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Continuous growth of hydrogenetic ferromanganese crusts since 17 Myr ago on Takuyo-Daigo Seamount, NW Pacific, at water depths of 800–5500 m

Akira Usui [a,*], Keisuke Nishi [a], Hisaaki Sato [a], Yoshio Nakasato [a], Blair Thornton [b], Teruhiko Kashiwabara [c], Ayaka Tokumaru [d], Aya Sakaguchi [e], Kyoko Yamaoka [f], Shingo Kato [c], Shota Nitahara [g], Katsuhiko Suzuki [c], Koichi Iijima [c], Tetsuro Urabe [h]

[a] Center for Marine Core Research Institute, Kochi University, Japan
[b] Institute for Industrial Science, University of Tokyo, Japan
[c] R & D Center for Marine Resources, JAMSTEC, Japan
[d] Metals Exploration Dept., JOGMEC, Japan
[e] Division of Chemistry, Tsukuba University, Japan
[f] Geological Survey of Japan, National Inst. Advanced Industrial Science and Technology (AIST), Japan
[g] Tokyo University of Pharmacy and Life Sciences, Japan
[h] Emeritus Professor, University of Tokyo, Japan

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A B S T R A C T

Ferromanganese crusts cover all outcrops on Takuyo-Daigo seamount traversed during remotely operated underwater vehicle (ROV) dives, except in places covered by foraminifera sand. Takuyo-Daigo is a Cretaceous seamount located in the northwest Pacific Ocean. Geological and bathymetric mapping provide the framework for this study. Chemical and mineralogical analyses of the hydrogenetic ferromanganese crusts show temporal and spatial variations typical of those found in previous studies. Outcrops from 800 to 5500 m water depths are covered with ferromanganese crusts up to 105 mm thick. Beryllium isotope dating shows that the crusts have apparently been growing continuously at all water depths, even through the modern oxygen minimum zone (OMZ), contrary to some earlier models for deposition. Growth rates vary from 2.3 to 3.5 mm/Myr, with Fe or Mn fluxes of 0.07–0.11 g/cm^2/Myr since the early-middle Miocene. Co/Mn ratios decrease with water depth while Fe/Mn and other metallic elements increase or show no change, based on the analysis of the uppermost crust surface. This is probably because Co is the most abundant redox-sensitive element derived from seawater that occurs in crusts.

1. Introduction

Northwest Pacific offshore seamounts are expected to be future marine mining sites for ferromanganese (Fe-Mn) crusts, which contain metals necessary for high-tech industries (Hein et al., 2013), such as Co, Ni, Te, Ti, Pt, and rare earth elements (REEs). These crusts are archives of climate and ocean history (e.g. Bayon et al., 2004; Halliday et al., 1998; Koschinsky et al., 1996). However, little is known about their small-scale distribution patterns, mineral diversity and variability, and genetic controls, because of the lack of high-resolution mapping and comparative analyses from various crust deposits (Suave et al., 1989; Glasby, 2000). Hydrogenetic Fe-Mn crusts are condensed stratigraphic sections that have accumulated over millions of years, precipitating from changing compositions of seawater and environment. Comprehensive studies have been lacking, but are critical to more fully understand crust genesis on regional, local, and outcrop scales (Glasby et al., 2007; Hein et al., 2000).

On-site geological observations and microscopic, geochemical, and mineralogical analyses are essential for discussing the depositional processes and environments, as well as for exploration and economic evaluation. Previous manned-submersible and ROV dives have shown a common occurrence of Fe-Mn crusts and bio-diversity on seamounts (Templeton et al., 2009; Schlacher et al., 2014), but only limited

* Corresponding author.
E-mail address: a-usui@kochi-u.ac.jp (A. Usui).

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geological results have been published. Our team, comprising geologists, mineralogists, geochemists, physical engineers and microbiologists, utilized remotely operated underwater vehicles (ROVs) for in situ measurements, observations, and sampling of undisturbed and uncontaminated Fe-Mn crusts at a model seamount, the Takuyo-Daigo seamount (Figs. 1 and 2). The seamount is located within the Japanese Exclusive Economic Zone (100 nm from the Minami-Torishima Island, or Marcus Island) in the northwest Pacific (Fig. 2), and only 300 nm from Japan's licensed area for exploration of Co-rich Fe-Mn crusts under the International Seabed Authority. In 2009, the first Japanese ROV geological survey of Fe-Mn crusts was successfully completed with Hyper-Dolphin 3K of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) at the Takuyo-Daigo seamount (Usui et al., 2011). The ROV cruises to nearby seamounts (Usui et al., 2013) utilized this powerful and efficient tool for seafloor observation and delicate sampling of crusts. A total of 25 ROV dives of the Hyper Dolphin 3K/4K ROV and the Kaiko Mark IV ROV provided excellent seabed views, fine-scale seabed features, and tightly controlled samples for analyses, rather than using a chain-bag dredge, manned submersible, or remotely operated drill (Table 1; Fig. 3). Undisturbed and continuous sampling over five tracks was achieved with a continuous seabed observation with 2–3 m altitude during the R.V. Natsushima Cruise NT09-02 from the southernmost ridge of Takuyo-Daigo seamount, collecting >1 ton of crust material at about 110 sites along approximately a total of 10 km of lines. In addition, real-time monitoring of position, water depth, temperature, salinity, and dissolved oxygen was achieved, and most samples were found to be suitable for millimeter-scale compositional analyses and stratigraphic and magnetostratigraphic laboratory measurements. The intact surface of the crust material, collected without any abrasion and breakdown, was also valuable for microbiological study and structural characterization of surface precipitates.

