Observations of anomalous subcrustal reflections along the East Pacific Rise: Possible detection of a melt permeability barrier

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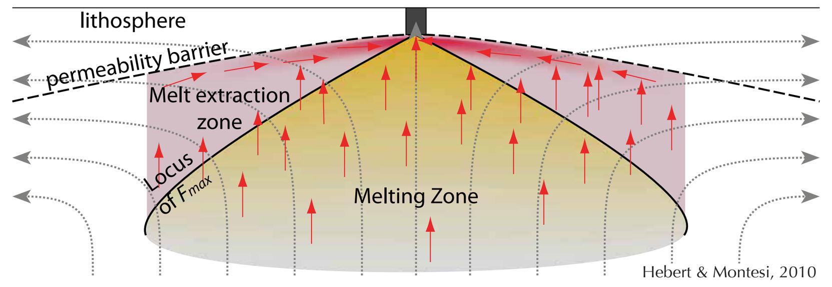
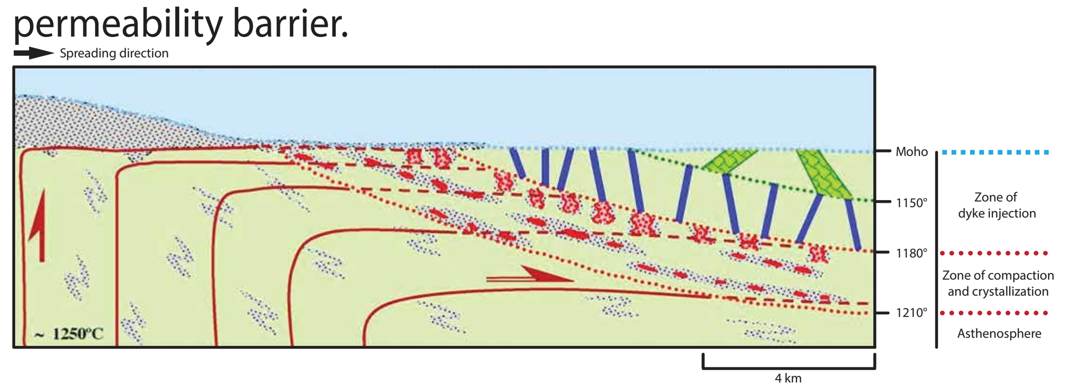
Introduction

Several mechanisms have been proposed to facilitate focused ridge magmatism, the predominant being melt-impermeable boundaries at the base of the sloping lithosphere. However, seismic evidence of these features is lacking. We present seismic observations of anomalous subcrustal reflections along the East Pacific Rise (EPR) that we interpret to originate from a permeability barrier.

