

## Reflective body observed by multi-channel reflection survey off Niijima and Kozushima, Japan

Tetsuro Tsuru<sup>1</sup> and Gou Fujie<sup>1</sup>

**Abstract** Seismic reflection characters provide useful information on not only geometry of tectonic structures but also magmatic processes. A multichannel seismic reflection survey has been conducted on November 2000, in order to clarify the sub-surface structures around Niijima, Kozushima and Miyakejima of the northern Izu islands, where volcanic activities with earthquake swarm have been repeatedly occurring. As a result, a chain of intermittently continuous reflectors with strong amplitude was observed at 3.5-5 km depth beneath the basement high between Niijima and Kozushima, which is called the Zenisu ridge and an NE-SW oriented echelon ridge across the Northern Izu Arc. The reflective zone has about 10 km length in NW-SE direction whereas it would have extremely thin width in NE-SW direction. Moreover, an isolated reflector is visible below the NW-SE trending basement rise, which is capped by a small seamount chain extending toward SE from Kozushima. Based on the previous study in crustal deformation modeling and seismic characters of the reflections, the reflectors are considered to show the magma intrusions that have been repeatedly occurring there, demonstrating one of the processes of crustal evolution in the study area. Furthermore the seismic attribute analysis shows the remarkable contrast in frequency-dependent attenuation of seismic reflections between the Zenisu ridge and the depression of igneous basement between Miyakejima and the ridge, implying the difference in the extent of destruction of the igneous basement rocks or that in lithology. Finally the AVO and frequency component analyses suggest the existence of volcanic gas at very limited part of the reflectors.

**Keywords:** Niijima, Kozushima, Miyakejima, Reflective body, Volcanic activity

### 1. Introduction

Niijima, Kozushima and Miyakejima are located SE off the Izu peninsula and they belong to the northern Izu islands (Fig. 1), at where volcanic activities accompanied by earthquake swarms have been repeatedly occurring<sup>1, 2)</sup>. In 2000, the latest swarm initiated at Miyakejima and then moved toward the direction of Niijima and Kozushima<sup>3)</sup>. Seismic refraction studies discovered an intra-crustal reflection phase immediately below the swarm<sup>4)</sup> and relatively low P-wave velocity zones in the upper crust between Kozushima and Miyakejima<sup>5)</sup>. In order to clarify detailed shallower crustal structures around the islands, Japan Marine Science and Technology Center (now Japan Agency for Marine-Earth Science and Technology, JAMSTEC) conducted a multi-channel seismic (MCS) reflection survey in the area<sup>6)</sup>.

There are few successful examples in MCS reflection experiments relating active volcanism in volcanic islands, except a few ones<sup>7-9)</sup>. Scattered waves are generated by random and relatively short-wavelength heterogeneity in the media, so the scattered waves contain higher frequency components than seismic reflections to be used for the structural imaging e.g.,<sup>10)</sup>. In this survey, we therefore used a seismic energy source that is domi-

nated by low frequency components. Resulting seismic records clearly show some characters suggestive of volcanic activities in the study area.

### 2. Data acquisition and processing

A total of 250 km long MCS reflection profiles have been collected at the offshore region around Niijima, Kozushima and Miyakejima on November 2000 (Fig. 1). The data acquisition was conducted using eight 25-liter airguns with shot spacing of 50 m and a 156-channel streamer cable with group interval of 25 m. The maximum offset length was 4100 m. The streamer cable was towed 20 m below the sea surface to suppress wave-noises by a seasonal wind during the whole survey period. The vessel was sideslipped 360 m westward at shot points (SP) 1450-1480 on line KR102 by a very strong current, leading irregular source-receiver geometry and then decreasing data quality there.

