Observations of anomalous subcrustal reflections along the East Pacific Rise: Possible detection of a decompaction channel

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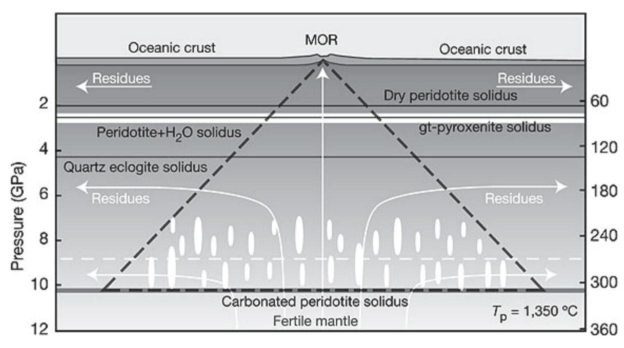
I. Introduction

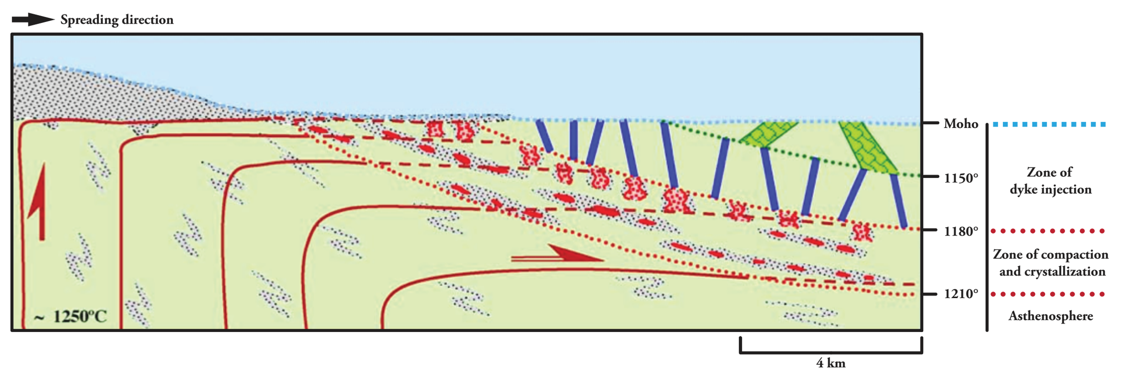
Crustal accretion along mid-ocean ridges requires the focusing of melt to the narrow neovolcanic zone at the ridge axis. However, the mechanics of magmatic focusing remain incompletely understood, partially owing to the lack of seismic evidence for melt migration pathways. We present evidence for a sub-lithospheric high-porosity decompaction channel ~20 km from the spreading axis of the East Pacific Rise that we infer to facilitate focused ridge magmatism.



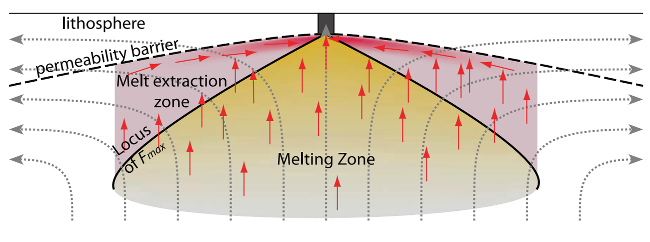
Left: *Diagram from Dasgupta & Hirschmann (2006) illustrating passive upwelling beneath a mid-ocean ridge (MOR). Beneath MORs, melting occurs over a broad volume of mantle that can extend to over 100 km on either side of ridge axis (Forsyth et al., 1998). The breadth of the melting regime, combined with the narrowness of the neolvolcanic zone at the ridge axis, requires magmatic focusing for efficient melt extraction.*

II. Magmatic focusing along mid-ocean ridges

One of the predominant mechanisms proposed to facilitate magmatic focusing at mid-ocean ridges is porous flow through high-porosity decompaction channels at the base of the lithosphere. Such channels develop in response to melt accumulations beneath melt-impermeable barriers that break, or decompact, the viscous mantle matrix. This mechanism is supported by observations in ophiolites as well as numerical modeling. Until now, however, they have never been seismically imaged.

