Seismological evidence for a low-velocity layer within the subducted slab of southern Taiwan

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Abstract

A thin low-velocity layer that continues from the surface down to at least 135 km depth has been detected within the subducted slab through the analysis of a three-component short-period set of digital data from seismic stations in southern Taiwan. Two distinct phases in the first few seconds of the P-waves generated by nine intermediate-depth earthquakes are observed at one station (TAW) located just at the intermediate up-dip of the Wadati–Benioff zone. Detailed analyses of these phases show the faster one is a refracted wave from the Moho of the subducting plate while the subsequent phase is the direct wave propagated within the subducting crust. These two distinct phases are not observed at any other stations, even at Station HEN which is only 20 km from the plate boundary. These phenomena suggest that the intermediate-depth earthquakes occurred in the low-velocity layer of the subducting crust and that the thickness of the low-velocity layer is less than 15 km. The continuity of such a thin low-velocity layer down to at least 135 km is hard to explain by the metastable persistence of dry gabbro at depths less than 60 km. Instead, however, the low-velocity layer might be largely attributed to the metastable persistence of hydro phases and/or fluid produced by a series of dehydration reactions during subduction. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: low-velocity zones; subduction crust; dehydration; fluid phase; Taiwan

1. Introduction

The presence of oceanic crust subducted into the mantle is usually characterized by a thin low-velocity layer within the subducted slab [1–6]. Such low-velocity layers have been earlier explained as the result of several independent mechanisms operating at particular depths. At shallow depths (less than 50–60 km), the low-velocity layer is caused by a slow transformation of the subducting crust to an eclogite [1,2]. At greater depths (around 100 km), the presence of partial melting might be responsible for low velocities within the subducting crust [4]. Alternatively, water infiltration of the overriding plate may generate a low-velocity layer at the bottom of the mantle wedge [7,8].

In addition to the possible mechanisms mentioned above, fluid within the subducting slab may play an important role in bringing about a low-velocity layer. It is well known that a series of dehydration reactions takes place during subduction [9,10]. Released water may infiltrate the over-
riding plate thereby triggering magma generation and meanwhile may be reabsorbed by adjacent rock within the subducting crust. Thus, the net effect of local dehydration and rehydration might be to homogenize the H$_2$O content within the subducting crust, where the H$_2$O content is originally highly variable, and therefore reduce its velocity [9].

Dehydration reactions within a subducting slab have previously been successfully approached through a variety of theoretical experimental studies [8,9,11]. However, due to the limitation of spatial resolution, direct physical observations of the water effect within a subducting crust have only been reported for a few subduction zones [5,6,12,13].

In this study, we first identify two distinguishable phases from the first P-wave seismograms that were generated by a number of intermediate-depth earthquakes within a subducted slab and recorded at stations around the subduction zone in the southern Taiwan area. The travel times and the amplitudes of the identified P-phases are then calculated from a forward model for a variety of raypaths through the subduction slab. Based on the observations and the forward modeling, it is concluded here that a thin low-velocity layer continues down to a depth of at least 135 km within the subducted crust. It is finally proposed that the continuity of such a low-velocity layer is directly associated with a series of dehydration reactions during subduction.

2. Tectonic background

Taiwan is located at the convergent boundary between the Eurasian and Philippine sea plates (Fig. 1). Subduction of the oceanic plate of the South China Sea (SCS), part of the Eurasian Plate, eastward under the Philippine Sea Plate (PSP) north of Luzon also takes place south of Taiwan. The plate boundary strikes almost N-S along the Manila Trench north of Luzon but probably shifts to the east along the eastern coast of the Hengchun Peninsula around the island of Taiwan [14]. The Hengchun Peninsula at the southern tip of Taiwan is part of the subducting Eurasian Plate. The islands of Lanhsu and Lutao constitute a volcanic arc on the overriding PSP.

More detailed evidence for the subducted SCS oceanic plate can be delineated from the seismicity in the southern Taiwan area [15–17]. Fig. 2a presents the earthquakes of magnitudes greater than 3 as located by the Central Weather Bureau Seismic Network (CWBSN) in the southern Taiwan area between 1992 and 1997. The projection of these earthquakes in an E-W direction (Fig. 2b) shows the Wadati–Benioff zone with a thickness of 15–20 km dipping about 60° to the east beneath the southern tip of Taiwan (Fig. 2b).

