Attenuation in the Oceanic Lithosphere and Asthenosphere: Results from Arrays of Ocean Bottom Seismometers

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Using Rayleigh waves, we have measured shear attenuation beneath 4 arrays of ocean-bottom seismometers: MELT and GLIMPSE near the East Pacific Rise; PLATE on 150-160 Ma seafloor in the western Pacific, and the Cascadia Initiative deployments on the Juan de Fuca plate in seafloor 0-10 Ma old. In addition, we measured attenuation of P waves in the 1-15 Hz band beneath PLATE using body waves from intermediate and deep focus earthquakes. For Rayleigh waves, we employed the two-plane-wave technique to account for multi-path interference arising from velocity heterogeneities outside the arrays, the Born approximation to account for focusing and defocusing within the study areas, and station corrections to account for site response and errors in instrument response. Rayleigh wave attenuation coefficients extend from periods of 20 s up to 143 s for Juan de Fuca. The Juan de Fuca area is slightly more attenuating than seafloor of similar age near the East Pacific Rise. Beneath Juan de Fuca, the minimum shear quality factor Q is found centered at about 80 km, just below the expected dry solidus. Q averaged over the well-resolved depth range of 70 to 110 km is 45-50. The existence of the maximum attenuation below the dry solidus beneath young seafloor points to the role of melt removal and consequent dehydration in altering the composition and melting temperature of the mantle. A component of convective downwelling is needed to explain both the rapid increase in shear wave velocity away from the ridge and the attenuation pattern. Comparison of the attenuation of low frequency surface waves with high frequency body waves indicates that intrinsic attenuation is frequency dependent, but that the usually assumed power law form is unlikely to persist throughout the seismic frequency band.

Keywords: Attenuation, Oceanic Lithosphere and Asthenosphere

Rayleigh wave attenuation in the central Pacific upper mantle from the NoMelt experiment

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Ocean basins record fundamental plate-tectonic processes, most notably the creation and evolution of oceanic lithosphere and its interaction with the underlying asthenosphere. The NoMelt array of ocean-bottom seismometers was deployed on ~70 Ma Pacific seafloor with the aim of characterizing the seismic and electrical structure of normal mature oceanic lithosphere-asthenosphere system. Analyses of surface-wave travel times have revealed that the seismic velocities within the array are strongly anisotropic (Lin et al., 2016; Russell et al., 2016), which complicates attempts to infer the thermal structure of the lithosphere and the volatile and partial-melt content of the asthenosphere from isotropic seismic velocity. We present the first measurements of seismic attenuation determined from the NoMelt data set. Rayleigh wave amplitudes and travel times were measured using the Automated Surface Wave Measuring System (Jin and Gaherty, 2015) in the period range 20-150 s. The amplitude data are corrected for the effects of propagation outside the array and used to solve for a single frequency-dependent attenuation coefficient within the array as well as a frequency-dependent term for each receiver. Preliminary results show that the Rayleigh wave attenuation nearly doubles between periods of 40 s and 50 s. A possible interpretation is that this abrupt change corresponds to the transition from low-absorption lithosphere to strongly attenuating asthenosphere. Inverting these values for depth-dependent shear attenuation allows the transition to be more accurately located in depth and inferences about lithospheric thermal structure and the presence of volatiles and melt in the asthenosphere to be drawn.

