Seismic structure of the northern end of the Ryukyu Trench subduction zone, southeast of Kyushu, Japan

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P-wave velocity models related to the Philippine Sea plate subduction have been obtained from seismic explorations at the northern end of the Nansei-Shoto (Ryukyu) Trench. Both multi-channel seismic reflection and ocean bottom seismographic records provide clear images of the rough seafloor topography and irregular P-wave velocity structure of the northwestern extension of the Kyushu-Palau Ridge and Amami Plateau below the landward trench slope. Low velocity ($V_p \leq$ 4–5 km/s) and thick (>7 km) materials above the plate boundary characterize the landward trench slope structure. An exception to this is found where the subducting plate contacts higher velocity ($V_p >$ 5 km/s) materials of the landward plate at the estimated position of the seismic asperity of 1968 Hyuganada earthquake (M_w 7.5).

Key words: Marine seismics, Ryukyu (Nansei Shoto) Trench, Kyushu-Palau Ridge, Philippine Sea plate subduction.

1. Introduction

The Philippine Sea (PHS) plate subducts beneath the Eurasian plate along the Nankai Trough and Nansei-Shoto (Ryukyu) Trench at a rate of about 5 cm/yr (Fig. 1). Magnitude 8-class earthquakes have occurred repeatedly along the Nankai Trough, while the largest earthquake ever recorded is at most M 7.6 along the northernmost Ryukyu Trench (e.g. The Headquarters for Earthquake Research Promotion, 2004). Several bathymetric highs, such as the Kyushu-Palau Ridge (KPR) and Amami Plateau, on the PHS plate are subducting in the region, which might be one of the causes for sizes of earthquake asperities and the difference in the maximum magnitude of earthquakes. Therefore, it is very important to obtain detailed seismic structural models related to these topographic irregularities for estimating earthquake asperities.

Except for a few seismic refraction experiments including Iwasaki *et al.* (1990) and Ichikawa (1997) in the northern end of the Ryukyu Trench, the number of seismic explorations is very small in this region compared to that in the Nankai Trough region. We, Japan Coast Guard, had carried out many ocean bottom seismographic (OBS) and multi-channel seismic (MCS) profiles to the south of Japan under the national continental shelf survey project. In this paper, we present P-wave velocity models related to the PHS plate subduction in the northernmost Ryukyu Trench region for four profiles (DAr2, DAr5, KPr1 and KPr2 in Fig. 1) among the continental shelf surveys.

2. Survey and Data Processing

The seismic experiments were conducted in 2005 and 2006 and the detailed information was described in cruise reports (Noda *et al.*, 2006; Tanaka *et al.*, 2008). We shot a tuned airgun array with a volume of 8,040 cubic inches (132 l) at an interval of 200 m for the wide-angle seismic profiles and at 50 m for the MCS (480 channels, 6000 m, 60 fold) profiles. The OBSs were deployed at an average interval of 5 km, which provided us dense data of high quality. Shot and OBS locations were provided by the ship's GPS navigation system, and each OBS was relocated using the direct water wave arrivals (Oshida *et al.*, 2008). The maximum distance between deployment and relocated positions was over 1 km due to the strong Kuroshio Current. The horizontal deviations from the profile, however, were at most 500 m and the OBS data with large horizontal offsets from the profile were used only as reference.

The procedure of data processing and velocity analysis in this study is same as Kasahara *et al.* (2007) and Nishizawa *et al.* (2007, 2009). Firstly, top-most sediment structure is modeled using MCS data. Then, we built P-wave velocity models by a tomographic inversion (tomo2d: Korenaga *et al.*, 2000) and forward modeling using a two-dimensional raytracing algorithm (Fujie *et al.*, 2000; Kubota *et al.*, 2009). To model reflection arrivals and low amplitude refraction signals at far offsets, we carried out forward modeling. In this paper, we estimated thick and low V_p upper crustal structure beneath the landward trench slope mainly by trial and error method.

