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Complex slab structure and arc magmatism beneath the Japanese Islands

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ABSTRACT

A dense nationwide seismic network recently constructed in Japan has resulted in the production of a large amount of high-quality data that have enabled the high-resolution imaging of deep seismic structures in the Japanese subduction zone. Seismic tomography, precise locations of earthquakes, and focal mechanism research have allowed the identification of the complex structure of subducting slabs beneath Japan, revealing that the subducting Philippine Sea slab underneath southwestern Japan has an undulatory configuration down to a depth of 60–200 km, and is continuous from Kanto to Kyushu without disruption or splitting, even within areas north of the Izu Peninsula. Analysis of the geometry of the Pacific and Philippine Sea slabs identified a broad contact zone beneath the Kanto Plain that causes anomalously deep interplate and intraslab earthquake activity. Seismic tomographic inversions using both teleseismic and local events provide a clear image of the deep aseismic portion of the Philippine Sea slab beneath the Japan Sea north of Chugoku and Kyushu, and beneath the East China Sea west of Kyushu down to a depth of ~450 km. Seismic tomography also allowed the identification of an inclined sheet-like seismic low-velocity zone in the mantle wedge beneath Tohoku. A recent seismic tomography work further revealed clear images of similar inclined low-velocity zones in the mantle wedge for almost all other areas of Japan. The presence of the inclined low-velocity zones in the mantle wedge across the entirety of Japan suggests that it is a common feature to all subduction zones. These low-velocity zones may correspond to the upwelling flow portion of subduction-induced convection systems. These upwelling flows reach the Moho directly beneath active volcanic areas, suggesting a link between volcanism and upwelling.

1. Introduction

The Japanese Islands are located in a region of subduction zones, where earthquakes occur frequently including many destructive earthquakes that have caused extensive damage to inhabited areas. The M9.0 11 March 2011 great Tohoku-oki earthquake, which occurred along the plate interface east of Tohoku, northeastern Japan, is an example of a significantly destructive earthquake in the region. This was the largest-magnitude event in the modern history of Japan and caused severe damage to eastern Japan, resulting in ~20,000 dead and missing.

Four tectonic plates converge beneath the Japanese Islands (Fig. 1), comprising two oceanic plates subducting beneath two continental plates. Northeastern Japan is located on the southernmost portion of the North American Plate, with southwestern Japan forming part of the eastern edge of the Eurasian Plate. These two plates converge along the Itoigawa-Shizuoka Tectonic Line in the south and along the eastern margin of the Japan Sea in the north. Beneath southwestern Japan, the Philippine Sea Plate subducts northwestward at a rate of 3–5 cm/yr along the Sagami trough in the east, along the Nankai trough in the west, and along the Ryukyu trench in the southwest (Heki and Miyazaki, 2001; Miyazaki and Heki, 2001; Seno et al., 1993, 1996; Wei and Seno, 1998). Beneath northeastern Japan, the Pacific Plate subducts west-northwestward at a rate of 8–9 cm/yr along the Kuril trench in the north and along the Japan trench in the middle, and at a rate of ~6 cm/yr along the Izu–Bonin trench in the south (DeMets et al., 1994).

This complex tectonic convergence generates not only significant and frequent seismic activity, but also leads to a complex structure of subducting slabs beneath the Japanese Islands, in addition to volcanism. A recently constructed dense (station separation of ~20 km) nationwide seismic network, called "Kiban seismic network", covers all of the Japanese Islands, enabling the imaging and determination of deep structures beneath the region. Data from this network have been used in a number of seismic structural studies, the results of which are summarized here. The

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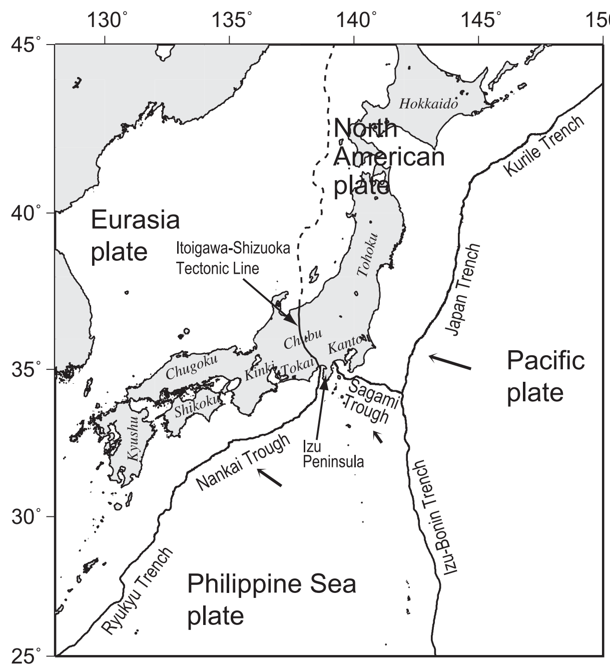

Fig. 1. Tectonic setting of Japan. The plate boundaries such as the trenches, troughs and tectonic lines are shown by thick solid or broken lines. Thick arrows indicate directions of the plate motion relative to the NA plate.

implications of these data for arc magmatism and the form of subduction beneath Japan are discussed in detail.

