GEOPHYSICAL RESEARCH LETTERS, VOL. 15, NO. 4, PAGES 369-372, APRIL 1988

SEISMIC OBSERVATION OF A HIGH-VELOCITY SLAB 1200-1600 KM IN DEPTH

John E. Vidale and Douglas Garcia-Gonzalez

Tectonics Organized Research Unit, University of California, Santa Cruz

Abstract. A slablike high-velocity region 1200-1600 km beneath the east coast of North America apparently has a half-width of 450 km and a lateral extent of 3000 km and a depth extent of more than 800 km. This slab lies beneath the boundary where the Farallon Plate had been subducting for up to 120 MA. The high-velocity anomaly has been inferred previously from travel-time studies; this study uses body-waveforms to verify and refine its structure. The anomalous region has a peak shear wave velocity 1.5 % greater than the surrounding region and compressional velocity 0.6 % greater. The width and smoothness of this anomaly is constrained by the complexity observed in SH waveforms from deep earthquakes beneath South America observed at GDSN stations in North America. This slab is about 5 times broader and 5 times weaker in its velocity anomaly than most slabs observed in the upper mantle. This observation implies that if this slab has passed through the 650 km discontinuity, which is the most likely explanation for the observation, it has been spread by more than simply thermal conductivity. The possibility that there is two-layer convection with thermal coupling is not ruled out, however, as thermal coupling could lead to a similar pattern.

Introduction

The question of whether subducting slabs penetrate the 650 km discontinuity remains of great interest to earth scientists. The most plausible theories of mantle convection have as end members the entire mantle overturning in a single layer and two chemically distinct layers of mantle convection separated by a boundary near 650 km depth. Evidence from seismology, geochemistry, geodynamics, and mineral physics has been cited to support various models of convection. The most detailed pictures of subducting slabs, so far, result from seismological studies.

Residual sphere analysis [Fischer et al., 1988, Creager and Jordan, 1986, Jordan, 1977] of seismic travel times strongly suggests that the high-velocity anomalies associated with cold, subducting material cross the 650 km boundary and extend to depths of at least 900-1000 km. Least squares inversion of travel times including surface reflection phases, with simultaneous relocation of epicenters allows good resolution of the 0 to 400 km depth slab structure in the Aleutians [Engdahl and Gubbins, 1987]. Tomographic analyses of ISC travel time data [Van der Hilst, 1987, Zhou et al , 1987] are more ambiguous, generally imaging relatively narrow velocity anomalies coincident with slabs in the upper mantle, but more diffuse or absent anomalies at the proposed locations of deep slabs.

More recent P-wave tomographic results [R. Van der Hilst, personal communication, 1988] show a slab relatively continuous from the surface to 1200 km depth, the bottom of the inversion, with a peak velocity anomaly of 1.0 to 1.5%. This image shows a narrow slab at the surface spreading to 500 km halfwidth at 1200 km depth. The shape is in agreement with the conclusions of this study, the amplitude is about twice as large as what we find for P-waves.

Seismic body-waveforms have been used to infer details of subducting slabs originally by Sleep [1973] for the upper mantle. The question of the structure below 650 km depth is more subtle. Vidale [1987] and Engdahl et al. [1987] calculated the effect on bodywaves of several possible slab models, and found that the only slabs consistent with the lack of resolvable waveform distortion for body waves leaving the source region in a down-dip direction are relatively wide and/or weakly anomalously fast below 400 km depth. Cormier [1986] argued with Gaussian beam calculations that the waveform broadening from slabs would be more severe for body waves traveling in the strike direction than in the downdip direction. Silver and Chan [1986] observed broadened SH body-wave arrivals that had traveled along the strike of the subduction zone, possibly due to slab material in the lower mantle, but had difficulty explaining the observations with ray tracing. Beck and Lay [1986] test the correlation of waveform distortion with azimuth to test the hypothesis that distortion is due to interaction with slab structure, but find ambiguous results.