The resolution and reliability of our velocity models were examined in two ways; one of them is a checkerboard test by the first arrival tomographic inversion. The size of grid interval in the tomography is same between model construction and checkerboard test, in which the horizontal grid spacing is 0.5 km and the vertical grid spacing gradually increases with depth according to the relation $0.05 + (0.01 * \text{depth (km)})^{1/2}$ km. We built a reference model by adding sinusoidal anomalies with a maximum amplitude of ±5%

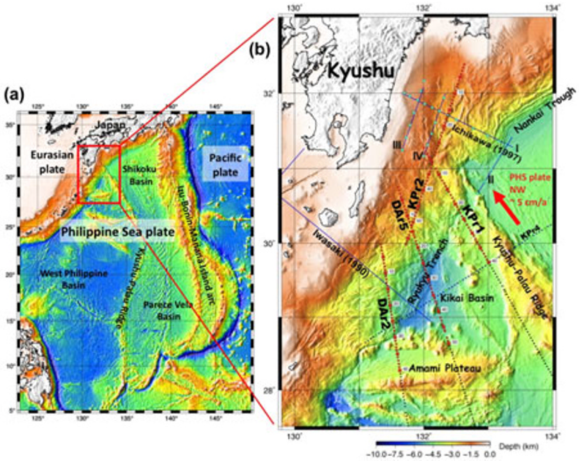

Fig. 1. (a) Tectonic map around the experimental area. (b) Location of the seismic profiles. In this paper, the P-wave velocity models are presented for four profiles shown by red dotted lines. Each red dot denotes a position of an OBS. Previous seismic explorations were carried out along blue lines (Iwasaki *et al*., 1990; Ichikawa, 1997).

to the our preferred final model. The resolution is indicated with the checkerboard pattern. In addition to checkerboard test results, we displayed ray coverage to represent model reliability. Higher ray density indicated better resolution.

In a final step, 2-D synthetic seismograms were calculated by a finite difference method, E3D (Larsen and Schultz, 1995) and compared with the observed field data.

The MCS data were processed by a conventional procedure. Depth converted sections were produced on the basis of the velocity models obtained from the OBS data. Pre-stack depth migration velocity analysis was carried out only on the limited area landward of the trench axis for KPr1. Other MCS sections for DAr2, DAr5 and KPr2 were obtained by post-stack migration analysis.

3. Results

3.1 Profile DAr2

Along DAr2, bathymetric highs belonging to the Amami Plateau are estimated to be subducting beneath landward slope of the Ryukyu Trench (Fig. 1). Figure 2(b) shows the P-wave velocity model showing subduction of several swells under the landward plate. The plate boundary (the top of the subducting PHS plate) is well imaged in the MCS depth-converted section in Fig. 2(a). Several OBSs at distances of 50–150 km recorded reflection signals from the plate boundary, which could constrain the depth of the boundary. Although the plate boundary was imaged as a velocity discontinuity in Fig. 2(b), we could not estimate the velocity of the top layer of the subducting plate. Thick low velocity materials with P wave velocity less than 5 km/s exist beneath the landward slope of the Ryukyu Trench. The maximum thickness of the wedge exceeds 12 km.

3.2 Profile DAr5

DAr5 transverses the Kikai Basin, Ryukyu Trench and landward trench slope. The crustal model at the northern end of the profile is not determined because of lack of rays propagating in the deeper region (Fig. 3(c, d)). Inhomogeneous and low $V_p < 4$ km/s materials with a thickness of about 7 km are estimated beneath the landward slope. The

