Seismic constraints on the water flux delivered to the deep Earth by subduction

SUPPLEMENTAL MATERIAL

A need for a low wave speed layer with a large number of wave speed discontinuities along the top surface of the subducting plate is demonstrated through the comparison of data with synthetic seismograms, computed by finite difference in 3-D unless noted otherwise, from a suite of subducting plate models. In the following supplementary sections, models and associated synthetics demonstrate the importance of different structural features to generate the secondary seismic arrivals. Supplemental Section DR1 includes three model types that vary the kind of oceanic crustal structure on top of the subducting plate: (1) a meta-stable MORB (mid-oceanic ridge basalt), (2) eclogite from a MORB protolith, and (3) MORB in the top 300 km and eclogitized MORB at greater depth. Along with varying the crustal properties, a low wave speed channel was added to demonstrate its importance. Wave speeds for MORB and eclogite are derived from Hacker et al. (2003) and are taken relative to the velocity of the subducting plate ($\Delta V = +7.5\%$). The background wave speed model is iasp91 (Kennett, 1991).

Along with synthetics from these different crustal models, Supplemental Section DR2 provides synthetic responses from varied properties of the low wave speed layer to demonstrate how the secondary arrival behaves as a function of the layer thickness, wave speed, and depth/position.

Supplemental Section DR3 describes the water flux calculation and the conversion from serpentine to Phase A.

Forward modeling of the low wave speed layer demonstrates a direct relationship between amplitude and wave speed reduction, while the thickness of the low wave speed layer modifies the amplitude and the frequency content.
SECTION DR1

1.1. No Low Wave Speed Layer

1.1.1 Meta-stable Mid-Oceanic Ridge Basalt

A layer of meta-stable MORB along the entire length of the subducting plate from 0 to 800 km ($\Delta V = -17\%$) does contribute to additional larger arrivals following the initial P wave (Figure DR1).

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Figure DR1. Simple subduction zone model with subducting plate and meta-stable MORB crust from 0-800 km. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star. Notice the increase in amplitude immediately following the P arrival, but not before the S arrival.

1.1.2 Eclogite

Addition of an eclogite, with a MORB protolith, ($\Delta V = -6\%$) produces a layer with a wave speed very close to the surrounding mantle after accounting for the change in temperature due to the subducting plate (Figure DR2). This renders the eclogite layer indistinguishable from the surrounding mantle and the subsequent synthetic response similar to an unmodified subducting plate.
Figure DR2. Subduction model with eclogite along the entire length of the subducting plate. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star.

1.1.3 Mid-Oceanic Ridge Basalt / Eclogite
The combined effect of MORB in the top 300 km (ΔV = -17%) and eclogite at greater depths, 300-800km (ΔV = -6%), reduces the effects from deep meta-stable MORB identified in Figure DR1, particularly near the direct P wave arrival (Figure DR3). Simulations from this model, which are more physically plausible than the two previous models, generate responses similar to the model with only eclogite but with additional small amplitude arrivals halfway between the direct arrivals.
Figure DR3. Subduction model with MORB in the top 300 km and eclogite from 300 - 800 km. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star.
1.2. Low Wave Speed Layer

1.2.1 Meta-stable Mid-Oceanic Ridge Basalt overlying a low wave speed layer
Addition of a low wave speed layer to the model in Section 1.1 generates a response with much larger amplitude arrivals throughout the time window between the direct arrivals (Figure DR4). Wave speeds of the meta-stable MORB layer are quite reduced relative to the mantle (-17%) but not as reduced as the low wave speed layer beneath (-25%). The importance of the meta-stable MORB layer is diminished, as its effects are masked by the dominance of the low wave speed layer.

![Figure DR4](image.png)

**Figure DR4.** Subduction model with meta-stable MORB along entire plate length with the low wave speed, variable thickness layer beneath. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star.

1.2.2 Eclogite overlying a low wave speed layer
Adding the low wave speed layer to the model with an eclogite layer throughout the entire length of the subducting plate shows a similar response to that in section 1.2.1 (Figure DR5).
Figure DR5. Subduction model with eclogite along entire plate length with the low wave speed, variable thickness layer beneath. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star.
1.2.3 Mid Oceanic Ridge Basalt / Eclogite overlying a low wave speed layer

The most physically plausible model includes a phase change of MORB to Eclogite and the addition of the low wave speed layer, which increases the amplitude of the secondary phase between the direct arrivals (Figure DR6). This style of model is again difficult to differentiate from other models in section 1.2 that include the low velocity, variable thickness layer intended to simulate a hydrated slab mantle. The addition of the low wave speed layer in all three models, however, is able to reproduce the style and amplitude of arrivals identified in the data.

