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

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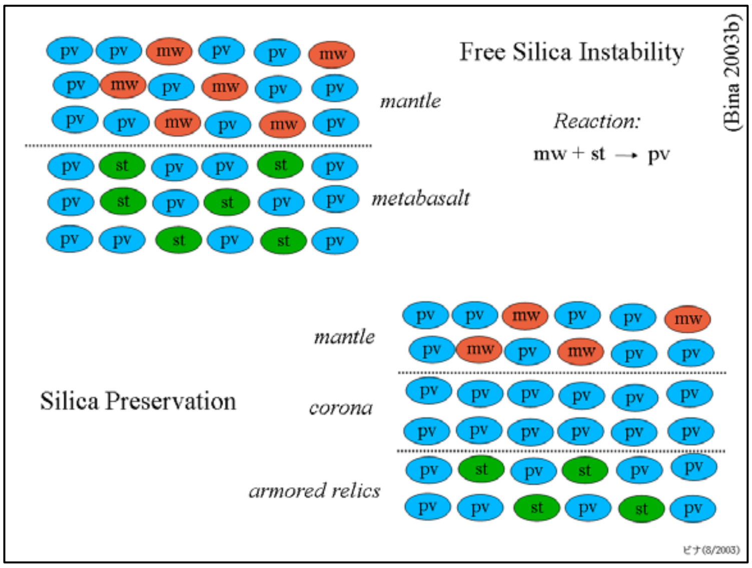
Seismic velocity anomalies and scatterers of seismic energy in the lower mantle often are attributed to subducted oceanic lithosphere. In particular, silica-saturated basalts in oceanic crust (MORB) under lower mantle conditions should contain high-pressure phases of free silica among assemblages otherwise 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 $CaCl_2$-structured silica may also generate locally slow shear-wave velocity anomalies due to displacive shear-mode transitions (Bina 2003b, Lakshtanov 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 (magnesiowüstite) 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 Ibarguchi 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/s^2, the characteristic length $L=(D\cdot t)^{1/2}$ is ~5 mm over 1 Myr (Ashworth & Sheplev 1997). High temperatures (~2000 K) and pressures (~25 GPa) may increase D by perhaps a factor of ~10^7 (for Arrhenius activation energies ~200 kJ/mol and activation volumes ~2 cm^3), yielding L of ~20 m. This rises to ~150 m over the ~60 Myr necessary for basalt subducting at ~5 cm/yr to traverse the mantle. However, recent experiments suggest unusually low effective diffusion coefficients of only 10^{-20} to 10^{-18} m/s^2 in silicate perovskite under lower mantle P,T conditions, yielding 60-Myr characteristic lengths of only ~5 cm, 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 (Metcalfe et al 1995, Van Keken et al 2002), and simultaneous diffusion and reaction may consume or aggregate thinner lamellae while preserving thicker remnants by isolation of reactants (Ottino 1982, Ottino 1991). However, in the absence of interconnected grain boundary fluids or melts, polycrystalline armored silica relics may persist in the lower mantle at scales of 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).



Ashworth JR, Sheplev VS (1997) Diffusion modelling of metamorphic layered coronas with stability criterion and consideration of affinity, *Geochim. Cosmochim. Acta* **61**, 3671-3689.

Bina CR (2003a) Seismological constraints upon mantle composition, in *Treatise on Geochemistry* (ed. R Carlson) **2**, 39-59, Elsevier Scientific Publishing.

Bina CR (2003b) Seismic velocity and density anomalies from subducted basalts, *Abstracts of the 8th European Workshop on Numerical Modeling of Mantle Convection and Lithospheric Dynamics, Zámek Hrubá Skála, Czech Republic*, 13-15.

Cao A, Romanowicz B (2007) Locating scatterers in the mantle using array analysis of PKP precursors from an earthquake doublet, *Earth Planet. Sci. Lett.* **255**, 22–31.