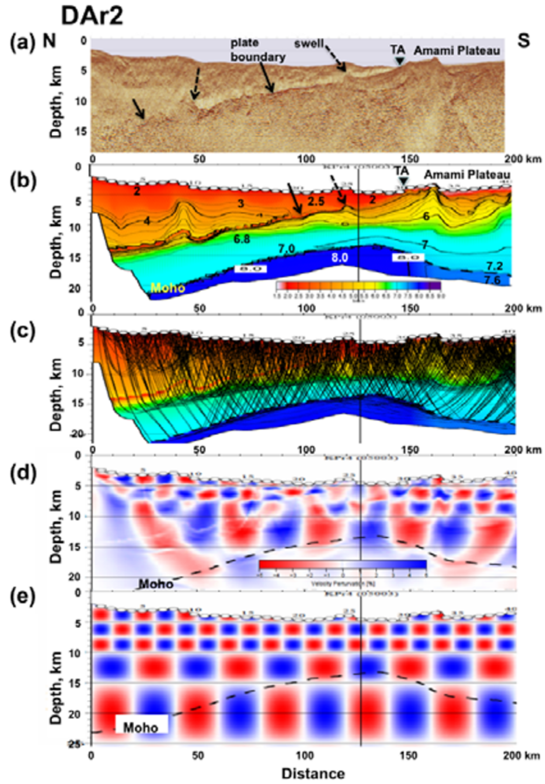

Fig. 2. (a) MCS depth converted profile for DAr2. Solid and dotted arrows show the top of the subducting PHS plate and swells on the plate, respectively. TA: trench axis. (b) P-wave velocity model derived from two-dimensional ray tracing and tomographic inversion. Circles show OBS position. Dashed line indicates Moho. Iso-velocity contours with an interval of 0.25 km/s are shown for the region with P-wave velocity larger than 3.5 km/s. The root-mean-square (RMS) misfits between the observed and calculated first-arrival travel times for the final model are 50 ms. Areas of no ray coverage are masked. (c) Ray geometry through the upper mantle. (d) The result of the checkerboard test for the test pattern shown in (e). The checkerboard test pattern of the velocity anomalies is recovered well in the crust when the Moho depth is shallower than 15 km. (e) The checkerboard test pattern for profile DAr2. Same pattern is used for other profiles except for the bathymetry. Vertical line at a distance of 130 km indicates the position across the profile KPr4 (Fig. 1).

plate boundary is clearly traced at distances of 70–150 km in both the MCS section and V_p model (Fig. 3(a, b)). The crustal structure inside the subducting PHS plate is irregular, especially at distances of 80–130 km in Fig. 3(b) characterized by thicker crust, higher V_p at the bottom of the crust, and lower V_p at the uppermost mantle than in a typical oceanic crust/uppermost mantle. The ray diagram in Fig. 3(c) and result of the checkerboard test in Fig. 3(d) indicate these irregularities are certain.

3.3 Profile KPr1

KPr1 is parallel to the KPR axis and is positioned to the west of the KPR bathymetric peaks. The top of the subducting plate beneath the landward slope of the trench can be traced in the pre-stack depth migration section of the MCS records in Fig. 4(a). Low $V_p < 4$ km/s materials prevail under the landward slope and thicken toward the north. Several OBS records showed small amplitude or invisible first arrivals propagating through the area shown by an ellipsoid in Fig. 4(b). Synthetic seismograms with assumed V_p of 3.2–3.3 km/s in the ellipsoid could explain

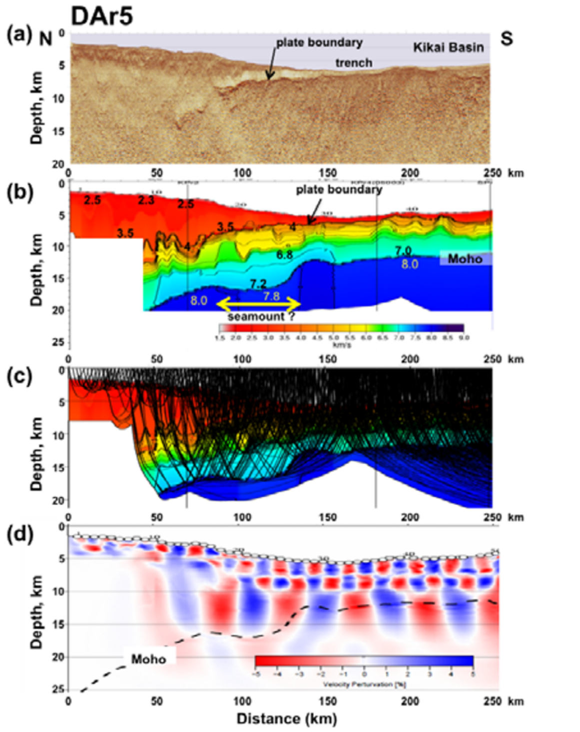

Fig. 3. (a) MCS depth converted profile for DAr5. (b) P-wave velocity model. (c) Ray geometry. (d) Checkerboard test result.

