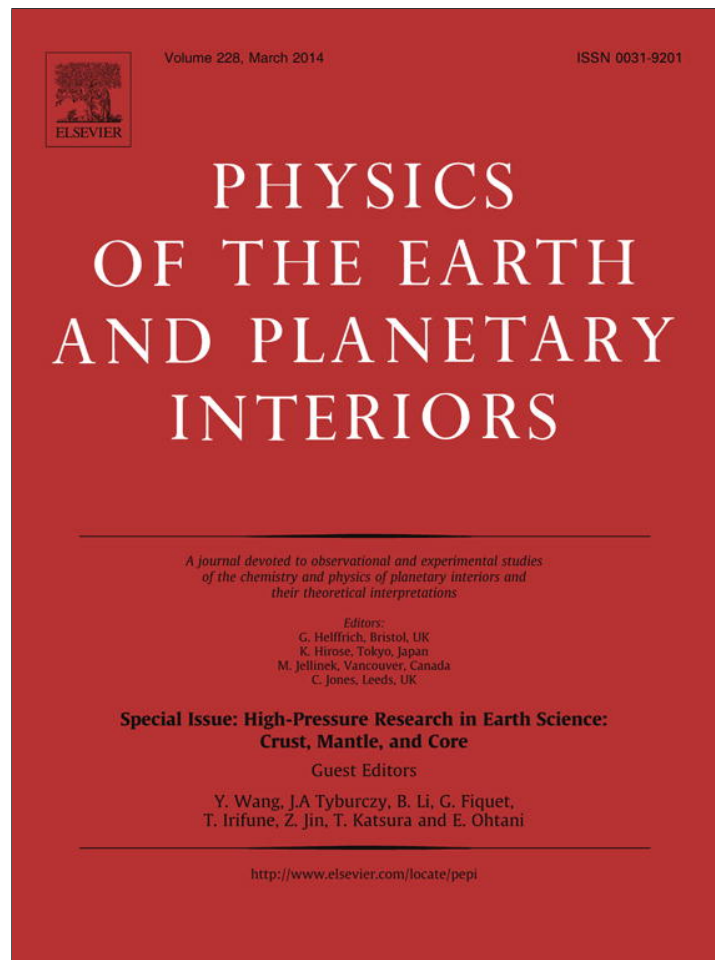


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## Does partial melting explain geophysical anomalies?



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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.

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### 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<sup>+</sup>, K<sup>+</sup>, Na<sup>+</sup>) 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<sup>-2</sup> 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,  $\delta_c$ , and the compaction time,  $\tau_c$ , viz. (Richter and McKenzie, 1984),

$$\delta_c = \sqrt{\frac{k\eta_s}{\eta_m}} \quad (1)$$

$$\tau_c \approx \sqrt{\frac{\eta_s \eta_m}{k}} \frac{1}{\Delta\rho \cdot g} \quad (2)$$

where  $\eta_m$  is the viscosity of melt,  $\eta_s$  is the viscosity of the solid skeleton,  $k$  is permeability,  $\Delta\rho$  is the density difference between melt and solid and  $g$  is acceleration due to gravity. For simplicity I assume that the viscosity of the solid skeleton is the same as that of the solid (viscosity of solid skeleton can be different from that of the solid at large porosity (e.g., Bercovici et al., 2001), but I ignore this difference). Using representative values of these parameters adopted by Richter and McKenzie (1984) (similar values would hold for the D'' layer), I get  $\delta_c \sim 1\text{--}100$  m and  $\tau_c \sim 0.01\text{--}1$  M years. After  $\sim 10 \tau_c$ , a large portion of melt is accumulated in a thin region with a thickness of the compaction length (Richter and McKenzie, 1984). I conclude that a majority of the material will have a substantially less melt fraction (less than 10% of the initial amount) if the influence of compaction is included.

