Structure of the Oceanic Mantle: Geophysical Constraints on Lithosphere Evolution

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If we want to understand the nature of the Earth's lithosphere, its formation and evolution, then an obvious place to start is in the oceans. Here, the range of crustal compositions is narrow, the geometry of plate formation well defined, and we can image lithosphere from its formation out to ages of roughly 200My. To first order, thermal cooling of the plate as it moves away from the ridge adequately describes heatflow and subsidence with age, but there are discrepancies in this model both at the ridge crest -due to hydrothermal flow and rift valley formation - and at plate ages greater than about 65Ma -an observation that has yet to be fully explained. Furthermore, predictions from laboratory and theoretical studies suggest that lithospheric properties are not in fact primarily controlled by thermal structure. In particular, observed seismic velocity gradients within the lithosphere and an observed, apparently age-independent velocity discontinuity at ~70 km are not predicted by models in which velocity varies solely with temperature. Electrical conductivity near the ridge crest also suggests a more complex behaviour, at least at young plate ages. These discrepancies suggest that other factors, such as composition, variations in water content, fabric or the presence of melt influence lithospheric properties, and that the oceanic lithosphere has an internal structure more complex than initially envisioned.

The range of processes involved in lithosphere formation that result in structural complexity include mantle dehydration at the ridge axis, incorporation of a gabbroic component just beyond the mid-ocean-ridge melting region, and thermal cracking and re-hydration at mid-plate ages. These processes have implications for global geochemical budgets and for the behaviour of tectonic plates as a function of age.

Despite the central role that oceanic lithosphere plays in plate tectonics, our understanding of its structure is surprisingly poor. In particular, recent advances in laboratory measurement of the seismic properties of olivine and other mantle mineralogies [*Jackson et al., 2004; Faul and Jackson, 2005*], as well as new theoretical models of the properties of realistic mantle lithologies [*Stixrude and Lithgow-Bertelloni, 2006*], predict seismic velocity profiles for mature oceanic lithosphere that are fundamentally inconsistent with the best observations of seismic velocities in two important ways. First, the experimental and theoretical models consistently display negative velocity gradients with depth in the lithosphere, while observed velocity profiles have positive velocity gradients (Figure 1). Second, the theoretical models predict a lithosphere-to-asthenosphere transition that is thermally controlled and, at old ages, this transition is much deeper and nowhere near sharp enough to match the transition that is observed seismically (Figure 2). These inconsistencies suggest that non-thermal factors such as composition, mineralogy, mineral fabric, grain size, and the presence of partial melt play important roles in controlling the formation of the lithosphere. There is little consensus on the dominant factors, however, in part because of the limited number of observations of detailed lithosphere structure. One strong possibility is that the positive seismic velocity gradients in the shallow Pacific lithosphere are related to the retention and subsequent off-axis crystallization of melt produced near the mid-ocean ridge.

