JAMSTEC Report of Research and Development, Volume 3, March 2006, 31 – 42

Subsurface Structure of the "Petit-spot" Intra-plate Volcanism, in the Northwestern Pacific

Toshiya Fujiwara[1], Naoto Hirano[2], Natsue Abe[1], and Kaoru Takizawa[1]

Abstract Single-channel seismic reflection surveys were conducted in the northwestern Pacific to investigate subsurface structure and nature of volcanic eruption of small volcanic knolls considered to be formed by "petit-spot" intra-plate volcanism, and also morphology of a sedimentary basin and oceanic basement around the knolls in the area. Seismic profiles reveal the sedimentary layer is acoustically transparent, having some horizontal reflectors within the layer. Oceanic crust of the Pacific Plate lies flatly beneath the sedimentary layer with nearly constant thickness of ~200-300 m. The layer beneath the small knolls is acoustically opaque, possibly caused by inhomogeneous structure due to feeder dykes or cryptodome and volcanic deposits. Strong reflectors at base of the sedimentary layer, identified in the vicinity of small knolls, are probably reflections from volcanic sills. The oceanic crust beneath the small knolls is depressed by weight of the volcanic deposits.

Keywords: Petit-spot, Intra-plate volcanism, Northwestern Pacific, Seismic reflection

1. Introduction

A prologue of our study was a discovery in 1997. *ROV Kaiko* sampled basalts on a seaward slope of the Japan Trench at 39.5°N, off Sanriku in the northeastern Japan (Figure 1). The basalts were anomalously young (~6 Ma) alkali basalts [Hirano et al., 2001]. This substantial discovery suggests that intra-plate volcanism occurs and new volcanoes are built on the ~130 Ma old, consequently cool and thick, oceanic lithosphere. To validate this hypothesis, we have carried out geological and geophysical surveys in the northwestern Pacific in 2003-2005 [Abe et al., 2005]. The survey area locates in ~600 km upstream of the Pacific Plate motion [DeMets et al., 1990] away from the *Kaiko* sampling site in the Japan Trench. As a result of detailed bathymetric survey, we found small knolls, with 2-3 km in diameter and <100 m in relative height, situated on ~6000 m deep seafloor. Alkali basalts were collected from one of the small knolls, and the rock's ages indicated <1 Ma [Hirano et al., 2005]. That was confirmation of the intra-plate volcanism, and then we termed "petit-spot" as the small-scale volcanism. In this paper, we present descriptive results of single-channel seismic reflection surveys aboard R/Vs *Yokosuka* (cruise ID: YK05-06) and *Kairei* (KR05-10) conducted in 2005. The aim of the seismic surveys was to provide subsurface structure of these volcanic knolls and nature of volcanic eruption of the "petit-spot".

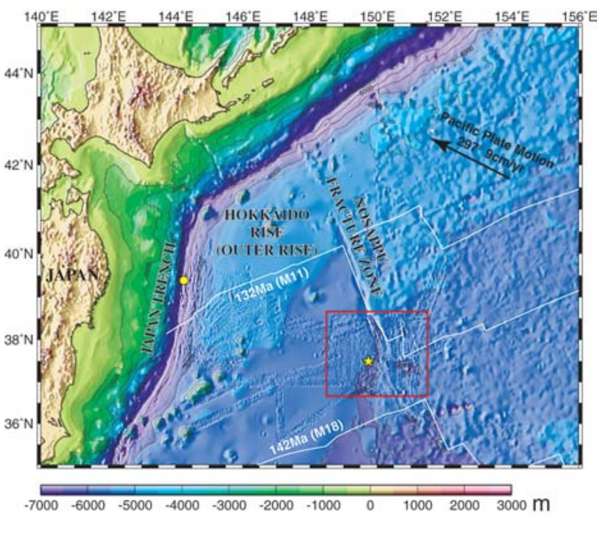

Figure 1: Index map of the survey area. Bathymetric data are from our swath bathymetry, JTOPO30 (west of 150°E), and ETOPO2 (east of 150°E). The red square shows the survey area. A circle points the sampling site where ROV *Kaiko* has collected ~6 Ma aged basalts. A star points the 6K#877 Knoll where we collected <1 Ma aged basalts. Solid lines indicate crustal age identified magnetic isochrons.

2. Geological Background

The survey area is situated in a regional topographic low on the east of outer-rise of the Japan Trench (Figure 1). In the center of the survey area, the Nosappu Fracture Zone, which is considered as a paleo-transform fault [Nakanishi, 1993], is extending in the direction of NNW-SSE. The survey area has a series of parallel magnetic anomalies (Japanese Lineation Set) in the direction of WSW-ENE. In the west of the fracture zone, the mag-

1 Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
2 Department of Earth Planetary Sciences, Tokyo Institute of Technology

netic lineations are identified as chron M12-M15, as for the east of the fracture zone, M10N-M11 is identified [M. Nakanishi, personal communication, 2005]. Therefore, the crustal age varies from ~135 Ma to ~140 Ma (Early Cretaceous) [Gradstein et al., 2004].

During all research cruises, swath bathymetric data were collected using a SeaBeam 2112 multi-narrow beam echo sounder. The survey area is typical for deep ocean, water depths of 4700-6300 m (Figure 2). Morphology of the Nosappu Fracture Zone, in the northern portion of the survey area, shows a double line of grabens and a ridge between the grabens. In the middle portion, the fracture zone becomes wider and topographic relief becomes lower. Topographic high with *En echelon* ridges are found in the south. The detailed bathymetry depicts small knolls with a few km in diameter and <100 m in relative height are distributed in a sedimentary basin in the west of the fracture zone. High backscatter intensity at these knolls suggests that little sediment covered, thus hard igneous rocks exposed (Figure 3). *Shinkai 6500* submersible dives (dive ID: 6K#877-#879) were performed at some of the knolls. The basin was fully covered with soft pelagic sediment. Pillow lavas and robes outcropped along the slope of the knolls. The outcrops were limited around summits of the knolls [Machida et al., 2005]. One of the knolls intensively surveyed is named the 6K#877 Knoll, located at 149°45'E, 37°30'N in 5900 m water depth. Sampled rocks from the knoll indicate the volcanic edifice consists of porous alkali lavas containing abundant mafic xenocrysts and xenolith fragments of gabbros and mantle peridotites in rare case. Petrological and geochemical data suggest the alkali basalts are similar to Mid-ocean Ridge Basalt (MORB) with a small melt fraction rather than Oceanic Island Basalt (OIB) that is hotspot and mantle plume origin. These rocks are inferred to originate from a base of the lithosphere or athenosphere ~100 km below the seafloor [Hirano et al., 2005].

These knolls are commonly surrounded by moats, and the deepest places of the moats are at the northwest or north of the knolls (Figure 4). Possible explanations for origin of these moats include collapse calderas, explosion craters of volcanoes, erosional sedimentary layer by deep-sea currents, or a combination of these.