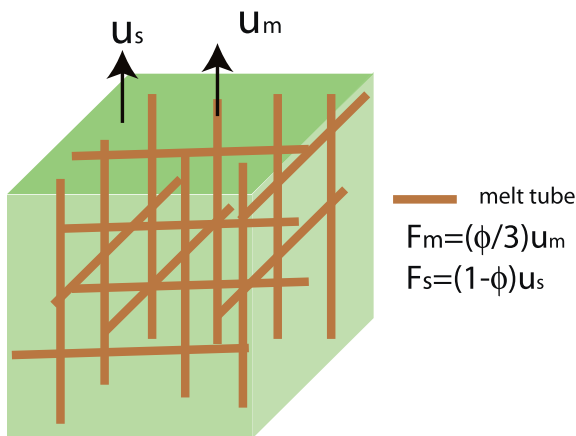
### 3.3. Melt fraction in a system where both melt generation and melt migration occur

The above discussion ignored the influence of melt generation. A more realistic system is a system where melt is generated and transported. Let us consider a system beneath a mid-ocean ridge (Fig. 1). Although both melt generation and transport processes can be complicated, one can estimate the melt fraction using a simple model.

Because the thickness of the oceanic crust is  $\sim 7$  km and that of the oceanic lithosphere is  $\sim 70$  km, the ratio of the flux of melt to the flux of solid under a mid-ocean ridge is  $\frac{F_m}{F_s} \approx \frac{7}{70} = 0.1$  where  $F_m$  is the flux of melt ( $\text{m}^3/\text{m}^2/\text{s}$ ) and  $F_s$  is the flux of solid. Assuming permeable flow, the melt flux can be expressed as (e.g., Schubert et al. (2001))

$$F_m = \frac{\phi}{3} u_m = \frac{d^2 \phi^2 \Delta\rho \cdot g}{72 \phi \eta_m} \quad (3)$$

where  $u_m$  is the velocity of melt migration,  $d$  is grain-size,  $\phi$  is melt fraction (porosity). From the plate velocity, the solid flux is given as  $F_s = (1 - \phi)u_s \approx u_s \approx 10^{-9}$  m/s ( $u_s$  is the velocity solid (velocity of mantle convection)). Inserting the plausible values of parameters



**Fig. 1.** A schematic diagram showing the flux of melt and solid near a mid-ocean ridge. In a region where melt is continuously produced and migrates, the melt fraction can be estimated from the flux of solid and melt inferred from the geological structure. In case of the oceanic upper mantle, the melt flux can be inferred from the thickness of the oceanic crust and the solid flux from the plate velocity. Melt flux and solid flux are related to their respective velocity, i.e.,  $u_m$  and  $u_s$  through the melt fraction (porosity),  $\phi$ , as  $F_m = \frac{\phi}{3}u_m$  and  $F_s = (1 - \phi)u_s \approx u_s$  respectively. Assuming the permeable flow that depends strongly on the melt fraction, the melt fraction is estimated to be on the order of  $\sim 0.1\%$ .

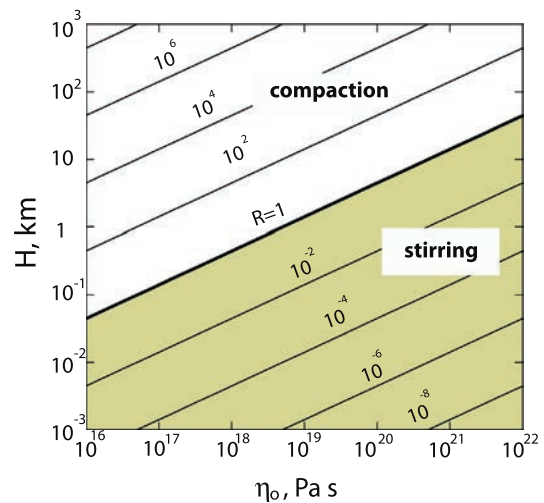
in Eq. (3) ( $d = 1$  cm,  $\Delta\rho = 500$  kg/m<sup>3</sup>,  $\eta_m = 1$  Pa s), one obtains  $\phi \approx 10^{-3}$  ( $\approx 0.1\%$ ). A small value of melt fraction is due essentially to the fact that melt migration velocity is much faster than the velocity of mantle convection. Spiegelman and Elliott (1993) inferred a similar melt fraction below mid-ocean ridges based on the isotope observations.