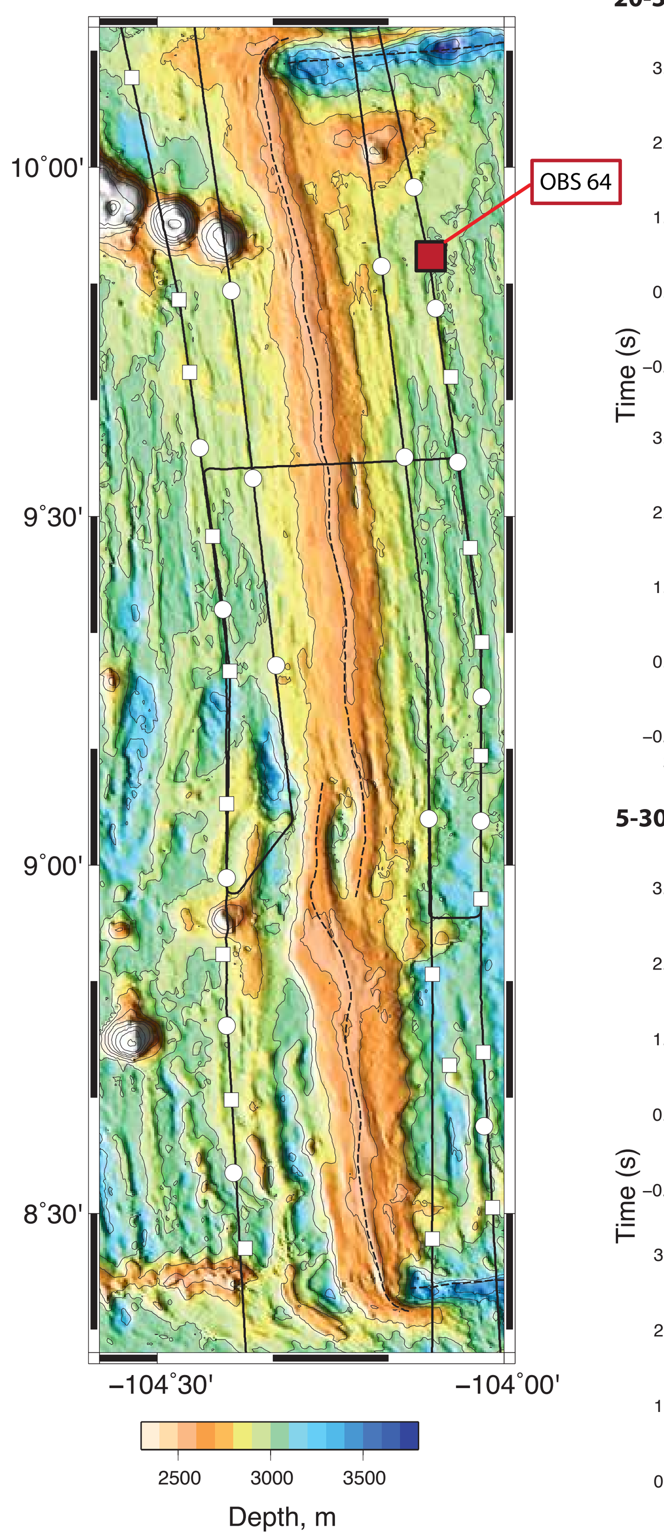




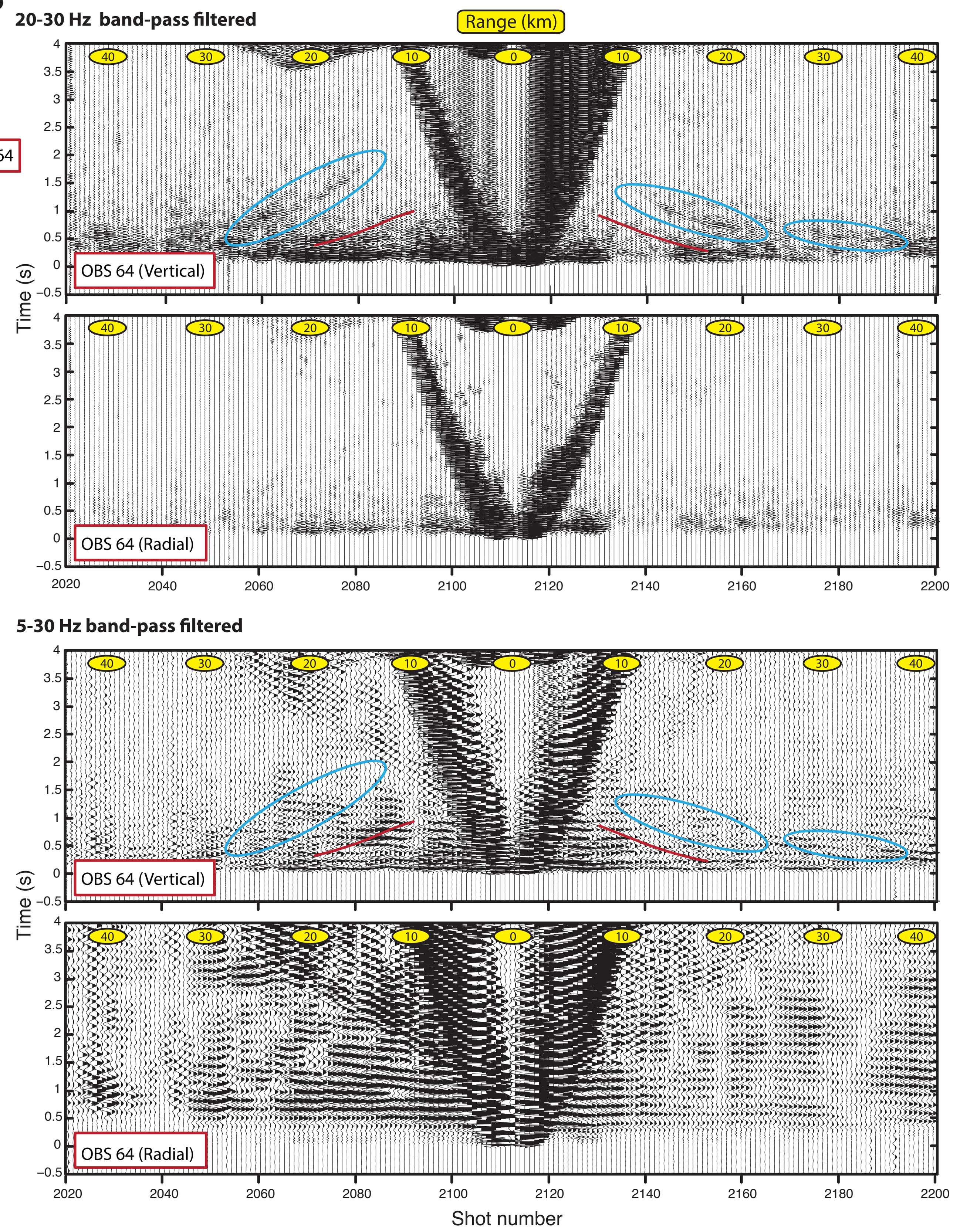
Above: Conceptual model for melt focusing to the spreading axis. Melts are generated in the melting zone and ascend buoyantly until they contact the thermal boundary layer at the base of the lithosphere where crystallization of the ascending melts occurs, forming a permeability barrier.

Left: Modified from Rabinowicz & Ceuleneer (2005). Distribution of lithologies associated with melt migration in the mantle section of the Oman ophiolite. Small stipled regions: folded dunites, red shaded regions: troctolitic porous flow channels, blue lines: olivine gabbro dykes, green features: pyroxenites and gabbronorites, pale green: harzburgites, pale blue: layered gabbros, solid and dashed red lines: solid-state flow lines in harzburgites.

Seismic Observations



Map of the East Pacific Rise from the Undershoot seismic tomography experiment. Dashed lines show the location of the plate boundary. Seismic data were collected on 20 ocean bottom seismometers (OBS; open squares) and 17 ocean-bottom hydrophones (OBH; open circles). Black lines represent source locations.