Poststack time migrated records of lines KR101 and KR102 are shown in Fig. 2a and Fig. 3a, respectively, which were produced by careful trace editing, deconvolution, NMO correction, multiple suppression, CDP stacking and so on. As seen in these figures, a chain of intermittently continuous reflectors appear about 3 seconds in time at SP 1300-1500 on the KR101, and an iso-

<sup>1</sup> Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, 3173-25, Showa-machi, Kanazawa-ku, Yokohama 236-0001, JAPAN

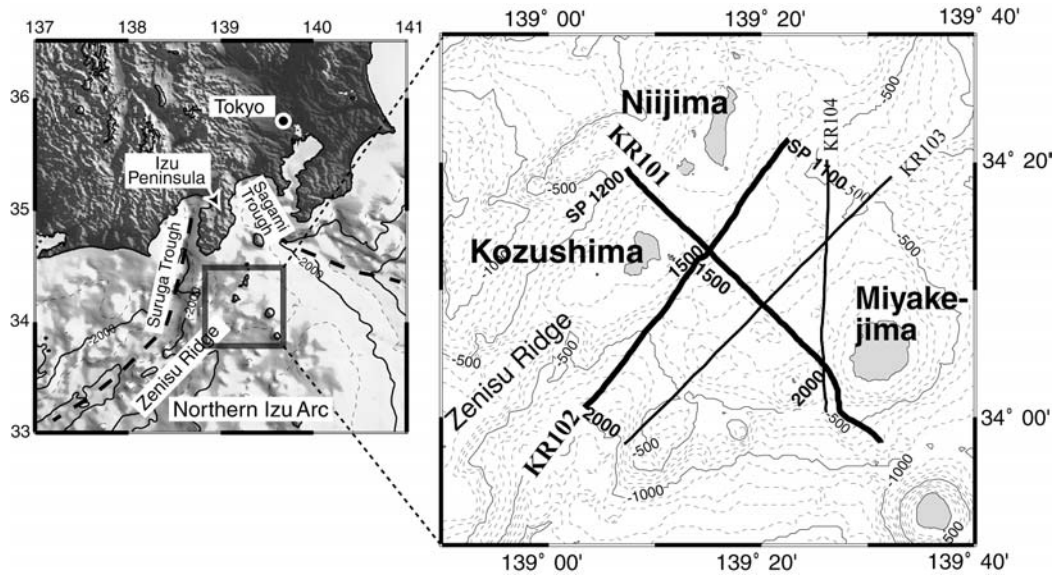
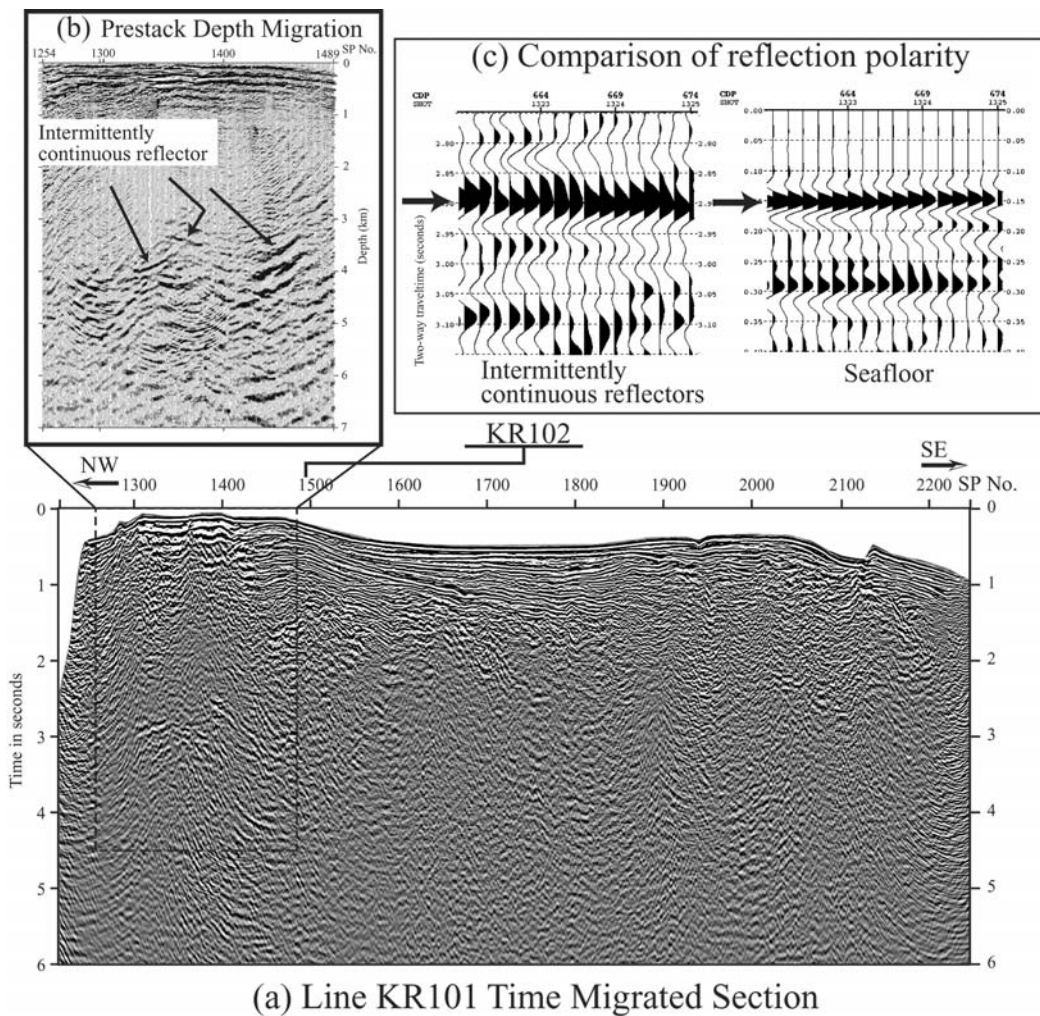