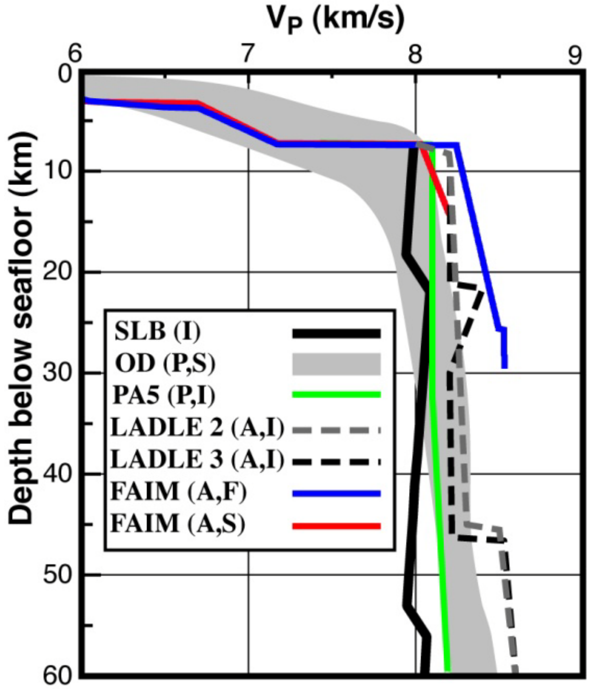

Fig. 1. P-wave velocity profiles predicted from laboratory data and measured from far-offset refraction experiments in the oceans. SLB: Predicted isotropic profile from *Stixrude and Lithgow-Bertelloni* [*2005*]. OD: *Orcutt and Dorman* [*1977*], from 70-My Pacific lithosphere acquired perpendicular to the spreading direction (slow (S) anisotropy direction). FAIM: from the Atlantic, with a longer profile shot in the fast (F), spreading-parallel direction [*Lizarralde et al*., *2004*]. The slow-direction Pacific velocities are lower than the slow-direction Atlantic velocities, consistent with observed smaller anisotropy in the Atlantic [*Gaherty et al.*, *2004*]. Dashed lines are preferred models 2 and 3 of LADLE experiment [*LADLE, 1983*], with a line orientation intermediate (I) between the fast and slow orientations. PA5 isotropic V_P profile estimated from *Gaherty et al.* [*1996*]. OD indicates that positive gradients are expected for the Pacific, and all the refraction results are at odds with SLB, which is based on a pyrolite model and so predicts an even stronger negative gradient when the effects of depletion are included.

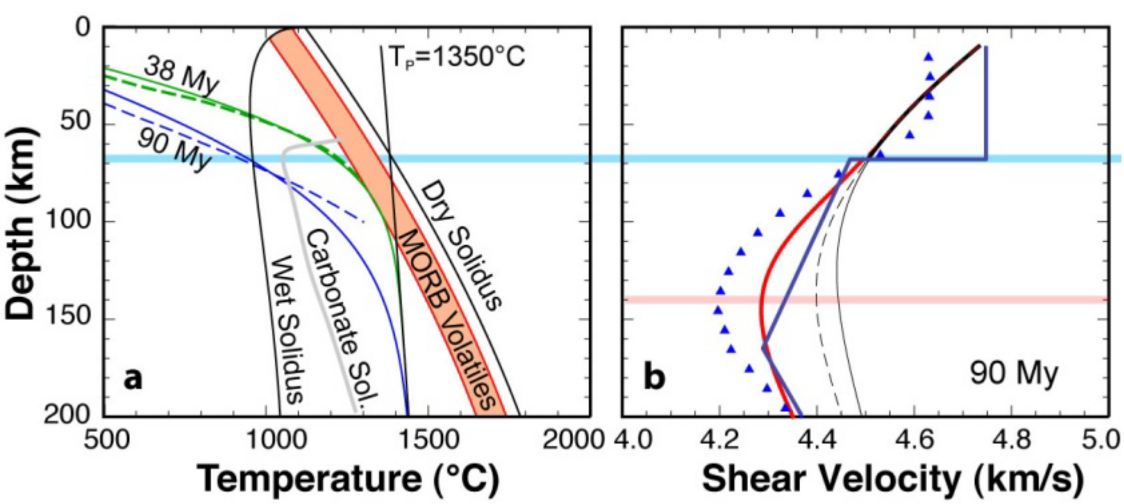

Fig. 2. Peridotite phase diagram, geotherms and velocity profiles for oceanic lithosphere.

a) Geotherms for 38 and 90 My old lithosphere superimposed on a phase diagram for peridotite. Solid geotherms are half-space cooling, dashed are the plate model of *McKenzie et al.* [*2005*]. The MORB Volatiles field represents the solidus for peridotite with bulk CO_2 and H_2O appropriate for the sub-ridge mantle [*Dasgupta et al. 2006*; *Katz et al., 2003*]. Carbonate solidus based on *Dasgupta and Hirschmann* [*2006*].

