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The seismic Moho structure of Shatsky Rise oceanic plateau, northwest Pacific Ocean

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ABSTRACT

Oceanic plateaus are large igneous provinces formed by extraordinary eruptions that create thick oceanic crust, whose structure is poorly known owing to the lack of deep-penetration seismic data. Multichannel seismic (MCS) reflection and wide-angle refraction data allow us to show Moho structure beneath a large part of the Shatsky Rise oceanic plateau in the northwest Pacific Ocean. Moho reflectors in the two data sets can be connected to trace the interface from the adjacent abyssal plain across much of the interior. The reflectors display varied character in continuity, shape, and amplitude, similar to characteristics reported in other locations. Beneath normal crust, the Moho is observed at ~13 km depth (~7 km below the seafloor) in MCS data and disappears at ~20 km depth (~17 km below the seafloor) beneath the high plateau. Moho at the distal flanks dips downward towards the center with slopes of ~0.5°–1°, increasing to 3°–5° at the middle flanks. Seismic Moho topography is consistent with Airy isostasy, confirming this widely-applied assumption. Data from this study show that crustal thickness between the massifs in the interior of the plateau is nearly twice normal crustal thickness, despite the fact that this crust records apparently normal seafloor spreading magnetic lineations. The Moho model allows improved estimates of plateau area (5.33×10^5 km^2) and volume (6.90×10^6 km^3), the latter assuming that the entire crust was formed by Shatsky Rise volcanism because the massifs formed at spreading ridges. This study is unique in showing Moho depth and structure over an extraordinarily large area beneath an oceanic plateau, giving insight to plateau structure and formation.

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1. Introduction

The geometry of the Mohorovičić discontinuity (also known as Moho) is important for understanding crustal structure and thickness, the degree and style of isostatic compensation, and magmatic flux from mantle to crust (Steinhart, 1967). The structure of the Moho is still poorly known at most places on Earth because of the scarcity of deep penetration seismic data. Whereas the Moho depth is often inferred by assuming a model of isostatic compensation based on the topography of surface features (e.g., Kearey et al., 2009), seismic measurement is the only direct way to measure Moho structure and assess the validity of isostatic models.

When crustal thickness is on the order of tens of km, our knowledge of the seismic Moho comes primarily from wide-angle seismic refraction (Braile and Chiang, 1986; Mooney and Brocher, 1987). The seismic Moho is defined as a first-order velocity discontinuity where P-wave velocities increase abruptly from crustal values (<7.2 km s^{-1}) to mantle values (>8.0 km s^{-1}) (Rohr et al., 1988; Holbrook et al., 1992). The seismic Moho may not correspond to the petrologic Moho, which is the boundary between non-peridotitic crustal rocks (with gabbroic composition) and olivine-dominated mantle rocks (with peridotitic composition) (Mengel and Kern, 1992; Nedimovic et al., 2005). The advantage of wide-angle refraction for plumbing the Moho is that it can often be inferred from travel time and amplitude differences between the mantle and crustal phases. In some situations, Moho depth can also be estimated directly from seismic waves reflected from the Moho (*PmP* arrivals) (Holbrook et al., 1992). A drawback of this technique is that only a smoothed version of the Moho geometry is inferred from refraction data.

Near-vertical incidence multichannel seismic (MCS) profiling is usually designed to image upper crustal structure, but sometimes reflections from the Moho are observed. MCS data have the advantage of delineating Moho geometry in greater detail than provided by refraction data. Typically the Moho is observed where the crust

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is thin, such as areas of normal oceanic crust (e.g. Kent et al., 1994; Aghaei et al., 2014). In areas with thick crust, such as continental crust, seamounts, and oceanic plateaus, the Moho reflection is suppressed by attenuation unless powerful seismic sources are used. Moho reflections are often intermittent because the near-vertical incidence of seismic waves limits the imaging efficiency at great depths (Mutter and Carton, 2013). Hence, a combination of MCS and wide-angle refraction data can produce a more comprehensive seismic model of the crust than with one method alone (e.g. Mjelde et al., 1993; Gallart et al., 1995; Lizarralde and Holbrook, 1997).

Oceanic plateaus are large submarine mountains, many of which were formed by extensive basaltic volcanism (Coffin and Eldholm, 1994). Wide-angle seismic refraction surveys reveal that they have anomalously thick crust, typically 20–40 km in thickness (Gladczenko et al., 1997; Korenaga, 2011; Charvis and Operto, 1999; Gohl and Uenzelmann-Neben, 2001; Parsiegla et al., 2008; Korenaga and Sager, 2012; Pietsch and Uenzelmann-Neben, 2015). Such thick crust is often compensated nearly completely by Airy isostasy (Sandwell and MacKenzie, 1989). This is because large loads on the lithosphere exceed its yield strength (Watts and Ribe, 1984), particularly when plateaus are formed on the thin lithosphere at or near mid-ocean ridges (Coffin and Eldholm, 1994; Sager, 2005).