### 3.4. Influence of convective stirring

Although compaction due to gravity will segregate melt in a static system (system without melt generation), a substantial amount of melt could still be kept in such a system if the pressure gradient caused by convection in a layer next to the partial melt layer causes melt circulation (Hernlund and Jellinek, 2010). The degree to which convective stirring keeps melt in a layer can be evaluated by a non-dimensional parameter,

$$R = \frac{\Delta\rho \cdot gH^2}{\eta_o v} \quad (4)$$

where  $\Delta\rho$  is the density contrast between melt and surrounding solid,  $g$  is the acceleration due to gravity,  $H$  is the horizontal scale at which the pattern of convection in a layer above a partial melt layer changes,  $\eta_o$  is the viscosity of solid next to the partial melt layer where convection occurs, and  $v$  is the velocity of convective flow. If  $R \ll 1$ , then convection dominates and melt will be stirred and a substantial amount of melt could be kept in a layer against gravitational compaction. The ability for convective pressure gradient to stir melt against compaction depends strongly on the viscosity of a layer where convection occurs ( $\eta_o$ ) and the space scale at which the convection pattern in the nearby layer changes ( $H$ ). Fig. 2 shows the values of  $R$  as a function of ( $\eta_o$ ) and  $H$  where I assume the convective velocity of  $10^{-9}$  m/s. In order for the melt to be stirred by convection-induced pressure gradient, a high viscosity and the small scale of flow geometry are needed. For the asthenosphere where the density difference is  $\sim 500$  kg/m<sup>3</sup> (e.g., Richter and



**Fig. 2.** Influence of viscosity ( $\eta_o$ ) and space scale of flow ( $H$ ) in the nearly solid layer on stirring the melt in a partially molten region. Convective flow near a partial melt layer could stir melt in a partially molten layer due to dynamic pressure. The influence of convective flow on melt distribution is characterized by a non-dimensional parameter,  $R = \frac{\Delta\rho \cdot gH^2}{\eta_o v}$ :  $\Delta\rho$ : density contrast between melt and solid ( $\sim 500$  kg/m<sup>3</sup>),  $g$ : acceleration due to gravity,  $H$ : the horizontal scale where the geometry of convective flow changes,  $\eta_o$ : viscosity of solid in a convecting region,  $v$ : velocity of flow in a convecting region ( $\sim 10^{-9}$  m/s) (this is a canonical value for a typical mantle). Near the ULVZ region where a large density anomaly likely exists, much larger velocity would be possible. For details see text and Hernlund and Jellinek (2010), Jellinek and Manga (2002). If  $R \ll 1$ , then convective stirring will keep melt in a region.

McKenzie, 1984) and the viscosity is estimated to be  $\sim 10^{18}$ – $10^{20}$  Pa s (e.g., Nakada and Lambeck, 1989; Pollitz et al., 1998), one needs to have  $H < 0.4$ – $4$  km in order to have  $R < 1$  (stirring). For the ULVZ for which the viscosity of the nearby solid layer is  $\sim 10^{18}$  Pa s (Nakada and Karato, 2012), one would need  $H < 0.4$  km (assuming the same density contrast as in the asthenosphere). These characteristic space scales are much less than those expected in the layer below the asthenosphere (1000s of km) and in the layer near the ULVZ (10s of km).

It appears that maintaining a melt against compaction is difficult. However, if the topography of the ULVZ region is maintained by the pressure gradient caused by the convective current above that region, as proposed by Hernlund and Jellinek (2010) (see also Jellinek and Manga, (2002)), then the velocity of convective current and the physical properties of the ULVZ are not independent and the above approach will not work. If one accepts this model, then there will be strong current ( $\sim 10^{-6}$  m/s; I assume  $\Delta\rho = 100$  kg/m<sup>3</sup>,  $H = 50$  km,  $\eta = 10^{18}$  Pa s). In such a case, one might expect the presence of some melt in the ULVZ, but it is difficult to assess the plausibility of partial melt explanation for the low velocity quantitatively because the wetting behavior of these melts is unknown.