b) Predicted and observed $V_S(z)$ for 90 m.y.-old lithosphere. Pale red line: base of the thermal boundary layer; pale blue line: depth to the G discontinuity in PA5, which also closely corresponds to the depth of the dehydration boundary determined by *Hirth and Kohlstedt* [*1996*]. Solid gray line: lab-based predicted $V_S(z)$ for dry mantle.[1] Black/dashed-gray line: predicted $V_S(z)$ with attenuation considered.[2] Red dashed/bold line: predicted $V_S(z)$ with attenuation and the influence of water.[3] Blue line: the PA5 velocity model. Blue symbols: the 52-110 My *Nishimura and Forsyth* [*1989*] velocity model.

[1]Pyrolite model of *Stixrude and Lithgow-Bertolini* [*2005*] (SLB), with their "null hypothesis" model extrapolated to depths above 50 km, where it predicts velocities similar to their Harzburgite model.

[2]Attenuation added to the SLB model using the lab-based model of Q^{-1} from *Faul and Jackson* [*2005*] with an activation energy of 440 kJ/mole [*Jackson et al., 2004*], an activation volume of 13 cm^3/mol, and a constant grain size of 10 mm motivated by analyses of the roles of dynamic recrystallization and grain growth [e.g., *van der Wal et al.*, *1993*; *Evans et al.*, *2001*] and observations from xenoliths and ophiolites.

[3]Based on *Karato and Jung,* [*1998*] and *Karato,* [*2003*]. The magnitude of the velocity effect is constrained by the influence of water on viscosity and estimates for the water content of the MORB source [*Mei and Kohlstedt*, *2000; Hirth and Kohlstedt, 2003; Karato and Jung, 2003*].

A primary control on electrical conductivity is temperature, suggesting that measurements of mantle conductivity structure should respond to the thermal evolution of the lithosphere with age. Despite this, the structure of young lithosphere at the fast spreading Southern East Pacific Rise shows a much thicker resistive "lid" than would be expected from thermal considerations alone [*Evans et al., 2005*]. Beneath this lid the asthenosphere is electrically anisotropic and conductive, with a higher conductivity in the direction of plate spreading. Both silicate melt [*Roberts and Tyburczy, 1999*] and, as recently shown, carbonatite melts can enhance conductivity [*Gaillard et al., 2008*], with carbonatites particularly effective conductors. Although still controversial, there is also strong evidence that hydration of olivine can also result in enhanced conductivity [*Wang et al., 2006; Yoshino et al., 2006*]. The lid thickness is roughly consistent with seismic observations of the depth to the "G" discontinuity elsewhere, suggesting that its base represents a transition from a dry, melt depleted upper region overlying a wet and possibly melt bearing asthenosphere. The competing effects of water and melts of various compositions make it difficult to unequivocally identify the dominant mechanism within the anisotropic conductor.

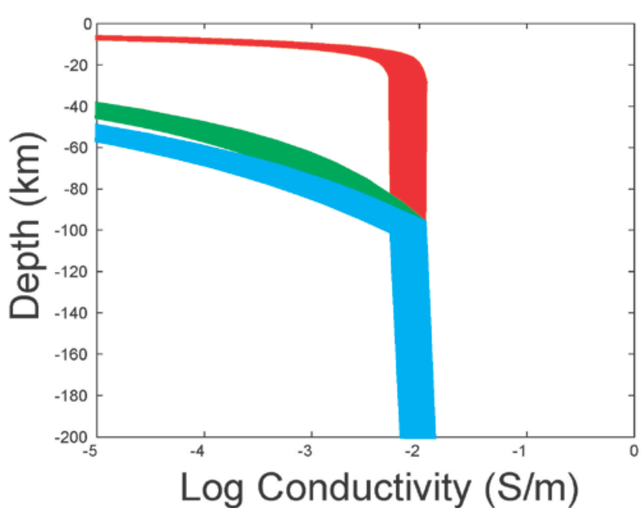

Fig. 3. Predicted electrical conductivity profiles of oceanic mantle for plate ages of zero (red), 50My (green) and 100My (blue) assuming that conductivity is solely controlled by temperature. The upper and lower bounds of each age curve are for +/- 100°C with adiabatic temperatures of 1350°C and 1450°C.