The geometry of the subducted slab as well as the station coverage in southern Taiwan make this an ideal site to observe the fine structure of the subducted crust (Fig. 2a,b). Seismic stations located on both the subducting and overriding plates around the plate boundary allow the direct collection of waves channeled within the subducted crust as well as other phases propagated through the deeper parts of the subducted slab. In particular, seismic data directly recorded at a subducting plate in such a subduction zone are valuable in detecting waves channeled within the
subducted crust because most other subduction zones do not have stations situated on land near any trench.

3. Seismic data

In this study, P-waveforms are examined for all 10 intermediate-depth earthquakes (100–150 km) of magnitude greater than 4 that occurred in the southern Taiwan subducted slab between 1992 and 1997 as recorded by the CWBSN (Fig. 2 and Table 1). Nine of these earthquakes were within the Wadati–Benioff zone; one earthquake (Event 4) was 30 km east of the subducted slab (Fig. 2b). Seismograms in this study were re-
corded at 12 stations in the southern Taiwan area, from among a total of 79 stations of the CWBSN. These seismograms were recorded at a rate of 100 samples per second by three-component short-period S-13 seismometers (a Teledyne product) and provide a high accuracy for routinely locating earthquakes in the area. In addition, it is noteworthy that the seismic stations of the CWBSN in the southern Taiwan area cover both the Eurasian and the Philippine sea plates. Seismic Stations TAW, HEN and SCZ are located at the Hengchun Peninsula, part of the Eurasian Plate; other stations, such as LAY, are located on the Luzon volcanic arc of the PSP (Fig. 2a).

Fig. 3 shows an example of the seismograms generated by one local earthquake (Event 3 in Table 1) at a depth of 136 km. The first few seconds of the seismogram recorded at Station TAW are significantly different from those at other stations. The first arrivals at Stations LAY, SCZ and others have a distinct P-wave onset with a sharp impulse, which is very typical of the waveform of an intermediate-depth (or deep) earthquake. Those arrivals can be roughly fitted by a calculated curve based on a simple normal-moveout correction. In contrast, the first arrivals recorded at Station TAW are barely identifiable due to their smaller amplitude. A detailed analysis of the seismograms at TAW shows that a strong phase with larger amplitude arrives about 1.6 s later (Figs. 3 and 4). In other words, two distinguishable phases were recorded in the first few seconds at Station TAW. A further investigation of the particle motion of these two clearly marked phases shows that the particle motion is vertical for the first arrival phase, but dips about 60° to the east in the later arrival phase (Fig. 4).

The prominent difference in the first P-waves recorded at Station TAW and those at other stations is observed by comparison with the seismograms generated by all of the other events. To illustrate this, the first P-waves at Stations TAW and SCZ are shown in Fig. 5. Just as in Fig. 3, the sharp onsets of the first P-wave at Station SCZ are clearly recognizable (Fig. 5a). On the other hand, two clearly distinct P-phases are found at Station TAW, and the travel-time difference between each phase ranges from 0.8 s to 1.6 s, roughly depending on the hypocentral distance (Fig. 5b). It is evident that these two distinguishable phases are most unusual when compared with the seismograms generated by either intermediate-depth or deep earthquakes.

4. Forward modeling

To ascertain the nature of the two distinguishable phases observed at TAW and the one clear phase observed at other stations, the travel times and amplitudes for those phases are computed according to a two-dimensional model (Fig. 6). This model simply consists of a plate subducting with an eastward dip of 60°. The crust of the subducted plate is 15 km thick. Velocities are assumed to be 5.9 km/s near the surface of the crust and 7.2 km/s at the bottom of the crust. These crustal velocities are increased to 7.2 km/s and

<table>
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<th>Latitude (°)</th>
<th>Depth (km)</th>
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7.4 km/s, respectively, where the subducting crust penetrates beneath the Moho of the upper plate. Velocities in the mantle increase slightly from 8.1 km/s just below the crust to 8.3 km/s at the bottom of the model (170 km depth).

