CMB Group Brief Report

A silicate-iron-enriched melt layer at CMB

Dave Rubie, Ed Garnero, Emma Rainey, Lingling Ye, Martina Ulvrova, Ondrej Smarek, Quentin Williams, Razvan Caracas, Stefanie Hempel, Xi Liu, Yang Wang, Ying Xias

Question

What are the rules that would govern the genesis, evolution, dynamics and observability of a silicate melt layer* at the bottom of the mantle?

*OCIZ – Outermost core igneous zone

Motivation

There is a long-term history of complexity at the core-mantle boundary. On the mantle side, ultra-low velocity zones, the post-perovskite phase transition and its spatially variable manifestations, complex anisotropic properties, and interpretations of subduction-related structures in this region have been discussed over the past 40 years (Wright, 1973, Lay and Helmberger, 1983, Wookey et al., 2005). The literature on each of these features is extensive, and frequently contributions are oriented towards characterizations and interpretations of single features.

In addition, core-side heterogeneities have been sporadically invoked for at least the last 30 years (e.g., Braginsky, 1984), based on a range of seismic, geodetic and geomagnetic observations and modeling (e.g. Rost et al., 2001). For example, stably stratified zones have recently been invoked based on large values of iron thermal conductivity and hence rapid core cooling rates (Pozzo et al., 2012), and lighter alloying-enriched regions in the uppermost outer core have been proposed based on progressive reactions with the overlying mantle (Buffett and Seagle, 2010)—and the history of seismic observations of anomalous zones at the top of the core is long (e.g., Young and Lay, 1990; Garnero et al., 1993; Eaton and Kendall, 2006; Helffrich and Kaneshima, 2010). The most common outcome of the seismic studies is a gradational decrease in compressional wave velocity in the outermost ~100 km or so of the core, culminating in a maximum anomaly of a few percent. Yet, the degree to which these studies are biased by path differences within the overlying mantle for rays multiply reflecting off the core-side of the CMB remain unclear; and, there are indications that more complex (and increased) velocity structures could be present near the top of the outer core (Rost and Revenaugh, 2001; Eaton and Kendall, 2006).

With this past work in mind, coupled with the presence of partially molten ultra-low velocity zones and the long-term evolution of a basal magma ocean (Williams et al., 1996, Labrosse et al., 2007), the CMB group poses the following query: **What are the rules that would govern the genesis, evolution,**

dynamics and observability of a silicate melt layer at the bottom of the mantle? Naturally, it is not apparent that such a layer does exist---but, if negatively buoyant melts are common features in the deep Earth (at present, a mildly controversial statement), and barring extensive dynamical entrainment (possible in some geodynamic environments) and the completed partial solidification of the early magma ocean, a silicate melt layer (even of a few km thickness) would be a reasonable outcome of a broad range of evolutionary histories.

The genesis of such a mantle-derived core-side layer (liquid, but of silicate composition/ provenance) could prospectively arise from at least three different effects. First, the layer could be primordial: arising from the original magma ocean. In this sense, such a layer could be the last fossilized remnant of the crystallization of the bulk planet post-accretion. Second, it could arise or be replenished from drainage of melt from the ULVZ. One of the primary uncertainties attached to the ULVZ is associated with the retention of melt in this zone: indeed, melt segregation of negatively buoyant melt is anticipated, unless dynamic entrainment of melt is extreme within the ULVZ. Third, if subducted material is introduced into the high-temperature-gradient boundary layer, melt would be anticipated to be generated from lower melting temperature components. These might include hydrous- and carbon-bearing materials; whether these would be negatively buoyant or not is unclear, but hinge critically on the degree of iron partitioning into volatile-rich melts at high pressures—a poorly constrained parameter at CMB conditions. Nevertheless, melting of subduction-related heterogeneities near the CMB could result in replenishment of melt both within the ULVZ, and prospectively within a basal layer.