Thus it remains debated whether the "G" discontinuity defines the mechanical base of the plate and is related to dehydration during mid-ocean ridge melting or whether a small amount of carbonatite melt accumulates at this depth and causes the resultant drop in seismic velocity and enhancement in electrical conductivity. There is good evidence that tiny amounts of carbonatite can be detected at depths of 200-300km in the mantle [*Baba et al., 2006*], but how carbonatites will mix with silicate melts at shallower depths and the impact of such mixing on bulk conductivity remains unknown [*Gaillard, 2008; Evans, 2008*]. There are several arguments against melt. First, it is difficult to conceive how melt would form the kind of network necessary to explain the observed electrical anisotropy. Second, the "G" discontinuity is seen seismically in oceanic lithosphere of all ages (where it has been measured): whether carbonatites can remain molten within old oceanic lithosphere is unclear.

A number of ideas exist for both the internal structure of the lithosphere and the nature of the lithosphere-asthenosphere transition. Testing these models will require detailed measurements to be made in old oceanic lithosphere, at ages where the thermal boundary layer has "grown" through the "G" discontinuity. Such measurements have been proposed to the National Science Foundation and are currently under consideration.

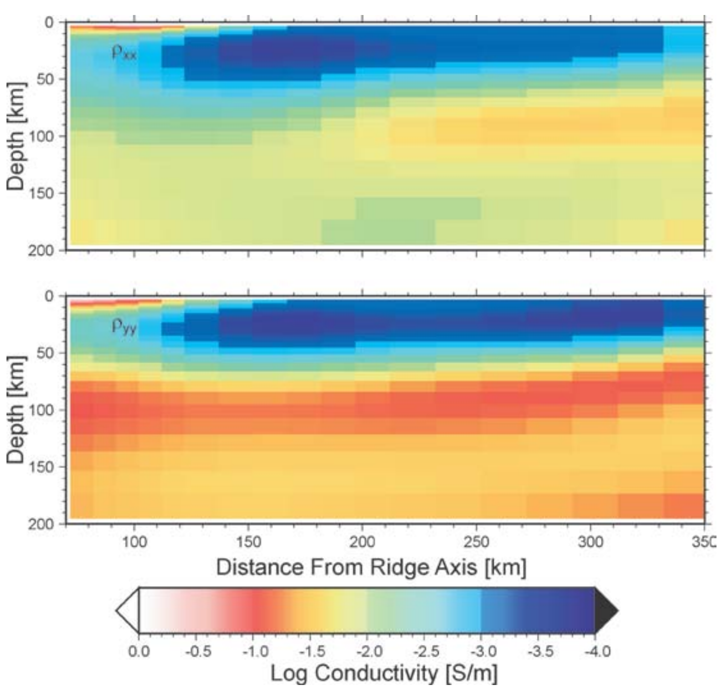

Fig. 4: anisotropic models of electrical conductivity from the MELT area of the Southern East Pacific Rise [*Evans et al., 2005*]. The top panel shows conductivity in the direction parallel to the spreading center and the lower panel shows conductivity in the direction of plate spreading. The model consists of a resistive plate in the uppermost ~60km, the thickness of which is roughly constant across the ages of crust spanned by the profile (~3 My). This upper plate is underlain by a conductive asthenospheric mantle which has appreciably higher conductivities in the direction of plate spreading. The electrical anisotropy is consistent with a wet mantle, although melt in a tube-like network is also a possible explanation for the observed structure. Inversions of Rayleigh- and Love-wave data from the same area also find structure that is nearly independent of age. After a rapid increase in shear velocity to a depth of about 60 km beneath young sea floor within 100 km of the spreading centre, the velocity contours to the east of the ridge are nearly horizontal.

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