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# The *P* wavespeed structure in the mantle to 800 km depth below the Philippines region: geodynamic implications

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**Abstract**

*P* waves from earthquakes south of Taiwan, recorded by the BATS seismic array and CWB seismic network, were used define the *P* wavespeed structure between depths of 100 and 800 km below the Philippines region. The presence of a low wavespeed zone in the upper mantle is inferred, although the details are unclear. Wavespeeds in the uppermost mantle are low, as expected for seismic energy propagating within an oceanic plate. The estimated depths of the 410- and 660-km discontinuities are 325 and 676 km respectively. The unusually shallow depth of the upper discontinuity below and to the east of Luzon is inferred by clearly resolving the travel-time branch produced by refraction through the transition zone. A possible explanation for the northern part of the region covered is that seismic energy reaches its maximum depth within or close to the cool, subducted oceanic South China Sea slab where subduction has been slow and relatively recent. Further south, however, the presence of a broken remnant of the South China Sea slab, formed during a period of shallower subduction, is suggested at depths below 300 km to explain the broad extent of the elevated 410-km discontinuity. The 660-km discontinuity is slightly deeper than usual, implying that low temperatures persist to lower mantle depths. The wavespeed gradients within the transition zone between depths of 450 and 610 km are higher than those predicted by both the pyrolite and piclogite models of the mantle, possibly due to the presence of water in the transition zone.
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*Keywords:* *P* waves; Philippine Sea Plate; Subduction zones; Transition zone

## 1. Introduction

The existence of two major discontinuities at depths of about 410 and 660 km that define the top and bottom of the transition zone was established over 40 years ago (Niazi and Anderson, 1965). Since that time, numerous studies of this region have been published using a variety of seismological techniques. While these discontinuities have been explained in terms of the phase transformations expected in olivine, pyroxenes and garnets (Ringwood, 1991), there are still difficulties in reconciling the wavespeed and density models obtained from seismology with the properties of the mineral phases established from experimental petrology and mineral physics (Anderson and Bass, 1984; Bass and Anderson, 1984; Fujisawa, 1998; Nishihara and Takahashi, 2001). Moreover, there are still many regions of the earth, especially in oceanic regions, for which knowledge of the structure of the upper mantle and transition zone is poor. Estimates of the wavespeed and density changes across the discontinuities are often poorly resolved, and accurate definition of wavespeed gradients within the transition zone has rarely been obtained.

There are two main objectives in this paper. The first is to define the average *P*-wave structure of the upper mantle and transition zone below a region previously studied only by Nowack et al. (1999): the western margin of the Philippine Sea Plate in the Philippines region underlain by the subducting oceanic portion of the Eurasian Plate, called the South China Sea Plate (or slab). The second objective is to examine possible geodynamic implications of the inferred seismic structure of this complex region of plate convergence and subduction, particularly any unusual characteristics, such as depths to discontinuities and magnitudes of wavespeed gradients. The observations are provided by earthquakes within and to the south of the Philippines region recorded by two networks in Taiwan: the broad-band BATS array (Broad-band Array in Taiwan for Seismology) and the short-period CWB (Central Weather Bureau) seismic network, which were used to generate

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seismic refraction data to define mantle structure between depths of 100 and 800 km. The epicentres of the thirty earthquakes used are plotted in Fig. 1. The ray paths between the earthquakes and stations, projected on to the surface, are also shown to define the region of the earth covered by the present study.

## 2. Plate tectonic setting

Fig. 2 (left) shows the surface features that define the plate structure south of Taiwan to the central part of the Philippines. The Manila Trench in the west is where the oceanic South China Sea Plate is subducted below the Philippine Sea Plate. Yang et al. (1996) provided a tectonic model to explain the double island arc between Taiwan and Luzon, and interpreted the seismological data as suggesting an abrupt increase in the dip angle of the subducted Eurasian Plate from 30° at 18°N to 80° at 20°N latitude due to the continent-ocean transition (COB zone in Fig. 2). The abrupt change in dip angle may have torn the slab. To the south, the dip increases again towards the ocean-continent transition, reaching almost 90° at latitude 13°N. The later model of Bautista et al. (2001) is a refinement of the earlier model of Yang et al., based on more extensive analysis of seismological data. A tear in the slab is inferred from an observed gap in strain energy release and the abrupt change in dip from steep to shallow south of 18°N. A gap in seismicity and strain energy release near latitude 17°N probably defines the location of the subducted extinct mid-ocean ridge (MOR in Fig. 2). Bautista et al. also suggested that a further tear in the slab occurs near latitude 16°N, where a rapid southward change from shallow to steep dip occurs.

