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The upper mantle beneath the Philippine Sea region from waveform inversions

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Abstract. We present a three-dimensional S-velocity model for the upper mantle beneath the Philippine Sea region. It was derived from inversions of 281 broad band vertical-component seismograms recorded in the area at the Global Seismological Network (GSN) and SKIPPY portable array stations. We have been able to obtain high-resolution tomographic images spanning the depths down to 200-300 km and locally down to the upper transition zone. High-velocity subducting slabs and low-velocity volcanic arc regions are the dominant features of the model. Fast, thin lithosphere of back-arc basins is underlain by a prominent low-velocity zone. Low velocities at lithospheric depths are observed beneath the extinct Central Basin Ridge in the West Philippine Basin and close to the Eauripik Ridge that separates the East and West Caroline basins. High upper-mantle heterogeneity and resulting scattering presents a difficulty and limits the resolution, especially below 200-300 km. Explicit modeling of seismic wave diffraction may be necessary for a significant improvement in resolution.

Introduction

The upper mantle beneath the Philippine Sea region has a complex structure that can be considered a record of the intriguing tectonic history of the area. The presence of active and recently active subduction zones, volcanic arcs, and spreading centers has resulted in extreme heterogeneity of the seismic velocity distribution which complicates seismic tomography in the area.

Subduction and back-arc spreading have dominated the tectonic evolution of the region. On the East (Fig. 1), old Pacific plate lithosphere subducts westward beneath the Philippine Sea plate at the Izu-Bonin and Mariana trenches. On the West, the Philippine Sea plate subducts at the Philippine and Ryukyu trenches, also westward. The eastern half of the plate was formed by back-arc spreading at 30-15 Ma [*Mrozowski & Hayes*, 1979, *Chamot-Rooke et al.*, 1987]. Spreading is currently active at the Mariana Trough, west of the trench. The origin of the older (about 60-35 Ma) West Philippine basin is disputed: it may be an unusually wide back-arc basin formed by spreading at the Central Basin Ridge or an entrapped portion of a normal oceanic plate with mid-ocean-type Central Basin Ridge [*Seno*, 1988]. To the South of Philippine Sea, the back-arc East and West Caroline basins formed at 36-28 Ma [*Weissel & Anderson*, 1978], and the Coral basin at 62-56 Ma [*Weissel & Watts*, 1979]. The Celebes basin, of uncertain origin, is situated to the southeast of the Philippines and is about 42-50 My old [*Silver & Rangin*, 1991].

There have been a number of successful regional delay-time studies in the area, including that conducted by *van der Hilst et al.* [1991], who were able to obtain P-velocity images of the lithosphere subducted under the Izu-Bonin and Mariana arcs down to the 660 km discontinuity and below. The applicability of body wave tomography, however, is limited to the areas with a high density of stations or sources, such as those near the Philippine Sea plate boundaries, which leaves the structure beneath the intraplate parts of the area largely unknown.

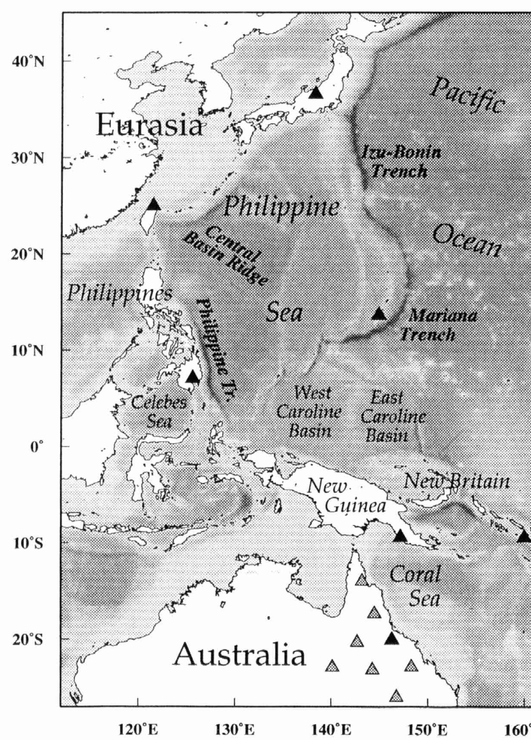

Figure 1. The study area and the seismic stations that contributed to the data set: black triangles – GSN stations, gray triangles – SKIPPY stations.

