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Archean crustal compositions promote full mantle convection

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ABSTRACT

Higher mantle potential temperatures characterized the early Earth, resulting in thicker, more mafic oceanic crust entering subduction systems. This change in the composition of subducted slabs, combined with the enhanced temperature contrast between the slab and ambient mantle, would have altered the buoyancy forces driving subduction in the early Earth. Here we investigate this "compositional effect" through a combination of petrologic and thermal modeling. Specifically, we construct density profiles for sinking slabs under modern and early Earth conditions based on a range of mafic crust and mantle compositions. Slab and mantle densities are then determined from mineral assemblages calculated using the thermodynamic modeling program Perple_X along slab geotherms estimated from an analytic thermal model. Consistent with previous studies, we find that modern MORB compositions are typically less dense than the ambient mantle in the basalt barrier zone, located immediately beneath the mantle transition zone. By contrast, possible early Earth oceanic crust compositions are denser than ambient mantle at all depths down to 1000 km. This compositional effect results in slabs that would have more readily penetrated the transition zone, promoting single-layered convection and effective mantle mixing in the early Earth.

1. Introduction

Seismic tomography reveals that subducted slabs today exhibit three distinct behaviors near the mantle transition zone, which marks the boundary between the upper and lower mantle (e.g., Fukao and Obayashi, 2013; Li et al., 2008): (1) stagnation in the mantle transition zone (e.g., Aleutian Arc – Gorbatov et al., 2000; Japan trench – Huang and Zhao, 2006); (2) stagnation in the uppermost lower mantle (e.g., Peruvian Andes – Fukao et al., 2001); and (3) descent, apparently unhindered, directly into the lower mantle (e.g., Central America – van der Hilst et al., 1997; Farallon plate under western North America – Sigloch et al., 2008; Tethys plate under India – Van der Voo et al., 1999). These tomographic observations suggest some form of whole mantle convection. However, models of the geochemical evolution of the mantle typically suggest discrete mantle reservoirs (e.g., Javoy et al., 2010; Kumari et al., 2016), and/or layered mantle convection for much of Earth's history (e.g., Allègre et al., 1996; Allègre, 1997). The apparent contradiction between these two sets of observations motivates a reexamination of the evolution of subducted slab behavior over Earth history. In particular, it is necessary to better understand how the dynamics of subducted slabs would have differed in the hotter mantle of the early Earth.

1.1. Behavior of subducted slabs in the modern Earth

The buoyancy of subducted slabs in the transition zone is controlled by two factors: (1) the thermal buoyancy of the cold slab, and (2) the chemical buoyancy resulting from different compositions and phase transitions in the subducting lithospheric mantle and oceanic crust relative to the ambient mantle. The density of mantle peridotite strongly increases due to the transitions from olivine to increasingly dense polymorphs wadsleyite and ringwoodite at 410 km and 525 km, respectively, and the subsequent breakdown of ringwoodite to form bridgmanite and ferropericlase at 670 km (Ringwood and Irifune, 1988; Tschauner et al., 2014; Fig. 1A). The first of these reactions has a positive Clapeyron slope and thus occurs at shallower depths in cold slabs relative to the ambient mantle, helping to drive subduction. In contrast, the last of these reactions has a negative Clapeyron slope and occurs at greater depths in the cold slab, resisting further sinking into the lower mantle. A range of values has been experimentally determined for this reaction (e.g. Frost, 2008). Numerical studies have shown that this reaction can have a significant effect on slab behavior at the largest determined Clapeyron slopes (i.e. <-2.5 Mpa/K; e.g., Christensen and Yuen, 1985;

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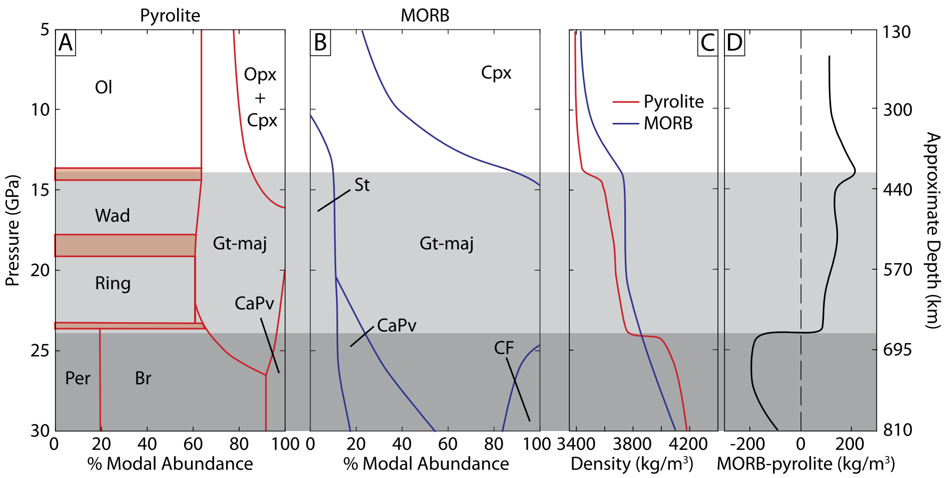

Fig. 1. Previously published experimental results for the mineralogy of pyrolite (A) and MORB (B) along adiabatic temperature gradients. Also shown are density profiles for both compositions (C) and density difference (D). The mantle transition zone is shown in light gray, while the basalt barrier zone, where MORB is less dense than ambient mantle is shown in dark gray. Pyrolite mineralogy after (Ringwood, 1991), MORB mineralogy and density profiles after (Irifune and Ringwood, 1993). Mineral abbreviations: Ol – olivine; Wad – wadsleyite; Ring – ringwoodite; Per – ferropericlase; Br – bridgmanite; CaPv – calcium perovskite; Gt-maj – Garnet (including majoritic solid solutions); Opx – orthopyroxene; Cpx – clinopyroxene; St – stishovite; CF – calcium ferrite structured aluminous phase.