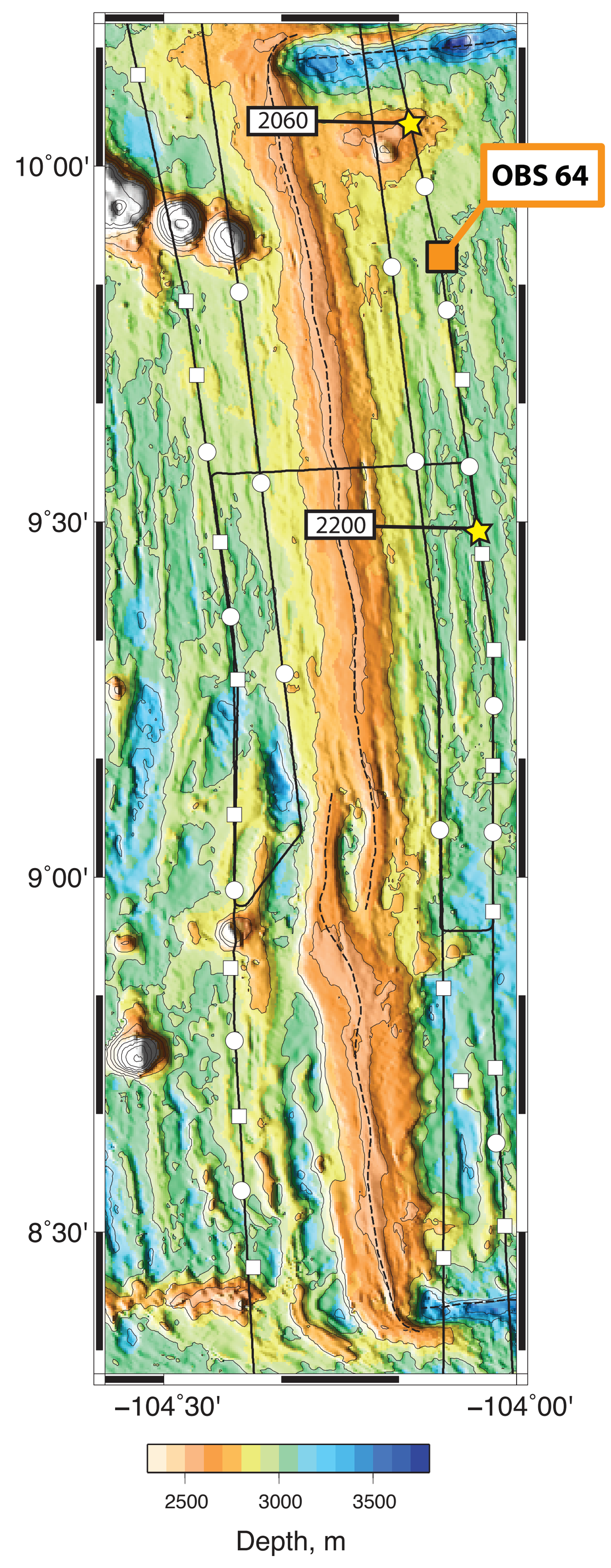


Left: *Modified from Rabinowicz and Ceuleneer (2005). Distribution of lithologies associated with melt migration in the mantle section of the Oman ophiolite. Small stippled regions: folded dunites; red shaded regions: troctolitic porous flow channels; blue lines: olivine gabbro dykes; green features: pyroxenites and gabbronorites; pale green: harzburgites; pale blue: layered gabbros; solid and dashed red lines: solid-state flow lines in harzburgites. Troctolites encased in dunite may represent melt-impermeable boundaries and/or high-porosity decompaction channels.*

