Acoustic characterization of pelagic sediments using sub-bottom profiler data: Implications for the distribution of REY-rich mud in the Minamitorishima EEZ, western Pacific

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Sub-bottom profiling was conducted in the Japanese Exclusive Economic Zone (EEZ) around Minamitorishima Island, western Pacific Ocean, to investigate the features and distribution of mud rich in rare earth elements and yttrium (REY-rich mud). Based on the echogram records, we distinguished three acoustic facies: opaque (O), transparent (T), and layered (L). The O-type facies is acoustically opaque and highly reflective, without visible structures beneath the top surface. The T-type facies is acoustically transparent, with a basal reflector from the acoustic basement. This facies is subdivided into irregular (TI) and smooth (TS) types according to the topography of its upper surface. The irregular surface morphology of the TI-type is generally parallel to the topography of the acoustic basement, whereas the smooth morphology of the TS-type is independent from the basement topography. The L-type facies is characterized by a layered sequence of multiple reflectors. It always overlies the T-type facies. Correlation of the acoustic facies of T- and L-types with lithological and geochemical characteristics of sediment core samples shows that T-type facies correspond to REY-rich mud and L-type facies correspond to non-REY-rich sediment covering REY-rich mud. Distribution of the O-type facies is restricted to seamounts or their immediate vicinity, suggesting that it corresponds to rocky outcrops. The T-type facies (REY-rich mud) mainly occurs in the southern and southeastern part of the Minamitorishima EEZ, whereas the L-type facies (non-REY-rich sediment) is widespread in the northern and western part of the EEZ. Our results reveal that, in the southern and southeastern part of the Minamitorishima EEZ, REY-rich mud lies at a shallow depth below the seafloor without a cover of non-REY-rich sediment. These areas, therefore, should be a primary target for future mining of REY-rich mud.

Keywords: REY-rich mud, Minamitorishima EEZ, sub-bottom profiler, sediment classification, western Pacific

INTRODUCTION

In 2011, a new deep-sea resource of sediment rich in rare earth elements and yttrium (REY), or REY-rich mud, was identified in a pelagic region of the Pacific Ocean (Kato et al., 2011). As a resource, REY-rich mud has five apparent advantages over onshore REY deposits: (1) a large resource potential by virtue of its wide distribution, (2) high REY concentrations with significant enrichment in heavy rare earth elements, (3) a stratiform distribution that allows relatively simple and cost-effective exploration, (4) very low concentrations of radioactive elements such as Th and U, and (5) ease of extraction of REY by acid leaching (Nakamura et al., 2015).

In 2012, REY-rich mud was also reported in the western Pacific, including the Japanese Exclusive Economic Zone (EEZ) around Minamitorishima Island (Kato et al., 2012). This discovery was based on chemical analyses of sediment core samples from two Deep-Sea Drilling
Project (DSDP) and Ocean Drilling Program (ODP) drill sites in the Minamitorishima EEZ (DSDP Hole 198A and ODP Hole 800A). However, the extent of the REY-rich mud layer was poorly constrained due to poor core recovery (Kato et al., 2012). More recently, more than 10 piston cores have been obtained from this area, and chemical analyses of the new piston core samples have demonstrated the presence of REY-rich mud (including highly concentrated REY-rich mud reported by Iijima et al., 2016) less than 10 m below the seafloor (Fujinaga et al., 2016). Even today, however, wide-area distribution of the REY-rich mud in the entire region of the Minamitorishima EEZ remains uncertain.

Sub-bottom profiling has long been used in deepwater environments to investigate the features and distribution of seafloor sediments (e.g., Damuth, 1975, 1980; Ikehara et al., 1990; Kuhn and Weber, 1993; Garcia-Garcia et al., 2004). Sub-bottom profiling provides high-density, continuous information along profiles much more efficiently than piston core sampling, and its penetration depths (up to ~100 m) are much greater than those of piston cores (less than 20 m). In this paper, to clarify the stratigraphic position and distribution of REY-rich mud in the Minamitorishima EEZ, we analyze the results of sub-bottom profiling performed around Minamitorishima Island and integrate them with multibeam sonar bathymetry and beam amplitudes, and with lithological and geochemical data from the piston core samples.