Shatsky Rise, located in the northwest Pacific Ocean, ∼1500 km east of Japan, is one of the largest oceanic plateaus. Until recently, its crustal structure was poorly known owing to the lack of modern deep-penetration seismic data. New marine seismic data were recently acquired on two cruises in 2010 and 2012 aboard R/V *Marcus G. Langseth* (MGL1004, MGL1206). During the 2010 cruise, wide-angle seismic refraction data were collected by ocean bottom seismometers (OBS) over the Tamu Massif, the largest edifice within Shatsky Rise (Fig. 1), allowing the construction of a tomographic cross section showing the maximum crustal thickness of ∼30 km (Korenaga and Sager, 2012). On both cruises, two-dimensional MCS reflection profiles were collected over the southern half of Shatsky Rise, giving a detailed picture of the upper crustal structure and showing that Tamu Massif is a massive, single shield volcano with low flank slopes (Sager et al., 2013; Zhang et al., 2015). MCS profiles over Ori Massif, the second largest volcano within Shatsky Rise (Fig. 1), show a similar structure (Zhang et al., 2015). In this paper, we combine MCS and OBS Moho observations from these seismic data to reveal a more complete view of crustal structure beneath the plateau. Shatsky Rise exhibits nearly zero free-air gravity anomaly (Sandwell and Smith, 1997), implying isostatic equilibrium. Thus, the plateau Moho structure is expected to show crustal thickening consistent with the Airy mechanism of isostatic compensation, an assumption that can be tested with the seismic MCS data in this study.

2. Formation and evolution of Shatsky Rise

Shatsky Rise has a reported area of 4.8×10^5 km^2 and consists mainly of three large volcanic highs, Tamu, Ori, and Shirshov massifs, and a low ridge, Papanin Ridge, extending from its north side (Fig. 1; Sager et al., 1999). Elevations are 3–4 km above the surrounding seafloor, which lies at ∼6–5.5 km water depth. The shallowest point is ∼1950 m water depth at the summit of Toronto Ridge, a late stage eruptive feature that rises from the top of Tamu Massif (Sager et al., 1999).

Because it is situated exactly at the junction of two Mesozoic magnetic lineation sets, the Japanese and Hawaiian lineations (Larson and Chase, 1972), Shatsky Rise must have erupted at a triple junction, likely with a ridge-ridge-ridge geometry (Hilde et al., 1976; Sager et al., 1988; Nakanishi et al., 1999). Initial Shatsky Rise eruptions began with Tamu Massif, which was emplaced just after the time of adjacent magnetic chron M21 (Nakanishi et al., 2015) (149 Ma, here and elsewhere using the time scale of Gradstein et al. (2012) for magnetic lineation ages), which is consistent with radiometric dates of 144.6 ± 0.8 Ma (Mahoney et al., 2005) and 144.4 ± 1.0 Ma (Heaton and Koppers, 2014) from basalt cores recovered, respectively, at Ocean Drilling Program (ODP) Site 1213 on the south flank of Tamu Massif and Integrated Ocean Drilling Program (IODP) Site U1347 on the east flank (Fig. 1). Toronto Ridge is ∼15 Myr younger than the Tamu Massif shield (Heaton and Koppers, 2014) and other similar ridges and parasitic cones occur on the Shatsky Rise massifs (Sager et al., 1999), implying post-shield building volcanism, but it appears that this late-stage volcanism was small in volume and did not greatly postdate the main edifice. Thus, the crustal structure of Shatsky Rise probably did not change appreciably after the primary eruptions.

Magnetic anomalies show that the age of the seafloor becomes younger to the NE and the axis of Shatsky Rise coincides with the triple junction until chron M1 (126 Ma) (Fig. 1). This age progression implies that Ori and Shirshov massifs and Papanin Ridge were emplaced progressively along the triple junction path after it moved NE away from Tamu Massif (Sager et al., 1999; Nakanishi et al., 1999). Tamu Massif may have formed rapidly, within a period of 3–4 million years or less (Sager and Han, 1993; Heaton and Koppers, 2014); however, based on the span of magnetic anomalies, it took ∼23 million years for the entire ∼2000 km length of Shatsky Rise to form.

Shatsky Rise is mostly covered by thin pelagic sediments of ≤∼300 m (Ludwig and Houtz, 1979), except for thick sediment accumulations up to ∼1 km thickness that are limited to the summits of the massifs (Sliter and Brown, 1993; Sager et al., 1999). Basaltic lava flow samples were recovered from Shatsky Rise at ODP Site 1213 (Shipboard Scientific Party, 2001; Koppers et al., 2010) and at IODP sites U1346, U1347, U1349 and U1350 (Sager et al., 2010, 2011), confirming the volcanic nature of this oceanic plateau.

3. Data and methods

Prior to the two recent seismic cruises, no digital, deep penetration seismic data had been collected over Shatsky Rise. Two OBS refraction lines (Korenaga and Sager, 2012) were obtained over Tamu Massif and twelve MCS reflection profiles, totaling 3350 km in length (Zhang et al., 2015), were recorded over the southern half of Shatsky Rise (Fig. 1). Both refraction and reflection data were acquired using a source array with 36-airguns (volume 108.2 L), but with 162-m and 50-m shot spacing, respectively. The refraction data were analyzed by joint reflection and refraction travel time tomography, defining crustal structure beneath center of Tamu Massif (Korenaga and Sager, 2012). For the reflection study, a 6-km-long, 468-channel streamer (hydrophone array) with a 12.5-m group interval was used as the receiver. The streamer and airgun array were towed in 9 m depth beneath the sea surface, with a 172-m offset from the source to the first channel. The raw data had a primary energy frequency range of 2–206 Hz. The reflection data were processed into time sections with common MCS processing steps, resolving the upper crustal structure to depths of 1–4 km (Sager et al., 2013; Zhang et al., 2015). All digitized interfaces (seafloor, igneous basement and the Moho) were picked in phase with the maximum positive amplitude of the reflection.

Although a Moho reflector was commonly observed in the MCS profiles with standard processing, these data were reprocessed using constant velocity stacks (CVS) to enhance these reflections. CVS is a processing method that uses a constant velocity for the entire time domain to stack the CMP traces, whereas normal CMP stacking uses a depth-dependent velocity model from semblance

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