The arrivals and synthetic seismograms generated by an earthquake that occurred within the subducted crust at a depth of 140 km are calculated using software developed by Zelt and Smith [18]. Three different groups of P-waves are traced in this model. The first are direct waves propagated through the mantle of the subducted plate to the surface. These arrivals are marked P1 in Fig. 6a. The second group (P2) consist of direct waves propagated within the subducting crust. The third group (P3) are waves refracted from the Moho of the subducted plate (Fig. 6b). As a result, at horizontal distances of less than 40 km, the P1 phase is the only one which arrives at the surface in this model (Fig. 6c). However, two phases are found around the horizontal distances of between 40 and 55 km which located immediately up-dip of the subducting crust. It is obvious that the P3 phases arrive first with a smaller amplitude and the P2 phases arrive 1.6 s later with a strong amplitude (Fig. 6d).

A further test of the model is computed under the assumption that the earthquakes occurred at different locations. If the earthquakes occurred in the subducting mantle (B) (Fig. 6b), but not in the subducting crust (A), then two distinguishable phases (P3 and P2) at Station TAW would not be expected. In fact, only the direct wave propagated through the subducting mantle can be observed at Station TAW and the later phase that propagated within the subducting crust is not detectable due to their smaller amplitude compared with the direct wave through the mantle.
5. Discussion

The results obtained from forward modeling provide a reasonable explanation for the seismograms recorded at stations in the southern area of Taiwan. The first few seconds of the seismograms recorded at Station TAW can be modeled as two different phases (Fig. 7). The first (P3), which ar-

Fig. 5. Comparison of the first P-waves generated by nine intermediate-depth earthquakes and recorded at Stations SCZ (a) and TAW (b). The hypocentral distances are shown as the x-axes.
rived early with an almost vertical incidence and smaller amplitude, is the refracted phase from the Moho within the subducted plate. The other (P2), which arrived 1.6 s later with an incident angle of about 60° and larger amplitude, is the direct wave propagated within the subducted crust from a depth of 140 km to the surface. The 1.6-s delay of the second phase indicates that the average velocity within the subducted crust is about 9% less than velocities in the mantle adjacent to the subducted crust, almost the same as that observed in Japan [1-3], but significantly larger than the value of under 4% in Alaska [5].

In addition to showing a 9% slower velocity anomaly within the subducted crust, the significant differences among the seismograms recorded at Station TAW and other stations provide a reasonable constraint on the thickness of the low-

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Fig. 6. Synthetic modeling of both the arrivals and amplitudes generated by an intermediate-depth earthquake in a simple model for a subducted slab. (a) Raypaths of P1 and P2 waves directly propagated through the mantle of the subducted plate and within the crust of the subducted plate in the velocity model, respectively. Numbers show the P-wave velocities in the model. Stars and triangles show earthquakes and seismic stations, respectively. (b) Raypaths of P3 waves refracted from the Moho discontinuity of the subducted plate in the model. Earthquakes which occurred at the subducting crust and the subducting mantle are marked by A and B, respectively. (c) Calculated arrivals of P1, P2 and P3 phases. (d) Synthetic amplitudes of the P1, P2 and P3 phases. The y-axes in panels c and d show the travel times reduced by a velocity of 8 km/s.
velocity layer. The two phases recognized at Station TAW are not observed at Station HEN, which is only 20 km away from the convergent boundary (Fig. 2a). This phenomenon implies that Station HEN is not located on the top of the subducted crust. Based on a simple geometrical correction, the thickness of the low-velocity layer is less than 15 km.

Different mechanisms have been proposed to explain the low-velocity layer within the subducting oceanic crust [1–6]. The primary candidate for the low-velocity layer is the basalt/gabbro within the subducted crust. Although a dry basaltic/gabbroic crust might convert to eclogite at depths of 20–30 km, the reactions may be too sluggish at slab temperatures [19]. Consequently, Hori et al. [2] suggested that gabbro might persist to depths of 50–60 km without being transformed to eclogite. Recent studies show that hydrous metabasalt phases, rather than dry basaltic rocks, might persist to deeper depths if temperatures are low [6,9,13]. For example, the blueschist might remain stable at 700°C and 20 kbar (65 km) [20], and lawsonite to >60 kbar [21,22]. These findings suggest that some hydrous phases might persist to great depths where low velocities are observed.