2. Subduction of the Pacific and Philippine Sea Plates beneath the Japanese Islands

2.1. Configuration of the Pacific Plate

Intermediate-depth intraslab earthquakes within the Pacific slab form a deep double-planed deep seismic zone beneath Hokkaido, Tohoku, and Kanto in northeastern Japan (Tsumura, 1973; Umino and Hasegawa, 1975; Hasegawa et al., 1978a; Suzuki et al., 1983). Hasegawa et al. (1978b) undertook the first investigation of the geometric relationship between this double-planed seismic zone and the subducting Pacific slab using converted ScS-to-P waves (ScSp phase) at the plate interface beneath Tohoku, determining that the upper interface of the subducting plate lies immediately above the upper seismic plane of the double-planed seismic zone. This observation was subsequently confirmed by Matsuzawa et al. (1986, 1990), who detected converted S-to-P and P-to-S waves (SP and PS phases) at the plate interface in seismograms from intermediate-depth intraslab events, using the arrival times of these waves to locate the upper interface of the subducting plate. Later, Zhao et al. (1997b) estimated the depth distribution of the upper interface of the subducting Pacific slab beneath Tohoku by inverting converted wave arrival-time data. These studies indicate that, at depths greater than ~50 km, the upper envelope of intermediate-depth intraslab seismicity approximately coincides with the upper surface of the subducting Pacific Plate.

Nakajima et al. (2009a) and Kita et al. (2008) determined the configuration of the upper surface of the subducting Pacific Plate down to a depth of ~500 km beneath all of Japan by relocating earthquake hypocenters observed by the nationwide Kiban seismic network and by using focal mechanism information for those earthquakes. They located plate interfaces at depths greater than ~50 km by adopting the upper envelope of relocated intraslab earthquakes as the upper plate interface, in accordance with the previous research. The plate interface at depths shallower than ~50 km was located by using the relocated hypocenters of interplate earthquakes, such as those with low-angle thrust-type focal mechanisms and small repeating earthquakes (Uchida et al., 2003)—seismic events that are thought to occur at the plate interface. The geometry of the subducting Pacific Plate beneath the Japanese Islands is shown as contours in Fig. 2.

2.2. Configuration of the Philippine Sea Plate

Until recently, the configuration of the Philippine Sea slab subducting beneath southwestern Japan was estimated by assuming the upper envelope of the distribution of intraslab earthquake hypocenters represented the upper slab interface (e.g., Mizoue et al., 1983; Yamazaki and Ooida, 1985; Ishida, 1992; Noguchi, 1996; Miyoshi and Ishibashi, 2004), as observed for the subducting Pacific slab. This is roughly supported by the following observations. ScSp waves were also detected and were used to estimate the upper surface of the Philippine Sea Plate subducting beneath southwestern Japan (Nakanishi, 1980; Nakanishi et al., 1981; Iidaka et al., 1990). Fukao et al. (1983), and later Hori et al. (1985), Hori (1990) and Ohkura (2000), detected seismic guided waves propagating within the oceanic crust of the Philippine Sea slab, which indicates that the oceanic crust remains untransformed to depths of at least ~60 km. These studies suggest that intraslab earthquakes in the Philippine Sea slab occur in the upper portion near the upper surface of the slab.

However, the configuration of the subducting Philippine Sea Plate beneath southwestern Japan remains poorly understood, primarily because only limited seismic activity is associated with subduction of this plate. Interplate earthquakes on the upper surface of the subducting plate are almost completely absent, meaning that reliable determination of the interface between the Philippine Sea Plate and the overlying continental plate is difficult. Moreover, simply regarding the upper envelope of intraslab seismicity as the upper plate interface is not a reliable approach, as indicated by seismic wide-angle reflection and refraction surveys undertaken along lines crossing the arc in the Tokai, Kinki, and Shikoku areas. These surveys suggested that the plate interface is several kilometers shallower than the upper limit of intraslab seismicity (Kodaira et al., 2000, 2002, 2004; Kurashimo et al., 2002; Ito et al., 2005).

Hirose et al. (2008a) used a double-difference tomography method (Zhang and Thurber, 2003) with arrival time data for earthquakes recorded by the Kiban seismic network in Japan to detect a layer with low S-wave velocity and high Vp/Vs, and located immediately above a region of intraslab seismicity in areas from Tokai to Kyushu in southwestern Japan. When this layer is compared with the upper interface of the Philippine Sea Plate estimated from the seismic reflection and refraction surveys, it becomes clear that this low-Vs and high-Vp/Vs layer represents oceanic crust of the Philippine Sea Plate (Fig. 3). Therefore, this layer can be used to reliably estimate the distribution of the upper interface of the subducting Philippine Sea Plate at depth; indeed, Hirose et al. (2008a) used this layer to determine the location of the upper interface of the Philippine Sea Plate at depths of 20–60 km across the entire area of southwestern Japan from Tokai to Kyushu, as shown by isodepth contours in Fig. 2. Here, the shallower portion of the subducting plate beneath the Pacific Ocean (isodepth contour of 10 km) was determined by Baba et al. (2002), who estimated the position of the upper interface of the Philippine Sea Plate using offshore seismic reflection and refraction surveys. In Fig. 2, the deeper portions (60–200 km) of the plate beneath Chubu and Chugoku-Kyushu represent the estimates of Nakajima and Hasegawa (2007), who determined the upper interface in the same area as the seismic tomography-derived upper envelope of the high-seismic-velocity slab.