In this work, we isolate the body wave distortion produced by a slab in the lower mantle and deduce the upper and lower limits on the width of this structure. The width of the slab is a crucial measure in determining the style of convection, as we explain in the conclusion.

Experiment

Figure 1 shows the anomaly at depth as mapped by Grand [1987] with the events and stations used. Grand [1987] tomographically inverted several thousand travel times from S and SS phases, including picks for several branches of the triplications to

Paper number 8L7307
0094-8276/88/008L-7307$03.00

Fig. 1. The southern stars with dates locate the earthquakes that are also listed in Table 1, the northern stars with labels show stations, and the hatched region is the projection of the fast anomaly from Grand [1987] at 1500 depth to the surface.

obtain a 3-D image of the shear wave velocity beneath North America.

This high-velocity body is most likely a result of 100 Ma or more of subduction along the Pacific coast of North America, subduction which has since converted to strike-slip motion in most of California. The velocity anomaly appears to strengthen with depth, perhaps because the residence time on the surface becomes longer for the slab farther down the subduction zone [Grand, 1987]. The anomaly that is examined in this paper is the primary feature observed below 400 km depth in the structure of Grand [1987]. This feature was first observed by Jordan and Lynn [1974] and has also been noted by Lay [1983]. Our contribution will be to determine lower and upper bounds for the width of this anomaly in the east-west direction, which is the direction most sensitive to the physical character of the high-velocity anomaly.

We model the bodywave complexity with a 2-D 4th order SH finite difference scheme. The dimension we ignore in our 2-D approximation is depth, because the velocity increase with depth simply serves to bend the rays back to the surface and does not introduce complexity for the distance ranges of 50^0 to 80^0 that we are analyzing. It is the transverse variation in velocity from slow on the west, to fast in the anomaly, back to slow on the east that leads to diffraction of waveforms in this case. This near-vertical slab produces the broadest, earliest arrivals where the ray path traveled along the middle of the anomaly. This differs from the case of the waveform distortion produced near the source, in a dipping slab, where it has been suggested by Cormier [1986] and Witte [1987] that paths oblique to the slab show the most noticeable effects. Parenthetically, in a previous study [Vidale, 1987], we ignored the effect of variation in the transverse direction, since in that case we were concerned with seismic energy traveling perpendicular to the subducting structure, where diffraction is caused by vertical and radial velocity variations.

The SH velocity model that best fits the data is shown in Figure 2. The length of the anomaly, 3000 km, is taken from the inversion results of Grand [1987] shown in Figure 1. The peak anomaly of 1.5 % results from the combination of the 3000 km length with the observation that the S-waveforms are 5-8 sec early. Grand [1987] shows a peak anomaly of 1 %, but argues for a true peak anomaly of 2 % that is masked by smearing in the tomographic inversion.

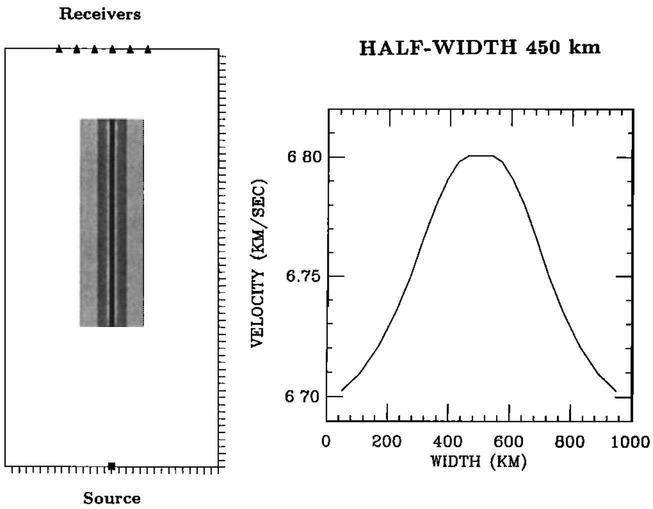

Fig. 2. 2a) Best-fitting model shown in map view. The receivers are 6000 km north of the source, and the anomaly lies about 500 km closer to the receivers than to the source. 2b) Detailed S-wave velocity cross-section through the slab.