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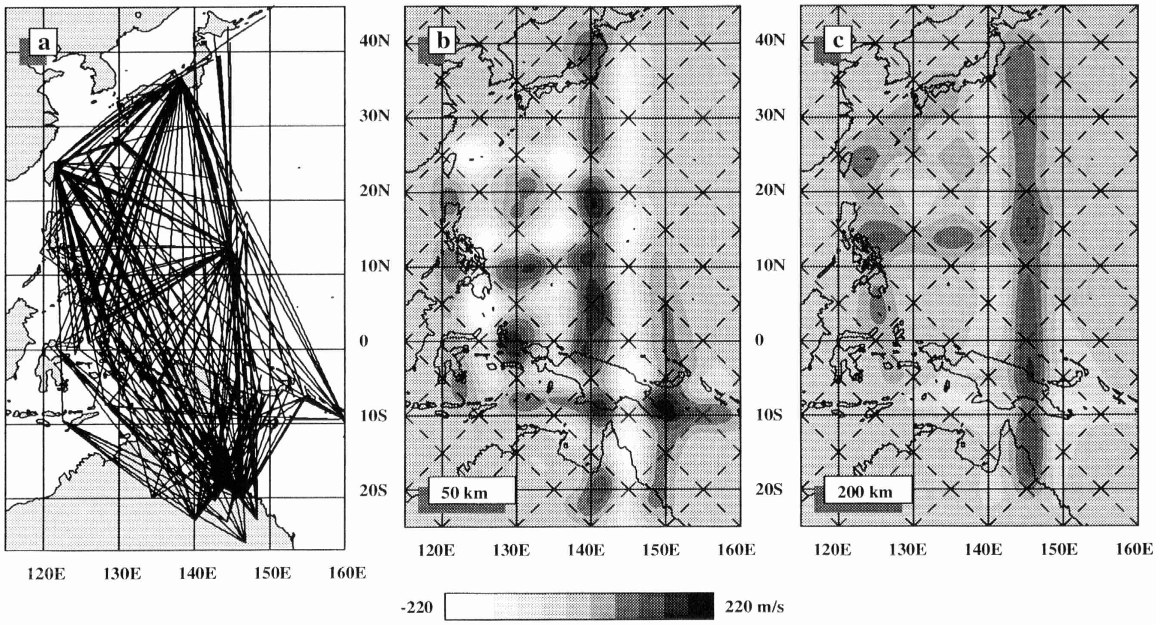

Figure 2. *a*: The 281 ray paths used in the imaging. *b, c*: the output of a checkerboard resolution test. Dashed lines show the boundaries between ±300 m/s velocity anomalies in the input synthetic model; the synthetic anomalies have opposite signs in the 20-100 and 100-300 km depth ranges.

Long- and intermediate-period surface waves carry the information necessary to fill the gaps. *Oda & Senna* [1994] measured Rayleigh and Love fundamental-mode group velocities using about 100 seismograms recorded at the perimeter of the Philippine Sea and inferred one-dimensional (1-D) models for the interiors of the plate with a 40-60 km thick lid above a pronounced low-velocity zone (LVZ). *Gaherty et al.* [1995] combined ScS reverberations data with 3-component body and surface wave delay-time measurements to constrain