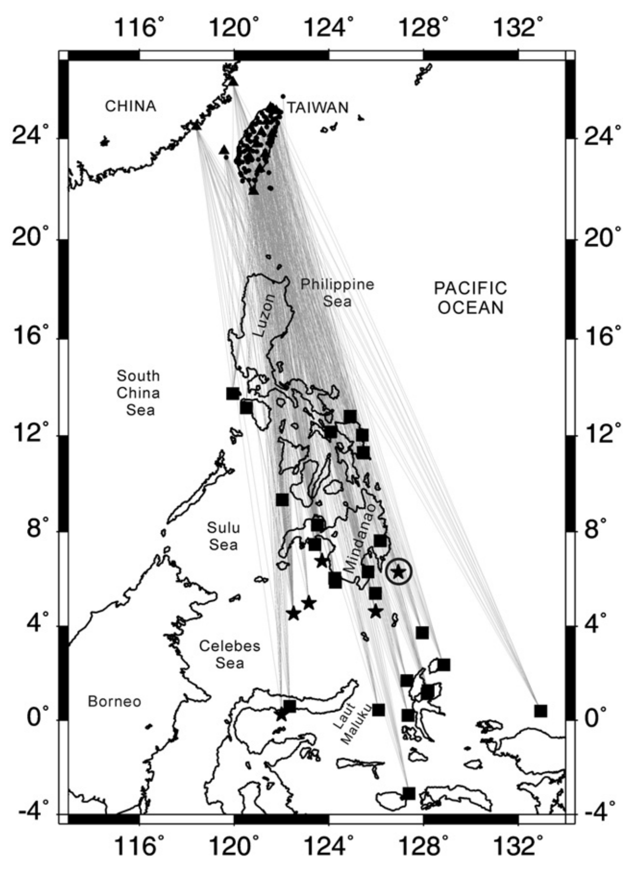


Fig. 1. Map showing distribution of events used to determine mantle structure, with great circle paths (dotted grey lines) to the stations providing seismograms for each event. Squares and stars denote events at depths of 150 km depth or less and depths greater than 150 km., respectively. The event for which seismograms are displayed in Fig. 5 is circled.

Yang et al. (1996) and Bautista et al. (2001) proposed that westward subduction at the East Luzon Trough and the Philippine Trench accommodates the north westward motion of the Philippine Sea Plate, because it is clear that the convergence is accommodated on both parts of Luzon (L in Fig. 2) to the west of the subduction zones. The two trenches are separated at about 15°N latitude by an east–west trending transform fault about 240 km long, which does not extend to the east of the Philippine Trench. Plate motion not accommodated by this easterly subduction system causes the Luzon block to be dragged westward over the Eurasian Plate. The Benham Rise (Fig. 2), east of the East Luzon Trough, is a buoyant mass consisting of thickened oceanic crust, which may slow down subduction below the East Luzon Trough. Using the results of global tomography (Bijwaard et al., 1998), Lallemand et al. (2001) suggested that a vertical South China Sea slab, not connected with the surface and defined as a zone of high wavespeeds, could be overturned in the transition zone at 20°N. They also interpret another high wavespeed zone as a possible Pacific remnant slab. Further south at 18°N, their section shows the South China Sea Plate, also disconnected from the surface at about 70 km depth, dipping shallowly eastward until it reaches a depth of around 300 km.

The present work focusses on the structure below and adjacent to the Philippine landmass, located in the boundary region between the converging Philippine Sea and Eurasian plates. Bautista et al. (2001) and Lallemand et al. (2001) show that the region has a complicated tectonic evolution, and consists of an assemblage of continental fragments, island arcs from different localities, obducted crust and marginal basins, resulting from episodes of rifting, collision, subduction, volcanism and accretion. Knowledge of the structure of the underlying mantle and transition zone will assist in developing a better geodynamic model for the evolution of a region of such complexity.

## 3. Methods of data analysis

A full description of the methods of data analysis was provided by Wright and Kuo (2007), so that only a summary of the procedures is provided here. Times of the earliest *P*-wave arrivals measured on records of 30 earthquakes (Fig. 1) from 13 stations of BATS and 4 earthquakes from 65 stations of CWB, bandpass-filtered between 0.4 and 5.0 Hz, were the primary input data. For each record, the distances and times were corrected by ray tracing to make all events appear to be located on the surface. The resulting travel times from both BATS and CWB stations are plotted in the upper half of Fig. 3. While times of later arrivals were picked, only the earliest arrivals are shown. Fig. 3 also shows the travel-time curve calculated by ray tracing for a surface

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