Evolution of oceanic upper mantle structure

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Abstract

Love and Rayleigh wave phase velocities increase systematically with increasing age of oceanic lithosphere up to 150 Ma. The rates of increase differ between oceans and vary for different age intervals. Modeling of lithospheric age–phase velocity relations indicates that the high velocity seismic lid thickens and the velocities in the sub-lithospheric low velocity zone (LVZ) increase with age at different rates between oceans. The initial thickness of the lithosphere near mid-ocean ridges, as averaged by long-period surface waves, varies between 10 and 45 km, and 100 Ma lithosphere has thickness from 83 to 110 km, for models with isotropic shear velocities. Hotspots in oceanic areas appear to modify oceanic lithosphere evolution, producing deviations from average patterns with increasing age. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Oceanic lithosphere is the stiff, coherently translating portion (plate) of the chemical and thermal boundary layer at the top of the Earth’s dynamic convection system. Understanding how oceanic lithosphere evolves from its creation at upwellings beneath mid-ocean ridges until it plunges into the interior at subduction zones is a key geodynamic problem which is not yet resolved. Seismological evidence generally indicates that the oceanic ‘seismic’ lithosphere, as defined by the depth to the base of the high velocity ‘lid’ overlying the sub-lithospheric low velocity zone (LVZ), increases in thickness with age (Forsyth, 1977; Yu and Mitchell, 1979; Anderson and Regan, 1983; Wiens and Stein, 1983; Nishimura and Forsyth, 1989; Zhang and Tanimoto, 1991, 1992, 1993), but there is significant variation in seismic models for oceanic upper mantle structure. For example, for 100 Ma oceanic plate, various models indicate that the thickness of the seismic lithosphere is as little as 50 km (Anderson and Regan, 1983) or as much as 90 km (Forsyth, 1977; Zhang and Tanimoto, 1991, 1992).

Zhang and Lay (1996) determined global Love and Rayleigh wave phase velocity variations for periods from 85 to 250 s. Their data and inversion stability were carefully checked, and the results are compatible with other recent global and regional seismic studies (Laske and Master, 1996; Ekström et al., 1997). Using the Love and Rayleigh wave phase velocity dispersion data (Zhang and Lay, 1996) and the recent seafloor age map (Mueller et al., 1995), we obtained lithospheric age–phase velocity curves for Pacific (PAC), Indian (IND) and Atlantic (ATL)
oceans. We found that surface wave phase velocities increase systematically with increasing age of oceanic lithosphere up to 150 Ma, and that the rates of increase differ between oceans and vary for different age intervals.

Assuming that the surface wave phase velocities are determined by the upper mantle structure, and that the oceanic upper mantle structures vary with age and depth, we modeled the lithosphere age–surface wave phase velocity relations in three oceans and constructed oceanic upper mantle structure models. The results indicate that the high velocity seismic lid thickens and the velocities in the sub-lithospheric LVZ increase with age. The rates are different between oceans. The initial thickness of the lithosphere near mid-ocean ridges varies from 10 and 45 km, and 100 Ma lithosphere has thickness between 83 and 110 km, for models with isotropic shear velocities.

Hotspots, the surface feature of mantle plumes, are generally accepted to be connected to the deep convective systems (Morgan, 1972, 1984; Wilson, 1973). Several recent seismic studies indicated that some hotspots are associated with slow velocity anomalies in the mantle (Zhang and Tanimoto, 1992, 1993; Grand, 1994; Wolfe et al., 1997), but their nature remains enigmatic. Using obtained oceanic upper mantle models, we calculated surface wave phase velocity dispersions, and constructed surface wave phase velocity residual maps for the PAC, IND, and ATL in the current study. We found that many hotspots are in or near to the slow velocity regions in the residual maps. Hotspots in oceanic areas appear to modify oceanic lithosphere evolution, producing deviations from average patterns with increasing age.

2. Phase velocity vs. lithosphere age

Using about 30,000 seismograms from earthquakes with $M \geq 6.0$, Zhang and Lay (1996) determined Love and Rayleigh wave phase velocity variations from 85 to 250 s. All seismograms underwent careful quality control in the time and frequency domains. Fig. 1 shows maps of resulting Love and Rayleigh wave phase velocity variations at a period of 150.1 s. The seismic phases G1, R1, G2 and R2 are used. These phase velocity variation maps are with a hybrid parameterization, in which an initial iteration retrieves the low order spherical harmonic components that are used as an aspherical reference model for performing final block model inversions. These models are corrected for crustal thickness variations, which mainly affect the baseline between oceans and continents. Results for other periods can be found in the work of Zhang and Lay (1996), and the patterns in the period range 85 to 150 s are quite similar. These results are used here to analyze first-order features of global oceanic upper mantle structure, allowing for the spatial smoothing of the inversions and the intrinsic averaging properties of intermediate to long-period surface waves. Casual inspection of the surface wave phase velocity maps indicates that velocities generally increase with lithospheric age in oceanic regions, but there are some strong departures from this pattern (note, for example the relatively low velocities northwest of Hawaii).