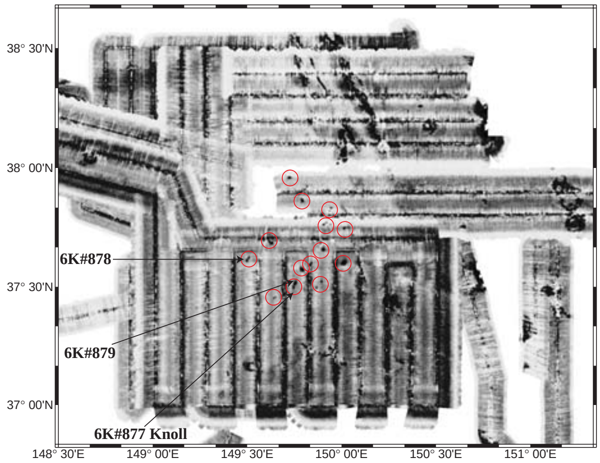

Figure 3: SeaBeam backscatter image of the survey area. Dark color indicates high backscatter intensity. Red circles enclose small knolls with high backscatter intensity.

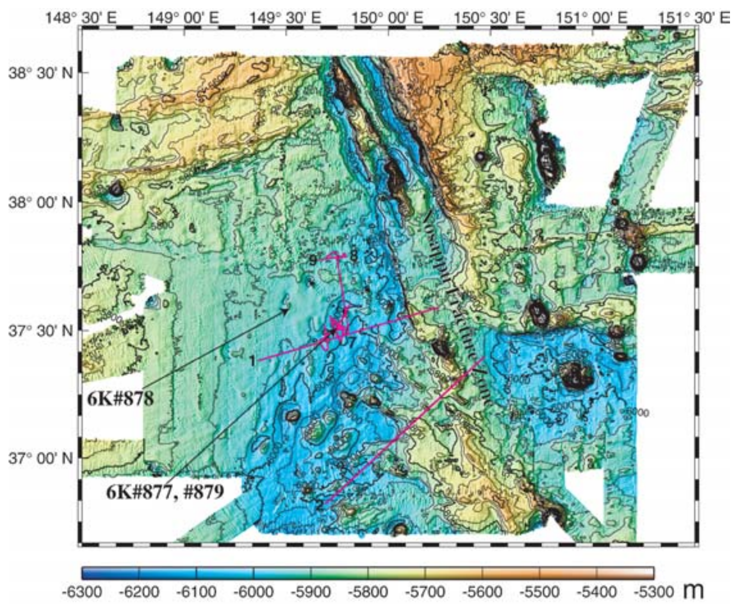

Figure 2: SeaBeam bathymetric map of the survey area gridded at 100 m. Contour interval is 50 m. Solid lines delineate single-channel seismic reflection survey lines annotated in line numbers.

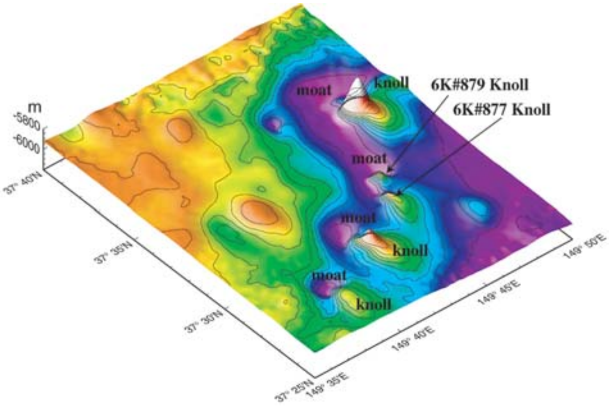

Figure 4: Bathymetric whale eye's view around the 6K#877 Knoll. Vertical scale is arbitrary.

3. Data Collection and Data Processing

Seismic data were collected in the nighttime during the cruises: 2 days of field operations in YK05-06 and 3 days in KR05-10, respectively. A total survey of 350 km was completed. A GI gun (true GI mode: Generator: 250 cu in., Injector: 105 cu in.) with air-pressure of 14.0 MPa was used for a seismic source. The GI gun was towed 30 m behind the ship and towing depth was ~3.5 m. A streamer, which consists of a 65 m active section with 48 hydrophones and a 200 m leading cable, was towed behind the ship. Towing depth of the streamer was 5-10 m. In YK05-06, shooting was distance-mode which was 60 meters with a ship speed of ~4 knots. In KR05-10, survey ship speed was ~4 knots, and shots were fired at a time spacing of 15 seconds (~30 m spacing) for Line-1, 12 seconds (~23 m spacing) for Line-2, and 10 seconds for Line-3~9 (~20 m spacing).

In YK05-06, the survey consists of two cross track lines of 9-15 km in length (Figure 5). The cross tracks were designed to run along the long- and short-axis of the small knolls to evaluate their volume and shape. Even the diameter of the knolls is a few km, the track length of >9 km is necessary because the subsurface structure of the knolls might have similar figures to the surface appearance, that is just "the tip of the iceberg". A point is one of the cross lines is designed to pass the deepest places of the moats appearing accompanied with the knolls (Figure 4). In KR05-10, the seismic survey consists of two long lines crossing the Nossapu Fracture Zone and seven lines crossing the small knolls and moats (Figures 2 and 5). Line-1, with a length of 80 km, passes the south of the 6K#877 Knoll in the sedimentary basin, and crosses the western boarder of the fracture zone in the middle portion of the survey area. Line-2, with a lengh of 90 km, crosses the fracture zone and goes through *en echelon* ridges in the south. Line-3~9 cross small knolls or moats.

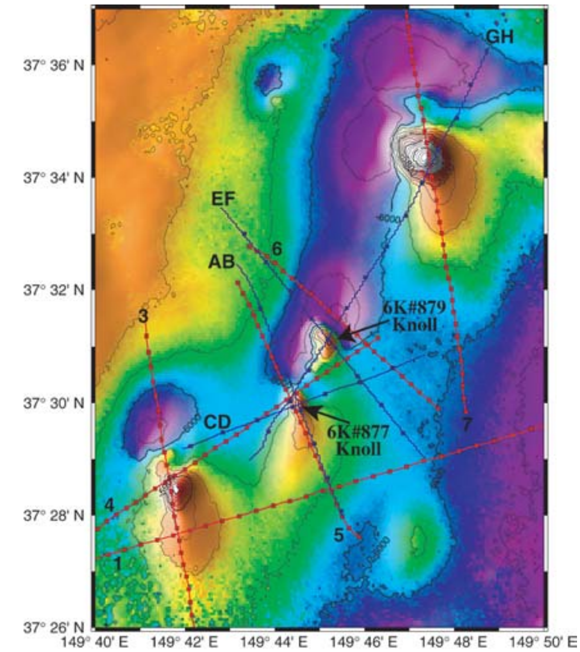

Figure 5: Closeup view of survey tracks around the 6K#877 Knoll. Red lines are tracks acquired during KR05-10, and blue lines are for YK05-06, respectively. Squares are marked at every 20 shots. Bathymetric contour interval is 25 m.

The seismic data were processed using ProMAX2D software. The data were processed through the following sequence: datum correction to mean sea level, amplitude recovery, predictive deconvolution, bandpass filter (25-180 Hz), kirchhoff time migration, and auto gain control (4.0 sec window).