Figure 1: Study area. A total of 250 km seismic lines were observed around Niijima, Kozushima and Miyakejima. The bold lines mark segments of the profiles shown in Figs.2a (KR101) and Fig.2b (KR102).



(a) Line KR101 Time Migrated Section

Figure 2: Seismic reflection records of KR101. Poststack time migrated section is shown in (a). A chain of intermittently continuous reflectors are highlighted in enlarged section of prestack depth migrated section (b). Reflection polarity of intermittently continuous reflectors is compared with that of seafloor in (c).

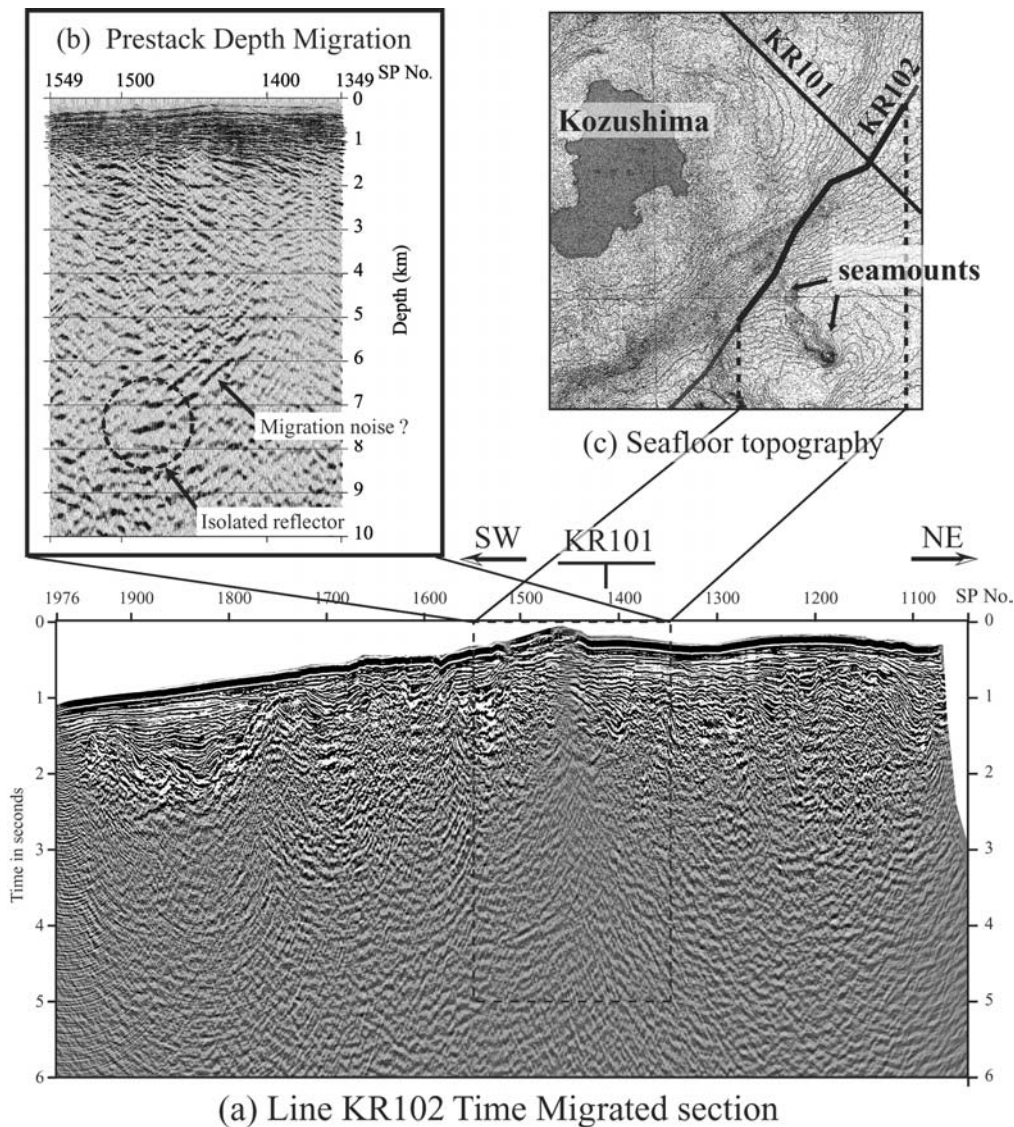


Figure 3: Seismic reflection records of KR102. Poststack time migrated section is shown in (a) and an isolated reflector is visible at about 4 seconds just below the peak of seafloor topography. The reflector is also indicated on prestack depth migrated section (b) and is located on a small seamount chain that is lined up from SE of Kozushima (c). The bathymetry map was provided by Hydrographic and Oceanographic Department, Japan Coast Guard.

lated reflector is observed about 4 seconds at SP 1470-1520 on the KR102. In order to estimate depth of those reflectors, we conducted prestack depth migration (PSDM) for the parts of interest on each line and their results were shown in Fig. 2b and Fig. 3b.