Using the recent seafloor age map (Mueller et al., 1995), we determine lithospheric age–phase velocity relationships for both Love and Rayleigh waves with periods from 85 to 250 s in the PAC, IND, and ATL, along with an average (AVE) for all three oceans. Marginal basins and some boundary areas of oceans are not included because their ages are not well characterized.

Fig. 2 shows lithospheric age–phase velocity relations for PAC, IND, ATL and AVE for Love wave periods of 85.5, 100.6, 150.1 and 200.8 s, and Rayleigh wave periods of 85.5, 100.6, and 150.1 s. Phase velocities increase systematically with ocean floor age in every region, but this age-dependence is strongest for short-period surface waves and decreases with period, indicating that plate effects are confined to the uppermost mantle. The other interesting feature is the lithospheric age–phase velocity relation differences between oceans. For young lithosphere, the fast spreading PAC has the lowest phase velocities, while the slow spreading ATL has the highest phase velocities. This indicates a spreading rate control on the seismic structure (Zhang and Tanimoto, 1991, 1993). Ridge with a slow spreading rate will have a slower upwelling, which produces more cooling to the surface beneath the ridge, and thickens the lithosphere at the axis and terminates melting at a greater depth. Given the smoothing
effects of the tomographic inversion, one must allow for the difference in lateral averaging in each region (a larger range of lithospheric age is sampled by a given long-period surface wave in the ATL than in the PAC), but the differences in Fig. 2 are not accounted for by this effect. Variations are also found between plates with different spreading rates for heat flow measurements within regions less than 80 Ma (Parsons and Sclater, 1977; Sclater et al., 1980; Anderson and Skilbeck, 1981; Stein and Stein, 1992) and in seismic attenuation structure beneath the Mid-Atlantic Ridge and the East Pacific Rise (Canas and Mitchell, 1981).

Conventional models for oceanic thermal evolution (Parsons and Sclater, 1977; Sclater et al., 1980; Stein and Stein, 1992) suggest that oceanic lithosphere cools and subsides as the thermal boundary layer thickens in the first 60–80 Ma, but then the thickness of the thermal lithosphere becomes constant, possibly due to small-scale convection (Parsons and McKenzie, 1978), viscous shear stress heating of the base of the lithosphere (Schubert et al., 1976), and/or thermal rejuvenation effects of superplumes and hotspots (McNutt and Judge, 1990; Larson, 1991; Larson and Olsen, 1991). Fig. 2 indicates that surface wave phase velocities continue to increase with lithospheric age up to 150 Ma in each ocean, in contrast to the behavior of heat flow and water depth. The lithospheric age–phase velocity curves can be roughly divided into three domains.
The first is for ages less than 40 Ma, where surface wave phase velocities in IND, PAC, and AVE increase with age rapidly and are correlated with spreading rate. The rate of increase for ATL is lower. The second domain is from 40 to about 100 Ma. The rate of increase of phase velocities reduces relative to the first domain, and there are even decreases in velocity at some frequencies. Love wave phase velocities for IND increase to exceed those of ATL, while Rayleigh wave phase velocities for IND remain lower than those for ATL. Observed heat flow measurements for ages from 40 to 100 Ma generally have higher values than in theoretical calculations (Parsons and Sclater, 1977; Sclater et al., 1980; Anderson and Skilbeck, 1981; Stein and Stein, 1992), suggesting that thermal perturbations affect this age range. Many hotspots, such as Arnold, Crozet, Discovery, Hawaii, Marquesas, MacDonald, Reunion, St. Helena, Tahiti, and Trindade, are located in ocean regions in the 40–100 Ma range (Fig. 1), and thermal anomalies associated with these upwellings may account for both the seismic and heat flow behavior. Love wave phase velocities in the three oceans converge near ages of 100 Ma, and diverge at larger ages. The third domain is from ages of 100 to 150 Ma. Phase velocities in this domain increase, but at different rates between the oceans. Phase velocities tend to decrease beyond 150 Ma, but this may be an artifact of small ocean floor areas and seismic velocities that are biased by proximity to subduction zones.

