat pipe tectonics whereby subsurface magma erupts periodically, burying older lava flows under younger until the base of the volcanic pile sinks back into the magma (Moore and Webb, 2013). Venus is also tectonically and magmatically active, but dominated by mantle plumes and lithospheric drips (Gerya, 2014). Mars is a geriatric planet but still has igneous activity in the Tharsis and Elysium regions and tectonic activity centered on the Vallis Marineris. These planets share a stagnant lid tectonic style, where a single plate makes up the lithosphere and this is the dominant tectonic style of active planets, dwarf planets, and moons. Based on what we know about these bodies, there is a large range in stagnant lid behavior that is expected over the life of a planet. It is likely that Earth also experienced stagnant lid tectonics before plate tectonics evolved.

Our second counterargument is that geoscientists are increasingly interpreting ancient rock sequences on Earth in terms of tectonic transitions (Condie and Aster, 2010; Arndt and Davaille, 2013; Hawkesworth et al., 2016). Figure 1A shows a recent subdivision of Earth into "pre-subduction" and "subduction" episodes that is consistent with the rock record (Hawkesworth et al., 2016); these could also be called "plate tectonic" and "pre-plate tectonic" episodes. Figure 1B is our modification, based on the distribution of key plate tectonic indicators. Our preferred interpretation of Earth history identifies stagnant lid and plate tectonic episodes; note that a short episode of something similar to plate tectonics in terms of ophiolites is identified ~1.9–2.0 and ~1.1 Ga. The door is opening to further explorations of pre-plate tectonic Earth history.

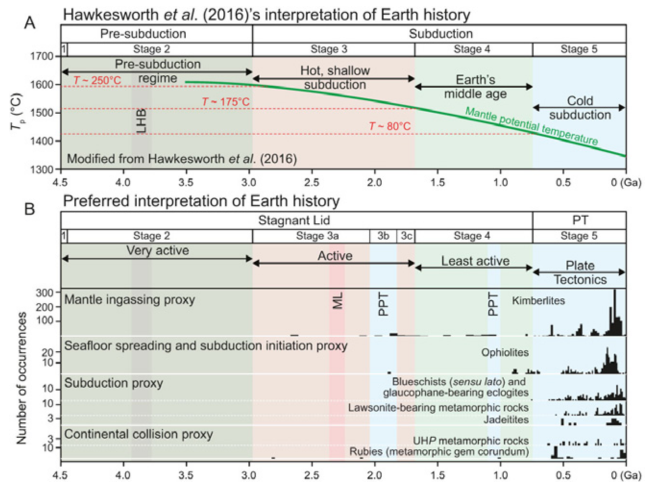

Figure 1. Alternate versions of Earth's tectonic evolution, both with subduction/plate tectonics, late, and pre-subduction/stagnant lid, early. A: The five stages of Hawkesworth et al. (2016). Stage 1—First few tens of millions of years: initial accretion and differentiation and magma ocean. Stage 2—Older than 3.0 Ga: generation of crust in a pre-plate tectonic regime. Stage 3—3.0–1.7 Ga: early plate tectonics–hot subduction with shallow slab breakoff. Stage 4—1.7–0.75 Ga: Earth's middle age, characterized by environmental, evolutionary, and lithospheric stability. Stage 5—younger than 0.75Ga: modern cold subduction. LHB—late heavy bombardment; PPT—proto plate tectonics; ML—magmatic lull of Condie et al., (2009). B: Our preferred alternate interpretation of Earths tectonic history. Stage 1—First few tens of millions of years: initial accretion and differentiation and magma ocean. Stage 2—Older than 3.0 Ga: very active stagnant lid environment: many drips and plumes. Stage 3—3.0–1.7 Ga: active stagnant lid: fewer, larger drips and plumes, komatiites and trondhjemite-tonalite-granodiorite intrusions during stage 3a, proto plate tectonics including ophiolites during stage 3b, abundant crustal production during stage 3c. Stage 4—1.7–0.75 Ga: least active stagnant lid: granites and anorthosites. Stage 5—younger than 0.75 Ga: sustained lithospheric subduction and true plate tectonics.

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