4. Results

4.1 Sedimentary Layer and Basement Morphology

Resultant seismic profiles are shown in Figures 6-16, and features of sedimentary layers and basement morphology are well characterized in Line-1 and Line-2 (Figures 6 and 7). Reflections from the seafloor are commonly weak in amplitude (e.g., Figure 6). The result suggests sediment, lying beneath the seafloor, is unconsolidated or semi-consolidated. The sedimentary layer is found to be acoustically transparent. Some horizontal reflectors are identified within the sedimentary layer. More or less 0.2-0.3 sec two-way travel time (TWT) below the seafloor, flat, continuous, and high amplitude reflection signatures are identified (Figures 6-16). These acoustic basements are presumed to represent top surface of oceanic igneous crust of the Pacific Plate. Therefore, the seismic profiles indicate sediment thickness of ~200-300 m, if an average velocity of 2000 m/s in the sedimentary layer is assumed to calculate a depth scale. The thickness is comparable to a general value of other the

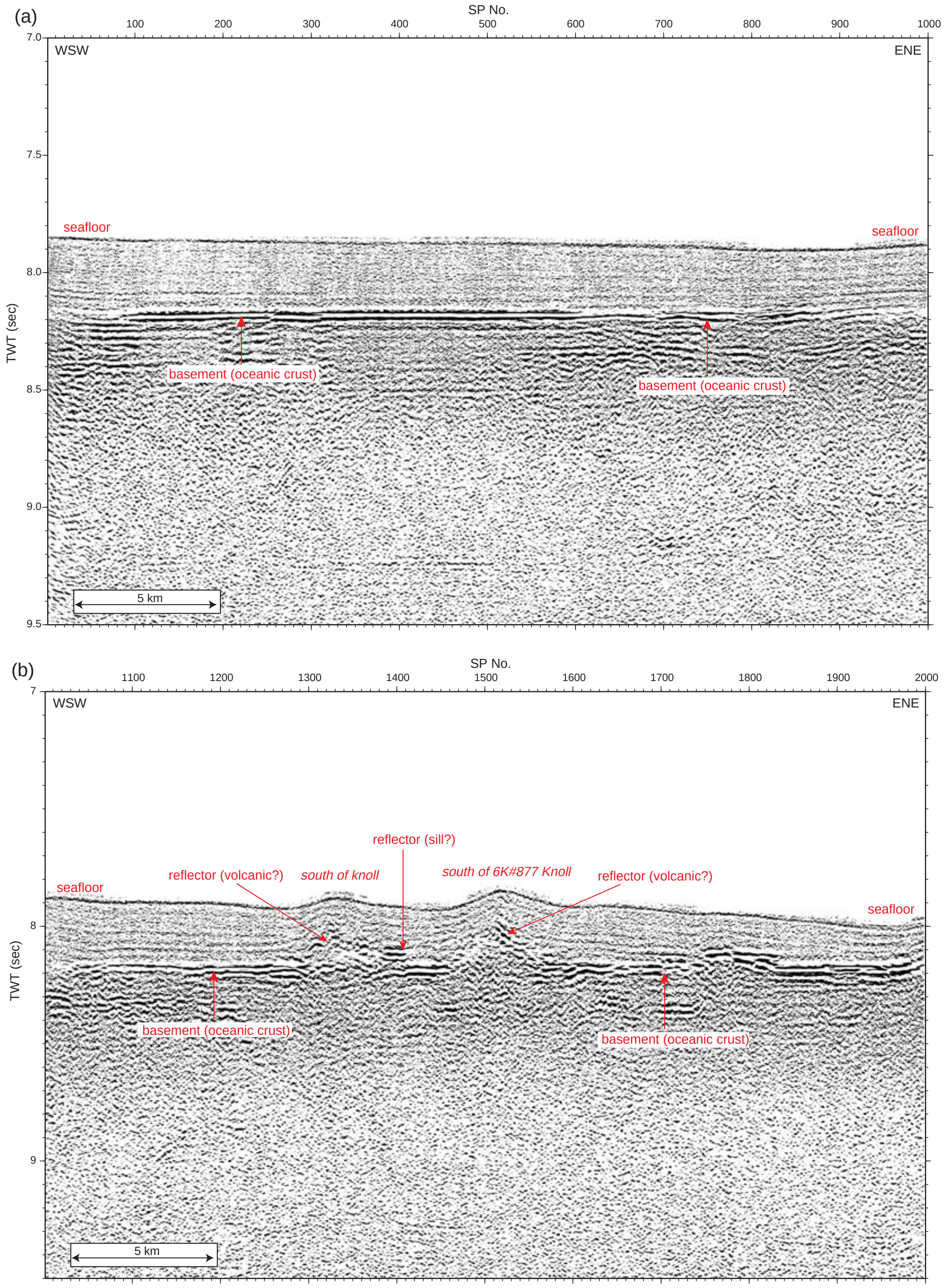

Figure 6: Seismic profile of KR05-10 Line-1. Horizontal axis indicates trace of shot numbers and vertical axis indicates two-way travel time (TWT: sec). The profile shows a cross section of the Nosappu Fracture Zone and the sedimentary basin to the west, in the direction of WSW-ENE. (a) westernmost section (shot: 0-1000), (b) middle section (shot: 1000-2000), and (c) easternmost section (shot: 2000-3000).

northwestern Pacific basins [e.g., Divins, 2001].

In Line-1, the sedimentary layer is found to be relatively thin at topographic highs in the Nosappu Fracture Zone (Figure 6). At the western boarder of the fracture zone, the basement is offset by ~0.3 sec TWT, and the eastern basement is elevated. Within the eastern sedimentary layer, seismic reflectors indicating strata in the lower section are tilted toward the offset. This result suggests that the eastern crustal block has suffered uplift movement at the offset by succeeding tectonism. In

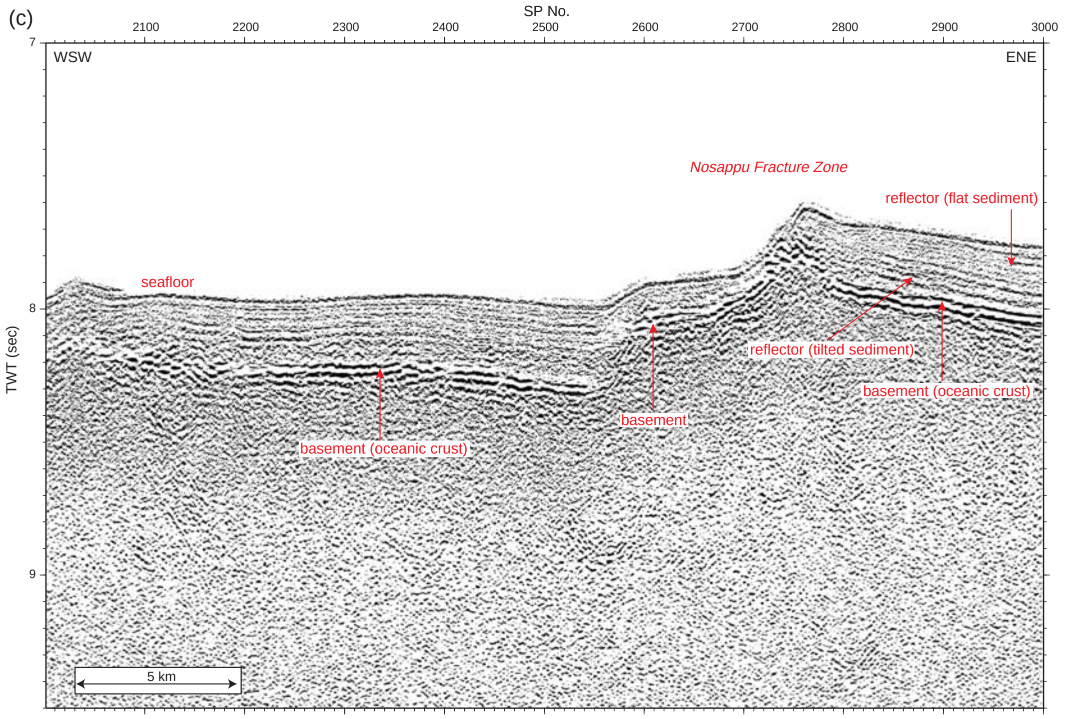

Figure 6: (continued).