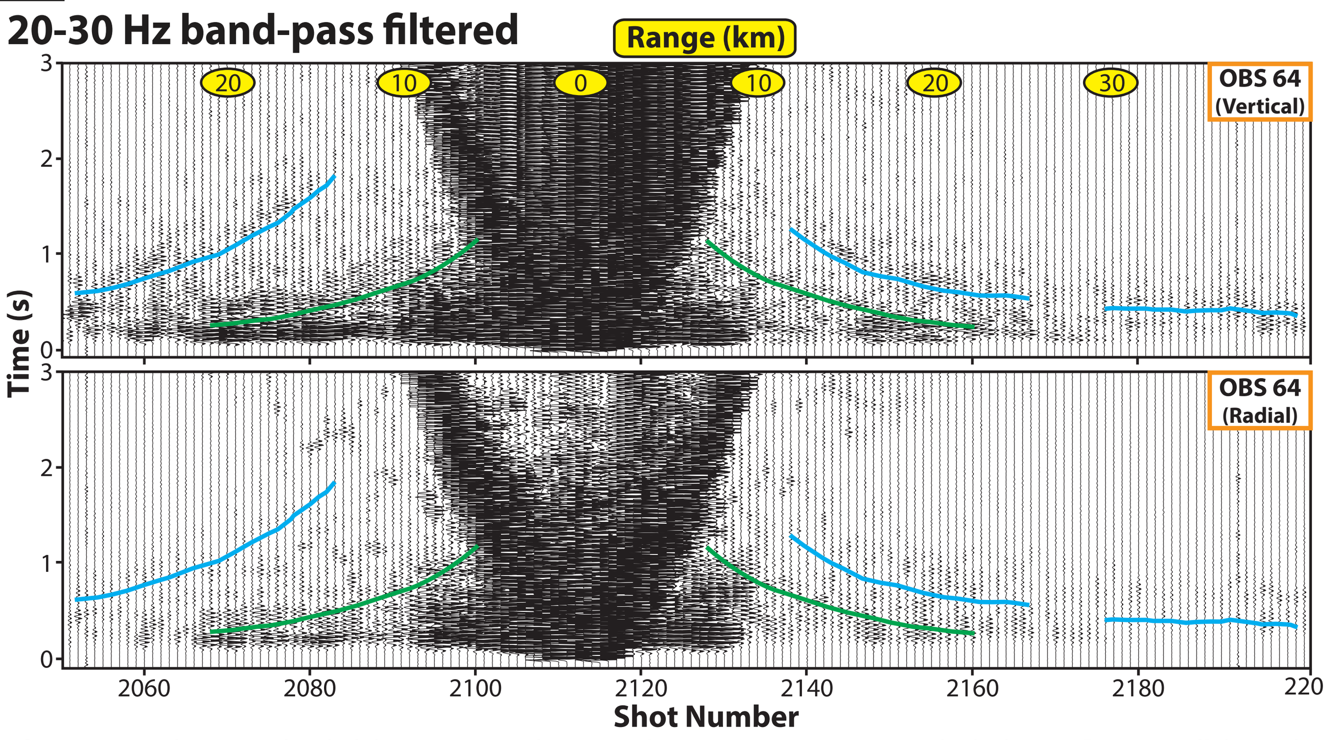


Above: *Conceptual model for melt focusing to the spreading axis of a mid-ocean ridge (from Hebert and Montési, 2010). Melts are generated in the melting zone and ascend buoyantly until they contact the thermal boundary layer at the base of the sloping lithosphere where crystallization occurs, forming a permeability barrier. High-porosity channels, which develop beneath the barrier via decompaction, facilitate melt transport to the ridge axis because of its sloping topology.*

III. Seismic observations



20-30 Hz band-pass filtered



Above: *Vertical (top) and radial (bottom) record sections for seismometer OBS 64, which show reflections off the Moho, PmP (green lines), and later-arriving large amplitude P wave reflections (blue lines) that are the focus of this study. Record sections are aligned by shot number (bottom axis), ranges are shown in yellow ovals (top axis), and amplitudes are fixed scaled. Time on the vertical axis is corrected for the travel time of the first arriving phase (Pg and Pn) to remove timing fluctuations caused by seafloor topography. Note that the anomalous reflections possess very little S wave energy.*

