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Subsurface structure of the "petit-spot" volcanoes on the northwestern Pacific Plate

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[1] A seismic reflection survey was conducted in the northwestern Pacific to investigate subsurface structure of small volcanoes considered to be formed by the newly-discovered "petit-spot" intra-plate volcanism. In contrast with an acoustically transparent sedimentary layer in the ambient northwestern Pacific, sedimentary layers are acoustically opaque with interbedded strong reflections beneath the volcanoes. These reflections are possibly caused by inhomogeneous structure due to intrusion of central vent. Subhorizontal strong reflections at base of the sedimentary layer, identified in the vicinity of volcanoes, are probably reflections from sills of dense lavas flowing out within the sedimentary layer. These volcanoes could be monogenetic volcanoes produced by small amount of magma intrusion, <1 km^3 in volume. Although such small volcanoes have never been discovered unless through a high-resolution bathymetric mapping, the "invisible" intra-plate volcanism affects successive evolution/modification of the crustal architecture of old-age oceanic plates. **Citation:** Fujiwara, T., N. Hirano, N. Abe, and K. Takizawa (2007), Subsurface structure of the ''petit-spot'' volcanoes on the northwestern Pacific Plate, *Geophys. Res. Lett.*, *34*, L13305, doi:10.1029/2007GL030439.

1. Introduction

[2] A prologue of our study was a discovery made in 1997. Basalts were sampled on a seaward slope of the Japan Trench of ~7300 m water depth (ROV *Kaiko* site: red circle, Figure 1). The basalts were unexpectedly young (^{40}Ar$-^{39}$Ar age dating: 5.95 ± 0.31 Ma) alkali basalts [*Hirano et al.*, 2001]. There are no known hotspots in the vicinity. This substantial discovery suggests that unknown intra-plate volcanism occurs and new volcanoes are built on the ~130 Ma old Cretaceous Pacific Plate, that is, cool and thick oceanic lithosphere.

[3] To validate this hypothesis, we have carried out geological and geophysical surveys in the northwestern Pacific since 2003 [*Abe et al.*, 2005]. The survey area extends from the ROV *Kaiko* site to the southeast (~120°) upstream of the Pacific Plate motion [e.g., *DeMets et al.*, 1990]. The area is up to ~600 km away from the trench, and is supposed to be the birthplace of the ~6 Ma basalts. As a result of the survey, we found small knolls (red star, Figure 1). Alkali basalts collected from the small knolls indicate <1 Ma age [*Hirano et al.*, 2006]. The intra-plate volcanism was finally confirmed, and then termed "petit-spot". In this paper, we present our seismic reflection survey conducted in 2005. The aim of the survey was to evaluate the subsurface volume of magma and the structure of lava flows and/or sills of the "petit-spot" volcanoes. It will provide insights on the thermal/mechanical structure of the oceanic lithosphere and the magma production process in the shallow upper mantle.

2. Geological Background

[4] The survey area is situated in a regional topographic low, east of the outer-rise near the Japan Trench (Figure 1). The area has a series of parallel magnetic anomalies (Japanese Lineation) in the WSW-ENE direction. The magnetic lineations are identified as chron M12-M15 in the survey area [*Nakanishi et al.*, 1989]. Therefore, the crustal age varies from ~138 to ~140 Ma (Early Cretaceous) [*Gradstein et al.*, 2004]. East of the survey area, the Nosappu Fracture Zone (NFZ) which is considered as a paleo-transform fault [*Nakanishi*, 1993] is elongated perpendicular to the magnetic anomalies (Figure 1). NFZ offsets the Pacific Plate by ~250 km (~5 m.y.).

[5] Swath bathymetric and backscattering data were collected during our research cruises (Figure 1). The detailed bathymetry depicts small knolls, a few km in diameter and ~100 m in relative height, distributed on a sedimentary basin ~6000 m deep. These knolls are surrounded by moats, whose deeper parts are at the northwest or north of the knolls (Figure 2). High backscatter intensity at these knolls suggests little sediment coverage, thus hard igneous rocks exposed. The *Shinkai 6500* submersible dives were performed at some of the knolls. The basin surrounding the knolls is fully covered with soft pelagic sediment. In contrast, pillow lavas and robes outcropped along the slope of the knolls. The outcrops were limited around summits [*Machida et al.*, 2005]. Sampled rocks indicate the volcanic edifice consists of porous (up to 60 % of porosity) alkaline lavas. Noble gas isotopic data suggest the source mantle of alkali basalts is similar to that of MORB rather than that of OIB. These rocks origin is inferred to the base of the lithosphere or asthenosphere ~90 km below the seafloor [*Hirano et al.*, 2006]. The lava contains abundant mafic xenocrysts and xenolith fragments of basalts, dolerites, gabbros and mantle peridotites which are typical of the oceanic lithosphere [*Abe et al.*, 2006].

