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The 410-km-depth discontinuity: A sharpness estimate from near-critical reflections

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Abstract. The abrupt increase in seismic velocity and density about 410 km below the surface of the Earth occurs at the depth where a phase change in olivine is expected [*Akaogi et al.*, 1989; *Katsura and Ito*, 1989; *Ringwood*, 1969]. We have assembled recordings from 22 short-period seismometers in Washington and British Columbia of 35 nuclear explosions in Nevada. These data reveal relatively noise-free reflections from the "410" discontinuity. Most of the transition is completed within a depth interval of less than 10 km under the western United States. This result adds to the accumulating seismic evidence of a fairly sharp "410" transition.

Background

Phase changes caused by the increase of pressure with depth in the Earth occur near 410 and 660 km depths. The fine structure of the "410" boundary has proven difficult to examine. Inconsistencies in seismic measurements of boundary sharpness are difficult to reconcile with the prevailing α-to-β olivine phase transition models for this boundary. These variations may signify either extreme sensitivity of transition thickness to temperature [*Bina and Helffrich*, 1994; *Helffrich and Bina*, 1994], though apparently not accompanied by the predicted 50 km of topography; a non-equilibrium boundary [*Solomotov and Stevenson*, 1994]; or the occasional coincidence of the olivine phase change with a sharp contrast in composition or degree of melt [*Nolet and Zielhuis*, 1994; *Revenaugh and Sipkin*, 1994].

Critical Reflections

We examine near-critical reflections in the distance range of 11.5° to 14°, which provide the strongest constraints on fine-scale velocity structure near 410-km depth. 35 large nuclear explosions at the Nevada Test Site are used for seismic sources. 22 short-period vertical-component stations are selected, on the basis of low levels of background noise and the absence of strong near-station reverberations from the University of Washington Regional Seismic Network and the Pacific Geoscience Centre Seismic Network (Fig. 1). An additional 70 stations in the distance range from 8° to 11.5° were also processed, but were only used for traveltimes to constrain the velocity structure above 410-km depth.

For each station, the high-quality records of 10 to 30 explosions are stacked to form a composite record (Fig. 2). Before each station stack, the records are shifted according to their distance from NTS with a reduction velocity of 10 km/s, which is that expected for seismic waves turning near 410 km depth.

A station correction, calculated by averaging the delays measured from four earthquakes in Central America (J. Vandercar, pers. comm., 1994) has been applied. The waves from these earthquakes have near-station ray paths similar to the explosion waves, so the corrections reduce travel time variations caused by near-receiver structure. There is a correction for each explosion, as well, constructed to reduce the travel time perturbations from near-source basin structures. This correction is calculated to align Pn arrivals across several stations near 8° distance, with the assumption that Pn and 410-reflection corrections are similar. Both source and station corrections significantly improve the alignment of the 410 reflections.

A clear set of arrivals reflected from the "410" may be seen across the stacked traces. These arrivals are similar in timing and slowness to those described for similar explosions in the 1960's [Carder et al., 1966].

Determination of mantle structure

We reconstruct the compressional-wave (P) velocity as a function of depth from the arrival times of the "410" reflection and initial P waves across the distance range 8°-14°. Stacks constructed using a phase velocity of 8.0 km/s show the initial arrivals at most stations unambiguously. Observations in southern California from two particularly sharp earthquakes offshore Oregon (1/30/86 and 10/05/86) show the same timing for initial P arrivals and "410" reflections, and strong reflections at least in to 12.5°, effectively reversing the nuclear profile.

One constraint is imposed; the discontinuity is placed at 410 km depth, in accord with long-period high-angle reflections that yield a global average depth of 410 km and a local depth of 420 ± 10 km beneath the northern Basin and Range [*Shearer*, 1993]. We cannot estimate the reflector depth with only our data because depth trades off with the overlying velocity. We note, however, that if the discontinuity is actually 20 to 30 km shallower, a wider transition is permissible, since the critically-reflected arrivals would appear at a closer range. However, to match the observed timing of the "410" reflection, a