In summary, the melt fraction in all cases considered is less than or close to  $\sim 0.1\%$  that is too small to explain low seismic wave velocities although it is close to the value necessary to explain electrical conductivity. An exception is the deep upper mantle just above 410-km, where a complete wetting likely occurs (Yoshino et al., 2007). In regions above 410-km, continuous melt production is expected if the water content in the transition zone exceeds a critical value ( $\sim 0.05\%$ ) (e.g., Karato, 2012; Karato et al., 2006). Consequently, a minute amount of melt (less than 0.1%) must always exist in these regions (even if compaction occurs). Such a small amount of melt has negligible influence on physical properties such as seismic wave velocity as far as melt does not completely wet grain-boundaries. However, if the melt completely wets grain-boundaries then the grain-boundaries will lose the strength and a substantial reduction of seismic wave velocities is expected even for a small melt fraction (see Stocker and Gordon, 1975; Takei, 2002). A classic theory by Raj and Ashby (1971), Zener (1941) suggest a large velocity drop, 20–30%. A more recent sophisticated analysis shows a substantially smaller velocity reduction (e.g., Lee and Morris, 2010; Morris and Jackson, 2009), but a few% velocity drop is estimated as far as some melt is present on grain-boundaries. Yoshino et al. (2007) showed that complete wetting of melt occurs in olivine-rich rocks in the deep mantle ( $\sim 300$  km or deeper). Seismologically inferred thick ( $\sim 30$ – $100$  km thick) low velocity regions above the 410-km discontinuity (Tauzin et al., 2010) could be due to the presence of a small amount of melt that completely wets olivine grain-boundaries.

Hier-Majumder and Coutier (2011) discussed that near neutral density melt could be present atop the 410-km discontinuity. However, they did not consider the effect of complete wetting nor continuous melting suggested by the phase relationship.

#### 4. Discussions

The foregoing discussions showed that in order to reduce seismic wave velocity at the lithosphere–asthenosphere boundary by 5–10%, one would need 3–6% of melt. This is much larger than any plausible melt fraction except for the very vicinity of a mid-ocean ridge. In contrast, one would need only  $\sim 0.1\%$  melt to explain the observed electrical conductivity in the asthenosphere away from the mid-ocean ridges. In other words, if there is enough melt (3–6%) to explain velocity reduction, electrical conductivity will be too high. For these two reasons, partial melt model with

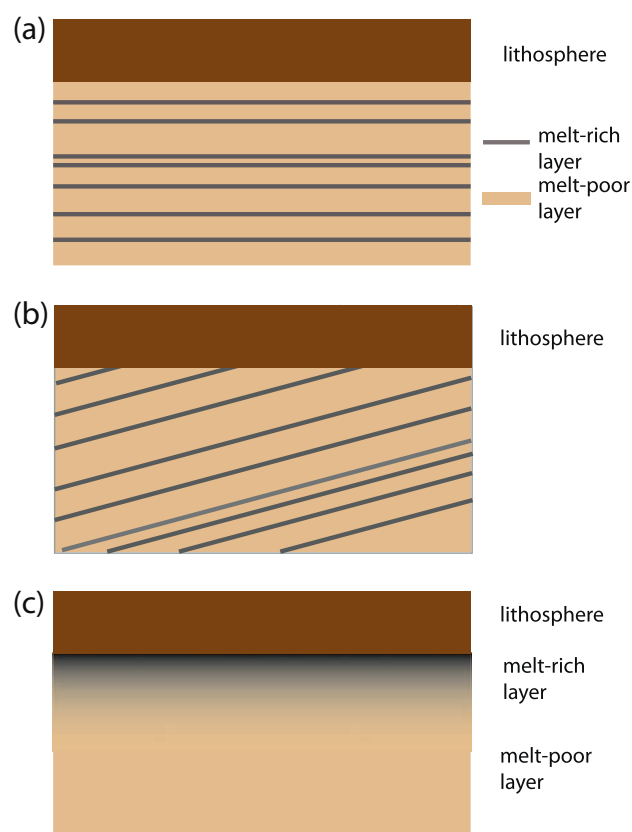
homogeneous melt distribution can be ruled out for a model for geophysical anomalies of the asthenosphere.