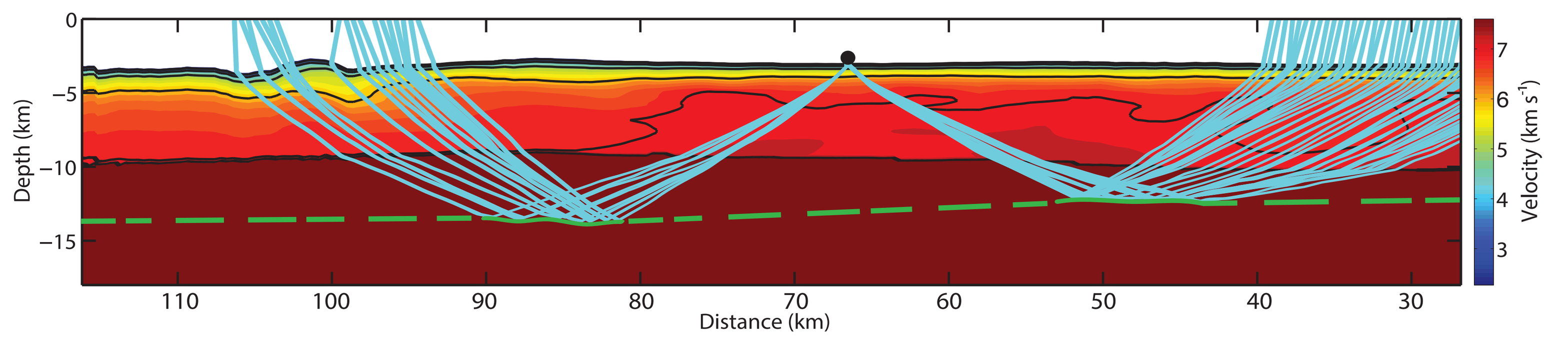
Seismic record section aligned by shot number (bottom axis), ranges are shown in orange ovals (top axis) and amplitudes are scaled according to the band-pass filter applied (2e9 for 5-30 Hz and 2.5e10 for 20-30 Hz). Time in the vertical axis is the resulting time after a static correction was applied, where the subtracted time is the onset of thefirst arrival for each trace (Pg and Pn); this was done to remove timing fluctuations caused by seafloor topography.

- Anomalous reflections are present in the 5-30 Hz range and are easily visible from 20-30 Hz.
- Asymmetry in T-X curve from the north to the south side of station 43 (later arrivals to the north).
- High P wave energy at intermediate to wide angles with minimal S wave energy.

Forward modeling of travel times

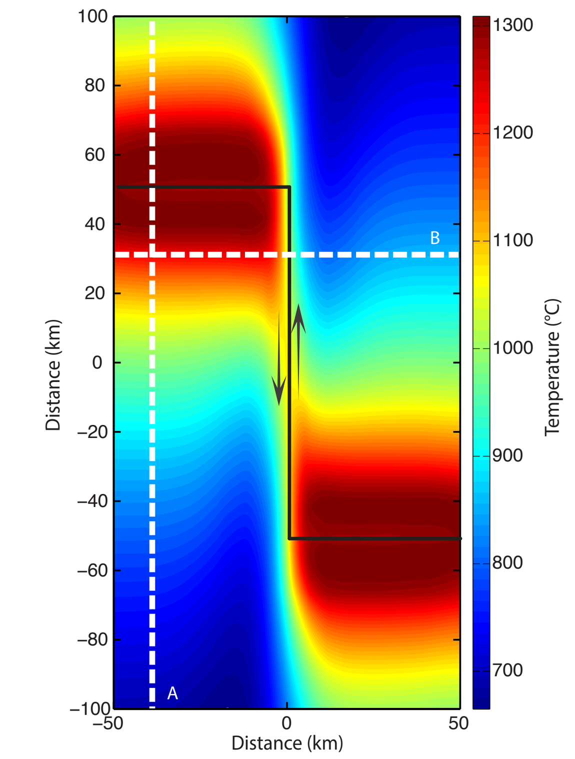
An interface was inserted into the upper mantle of a previously resolved velocity model and the travel times of the anomalous reflections were forward modelled to constrain the depth and geometry of the reflector.

