

Scale limits on free-silica seismic scatterers in the lower mantle

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Seismic velocity anomalies and scatterers of seismic energy in the lower mantle often are attributed to subducted oceanic lithosphere. In particular, silica-saturated basalts in oceanic crust (MORB) under lower mantle conditions should contain high-pressure phases of free silica among assemblages otherwise dominated by silicate perovskite. Free silica phases such as stishovite are expected to generate seismic velocity anomalies that are fast by a few percent relative to surrounding ultramafic peridotite or harzburgite assemblages (Mattern et al. 2002, Bina 2003a, Ricard et al. 2005), and post-stishovite phases such as CaCl₂-structured silica may also generate locally slow shear-wave velocity anomalies due to displacive shear-mode transitions (Bina 2003b, Lakshatanov 2007, Konishi et al. 2008).

Such models, however, must address the thermodynamic instability of free silica phases in the presence of peridotites or harzburgites, as the silica will react with adjacent ferropericlase (magnesiowustite) to form silicate perovskite. Thus, any free silica phases preserved in the lower mantle may persist as armored relics, in which silica phases are insulated from surrounding ferropericlase phases by coronas of silicate perovskite. This parallels the situation in crustal metamorphic rocks where, for example, staurolite crystals are often found as armored relics within garnet phases, or spinel crystals can be found as relics armored by staurolite poikiloblasts (Whitney 1991, Gil Ibarra et al. 1991). In crustal metamorphic rocks, such relics generally occur at grain scales, as metamorphic fluids facilitate transport along grain boundaries. However, if lower mantle rocks are essentially dry, then larger, polycrystalline relics containing assemblages of free silica and silicate perovskite become plausible. In such cases, the sizes of relic silica-bearing assemblages will be limited by the rate of diffusion of Si, Mg, or Fe through silicate perovskite coronas, either by volume (lattice) diffusion or by dry grain-boundary diffusion.

Assuming effective diffusion coefficients of order 10^{-18} m/s², the characteristic length $L=(D*t)^{1/2}$ is about 5 mm over 1 Myr (Ashworth & Sheplev 1997). However, recent experiments suggest unusually low effective diffusion coefficients of only 10^{-20} to 10^{-18} m/s² in silicate perovskite under lower mantle P,T conditions, yielding characteristic lengths of less than 5 cm over the ~60 Myr necessary for basalt subducting at ~5 cm/yr to traverse the mantle, potentially rising to 30 cm if significant grain-boundary diffusion (from grain-size reduction) occurs (Yamazaki et al. 2000, Holzapfel et al. 2005).

Subducted basaltic crust may be thinned from its initial 10-km thickness by the effects of stretching and folding in the convecting mantle (Metcalf et al. 1995, Van Keken et al. 2002), but free silica will be dispersed within rocks such as quartz tholeiites. Simultaneous diffusion and reaction may consume or aggregate thinner lamellae while preserving thicker remnants by isolation of reactants (Ottino 1982, Ottino 1991). In the absence of interconnected grain boundary fluids or melts, polycrystalline armored silica relics potentially may persist in the lower mantle at scales of up to 1-10 km over time scales of order 100 Myr. Lower mantle seismic scatterers exhibit velocity anomalies of a few percent over just such length scales, of order 1-10 km (Hedlin et al. 1997, Cormier 1999, Kaneshima & Helffrich 1999, Niu et al. 2003, Kaneshima 2003, Cao & Romanowicz 2007, Rost et al. 2008).