[6] On the other hand, additional rock sampling and bathymetric survey were also conducted in the *Kaiko* site. Basaltic lavas from volcanic knolls are highly vesicular (10–40 %). While, less vesicular (0–20 %) lavas and cherts were collected on fault scarps where probably deeper parts

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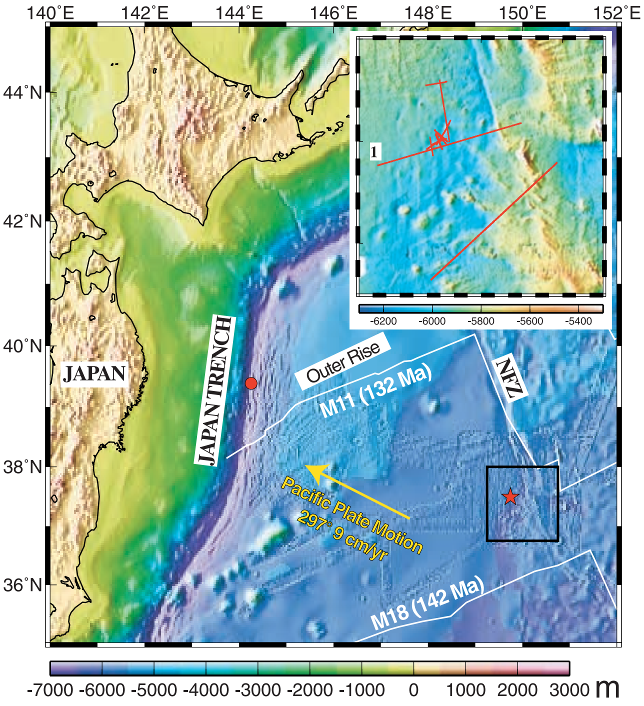

Figure 1. The black square shows the survey area. The circle points to the sampling site where ROV *Kaiko* collected ~6 Ma basalts. The star points to "petit-spot" volcanoes where we collected <1 Ma basalts. Solid white lines indicate crustal age identified magnetic isochrons. NFZ, Nosappu Fracture Zone. The inset is swath bathymetry of the survey area. Solid lines delineate seismic survey lines.

of the volcanic knolls and/or sills were exposed by horst-graben normal faulting. Additional ^{40}Ar$-^{39}$Ar ages obtained were 4.23 ± 0.19 Ma and 8.53 ± 0.18 Ma [*Hirano et al.*, 2006].

3. Data Collection and Processing

[7] Seismic data were collected with R/Vs *Kairei* (Cruise KR05-10) and *Yokosuka* (YK05-06) towing a single-channel streamer. A GI gun (Generator: 250, Injector: 105 cubic-inch) was used for a seismic source, fired every ~20–30 m (KR05-10) or 60 m (YK05-06) at a 14.0 MPa pressure. The record lengths were 3.5–8.0 sec with a delay time of 6.0 sec. No water bottom multiples were recorded to allow calibration of the amplitude due to great water depth. Details on description of the seismic experiments are given by *Fujiwara et al.* [2006].

[8] A total of thirteen survey lines and total length of 350 km were completed (Figure 1). Two long lines cross NFZ and one line runs sub-parallel to NFZ to examine the structure of the sedimentary basin apart from in the vicinity of volcanic knolls. The rest of lines crisscross the knolls. A pair of cross lines is designed to run along and across long-axis of the knoll. One of the cross lines is also designed to pass the deeper part of moat (Figure 2).

[9] The seismic 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

[10] Sedimentary layers and basement morphology are well characterized in all seismic profiles (e.g. <SP 400, Figure 3a). Reflections from the seafloor are very weak in amplitude. The result suggests that the sediment is unconsolidated or semi-consolidated. The sedimentary layer is found to be acoustically transparent. Some subhorizontal reflections, thus acoustically stratified sequence interbedded, are identified within the sedimentary layer. The reflection pattern of the sedimentary layer is similar to that of the nearest high-resolution multi-channel seismic (MCS) profile conducted ~200 km eastward from the area [*Ranero et al.*, 1997; *Reston et al.*, 1999].