GEOLOGICAL BACKGROUND

The study area is the Japanese EEZ around Minamitorishima Island, which is on the western part of the Pacific plate approximately 1000 km east of the Bonin (Ogasawara) Islands (Fig. 1). The age of the oceanic crust in this area is estimated to be 150–160 Ma on the basis of magnetic lineations (Nakanishi et al., 1992; Tominaga and Sager, 2010) and biostratigraphy (Matsuoka, 1992). A reconstruction of plate motions using Gplates software (http://www.gplates.org; Boyden et al., 2011) suggests that the oceanic crust in the Minamitorishima EEZ originated in the southeastern Pacific Ocean and then moved toward the northwest (Fig. 2). Core samples from DSDP/ODP drill sites within and around the Minamitorishima EEZ have shown that siliceous ooze was deposited on the oceanic crust until 75 Ma (Wightman...
and Kuht, 1992), later becoming chert, which constitutes the acoustic basement in the study area (Heezen et al., 1973). Subsequently, pelagic brown clay was deposited (Wightman and Kuht, 1992). From ~75 Ma to ~25 Ma, the Minamitorishima EEZ passed through the region of REY-rich mud deposition in the central north Pacific (Fig. 2) and then reached the western Pacific, where non-REY-rich sediment predominated (Kato et al., 2011). The plate motion history of the Minamitorishima EEZ described above implies that REY-rich mud is always covered by non-REY-rich sediment in the Minamitorishima EEZ, and thus REY-rich mud may lie somewhat deeper than in the regions where REY-rich mud is now being deposited (Fig. 2) (Kato et al., 2011). Therefore, possible future exploitation of REY-rich mud in this area depends on mapping the regions where REY-rich mud lies at shallow depths below the seafloor.

**METHODS**

Sub-bottom profiling surveys were carried out from 2013 to 2015 during research cruises KR13-02 and KR14-02 of R/V Kairei, and MR13-E02 Leg 2, MR14-E02, MR15-E01 Leg 2, MR15-E01 Leg 3, and MR15-02 of R/V Mirai. Echo-sounder recordings were run continuously during these cruises. Reflection data from the upper sediment column were obtained, covering the entire extent of the Minamitorishima EEZ (Fig. 3). These data were recorded by two different sub-bottom profilers: Sea Beam 2112.004 (SeaBeam Instruments Inc.) and Bathy 2010 (SyQwest Inc.). The Sea Beam 2112.004, which was only used during cruise KR13-02, uses an array of 60 TR-109 projectors, operating at 4 kHz, to form a transmit beam pattern that spans 45° athwartship by 5° in the fore-aft direction. The Bathy 2010 system, used during the other cruises, operates at 3.5 kHz and its main energy is radiated in a cone with an apical angle of about 23°. Sediment thickness was calculated on the basis of a seismic velocity of 1.74 km/s (Heezen et al., 1973).

We also characterized the seafloor topography using multibeam bathymetry and beam intensity data that were collected by the Japan Coast Guard as part of a continental shelf survey from 1998 to 2008 using Sea Beam 210 and Sea Beam 2112 multibeam echo sounders operating at 12 kHz. We removed erroneous soundings from the original raw data reported by Oikawa and Morishita (2009) and gridded the data at 0.1 arc min intervals. The compiled maps are shown in Fig. 4.
Fig. 3. Bathymetric map of the Minamitorishima EEZ showing (A) sub-bottom profiling tracks from seven research cruises and (B) the location of SBP profiles shown in Figs. 5, 6, and 7.
Fig. 4. Compiled multibeam (A) bathymetry and (B) beam amplitude of the Minamitorishima EEZ and surrounding area.
CLASSIFICATION AND CHARACTERIZATION OF ACOUSTIC FACIES

Figure 3B shows the positions of the acoustic profiles presented in Figs. 5, 6, and 7. We classified the sub-bottom profiler data into three acoustic facies on the basis of the shape and pattern of the reflectors: an opaque type (O-type), a transparent type (T-type), and a layered type (L-type).

The O-type facies is acoustically opaque and highly reflective (Fig. 5). This facies is recognized only at or around seamounts, and no structures suggesting deposition of sediment can be identified beneath its surface. The acoustic features together with the distribution suggest that the O-type facies corresponds to hard rock outcrops without soft sediment cover. The T-type facies is acoustically transparent, without any visible internal structure between its upper boundary and a strong reflector from the underlying acoustic basement (Fig. 6A). It can be subdivided into Irregular (TI) and Smooth (TS) types on the basis of the morphology of its upper boundary. The TI-type facies has an irregular upper boundary that is generally, if not always, parallel to the topography of the acoustic basement (Figs. 6 and 7). In contrast, the TS-type facies has a flat upper boundary that is completely independent from the bottom topography (Figs. 6 and 7). Other than their differing upper surfaces, they are identical. The L-type facies is characterized by multiple reflectors that are generally continuous and parallel to the seafloor, but not always parallel to the bottom topography (Fig. 6B). It always overlies the T-type facies, the TS-type in most cases (Fig. 6B).

Along Profile 7A, the uppermost layer changes from L-type to TS-type (Fig. 7A). At the transition, the underlying L-type facies gradually becomes thinner and finally fades out (Fig. 7A). In addition to thickness, the layered structure of the L-type facies also becomes unclear toward the boundary (Fig. 7A). Because the surface morphology of both the L-type and TS-type facies is essentially the same (i.e., smooth), there is no significant change in seafloor topography at the transition between the two acoustic facies (Fig. 7A). Along Profile 7B, the uppermost layer changes from L-type to TI-type (right side of Fig. 7B). As is the case for the transition between the L-type and TS-type facies, the thickness of the underlying L-type facies also gradually reduces and the layered structure becomes obscured at the transition between the TI-type and TS-type facies (Fig. 7B). The surface morphology of the TI-type and L-type facies is, however, significantly different. Reflecting this, at the transition between the TI-type and L-type facies, seafloor topography gradually changes from smooth in the area of the L-type facies to irregular at the area of the TI-type facies, with decreasing thickness of the overlying L-type facies (Fig. 7B). In both cases (TS-type/L-type transition and TI-type/L-type transition), the underlying TI-type and TS-type facies do not change significantly (Figs. 7A and B). In contrast to the gradual change between the TI-type and TS-type facies, the boundary between the TI-type and TS-type facies is generally sharp and clear (Figs. 7B and C), although it becomes complicated in some places (left side of Fig. 7B). Seafloor topography also changes rapidly, reflecting the sharp boundary of the contrasting surface morphologies between the TI-type and TS-type facies (Figs. 7B and C). At the boundary between these two facies, it is also well recognized that the seafloor topography of the TI-type facies region is always higher than that of the TS-type facies region (Figs. 7B and C).

Interestingly, acoustic facies recognized by sub-bottom profiling are generally related to beam amplitude (beam backscattering strengths) of multibeam echo sounding records. As shown in Fig. 8, TS-type and L-type facies show relatively low beam amplitudes (less than 13.5 dB), whereas TI-type facies, as well as O-type facies, are characterized by higher beam amplitudes (higher than 13.5 dB). At the transition between L-type and TS-type facies, these two facies cannot be distinguished by beam amplitude (Fig. 8A). On the other hand, relatively sharp changes in beam amplitude can be observed at the transition between TI-type and TS-type facies (Figs. 8B and C). It should be noted that, at the transition from TI-type to L-type, the beam amplitude decreases gradually (right side of Fig. 8B), probably reflecting the gradual change in the surface topography from irregular (TI-type facies) to smooth (L-type facies), associated with increasing thickness of the L-type facies.
COMPARISON WITH SEDIMENT CORE SAMPLES

In order to identify the sediment types corresponding to the T-type and L-type acoustic facies, we compared these acoustic facies with the lithological and geochemical features of sediment core samples (published in Fujinaga et al., 2016; Iijima et al., 2016). Excluding three very short (<3 m) cores (KR13-02 PC01, KR14-02 PC01 and PC03), we used the data from eleven piston cores from both T-type and L-type facies regions.

From the T-type facies region, seven piston cores were obtained. Among them, three cores (KR13-02 PC02, KR14-02 PC02, and KR14-02 PC04) are from the TI-type facies region. The upper parts of the cores are brown to dark brown clay, composed of clay minerals with minor quantities of quartz and phillipsite; whereas the lower parts are composed of dark brown clay with zeolite and zeolitic clay, and are characterized by an increase in the amount of phillipsite (Fig. 9A). Penetration depths of the piston cores from T-type regions are relatively short (less than 10 m) (Fig. 9A). This is attributed to the presence of a relatively hard portion with ferromanganese micronodules/volcaniclastic fragments at the uppermost part (<5 m) of the cores.

Four cores (KR13-02 PC04, 05, 06, and 07) are from the T2-type facies region. The uppermost parts of the cores are dark brown and brownish-black clay (Fig. 9B), which is composed of clay minerals and minor amounts of...
Fig. 7. Characteristic echograms of transitions between (A) L-type and T_S-type facies, (B) L-type, T_T-type, and T_S-type facies, and (C) T_I-type and T_S-type facies. Red dashed lines represent facies boundaries.
Fig. 8. Comparison of acoustic facies recognized by sub-bottom profiling and beam amplitude of multibeam echo sounding records. Beam amplitude profiles are obtained by sampling the filtered amplitude grid (5-km length median filter) along the SBP survey lines.
Fig. 9. Depth profiles of color, lithology, and REY concentrations of the sediment cores recovered from the (A) T$_1$-type, (B) T$_2$-type, and (C) L-type facies regions (modified from Fujinaga et al., 2016 and Iijima et al., 2016).
Distribution of REY-rich mud in the Minamitorishima EEZ