An initial velocity model for the PSDM was constructed based on a conventional velocity analysis for the shallowest unit that characterized by stratified reflections above the acoustic basement, and on the results of previous seismic refraction experiments<sup>11, 4)</sup> for the unit beneath the acoustic basement. In order to examine uncertainty in depths of the reflectors observed, we conducted PSDM velocity analysis<sup>12, 13)</sup>,

as shown in Fig. 4. The figure demonstrates nine PSDM images at SP 1270-1420 on KR101, which were processed by using velocity models with different velocity gradients. Accordingly we are able to understand that the velocity gradients of 0.4-0.6 (m/s)/m produce the most focused reflections with stronger amplitude and better continuity than the other ones for the target reflections. Therefore, reliable depths of the reflectors are estimated to be 3.8-4.2 km at this location. Here, we finally adopted 0.5 (m/s)/m as a velocity gradient of the basement rock in the velocity model for the PSDM shown in Figs 2b and 3b.

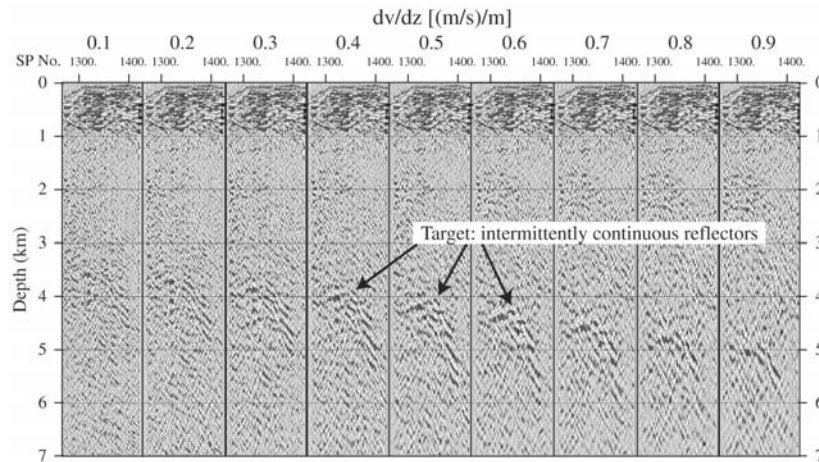


Figure 4: An example of velocity analysis conducted on KR101. Prestack depth migration velocity analysis was conducted in order to evaluate the accuracy of depths of the intermittently continuous reflectors observed on KR101. Nine velocity models with different velocity gradients were examined, and then the central one was adopted in the velocity model for the depth migration shown in Figs 2b and 3b, because of the strongest amplitude and the best continuity of the target reflections.

