SEISMIC IMAGING OF SUBDUCTED SLABS: 
TRADE-OFFS WITH DEEP PATH AND NEAR-RECEIVER EFFECTS

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Abstract. The most promising procedures for determining detailed velocity structure of subducting lithosphere (seismic tomography and residual sphere analysis) require isolation of near-source contributions to total travel-time anomalies of seismic waves from earthquakes in the slab. Effects of heterogeneous structure along the raypaths through the deep mantle, lithosphere and crust beneath the recording stations must be removed from the data, using either empirical procedures or aspherical models. Comparisons of observed S wave travel-time anomalies for earthquakes in the Kurile slab with both empirical path corrections and corrections computed for a high resolution tomographic shear velocity model beneath North America indicate that near-source contributions are significantly smaller than suggested by recent slab modeling efforts that fail to fully remove the distant path effects. Imaging deep slab velocity structure and depth of penetration is likely to prove more difficult than originally expected, given that slab velocity heterogeneity may be relatively weak at depths greater than 300 km.

Introduction

Despite great advances in our understanding of plate tectonics, many fundamental questions remain about first-order geophysical problems such as the configuration of mantle convection, the detailed thermal and petrological structure of oceanic lithosphere, and the deformation and penetration depth of subducting slabs. Resolving slab elastic wave velocity structure using seismological procedures can address these questions, in combination with mineral physics and geodynamic modeling; however, progress in seismological imaging of deep slab structure is impeded by our limited knowledge of deep earth heterogeneity on a global scale. All seismological procedures for imaging slab structure require correction of the data for path effects at large distances from the source. Unfortunately, these corrections are highly uncertain and researchers disagree about the most reliable procedure for isolating the near-source velocity heterogeneity. This is manifested as a great diversity of seismological models of subducting slabs, which have profoundly different, and inconsistent, implications for mantle dynamics.

Travel-time corrections are often made using a combination of crust/shallow mantle station anomalies, usually obtained in analyses of great numbers of travel time residuals at different receivers [e.g., Dziewonski and Anderson, 1983; Toy, 1989], and deeper mantle anomalies, obtained by raypath integration through existing low resolution models of mantle aspherical structure [e.g., Dziewonski, 1984; Inoue et al., 1990]. Many studies treat these corrections as precise, arguing that any remaining slowly varying patterns in the data must arise from near-source heterogeneity. There is an increasing appreciation of the potential for incompletely suppressed deep path and near-receiver anomalies to contaminate even the slowly varying components of 'corrected' patterns, leading to misinterpretation as near-source structure. This has led to several attempts [Gaherty et al., 1991; Grand and Ding, 1989; Schwartz et al., 1991, Suetsugu, 1989; Zhou and Anderson, 1989; Zhou et al., 1990] to determine empirical path corrections for a particular source geometry, rather than relying on existing models and station corrections that are, at best, heavily smoothed versions of real earth heterogeneity.

The purpose of this article is to explore the trade-off between near-source and distant velocity heterogeneity for S waves from intermediate and deep focus earthquakes in the Kurile slab recorded at stations in North America. A relatively high resolution model of shear velocity in the upper and lower mantle below North America, derived from totally independent data, is used to predict the path effects at large distance from the source region. Empirically derived path corrections from aS phases from the Kurile events are also considered. The primary result is that both empirical and model path corrections, significantly stronger than station corrections used in earlier slab modeling efforts, almost entirely remove the signal which has previously been attributed to near-source structure. Slab shear velocity heterogeneity may thus be weaker than indicated by recent models, a result with important implications for thermal and petrological interpretations of deep slab structure.

S Wave Data and Analysis

We measured travel time anomalies for long-period transverse component S, ScS, aS, and sScS phases from 16 intermediate and deep focus Kurile slab events [full event information is given in Schwartz et al., 1991]. The anomalies were calculated with respect to PREM [Dziewonski and Anderson, 1981] using the ISC source locations, and corrected for ellipticity. The data span a 60° azimuth range straddling the strike of the Kurile slab; a range expected to have strong azimuthal gradients for proposed slab models [Jordan, 1977; Creager and Jordan, 1986]. The azimuthal coverage is inadequate to stably relocate the events using the S wave data...
alone, but preliminary analysis of the complete azimuthal patterns for both intermediate and deep events (Y. Zhou and T. Lay, pers. comm., 1991) indicates that relocation will not strongly change the patterns over this azimuth range.