3. Modeling oceanic upper mantle structure

We modeled the upper mantle structure causing the lithospheric age–phase velocity patterns using simply parameterized models, which fit the Love and Rayleigh wave dispersion simultaneously. After inspecting the lithospheric age–phase velocity relations, we excluded Love waves with periods longer than 200 s and Rayleigh waves with periods longer than 150 s, because the data and relationships appear unstable in those cases. Ocean bathymetry and crustal thickness have large effects on surface wave propa-
Seismic velocity structure is a manifestation of temperature, composition, partial melting and dynamic state (via anisotropy) of the mantle. However, there are few clear relationships between these parameters other than a handful of laboratory experiments. Simple parametric forms of the velocity variations are used given that we have little a priori constraint on the structure. We assume that the velocity in the LVZ is a function of depth and lithospheric age given by:

$$V(t, z) = V_o + \frac{\partial V}{\partial t} \Delta t + \frac{\partial V}{\partial z} \Delta z,$$

where $V_o$ is the shear wave velocity beneath the mid-ocean ridge at the top of LVZ, $t$ is the oceanic lithospheric age in Ma, and $z$ is the depth from a reference position at the base of the region being perturbed to the bottom of the lid. Two basic types of thermal models, the half-space cooling model (Turcotte and Oxburgh, 1967; Parker and Oldenburg, 1973; Crough, 1975; Yoshii, 1975) and the plate model (McKenzie, 1967; Sleep, 1969; Parsons and Sclater, 1977; Sclater et al., 1980; Stein and Stein, 1992) have been used to model young ocean heat flow and water depth successfully. These models predict that heat flow and water depth vary with age$^{-1/2}$ and age$^{1/2}$, respectively. In this study, we adopt an age$^{1/2}$ relationship for thickness of the oceanic lithosphere as a function of age,

$$H = A + B\sqrt{t},$$

where $A$ and $B$ are constants, and $t$ is the oceanic lithospheric age in Ma. We step through models with $A$, $B$, $V_o$, $\partial V/\partial t$, and $\partial V/\partial z$ varying with increments of $0.2$ km, $0.1$ km Ma$^{-1/2}$, $5 \times 10^{-5}$ km s$^{-1}$, $10^{-5}$ km s$^{-1}$ Ma$^{-1}$, and $10^{-3}$ s$^{-1}$, respectively, calculating the misfit of observed phase velocities for Love wave for periods of 85.5, 100.6, 150.1, 200.1 s and Rayleigh wave for periods of 85.5, 100.6, and 150.1 s. The misfit that we seek to minimize is:

$$\sigma = \left[ \frac{1}{n-1} \sum_{i=1}^{n} (V_i - \bar{V})^2 \right]^{1/2},$$

where $V_i$ is the observed average phase velocity in every 10 Ma increment for each frequency and wave type, $\bar{V}$ is the calculated phase velocity, and $n$ is the total number of data. The preferred model is that with the smallest misfit, although this assumes validity of the basic model parameterization.

The lithosphere age–phase velocity relation changes between oceans, and a single model cannot fit the observations for all three oceans to within the precision of the measurements. Therefore, we determine models for ATL, IND, and PAC independently, as well as for AVE. As noted above, the lithosphere age–phase velocity curves (Fig. 2) show some variations as a function of age, so we determined three sets of models; the first uses data up to 40 Ma, the second uses data up to 110 Ma, and the third fits the data up to 150 Ma. The results for data less than 40 Ma can be compared to heat flow and ocean depth observations in young oceanic regions.

Not all of the parameters in our simple models proved to be resolvable. Parameters $A$, $B$, and $\partial V/\partial t$ affect the misfit strongly, while parameters $V_o$ and $\partial V/\partial z$ are not resolvable. Table 1 gives the optimal parameters and standard deviations obtained for the three cases. It appears that mid-ocean ridge spreading rate, which is related to both slab pull and ridge push forces, plays an important role in determining the oceanic upper mantle structure. For example, the parameter $B$, which is associated with thermal evolution of the boundary layer, correlates with spreading
Table 1
The best fitting models

<table>
<thead>
<tr>
<th>Ocean</th>
<th>A</th>
<th>B</th>
<th>( V_u )</th>
<th>( \partial V/\partial t )</th>
<th>( \partial V/\partial z )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAC</td>
<td>6.0</td>
<td>10.700</td>
<td>4.280</td>
<td>0.00045</td>
<td>0.001</td>
<td>0.0093</td>
</tr>
<tr>
<td>IND</td>
<td>39.4</td>
<td>4.900</td>
<td>4.355</td>
<td>0.00073</td>
<td>0.000</td>
<td>0.0122</td>
</tr>
<tr>
<td>ATL</td>
<td>15.8</td>
<td>7.300</td>
<td>4.360</td>
<td>0.00015</td>
<td>0.001</td>
<td>0.0110</td>
</tr>
<tr>
<td>AVE</td>
<td>16.2</td>
<td>7.500</td>
<td>4.365</td>
<td>0.00052</td>
<td>0.000</td>
<td>0.0097</td>
</tr>
</tbody>
</table>