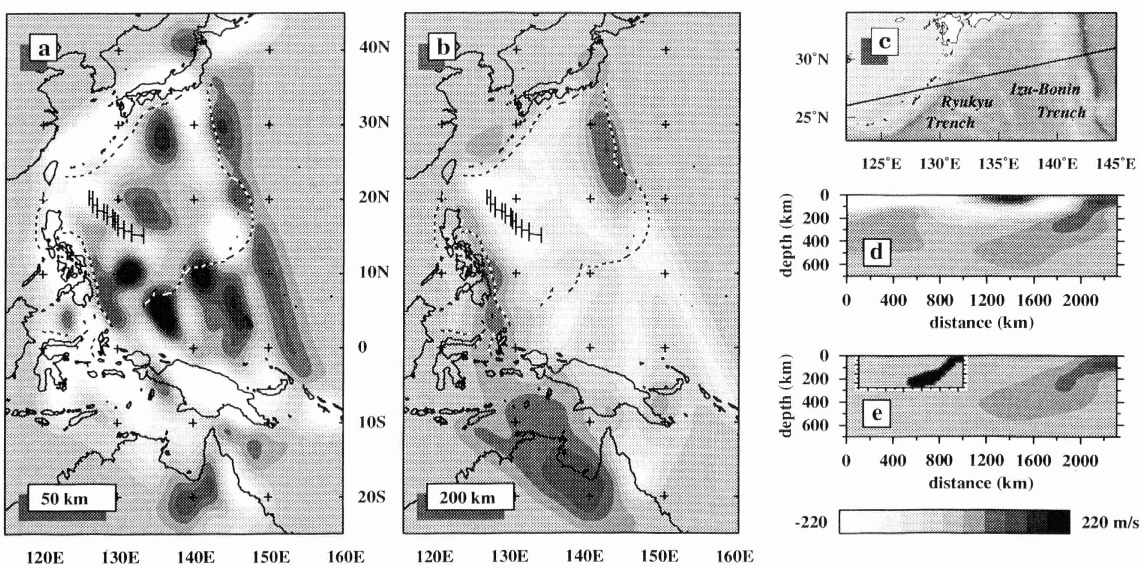

Figure 3. *a, b*: Shear wave velocity distribution at 50 and 200 km depths; dashed lines – deep-sea trench axes; locations of the Central Basin Ridge segments and fracture zones are adapted from *Hilde & Lee*, 1984. *c*: the position of a vertical mantle cross-section across the Izu-Bonin arc; *d*: the image of the Izu-Bonin subducting slab; *e*: input (inset) and output (large frame) of a resolution test. Down to 300 km depth the synthetic "slab" is 350 m/s fast and has a constant width, below 300 km it is 250 m/s fast and widens with depth. More cross-sections through the model and output of other tests can be viewed at `http://geo.princeton.edu/grads/lebedev/PS96.html`

a 1-D model for a corridor between South Philippines and Japan. Their model had an anomalously slow and thick (more than 100 km) lithosphere and was radially anisotropic in the upper 170 km.

In this study, we obtain a three-dimensional (3-D) S-velocity model for the entire region. The model is constrained by 281 vertical-component broad band seismograms, and is based upon the inversion of full seismic waveforms. Both surface and body waves contribute information; higher as well as fundamental Rayleigh modes are taken into account.

Data and inversion

We inverted a few hundred long period and broad band vertical-component seismograms recorded, respectively, by GSN and SKIPPY [*van der Hilst et al.*, 1994] seismometers (Fig. 1) in 1991-1995. To compute a synthetic waveform for each record we summed the first 30 Rayleigh modes and used non-linear optimization to find an average model along the source–station path that minimized the data–synthetic misfit [*Nolet*, 1990]. In this manner, we expressed the information contained in a seismogram in terms of uncorrelated linear constraints on Earth structure (10-16 linear equations per path). Subsequently, the constraints from different paths were combined and a 3-D S-velocity model was computed using LSQR [*Paige and Saunders*, 1982], as described by *van der Lee* [1996].

We adopted the WKBJ approximation and assumed that the modes propagate along the great circle arcs through an isotropic mantle. A horizontal smoothing was applied to account for the finite width of the rays. The waveforms were band-pass filtered between 20-40 and 200 seconds (for the SKIPPY seismograms the upper limit was 125 seconds or, when the low-frequency noise was excessive, 80 seconds). The lower limits were usually the periods below which it was no longer acceptable to ignore the scattered waves.

Strong mantle heterogeneity greatly complicates the excitation and propagation of the modes, which limits the applicability of the approximations we used, especially at higher frequencies. As a result, the percentage of the seismograms we could fit with a WKBJ synthetic was reduced; the frequency band in which an acceptable fit could be obtained was often narrowed, resulting in a decrease in vertical resolution. 40-45% of the seismograms could not be modeled because of pronounced scattering effects [*Meier et al.*, 1997] and had to be rejected.

We used records of the earthquakes in the area with surface wave magnitudes 5 – 6.9 and depths down to 200 km. Excited by such events, the fundamental Rayleigh mode best constrains the S-velocity structure of the upper 150 km of the mantle. At 200–350 km, the fundamental mode sensitivity gradually decreases and the higher modes gain more influence. We obtain useful resolving power even in the transition zone, but it comes entirely from the higher modes, most of it provided by the S, SS, and SSS wavetrains.

Earthquakes in subduction regions may be located with significant systematic errors, especially if nearby seismic stations are distributed as unevenly as in the Philippine Sea area. Interestingly enough, we found that the "Harvard" centroid locations [e.g., *Dziewonski et al.*, 1993] for the events near both Philippine and Izu-Bonin–Mariana trenches are on average about 20 km east of the epicenters reported in the NEIC monthly bulletins. We computed our waveform fits and 3-D model twice, first using the locations and origin times from the NEIC bulletins and then from the Harvard catalogues. A series of tests has shown that the inversions with the NEIC parameters generally result in a somewhat greater variance reduction. We took this as evidence that the NEIC locations and origin times are more consistent in the region and used them in our final inversions together with the Harvard CMT solutions and duration times. Our tests have also shown that the 3-D models resulting from the inversions with the two different location sets are very similar. Major anomalies preserved their shape and position, which indicated robustness of the solution relative to location errors.