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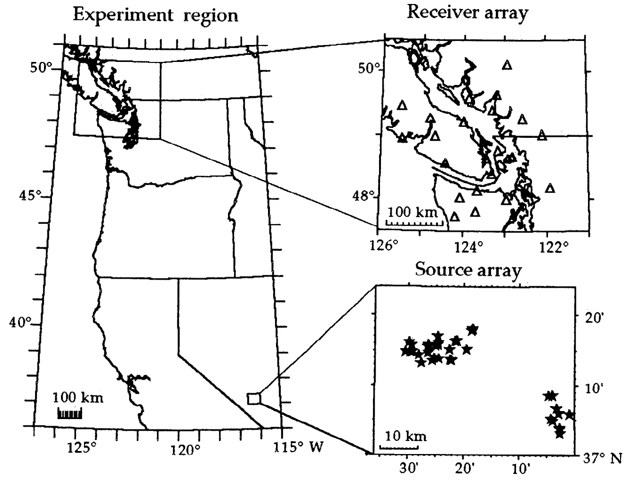


Fig. 1. Map of study area. The 35 NTS sources and 22 receiver locations (in boxes) are presented at larger scale on the right.

shallower "410" would necessitate an implausibly slow velocity above the reflector.

Our velocity just below the "410" is slightly higher than published models based on long-period modeling of the entire "410" triplication [*Burdick and Langston*, 1977; *Walck*, 1984]. Thus it is also implausible that the velocity below 410 is in reality high enough to allow the observed reflections without a fairly sharp boundary.

Our P wave velocity model (Fig. 3a) is slower than those of standard reference models [*Kennett and Engdahl*, 1991], as has previously been reported beneath the tectonically active Basin and Range province [*Grand and Helmberger*, 1984]. The rest of this paper uses this velocity structure, but the conclusions do not depend on details above 410 km depth.

The arrival times of the observed and simulated seismic energy match well (Fig. 3b). Ray tracing indicates that only the "410" arrivals at distances greater than about 14° are post-critical reflections. Thus, the arrivals that are observed between 12° and 14° are pre-critical reflections, which are diagnostic of boundary sharpness. Spreading the "410" velocity contrast across 20 km reduces the range over which the reflection would be visible (Fig. 4). We assume a linear gradient in our gradational model, but more complicated profiles are possible [*Bina and Helffrich*, 1994; *Helffrich and Bina*, 1994].

Our data are consistent with an absolutely sharp "410" boundary, but a width up to 10 km cannot be ruled out. Topography on the "410" boundary would add further uncertainty to our conclusion.

Implications

There is not a consensus on "410" sharpness in previous studies. In the only other critical-reflection seismic profiles of comparable quality, the boundary has been interpreted to have a transition thickness of 35 km beneath the Russian platform [*Priestley et al.*, 1994]. The lack of precritical reflections on additional nuclear explosion profiles (T. Ryberg, pers. comm., 1995) reinforce the conclusion that the "410" is much more spread out beneath Eurasia.

Other near-critical reflection studies also suggest variable properties of the "410" [*Bowman and Kennett*, 1990; *Dey et al.*, 1993; *Mechie et al.*, 1993].

The finding of a sometimes sharp "410" is consistent with and extends the results from studies of P'P' precursors, which are near-vertical reflections [*Benz and Vidale*, 1993; *Lees et al.*, 1983; *Nakanishi*, 1988; *Yamazaki and Hirohara*, 1994]. Since observations of P'P' reflections are made near a caustic, it is difficult to assess the amplitude of the velocity contrast that acts as a reflector. Our measurements of the "410" reflection, with both slowness and frequency information, show that the entire velocity contrast generally attributed to the "410" lies within a narrow depth range beneath the Basin and Range province.

The "410" width appears variable from P'P' precursors, as well. In one study [*Benz and Vidale*, 1993] only one of four high signal-to-noise observations showed clear high-frequency reflections from near 400 km depth that required strong gradients over 2-4 km. Other events were consistent with a transition width of 5-10 km or more [*Benz and Vidale*, 1993]. In another study, the "410" appeared to have strong gradients across about 5 km [*Nakanishi*, 1988]. Further work in progress corroborates