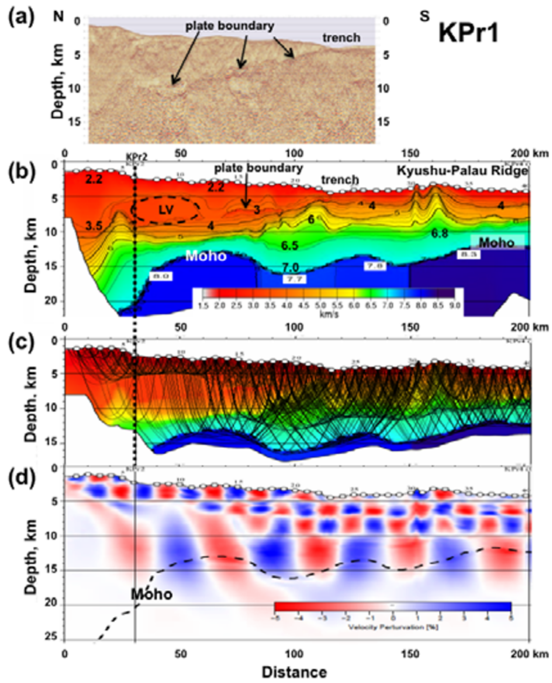

Fig. 4. (a) MCS pre-stack depth migration profile for KPr1. (b) P-wave velocity model. A dashed ellipsoid indicates an estimated low velocity area. (c) Ray geometry. (d) Checkerboard test result. Vertical dotted line indicates the position across the profile KPr2.

the observed record sections. V_p in the upper crust of the small bathymetric highs on the KPR at distances of 150–160 km is higher than that of adjacent region and the crust is rather thick there. The crustal thickness of the subducting plate shows several undulations.

3.4 Profile KPr2

KPr2 is positioned along the landward slope off Kyushu. The depth of the plate boundary could be estimated by intermittent reflections in the MCS record in Fig. 5(b) to a depth of around 10 km within distances of 180 km from the southwestern end of the profile. Only the region shallower than 5 km could be determined by the first arrival tomographic inversion. Because of very few first arrivals propagating in the deeper part with thick and low velocity, we mainly conducted forward modeling using later arrivals both of refraction and reflection. Many OBSs recorded relatively clear Moho reflections in the subducted PHS plate. Estimating the fitting error between observed and calculated travel times is difficult, but in most cases the fitting errors for clear signals are within 0.1 s. The V_p model in Fig. 5(c) is roughly consistent at the intersection with KPr1 and DAr5 with each other. More than 7 km thick and $V_p \leq 4$ km/s materials exist along profile KPr2 except for the northeastern region, where the inferred plate boundary becomes deeper and higher $V_p > 5.0$ km/s materials are placed at shallower depths and are in contact with the subducted slab.

Another significant feature of the model is that materials with $V_p = 6.0$–6.8 km/s at distances of 130–170 km are thicker than the neighboring area. In the region, the Moho depth tends to be deeper toward distances around 150 km and P_n velocity tends to be slower. This feature is located where the northwestern extension of the KPR topographic peak intersects the trench axis and outer subducted wedge (Fig. 5(a)).

4. Discussion

We have presented P-wave velocity models related to the PHS plate subduction for four seismic transects at the northern end of the Ryukyu Trench. Noteworthy characteristics for the P-wave velocity models in this region are as follows:

1. Thick (7–12 km) and low velocity ($V_p < 4$–5 km/s) materials prevail beneath the landward trench slope. Structures of the low V_p regions vary horizontally and sometimes show velocity inversion with depth. This is consistent with the previous results by Iwasaki *et al.* (1990) and Ichikawa (1997).

2. The top position of the subducting PHS plate can be traced continuously, especially in the MCS records. Two swells on the subducting plate boundary at 40–50 km and 125 km from the north end of DAr2 (Fig. 2(a, b)) seem to belong to the bathymetric highs of the Amami Plateau. The V_p model within the subducting PHS plate at distances 80–130 km on DAr5 shows thicker crust, higher V_p at the bottom of the crust, and lower P_n velocity than those of a normal oceanic crust/uppermost mantle. This is similar to the structure of seamounts and other bathymetric highs (e.g. Nishizawa *et al.*, 2009). Iwasaki *et al.* (1990) illustrated a severe undulated basement of the subducting plate along the profile intersect with DAr2. These results indicate the subducting plate in this region does not have a simple oceanic crust but paleo-arc crust such as Amami Plateau and KPR. This is different from the typical oceanic crust subduction at the middle Ryukyu Trench (Kodaira *et al.*, 1996).