Keywords: attenuation, lithosphere, volatiles

Seismic properties of hydrous and partially molten synthetic dunites

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The influence of hydrous, but water-undersaturated conditions and aspects of the role of partial melting of upper-mantle materials, remain to be clarified through ongoing experimental work.
Water-undersaturated conditions have been realised in the laboratory in the relatively oxidizing environment within Pt capsules/sleeves. Specimens of synthetic Ti-doped olivine have been hot-pressed within Pt capsules with a range of Ti concentrations from 176 to 802 atom ppm Ti/Si. At sufficiently oxidizing conditions, a stable extended defect is formed involving Ti/Mg substitution charge balanced by double protonation of a neighbouring Si vacancy (Berry et al., *Geology*, 2005)., The concentrations of chemically bound H range between 330 to 1150 atom ppm H/Si (Berry et al., *Geology*, 2005). Torsional forced-oscillation tests were conducted at seismic periods of 1 –1000 s and 200 MPa confining pressure during slow staged cooling from 1200 to 25°C. Each Ti-doped specimen showed mechanical behaviour of the high-temperature background type involving monotonically increasing dissipation and decreasing shear modulus with increasing oscillation period and increasing temperature. The modulus dispersion and dissipation measured under these water-undersaturated conditions are markedly stronger than for a similarly prepared specimen tested dry within an Ni-Fe sleeve under more reducing conditions. However, the data for the hydrous specimens display only limited sensitivity of the seismic properties to variation of the concentration of the Ti-hydroxyl defect. The lower shear moduli and higher dissipation measured under water-undersaturated conditions are clearly attributable to the different chemical environment. Presumably, the contrasting chemical compositions (and hence effective viscosities) of grain-boundary regions and/or differing populations of lattice defects are responsible. Clarification of the relative roles of grain-boundary sliding and any additional intragranular relaxation under increased f_{H2O} and f_{O2} thus offers the prospect of an improved understanding of the seismological signature of more oxidized/hydrous portions of the Earth’s upper mantle, such as subduction zone environments (Cline et al., *Nature Geoscience*, submitted). Concerning the seismic properties of partially molten lherzolite, bulk modulus relaxation caused by stress-induced change in the proportions of coexisting crystalline and melt phases has recently been proposed (Li and Weidner, *PEPI*, 2013). In order to further assess this possibility, a forced oscillation experiment has been conducted at seismic frequencies on a newly prepared synthetic dunite specimen (sol-gel olivine + 2.6% added basaltic melt glass) utilizing an enhanced capacity of the ANU apparatus to operate in both torsional and flexural oscillation modes. Shear modulus and dissipation data are consistent with those for melt-bearing olivine specimens previously tested in torsion, with a pronounced dissipation peak superimposed on high-temperature background. Flexural data exhibit a monotonic decrease in the complex Young’s modulus with increasing temperature under trans-solidus temperatures. The observed variation of Young’s modulus, closely comparable with that measured by Li and Weidner, is well described by the approximation 1/E ~ 1/3G, which holds when G/3K << 1. At high homologous temperatures, when the shear modulus is low, extensional and flexural oscillation measurements thus offer little resolution of bulk modulus –leaving the possibility of its partial relaxation unresolved. Planned experiments involving the measurement of volume changes caused by oscillating confining pressure may provide the answer (Cline and Jackson, *GRL*, 2016).

Keywords: seismic wave attenuation, water-undersaturated conditions, partial melting

Experimental study of polycrystal anelasticity at near-solidus temperatures and its seismological applications

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For a quantitative interpretation of the seismic velocity and attenuation structures in the upper mantle, we need to clarify the rock anelasticity [e.g., Jackson et al. 2002]. In particular, scaling law to extrapolate experimental results to the mantle is necessary. Polycrystal anelasticity follows the Maxwell frequency scaling $Q^{-1}(f/f_M)$ with f_M = unrelaxed elastic modulus / diffusion creep viscosity [Morris and Jackson 2009; McCarthy et al. 2011]. However, the applicability of this scaling law is limited to $f/f_M < 10^4$ [Takei et al. 2014], and the scaling law applicable to the seismic frequency range ($10^6 =< f/f_M =< 10^9$) has been unknown.
We made an experimental approach to the polycrystal anelasticity at near-solidus temperatures by using a rock analogue (organic polycrystals) and found that the deviation from the Maxwell frequency scaling at high normalized frequencies can be described by using homologous temperature T/T_m, where T_m represents solidus [Yamauchi and Takei 2016]. The most remarkable finding is that polycrystal anelasticity is significantly enhanced just below the solidus temperature ($0.94 < T/T_m < 1$) in the absence of melt. Viscosity is also reduced in the same temperature range. These changes, which are caused by a solid-state mechanism, were large even for the samples which generate very small melt fraction (< 1%) at $T = T_m$. In contrast, when melt fraction is small (< 1%), the effects of melt generation at $T = T_m$ on elasticity, anelasticity, and viscosity were negligibly small. We established a new anelasticity model by parameterizing these experimental data.
The applicability of this new model to the mantle was shown by the fitting to the horizontal profiles of seismic shear wave velocity in the Pacific mantle at 50 and 75 km depths, which shows a steep reduction of V_S just below the solidus temperature [Priestley and McKenzie 2013]. Then, we applied the new anelasticity model to the vertical profiles of V_S showing a discontinuous (steep) reduction at LAB; we used the temperature profiles calculated by the plate-cooling model and the solidus temperature calculated by assuming various distributions of volatile (H_2O). The new anelasticity model enables us to interpret these seismological structures, including the seismic discontinuity, by the solid-state mechanism at near-solidus temperatures without invoking melt.