Quartz. The uppermost clay layer is underlain by brownish-black clay, with zeolite or zeolitic clays that are marked by the presence of significant amounts of phillipsite. Below the zeolitic clay layer, dark brown and brownish-black clays are again presented in the cores. Only in the lowermost parts of KR13-02 PC05 and PC06 are brownish-black clays with zeolite or zeolitic clays again presented. In addition, thin layers of clay with phosphate, and clay with phosphate and zeolite, which are characterized by the presence of considerable amounts of biogenic calcium phosphate (BCP), occur in the cores KR13-02 PC04, PC05, and PC06 (Fig. 9B). These BCP-rich layers correspond exactly to the highly/extremely REY-rich mud layers presented in the cores (Fujinaga et al., 2016; Iijima et al., 2016).

Four piston cores (KR13-02 PC03 and MR13-E02 PC01, 02, and 03) were recovered from the L-type facies region. In MR13-E02 PC01, 02, and 03, the upper part consists of yellowish-brown to brown clay with diatoms (biogenic silica) (Fig. 9C). However, the lower part is mostly brown to dark brown clay that is composed mainly of clay minerals and minor amounts of quartz. In these cores, alternating diatom-rich layers and clay-rich layers are recognized (Fig. 9C). Moreover, these layers are further intercalated by many thin (several centimeter thick) lighter-colored layers that mainly consist of diatoms (Fig. 10). These layered structures recognized in the cores from the L-type facies region could cause the multiple reflectors recognized in the L-type acoustic facies. In the case of one core, KR13-02 PC03, the lithology of the shallow part of the core is not fully understood due to the lack of samples from sections 4–9, caused by damage to the core liner (Fig. 9C). The uppermost part of the core is brown clay, consisting of clay minerals and minor amounts of quartz. However, the deeper part of the core is brownish-black clay that contains a certain amount of phillipsite. The lithological features of the deeper part of KR13-02 PC05 are similar to the cores from the T-type facies region rather than those from the L-type facies region.

Total REY concentrations ($\Sigma$REY) of the cores recovered from the $T_T$-type and $T_L$-type facies regions exceed 400 ppm within 10 m below the seafloor (Figs. 9A and 10).
Fig. 11. (A) Beam amplitude map with observed acoustic facies beneath the sub-bottom profiling tracks. (B) Bathymetric map showing locations of sediment cores used in this study and the distribution of acoustic facies. Uncolored areas in (B) represent the O-type facies.
B). This clearly suggests that the T-type acoustic facies correspond to REY-rich mud. In contrast, $\Sigma^{\text{REY}}$ concentrations of all the samples from the cores MR13-E02 PC01, 02, and 03 (recovered from the L-type facies region) were less than 400 ppm (Fig. 9C), indicating that L-type facies correspond to non-REY-rich sediment. Only the lower part of core KR13-02 PC03 (also from the L-type facies region) exhibits $\Sigma^{\text{REY}}$ concentrations of approximately 400–500 ppm (Fig. 9C), which is consistent with the lithological features of the samples discussed above (i.e., similar to T-type facies mud).

The three cores of MR13-E02 PC01, 02 and 03 are from the northern part of the Minamitorishima EEZ, where L-type facies several tens of meters thick, with clear layered structure, are recognized in the echograms (Fig. 6B). Indeed, REY-rich mud was not recovered in ~15 m piston cores (Fig. 9C). However, the core KR13-02 PC03 is from the transition between the L-type facies and TS-type facies, where the overlying L-type facies becomes thinner (~10 m with the assumed seismic velocity of 1.74 km/s) and the layered structure of the acoustic facies becomes unclear (Fig. 7A). This leads us to consider that the piston core penetrated the thin L-type facies and sampled the underlying REY-rich mud (T-type facies).

The results of the comparison of the acoustic facies with sediment lithology and rare-earth element geochemistry confirm that the T-type facies correspond to REY-rich mud and the L-type facies correspond to overlying non-REY-rich sediment. Furthermore, taking into consideration both the lithological/geochemical results and the reconstructed path of Minamitorishima Island since 75 Ma (after the end of deposition of chert) (Fig. 2), it can be considered that the T-type facies (REY-rich mud) and L-type facies (overlying non-REY-rich sediment) correspond to pelagic mud deposited at the central north Pacific Ocean, and hemipelagic sediment deposited at the western margin of the north Pacific Ocean, respectively.