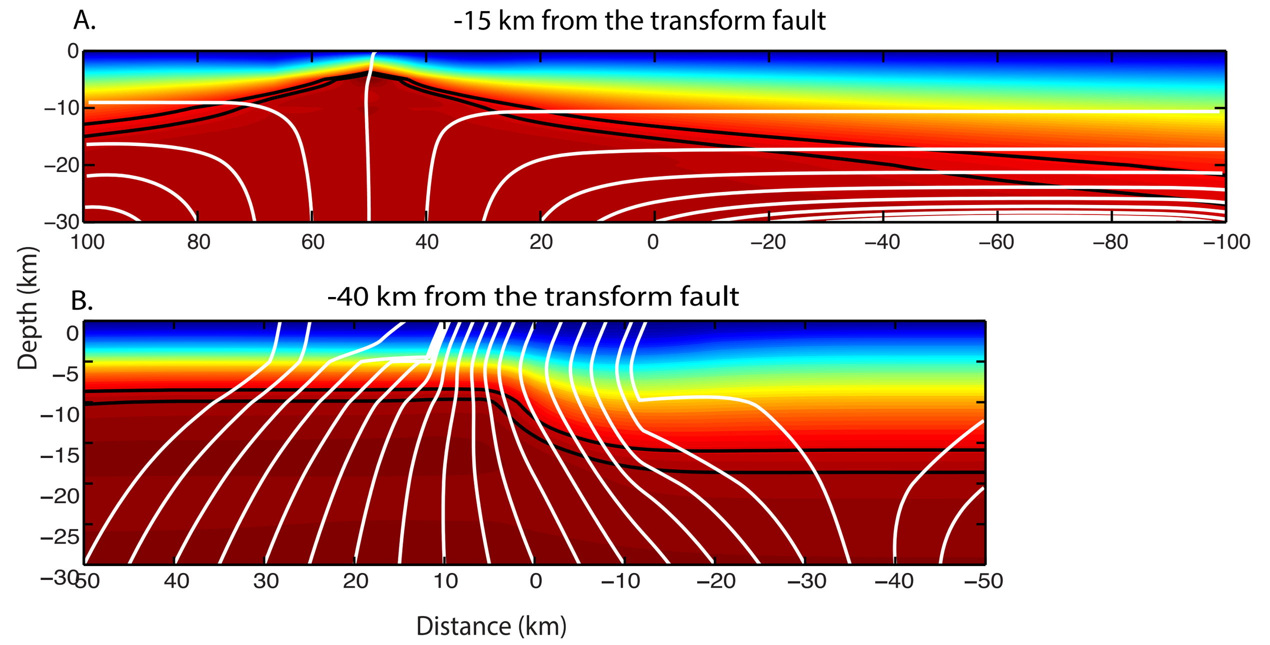
- The preferred interface slopes toward the Clipperton transform fault.



Left: Velocity structure along the eastermost shotline of the Undershoot experiment, extending from shots 2000:2200. Black line shows the Moho, green line indicates anomalous reflector. The cross section extends from north (left) to south (right).

Thermal Models





Above: Cross sections along lines in the figure to the left. White lines illustrate the streamlines of mantle flow. Black lines indicate the location of the 1910 and 1250 ºC isotherms. (A) Ridge-perpendicular cross section -15 km from the tranform fault. (B) Ridge parallel cross section -20 km from the spreading center.

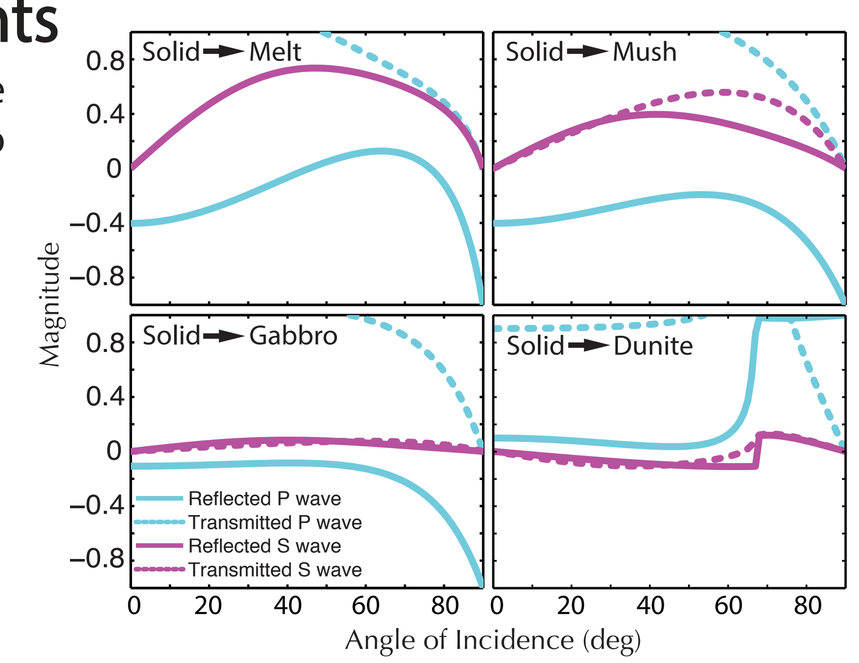
Left: Map view of a thermal model near an oceanic tranform fault (Roland et al., 2010) at 9 km depth. The model incorporates a full spreading rate of 12 cm/yr, fault length of 100 km, and hydrothermal cooling limited to 6 km depth. Isotherms are contoured every 1ºC. Solid black line with arrow depicts the location of the oceanic transform fault, whereas the other solid black lines delineate the two spreading axes of the mid-ocean ridges, respectively. White lines are the cross-section lines for the figures above, at -15 and -40 km from the transform fault.

