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# Long-term preservation of early formed mantle heterogeneity by mobile lid convection: Importance of grainsize evolution

Bradford J. Foley [a,b,*], Hanika Rizo [c,d]

[a] Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, DC, USA
[b] Department of Geosciences, Pennsylvania State University, University Park, PA, USA
[c] GEOTOP, Université du Québec à Montréal, Montréal, Québec H3C 3P8, Canada
[d] Department of Earth Sciences, Carleton University, Ottawa, ON K1S 5B6, Canada

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ABSTRACT

The style of tectonics on the Hadean and Archean Earth, particularly whether plate tectonics was in operation or not, is debated. One important, albeit indirect, constraint on early Earth tectonics comes from observations of early-formed geochemical heterogeneities: $^{142}$Nd and $^{182}$W anomalies recorded in Hadean to Phanerozoic rocks from different localities indicate that chemically heterogeneous reservoirs, formed during the first ∼500 Myrs of Earth's history, survived their remixing into the mantle for over 1 Gyrs. Such a long mixing time is difficult to explain because hotter mantle temperatures, expected for the early Earth, act to lower mantle viscosity and increase convective vigor. Previous studies found that mobile lid convection typically erases heterogeneity within ∼100 Myrs under such conditions, leading to the hypothesis that stagnant lid convection on the early Earth was responsible for the observed long mixing times. However, using two-dimensional Cartesian convection models that include grainsize evolution, we find that mobile lid convection can preserve heterogeneity at high mantle temperature conditions for much longer than previously thought, because higher mantle temperatures lead to larger grainsizes in the lithosphere. These larger grainsizes result in stronger plate boundaries that act to slow down surface and interior convective motions, in competition with the direct effect temperature has on mantle viscosity. Our models indicate that mobile lid convection can preserve heterogeneity for ≈0.4–1 Gyrs at early Earth mantle temperatures when the initial heterogeneity has the same viscosity as the background mantle, and ≈1–4 Gyrs when the heterogeneity is ten times more viscous than the background mantle. Thus, stagnant lid convection is not required to explain long-term survival of early formed geochemical heterogeneities, though these heterogeneities having an elevated viscosity compared to the surrounding mantle may be essential for their preservation.



## 1. Introduction

The style of mantle convection and surface tectonics on the early Earth is poorly constrained and strongly debated (e.g. see Condie and Kröner, 2008; Korenaga, 2013; O'Neill and Debaille, 2014, for reviews). The Hadean and Eoarchean rock record is sparse, consisting only of Hadean zircons from the Jack Hills region in Australia and highly metamorphosed terranes such as the Nuvvuagittuq greenstone belt and the Acasta gneiss complex in Canada (e.g. Iizuka et al., 2006; O'Neil et al., 2012; Valley et al., 2014), and is difficult to interpret in terms of global tectonic processes. Although some authors have argued for subduction based on the petrology, geochemistry, and structural geology of the Hadean and Eoarchean geologic record (e.g. Harrison et al., 2005; Hopkins et al., 2008; Polat et al., 2011; Turner et al., 2014; Komiya et al., 2015), these interpretations are controversial and a lack of subduction and surface plate mobility on the early Earth is also argued (e.g. Kemp et al., 2010; O'Neill and Debaille, 2014; Reimink et al., 2014). However, another line of geochemical evidence that can potentially shed light on early Earth dynamics is the presence of early formed isotope variations in mantle-derived rocks, which constrain how long heterogeneity survived before being remixed into the mantle during Earth's early evolution. In fact, attempts to use primordial isotope variations to constrain early Earth tectonics have been made in previous studies (see §1.2). In this paper the extent to which the survival time of early formed mantle chemical heterogeneities can be used to constrain early Earth mantle

* Corresponding author at: Department of Geosciences, Pennsylvania State University, University Park, PA, USA.
*E-mail addresses:* bjf5382@psu.edu (B.J. Foley), hanikarizo@cunet.carleton.ca (H. Rizo).

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dynamics and surface tectonics is re-assessed using new models of mantle convection.

### 1.1. Geochemical constraints on early Earth mantle dynamics

The time of formation and length of survival of chemical reservoirs created in the early Earth can be studied using short-lived isotope systems. The parent nuclides of these systems were only decaying during the first tens to few hundreds of millions of years of Earth's history, therefore, variations in the abundance of daughter nuclides reflect geological processes occurring during, or shortly after, the Earth's accretion. Mantle derived rocks that show resolvable variations in these early-formed isotopes allow the age of their mantle source to be constrained, and the persistence of these variations through the geologic record documents the duration of survival of chemical reservoirs through time.

Two important short-lived isotope systems are the decay of $^{182}$Hf into $^{182}$W ($t_{1/2} = 8.9$ Ma) and the decay of $^{146}$Sm into $^{142}$Nd ($t_{1/2} = 103$ Ma); these systems are sensitive to differentiation processes that occurred during the first ∼50 Ma and ∼500 Ma of Earth's history, respectively. Variations in $^{182}$W and/or $^{142}$Nd have now been detected in Hadean rocks from the Nuvvuagittuq greenstone belt and the Acasta gneiss complex (O'Neil et al., 2012; Touboul et al., 2014; Willbold et al., 2015), in Eoarchean rocks from the Isua supracrustal belt and Saglek–Hebron gneiss complex (e.g. Caro et al., 2006; Rizo et al., 2013; Willbold et al., 2011; Liu et al., 2016; Rizo et al., 2016a; Morino et al., 2017), in Late Archean rocks from the Abitibi, Barberton, and Kostomuksha greenstone belts (Debaille et al., 2013; Touboul et al., 2012; Puchtel et al., 2016), and recently, in Phanerozoic basalts (Rizo et al., 2016b; Mundl et al., 2017). Altogether, these observations imply that silicate chemical reservoirs created more than 4.1 billion years ago have the potential to survive their re-mixing by mantle convection for long timescales.