The units are, \( A \): km; \( B \): km Ma\(^{-1/2} \); \( V_u \): km s\(^{-1} \); \( t \): Ma; \( z \): km; \( \sigma \): km s\(^{-1} \).

rate. PAC has the largest value and ATL has the smallest value. Parameter \( A \), the initial lithosphere thickness beneath the mid-ocean ridges, as averaged over by our surface wave data, has large variations between oceans. It is 12 ± 6 km in PAC, 36 ± 4 km in IND, and 30 ± 15 in ATL.

Parameter \( B \) for ATL in the first set of models is 0.8, much smaller than for the other two groups; the initial lithosphere thickness, \( A \), for ATL changes from 15 to 45 km for the three cases, and parameter \( B \) for ATL and IND swap in relative size in fitting the data out to 150 Ma. Thus, the specific model parameters are not uniquely defined in the study. One reason is that the horizontal resolution of the phase velocity maps used in this investigation is about 1600 km, the ATL is associated with a half spreading rate about 40 km Ma\(^{-1} \), then, the used surface wave phase velocity data cannot resolve the detail variation near the Mid-Atlantic Ocean Ridge, or the current results have large uncertainty. Note that there are relatively few data points for areas older than 100 Ma as well, so the results of the third group of models are less stable.

Even if some model parameters are not stable, the basic features are robust in this study. \( V_u \), the velocity at the top of LVZ, increases from PAC to IND to ATL in all three groups of models, and does not vary much between sets of models. We found that \( \partial V/\partial t \) is resolvably non-zero, while \( \partial V/\partial z \) is essentially zero in all cases. The shear velocity in the LVZ increases with age (Yoshii, 1975; Forsyth, 1977). It is reasonable to suggest that cooling occurs within the LVZ as the age of the overlying plate increases. This feature is in conflict with the plate model (Parsons and Sclater, 1977; Sclater et al., 1980; Stein and Stein, 1992).

Considering the data quality and stability of the results, we prefer the models obtained by fitting data...
out to 110 Ma. Fig. 3 shows the upper mantle seismic models for this case. The thickness of the oceanic lithosphere increases with age, consistent with previous seismological studies (Forsyth, 1977; Yu and Mitchell, 1979; Anderson and Regan, 1983; Wiens and Stein, 1983; Nishimura and Forsyth, 1989; Zhang and Tanimoto, 1991, 1992, 1993). However, the rate at which the lithosphere thickens varies from plate to plate. The base of the lid for 100 Ma plate is at 113.0, 99.4, 83.4 and 96.0 km for PAC, IND, ATL and AVE, respectively. These values are consistent with the lithosphere thickness of the recent plate model GDH1 (Stein and Stein, 1992), 95 ± 15 km, obtained using heat flow and sea floor depth. The velocity, $V_o$, at the top of LVZ below mid-ocean ridges is 4.280, 4.350, and 4.360 km s$^{-1}$ for PAC, IND, and ATL, respectively. These subtle variations may be related to the composition, temperature, and degree of partial melting under each mid-ocean ridge, which is expected to vary due to the plate spreading rate and relative importance of passive vs. active upwelling. The velocity structures are very similar in the youngest oceans, and the differences increase out to an age of 110 Ma.

Fig. 4a and b indicate the observed and calculated Love and Rayleigh wave phase velocity using models in Fig. 3 for PAC and ATL. Most of the calculations are within one standard deviation, and Love wave phase velocity has better fitting than Rayleigh wave. The current study indicates that a simple boundary layer model (Turcotte and Oxburgh, 1967; Parker and Oldenburg, 1973), which has only two parameters, the initial temperature and the age, cannot explain these differences between oceans, and the seismic velocity structures motivate a more complex model for ocean lithosphere evolution.
4. Phase velocity residual maps

Our preferred model has lateral variations and differences from plate to plate, but it is notable that satisfactory fits to the long-period dispersion data were obtained with purely isotropic shear velocity models. This may reflect the averaging involved in the construction of the age–phase velocity curves for each plate, with azimuthal anisotropy effects averaging out. While dispersion curves for anisotropic structures can be computed and compared with the data quite readily, the number of additional parameters involved causes this to be an underdetermined problem. Our general sense is that the basic phase velocity differences between oceanic regions are rather robust, and anisotropic modeling may change some aspects of the isotropic models determined for each region in this study, but the basic structural differences will persist.