- The inferred reflector conforms to the thermal structure near an oceanic transform fault (Roland et al., 2010)
- The interface lies approximately within the 1190-1250 ºC range, which is the approximate temperature range at which permeability barriers are generated.

Reflection and Transmission Coefficients

Theoretical reflection and trasmission coefficients for a P wave incident upon a half space interface were calculated to estimate reflection amplitudes.

- Large S wave reflections occur at a solid-liquid and solid-mush interface at intermediate to wide angles.
- Relatively large P wave reflections are produced at a solid-solid interface with minimal S wave amplitudes at intermediate to wide angles.
  - Upper layer (all cases): $V_p = 7.8$ km s^{-1}, $V_s = 4.1$ km s^{-1}, $\rho = 3.13$ Mg m^{-3}
  - Mush: $V_p = 4$ km s^{-1}, $V_s = 2$ km s^{-1}, $\rho = 2.6$ Mg m^{-3}
  - Melt: $V_p = 4$ km s^{-1}, $V_s = 0$ km s^{-1}, $\rho = 2.6$ Mg m^{-3}
  - Gabbro: $V_p = 6.9$ km s^{-1}, $V_s = 3.77$ km s^{-1}, $\rho = 2.85$ Mg m^{-3}
  - Dunite: $V_p = 8.5$ km s^{-1}, $V_s = 4.71$ km s^{-1}, $\rho = 3.5$ Mg m^{-3}



