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A geodynamic and mineral physics model of a solid-state ultralow-velocity zone

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ABSTRACT

Recent results (Wicks et al., 2010) suggest that a mixture of iron-enriched (Mg,Fe)O and ambient mantle is consistent with wavespeed reductions and density increases inferred for ultralow-velocity zones (ULVZs). We explore this hypothesis by simulating convection to deduce the stability and morphology of such chemically-distinct structures. The buoyancy number, or chemical density anomaly, largely dictates ULVZ shape, and the prescribed initial thickness (proxy for volume) of the chemically-distinct layer controls its size. We synthesize our dynamic results with a Voigt–Reuss–Hill mixing model to provide insight into the inherent seismic tradeoff between ULVZ thickness and wavespeed reduction. Seismic data are compatible with a solid-state origin for ULVZs, and a suite of these structures may scatter seismic energy to produce broadband PKP precursors.

1. Introduction

The large chemical, density, and dynamical contrasts associated with the juxtaposition of liquid iron-dominant alloy and solid silicates at the core–mantle boundary (CMB) are associated with a rich range of complex seismological features. Seismic heterogeneity at this boundary includes small patches of anomalously low sound velocities, called ultralow-velocity zones (ULVZs). Their small size (5 to 40 km thick) (e.g., Garnero and Helmberger, 1996) and depth (>2800 km) present unique challenges for seismic characterization.

ULVZs were first noted with teleseismic SPdKS phase diffracting along the CMB to determine the P-wave velocity at the base of the mantle beneath the central Pacific (e.g., Garnero and Helmberger, 1995, 1996; Garnero et al., 1993; Helmberger et al., 1996). The compressional wavespeed decreases by 5 to 10% over a depth of 5 to 40 km above the CMB, consistent with PcP precursors (e.g., Hutko et al., 2009; Mori and Helmberger, 1995; Revenaugh and Meyer, 1997). In other locations, ULVZs are seismically absent or below the detection threshold, such as the North Pacific (Rost et al., 2010b), which may imply they are not globally ubiquitous (see Thorne and Garnero, 2004). ULVZs have been correlated with the location of hotspots (Williams et al., 1998) and tentatively to the edges of large low shear velocity provinces (e.g., Lay et al., 2006). Recent thermochemical convection calculations lend support to these spatial correlations (McNamara et al., 2010).

Precursors and postcursors to the converted core-reflected phase ScP can potentially constrain the P and S wavespeed, thickness, and density of ULVZs (e.g., Garnero and Vidale, 1999; Reasoner and Revenaugh, 2000). Based on this approach, analyses using small-aperature and short-period arrays have elucidated the structure between Tonga–Fiji and Australia at high resolution (Idehara et al., 2007; Rost and Revenaugh, 2003; Rost et al., 2005, 2006, 2010a). These studies report P and S wavespeed reductions of ≈8% and ≈24% respectively, a thickness of about 10 km, and a density increase of around 10%.

All of these studies characterize structure by a 1-D model. Although quasi-1D models utilize different structures for the source and receiver paths (e.g., Garnero and Helmberger, 1996; Helmberger et al., 1996), only a few 2-D models have been reported. Probing the CMB beneath the southwest Pacific, Wen and Helmberger, (1998b) model SKS-SPdKS observations with Gaussian-shaped ULVZs of approximately 40 km in height, 250 to 400 km lateral extent, and a P-wavespeed drop of about 10%. PKP precursors suggest that these larger structures are composed of smaller undulations (Wen and Helmberger, 1998a). A concave-down upper interface is necessary to model structures beneath Africa and the eastern Atlantic (Helmberger et al., 2000). In both 1-D and 2-D models there are tradeoffs between the height and velocity decrease of ULVZs (e.g., Garnero and Helmberger, 1998; Wen and Helmberger, 1998b).

A partial melt origin for the ULVZs predicts a P to S wavespeed reduction of about 1:3 (Berryman, 2000; Hier-Majumder, 2008; Williams and Garnero, 1996). In this model, the velocities of the average assemblage are decreased by melt formed either by fluid reaction products of Fe liquid with silicate mantle or by partial

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melting of Fe-rich mantle. The hypothesis is consistent with the correlation between ULVZs and hot spots (Williams et al., 1998) and the broad agreement with P to S velocity reductions determined from core-reflected phases. Early dynamical calculations question the ability to produce a dense and non-percolating melt phase in the deep Earth (Hernlund and Tackley, 2007). However, the stirring of ULVZs by the larger-scale convective motions of the mantle can potentially maintain a partially molten region (Hernlund and Jellinek, 2010). Partial melt may also be trapped within ULVZs because of textural changes (e.g., Rost et al., 2005, 2006), but theoretical and experimental justifications are incomplete, particularly at the temperatures and pressures of the CMB region.

Iron enrichment of solid phases, specifically the increase in Fe/(Fe + Mg) ratio, can simultaneously increase density and reduce compressional and shear velocity (e.g., Karato and Karki, 2001). This partly inspired the notion of solid, iron-rich ULVZs, such as a metal-bearing layer (Knittle and Jeanloz, 1991; Manga and Jeanloz, 1996), subducted banded iron formations (Dobson and Brodholt, 2005), or iron-enriched post-perovskite (Mao et al., 2006; Stackhouse and Brodholt, 2008). Iron-rich systems are typically denser than the surrounding mantle, which is required to explain the locations of ULVZs at the base of the mantle.