### 3. Tectonic structures observed on seismic profiles

#### 3.1 Stratified reflections between Kozushima and Miyakejima

The shallowest unit of about 1 km thickness with P-wave velocity of 1.5-1.8 km/s overrides the acoustic basement in a topographic depression between Kozushima and Miyakejima, as seen in Fig. 2a. Stratified reflections are visible inside the unit, while they are invisible at a structural high between Niijima and Kozushima (SP1310-1410). This boundary in visibility of the stratified reflections is located at the SE end of the reflective body, and the location is consistent with the NW end of the main seismic swarm activity of 2000<sup>14)</sup>, which was initiated at Miyakejima and moved toward Kozushima<sup>3)</sup>.

#### 3.2 Intermittently continuous reflectors between Niijima and Kozushima

A chain of intermittently continuous reflectors having strong amplitude is visible at SP1300-1500 on line KR101 (Fig. 2), depths of which are 3.5-5 km. Their horizontal extension is about 10 km in NW-SE direction, however it is difficult to measure exact horizontal width of the reflective body, because continuous reflection phases that correspond to the reflectors on KR101 are not visible on NE-SW profile (KR102). Distribution of the reflective body is limited only beneath the structural high, without thick sediments, between Niijima and Kozushima. This high is just located on the axis of the NE-SW trending echelon ridge (Zenu ridge) of the Northern Izu islands<sup>15)</sup>.

#### 3.3 Isolated reflector observed at SE of Kozushima

As shown in Fig. 3b, an isolated reflector was observed approximately 7.5 km in depth at SP 1480-1500 of line KR102 (at about 7 km SE of Kozushima). Interestingly, this reflector is mapped on the line of a small seamount chain lined up southeastward from Kozushima, as shown in Fig. 3c. Above the isolated reflector, a basement high is formed and only thin sediment covers the high. The strike of the sediment thin is shown to be NW-SE by Nishizawa et al.<sup>5)</sup>. Unfortunately, the quality of MCS data at SP 1450-1480 was reduced by the very strong tidal current, therefore the northeastern end of the reflector is not clear.

### 4. Amplitude and frequency analyses

#### 4.1 Seismic attribute analysis

The instantaneous frequency analysis, one of the seismic attribute analyses of MCS data<sup>16, 17)</sup>, also provides contrast in frequency content between the Zenu ridge and the basement depression; lower frequency dominates beneath the ridge between Niijima and Kozushima, whereas higher frequency covers beneath the depression between the ridge and Miyakejima (Fig. 5). Here, the instantaneous frequency analysis is useful in the detection of frequency-dependent attenuation<sup>e.g., 18)</sup>.

#### 4.2 Observation of reflection polarity

Below the intermittently continuous reflectors, no coherent signals are recognizable on line KR101 (Fig. 2). Consequently no velocity information can be obtained and then it is impossible to evaluate physical properties of rocks beneath the reflectors from the

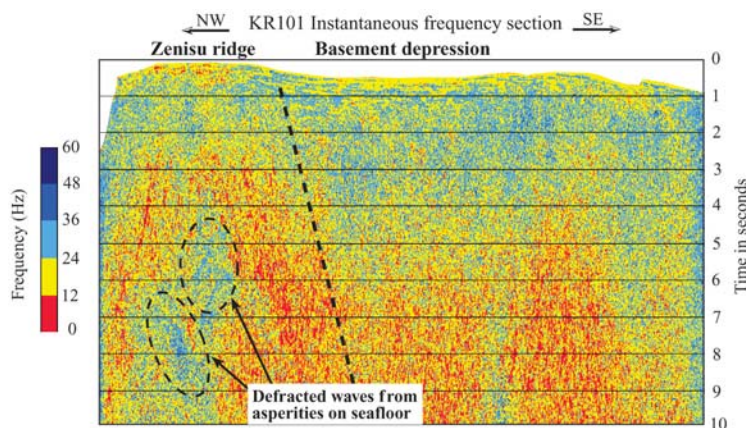


Figure 5: Instantaneous frequency analysis on KR101. Lower frequency dominates beneath the structural high whereas higher frequency is predominant beneath the topographic depression. Frequency value is shown by the color scale bar in the figure.