Differences between oceanic regions younger than 40 Ma and regions from 40 to 110 Ma are found in heat flow (Parsons and Sclater, 1977; Sclater et al., 1980; Anderson and Skilbeck, 1981; Stein and Stein, 1992), ocean water depth (Parsons and Sclater, 1977; Sclater et al., 1980; Stein and Stein, 1992), and our lithosphere age–phase velocity relations. To probe this issue further, we subtract parametric phase velocity predictions, calculated using the models for each ocean in Fig. 3, from the observed phase velocity maps (Fig. 1). This results in surface wave ‘residual’ phase velocity maps, which indicate the spatial patterns in deviations from the simple velocity models that fit each plate on average. Fig. 5 shows the residual maps at a period of 150.1 s. At this period,
the surface waves are quite sensitive to shear wave structure in the upper 300 km of the mantle. To allow application to the entire ocean, we extrapolated the ocean models up to 160 Ma old lithosphere.

Comparing Fig. 5 with Fig. 1, the mid-ocean ridge features have disappeared, and there is no obvious age-dependence in the residual phase velocities. This indicates that our models provide reasonable approximations to the average plate structure in each ocean basin. There are relatively fast and relatively slow velocity regions in Fig. 5. There are 35 hotspots with locations in the ocean basins, many of them are located in slow velocity areas in the residual maps. Caroline, Easter, Galapagos, Hawaii, Juan Fernandez, Marquesas and Tahiti in the PAC, Ascension, Azores, Bermuda, Bouvet, Cape Verde, Discovery, Fernando, New England, St. Helena, Tristan de Cunha and Yema in the ATL, Amsterdam and Crozet in the IND are located close to slow velocity peaks. Given the general notion that many hotspots are associated with deep mantle plumes (Morgan, 1972, 1984; Wilson, 1973; Yoshii, 1975; Vogt, 1981; Vink et al., 1985; White and McKenzie, 1989; Campbell and Griffiths, 1990; Griffiths and Campbell, 1990; Sleep, 1990; Duncan and Richards, 1991) and have high temperature and high degree of partial melting, it appears that hotspot upwellings are responsible for perturbations about the mean plate trends solved for in Fig. 3. The local perturbations in lithospheric temperature structure associated with the hotspots may also be manifested in the heat flow and water depth anomalies in oceanic lithosphere of intermediate age. This does not preclude other factors such as basal heating or small scale convection beneath the plate from playing a role, but it appears that oceanic lithosphere should be modeled with dynamic parameters such as spreading rate and hotspot thermal resetting being included. Note some hotspots are associated with slow velocity peaks in one map, but not in the other map in Fig. 5, this may indicate the depth, anisotropy, or other effects. Clearly, more detailed investigation is needed.

5. Conclusions

Rayleigh and Love phase velocities in PAC, IND, and ATL are used to probe the oceanic upper mantle structure simultaneously. The Rayleigh and Love wave phase velocities in period range 85 to 150 s increase systematically with increasing age of oceanic lithosphere up to 150 Ma. Using the recent seafloor age map (Mueller et al., 1995), we found that the age-dependence is strongest for short-period surface waves and decreases with period, indicating that plate effects are confined to the uppermost mantle, and that the fast spreading PAC has the slowest phase velocities, while the slow spreading ATL has the highest phase velocities in the young ages, indicating that the spreading rate controls the oceanic upper mantle evolution.

Assuming that the lithosphere structure and seismic velocity in the upper mantle varies with depth and age, we modeled the oceanic upper mantle structure in PAC, IND, ATL and AVE, that the velocity change with age affects oceanic upper mantle structure strongly, while the depth effect is small. The initial thickness of the lithosphere near mid-ocean ridges, as averaged by long-period surface waves, varies between 10 and 45 km, and 100 Ma lithosphere has thickness from 83 to 110 km.

To further probe oceanic upper mantle structure, we subtracted parametric phase velocity predictions, calculated using the obtained models for each ocean, from the observed phase velocity maps. The age-dependence and mid-ocean ridges disappeared in the residual maps. Many hotspots are located in slow velocity areas, and many of them are associated with or near to slow velocity peaks in the residual maps, suggesting that hotspot in oceanic areas modify oceanic lithosphere evolution and produce deviations from average patterns with increasing age.

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