Keywords: anelasticity, partial melting, seismic attenuation, seismic low velocity, LAB

Significant shear and bulk attenuation in the Tonga-Lau subduction system

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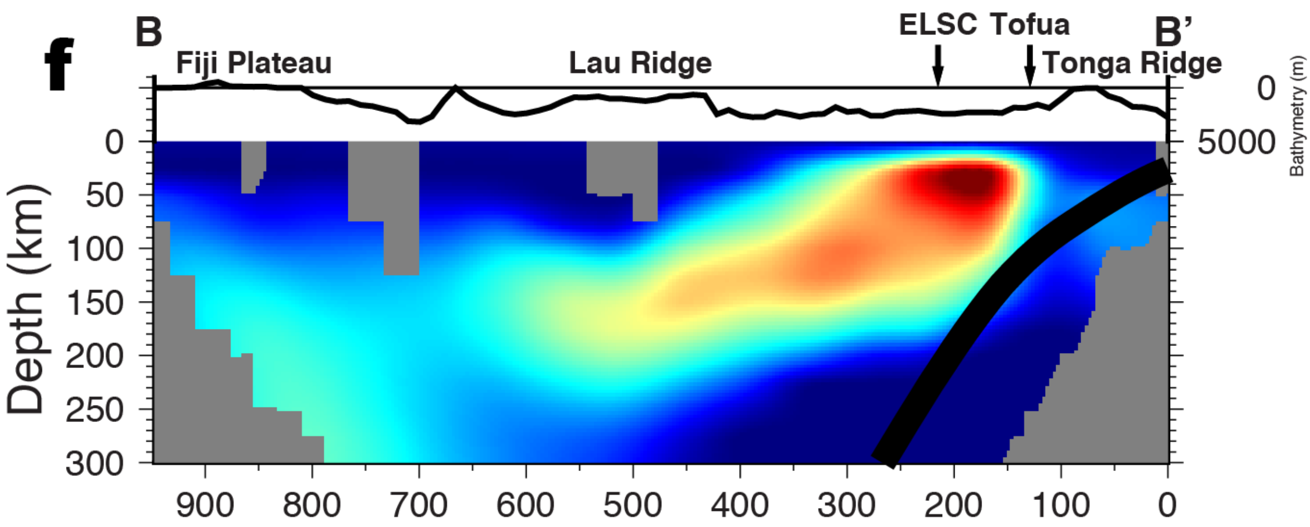
We image the 3-D attenuation structures of the Tonga subduction zone and the Lau back-arc basin using local earthquake waveforms recorded by the 2009-2010 Ridge2000 Lau Spreading Center Imaging project. Amplitude spectra of P and S waves from local earthquakes are inverted for the path-average attenuation operator (t^*) along with the seismic moment and corner frequency with varying frequency-dependent exponent (α). Analysis shows that the data are best fit by the assumption of $\alpha \approx 0.3$, supporting the laboratory-based models of grain boundary sliding. The t^* measurements are inverted with various techniques to obtain 3-D tomographic models of Q_P, Q_S, and Q_P/Q_S. Results show strong anomalies of high *P*- and *S*-wave attenuation within the upper 100 km of the mantle beneath the back-arc basin. Perhaps the highest seismic attenuation ($Q_P < 30$ and $Q_S < 20$) known in the mantle is found immediately beneath the spreading center. High attenuation anomalies form an inclined zone dipping from the back-arc spreading centers to the west away from the slab. This high-attenuation zone in the back-arc requires not only abnormally high temperature but also the existence of partial melt, suggesting that hot materials supplied from the Australian mantle upwell along with the mantle wedge flow pattern, triggering extensive decompression melting near the back-arc spreading centers. The back-arc basin attenuation anomalies show low Q_P/Q_S ratios (< 1.5), in contrast to more conventional Q_P/Q_S ratios (> 1.8) beneath the Fiji Plateau. This suggests that the bulk attenuation is as large as the shear attenuation beneath the back-arc spreading centers and near the Tonga slab, where abundance of partial melt and free water are expected, invoking mechanisms of bulk attenuation involving free fluids.

Keywords: Back-arc spreading, Seismic attenuation, Partial melting, Tonga subduction zone, Lau basin



Seismic attenuation beneath Japan: Close links to arc magmatism, seismogenesis and crustal deformation

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Nakajima et al. (2013, JGR) proposed a new technique to precisely estimate seismic attenuation along a ray path, which can minimalize a strong tradeoff between corner frequency and attenuation term. They estimated 3D P-wave attenuation structure beneath Tohoku, Japan, and discussed magmatism is controlled by a mantle-wedge process that depends strongly on spatial variations in the degree of partial melt in the upwelling flow. In recent years, we have estimated 3D P-wave seismic attenuation structures beneath Kanto (Nakajima, EPS, 2014), Kyushu (Saita et al., GRL, 2015), and central Japan (Nakajima and Matsuzawa, EPS, 2017) using the method of Nakajima et al. (2013). These studies have provided important constraints on the genesis of earthquakes in the subducting Philippine Sea slab, an along-arc variation in arc magmatism in Kyushu, and the cause of a high-strain-rate zone called the Niigata-Kobe Tectonic Zone. We will review the results of these studies and show the relationship between seismic attenuation and velocity structures in the crust and the uppermost mantle in different tectonic settings, providing important roles of seismic attenuation on the understanding of ongoing processes in the Earth.