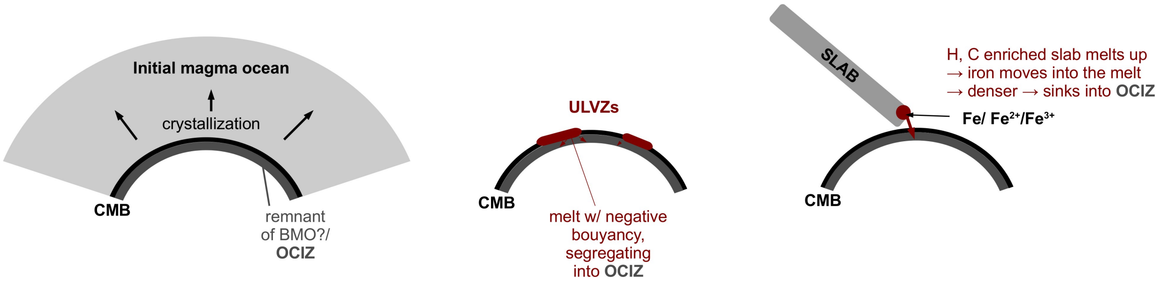

Fig. 1: Three different hypotheses for how the thin layer between core and mantle may have formed. See text for details.

The chemical modifications of such a layer through time are similarly three-fold. First, diffusive inputs (and outputs) will occur into/out of the outer core. Diffusion rates at CMB conditions have a few constraints on them (primarily, but not entirely theoretical), and preliminary results suggest diffusional distances of a few km over a billion-year timeframe. Second, depending on the rate at which material is generated via melting from heterogeneities from above, ingress of melts could modify and renew material within this layer on an ongoing basis. In this context, it is important to note that our cold thermal boundary layer at the top of the planet has generated an average thickness of ca. 15 km of magmatic crust---how much magmatic material might be generated by a hot boundary layer is ill-constrained. Third, both entrainment and reactions associated with any such layer could be important, but are highly contingent on dynamic effects: the shear rate and viscosity within the coexisting layers control the degree of entrainment. Correspondingly, the progress of chemical reactions hinges on the rate of refreshment/ renewal of the immediate boundary layer.

Approach

So, what do we plan to do that is achievable within the framework of CIDER?

(1) Constrain the degree to which silicate melt layers of variable thickness, and various degrees of diffusive equilibration, can be detected via seismic waveform analysis. In short, what thickness of layer might be detectable, and by what means?

(2) Derive dynamic and thermal constraints on prospective thin silicate melt layers. In this instance, the results are not only relevant to the present-day Earth (possibly), but also to the earlier Earth, given the expectation that silicate magmatic material could have been juxtaposed with Earth's core during the later evolution of Earth's magma ocean.

(3) Produce insights into the igneous geochemistry of this layer, given nascent and emerging constraints on the eutectic of mantle materials at CMB conditions, and the limited state of knowledge on element partitioning at the CMB.

Mineral physical approach

The long-term persistence of a melt layer at the base of the mantle would have important implications for thermal and electromagnetic core-mantle coupling and evolution over Earth's history. In order to determine the implications of such a melt layer for the thermal state and evolution of the core and mantle we propose the following approach. It should be noted that the properties of melts at high pressure are not well known, and large extrapolations will be required to estimate melt properties at CMB conditions. Further experimental, theoretical, and/or computational work may be required to complete this part of the project.

(1) We will explore the potential chemical compositions of basal melt layers based on the melt generation scenarios described above, and considering possible interactions of a silicate melt layer with the core. The chemical composition of a basal melt has implications for the transport properties of the layer, and also provides a constraint on the temperature at the core-mantle boundary. Recent work on eutectic melting of mantle materials at high pressure (Fiquet et al., 2010) provides a starting point for this task.

(2) We will estimate the thermal and electrical conductivity of plausible melt layers. These are not well-determined parameters, and extrapolations from pressure/temperature ranges where data exist are long. On the positive side, order of magnitude estimates for these parameters are probably sufficient to loosely constrain the implications of such a layer for the transport of heat and the magnetic field. As a starting point we will use previous measurements on the pressure- and temperature-dependence of thermal conductivity for silicate melts and glasses (Shimada et al., 1985; other refs).

(3) We will use thermal history models to determine the effect of a persistent melt layer at the base of the mantle on core cooling rates. This is of particular importance for the effects of this layer on the Earth in deep time: a thicker layer would be anticipated to have a more dramatic effect on thermal transport in the Earth relative to the (at best) quite thin layers that might be present today.

Geodynamical approach

The roughness of the boundary between the core and the basal liquid layer would depend on buoyant effects vs kinetic energy effects. Dominant buoyancy, that would be expected for the system, prevents Kelvin-Helmholz instabilities (instabilities due to velocity shearing) to be developed, implying that the boundary would be relatively sharp.