Mixing timescales do not appear to be the same throughout the Earth's mantle. While the southwest Greenland mantle heterogeneities seem to be effectively eradicated by 3.4–3.3 Ga (Rizo et al., 2013), suggesting ∼1 Ga mixing time scales, early-formed isotope variations in 2.8–2.7 Ga komatiites (Debaille et al., 2013; Touboul et al., 2012) imply the persistence of heterogeneities for ∼2 Ga. Furthermore, while $^{142}$Nd isotope variations have not been observed in modern mantle-derived rocks (e.g. Cipriani et al., 2011), the recent $^{182}$W anomalies found in modern basalts imply that at least some mantle domains formed during the Earth's accretionary period still remain in the modern mantle. A key observation of these recent results, however, is that the isotope anomalies were detected in plume-related magmatism, which has often been associated with the large low seismic shear velocity provinces (LLSVP) imaged at the base of the mantle (e.g. Garnero and McNamara, 2008). If the source of the $^{182}$W anomalies detected in the Phanerozoic rocks is the LLSVP regions, it would imply that early-formed mantle domains can survive through 4.5 Ga of dynamic Earth history.

An important question is then whether early-formed chemical reservoirs survived within the convecting mantle, or were essentially isolated from the convecting mantle and its propensity for mixing and erasing heterogeneity. The recently observed $^{182}$W anomalies found in Phanerozoic basalts may well have been sequestered from the convecting mantle in dense piles at the core-mantle boundary region, potentially explaining how they survived for nearly all of Earth's history. However, there is no evidence that the Hadean and Archean rocks recording $^{142}$Nd and $^{182}$W anomalies are sourced from the LLSVP regions. As such these observations indicate that mixing by mantle convection must have been slow enough during the Hadean and Archean to preserve heterogeneity for at least 1–2 Gyrs.

### 1.2. Previous geodynamic estimates of early Earth mantle mixing and implications for the style of tectonics

Preservation of mantle heterogeneity for such a long timescale during Earth's early history is seemingly difficult to explain. The early Earth was hotter due to a larger supply of primordial heat and higher rates of radiogenic heating (e.g. Korenaga, 2006), and hotter temperatures act to decrease the average mantle viscosity and in turn increase the vigor of convection and the speed of mixing. Thus, the mixing time for chemical heterogeneity under these high mantle temperature conditions is typically estimated at ∼100 Myrs (Coltice and Schmalzl, 2006). In a recent study, Debaille et al. (2013) (see also O'Neill and Debaille, 2014) proposed that the long-term preservation of early formed chemical heterogeneity is evidence for stagnant lid convection on the early Earth. Debaille et al. (2013) found that mobile lid convection produces rapid mixing, on the order of 100 Myrs at early Earth conditions (consistent with previous studies), while stagnant lid convection produces slower mixing times of ∼1 Gyrs, consistent with the geochemical observations.

The convection models used in Debaille et al. (2013) assumed a temperature dependent viscosity with a yield stress criterion for generating subduction and surface mobility. The yield stress formulation produces mobile lid convection by allowing the lithosphere to "fail" at a specified stress, the yield stress. Failure is parameterized as a viscosity reduction in the lithosphere, such that weak, localized plate boundaries (which are necessary for generating plate-like mantle convection (Bercovici et al., 2015)) can form. Convection with a yield stress rheology has been found to behave similarly to constant viscosity convection, where the ambient mantle viscosity dictates the speed at which plates move such that they follow the classic scaling law where velocity is proportional to the Rayleigh number to the 2/3 power (e.g. Moresi and Solomatov, 1998). Thus a lower mantle viscosity, caused by higher mantle temperatures, leads directly to faster plates and rapid mixing.

However, the physics of lithospheric shear zone formation is known to be more complicated than the simple pseudoplastic yield stress formulation. The pseudoplastic rheology does not allow for dormant plate boundaries (plate boundaries immediately regain their strength once they become inactive), which play a vital role in subduction initiation (Toth and Gurnis, 1998), and does not consider the micro-scale processes, such as grainsize reduction, that are likely important for plate boundary formation (Bercovici et al., 2015). Using a more complex rheology for generating plate tectonics from mantle convection could potentially lead to very different relationships between mantle temperature, plate speed, and mixing efficiency than those previously observed in pseudoplastic models.

### 1.3. Role of grainsize evolution in early Earth mantle dynamics, and purpose and scope of this study

Grain-damage, a recently developed theory for plate generation based on grainsize reduction in the mid-lithosphere, allows for dormant plate boundaries and better represents the microphysical processes occurring in lithospheric shear zones (e.g. Bercovici and Ricard, 2012). With the grain-damage mechanism, weak plate boundaries are generated by grainsize reduction, as small grainsizes lead to lower viscosities when deformation is predominantly in the diffusion creep or grain-boundary sliding regime (e.g. Hirth and Kohlstedt, 2003). An important aspect of grainsize evolution is that grains grow more quickly at high temperatures than at cold temperatures (e.g. Karato, 1989), so high temperature conditions impede grainsize reduction. The effect of temperature on grain-growth means that increasing mantle temperature has two competing effects on plate speed, and thus mantle mixing efficiency: