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Magnetic anomaly map of Ori Massif and its implications for oceanic plateau formation

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ABSTRACT

Many oceanic plateaus have been emplaced at or adjacent to mid-ocean ridges. To explain plateau volume and thickened crust compared to normal oceanic crust, hotspot–ridge interaction is commonly assumed, but the manner of interaction remains unclear. The Shatsky Rise oceanic plateau is a large volcanic mountain that formed at a triple junction during Late Jurassic and Early Cretaceous time. Recent drilling and seismic investigations suggest that the intermediate edifice in the rise, Ori Massif, is a central volcano. Paradoxically, magnetic lineations were traced across parts of Ori Massif, implying formation at a spreading ridge. In this study, we examined magnetic anomalies over and around Ori Massif to obtain insights about the formation of this volcanic edifice. Magnetic data from 21 cruises were corrected, combined, and gridded to construct a magnetic anomaly map. Forward and inverse magnetic modeling was done to investigate the magnetic structure of Ori Massif. The results imply that this large volcanic edifice is predominantly characterized by linear magnetic anomalies resulting from alternating normal and reversed polarity magnetization blocks, analogous to magnetic anomalies recorded by spreading-ridges. This magnetic structure is not expected for a central volcano that was built by long runout lava flows, implying that Ori Massif eruptions must have been constrained near the ridge axis. Magnetic bights on the north and south boundaries of Ori Massif imply that it was bracketed by triple junctions, indicating complex ridge tectonics during the formation of Shatsky Rise. The surprising finding that Ori Massif is traversed by coherent linear magnetic anomalies indicates that oceanic plateaus can record seafloor spreading magnetic anomalies despite large crustal thickness. Other oceanic plateaus also record linear magnetic anomalies, implying a link between divergent plate boundaries and oceanic plateau volcanism.

1. Introduction

Shatsky Rise is a basaltic large igneous province (LIP) located in the northwest Pacific Ocean. Linear magnetic anomalies (LMA) recorded by seafloor spreading within and around Shatsky Rise indicate that it formed at the Pacific–Farallon–Izanagi (P–F–I) triple junction during Late Jurassic and Early Cretaceous time (Hilde et al., 1976; Sager et al., 1988; Nakanishi et al., 1999). Recent research indicates that the rise primarily consists of three massive volcanoes (Sager et al., 2013, 2016). This raises an important question: how could such large volcanoes form at mid-ocean ridges, which are themselves enormous volcanoes?

Mid-ocean ridges are formed by linear volcanism confined to the plate boundary (Macdonald, 1982), whereas large volcanoes, formed by magmatic eruptions from a central vent or vents, construct edifices with a radial pattern (Mitchell, 2001). How do these processes interact at Shatsky Rise? Many oceanic plateaus appear to be formed at mid-ocean ridges, such as Iceland and the Azores Plateau in the Atlantic (Gente et al., 2003; Foulger et al., 2005), the Magellan Plateau, Hess Rise, and Ontong Java Nui (Manihiki Plateau, Hikurangi Plateau, and Ontong Java Plateau) in the Pacific (Sager, 2005; Taylor, 2006), and Rio Grande Rise (Cande et al., 1988), in the Atlantic. Thus, Shatsky Rise may be representative

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of many oceanic plateaus, so the study of this geologic setting can provide important clues for understanding oceanic plateau formation and mantle melting.

Magnetic anomalies over oceanic plateaus have the potential to provide constraints on their formation. Mid-ocean ridges record linear polarity zones in the upper crust as it cools near the ridge crest and is magnetized in the direction of the ambient magnetic field. This process leaves behind a tell-tale pattern of LMA that have been used to determine the age of the seafloor and the past positions of mid-ocean ridges (e.g., Vine and Matthews, 1963; Heirtzler et al., 1968). The observation of LMA implies that volcanism is localized to a narrow, linear eruption zone (Gee and Kent, 2007). Additionally, magnetic modeling has been applied to seamounts to obtain paleomagnetic data and constraints on eruption history (e.g., Harrison et al., 1975). Typically, this technique assumes that the seamount is homogeneously magnetized or has limited changes in magnetization structure. Sager and Han (1993) applied this technique to Tamu Massif (the largest volcanic edifice of Shatsky Rise) and concluded that much of this edifice was formed within a single polarity period. In contrast, Shatsky Rise contains many LMA, including two interpreted to be crossing Ori Massif (Nakanishi et al., 1999).

This dichotomy in magnetic anomaly style suggests further study of Shatsky Rise magnetic anomalies is needed. Here we examine the magnetic anomaly structure of Ori Massif, the second largest edifice within Shatsky Rise. We combine new and old magnetic data over Ori Massif to create a magnetic anomaly map. Magnetic inversion modeling was used to obtain an unbiased estimate of the Ori Massif magnetization structure, which helps interpreting the magnetic anomaly map and sheds new light on the formation of this plateau.

