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New observational and experimental evidence for a plume-fed asthenosphere boundary layer in mantle convection

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ABSTRACT

The textbook view is that the asthenosphere is the place beneath the tectonic plates where competing temperature and pressure effects on mantle rheology result in the lowest viscosity region of Earth's mantle. We think the sub-oceanic asthenosphere exists for a different reason, that instead it is where rising plumes of hot mantle stall and spread out beneath the strong tectonic plates. Below this plume-fed asthenosphere is a thermal and density inversion with cooler underlying average-temperature mantle. Here we show several recent seismic studies that are consistent with a plume-fed asthenosphere. These include the seismic inferences that asthenosphere appears to resist being dragged down at subduction zones, that a sub-oceanic thermal inversion ~250–350 km deep is needed to explain the seismic velocity gradient there for an isochemical mantle, that a fast 'halo' of shear-wave travel-times surrounds the Hawaiian plume conduit, and that an apparent seismic reflector is found ~300 km beneath Pacific seafloor near Hawaii. We also present 2D axisymmetric and 3D numerical experiments that demonstrate these effects in internally consistent models with a plume-fed asthenosphere. If confirmed, the existence of a plume-fed asthenosphere will change our understanding of the dynamics of mantle convection and melting, and the links between surface plate motions and mantle convection.

1. Introduction

The Earth's mantle underneath the tectonic plates, commonly referred to as asthenosphere, is known to be the lowest viscosity region of the upper mantle. Several potential mechanisms have been suggested to be responsible for this low viscosity zone. These mechanisms, each further discussed in Karato (2008a, 2008b, 2012) and Yamamoto et al. (2007) include: (1) the temperature and pressure dependence of the mantle rheology may lead to a viscosity minimum between 70 and 200 km depth; (2) a small and immobile fraction of partial melts may weaken the mantle; (3) wet mantle below its dry solidus (deeper than about 70 km) would be expected to be weaker than shallower mantle that dehydrated during partial melting at mid-ocean ridges (MOR) (Hirth and Kohlstedt, 1996; Morgan, 1994, 1997)—but this mechanism does not explain the physical origin for the base of the asthenosphere; (4) a reduction in mantle grain size within the asthenosphere. Here we investigate an alternative view that the sub-oceanic asthenosphere forms because it is the "graveyard" for rising (i.e. hotter-than-average mantle) plumes (Deffeyes, 1972; Kumagai et al., 2008) (cf. Fig. 1b–d). In this view, below the plate-age-dependent ~60–100 km-thick oceanic lithosphere there exists a pool of hot plume material that has risen as far as the overlying thermal and/or compositional lithosphere (Hirth and Kohlstedt, 1996; Morgan, 1994, 1997) will allow. At the base of this pool of hotter-than-average mantle corresponding to the base of the seismic low-velocity zone (LVZ), there would be a negative vertical gradient in density and potential temperature (potential temperature is temperature corrected for adiabatic effects). This density inversion may be augmented by the density reduction associated with partial melting where this has also occurred. Such a thermally and compositionally buoyant asthenosphere offers a particularly simple explanation for a set of recent seismic observations that are otherwise difficult to explain. The conceptual scenario of a PFA and its geodynamic predictions have been discussed elsewhere (Morgan et al., 1995b; Yamamoto et al., 2007), where previous observational hints for the effects of a plume-fed asthenosphere (PFA) on patterns in seismic anisotropy, geoid, dynamic topography, and ocean island basalt/mid-ocean ridge basalt geochemistry were evaluated. Here we will focus on several new observations (cf. Figs. 2–4) and interpret these in Section 2 in the context of the PFA scenario as well as in the context of alternative views (see above). In Section 3 we will present results from 2D axisymmetric and 3D numerical experiments on the PFA scenario that predict mantle flow and thermal structures consistent with these new observations.

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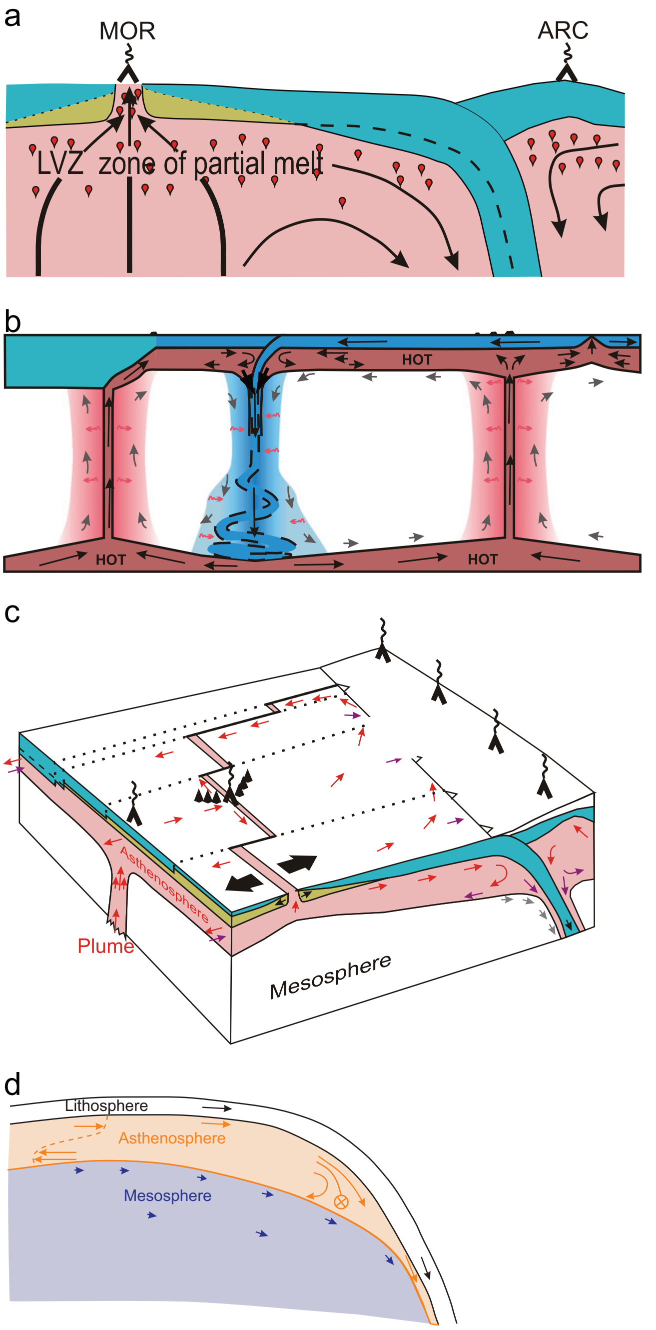

