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Does partial melting explain geophysical anomalies?

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ABSTRACT

The existence of partial melt is frequently invoked to explain geophysical anomalies such as low seismic wave velocity and high electrical conductivity. I review various experimental and theoretical studies to evaluate the plausibility of this explanation. In order for a partial melt model to work, not only the presence of melt, but also the presence of appropriate amount of melt needs to be explained. Using the mineral physics observations on the influence of melt on physical properties and the physics and chemistry of melt generation and transport, I conclude that partial melt model for the asthenosphere with homogeneous melt distribution does not work. One needs to invoke inhomogeneous distribution of melt if one wishes to explain observed geophysical anomalies by partial melting. However, most of models with inhomogeneous melt distribution are either inconsistent with some geophysical observations or the assumed structures are geodynamically unstable and/or implausible. Therefore partial melt models for the geophysical anomalies of the asthenosphere are unlikely to be valid, and some solid-state mechanisms must be invoked. The situation is different in the deep upper mantle where melt could completely wet grain-boundaries and continuous production of melt is likely by "dehydration melting" at around 410-km. In the ultralow velocity zone in the D″ layer, where continuous production of melt is unlikely, easy separation of melt from solid precludes the partial melt model for low velocities and high electrical conductivity unless the melt density is extremely close to the density of co-existing solid minerals or if there is a strong convective current to support the topography of the ULVZ region. Compositional variation such as Fe-enrichment is an alternative cause for the anomalies in the D″ layer.

1. Introduction

Interpretation of geophysical anomalies such as the low velocity and high electrical conductivity is a key to the understanding of the dynamics and evolution of Earth. Before ~1970 when the materials properties under deep Earth conditions were not well understood, most of geophysicists thought that in order to explain low seismic wave velocities and high electrical conductivity one needs some liquids (e.g., Anderson and Spetzler, 1970). The partial melt hypothesis is an obvious choice because temperature in some regions of the mantle (e.g., the asthenosphere) likely exceeds the solidus.

However, subsequent laboratory studies showed that (i) the amount of melt produced in the asthenosphere away from the ridges is small (~0.1% or less) (e.g., Plank and Langmuir, 1992), (ii) most of the melts in the mantle do not completely wet grain-boundaries and hence the influence of partial melt to influence the physical properties is limited (e.g., Kohlstedt, 1992) and (iii) solids can show substantial reduction in elastic properties (e.g., Jackson, 2009) and high electrical conductivity (e.g., Karato and Wang, 2013) caused by the action of various crystalline defects including impurities such as hydrogen.

One of the important progresses is the recognition that the role of partial melt to modify the physical properties depends critically on the geometry of melt (e.g., the dihedral angle). Stocker and Gordon (1975) showed that earlier studies showing a large effect of a small amount of melt on elastic wave velocities and attenuation (e.g., Mizutani and Kanamori, 1964; Spetzler and Anderson, 1968) was due to the fact that in these systems liquids completely wet grain-boundaries, and that such may not be the case for Earth's upper mantle. Non-wetting behavior of basaltic melt has been confirmed by laboratory studies (e.g., Kohlstedt, 1992) although complete wetting was reported under deep upper mantle conditions (Yoshino et al., 2007).

Another important progress occurred in the experimental petrology showing that substantial partial melting is limited to the vicinity of the mid-ocean ridges and the degree of melting in the asthenosphere away from the ridge is small (~0.1%; e.g., Dasgupta and Hirschmann, 2007; Plank and Langmuir, 1992). Theoretical studies also showed that the melt-solid segregation is efficient in most cases making it difficult to keep a substantial amount of melt in the gravity field (e.g., McKenzie, 1984; Richter and McKenzie, 1984).

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At the same time, the importance of solid-state mechanisms to reduce seismic wave velocities and enhance electrical conductivity has also been noted. Gueguen and Mercier (1973) suggested that anelastic relaxation could result in low seismic wave velocity and high attenuation. This concept was elaborated by Goetze (1977) who also discussed a possible role of hydrogen. Karato (2012), Karato and Jung (1998) further extended these models to include the effects of hydrogen and grain-boundary sliding. Similarly Karato (1990) suggested a possible role of hydrogen to enhance electrical conductivity. Experimental studies to test these models have been conducted that largely support these early suggestions (e.g., Faul and Jackson, 2005; Jackson et al., 2002; Karato and Wang, 2013).

In short, these new developments imply that the role of partial melting to modify the physical properties is much more limited than previously thought, and that sub-solidus mechanisms involving some "defects" may account for most, if not all, of these geophysical anomalies. Despite these important progresses that have occurred during the last ~30 years, partial melt models for low seismic wave velocity and high electrical conductivity are still frequently discussed in geological and geophysical literatures (e.g., Gaillard et al., 2008; Hirschmann, 2010; Kawakatsu et al., 2009; Kumar et al., 2012; Lay et al., 2004; Mierdel et al., 2007; Ni et al., 2011; Williams and Garnero, 1996). However, in these papers, discussions to support various versions of partial melt models are not comprehensive, and many key issues were not addressed such as the processes to maintain the required amount of melt. The purpose of the present paper is to integrate the latest knowledge of the physics and chemistry of partial melting to evaluate the plausibility of partial melt models for geophysical anomalies. It is concluded that partial melt models are unlikely to explain geophysical anomalies except for the low velocity anomalies above the 410-km discontinuity.