The Kurile slab model derived from $P$ wave residual sphere analysis by Creager and Jordan [1986] steepens in dip by 20° at depths greater than 500 km due to a systematic change observed in relative $P$ residual patterns with depth. Searching for this effect in the $S$ wave data is complicated by uncertainty in the relative source locations found for $P$ and $S$ waves separately, as discussed by Schwartz et al. [1991], but our attention here is on a common relative $S$ wave residual pattern found for all depths. This common $S$ residual pattern, spanning a total range of over 8 s, is shared by events ranging in depth from 119 to 585 km. Relative $S$ and $ScS$ path anomalies, averaged for events in three different depth ranges, are shown before any corrections are applied (TT0) in Figure 1. The patterns are not very dependent on source depth, with correlation coefficients between the path residuals for different depths exceeding 0.79, suggesting a strong common path contribution.

These observations show a predominantly azimuthal pattern, with $S$ and $ScS$ anomalies having similar azimuthal gradients, although the $ScS$ pattern is slightly reduced relative to $S$ and the $ScS$ anomalies are shifted in baseline by ~-1.5 s. This baseline shift may reflect underestimation of the source depth (by as much as 80 km), the presence of a near-source slab anomaly varying with ray parameter that is common to all depths, or deviation of lower mantle shear velocity structure from the PREM model. For the moment, we simply remove this take-off angle pattern, using a least-squares procedure to estimate a common path term in all $S$ and $ScS$ observations at a given station, for all source depths. The resulting average path anomaly pattern is shown as a function of azimuth from the source in Figure 2a. If this common pattern is removed from the individual travel time patterns, along with the systematic 1.5 s ray parameter trend, very little in the way of coherent relative travel time anomaly pattern is left between events at either similar or different depths [Schwartz et al., 1991]. The common anomaly pattern has the magnitude predicted by the slab model of Jordan [1977], so it may plausibly arise from a common geometry of the slab structure for the full range of source depths. Alternatively, it may arise from systematic receiver and/or deep mantle variations. The question is, which is the case?

The standard procedure for isolating near-source heterogeneity in residual sphere analysis involves correction for independently-derived station anomalies [Jordan, 1977]. We applied station corrections from Toy [1989] and Wickens and Buchbinder [1980] (Figure 2b, and projection TT1 in Figure 1). About 2 to 3 s of the observed pattern is accounted for by the station corrections; the study by Jordan [1977] included station corrections of comparable magnitude. The receiver corrected pattern still has a 4 to 5 s systematic trend in the data, with the same sense as the observed travel time pattern. The receiver corrections may intrinsically underpredict anomalies for any particular path due to azimuthal averaging of the travel time residuals.

We determine additional corrections for the $S$ wave paths through the upper mantle under North America by integrating
through the upper and lower mantle tomographic model of shear velocity beneath the continent obtained by Grand (per. comm., 1991), which is an extension of Grand [1987]. This model does not at present extend far along the Aleutian arc and did not use any sources in the Kurile slab. Raypaths for direct $S$ for a deep focus Kurile event were used to integrate through the structure, as these represent an average path appropriate for the range of $S$ and $ScS$ raypaths combined into the observed path averages.

The observed travel time pattern after correction for propagation through the aspherical mantle model is shown in Figure 2c. Although the scatter at any particular azimuth is of the same magnitude as displayed in the observed travel time pattern (Figure 2a), the long wavelength azimuthal pattern is fully accounted for. This indicates that heterogeneity along the raypath through the mantle, lithosphere and crust is responsible for most of the observed $S$ residual travel time patterns.