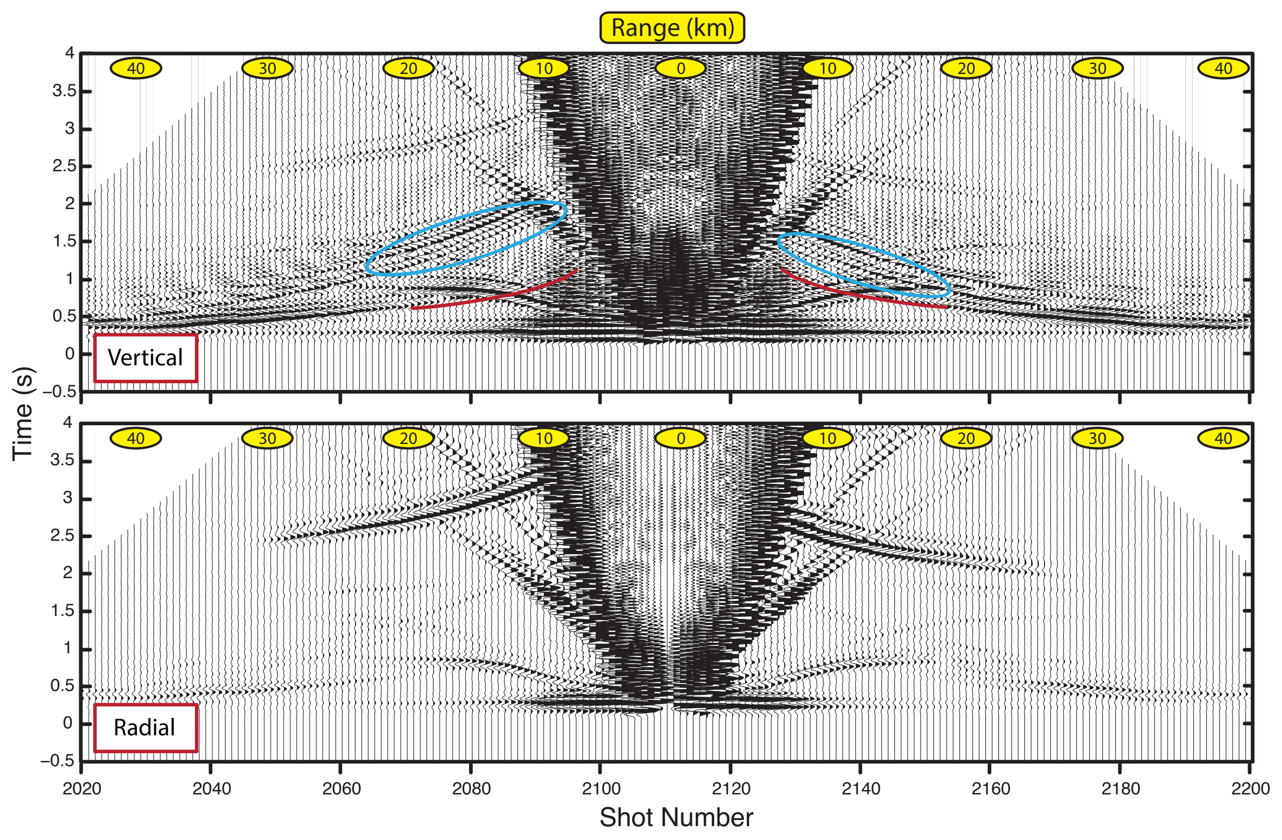
References

1. Hebert, L.B., Montesi, L.G., 2010. Generation of permeability barriers during melt extraction at mid-ocean ridges. Geochem. Geophys. Geosyst. 11, Q12008.
2. Durant, T.D., Toomey, D.R., 2009. Evidence and implications of crustal magmatism on the flanks of the East Pacific Rise. Earth and Planetary Science Letters. 287, 130-136.
3.