Line-2, beneath topographic highs in the *en echelon* ridges in the fracture zone, seismic reflectors of oceanic basement are found in shallow depth associated with seismic diffraction waves (Figure 7). Beacuse a thin sedimentary layer covers the basement, the seamounts in the *en echelon* ridges could be old and these ridges and seamounts could be not recent constructions by "petit-spot".

Line-1 is passing the south of the 6K#877 Knoll and other knolls. At such places of the small knolls, seismic reflection patterns of the basements are disorganized. It may suggest that the oceanic crust was deformed by "petit-spot" volcanism. Reflection patterns in the small knolls will be discussed the next section.

In addition, regarding seismic reflectors below the basement, reflectors dipping toward southwest beneath the basement are identified in places in Line-2 (Figure 7). The reflectors may indicate normal faults of oceanic crust. Somewhat horizontal lying seismic reflectors at ~0.8 s TWT beneath the basement are found in places, however these reflectors are unexplained.

4.2 Subsurface Structure of Small Knolls

The seismic profiles show most of all small knolls have similar appearance, thus similar in subsurface structure (Figures 7, 8, 9, 10, 11, 12, 14, 15, and 16). First of all, there is no dipping seismic reflectors extending from foot of the small knolls at the seafloor, which would indicate broad slopes of seamounts within the sedimentary layer. Therefore, we can conclude the small knolls are not "the tip of the iceberg" of buried big seamounts.

Appearance of irregular seismic patterns is limited in width of the surface volcanic edifices of the small knolls (a few km). In the portion of the knolls, seafloor reflectors are too unclear to distinguish likely due to topographic steep gradient (e.g., Figures 10 and 12). The sedimentary layer beneath the knolls is acoustically opaque. Seismic waves scattering and diffraction waves in the opaque sections indicate the sections contain vertically and horizontally inhomogeneous structures. In some places within sediments, seismic reflectors with high-amplitudes are also visible (e.g., Figures 10 and 12). Possible explanation of the inhomogeneous structure and the strong reflector is caused by volcanic dykes and/or volcanic deposits intruded in the sedimentary layer.

Horizontally lying strong reflectors within the sedimentary layer are often identified in the vicinity of small knolls up to ~0.1 sec TWT above the oceanic basement (e.g., Figures 10 and 12). These are probably reflections from sheet-like volcanic edifices related to the small knolls. Although volcanic sills are more likely because the reflectors are associated with existence of the volcanic knolls, the presence of chert layers cannot be ruled out. Chert layers can produce such horizontally lying strong reflections, and these are known for widely destribution in the western Pacific.

Reflectors of the oceanic basement dip downward at the knolls (e.g., Figures 10 and 12). The oceanic base-

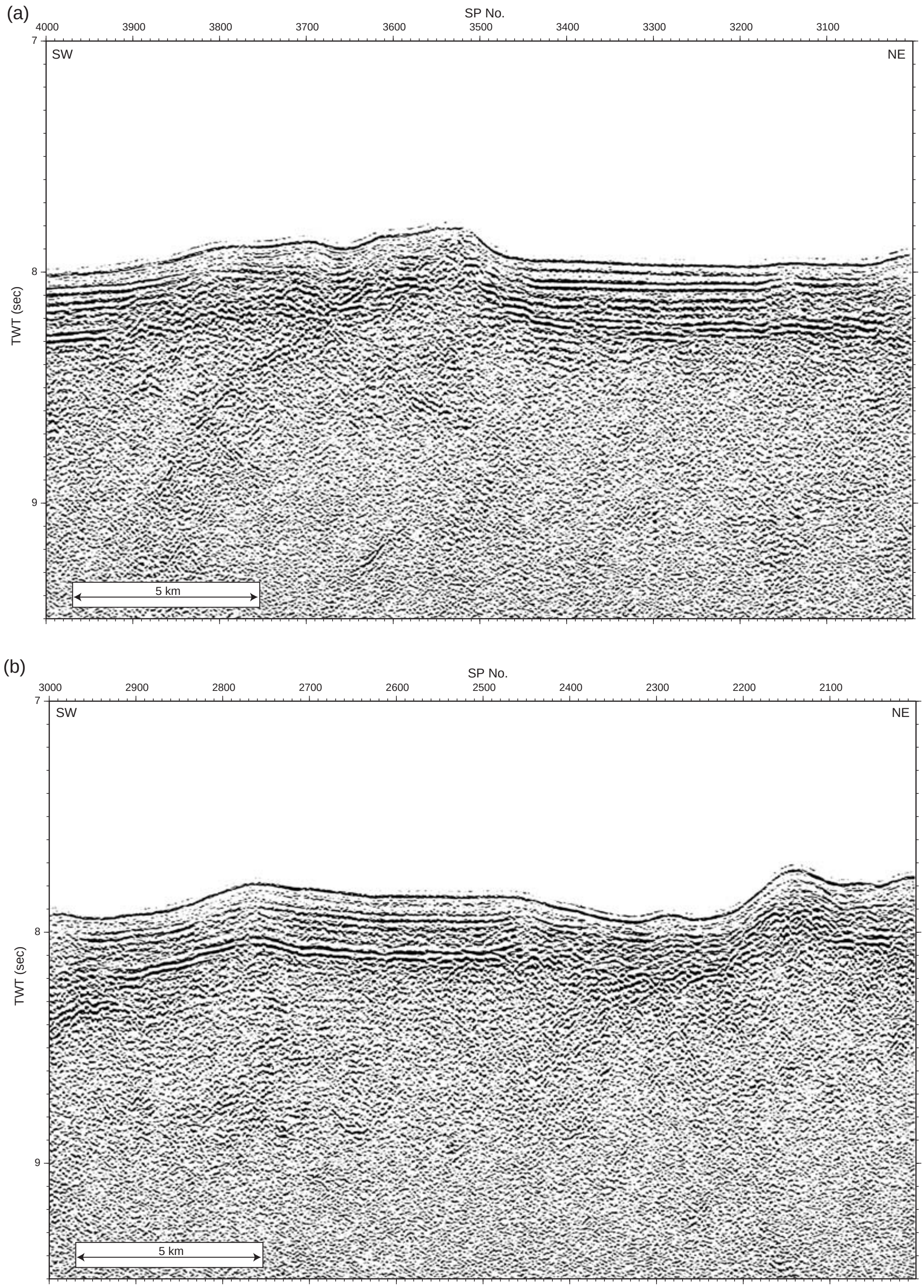

Figure 7: Seismic profile of KR05-10 Line-2. The profile shows a cross section of the Nosappu Fracture Zone and the sedimentary basin to the west, in the direction of SW-NE. (a) westernmost section (shot: 4000-3000), (b) middle-western section (shot: 3000-2000), (c) middle-eastern section (shot: 2000-1000), and (d) easternmost section (shot: 1000-0).

ments would be depressed by weight of the volcanic deposits.