A thicker mid crust with $V_p = 6.0$–6.8 km/s, probably lower P_n velocity, and deeper Moho detected at distances of 130–170 km under the landward trench slope along KPr2

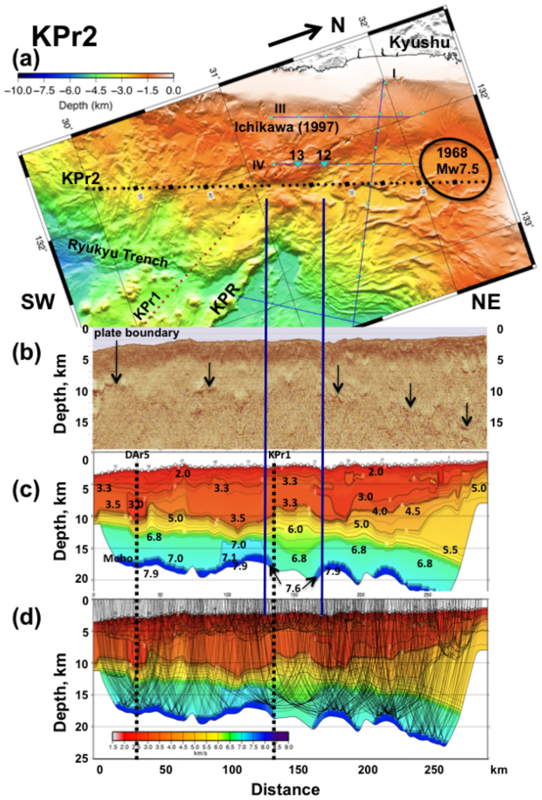

Fig. 5. (a) Shaded bathymetry around KPr2. An ellipsoid indicates the 1968 Hyuganada Earthquake (M_w 7.5) source area estimated by Yagi *et al.* (1998). Ichikawa (1997) modeled a high velocity upper crust beneath OBS 12 and 13 (blue inverse triangles) along profile IV. (b) MCS depth converted profile for KPr2. Arrows show the inferred top positions of the subducting PHS plate. (c) P-wave velocity model. (d) Ray geometry. A bathymetric high of the subducted KPR is estimated in the area between two blue vertical lines. Vertical dotted lines indicate the positions across the profile DAr5 and KPr1.

in Fig. 5(c) correspond to the northwestern extension of KPR and may be related to the subducted KPR crust on the PHS plate. The upper crust for Line IV of Ichikawa (1997) has higher velocities at the area between OBS12 and 13 in Fig. 5(a), which may also show the KPR crust.

3. At the northeastern end of KPr2, the plate boundary is inferred to become deeper than 15 km in Fig. 5(b), where the profile reaches to the source area of the 1968 Hyuganada Earthquake (M_w 7.5) estimated by Yagi *et al.* (1998) and is shown by an ellipsoid in Fig. 5(a). The top of the subducting PHS plate contacts the landward materials with $V_p > 5$ km/s in this region. It is unknown the $V_p > 5$ km/s materials compose some sort of structural irregularities such as seamounts. The $V_p > 5$ km/s materials may form the Kyushu arc crust landward of the backstop where updip limit of the seismogenic zone along the subducting plate boundary coincides to the higher velocity of arc crusts.

The magnitude-7 class earthquake source regions other than the 1968 event are positioned landward of the KPr2 (The Headquarters for Earthquake Research Promotion, 2004) and we could not find the relationship between the velocity structure and source regions. Yagi *et al.* (1998) suggested that the rupture area of 1968 Hyuganada Earthquake is limited by fracture of the subducting slab. Such structural heterogeneity including bathymetric highs of the KPR and Amami Plateau might one of the possible reasons why magnitude-8 class earthquakes have not occurred in this region. We need three-dimensional data to declare the structural heterogeneity of the source area.