If one wishes to maintain partial melt models to explain geophysical anomalies, then one needs to invoke heterogeneous distribution of melt. However, such models have a number of assumptions and adjustable parameters. Therefore the validity of such models needs to be examined on the basis of physical plausibility and in comparison to geophysical observations. I will discuss two of these models.

##### 4.1. Layered structure with thin melt-rich layers (Fig. 3a)

Kawakatsu et al. (2009) proposed that the seismologically inferred large and sharp velocity reduction at the lithosphere–asthenosphere boundary in the old oceanic upper mantle is caused by the presence of thin melt-rich layers in the asthenosphere formed by shear deformation. If indeed such melt-rich layers are stably present, and if the structure of such a layer satisfies certain conditions, then one would explain the observed low velocities.

If the spacing of layers is much less than the wavelength of seismic waves, then such a material can be viewed as homogeneous but anisotropic material: horizontally polarized shear wave has higher velocity than vertically polarized shear waves. When the receiver function technique is used with nearly vertically traveling



**Fig. 3.** Some models of inhomogeneous melt distribution. (a) A horizontally layered structure with thin melt-rich layers. The velocity of vertically polarized shear waves in the asthenosphere with a layered structure will be less than the velocity of horizontally polarized shear waves. (b) A layered structure with thin melt-rich layers with some tilt consistent with the results by Holtzman et al. (2003). According to the experiments by Holtzman et al. (2003), melt-rich layers are tilted with respect to the shear plane (horizontal plane) by  $\sim 15^\circ$ . Melt in the melt-rich layers will be drained by gravity. (c) A model of melt accumulation at the lithosphere–asthenosphere boundary. Buoyant melt will migrate upward until it reaches the permeability barrier at the lithosphere–asthenosphere boundary. Without continuous melt generation, this layer will be too (1–100 m) thin to be detected seismologically. With melt-generation caused by small-scale convection, a thicker layer might be formed.

waves, one determines the velocity contrast of vertically polarized shear waves, and consequently, there is a velocity drop at the lithosphere-asthenosphere boundary. The velocity contrast between two orientations caused by such a structure is approximately given by (e.g., Anderson, (1989))

$$\frac{V_{SH} - V_{SV}}{V} \approx \frac{f}{2} \left( \frac{M_1 - M_2}{\sqrt{M_1 M_2}} \right)^2 \approx \frac{1}{2} \frac{\phi_o}{\phi} \left( \frac{1 - M_2/M_1}{\sqrt{M_2/M_1}} \right)^2 \quad (5)$$

where  $V_{SH(SV)}$  is the velocity of horizontally (vertically) polarized waves,  $f$  is the volume fraction of low velocity layer,  $\phi_o$  is the average melt fraction ( $\sim 0.1\%$  away from the ridges),  $\phi$  is the melt fraction in a melt-rich layer ( $f \approx \frac{\phi_o}{\phi}$ ),  $M_2$  is the velocity of a melt-rich layer, and  $M_1$  is the velocity of a melt-free material. In order for this model to work, there must be a unique relation between  $\phi/\phi_o$  and  $M_2/M_1$  corresponding to the relation (5) (Fig. 4). However, such a relation (i.e., the relation between the elastic modulus and the melt fraction) must also be consistent with a physical model such as a model by Takei (2002). From this, one finds that a melt fraction in a melt-rich layer to explain velocity anomaly is  $\sim 14\%$  (for  $\phi_o = 0.1\%$ ) or  $\sim 12\%$  (for  $\phi_o = 1\%$ ) (Fig. 4). This melt fraction is relatively insensitive to the assumed average melt fraction,  $\phi_o$ . However, the modulus defect,  $M_2/M_1$ , and hence the velocity reduction,  $\Delta V/V$ , is highly sensitive to the exact value of  $\phi$  (Fig. 4). If  $\phi$  is 15% or 10% rather than 14% for an average melt fraction of 0.1%, then the velocity reduction will be 100% or 0.5% respectively rather than 5–10% as observed. Consequently, if this model were to explain the observed velocity reduction (of 5–10%), there must be a good reason to have such a melt fraction ( $\sim 14\%$  for  $\phi_o = 0.1\%$ ) in the melt-rich regions. There is no model to explain how such a melt fraction is realized in the melt-rich region.