velocity information. Therefore we investigated reflection polarity of the intermittently continuous reflectors to investigate physical properties. All of the reflections from the reflectors have the same polarity as that of seafloor reflections (Fig. 2c). This reflection polarity is so called “normal polarity”, which means that the lower unit of the interface (reflector) has greater acoustic impedance than the upper unit.

#### 4.3 AVO analysis

In order to educe further geological information from the characteristics of reflections, we examine amplitude variation of the intermittently continuous reflections using MCS data before stack. Figs. 6a and 6b show two contrastive patterns in amplitude variation with the angle of incidence at CDP 818-822 (SP 1361-1362) and CDP 834-838 (SP 1365-1366) on KR101, respectively. The former case shows positive amplitude for the target reflections (arrows in the figure) throughout the whole incident angles, and this pattern can be observed at every location other than CDP 834-838. The latter case demonstrates that amplitude of the target reflections has positive value at small angle, decreases with angle and becomes negative value at large angle.

Here we apply AVO (amplitude variation with offset) analysis, which is often used for the discrimination of pore fluid in rocks by utilizing amplitude variation of reflections with offset (source-receiver distance) or angle of incidence<sup>e.g., 19)</sup>. Fig. 6c shows amplitude variations of both cases of Figs 6a and 6b on a graph with the relative amplitude versus the angle. As many authors reported, the former is a well-known pattern of water-bearing rocks while the latter is one of the typical patterns of gas-bearing rocks<sup>e.g., 20, 21)</sup>.

#### 4.4 Frequency component analysis

Additionally, frequency components were evaluated at five locations: SP 1358, 1362, 1366, 1370 and 1374 (Fig. 7). Two traces were respectively used for the frequency component analysis at each location. Among the five locations, the middle one is the place where the existence of gas was suggested by the AVO analysis. At the other four locations, no gas effects were recognized from the AVO.

The vertical axis of the five panels is the two-way-traveltime (TWT) and the horizontal axis represents frequency components. A color scale bar in the figure provides the powers of frequency components. Arrows show the locations of the strong-amplitude reflectors observed on KR101. Here we can understand the low-frequency components <12 Hz are dominant below the reflectors (3.0 seconds in TWT) and the powers of the frequency band are decreased more strongly in the middle panel than in the other ones.

#### 5. Discussion

Our MCS data figured out the geological structures in the shallow part of the crust, which are in good agreement with the previous study<sup>5)</sup>. The shallowest unit characterized by the stratified reflections in the topographic depression between the Zenisu ridge (structural high) and Miyakejima can be interpreted as a pyroclastic deposit, according to the velocity, the internal reflection pattern and geological setting in the study area. Reversely, no stratified reflections cover the Zenisu ridge, where volcanic islands including Niijima and Kozushima stand in a row along its axis. The contrast in thickness of the stratified-layer unit suggests an upward movement of the igneous basement formed by the volcanic activities, resulting in distribution of only thin