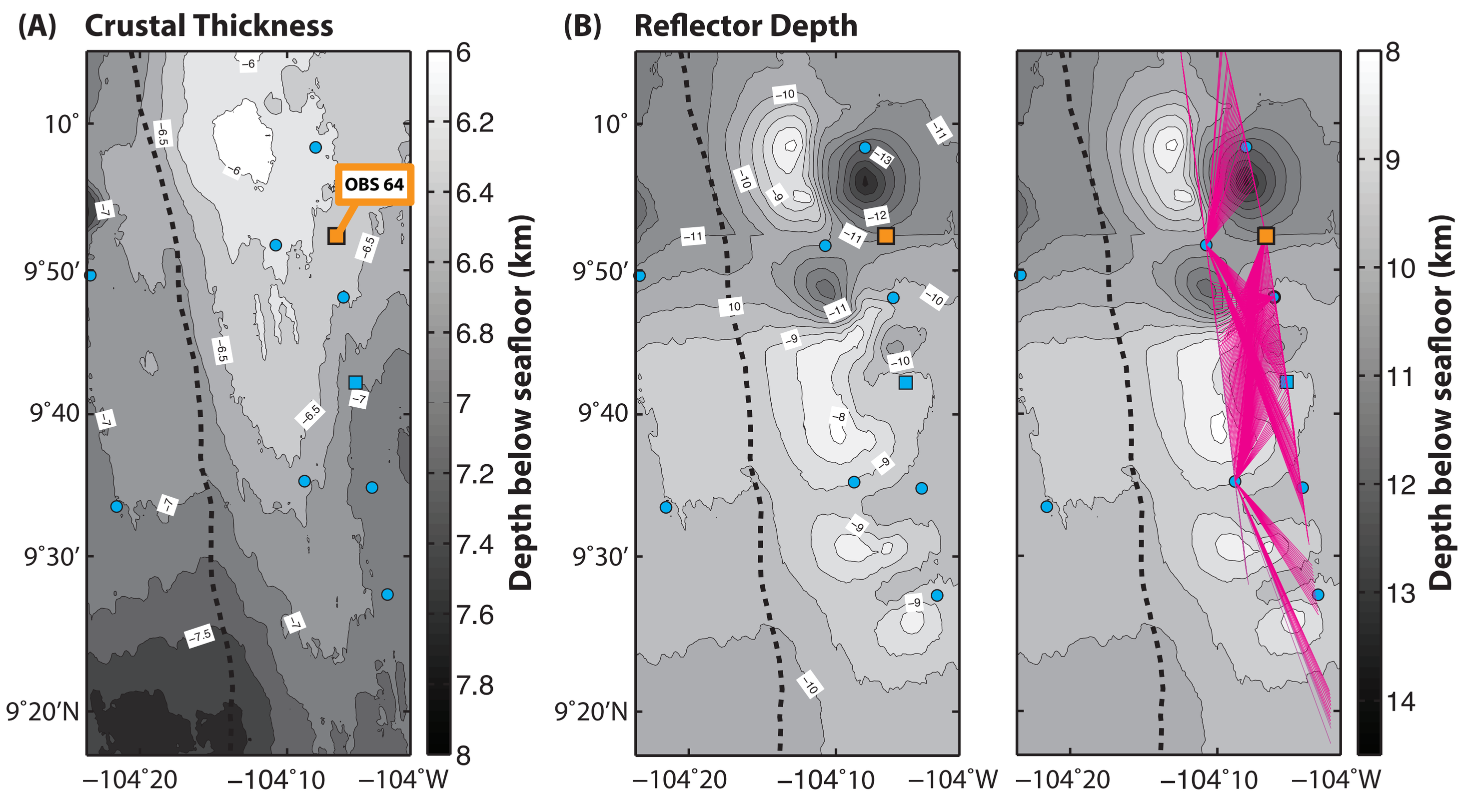
Left: *Map of the East Pacific Rise from the Undershoot seismic tomography experiment. Dashed lines show the location of the plate boundary. Seismic instruments used in the study are shown by open circles (hydrophones; OBH) and open squares (seismometers; OBS). Black lines show source locations with yellow dots as those associated with record sections.*