Another problem with this model is the fact that, if this were the cause of low velocity of the asthenosphere, then there must be strong radial anisotropy whose amplitude is the same as the velocity reduction. Such strong radial anisotropy ( $V_{SH} > V_{SV}$  by 5–10%) is not observed in a majority of the asthenosphere (e.g., Montagner and Tanimoto, 1991).

Furthermore, the experimental study by Holtzman et al. (2003) showed that the orientation of the melt-rich layers is tilted relative

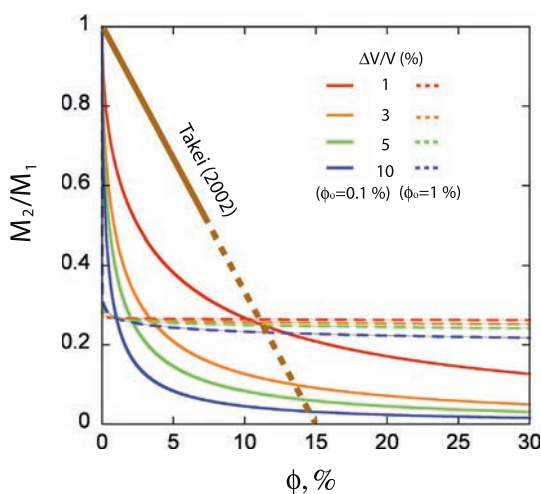
to the shear plane (the horizontal plane in our case) by  $\sim 15^\circ$  (Fig. 3b). Then the gravity will drain the melt and this model will no longer work. In addition, if such melt-rich layers were present, there is substantial density contrast between those layers and the surroundings causing a fluid dynamic instability to destroy such layers (e.g., Hernlund et al., 2008a,b).

#### 4.2. Melt accumulation at the permeability barrier (Fig. 3c)

Another model is to invoke that melt is accumulated at the bottom of the lithosphere possibly by the permeability barrier. In such a model, the thickness of melt-rich layer needs to be much larger than the (static) compaction length (1–100 m), otherwise such a layer will not be detected geophysically. To create a melt-rich layer thicker than the (static) compaction length, dynamic melt production and migration must occur. The structure of such a melt accumulation layer depends critically on the processes of melt generation and transport. Far from the mid-ocean ridge, a possible process of melt generation in the asthenosphere is decompression melting caused by the vertical motion associated with the secondary-scale convection in the asthenosphere (Parmentier and Hirth, private communication). Again, however, in order such a model to explain the observed velocity drop at the oceanic lithosphere-asthenosphere boundary, highly tuned combination of a number of parameters (solid viscosity, melt fraction, melt permeability etc.) is needed. More seriously, it is difficult to explain both low seismic wave velocities and high conductivity simultaneously. If such a layer were to explain seismic low velocity, its thickness must be much larger than the wave-length of seismic waves (thickness  $> 20$  km). Also to cause 5–10% velocity reduction, that layer should have 3–6% of melt and the electrical conductivity will be on the order of  $10^{-1}$  S/m. Presence of a layer of electrical conductivity of  $\sim 10^{-1}$  S/m with a thickness exceeding  $\sim 20$  km is ruled out away from the mid-ocean ridge. Therefore I conclude that these models of inhomogeneous melt distribution are not supported by the available observations.