Fig. 1. Cartoons of flow patterns in conventional asthenosphere and plume-fed asthenosphere. (a) Schematic of conventional view of upper mantle convection. (b) Schematic of flow structures in a convecting mantle that includes a plume-fed asthenosphere (PFA). (c) Schematic of 3D flow characteristics within the PFA. (d) Schematic showing how buoyant asthenosphere resists slab dragdown at trenches, consistent with recent global seismic patterns mapped by Long and Silver (2008, 2009).

2. New observations supporting a plume-fed asthenosphere

2.1. Seismic and mineral physics inversions for upper mantle temperature profiles

One new line of seismic evidence is direct inversions of long period seismic waveforms for mantle temperature along vertical profiles in a global upper mantle wavespeed model that aims to match 3D travel time data and attenuation (Cammarano and Romanowicz, 2007). While Cammarano and Romanowicz (2007) assumed a homogeneous pyrolitic mantle composition and inverted only for best-fitting vertical temperature profiles, the inversion study by Cammarano et al. (2009) tested different vertical compositional profiles to obtain best-fitting thermochemical models. These studies find that globally a strong positive gradient in shear-wave velocity is required between 250 and 350 km depths. If thermal in origin, it implies negative temperature gradients at 250 km depths beneath ocean basins but not continental cratons, and if compositional in origin it implies a gradual enrichment into a more garnet–pyroxene rich composition with depth beneath ocean basins. We will show that the PFA model is able to explain either possibility and in fact favors a combination of the two.

Inverting for temperature variations alone results in the seismically-inferred geotherms shown in Fig. 2a (Cammarano and Romanowicz, 2007). Note that Fig. 2a shows inverted in-situ temperatures rather than potential temperatures corrected for the adiabatic depth-dependent increase in temperature which are shown in Fig. 2b. Beneath continental cratons—solid lines in Fig. 2b—the inferred temperature is consistent with the thermal structure for a 40 mW/m^2 surface heatflow, and reaches an in-situ temperature of ~1300 °C at ~250 km corresponding to a potential temperature of ~1200 °C at ~250 km when corrected for a typical mantle adiabatic temperature gradient of ~0.33 °C/km. In contrast, sub-oceanic upper mantle (dashed lines in Fig. 2b and c) follows a strikingly different geotherm that reaches in-situ temperatures of ~1475 °C (potential temperatures of ~1400 °C) at ~225 km before decreasing to in-situ temperatures of ~1250 °C (potential temperature of ~1150 °C) at ~325 km, identical to the sub-cratonic temperatures at this depth. Between ~225 and 325 km, however, the potential temperatures in the oceanic asthenosphere are about 200 °C hotter than those inferred below cratons. Cammarano et al. (2009, 2011) pointed out that the thermal profiles are nonunique, but depend on the mantle composition assumed for the inversion. In fact Cammarano et al. (2009) refer to the negative temperature gradient as being "unrealistic" and prefer models in which compositional variations with depth lead to temperature profiles without this intriguing feature. Here we offer an alternative explanation, that the negative thermal gradient implied for a near-uniform mantle composition may be real and physically reasonable.

If mantle plumes are hotter than average mantle and feed a sub-oceanic pool of asthenosphere, while temperatures at depths greater than 325 km more closely reflect average mantle temperatures, then the temperature contrast discussed above would be anticipated between a PFA being well-developed beneath relatively thin sub-oceanic asthenosphere and poorly-developed or absent beneath the much thicker continental cratons. This argument has been further discussed for better-constrained North American seismic data in Reston and Morgan (2004). In the PFA scenario (Morgan et al., 1995b; Reston and Morgan, 2004; Yamamoto et al., 2007), a continental craton will only be underlain by hotter-than-average plume material when passing directly over a plume that then drains laterally towards the adjacent ocean basin (cf. Fig. 1b) or when lying over a regional 'superswell' such as present-day S. Africa.

Attributing all or even a part of the strong positive gradient in shear-wave velocity between 250 and 350 km depth to a change in mantle composition, as suggested by Cammarano et al. (2009), requires a geochemical or fluid dynamical mechanism for the gradual increase of mantle enrichment with depth. Melt extraction at mid ocean ridges is an efficient mechanism to remove enriched mantle components (e.g. eclogite, pyroxenite) and thereby leave a residue that is less dense and richer in depleted harzburgites. However, mantle will not extensively melt at ambient