- Anomalous reflections are present throughout the study area with the largest and most prominent group observed on seismometer OBS 64.
- Locally extensive near OBS 64, extending for more than 80 km along the easternmost shotline from ~10°10′ N to 9°20 N.
- The reflections possess energy in the 5-30 Hz range, although they are most easily visible from 20-30 Hz.
- Asymmetry in the travel time curve from the north to the south side of OBS 64 (later arrivals to the north). This observations suggests a sloping interface.
- Reflections possess large *P* and small *S* wave amplitudes at intermediate- to wide-angles.
- Reflections are not phase-inverted relative to *Pg*.
- *P* wave amplitudes generally increase with offset, although intermittent attenuation obscures waveforms in some instances, as observed on OBS 64.

IV. Interface geometry

An approximate interface was inserted into the upper mantle of a previously defined velocity model. The local geometry of the interface near OBS 64 was constrained by inverting ~450 anomalous reflection delay times.

The observed reflector is shallower closer to the ridge axis and deepens toward the Clipperton transform fault to the north, reaching a maximum depth below seafloor of ~14 km.

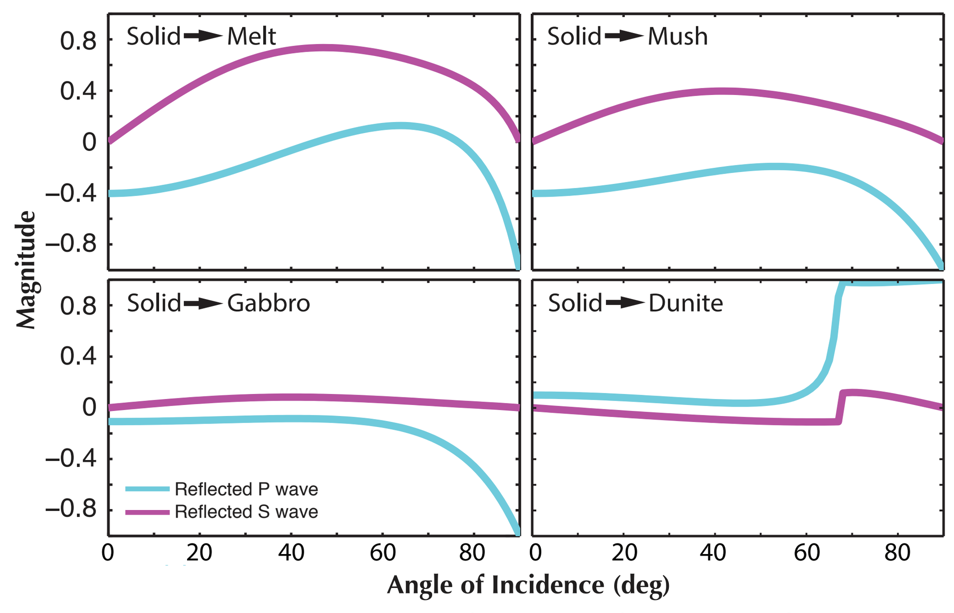


Left: *(A) Crustal thickness map interpolated from seismic refraction data (Canales et al., 2003). Contour interval is 0.25 km. Thick dashed line delineates ridge axis. Map is unmasked, although there is no constrained data available beneath the ridge axis. (B) Depth below seafloor of the anomalous reflector, determined by inverting ~450 travel times. Right hand figure shows ray coverage for the picks used in the inversion and thus, where data is constrained. "Bullseyes" in the depth are a result of low smoothing and limited data used in the inversion. Results still provide a good first order approximation for the interface topology, which is shallower near the ridge axis. Contour interval is 0.5 km; thick dashed line represents the ridge axis. Seismic instruments used in the study are shown by blue open circles (OBH) and open squares (OBS) on each figure. OBS 64 is shown by the orange open square.*

V. Reflection coefficients

Theoretical reflection and transmission 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-melt and solid-mush interface.
- Large *P* wave reflections (phase is inverted in gabbro case) are produced at a solid-solid interface with small *S* wave amplitudes at intermediate- to wide-angles.