2. How much melt do we need to explain geophysical anomalies?

The first question to be addressed is how much melt do we need to explain geophysical anomalies? Let us focus on seismic wave velocities and electrical conductivity because these are the most frequently used observations to infer the internal structure of Earth's mantle. Also let us first focus on models where melt is distributed homogeneously. The influence of inhomogeneous melt distribution will be discussed in the Section 4.

As discussed above, the influence of partial melting depends on the geometry of melt (dihedral angle). For a likely dihedral angle appropriate to the shallow asthenosphere (i.e., 20–40°), one needs 3–6% of liquid to explain observed 5–10% of velocity reduction (e.g., Takei, 2002). Note, however, that the dihedral angle changes with pressure and becomes close to 0° (complete wetting) in the deep upper mantle (below ~300 km) (Yoshino et al., 2007). If melt completely wets grain-boundaries (dihedral angle = 0°) then even a small amount of melt (~0.1%) can significantly reduce the seismic wave velocities.

The amount of melt to explain electrical conductivity (without any other effects) is sensitive to the impurity content in the melt that modifies the electrical conductivity of melt. For basaltic melt with a small amount of impurities, one would need a few % of melt to enhance conductivity to explain geophysical observations (e.g., Shankland et al., 1981). However, recent studies showed the importance of impurities on the electrical conductivity of melts (Gaillard et al., 2008; Ni et al., 2011; Yoshino et al., 2010). These studies showed that when a large amount of highly mobile ions (e.g., H^+, K^+, Na^+) are dissolved in the melt then the electrical conductivity of melts increases significantly (high electrical conductivity of carbonatite melt observed by Gaillard et al. (2008) is mainly due to the high concentration of Na and K).

The high conductivity of these melts implies that one will need only a small amount of melt to enhance electrical conductivity. If one uses these new results on realistic melt compositions, one would only need ~0.1% of melt in order to explain the electrical conductivity of ~10^{-2} S/m in the asthenosphere away from the ridges (e.g., Baba et al., 2006).

3. How much melt could we have in the mantle?

Now we should ask if we can have an enough amount of melt in these regions (e.g., the asthenosphere, ultra-low velocity regions) to explain geophysical observations. This question can be addressed by considering the following hypothetical situations:

3.1. Partial melting in a system without gravity

If there were no gravity, then melt produced by partial melting would stay there and the system would behave like a closed system. The melt fraction in such a system agrees with the degree of melting and can be calculated directly from the phase diagram (melt fraction and the degree of melting do not agree in an open system and the melt fraction in an open system cannot be calculated from the phase diagram alone). At a given temperature and pressure for a given composition, one can calculate the volume fraction of melt from the experimentally determined phase diagrams. This can be done for the upper mantle where the melting relationship is well established (e.g., Hirschmann, 2010; Kushiro, 2001; Plank and Langmuir, 1992). In the shallow upper mantle, partial melting occurs in the upwelling materials beneath a ridge, initially helped by volatiles (such as water and carbon dioxide) at ~80–120 km. Under these conditions, the amount of melt is controlled by the amount of volatiles, and given a plausible estimate of volatile content in the upper mantle (e.g., Hirschmann, 2006; Wood et al., 1996), it is estimated to be on the order of ~0.1%. In the shallow portions of an upwelling column, substantial melting, up to ~10%, starts when the geotherm exceeds the dry solidus (~60–80 km below a typical ridge; the exact depth depends on the potential temperature). Away from the ridge, the amount of melt in the closed system will be ~0.1% or less (see e.g., Hirschmann, 2010; Plank and Langmuir, 1992).

3.2. Influence of compaction by gravity

When gravity is present, then melt will migrate upward or downward depending on its density relative to the density of the surrounding rock. Consequently, the melt fraction in such a system cannot be completely predicted by the phase diagram.

The physics of melt separation has been studied by McKenzie (1984), Ribe (1985), Richter and McKenzie (1984). If the density of the melt is different from that of the solid, then melt and solid will be separated by gravity. This process involves melt migration through the solid through percolation, but solid must also deform to allow the change in the melt fraction. Therefore this process is controlled by the viscosity of both solid and melt as well as the melt permeability that depends in turn on the melt fraction. Two parameters characterize this process, namely the compaction length, $\boldsymbol{\delta}_c$, and the compaction time, $\boldsymbol{\tau}_c$, viz. (Richter and McKenzie, 1984),

$$\boldsymbol{\delta}_c = \sqrt{\frac{k\boldsymbol{\eta}_s}{\boldsymbol{\eta}_m}} \tag{1}$$