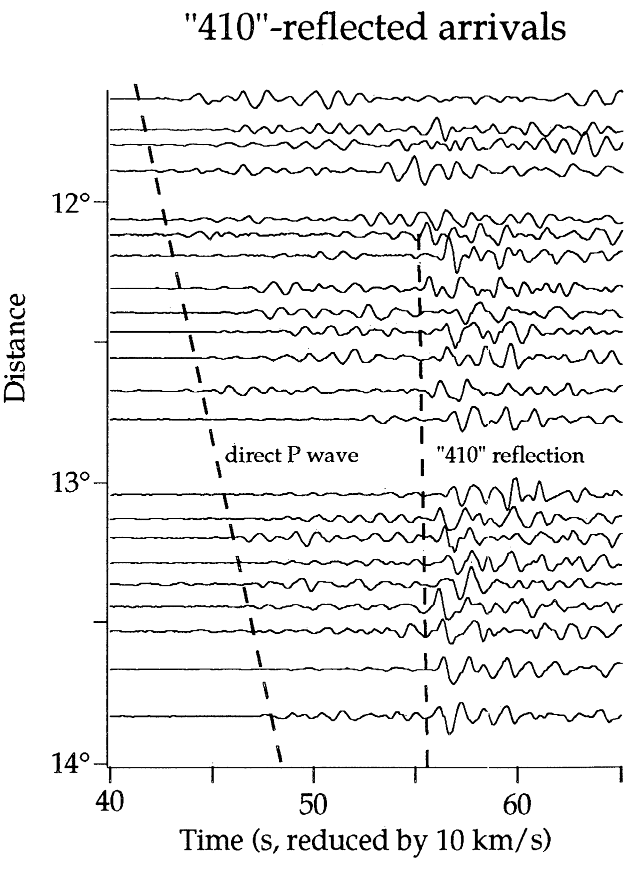
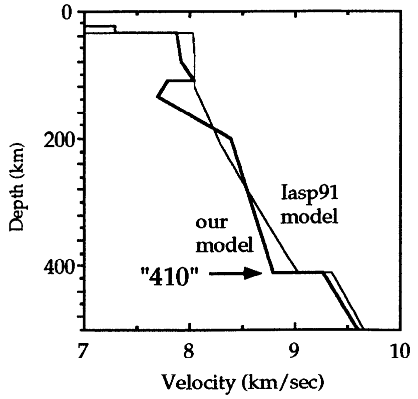


Fig. 2. Beam-formed seismograms from 22 short-period, vertical-component stations. Each trace is the sum of seismograms from 10 to 35 explosions at a common station time-shifted to enhance arrivals with a phase velocity of 10 km/s. Stacking with this phase velocity will amplify the "410" reflections relative to the direct arrivals by up to a factor of 2. The traces are offset by up to 0.1° to improve clarity.

(a) Compressional velocity versus depth



(b) Observed vs. calculated arrival times

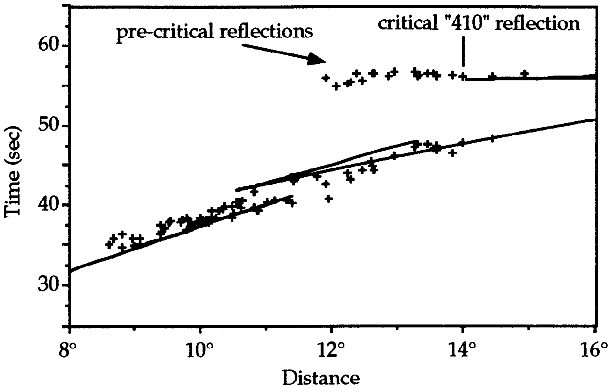


Fig. 3. (a) The P wave velocity as a function of depth found by this study is compared to average earth model iasp91[*Kennett and Engdahl,* 1991]. (b) Comparison of observed and predicted traveltimes for direct and "410" reflected arrivals for our velocity model.

these findings for a variety of reflection locations (pers. comm., P. Earle).

The variation in P'P' observations cannot plausibly be attributed to "410" topography. The "660" precursors are always observed when "410" precursors are, but not vice versa. Greater topography on the "410" than the "660" boundary would cause the "410" reflections to be more intermittent due to focusing, but in fact smaller topography is inferred for the "410" than the "660" [*Shearer,* 1993].