Cormier CF (1999) Anisotropy of heterogeneity scale lengths in the lower mantle from PKIKP precursors, *Geophys. J. Int.* **136**, 373–384.

Gil Ibarguchi JI, Mendia M, Girardeau J (1991) Mg- and Cr-rich staurolite and Cr-rich kyanite in high-pressure ultrabasic rocks (Cabo Ortegal, northwestern Spain), *Amer. Mineral.* **76**, 501-511.

Hedlin MAH, Shearer PM, Earle PS (1997) Seismic evidence for small-scale heterogeneity throughout the Earth's mantle. *Nature* **387**, 145–150.

Holzapfel C, Rubie DC, Frost DJ, Langenhorst F (2005) Fe-Mg interdiffusion in $(Mg,Fe)SiO_3$ perovskite and lower mantle reequilibration, *Science* **309**, 1707-1710.

Kaneshima S (2003) Small-scale heterogeneity at the top of the lower mantle around the Mariana slab, *Earth Planet. Sci. Lett.* **209**, 85-101.

Kaneshima S, Helffrich G (1999) Dipping lower-velocity layer in the mid-lower mantle: Evidence for geochemical heterogeneity, *Science* **283**, 1888-1891.

Konishi K, Kawai K, Geller RJ, Fuji N (2008) MORB in the lowermost mantle beneath the western Pacific: Evidence from waveform inversion, *Nature*, submitted.

Lakshtanov DL, Sinogeikin SV, Litasov KD, Prakapenka VB, Hellwig H, Wang J, Sanches-Valle C, Perrillat J-P, Chen B, Somayazulu M, Li J, Ohtani E, Bass JD (2007) The post-stishovite phase transition in hydrous alumina-bearing SiO_2 in the lower mantle of the earth, *Proc. NAS* **104**, 13588–13590.

Mattern E, Matas J, Ricard Y (2002) Computing density and seismic velocity of subducting slabs. *Eos, Trans. AGU* **83**(47*), Fall Meet. Suppl.*, Abstract S51A-1011.

Metcalfe G, Bina CR, Ottino JM (1995) Kinematic considerations for mantle mixing, *Geophys. Res. Lett.* **22**, 743-746.

Niu F, Kawakatsu H, Fukao Y (2003) Seismic evidence for a chemical heterogeneity in the midmantle: A strong and slightly dipping seismic reflector beneath the Mariana subduction zone, *J. Geophys. Res.* **108**(B9), 2419.

Ottino JM (1982) Description of mixing with diffusion and reaction in terms of the concept of material surfaces, *J. Fluid Mech.* **114**, 83-103.

Ottino JM (1991) Unity and diversity in mixing: Stretching, diffusion, breakup, and aggregation in chaotic flows, *Phys. Fluids A* **3**, 1417-1430.

Ricard Y, Mattern E, Matas J (2005) Synthetic tomographic images of slabs from mineral physics, in, *Earth's Deep Interior: Structure, Composition, and Evolution*, (eds. RD van der Hilst, JD Bass, J Matas, J Trampert) *Geophysical Monograph* **160**, 283-300, American Geophysical Union.

Rost S, Garnero EJ, Williams Q (2008) Seismic array detection of subducted oceanic crust in the lower mantle, *J. Geophys. Res.* **113**, B06303, doi:10.1029/2007JB005263.

Van Keken PE, Hauri EH, Bellentine CJ (2002) Mantle mixing: the generation, preservation, and destruction of mantle heterogeneity, *Annu. Rev. Earth Planet. Sci.* **30**, 493-525.

Whitney DL (1991) Calcium depletion halos and Fe-Mn-Mg zoning around faceted plagioclase inclusions in garnet from a high-grade pelitic gneiss, *Amer. Mineral.* **76**, 493-500.

Yamazaki D, Kato T, Yurimoto H, Ohtani E, Toriumi M (2000) Silicon self-diffusion in $MgSiO_3$ perovskite at 25 GPa, *Phys. Earth Planet. Int.* **119**, 299-309.