Abstract
We conducted the side-scan sonar observations of the Yokoniwa Rise, a non-transform offset massif at the southern Central Indian Ridge using the autonomous underwater vehicle AUV-r2D4 fitted with a 100 kHz sidescan sonar system. We identified two terrain types with high backscattering signals; one terrain type exhibited typical volcanic features, while the other appeared to correspond to peridotite outcrops. The orientation of linear features identified in the survey area was highly variable, but appeared to be affected by local bathymetry. The standard deviations of the orientation and average length of these linear features were larger and smaller, respectively, than those of similar features observed along the East Pacific Rise. These observations showed that the linear features on the sonar image were likely to be flow channels or areas of the seafloor that had experienced gravitational collapse. A few small chimney-like structures were also detected.

Keywords
Peridotite outcrops • Side-scan sonar • Yokoniwa rise

35.1 Introduction
The Yokoniwa Rise is a non-transform offset massif (NTO) situated along the southern Central Indian Ridge (CIR), immediately north of the Rodriguez Triple Junction in the Indian Ocean. It is a rectangular-shaped topographic high located at the boundary between CIR segments 1 and 2 to the north of the Kairei Hydrothermal Field (Fig. 35.1) (Okino et al., Chap. 11). A dive by the submersible Shinkai6500 in 2009 discovered a group of inactive chimneys and widely exposed peridotite outcrops on the eastern slope and top of the Yokoniwa Rise (YK09-13 leg2 cruise report available at http://www.godac.jamstec.go.jp/darwin/cruise/yokosuka/yk09-13_leg2/e), suggesting past activity of ultramafic-hosted hydrothermal system in this area. Surveys of this area will improve our understanding of the geological control of ultramafic-hosted hydrothermal activity. Here we present the results of a sidescan sonar survey of the Yokoniwa Rise using the autonomous underwater vehicle AUV-r2D4 fitted with a 100 kHz interferometric sidescan sonar system that was conducted on cruise KH-10-06 in 2010, and geological maps produced from the obtained acoustic data set.
35.2 Data Acquisition

35.2.1 Description of Sidescan Sonar System and Processing Procedures

Dive 68 of AUV-r2D4 was conducted above the Yokoniwa Rise (Fig. 35.1). The r2D4 is equipped with a 100/500 kHz dual frequency sidescan sonar system (Klein System). The half swath range of the sonar image is 300 m and an L-shaped hydrophone array is used to calculate interferometric bathymetry with high accuracy (Koyama et al. 2007).

We conducted a 19 km survey of the top of the Yokoniwa Rise in a north–south direction along four sub-parallel survey lines that covered an area of 6.3 km (north–south) × 2.4 km (east–west) (Fig. 35.1). The vehicle altitude during the dive was kept at 30–150 m above the seafloor during the survey.

We first converted the file format from that of the vendor (*.5kd) to a generalized XTF format, and then applied the necessary corrections to produce a mosaic image of the area using software. The resulting sonar image is shown in Fig. 35.2a. Correction and processing of the interferometric bathymetry data were conducted using proprietary software (Koyama et al. 2007). The processed interferometric bathymetry data covered 18 % of the total survey area (Fig. 35.2b). The results of the 500 kHz sonar survey data will be presented in future.

35.2.2 Data Limitations and Considerations

The sonar image was distorted in several places, possibly due to issues related to the stability and heading of the AUV. In addition, wedge-shaped acoustic noises, likely attributed to communication signals between the vehicle and the mother ship at 10-second intervals, were also observed (see Fig. 35.3). Since gain modification was occasionally inappropriate during data acquisition, comparisons of backscattering intensity between the port and the starboard sides require careful consideration.

35.3 Observed Results

As shown in Fig. 35.2, the sidescan sonar imagery revealed the presence of numerous areas with high backscattering signals. The boundaries between these areas and terrain with low backscattering were indistinct. Terrains with high backscattering signals covered 42.5 % of the study area and can be classified into two types. One type was characterized by facies with volcanic features typically associated with the neo-volcanic zones of mid-ocean ridges, such as hummocky and sheet lava patterns (Smith et al. 1995; Briais et al. 2000; Sauter et al. 2002; Cann and Smith 2005; Searle et al. 2010). This type of terrain was found in the west of the observed area, on the gentle west-facing slope near the top of the Yokoniwa Rise (Fig. 35.3a). The second type of high backscattering terrain was not
Fig. 35.2 (a) Sidescan sonar imagery collected by the AUV-x2D4. Contours show shipboard multibeam bathymetry data. Areas with high backscattering intensity appear lighter in color. *Blue lines* indicate the tracks of the *Shinkai* 6500 submersible (*OK9-13_leg2 cruise report*, 2009). *Boxes* indicate the areas shown in Fig. 35.3. (b) Shipboard multibeam bathymetry overlaid with interferometric bathymetry data (color). *Boxes* indicate the areas shown in Fig. 35.3. (c) Interpretation map of the sidescan sonar imagery. High backscattering terrains are colored *pale green*. Locations where the small, chimney-like, columnar structures were observed are shown by *red circles*. *Boxes* indicate the areas shown in Fig. 35.3.
associated with any obvious acoustic shadows, suggesting that these areas consisted of flat seafloor (Fig. 35.3b). This type of terrain was distributed throughout the survey area, and might be indicative of flat areas with peridotite outcrops covered by either no or little sediment. Video image of peridotite outcrops covered by little sediment was recorded (dive 1176 of Shinkai6500) in this type of terrain (Fig. 35.4) (Nakamura and Onboard Scientists 2009). The indistinct boundary between the terrains with high and low backscattering signals might reflect a gradual change in the degree of sedimentation between these areas.

Fig. 35.3 Enlarged sidescan sonar images (left), interpretation map (center), and interferometric bathymetry data (right). The legend is the same as that used in Fig. 35.2c. The wedge-shaped lines of high backscattering across tracks are acoustic noise. (a) Volcanic features, (b) linear features in a region of high backscattering without acoustic shadows, and (c) small, columnar, structures with acoustic shadows. Dotted circles in interpretation map indicate acoustic shadows.
Linear features were identified in both types of terrain in the study area (Fig. 35.3a, b). We identified a total of 216 linear features and measured their orientation and length. The orientation of these linear features was primarily parallel or orthogonal to local bathymetric variation (based on bathymetry data obtained by the Seabeam2112 system), and not in the direction of plate motion. Average and standard deviation of the elongation direction were N1°W ± 20°. And average length of the linear features was 0.14 km. At 20°, the standard deviation of the direction was larger than the value of 7.94° along the East Pacific Rise (EPR) 9°05'-10°03'N (based on DSL-120 data, which is 120 kHz sidescan sonar observation data; Asada unpublished data). In addition, the average length of the linear features was less than that along the EPR (0.2 km). These observations suggest that the linear features would not attribute to be tectonic origin, but to reflect either flow channels or gravitationla collapse.

We also observed small columnar structures with acoustic shadows in terrains with high backscattering signals (Fig. 35.3c). Although these structures were interpreted to be hydrothermal chimneys, we did not observe any other indication of hydrothermal activity such as hydrothermal mounds or acoustic anomaly in water column in the observed images.
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