The range of transition widths inferred by P'P' precursors, 2 to >5-10 km, is consistent with this paper's estimate of less than 10 km transition width. Our results cannot verify or contradict the inferences from P'P' precursors that the fine-scale sharpness of the "410" varies. The Soviet deep sounding data suggests much greater transition widths [*Priestley et al.,* 1994], and may benefit from reanalysis to see if alternate interpretations are possible.

Conclusions

Both refraction and P'P' precursor observations suggest lateral variations in "410" transition width, possibly across the range from 2 to 35 km, and several mechanisms have been proposed that may account for this variation. While it is premature to state that these variations have been definitely resolved, a summary of these mechanisms may be useful.

Extreme sensitivity to temperature may be invoked to preserve the interpretation of the "410" solely as a phase change and explain the observed variations in the sharpness of the transition. This scenario is unlikely, however. The laboratory prediction of the width of the phase transition at 950° C is 20 km, while the width at 1750° C is 10 km [*Bina and Helffrich,* 1994]. The best observations of sharp "410"s are indeed in areas that are probably hot, beneath the Basin and Range province and the Indian Ocean [*Benz and Vidale,* 1993]. However, measured depths in these two areas are 420 km [*Shearer,* 1993] and 410 km [*Benz and Vidale,* 1993], close to the global average depth, in disagreement with the prediction that the phase boundary should be depressed to at least 435 km for such a sharp boundary for such strong variations in temperature. In addition, the wide transitions observed beneath the Russian platform are also centered near the average depth of 410 km rather than 25 km shallower as predicted for very cold mantle [*Bina and Helffrich,* 1994].

Another possibility, though not yet proven to occur in the mantle is phase-transition sharpening by metastability [*Solomotov and Stevenson,* 1994]. Factors that might cause the metastable sharpening of the phase transition to vary from a few to tens of km, such as temperature or upwelling versus downwelling, are speculative at this point.

The most likely explanation for the width variability, if it is real, is that the phase transition is sometimes coincident with a compositional contrast or contrast in melt fraction. Although most attention is now focused on the possibility of a thermal boundary layer and compositional layering near 660 km depth [*Lay,* 1994], there have been many suggestions that upper mantle contains composition variations [*Anderson,* 1989].

The amplitude of the compressional velocity variation that might be expected from compositional variation is not well known but may be similar to or a factor of two smaller than the 5% contrast observed across the "410" [*Duffy and Anderson,* 1989]. Differences between

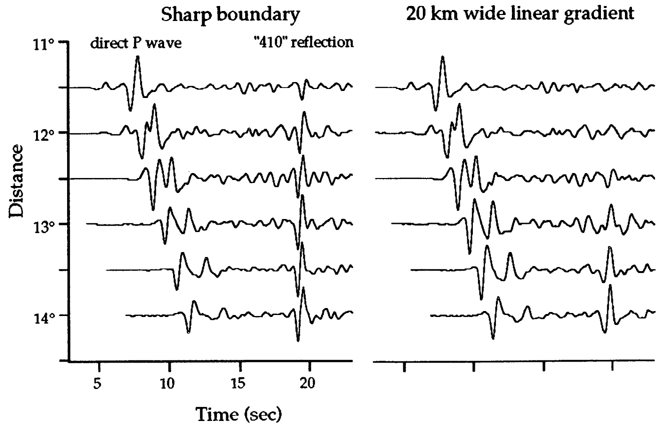


Fig. 4. Reflectivity seismograms for a sharp "410" and a boundary distributed linearly over 20 km, between 400 and 420 km depth.

continental and oceanic upper mantle persist to at least 400 km depth [*Grand*, 1994; *Jordan*, 1981]. Surface-wave inversion suggests about 5% shear-wave velocity variation at 400 km depth beneath Europe [*Nolet and Zielhuis*, 1994], It has also been proposed that there may be a change in viscosity in the olivine component associated with the "410" phase change [*Karato and Li*, 1992] and that a layer of partial melt may sometimes lie atop the "410" [*Revenaugh and Sipkin*, 1994].

Thus, if the lateral variations in the "410" stand further scrutiny, either the α-to-β phase change in olivine is more complicated than current models suggest, or the increase in seismic velocity near 410 km depth sometimes indicates more than just a phase change. Once we learn to identify such heterogeneity within the upper mantle, we may be able to trace the eddies of mantle circulation on a finer scale and decipher the compositional heterogeneity deep in the Earth.

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