From the dynamical point of view, the state of the silicate melt would depend on its viscosity, the crucial parameter that is still ill-constrained at high pressure and temperature conditions. However, its value is estimated to be very low and thus suggesting that the silicate layer would be highly convecting even if its thickness might be only of the order of kilometers. Chemical composition of the silicate melt would be modified by interactions with the core. Constant supply of chemical elements by diffusion is supposed to occur over the whole layer’s life-time that might be up to several billion years. In our project we intent to investigate the stability and entrainment of chemical species diffused across the rim from the core side of the boundary by means of numerical simulations.

Seismological approach

We use the elastic properties of different silicate-iron-enriched melts gathered by mineral physical experiments and calculations, combined with the available constraints on elastic parameters associated with 1-D velocity models of the deep Earth. We produce synthetic seismograms using a reflectivity method (Müller,1985) and axisymmetric spectral element method (Nissen-Meyer et al., 2007) for several density and seismic velocity contrasts across the mantle-OCIZ and OCIZ-core discontinuity. From geodynamical models we assume possible minimum and maximum thickness of a stable silicate-iron-enriched melt layer. We look for amplitude and waveform broadening effects of this layer on several phases Pdiff (Doornbos and Mondt,1979), PmKP, SKS, SKKS, SmKS, PcP, ScS and ScP, SPdKS, scattering ahead of PKKP and Pdiff.

Questions for synthetic modeling seismic wave propagation:

- How does variation in the thickness and elastic properties of OCIZ effect travel times/ amplitudes/ waveforms of several phases (e.g. Pdiff, SmKS, PcP, ScS, ScP and transversing waves)? (visible in amplitude of distance plumes as well as in array analysis)
- Can we produce waveforms similar to SmKS observations using only mantle side heterogeneities?

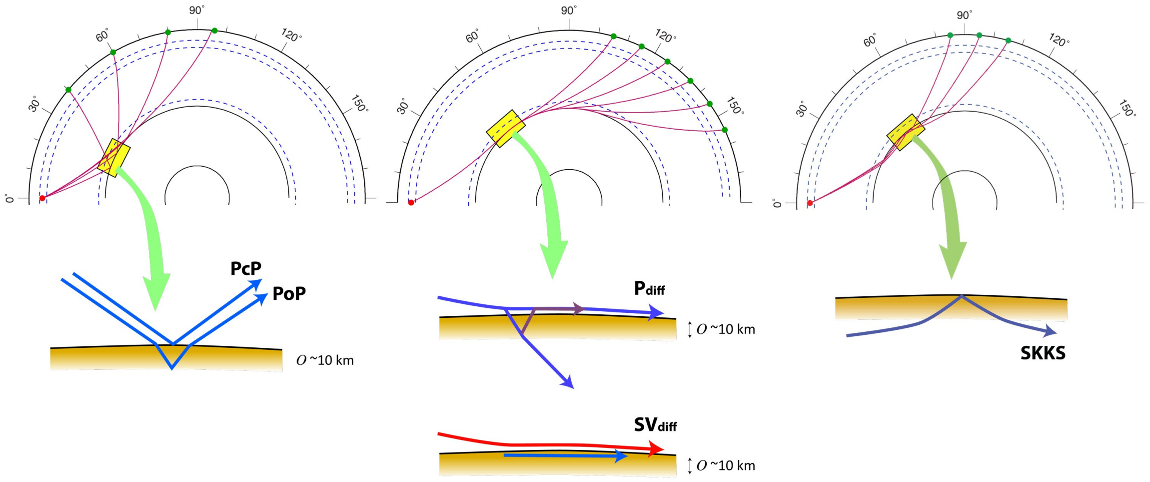

Fig. 2: Wave paths traveling through OCIZ or reflected off it.

After checking which phases are affected by the OCIZ, we look for these selected phases in seismic data at according distances (Pdiff at 100 to 140 degrees). We prefer densely covered areas of the lowermost mantle like the Northern Pacific, since we expect a lot of scattering around the core-mantle boundary (Thomas et al., in prep.).

In detail, two groups of data will be investigated to upper and lower sides of the layer respectively. For the upper side of the layer, waveform information of Pdiff and Sdiff from 100 to 140 degrees will provide some kind of strongest constraints on both elastic and inelastic properties of the OCIZ. The waveform information we use includes amplitude, broadening of the waveforms and frequency dependency. To sample the layer from below we use data that includes SmKS and PmKS phases. Slant stacking technique or master station method will be applied if necessary.

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