Recent results show that the sound velocities of a solid iron-enriched (Mg,Fe)O at CMB pressures are low enough, such that only a volumetrically small amount (~10–20%) mixed with coexisting silicates are needed to explain ULVZs (Wicks et al., 2010). We are motivated to generate a numerical convection model of a thin, iron-enriched (Mg,Fe)O-containing layer interacting with the lowermost thermal boundary layer. Mantle convection thickens (thins) a dense layer beneath upwellings (downwellings) and controls its spatial distribution (Davies and Gurnis, 1986). A persistent stable layer has a density contrast of a few percent (e.g., Garnero and McNamara, 2008) and may convect internally (Hansen and Yuen, 1988). We explore whether these characteristics are manifested in this iron-enriched (Mg,Fe)O-containing layer. We determine the steady-state morphology of such a layer and develop an integrated and self-consistent ULVZ model which uses constraints from geodynamics and mineral physics and is consistent with seismic data.

2. Numerical models

2.1. Equations and solution methods

We apply the Boussinesq approximation to model thermochemical convection using CitcomS (Tan et al., 2007; Zhong et al., 2000) because the pressure range of our domain is small and energy dissipation is negligible with a greatly reduced thermal expansion coefficient at high pressure. The equation for the conservation of mass for an incompressible fluid is:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

where **u** is velocity. The non-dimensional momentum equation is:

$$-\nabla P + \nabla \cdot (\eta \underline{\dot{\varepsilon}}) = (RaT - RbC)\hat{\mathbf{r}} \tag{2}$$

where P is the dynamic pressure, η is the viscosity, $\underline{\dot{\varepsilon}}$ is the deviatoric strain rate, Ra is the thermal Rayleigh number, T is temperature (non-dimensionally ranging from 0 to 1), Rb is the chemical Rayleigh number, and $\hat{\mathbf{r}}$ is the radial unit vector. Composition, C, ranging from 0 to 1, encompasses two chemical components. The first component ($C=0$) is ambient mantle, the second ($C=1$) is a two-phase mix containing iron-enriched (Mg,Fe)O that constitutes the distinct chemistry of the ULVZ. We equivalently refer to the latter component as the chemical, or (Mg,Fe)O-containing, component.

The Rayleigh numbers are defined as:

$$Ra = \frac{\rho \alpha \Delta T D^3 g}{\eta_0 \kappa} \tag{3}$$

$$Rb = \frac{\Delta \rho_{ch} D^3 g}{\eta_0 \kappa} \tag{4}$$

where the parameters and their values are provided in Table 1.

A useful non-dimensional parameter is the buoyancy number, B, which describes the chemical density anomaly normalized by the maximum thermal density anomaly, or equivalently the ratio of chemical to thermal buoyancy:

$$B = \frac{Rb}{Ra} = \frac{\Delta \rho_{ch}}{\rho \alpha \Delta T}. \tag{5}$$

The quantity of heat-producing elements in the lower mantle and the dynamic implications for small-scale structures such as ULVZs remain uncertain. For simplicity, we solve the non-dimensional energy equation for temperature without an internal heat source:

$$\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)T = \nabla^2 T \tag{6}$$

where t is time.

The equation for chemical advection is:

$$\frac{\partial C}{\partial t} + (\mathbf{u} \cdot \nabla)C = 0 \tag{7}$$

We represent the ULVZ component by a set of tracer particles (initially about 100/cell) that are advected using a predictor–corrector scheme (McNamara and Zhong, 2004). The volume fraction of ULVZ material is proportional to the absolute local concentration of tracers with a truncation applied to prevent unphysically large values (see Tackley and King, 2003, the truncated absolute method). In comparison to the ratio method (Tackley and King, 2003), this technique provides greater computational speed because fewer total tracers are required. Although the number of tracers per cell is greater for the absolute method to achieve the same resolution, a large volume fraction of ambient material in our models is devoid of tracers. By contrast, the ratio method requires tracers to fill the space of the entire domain.

Table 1
Model parameters.

Parameter	Symbol	Value	Units
Density	ρ	5500	kg m^{-3}
Thermal expansion coefficient	α	10^{-5}	K^{-1}
Temperature drop	ΔT	1500	K
Mantle depth	D	2890	km
Gravity	g	10.3	m s^{-2}
Thermal diffusivity	κ	10^{-6}	m^{2}s^{-1}
Reference viscosity	η_0	10^{22}	Pa s
Viscosity exponent	q	3	–
Thermal Rayleigh number	Ra	2×10^6	–
Thermal boundary layer initial thickness	d_t	66	km
Buoyancy number	B	0.5, 0.75, 1, 1.25, 2, 4, 6	–
Chemical density	$\Delta\rho_{ch}$	$B\rho\alpha\Delta T$	kg m^{-3}
Chemical Rayleigh number	Rb	BRa	–
Chemical layer initial thickness	d_{ch}	2, 4, 8, 16, 24, 32	km