- Upper layer (all cases): $Vp = 7.8$ km s^{-1}, $Vs = 4.1$ km s^{-1}, $\rho = 3.13$ Mg m^{-3}
- Melt: $Vp = 4$ km s^{-1}, $Vs = 0$ km s^{-1}, $\rho = 2.6$ Mg m^{-3}
- Mush: $Vp = 4$ km s^{-1}, $Vs = 2$ km s^{-1}, $\rho = 2.6$ Mg m^{-3}
- Gabbro: $Vp = 6.9$ km s^{-1}, $Vs = 3.77$ km s^{-1}, $\rho = 2.85$ Mg m^{-3}
- Dunite: $Vp = 8.5$ km s^{-1}, $Vs = 4.71$ km s^{-1}, $\rho = 3.5$ Mg m^{-3}

A dunite composition yields reflections that most closely resemble the observations.

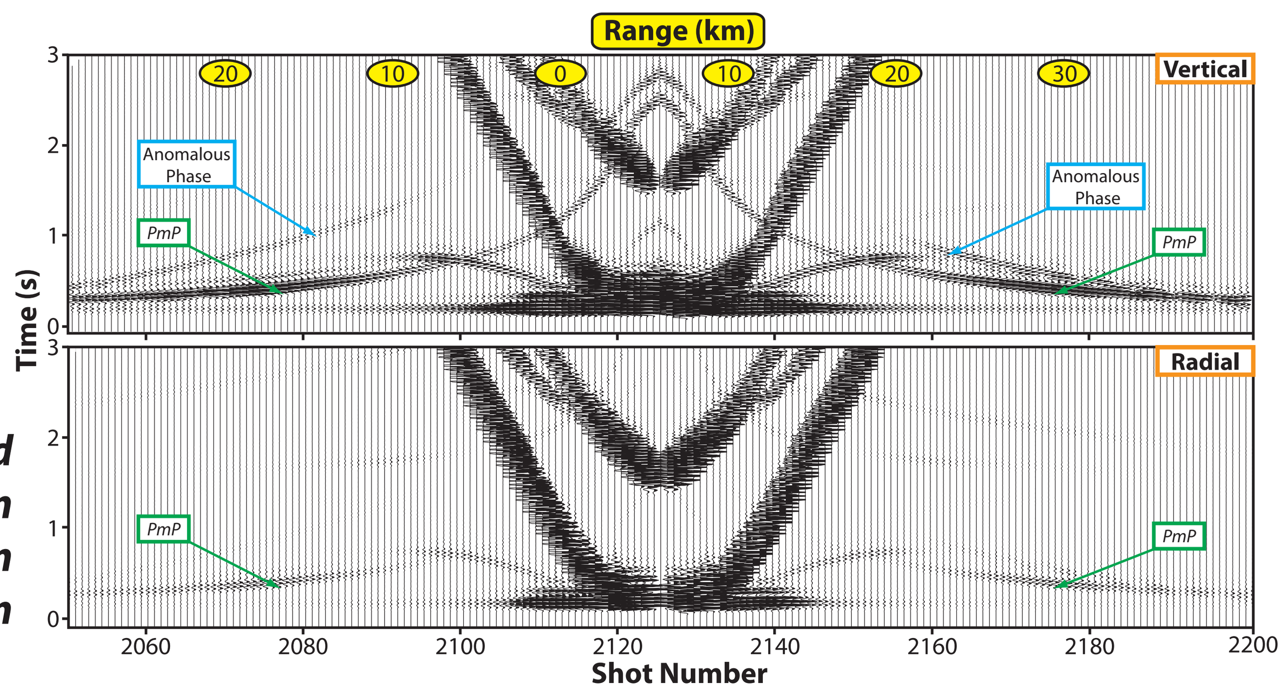
VI. Finite difference waveform modeling

We generate synthetic seismograms using finite difference wave propagation through a 2-D velocity structure representative of oceanic crust and upper mantle. We model a subcrustal reflector, inserted at depths determined from forward modeling, with the same physical properties used in the reflection and transmission analyses.