Figure DR6. Subduction model with MORB along the surface of the top 300 km of the subducting plate and eclogite from 300-800km. Vertical component data from station ATAT, along slab paths to Tonga, is shown on top and synthetics from the corresponding station are shown below. The earthquake location is identified by the white star.
SECTION DR2

In the following section, properties of the low wave speed layer are modified to demonstrate how each property affects the response. The preferred model for the low wave speed layer is a wave speed of -25% and triangle height and width at 8 km and 30 km, respectively, and for the layer to be present along the entire plate.

2.1 Layer Wave Speed

Changing the wave speed within the low wave speed region has a direct effect on the amplitude of the secondary arrival. Variations in wave speed, from -15 to -35%, relative to the subducting plate, are displayed in Figure DR7. A value of -25% was determined to be most reasonable based on the amplitude of the secondary arrival observed in the data.

Figure DR7. Comparison of the wave speed variations in the low wave speed regions of the proposed structure in the subducting plate keeping the triangle height/width constant at 8 km and 30 km, respectively. The larger, blue, tilted, rectangular region is a cartoon cross section of the top surface of the subducting plate and the triangular regions identify two of many low wave speed regions added to the subducting plate. Wave speed reductions in the low wave speed region vary from -15 to -35 % relative to the slab, and are presented as darker shades of green along side the resulting synthetic seismograms recorded on the plate side (Tonga). A decrease in the wave speed within the low wave speed region increases the amplitude of the secondary arrival.

2.2 Layer Thickness

Seismic responses due to changes in the maximum layer thickness are displayed in Figure DR8. Thickness is defined as the perpendicular distance from the upper surface of the subducting plate into the slab (i.e., the height of the triangles). Modifying the layer
thickness changes the amplitude and the frequency content of the secondary arrival. Changes to both amplitude and frequency content are primarily due to the triangular shapes. A thinner layer has a reduced amplitude and longer period secondary arrival. Both amplitude and frequency content increase as the layer thickens, and higher frequency arrivals are generated from models with thicker layers. Higher frequency arrivals contain most of the energy, but the applied source function (0.6 s half duration) diminishes these higher frequency, larger-amplitude arrivals. The increase in amplitude of the secondary arrival is evident from a comparison of the responses at 4 and 8 km layer thickness. As the layer thickens to 12 km, the frequency of the secondary arrival shifts slightly higher. Between 8 and 12 km layer thickness, amplitude appears constant, but the convolution of a source function with the synthetics filters out these larger amplitude, higher frequency arrivals.

![Figure DR8](image.png)

**Figure DR8.** Comparison of plate side responses with changing layer thickness. Responses are displayed using model layer thicknesses of 4, 8, and 12 km, keeping the velocity of the layer constant at -25% and width of the triangles at 30 km. The larger, blue, tilted, rectangular region is a cartoon cross section of the top surface of the subducting plate and the triangular green regions identify two of many low wave speed regions added to the subducting plate (not to scale relative to actual plate models).

### 2.3 Layer Position / Depth Extent

Attempts to identify the maximum depth extent of the layer are displayed in Figure DR9. Primary differences between the responses are the “arrival time” of the secondary arrival, the frequency content, and the amplitude and coherency of the direct S wave. Isolating the layer to shallow depths, < 300 km, obliterates the direct S wave amplitude. An isolated shallow layer also increases the dominant frequency immediately before the S arrival. Isolating a layer at greater depths, while somewhat unrealistic due to its disconnection with the surface, increases the secondary arrival amplitude within a time window between the P and S wave. When the isolated layer is located at greater depths,
the secondary arrival migrates from the time window before the direct S wave towards the direct P wave. Deeper isolated layers also preserve the direct S wave amplitude. Presence of a low wave speed layer throughout the full length of the subducting plate increases the amplitude throughout the region between the direct P and S waves, controls the frequency content, and preserves the amplitude of the S wave.

Figure DR9. Effect on responses from layer position / depth, keeping the velocity of the low velocity layer constant at -25%, and triangle height/width constant at 8 km and 30 km, respectively. The low wave speed layer was confined to three separate regions, < 300 km, 300 – 500 km, > 500 km and the full plate to isolate the effects of position. Cartoons for each subducting plate on the left, with isolated layers at various depths, show the general concept behind the construction of each model (not to scale relative to actual plate models).