Below the moats associated with small knolls, although the seafloor is concave, the seismic reflectors of strata within the sedimentary layers still appear to remain horizontally (e.g., Figure 10). This result suggests that the subsurface sedimentary layers preserve original horizontal bedding. Therefore these moats may be formed by erosion by deep-sea currents [e.g. Mitsuzawa and Holloway, 1998].

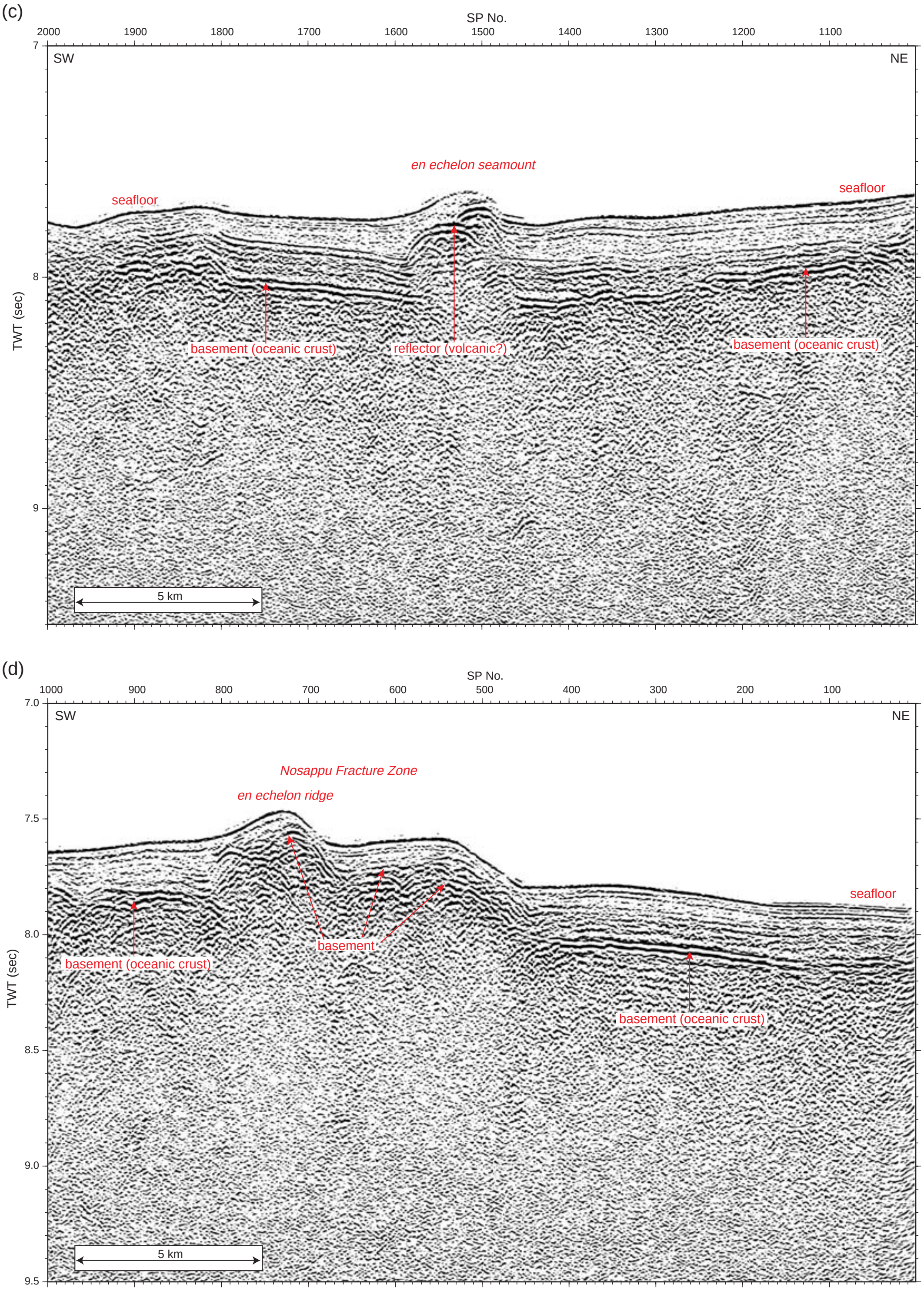

Figure 7: (continued).

5. Discussion

Our seismic surveys provide snapshots of the subsurface structure and the nature of volcanic eruption of "petit-spot" (Figure 17). That is, a small amount of magma injected into the sedimentary layer. A part of the lava flowed horizontally within the sedimentary layer and formed volcanic sills. Total thickness of sill formation may reach up to 100 m. The lava flow also formed feeder dyke or cryptodome in the sedimentary layer, erupted on the seafloor, and built the small knolls with 2-3 km in diameter and <100 m in relative height. In order to form such volcanoes, fissure eruption volcanism as the magma supply is possible. However, structural continuity between the small knolls remains unclear,

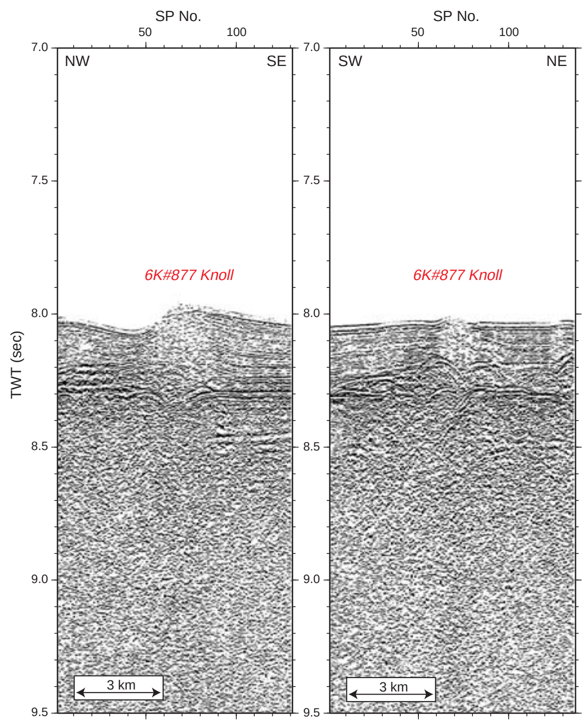

Figure 8: Seismic profile of YK05-06 Line-AB (left). The profile shows a cross section along the long-axis of the 6K#877 Knoll. The right shows seismic profile of YK05-06 Line-CD. The profile shows a cross section along the short-axis of the 6K#877 Knoll.

thus strikes and length of the fissures and the direction of stress field are unknown.