In addition to the effect of phase changes, partial melting has been said to account for the low velocity within the subducting slab, especially at depths between 80 and 150 km. Helfrich et al. [4] showed that the presence of 3–6% melt reduces seismic velocity by 5–10%. Besides, Defant and Drummond [23] reported that rocks with the geochemical characteristic of melts derived directly from the subducted lithosphere are present in some modern arcs where relatively young (less than 25 Ma) and hot lithosphere is being subducted. In the case of southern Taiwan, partial melting might be suspected at depths of 80–120 km because the magmas produced in the Luzon arc result from the subduction of the young oceanic crust of the South China Sea. However, the possibility of partial melting has to be ruled out since the isotopic evidence did not show any signature of partial melting from the Luzon arc [24].

The amount of fluid (H₂O) released during subduction might be another important factor giving rise to the low-velocity layer within the subducting crust [4,5,25]. This mechanism, different from those limited to particular depths or depth ranges, is dehydration within the subducting crust. This could take place continuously from the surface down to a depth of hundreds of kilometers. It is well known that a series of dehydration reactions take place continuously within the subducting crust [21]. Prior to subduction, the H₂O content of the oceanic crust is highly variable on the scale of millimeters to kilometers [9]. During subduc-

![Fig. 7. Schematic diagram of the subducting slab with a low-velocity layer within the crust. The subducting crust from the surface down to a few hundred kilometers is occupied by the uniform fluid (H₂O) that was generated by a series of dehydration reactions during subduction. Gabbro of the subducting crust might persist to 50–60 km without being transformed into eclogite. Partial melting could be generated at depths around 100 km, just beneath the volcanic arc. A variety of raypaths through the subducted slab are also plotted. The channel wave (P2) with stronger amplitudes propagated within the subducting crust is slower than other waves (P1 and P3) through the uppermost mantle.](image-url)
tion, various hydrous minerals within the subducting crust dehydrate, and the released water may leave the system and/or be reabsorbed by adjacent dry rocks. The net effect of local dehydration and rehydration reactions is to homogenize the H$_2$O content of the subducting crust. Such a series of processes generates uniform H$_2$O contents within the subducting crust and reduces its velocity [9]. Therefore, the fluid content generated by dehydration reactions during subduction could be responsible for the low-velocity layer that extends from the surface down to a depth of at least 135 km within the subducting crust, even when the persistence of both gabbro at shallow depths and hydrous phases at greater depths is ignored.

Although the dehydration process within the subducting crust could also produce H$_2$O that might infiltrate the overriding plate, the seismological observation in this study cannot be explained by a low-velocity layer at the bottom of the mantle wedge [7,8]. First, the observation of two distinguishable phases, P2 and P3 (Fig. 6), at Station TAW suggests that the earthquakes must have occurred within the low-velocity zone; otherwise, the P2 phase would not be detected at the surface. Focal mechanisms of down-dip extension within the Wadati-Benioff zone [26] suggest that the earthquakes occurred at the subducting slab, not the mantle wedge which is under horizontal compression. Consequently, the low-velocity layer observed in the subduction zone is within the subducting crust, not at the bottom layer of the mantle wedge.

Second, only a 3–4% lowering of elastic wave velocities at the slab/mantle wedge interface as estimated by Tatsumi [8], who compared the change of velocity in hydrous amphibolite with anhydrous granulites under the condition of 700°C and 1 GPa, is significantly less than 9% slower than other velocities observed in this study.

6. Conclusions

Detailed analyses of the first arrivals of the short-period P-waves provide direct evidence for fine-scale lateral variations within the subducted slab. Two distinguishable phases observed at Station TAW, which is just east of the convergent boundary, indicate the existence of a low-velocity layer within the subducted slab between the Eurasian and Philippine sea plates in the southern Taiwan area. Upon further analysis of traveltime and amplitude differences between these two phases, it is suggested that the velocity within the subducted crust is about 9% lower than that in the ambient mantle. The thickness of the low-velocity layer is limited to a maximum of 15 km. The intermediate-depth earthquakes occurred in the low velocity layer of the subducting crust, not in the mantle. The low velocities extend down to depths of 135 km or more and can seemingly only be explained by different mechanisms at different depths. In addition to the persistence of subducted gabbro untransformed to eclogite at shallow depths and hydrous phases stable at great depths, the low-velocity layer might be largely accounted for by the presence of fluid produced by dehydration reactions.

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