Ni et al. (2011) discussed that a partial melt model can explain both seismic wave velocity and electrical conductivity simultaneously. In their model, they used a total water content of 0.015 wt.%, and considered the partition of water (hydrogen) between the melt and the co-existing minerals. Then using the estimated conductivity of water-bearing basaltic melt corresponding to the estimated amount of water, they concluded that  $\sim 0.3$ –2% of melt is consistent with the observed electrical conductivity of  $\sim 0.03$ –0.1 S/m (high values corresponding to near ridges, and low values to off ridges). They argued that a smaller value,  $\sim 0.3\%$ , is compatible with the value estimated by Kawakatsu et al. (2009) to explain seismic wave velocity at the old oceanic upper mantle. However, this discussion is not correct. As shown before, if one assumes homogeneously distributed melt, 5–10% reduction in seismic wave velocity (observed in an old oceanic asthenosphere) requires 3–6% of melt, rather than 0.3%. 3–6% of melt would predict too high electrical conductivity. If melt were homogeneously distributed, then  $\sim 0.3\%$  of melt will reduce the velocity only by  $\sim 0.5\%$  Takei (2002). Therefore, a partial melt model cannot explain velocity reduction and electrical conductivity simultaneously if homogeneous melt distribution is assumed. If one wishes to seek consistency with the (Kawakatsu et al., 2009) model, then one would need to use a layered model assumed by Kawakatsu et al. (2009). But such a layered model is not consistent with various observations as discussed before.

In summary I conclude that both of these models have serious difficulties in reconciling with the physics of partial melt (e.g., stability of the assumed structures) or with the geophysical observations.



**Fig. 4.** Relationship between the melt fraction in a melt-rich layer and modulus ratio between melt-rich layer ( $M_2$ ) and melt-free layer ( $M_1$ ).  $\phi$ : melt fraction in a melt-rich layer.  $M_2$ : elastic modulus of a melt-rich layer.  $M_1$ : elastic modulus of a melt-free material. Thin curves: melt-fraction versus modulus ratio relationship required to explain an assumed velocity reduction ( $\Delta V/V$ ) (solid lines for  $\phi_o = 0.1\%$ , broken lines for  $\phi_o = 1\%$ ). Thick line: melt fraction versus modulus relation predicted by a physical model of partially molten materials (Takei, 2002) (a broken portion corresponds to the extrapolation from Takei, 2002).

## 5. Summary and concluding remarks

Partial melting likely occurs in the broad region of Earth's mantle. In particular, the whole upper mantle above 410-km (except for the lithosphere) should be partially molten if dehydration melting occurs near the 410-km discontinuity as discussed by Karato et al. (2006) and Karato (2012). However, the existence of partial melting does not necessarily mean that geophysical anomalies (low seismic velocity, high electrical conductivity etc.) are caused by partial melting. In other words, showing the presence of partial melting is not enough to conclude that partial melting is the cause of geophysical anomalies.

In order for partial melting to explain low seismic wave velocity and high electrical conductivity, one needs to have a certain amount of melt that depends on the melt geometry (dihedral angle). One needs to explain if such an amount of melt can exist in a realistic environment. After evaluating the amount of melt needed to explain geophysical anomalies, and the stability of such an amount of melt, I conclude that partial melt model can be ruled out for both homogeneously distributed melt model and for inhomogeneously distributed melt model except for the regions above the 410-km where melt likely wets grain-boundaries. The situation for the ULVZ is less clear because the mechanisms to support such a feature is unclear and the wetting behavior of melt at the D'' layer condition is unknown.

Given the implausibility or the large uncertainties of partial melt models, it will be interesting to explore an alternative model(s) to explain low seismic wave velocity and high electrical conductivity. Such models have been proposed for the upper mantle where the role of hydrogen is emphasized (Dai and Karato, 2009; Karato, 2011, 2012). Low velocities and high conductivities in some regions of the D'' layer (the ULVZ) may require a different explanation. One possible explanation for the low seismic wave velocities and high electrical conductivity in some of the D'' regions is the enrichment in metallic Fe (Otsuka and Karato, 2012). Another explanation is Fe-enrichment in minerals (e.g., Wicks et al., (2010)), but the origin of Fe enrichment in minerals is unknown (minerals at the bottom of D'' is likely depleted with Fe, if the core is undersaturated with oxygen, see Otsuka and Karato, (2012)). For additional discussions see also Wimert and Hier-Majumder, (2012).

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