The receiver corrections from Toy [1989] and Wickens and Buchbinder [1980] and the mantle corrections derived from the tomographic model are compared with the observed $S$ travel time anomaly pattern in Figure 3. The receiver corrections have a correlation coefficient of 0.7 with the observed anomalies while the mantle model corrections have a more impressive correlation coefficient of 0.9. A regression slope between the mantle and observed anomalies indicates that about 80% of the observed pattern is accounted for by the mantle model and Figure 2c shows that the 1 to 2 s residual is not azimuthally distributed with respect to the slab.

Fig. 4. The correlation between averaged $S$ wave path anomalies for downgoing ($S$ and $ScS$) phases and upgoing ($sS$ and $sScS$) phases. The strong correlation indicates that the anomaly is produced far from the source region.

**Discussion**

This study is a simple one, designed to emphasize the importance of the trade-off between near-source and deep path/near-receiver velocity heterogeneity in the study of subducting slab structure. It indicates both the difficult challenge faced in isolating near-source contributions and the progress being made by use of both empirical calibration procedures and by determination of improved aspherical models of mantle heterogeneity. The significant improvement between standard station statics and tomographic model predictions of path anomalies shown by Figure 3 is quite encouraging, assuming that the data are actually free of strong source contributions.

Several other recent studies have come to similar conclusions. Zhou et al. [1990] show that correcting $P$ residual spheres for path contributions from high resolution $P$ velocity tomographic models decreases the size of near-source anomalies. The empirical calibration efforts of Gaherty et al. [1991], Grand and Ding [1989], Schwartz et al. [1991], Suetsugu [1989], and Zhou and Anderson [1989] give comparable results, with the important common feature being that lower mantle heterogeneity as well as under-corrected upper mantle receiver heterogeneity can project as slowly-varying patterns in residual spheres. Such patterns can be mistakenly attributed to organized near-source heterogeneity.

Reduction of the size of relative anomalies due to near-source structure does not necessarily imply that slab structure is weak, given the suppressing effects of location errors and the limited ray coverage of seismic observations; however, it does raise several interesting issues. First of all, reduced near-source patterns make the slab imaging problem more difficult, particularly for amplitude and diffraction effects, and place greater demands on the accuracy of path corrections. Second, the relative scaling of $P$ and $S$ times is called into question. Estimates of the relative size of mantle elastic velocity perturbations, $dV_s/dV_p \approx 1.0$, and the associated in-
ference that \((dV_s/dT)_p \equiv (dV_p/dT)_p\), have been based on the observed factor of 3 to 4 scaling between teleseismic S wave and P wave travel-time anomalies. These numbers have been used to scale between P wave and S wave velocity models for slabs. It should be noted that the relative scaling of \(dV_s/dV_p\) inferred from mantle-traversing waves actually may not apply to the relatively low temperature environment of the slab. If partial melting or anomalous lower mantle behavior of rigidity is responsible for the teleseismic anomaly scaling, the relatively low temperature near-source slab thermal derivatives may be quite different from those for the ambient hot mantle.

Of course, it is also possible that actual deep slab velocity heterogeneity is actually weaker than inferred from early slab modeling efforts, that may have been contaminated by deep path effects. While there is good evidence for high seismic velocities in slabs at depths less than 300 km, the strength of overall slab anomalies at greater depth is much more ambiguous. While temperature variations probably result in 3 to 5% increases in slab velocity relative to ambient mantle at depths below 300 km, the effects of petrology of the slab are not clear. Kinetic suppression of phase changes, one mechanism which has been advocated as explaining deep earthquakes, will tend to compete with the thermal effect of the slab, potentially reducing the bulk slab velocity relative to the mantle at depths from 400 to 500 km. This is consistent with the absence of strong slab diffraction and defocussing effects predicted for conventional slab models [Vidale, 1987; Gaherty et al., 1991], as well as the intermittence of the deep slab velocity anomalies in tomographic models [e.g. Zhou and Clayton, 1990]. Identification of lower mantle slab penetration, intrinsically difficult due to the trade-offs with path effects, will be even more difficult if thermal heterogeneity causes only a few percent velocity anomaly, and especially if the slab structure is strongly distorted by resistance to penetration. Nonetheless, the importance of this issue mandates that seismologists enhance their slab imaging procedures in the future.

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