[11] The sedimentary layer in the northwestern Pacific has been shown by several Deep Sea Drilling Project (DSDP) holes [*Heezen et al.*, 1973; *Larson et al.*, 1975; *Langseth et al.*, 1980; *Heath et al.*, 1985]. It consists of Cenozoic clay and ooze, represented by an acoustically transparent zone, underlain by Cretaceous clay, limestone, and chert represented by an opaque zone. In the survey area, the opaque zone is not so evident, but in places, the strata in the middle of the sedimentary layer is rather highly reflective.

[12] More or less 0.3 sec two-way travel time (TWT) below the seafloor, flat, continuous, and exceptionally strong reflection signatures are identified in all profiles (TB, Figure 3). These acoustic basements are presumed to represent the top surface of oceanic igneous crust of the Pacific Plate. Therefore, the profiles indicate approximately ~270–300 m of sediment thickness, converted from TWT assuming velocity of ~1.8–2 km/s for the sedimentary layer [e.g., *Duennebier et al.*, 1987; *Bée and Bibee*, 1989; *Nagumo et al.*, 1990]. The thickness is comparable to values in adjacent northwestern Pacific basins [e.g., *Reston et al.*, 1999; *Divins*, 2001].

[13] Horizontal lying seismic reflections at ~0.2 and ~0.8 sec TWT beneath the top basement are found in some places. The 0.2 sec reflections (L2A, Figure 3) could be the base of seismic layer 2A [e.g., *Detrick et al.*, 1993]. The 0.8 sec reflections are probably seismic layer 2/3 boundary

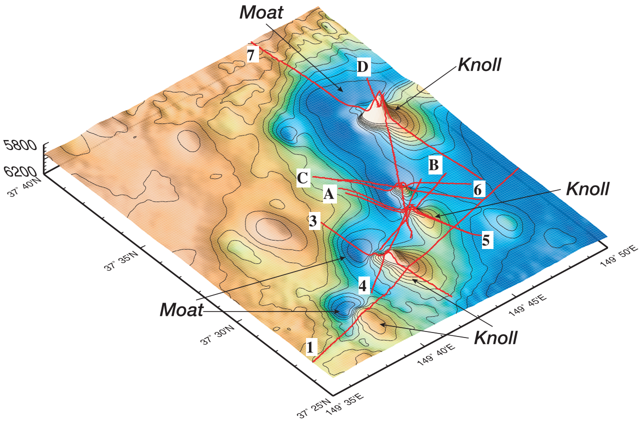

Figure 2. Closeup view around the "petit-spot" volcanoes. Solid lines delineate survey lines annotated in numbers.

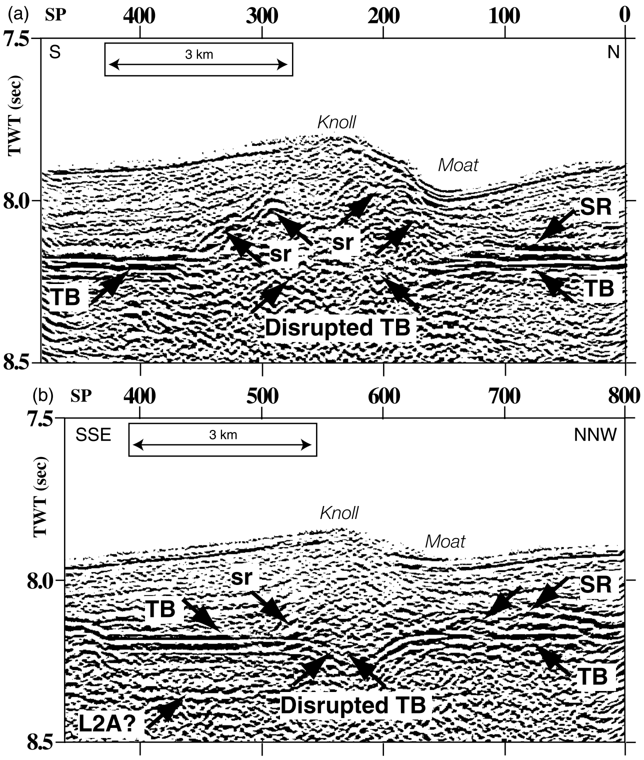

Figure 3. (a) Seismic profile of Line-3 (see Figure 2 for the location) showing along the long-axis of a "petit-spot" volcano. (b) Line-5 showing another volcano. The vertical axis indicates two-way travel time (sec). Horizontal axis indicates trace of shot numbers. TB, reflection from top of igneous basement; L2A, reflection from the base of seismic layer 2A; SR, strong reflection; sr, short-distance strong reflection.

compare with the MCS profile as mentioned above [*Reston et al.*, 1999]. Further discussion of these intra-crustal reflections will not be proceeded to from our single-channel profiles.