In Figure 3, the finite-difference synthetics from the best-fitting model in Figure 2 are compared to data deconvolved from GDSN stations in North America for the three events listed in Table 1. The seismic energy that traveled along the axis of the anomaly to station RSCP shows a waveform with a sharp rise at the front of the waveform and a gradual fall at the back. The arrival time is 8 seconds earlier than the Jeffreys-Bullen table would predict, and the waveform broadening has a width of 5 seconds or more. Several other stations along the axis show this pattern for the 1/1/83 event, and these stations show normal waveforms for events from other azimuths, so this

Table 1 : Earthquakes used in this study

Date	Latitude	Longitude	Depth (km)	Moment
01/01/83	-17.31	-69.28	172	3×10^{25}
12/21/83	-28.23	-63.20	604	3×10^{26}
10/31/85	-28.75	-63.19	595	5×10^{25}

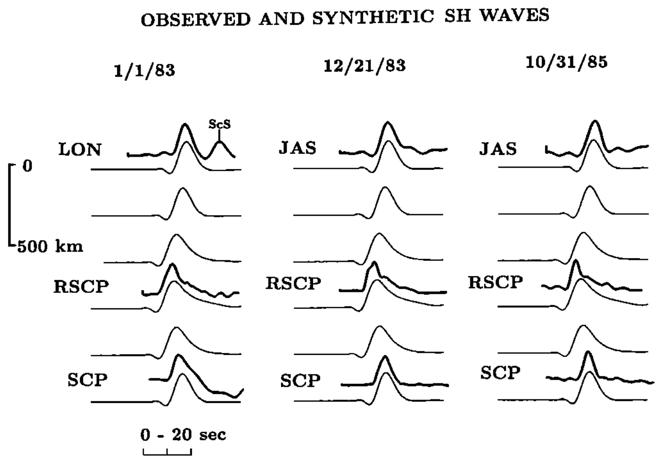

Fig. 3. Comparison between data (thick lines) and synthetic displacement records (thin lines) generated by an SH finite difference calculation. The data is aligned from west to east and is plotted so that in the absence of an anomaly, the signals would all line up vertically.

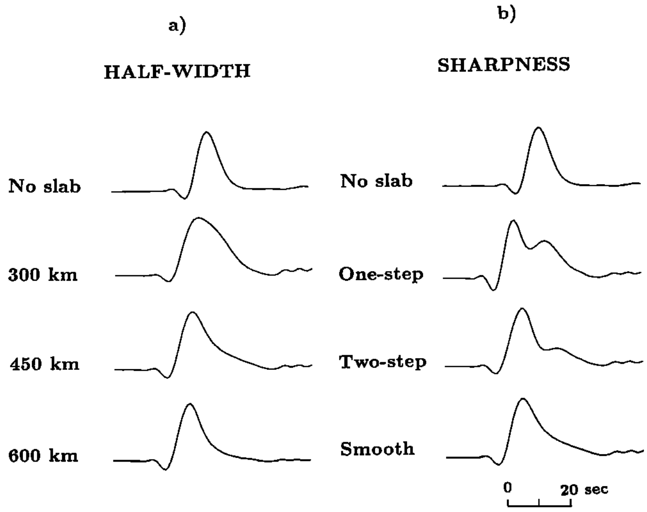

Fig. 4. 4a) Effect of slab width on waveform. 4b) Effect of smoothness of velocity gradient across slab.

waveform broadening is best explained by the lower mantle structure. The stations ANMO and JAS, which would actually plot 2000 km to the west of RSCP, show undisturbed waveforms, consistent with the modeling results where the zone of disturbed waveforms is only 500-1000 km wide. The stations SCP, slightly to the east of the axis, shows some broadening for the 1/1/83 event, and less for the other two events, which have a slightly different back-azimuth. These observations are similar in degree of broadening and magnitude of travel time anomaly to those of Silver and Chan [1986], but the patterns are more systematic, and there is a tomographically-mapped lower-mantle anomaly to use as a starting model. In view of our conclusion that our data shows slab-induced distortion, the data of Silver and Chan [1986] most likely also show the effect of a slab in the lower mantle.