Harzburgite-dunite interface

- Large amplitude *P* and small amplitude *S* wave reflections are observed on the vertical and radial component, respectively.
- Not phase inverted relative to *Pg*.

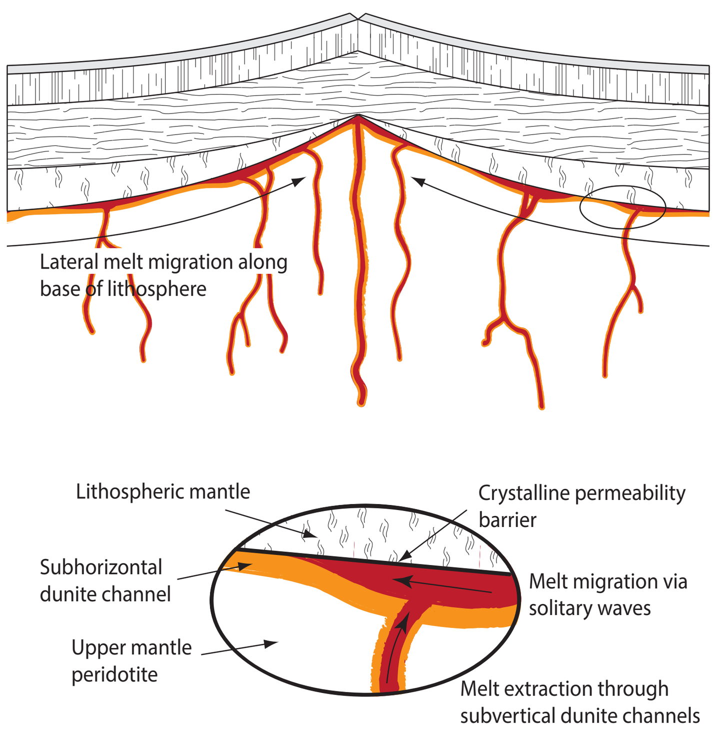
Synthetics are consistent with a solid reflector that is dunitic in composition and hence, similar to the composition of dissolution channels observed in ophiolites.



VII. Interpretation

High-porosity decompaction channels at the base of the lithosphere are commonly invoked to explain magmatic focusing at mid-ocean ridges despite the lack of seismic evidence. We infer anomalous reflections along the East Pacific Rise to originate from a geographically extensive, sub-horizontal dunite channel within the upper mantle. To maintain the chemical disequilibrium between mid-ocean ridge basalts and abyssal peridotites, the decompaction channels must be accompanied by dissolution channels that serve as chemically isolated conduits for melt transport. We therefore propose a sub-horizontal origin for dunitic dissolution channels via lateral melt migration within high-porosity decompaction channels.

The anomalous reflections, inferred to originate from a sub-horizontal dissolution channel, may represent the first direct seismic evidence to support high-porosity decompaction channels as a mechanism for focused ridge magmatism.



Left: *Conceptual model for magmatic focusing at mid-ocean ridges. Melt extraction from the mantle occurs within chemically isolated, spatially restricted dissolution channels. These channels are dunitic in composition, formed via the dissolution of pyroxene from peridotite by percolating melts. As the ascending melts contact the thermal boundary layer at the base of the lithosphere, they begin to crystallize rapidly. This crystallization greatly reduces the porosity, thereby generating a melt-impermeable barrier. The barrier impedes the ascension of subsequent melts and induces accumulation. The accumulating melts break the viscous mantle matrix, creating a high-porosity channel through which melt is transported to the ridge axis owing to the sloping nature of the lithosphere. The migration of melt through the high-porosity channels generates dissolution channels that are sub-horizontal. Melt migration is also time-dependent such that melts propagate through the decompaction channel as solitary waves. This yields regions beneath the permeability barrier that are void of melt, thereby contrasting harzburgite and dunite with a seismically undetectable permeability barrier in between.*

References

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