The implication, that total amount of magma is small, is supported by other geophysical observations conducted during our research cruises [Fujiwara et al., 2005]. Basaltic rocks sampled from the 6K#877 Knoll were found to have strong natural remnant magnetization (up to ~60 A/m) [Obi et al., 2005]. Thus, "petit-spot" volcanism may produce particular magnetic anomaly, if large volume of such basalts are extruded and/or intruded. However, original magnetic lineation patterns and amplitudes of the magnetic anomaly apparently are not disorganized by such the newly volcanism. This result suggests that magnetic anomaly due to the newly volcanism is not enough strong to obscure the magnetic anomaly lineation produced by magnetization recorded on the old oceanic crust. And in addition, the newly tectonism has not destroyed the magnetized layer in the old oceanic crust.

Bouguer gravity anomaly shows almost no local variation in the survey area [Fujiwara et al., 2005]. The Bouguer gravity anomaly indicates subsurface density variations. Because the sedimentary layer has nearly constant thickness in the survey area, to a first order, the gravity anomaly variation could be due to crustal thickness variation. The gravity result, therefore, suggests

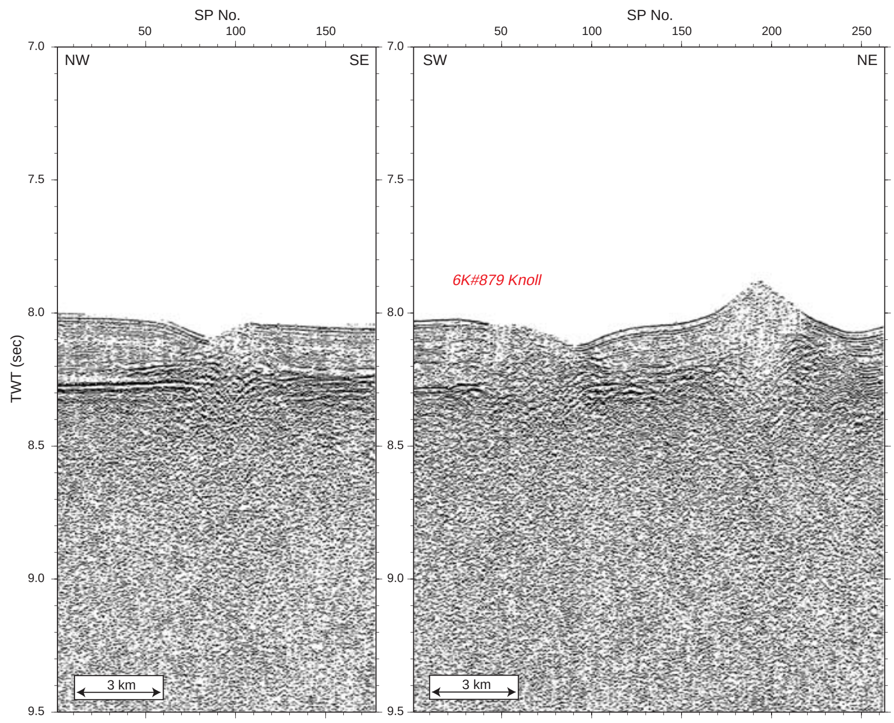

Figure 9: Seismic profile of YK05-06 Line-EF (left). The profile shows a cross section along the long-axis of a small knoll. The right shows seismic profile of YK05-06 Line-GH. The profile shows a cross section along the short-axes of two small knolls.

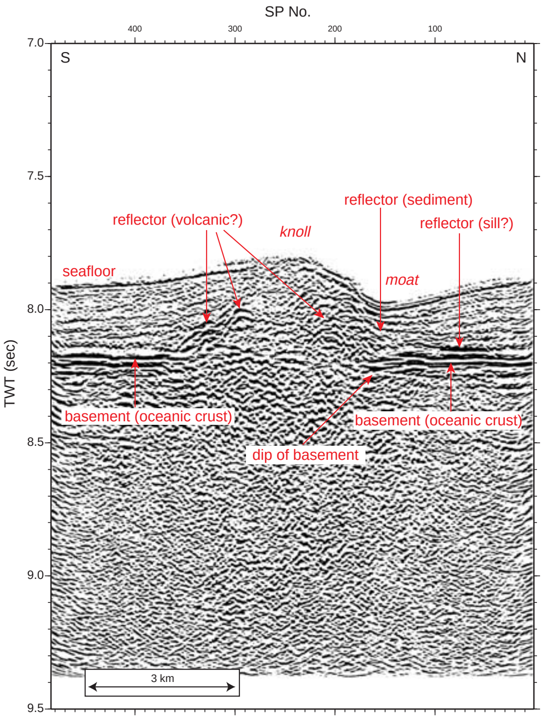

Figure 10: Seismic profile of KR05-10 Line-3. The profile shows a cross section along the long-axis of a small knoll.

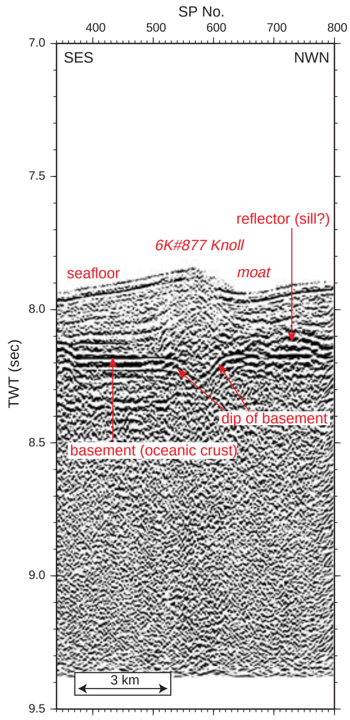

Figure 12: Seismic profile of KR05-10 Line-5. The profile shows a cross section along the short-axis of the 6K#877 Knoll.

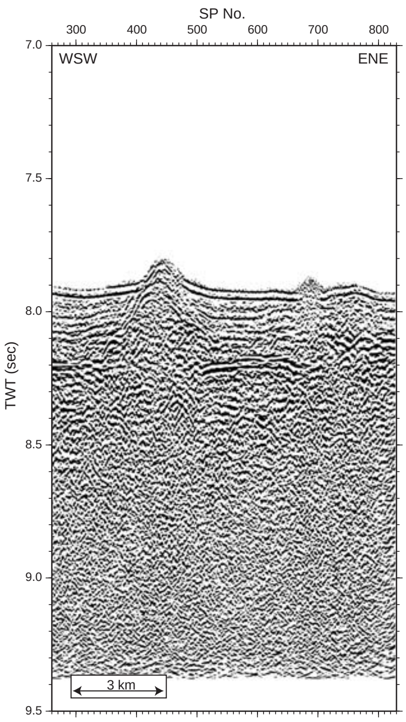

Figure 11: Seismic profile of KR05-10 Line-4. The profile shows a cross section along the short-axes of a small knoll and the 6K#877 Knoll.