2.4 Mantle Wedge Path Response
Paths away from the subducting plate travel through the mantle wedge and their associated responses do not show the large amplitude, secondary arrivals that are apparent in responses that traveled along the subducting plate. Figure DR10 contains synthetic responses for plate and mantle wedge paths in one model. All models with low wave speed layers contain minimal amplitude in the time window before the direct S wave along the path traversed through the mantle wedge.
Figure DR10. Comparison between plate and mantle wedge responses from the same simulation, keeping the wave speed of the low velocity layer constant at -25%, and triangle height/width constant at 8 km and 30 km, respectively. Paths along the subducting plate interact with the subducting plate and its internal structures leading to the larger amplitude secondary arrivals. Paths contained to the mantle wedge show simpler signals and show little indication of the secondary arrival.

2.5 Mantle Wedge Wave Speed Variations
Wave speed variations in the mantle wedge shift the responses very little towards the desired results shown in the data. Figure DR11 shows the difference between a simple model with a subducing plate and the same model with an addition of a lower wave speed mantle wedge. The addition of a low wave speed mantle wedge due to melt/volatiles in the mantle or a serpentine wedge is implemented as a homogenous region. Generation of a secondary arrival with a long duration requires many internal reflections and refractions of large impedance contrast. Models with reduced wave speed in the mantle wedge do not contain large impedance contrasts and therefore cannot generate the desired long duration.
Figure DR11. Synthetic responses recorded on the plate side from a simple model, black, and the same model with a low wave speed mantle wedge, red. Small differences are apparent between the two responses except for the delay in arrival time of the direct arrivals. Synthetics seismograms were computed using a 2D finite difference method.

SECTION DR3

3.1 Water Bearing Phase Change

Determination of the amount of water expelled during conversion from a serpentine phase, Mg$_{48}$Si$_{34}$O$_{85}$(OH)$_{62}$ (Antigorite; Schmidt and Poli, 1998), to Phase A, Mg$_{7}$Si$_{2}$O$_{8}$(OH)$_{6}$ (Schmidt and Poli, 1998), can be accomplished by following the formulation from Hacker et al. [2003],

$$1 \text{atg} \rightarrow 14.2 \text{opx} + 2.8 \text{PhA} + 22.6 \text{H}_2\text{O} \quad (1)$$

$$1 \text{Mg}_{48}\text{Si}_{34}\text{O}_{85}$(OH)$_{62} \rightarrow 14.2 \text{Mg}_2\text{Si}_2\text{O}_6 + 2.8 \text{Mg}_7\text{Si}_2\text{O}_8$(OH)$_6 + 22.6 \text{H}_2\text{O} \quad (2)$$

where atg is Antigorite, opx is Othopyroxene, and PhA is Phase A. The amount of molar water on each side of the relation in (1) and (2) is

$$31 \text{ (Antigorite)} \Rightarrow 8.4 \text{ (Phase A)} + 22.6 \text{ (H}_2\text{O)} \quad (3)$$

For every mole of water in serpentine, upon conversion to Phase A, only ~25% is conserved in the chemical structure (Phase A) and the remaining is driven off as H$_2$O, which enters the overlying subducting plate or the mantle wedge.
### 3.2 Water Flux Calculation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\Delta V$</td>
<td>-25 % Reduction in wave speed, This Study</td>
</tr>
<tr>
<td>$V$</td>
<td>148 mm / year Convergence Rate of Subduction, (Jarrard, 2003)</td>
</tr>
<tr>
<td>$L$</td>
<td>1460 km Subduction Zone Length, (Jarrard, 2003)</td>
</tr>
<tr>
<td>$W$</td>
<td>8 km Maximum Layer Thickness, Height of Individual Triangles, This Study</td>
</tr>
<tr>
<td>$c$</td>
<td>0.5 Geometric Factor for shape of the triangles</td>
</tr>
<tr>
<td>$wt(%)$</td>
<td>$-0.31*\Delta V(%)$ Conversion of velocity to water wt % in fraction (Carlson and Miller, 2003)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>$wt(%)*\rho_0$ Density of water in serpentine, Assumed serpentine density: $\rho_0 = 3000$ kg/m$^3$</td>
</tr>
<tr>
<td>$F$</td>
<td>$(L<em>W</em>c)<em>V</em>\rho$ Water Flux for Tonga Fiji in the Mantle Lithosphere Only from serpentine</td>
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### SUPPLEMENTAL REFERENCES