We were able to obtain acceptable waveform fits for slightly more than a half of all available records with a good signal-to-noise ratio. We rejected the paths with a considerable difference in the shape of the actual and synthetic waveforms as well as those with a substantial (two-fold or larger) difference in the amplitudes. A total of 281 remaining seismograms (Fig. 2a) contributed 3912 linear constraints. A damped LSQR inversion of the equations resulted in a 79% variance reduction once the final 3-D model was computed.

The model and discussion

Fig. 3 shows cross-sections through our 3-D model. Perturbations in S-velocity at different depths are relative to a radial background model which is a modified version of PEMO [*Dziewonski et al.*, 1975] with a 5 km deep ocean, 15 km thick crust and a constant S-velocity of 4.5 km/s from 20 to 220 km depth. In the cross-section at 50 km depth (Fig. 3a), the high-velocity Philippine Sea plate lithosphere is almost surrounded by low-velocity anomalies beneath the island arcs. At 200 km, the pattern is nearly the reverse: the LVZ below Philippine Sea is bounded by high-velocity subducting slabs. A fast lid and pronounced LVZ are also observed beneath the Celebes Sea, Caroline and Coral Seas and westernmost Pacific Ocean. The lithosphere beneath the back-arc basins is thinner than that beneath the western Pacific, and does not exceed 80 km in thickness (Fig. 3d). The lithosphere of the older southern portion of the West Philippine Basin, Caroline basins and the Pacific plate is 150-250 m/s fast. Extremely low velocities (up to 10% slow) are observed at shallow depths beneath the tectonically active Mariana Trough, Okinawa Trough west of Ryukyu Islands, central Philippines, Halmahera, and New Guinea.

An elongated low-velocity anomaly at lithospheric depths and down to about 200 km closely follows the Central Basin Ridge (Fig. 1, 3), the extinct mid-oceanic or back-arc spreading center [*Hilde & Lee*, 1984; *Seno & Maruyama*, 1984]. Spreading ceased around 35 My ago, so it is likely that these low velocities are caused by more than just thermal effects. We compared the velocities beneath the ridge with those beneath a location outside the anomalous area (20N130E, formed at about 45 Ma). Our estimates for a simple half space cooling model suggest that the temperature difference should be no more than $70°C$ between points at the same depth in the range 30–100 km below the two locations. This would amount to 20–30 m/s difference in S-velocity —

2–3 times less than that in the model. It is not clear what could cause the anomaly. The material beneath the ridge axis might be compositionally different, or it might contain a large proportion of differentiated and solidified melt. Another negative velocity anomaly is located just west of the Eauripik Ridge that separates the West and East Caroline basins. Its shape, however, may be poorly constrained because of the poor local ray-path coverage (Fig. 2).

Our image of the Izu-Bonin subducting slab (Fig. 3d) is consistent with that of *van der Hilst et al.* [1991] down to the upper transition zone. The slab in our model seems wider and smoother, because the model was constrained by seismic waves at longer periods and because the amount of the data used was much smaller. In the test illustrated by Fig. 3e, the input synthetic "slab" was not retrieved in the lower transition zone. This indicates that the perturbations at this depth in the model (Fig. 3d) are an artifact, probably, due to insufficient path coverage and off-great-circle-path propagation of body waves [*Marquering et al.*, 1996]. Apart from that, the shape of the slab is well constrained, due to the linear geometry of the trench and abundance of ray paths parallel to it. Because of variations of the back-arc geometry and the unevenness of the azimuthal ray-path coverage, other subducting slabs were not imaged equally well. A high-velocity anomaly below the curved Mariana arc could hardly be seen. Beneath the Philippines, a pronounced deep high-velocity anomaly was observed, but its shape was poorly constrained.

On the whole, we conclude that the WKBJ-based waveform inversions provide useful resolution in this complicated region. Deficiencies of the ray-path coverage cause variations of the resolution from one geographic location to another. Recent growth in the number of the broad-band stations in the area promises a somewhat better ray-path coverage in the near future. More importantly, however, the commonly used approximations that we adopted inevitably limit the resolution. A significant improvement will probably require explicit modeling of seismic wave diffraction effects, including multipathing, focusing, and back-scattering [*Meier et al.*, 1997].

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