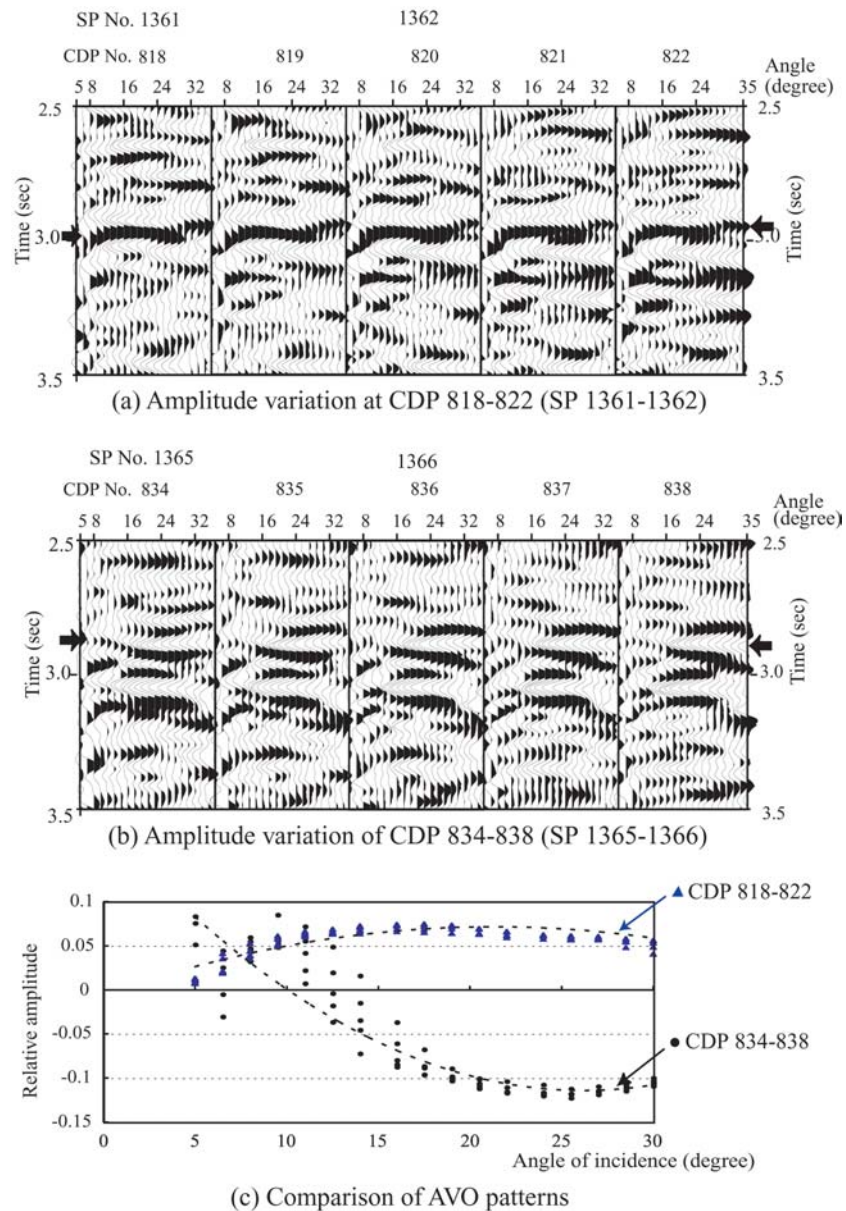


Figure 6: Amplitude variation of reflections from the intermittently continuous reflectors on KR101. Almost all of the reflections indicate a wholly-positive-amplitude pattern (a), only some of them however show a polarity-reversal pattern (b), and both two patterns are graphed in the bottom figure (c). The latter AVO pattern is well known as that of gas-bearing rock.

sediments over the ridge.

The instantaneous frequency analysis also showed the remarkable contrast between the two blocks: higher frequency in the depression and lower frequency in the rise, suggesting that the internal structure of the Zenisu Ridge is different from that of the depression. Considering the previous works in seismic and volcanic activities in the Northern Izu Arc, the observed difference in predominant frequency component is considered to reflect (1) difference in the extent of destruction of the igneous basement rocks or (2) difference in lithology, because (1) the seismicity is considerably higher

within the Zenisu ridge than around Miyakejima<sup>2)</sup> or (2) Niijima and Kozushima are characterized by felsic magmas<sup>e.g., 15, 11)</sup> while Miyakejima volcano is basaltic magma<sup>e.g., 22)</sup>, respectively.

Beneath the Zenisu ridge, the intermittently continuous reflectors were observed at 3.5-5 km depths with a horizontal extent of ~10 km on line KR101. They have possible NW-SE strikes and considerably thin widths, for example 100 m or less, because no corresponding reflectors can be seen on the intersecting line (KR102) and many normal faults with NW-SE predominant strike exist [written communication, Hydrographic