4.2. Subsurface Structure of Small Knolls

[14] Seismic profiles show that all the small knolls have similar patterns, thus similar subsurface structure (Figure 3). First of all, there is no continuous sloping seismic reflector continuing from a foot of the knoll at the seafloor, which would indicate a broad slope of the seamount within the sedimentary layer. Therefore, we can conclude the small knolls are not buried seamounts.

[15] Beneath the knolls, the stratified structure of the sedimentary layer is disorganized, and is acoustically opaque. Seismic waves scattering and diffraction waves in the opaque sections indicate that the sections contain inhomogeneous structures. In some places within sediments, seismic reflections with high-amplitudes are also visible (sr, Figure 3). A possible explanation for the inhomogeneous structure and the strong reflection is that these ones are caused by central vent and/or volcanic breccias intruded in the sedimentary layer. The reflections from top of the oceanic basement are annihilated at the volcanic knolls, suggesting that the oceanic crust is disrupted by the "petit-spot" volcanism.

[16] Subhorizontal strong reflections in positive polarity can be traced at <0.1 sec TWT above the top of oceanic basement for a few kilometers in the vicinity of volcanic knolls within the sedimentary layer (SR, Figure 3). The strong reflection is an unconformably seismic boundary. Velocities in the layer beneath the strong reflections can be estimated by assuming the ratio between reflection coefficients at the top basement (TB) and at the strong reflection (SR) is equivalent to be ratio of those reflection amplitudes. For instance, the velocity of the sedimentary layer is likely to be 1.8 km/s, and the velocity of the basement is assumed to be 4.5 km/s. Density-velocity relationship is from *Nafe and Drake* [1957] for computation of acoustic impedance. We applied the analysis to Line-3, 5, A, and C crossing the knolls. The ratios of amplitudes are 0.88, 0.41, 0.53, and 0.65. The resultant velocities are 4.0, 2.6, 2.8, 3.2 km/s, respectively. Lower velocities may be caused by thin-layer tuning effects.

[17] The most probable candidates for these higher velocity layers are volcanic sills flowed out in the sedimentary layer because the strong reflections are consistently associated with existence of the volcanic knolls. Observation in the *Kaiko* site suggests that deeper parts of the volcanic knolls and sills consist of dense lava (laboratory experiment of the sampled lava shows velocity $V_p = 4.76$ km/s, density = 2.85 g/cm^3, and porosity = 22.6 % [*Hattori et al.*, 2000]), and highly vesicular lava eject onto the seafloor.

[18] Beneath the moats associated with knolls, the seismic reflections of the top basements and strata within the lower sections of sedimentary layers still appear to remain horizontally or slightly tilted up toward the knolls although the seafloor is concave downward (Figure 3). This result suggests that the sedimentary layers preserve the original horizontal bedding. Therefore these moats may be formed by erosion of surface vortices of deep-sea currents [e.g., *Mitsuzawa and Holloway*, 1998; *Owens and Warren*, 2001] by the new volcanoes.

5. Discussion

[19] The subsurface structure revealed by our seismic survey provides information about the nature of volcanic eruption related to the "petit-spot" (Figure 4). A small amount of magma intruded into the sedimentary layer. Dense lava flowed out on the top basement and formed subhorizontal volcanic sills. The lava flow also intruded into the sedimentary layer and formed central vents. Highly vesicular, perhaps volatile, lava erupted on the seafloor and built the small knolls <1 km^3 in volume. In consideration of the volume and eruption style, the small knolls could be monogenetic volcanoes. Fissure eruption volcanism is a probable explanation for the formation of monogenetic volcanoes. The top basement disruption would tend to extend parallel to the long-axis of the volcano (NS to NNW-SSE); The direction may indicate the fissure's direction. However, as it stands, three-dimensional subsurface structure (i.e. continuity of TB disruption possibly related to eruption) remains unclear because of limited survey tracks. Thus strikes of the fissures reflecting local stress field are uncertain.