These studies enabled us to produce a paleoceanographic reconstruction essential for reliable mineral exploration and resource estimate. This is the first successful geological mapping effort using ROV for Fe-Mn crusts, which can be used as a standard method for characterizing hydrogenetic Fe-Mn crust deposits at offshore seamounts.

Our team addressed the following objectives: 1) to characterize the mode of distribution of Fe-Mn crusts on the substrate rocks, and relationships to microtopography and geology; and 2) to understand the growth processes and depositional history of critical metals over the last 10–15 Myr.

2. Geological setting and background

The tectonic theory of mantle plumes suggests that a large number of seamounts and plateaus were formed during the course of intensive upwelling from the Earth's interior during the Cretaceous (85–150 Ma) (Nakanishi et al., 1999; Koppers et al., 2003). Plume convection also formed the hotspot seamount chains between the East Pacific Rise and the northwest Pacific margins, which is a major island-arc system (Fig. 1) (Davis and Pribac, 1997; Koppers et al., 2003). The northwestern Pacific seafloor is characterized by the complex morphology of abundant and huge seamounts, where extensive hydrogenetic Fe-Mn crusts commonly occur (Glasby et al., 2007). The age of these seamounts ranges from Middle to Late Cretaceous. The seamounts and guyots (flat-top seamounts) in the modern northwestern Pacific formed at 10–20°S in the southern hemisphere during the Cretaceous period (Nakanishi and Winterer, 1998), many of which traversed the equator as carbonate reefs followed by subsidence (Larson and Freymueller, 1995; Winterer et al., 1993).

These seamounts are roughly of the same age as the oceanic crust (Koppers et al., 1998, 2003), which ranges from the Late Jurassic to the Late Cretaceous, with age increasing from the seamounts of the Marshall Islands toward the northwest. The Takuyo-Daigo seamount is a member of the North Wake hotspot chain, dated to be between 100 and 120 Myr (Koppers et al., 2003; Tokumaru et al., 2015). Although most seamounts formed during the Cretaceous, younger seamounts formed by hotspots are also distributed across part of the area (Fig. 2).

The thick hydrogenetic Fe-Mn crusts in the mid-Pacific seamounts were first described by German geologists in the 1980s (Halbach et al., 1983; Halbach and Puteanus, 1984). The crusts and nodules are expected to grow unless there is rapid biogenic sedimentation, mass wasting, or tectonic movement (Usui and Someya, 1997; Hein et al., 2000; Usui and Okamoto, 2010; Okamoto and Usui, 2014). Similar analyses have also been conducted for manganese deposits from various areas in the northwestern Pacific (e.g., Usui et al., 1994; Jeong et al., 2000;

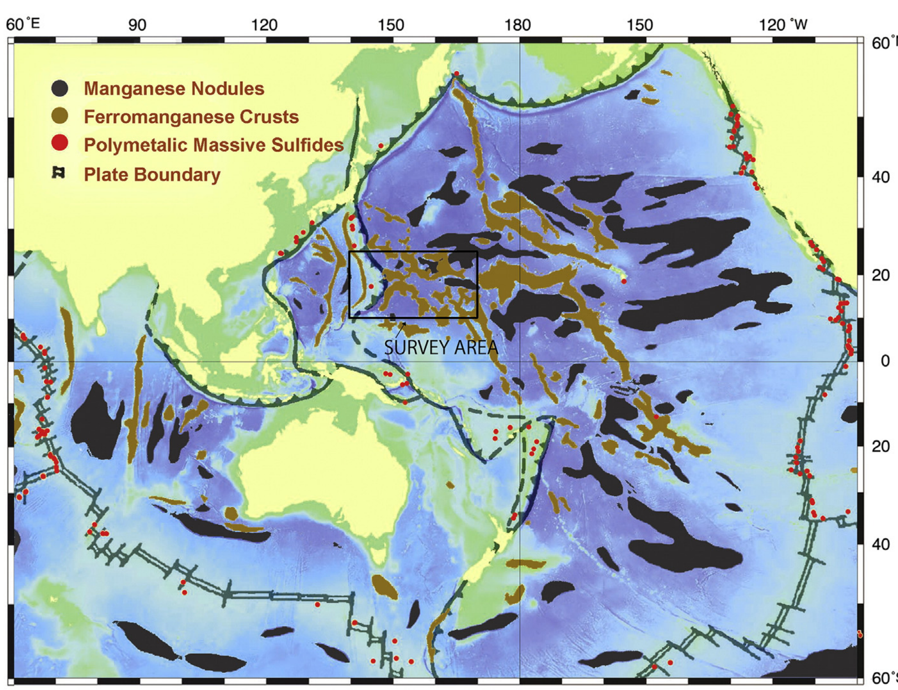

Fig. 1. Distribution of marine minerals of the Pacific.
Modified from Usui (2010).

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