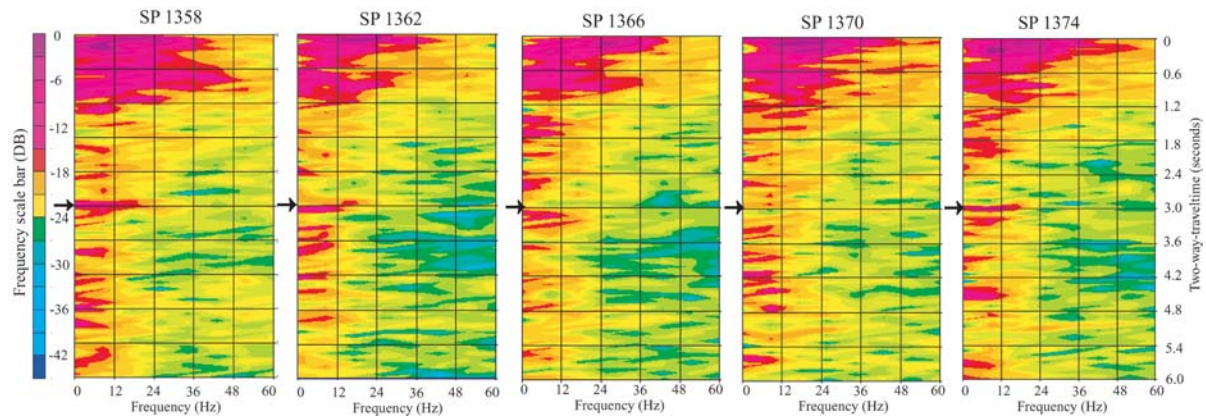


Figure 7: Comparison of frequency components on KR101. Arrows show the locations of the intermittently continuous reflectors. Attenuation effect beneath the reflectors is more evident at SP 1366 than the other locations.

Department of Japan Coast Guard, 2000]. The basement high above the isolated reflector observed on KR102 also has the same strike and is capped by a small seamount chain, which would be produced if the magma approached the seafloor in the area<sup>5</sup>).

Analysis of Global Positioning System (GPS) data shows the widening between Niijima and Kozushima during the period of the volcanic activity of Miyakejima in 2000<sup>23</sup>). Furthermore, a crustal deformation modeling revealed the migration of magma intrusion area from Miyakejima to the basement rise between Niijima and Kozushima<sup>23</sup>). These phenomena suggest magma intrusion that occurred beneath the basement rise (Zenusu ridge) during the 2000 event.

All of the reflections showed the normal polarity that indicates the existence of more solidified materials beneath the reflective interface. We would be observing the previously intruded magma 3.5-5 km beneath the Zenisu ridge, which is one of the magma activities that have repeatedly occurred there. Although it is not revealed directly from our data whether the magma intrusion occurred previously or the opening happened in advance, the basement rise should accompany with magma intrusion into open cracks.

The AVO analysis demonstrated the gas-bearing-rock pattern at very limited part of the reflectors on line KR101, extent of which is approximately 60 m in the NW-SE direction. Comparison of frequency components around this location strongly supports the gas existence, because seismic waves attenuate drastically due to the existence of gas. Although it is not clarified what kind of and how much gas is accumulated, for example, we may take account of volcanic gas such as CO<sub>2</sub> that was generated during the crystallizing process of melt<sup>24, 25</sup>) or SO<sub>2</sub> that migrated from basaltic magma to this place<sup>26</sup>).

Finally it can be concluded that all of the seismic characters observed are responsible to volcanic activi-

ties that have been occurred in the study area. In particular the intermittently continuous strong-amplitude reflectors suggest previously intruded magma there, which demonstrates evolution of crust from the inner side of the basement body in this area.

## 6. Conclusion

We conducted the MCS survey by using R/V Kairei on November 2000. As a result, some seismic reflection characters were observed; a chain of the intermittently continuous reflectors with strong amplitude beneath the NE-SW trending Zenisu ridge, the stratified continuous reflections in the topographic depression between the Zenisu ridge and Miyakejima, and the isolated reflection observed below the NW-SE trending seamount chain extending from Kozushima. Every character indicates traces of volcanic activities that have repeatedly occurred in the area, in particular the intermittently continuous reflectors strongly suggest the previously intruded magma there. The seismic attribute analysis implies the difference in structure or lithology between the Zenisu ridge and the depression. The results of AVO and frequency component analyses are suggestive of the existence of gas immediately below the reflectors. Thus these two analyses are thought to be useful in structural study of volcanoes.

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