Torii and Yoshioka, 2007; Wolstencroft and Davies, 2011; Agrusta et al., 2017). However, numerical simulations employing smaller values more consistent with recent experiments (i.e. ∼0 to −1 Mpa/K; Katsura et al., 2003; Fei et al., 2004; Litasov and Ohtani, 2005; Litasov et al., 2005) suggest that this reaction does not strongly control the behavior of slabs in the transition zone (e.g., King et al., 2015; Torii and Yoshioka, 2007; Agrusta et al., 2017). An additional complication results from the apparent sensitivity of this reaction's Clapeyron slope to the presence of water: it appears from experiments (Ohtani and Litasov, 2006) that the magnitude of the slope increases significantly for a wet mantle, as may be expected in subducted slabs.

These observations have led to additional work that focuses on the importance of phase transitions in the subducted oceanic crust as opposed to the subducted lithospheric mantle. In particular, the elevated aluminum content in modern mid-ocean ridge basalt (MORB) relative to mantle peridotite results in a significantly extended stability field of majoritic garnet below the base of the transition zone (Irifune and Ringwood, 1993; Fig. 1B). The enhanced majorite stability in MORB contributes significantly to its increased density relative to ambient mantle in the transition zone. However, stable majorite in the lower mantle is less dense than phases stable in mantle peridotite at equivalent depths, resulting in MORB that is positively buoyant between 670 km and the final breakdown of majorite at 720–800 km depth (Hirose et al., 1999; Irifune and Ringwood, 1993; Ringwood, 1967; Fig. 1C–D). This effect was termed the "basalt barrier" (Ogawa, 2003), and was shown in models to enhance slab stagnation (Christensen, 1997), or to cause intermittently layered convection (Davies, 2008; Ogawa, 2007, 2003). More recent experimental studies have shown that the density inversion associated with the basalt barrier zone may be smaller or even disappear if the slab is sufficiently cold (Litasov et al., 2004), or if the MORB component is sufficiently hydrated (Litasov and Ohtani, 2005), although it is highly uncertain how much water is carried with the slab into the transition zone.

A variety of additional explanations exist for the variable transition zone behavior of modern slabs, including: kinetically impeded phase transitions in the cold slab, resulting in metastable olivine polymorphs (Rubie and Ross, 1994; Bina, 1996; Bina et al., 2001) or pyroxene (Nishi et al., 2013; Agrusta et al., 2014; King et al., 2015; van Mierlo et al., 2013); rheological weakening of the slab due to grain-size reduction in the transition zone (Čížková et al., 2002; Karato et al., 2001); slab dip in the upper mantle (Billen, 2010; Christensen, 1996); and increased viscosity, either in (Garel et al., 2014; Quinteros et al., 2010; Yoshioka and Sanshadokoro, 2002), or below (Marquardt and Miyagi, 2015; Rudolph et al., 2015) the transition zone. While the exact depth, magnitude, and cause of the increase in mantle viscosity near the transition zone is unknown, numerous studies show it to be a global phenomenon (Čížková et al., 2012; Forte and Mitrovica, 1996; Hager, 1984; Lambeck et al., 1990; Mitrovica and Forte, 2004; Simons and Hager, 1997; Steinberger and Calderwood, 2006), and therefore mantle viscosity structure alone cannot be responsible for the range of slab behaviors without interactions with one or more additional parameters.

1.2. *Archean Earth*

While it is likely that complex combinations of many factors are required to explain the range of subducted slab behaviors observed in the transition zone today, it is possible to predict first order changes to the thermal and compositional buoyancy structure of subducted slabs that would result from a hotter early Earth. Multiple lines of evidence, including modeling (e.g., Korenaga, 2013), and the rock record (Abbott et al., 1994; Herzberg et al., 2010; van Hunen et al., 2008) suggest that the Earth's mantle was hotter in the past than it is today. Komatiites provide one line of evidence for a hotter mantle (Nisbet et al., 1993), although at least some komatiites may be arc derived hydrous melts (e.g., Parman et al., 2004; Wilson, 2003). The record of mafic rocks taken as a whole also documents a temporal shift in composition that can be linked to secular cooling (Abbott et al., 1994; Furnes et al., 2015; Herzberg et al., 2010; Keller and Schoene, 2012; van Hunen et al., 2008). Further, there is a growing consensus that modern style plate tectonics including subduction of oceanic crust was the dominant tectonic mode on Earth by at least 2.5–3.0 Ga (e.g., Brown, 2007; Polat and Kerrich, 2006; Shirey and Richardson, 2011; Turner et al., 2014), coincident with peak mantle potential temperatures inferred from the rock record and calculated in some models of mantle thermal evolution (Herzberg et al., 2010; Korenaga, 2013; Labrosse and Jaupart, 2007).

Although the identification of unequivocal Archean oceanic crust remains elusive (Bickle et al., 1994; Furnes et al., 2015), it is possible to predict key changes to MORB composition as a result of higher mantle potential temperatures from laboratory experiments (e.g., Walter, 1998), as well as from the composition of

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