Finite difference waveform modeling

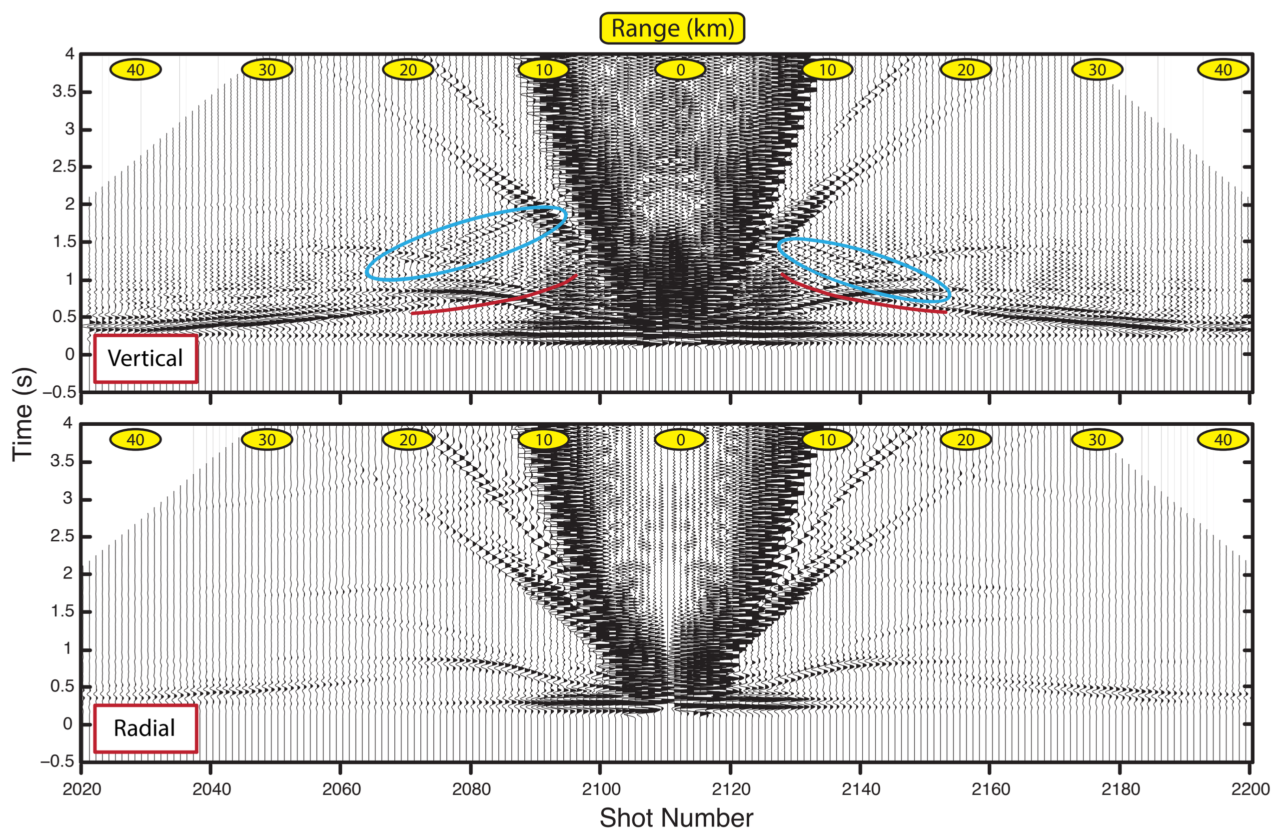
We generate synthetic seismograms using finite difference wave propogation through a 2-D velocity structure representative of oceanic lithosphere. The same values for the reflection and transmission analyses are used for the physical properties for the subcrustal reflector in these models.

- Synthetics are consistent with a solid reflector that is gabbroic in composition.



Solid to melt interface

- Large amplitude P wave reflections are observed on the vertical component.
- Larger amplitude S wave reflections at similar ranges are present on the radial component.
- Similar results are obtained for a solid to mush interface.
- These results do not resemble the nature of the subcrustal reflections along the EPR.



Solid to gabbro interface

- Large amplitude P wave reflections are observed on the vertical component.
- Minimal S wave energy at similar ranges on the radial component.
- Similar results are obtained for a solid to dunite interface, though the phase is inverted.
- The discrepancy between P and S amplitudes conforms to the observations along the EPR and therefore indicates the reflections originate from a solid interface that is gabbroic in composition.

Interpretation

Melt-impermeable boundaries at the base of the lithosphere are commonly invoked to explain focused ridge magmatism, as well as off-axis subcrustal melt accumulations. However, seismic evidence of these features is lacking. Anomalous subcrustal reflection along the East Pacific Rise are interpreted to originate from a solid melt-impermeable interface based upon the following observations:

- The T-X curve of the reflections is asymmetric about the receiver with greater time delays on the north side, suggesting a sloping reflector. Forward modeling reveals the reflector slopes toward the Clipperton transform to the north. Comparison of the interface to thermal models suggests it is thermally controlled.
- The observed reflections have high P wave and minimal S wave energy at intermediate to wide-angles. Reflection and transmission coefficent analyses indicate the reflections originate from a solid boundary.
- Finite difference waveform modeling also indicates the reflections originated from a solid to solid interface, with the lower medium being gabbroic in composition.