The width of the anomaly is constrained by the observation that the first arrival is sharp, but the tail of the arrival is gradual. This constraint is quantified in Figure 4a. An anomaly that has only a 300 km halfwidth is narrow enough that the first arrival is emergent, and the tail of the arrival is unaffected by the structure, also in contradiction to the data. The 450 km halfwidth has the correct behavior; the shorter (3-6 sec) period energy can travel through the anomaly and form a sharp onset to the waveform, while the longer (6-20) periods both travel through and diffract around the anomaly to form a gradual tail. With a slightly larger halfwidth of 600 km, most of the range of frequencies travel through the anomaly, and both the rise and fall of the displacement pulse are sharp, and the only sign of the anomaly is that the entire arrival is early.

The sharpness of the sides of the anomaly is constrained by the complexity of the back half of the displacement pulse. Models that reach the 1.5% anomaly in a single step, two steps, and by a smooth variation are compared in Figure 4b, and only the smooth model produces a gradual fall at the back of the waveform. Thus, to fit the observations, a smooth variation of velocity across the anomaly fits best.

The halfwidth of the thermal anomaly expected solely from thermal conduction is 100 km, to within a factor of 2. The uncertainty results from imprecise knowledge of thermal conductivity at lower mantle temperatures and pressure. It appears that if slabs are sinking through the 650 km discontinuity, they are broadening by more than simply conduction; perhaps advection and shortening are involved.

Conclusions

A thin, slab-like, high-velocity anomaly in the mid-mantle is suggestive of a cold, sinking, boundary layer in a convection cell. This observation in conjunction with previous work suggests that this tabular anomaly has a length ten times its half-width, and a depth extent at least 2.5 times its half-width, or more if the anomaly exists all the way to the surface. The most likely source of this structure is the material that has been subducting under the west coast of North America for the last 80 to 120 Ma. This explanation is reinforced by the lack of significant structure at the bottom of the upper mantle that should result from the subducting material stopping at the 650 km discontinuity, as is suggested by the most common models that require chemical segregation between the upper and lower mantles [Anderson, 1987].

The presence of anomalously fast material in the lower mantle is consistent with residual-sphere results around the western Pacific, [Jordan, 1977, Creager and Jordan, 1984, 1986, Fischer et al., 1988]. The observation is not consistent with the original, simple "slabs sink undisturbed to great depths" models [Creager and Jordan, 1984, 1986] either, however, although the length, not the width of the slabs, is the primary focus of these studies. The slab observed at 1200-1600 km depth is ten times broader and ten times less anomalously fast than slabs observed near the surface as described in Engdahl et al. [1987] and five times broader and less anomalously fast than slabs observed near 500 km depth by Creager and Jordan [1986]. The observation is consistent with the more recen "gradual spreading with depth" slab models that arise from reconciling waveforms and travel times [Fischer et al., 1988, Vidale, 1987], and may be reconciled with models where slabs broaden when they encounter higher viscosity at 650 km depth [Hager, 1986].

Thermally-coupled convection where the upper and lower mantle can remain unmixed [Nataf, 1987, for example] are still possible if the difference in thickness of the fast anomaly between the upper and lower mantles is attributed to the existence of two separate convection systems. Results where slabs remain slender until they sink to 650 km depth, and then suddenly become much broader [Zhou et al., 1987] are an alternative to the gradually spreading with depth scenario, and not inconsistent with the results of Fischer [1988].

We have verified, however, that a tabular patch of sinking material has been observed in the lower mantle, and this is reliable constraint on mantle dynamics.