1.1. Shatsky Rise geologic setting

The Shatsky Rise is a large basaltic mountain range located ~1500 km east of Japan, formed during the Late Jurassic and Early Cretaceous (e.g., Nakanishi et al., 1999; Sager et al., 1988, 1999). LMA suggest that Shatsky Rise is located at the intersection of the SW–NE trending Japanese lineations and the NW–SE trending Hawaiian lineations. The intersections of these magnetic anomalies (i.e., magnetic bights) indicate the past locations of the P–F–I (Pacific–Farallon–Izanagi) triple junction from Late Jurassic through Mid-Cretaceous time (Larson and Chase, 1972; Sager et al., 1988; Nakanishi et al., 1999). The triple junction migrated northeast along the axis of Shatsky Rise and jumped northeastward at least nine times during the rise emplacement (Nakanishi et al., 1999). Curved and discordant anomaly patterns also imply that several microplates may have been annexed to the Pacific plate during its formation (Sager et al., 1988; Nakanishi et al., 1999).

With an area of $\sim 5.3 \times 10^5$ km^2 (Zhang et al., 2016), Shatsky Rise consists of three large edifices (Tamu, Ori and Shirshov massifs) and a volcanic ridge (Papanin Ridge) (Fig. 1). The volume of the edifices progressively decreases from Tamu Massif to Papanin Ridge (Sager et al., 1999). Ori Massif, with an area of $\sim 3.3 \times 10^4$ km^2, is comparable in area to the Island of Hawaii ($\sim 3.0 \times 10^4$ km^2). Recent studies of coring data from Integrated Ocean Drilling Program (IODP) Expedition 324 suggest waning of volcanism with time as massive flows are thickest on the largest and oldest edifice, Tamu Massif, but are thinner and fewer on Ori Massif and lacking on Shirshov Massif (Sager et al., 2016). Cores drilled from Ori and Shirshov massifs are mainly characterized by pillow flows which indicate modest effusion rate (Sager et al., 2011).

Age constraints for Shatsky Rise are few because many samples are highly altered and not suitable for radiometric dating. Basalt flows cored from Tamu Massif at Ocean Drilling Program (ODP) Site 1213 (Fig. 1) yielded an Ar^{40}–Ar^{39} radiometric age of 144.6 ± 0.8 Ma (Mahoney et al., 2005). Similar radiometric dating from IODP Site U1347 (Fig. 1), also on Tamu Massif, produced an age of 143–145 Ma (Geldmacher et al., 2014; Tejada et al., 2016). These dates are in good agreement with the ages of the magnetic isochrons that bracket Tamu Massif (M21–M19, 149–145 Ma; Ogg, 2012), indicating that Tamu Massif formed near the triple junction spreading ridges. Late-stage or rejuvenated volcanism is also suggested as the uppermost flows of Site U1347 produced a younger age of ~139 Ma and the Toronto ridge, located near the summit of Tamu Massif, gave an age of ~129 Ma (Geldmacher et al., 2014; Tejada et al., 2016). As for Ori Massif, igneous rocks from IODP Site U1350, located on the southeast flank of the massif, gave a radiometric Ar^{40}–Ar^{39} date of ~134 Ma (Heaton and Kroppers, 2014). This age is ~4–6 Myr younger than magnetic anomalies M16 and M15 which cross Ori Massif (Nakanishi et al., 1999; Ogg, 2012). Possible factors for this discrepancy are (1) that Site U1350 lavas recorded late-stage volcanism, (2) that the M-anomaly time scale is inaccurately calibrated (Ogg, 2012), or (3) that the date is inaccurate.

Recent multichannel seismic data give insights into the structure of the edifices within the Shatsky Rise. Both Tamu and Ori massifs are seen to be large central volcanoes because sub-parallel lava packages are imaged dipping outward from the summits (Sager et al., 2013; Zhang et al., 2015). The crust beneath Ori Massif is estimated to be ~25 km thick using reflection imaging of the Moho and isostatic modeling (Zhang et al., 2016).

1.2. Study rationale and motivation

Nakanishi et al. (1999) mapped LMA within and around Shatsky Rise. Their isochron map shows two (M16 and M15) crossing Ori Massif, similar to those in nearby basins. This is an unexpected result considering the thickness of Ori Massif crust and the fact that seismic data indicate it to be a massive volcano. Ori Massif was not the focus of the Nakanishi et al. (1999) study, the magnetic data were shown at low detail, and the LMA crossing Ori Massif and their implications were not mentioned. Furthermore, Nakanishi et al. (1999) traced LMA by picking and correlating magnetic anomaly peaks, a subjective process. Because of the important implications of the LMA, the data deserve reanalysis. In this study, we combine new data collected during the past two decades with older data and take a more objective approach by gridding and plotting a magnetic anomaly map and using this product as input to magnetic modeling routines. The objective is to understand the magnetization structure of Ori Massif and thereby obtain clues about its formation.

2. Data and methods

2.1. Magnetic dataset

Our data set builds on that of Nakanishi et al. (1999) with the addition of four recent cruises, making a total of 21 cruises with ~9805 km of magnetic data (Table 1). This data set is heterogeneous because it spans a period of 51 yr (1964–2015), during which navigation systems have greatly improved. Moreover, ship track lines are unevenly distributed (Fig. 2) with most of the data concentrated over the summit of Ori Massif but sparse and irregular in the flank regions.

Magnetic data were processed with the following steps. (1) Outliers and spurious readings caused by instrumental errors and transcription errors in old cruises were identified and deleted by visual inspection. (2) Data were adjusted to the International Geomagnetic Reference Field 11 (IGRF11) (Finlay et al., 2010) to remove the internal magnetic field and its time variations and produce