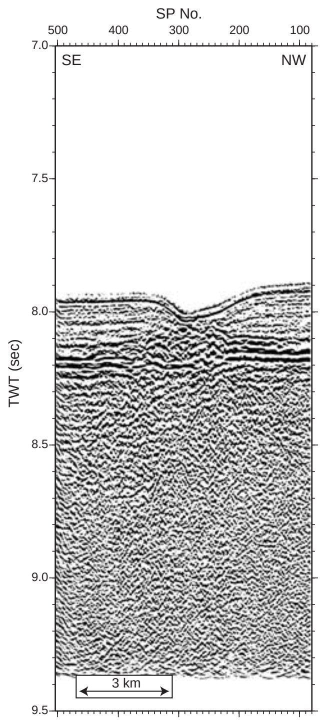

Figure 13: Seismic profile of KR05-10 Line-6. The profile shows a cross section across a moat.

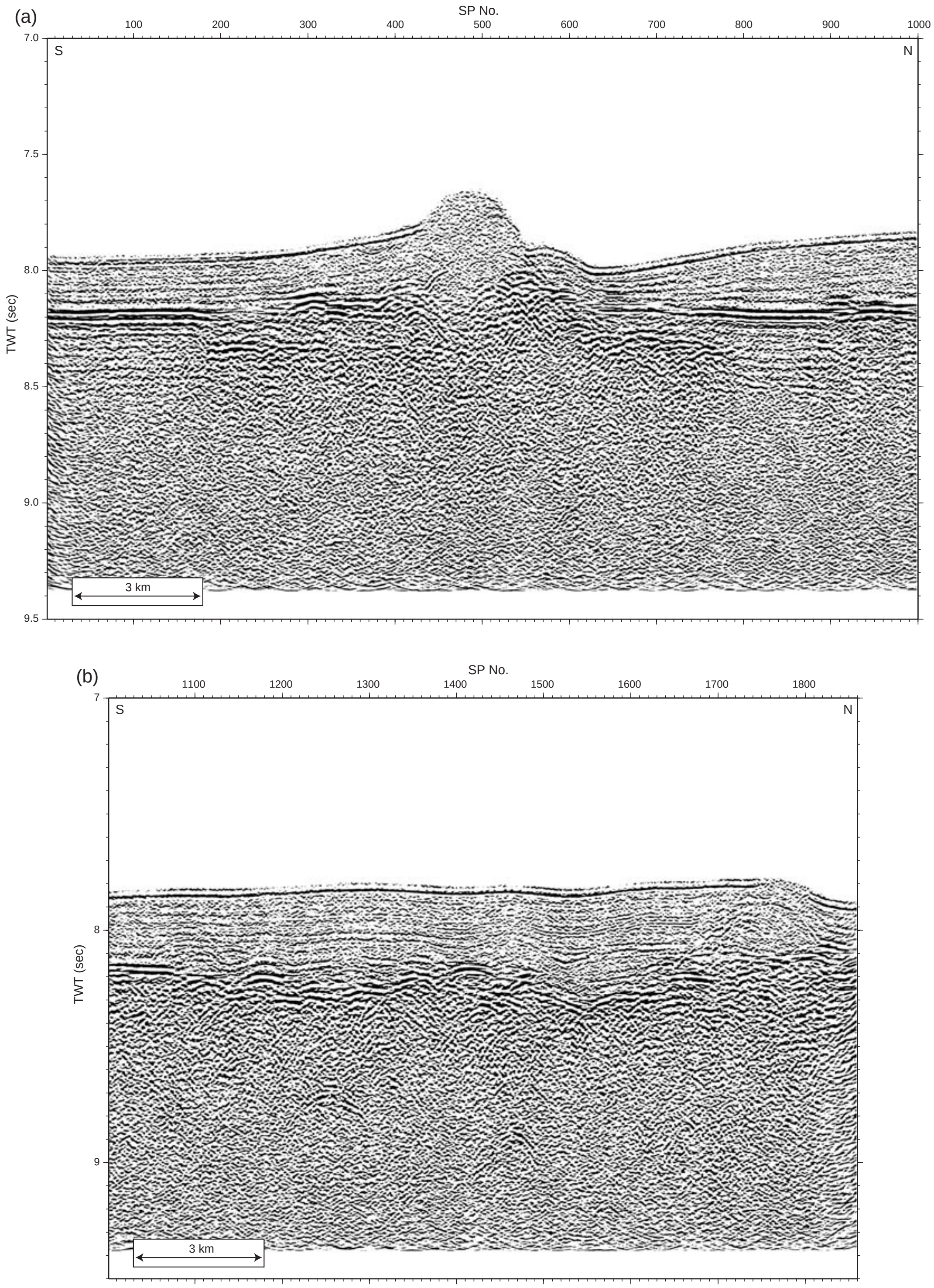

Figure 14: Seismic profile of KR05-10 Line-7. The profile shows a cross section of a small knoll in the parallel direction to the Nosappu Fracture Zone. (a) southern section (shot: 0-1000), (b) northern section (shot: 1000-1860).

there is no significant crustal thickening/thinning possible caused by magmatism and/or tectonism of "petit-spot".

If necessary in future, to reveal the whole picture of the subsurface structure, the nature of volcanic eruption, and the magma plumbing system of "petit-spot" intra-plate volcanism, a high-density seismic survey with well-organized seismic lines should be needed. Usage of different frequencies for lithostratigraphy identification and/or a large volumetric air-gun and multi-channel hydrophones for deep penetration seismic reflection could be helpful.

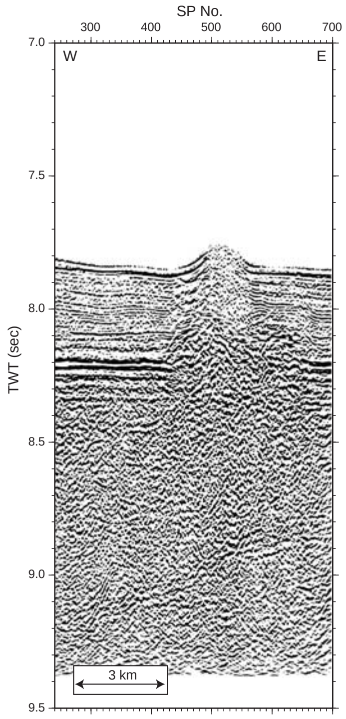

Figure 15: Seismic profile of KR05-10 Line-8. The profile shows a cross section along the short-axis of a small knoll.

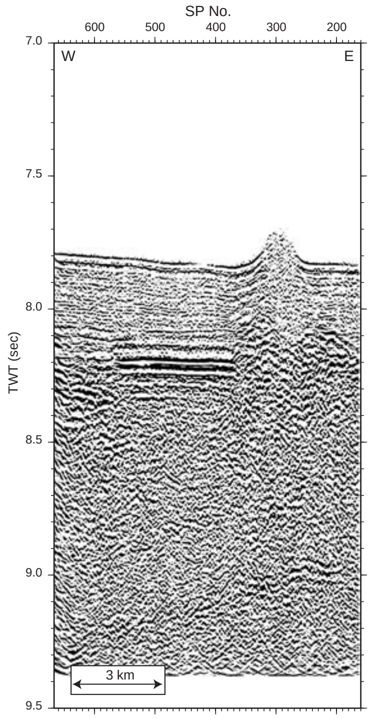

Figure 16: Seismic profile of KR05-10 Line-9.