Acknowledgements. This work has been supported by NSF grant EAR-8707578. We would like to acknowledge a grant from the Keck Foundation. Discussion with Ken Creager, Stephen Grand, Heidi Houston, and Thorne Lay helped. Preliminary results and interpretations were generously provided by Rob Van der Hilst. Several thorough, anonymous reviews improved the text. Contribution 46 from the Charles F. Richter Seismological Laboratory at the University of California, Santa Cruz.

References

Anderson, Don L., The mineralogy of deep slabs (abstract), *EOS Trans. AGU.*, 67, 379, 1986.

Beck, S.L. and T. Lay, Test of the lower mantle slab penetration hypothesis using broadband S waves, *Geophys. Res. Lett.*, 10, 1007-1010, 1986.

Cormier, V.F., Focussing and defocusing of S, SKS, and ScS waves by a descending lithospheric slab (abstract), *EOS Trans. AGU.*, 67, 1099, 1986.

Creager, K.C., and T.H. Jordan, Slab penetration into the lower mantle, *J. Geophys. Res.*, 89, 3031-3049, 1984.

Creager, K.C., and T.H. Jordan, Slab penetration into the lower mantle beneath the Mariana and other island arcs of the Northwest Pacific, *J. Geophys. Res.*, 91, 3573-3589, 1986.

Engdahl, E.R., and D. Gubbins, Simultaneous travel time inversion for earthquake location and subduction zone structure in the central Aleutian islands, *J. Geophys. Res.*, 92, 13855-13862, 1987.

Engdahl, E.R., J.E. Vidale, and Vernon Cormier, Wave propagation in subducted lithospheric slabs, *Proceedings of the 6th Course: Digital Seismology and fine modeling of the Lithosphere*, International School of Applied Geophysics, Majorana Center, Erice, Sicily, Plenum Publishing Co., 1988.

Fischer, K.M., T.H. Jordan, and K.C. Creager, Seismic constraints on the morphology of deep slabs, submitted to JGR, 1988.

Grand, S.P, Tomographic inversion for the shear wave velocity beneath the North American plate, *J. Geophys. Res.*, 92, 14065-14090, 1987.

Hager, B.H., Fluid dynamics of the 670 km discontinuity (abstract), *EOS Trans. AGU.*, 67, 381, 1986.

Jordan, T.H., Lithospheric slab penetration into the lower mantle beneath the sea if Okhotsk, *J. Geophys.*, 43, 473-496, 1977.

Jordan, T.H., and W.S. Lynn, A velocity anomaly in the lower mantle, *J. Geophys. Res.*, 79, 2679-2685, 1974.

Lay, T., Localized velocity anomalies in the lower mantle, *Geophys. J. R. astr. Soc.*, 72, 483-516, 1983.

Nataf, H.C., Thermal coupling in two-layer convection (abstract), *EOS Trans. AGU.*, 68, 1447, 1987.

Sleep N.H., Teleseismic P-wave transmission through slabs, *Bull. Seism. Soc. Am.*, 63, 1349-1373, 1973.

Silver, P., and W. Chan, Observations of body wave multipathing from broadband seismograms: evidence for lower mantle slab penetration beneath the sea of Okhotsk, *J. Geophys. Res.*, 91, 13787-13802, 1986.

Van der Hilst, R., and W. Spakman, A tomographic image of the Lesser Antilles subduction zone (abstract), *EOS Trans. AGU.*, 68, 1371, 1987.

Vidale, J.E., Waveform effects of a high-velocity, subducted slab, *Geophy. Res. Lett.*, 14, 542-545, 1987.

Witte, D., Numerical simulations of seismic waves distorted by subducting slabs (abstract), *EOS Trans AGU.*, 68, 352, 1987.

Zhou, H.W., and R.W. Clayton, Travel-time inversions for P and S velocities beneath the northwest edge of the Pacific: Slab fingering? (abstract), *EOS Trans. AGU.*, 68, 1379, 1987.

John E. Vidale and Douglas Garcia-Gonzalez, Earth Sciences, University of California, Santa Cruz, Ca. 95064

(Received: 29 January 1988
Revised: 18 March 1988
Accepted: 21 March 1988)