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References

Fujie, G., J. Kasahara, T. Sato, and K. Mochizuki, Traveltime and raypath computation: A new method in a heterogeneous medium, *J. Soc. Explor. Geophys. Jpn.*, **53**, 1–11, 2000.

Ichikawa, G., Ocean bottom seismographic experiment to study crustal structure in Hyuga-nada, Master's Thesis, Hokkaido University, Sapporo, Japan, 1997 (in Japanese).

Iwasaki, T. *et al.*, Crustal and upper mantle structure in the Ryukyu Island Arc deduced from deep seismic sounding, *Geophys. J. Int.*, **102**, 631–651, 1990.

Kasahara *et al.*, A new integrated method for the crustal structure analysis using OBSs and control sources, *Eos Trans. AGU*, **88**(52), Fall Meet. Suppl., Abstract S12A-06, 2007.

Kodaira, S., T. Iwasaki, T. Urabe, T. Kanazawa, F. Egloff, J. Makris, and H. Shimamura, Crustal structure across the middle Ryukyu trench obtained from ocean bottom seismographic data, *Tectonophysics*, **263**, 39–60, 1996.

Korenaga, J., W. S. Holbrook, G. M. Kent, P. B. Kelemen, R. S. Detrick, H.-C. Larsen, J. R. Hopper, and T. Dahl-Jensen, Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography, *J. Geophys. Res.*, **105**, 21591–21614, 10.1029/2000JB900188, 2000.

Kubota, R., E. Nishiyama, K. Murase, and J. Kasahara, Traveltime estimation of first arrivals and later phases using the modified graph method for a crustal structure analysis, *Explor. Geophys.*, **40**, 105–113, 2009.

Larsen, S. C. and C. A. Schultz, ELAS3D: 2D/3D elastic finite-difference wave propagation code, *LLNL internal report*, 18 p., 1995.

Nishizawa, A., K. Kaneda, Y. Katagiri, and J. Kasahara, Variation in crustal structure along the Kyushu-Palau Ridge at 15–21°N on the Philippine Sea plate based on seismic refraction profiles, *Earth Planets Space*, **59**, e17–e20, 2007.

Nishizawa, A., K. Kaneda, N. Watanabe, and M. Oikawa, Seismic structure of the subducting seamounts on the trench axis: Erimo Seamount and Daiichi-Kashima Seamount, northern and southern ends of the Japan Trench, *Earth Planets Space*, **61**, e5–e8, 2009.

Noda *et al.*, Preliminary report of multi-channel and wide-angle seismic surveys at the northern Kyushu-Palau Ridge (KPr4), the Daito Ridge and Amami Plateau (DAr2) and the mid Shikoku Basin (SPr7), *Technical Bull. Hydrogr. Oceanogr.*, **42**, 2006 (in Japanese).

Oshida, A., R. Kubota, E. Nishiyama, J. Ando, J. Kasahara, A. Nishizawa, and K. Kaneda, A new method for determining OBS positions for crustal structure studies, using airgun shots and precise bathymetric data, *Explor. Geophys.*, **39**, 15–25, 2008.

Tanaka *et al.*, Preliminary report of multi-channel and wide-angle seismic experiments in the vicinity of Kyushu-Palau Ridge (KPr1, KPr2 and SPr10) and traversing the Minami Daito Basin, Daito Ridge and Kyushu-Palau Ridge (DAr5), *Technical Bull. Hydrogr. Oceanogr.*, **44**, 2008 (in Japanese).

The Headquarters for Earthquake Research Promotion, Evaluations of occurrence potentials of subduction-zone earthquakes to date, http://www.jishin.go.jp/main/chousa/04feb_hyuganada/index.html, 2004 (in Japanese).

Wessel, P. and W. H. F. Smith, New, improved version of the Generic MappingTools released, *Eos Trans. AGU*, **79**, 579, 1998.

Yagi, Y., M. Kikuchi, S. Yoshida, and Y. Yamanaka, Source Process of the Hyuga-nada earthquake of April 1, 1968 (Mjma 7.5), and relationship to the subsequent seismicity, *Zisin*, **51**, 139–148, 1998 (in Japanese with English abstract).

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