**Mapping of Acoustic Facies**

We compiled the occurrences of the different acoustic facies on the seafloor along the survey lines (Fig. 11A). As described above, comparing the acoustic facies to the echosounder results showed that the T-type facies is characterized by relatively high beam amplitudes, whereas the TS-type and L-type facies represent lower beam amplitudes. On this basis, we then used the seafloor morphology and beam amplitude maps (Fig. 4) to interpolate between the survey lines and create a facies map for the whole study area (Fig. 11B) as follows.

Taking into consideration the acoustic facies and beam amplitudes observed under the survey lines, we first extracted the tops and slopes of seamounts, because these can be classified as the O-type facies, which correspond to hard rock outcrops without soft sediment cover. Next, we extracted the areas exhibiting relatively high beam amplitudes, corresponding to the observed T-type facies, which can be regarded as the T1-type facies region. Finally, we took the rest of the areas for the L-type or TS-type facies regions. Because these two acoustic facies cannot be distinguished based on the echosounder results, the boundaries between the L-type and TS-type facies were determined based only on the sub-bottom profiler data.

As shown in Fig. 11B, the T-type facies make up the majority of the seafloor in the southern and southeastern part of the Minamitorishima EEZ, whereas the facies are exposed only in small areas in the northern half. These facies are almost entirely of the T1-type. The TS-type facies occurs only in small patches in the southern part of the study area, although we cannot rule out the possibility that other small areas of TS-type facies exist within regions of L-type facies (both facies are characterized by low beam amplitudes and are thus indistinguishable).

As described above, the upper boundary of the T1-type facies is generally parallel to the topography of the acoustic basement, which is quite different from the case for the TS-type facies (Figs. 6 and 7). In addition, at the boundary of the T1-type and TS-type facies, the topography of the seafloor in the T1-type facies regions is always higher than that in the TS-type facies regions (Figs. 7B and C). This leads us to consider the possibility that the irregular surface of the T1-type facies represents the original topography, whereas the smooth surface of the TS-type facies results from erosion of the T1-type facies. Because both the T2-type and T3-type facies are overlain by the L-type facies, the erosion is considered to have occurred before the deposition of the L-type facies.

The L-type facies is extensively exposed on the seafloor in the northern half and western part of the study area. As mentioned above, this facies always overlies the T2-type facies (Figs. 6A, 7A, and 7B). This is consistent with the stratigraphic succession inferred from plate reconstruction (Fig. 2), in which REY-rich mud deposited at the central part of the Pacific Ocean is always covered by non-REY-rich sediment deposited near the present position of the Minamitorishima Island. The absence of the L-type facies in parts of the study area may represent a local hiatus/erosion that occurred during or after the deposition of the L-type facies.

Consequently, in southern and southeastern parts of the Minamitorishima EEZ where the T-type facies presents extensively without cover from the L-type facies (Fig. 11B), REY-rich mud exists at shallow depths (<~10 m). This leads us to propose that these areas should be a primary target for future exploitation of REY-rich mud in the Minamitorishima EEZ. In addition, it should be borne in mind that REY-rich mud is present even in areas...
of L-type facies, although at some depth, because the L-type facies (non-REY-rich sediment) always overlies the T-type facies (REY-rich mud).

CONCLUSIONS

Our analysis of sub-bottom profiler data and sediment core data from the Minamitorishima EEZ provides the following results:

1. Three acoustic facies can be distinguished in the echograms: opaque (O), transparent (T), and layered (L).
2. The T-type facies is subdivided into irregular (T_i) and smooth (T_s) types on the basis of their upper surfaces.
3. The O-type facies is acoustically opaque and highly reflective, without any structures suggesting deposition of sediment. The T-type facies is acoustically transparent and is bounded by a basal reflector from the acoustic basement. The irregular surface morphology of the T_s-type facies is generally parallel with the topography of the acoustic basement, whereas the smooth morphology of the T_i-type is independent from the basement topography. The L-type facies consists of a layered sequence of multiple reflectors that always overlies the T-type facies.
4. The T-type facies (REY-rich mud) is mainly exposed on the seafloor in the southern and southeastern part of the Minamitorishima EEZ, whereas the L-type facies (non-REY-rich sediment) is extensive in the northern and western part of the EEZ. Even in the L-type facies region, however, the T-type facies always exists under the L-type facies.
5. In the southern and southeastern parts of the Minamitorishima EEZ, the T-type facies (REY-rich mud) exists at a shallow depth below the seafloor (≤10 m) without a cover of L-type facies (non-REY-rich sediment). For future mining of REY-rich mud in the Minamitorishima EEZ, therefore, these areas should be a primary target.

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