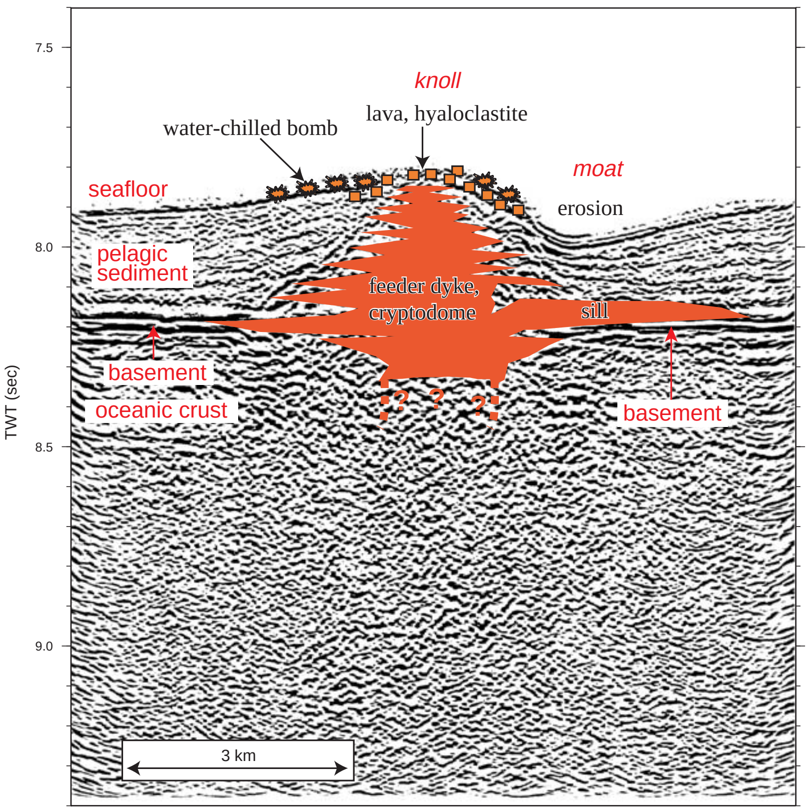

Figure 17: Implication of subsurface structure and nature of volcanic eruption of "petit-spot".

6. Conclusions

We conducted single-channel seismic reflection surveys around the "petit-spot" intra-plate volcanism in the northwestern Pacific. Our surveys yielded the following results regarding the subsurface structure and the volcanic eruption:

1. A sedimentary layer is acoustically transparent, having some horizontal reflectors within the layer. The sedimentary layer has nearly constant thickness of 0.2-0.3 sec two-way travel time (~200-300 m).
2. Oceanic crust of the Pacific Plate lies flatly beneath the sedimentary layer except for locations of small volcanic knolls and the Nosappu Feacture Zone.
3. The layer beneath the small knolls is acoustically opaque by the seismic waves scattering and diffraction waves. The opaque layer is possibly caused by inhomogeneous structure due to intrusion of volcanic dykes and volcanic deposits.
4. Horizontally lying strong reflectors at the base of sedimentary layer are often identified in the vicinity of small knolls. These are probably reflections from volcanic sills.
5. The oceanic crust could be depressed beneath the small knolls by weight of the volcanic deposits.
6. An implication of the nature of volcanic eruption is provided from the seimic surveys. A small amount of magma injected into the sedimentary layer. A part of the lava flowed horizontally within the sedimentary layer and formed volcanic sills. The lava flow also formed feeder dyke or cryptodome in the sedimentary layer, erupted on the seafloor, and built the small knolls.

Acknowledgements

We are grateful to the shipboard science party for collaboration at sea and in scientific discussions. We thank the officers and crew of R/Vs *Kairei*, *Yokosuka*, and submersible *Shinkai 6500* for outstanding professionalism and dedication that made the cruises successful. We are indebted to marine technicians of Nippon Marine Enterprises for their invaluable help at sea, and to T. Tsuru, and T. No for on shore data processing. We thank an anonymous reviewer for helpful review. Bathymetric data of JTOPO30 published by Marine Information Research Center, Japan Hydrographic Association and ETOPO2 published by NOAA were used to fill unsurveyed area. Part of this work is a contribution of the research program at the Institute for Research on Earth Evolution, JAMSTEC, and the Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan (No. 17340136).

References

Abe, N., N. Hirano, T. Fujiwara, S. Machida, E. Araki, K. Baba, M. Ichiki, M. Nakanishi, Y. Ogawa, H. Sugioka, K. Suyehiro, T. Ishii, T. Suzuki, A. Takahashi, E. Takahashi, J. Yamamoto, An outline of the interdisciplinary survey on a new type intra-plate volcanism, Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract V51A-1462, 2005.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int*., **101**, 425-478, 1990.

Divins, D., Total sediment thickness of the world's oceans and marginal seas, http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html, Mar. Geol. and Geophys. World Data Cent., Boulder, Colo., 2001.

Fujiwara, T., N. Abe, N. Hirano, M. Nakanishi, and Y. Ogawa, Geophysical survey around the "Petit-spot" intra-plate volcanism, in the northwestern Pacific (abstract in Japanese), Fall Meet. Seismo. Soc. Jpn, Sapporo, P095, 2005

Gradstein, F., J. Ogg, and A. Smith, A geologic time scale 2004, Cambridge University Press, Cambridge, 2004.

Hirano, N., K. Kawamura, M. Hattori, K. Saito, and Y. Ogawa, A new type of intra-plate volcanism; young alkali- basalts discovered from the subducting pacific Plate, northern Japan Trench, *Geophys. Res. Lett.*, **28**, 2719-2722, 2001.

Hirano, N., E. Takahashi, T. Hirata, J. Yamamoto, S. Machida, T. Ishii, and N. Abe, New type volcanism along fractures on the flexural Cretaceous Pacific Plate, Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract V51A-1461, 2005.

Machida, S., N. Hirano, S. Ingle, T. Ishii, N. Abe, Geological observation of the young Petit-spot volcanoes on the Early Cretaceous Pacific Plate using SHINKAI 6500, Eos Trans. AGU, 86(52), Fall Meet. Suppl., Abstract V51A-1463, 2005.

Mitsuzawa, K. and G. Holloway, Characteristics of deep currents along trenches in the northwest Pacific, *J. Geophys. Res*., **103**, 13085-13092, 1998.

Nakanishi, M., K. Tamaki, and K. Kobayashi, Mesozoic magnetic anomaly lineations and seafloor spreading history of the northwestern Pacific, *J. Geophys. Res*., **94**, 15437-15462, 1989.

Nakanishi, M., Topographic expression of five fracture zones in the northwestern Pacific Ocean. In The Mesocoic Pacific: Geology, Tectonics, and Volcanism, (edited by M. S. Pringle et al.), Geophys. Monogr. Ser., AGU, 77, 121-135, 1993.

Obi, A., T. Fujiwara, M. Nakanishi, N. Hirano, Y. Ogawa, and KR04-08, KR03-07 onboard science party, Magnetic anomaly in the seaward slope of the Japan Trench (in Japanese), Abstract 21st Shinkai Symposium, PS65, 2005.

(Received December 20, 2005)