[20] The implication of the small amount of magma is supported by other geophysical observations conducted

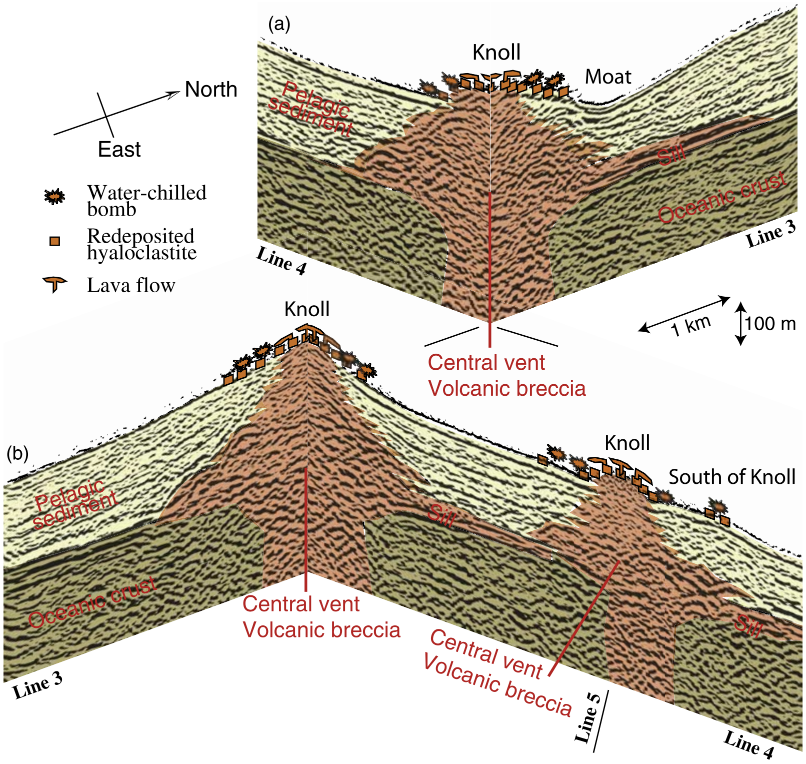

Figure 4. Three-dimensional view of Line-3 and Line-4 (see Figure 2 for the location) and implication of subsurface structure of the "petit-spot" volcanoes combined with submersible observation. The profiles are separated at the cross point: (a) northern and western parts of the profiles, and (b) southern and eastern parts.

during our research cruises. Basaltic rocks sampled from the knolls were found to have strong remnant magnetization (up to ~60 A/m) (T. Fujiwara, 2005, unpublished data,). And also, the volcanoes erupted approximately on-site (~38°N). Therefore the volcanoes should have higher angles of magnetization inclination. In contrast, the old crust of the Pacific Plate there has lower magnetic intensity (4–8 A/m) and low inclination referring to results from DSDP [*Larson and Lowrie*, 1975]. Thus, "petit-spot" volcanoes must have strong magnetization contrast to the old crust, and may produce particular magnetic anomaly, if large volume of such basalts are extruded and/or intruded. However, magnetic anomaly due to the newly volcanism is not strong enough to obscure the original magnetic lineation [*Fujiwara et al.*, 2005]. In addition, the newly tectonism has not severely destroyed the magnetized layer in the old crust. Bouguer gravity anomaly shows almost no local variation in the survey area [*Fujiwara et al.*, 2005]. Generally, Bouguer anomaly indicates subsurface density variations, which may be related to crustal thickness variation. Since our gravity result shows no variation, this suggests that there is no significant crustal thickening/thinning possible caused by magmatism and/or tectonism of "petit-spot".

[21] *Hirano et al.* [2006] proposed that these small volcanoes erupted along lithospheric fractures in response to plate flexure. Such intra-plate volcanism may be ubiquitous in the areas of front sides of trench outer-rises, thus widely spread throughout old-age oceanic plates. In fact, 4.2 to 8.5 Ma volcanoes were found during our "petit-spot" survey, suggesting episodic eruption of magma over a distance of 400 km of plate motion.

[22] Such small volcanoes have never been discovered unless through the use of high-resolution multi-narrow beam. The "invisible" volcanism slightly affects the successive evolution/modification of the crustal architecture of old-age oceanic plates. Considering such small-scale intraplate volcanism may be a common phenomenon, we should notice it may be important for geologic interpretation of, for example, ocean drilling records or volcanic material in accretionary complexes yielded on land because the central vents and sills must be much easier to accrete than massive oceanic crusts.

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