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Review

Geophysical implications for the formation of the Tamu Massif–the Earth's largest single volcano–within the Shatsky Rise in the northwest Pacific Ocean

Jinchang Zhang [a,b], Jie Chen [c,d,e,*]

[a] Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
[b] Key Laboratory of Marine Mineral Resources, Ministry of Land and Resources, Guangzhou 510075, China
[c] South China Sea Institute of Planning and Environmental Research, State Oceanic Administration, Guangzhou 510310, China
[d] Key Laboratory for Ecological Environment in Coastal Areas, State Oceanic Administration, Dalian 116023, China
[e] Key Laboratory of Integrated Marine Monitoring and Applied Technologies for Harmful Algal Blooms, State Oceanic Administration, Shanghai 200137, China

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ABSTRACT

Recent geophysical research programs survey the Tamu Massif within the Shatsky Rise oceanic plateau in the northwest Pacific Ocean to understand the formation of this immense volcano and to test the formation hypotheses of large igneous province volcanism. Massive sheet basalt flows are cored from the Tamu Massif, implying voluminous eruptions with high effusion rates. Seismic reflection data show that the Tamu Massif is the largest single volcano on Earth, characterized by a central volcanic shield with low-gradient flank slopes, implying lava flows emanating from its center and spreading massive area on the seafloor. Velocity model calculated from seismic refraction data shows that crustal thickness has a negative correlation with average velocity, implying a chemically anomalous origin of the Tamu Massif. Seismic refraction and reflection data reveal a complete crustal structure across the entire volcano, featured by a deep crust root with a maximum thickness of ~30 km, and Moho geometry is consistent with the Airy Isostasy. These recent findings provide evidence for the two end-member formation models: the mantle plume and the plate boundary. Both are supported by some results, but both are not fit with some either. Consequently, plume–ridge interaction could be a resolution that awaits future investigations.

1. Introduction

1.1. Oceanic plateau formation hypotheses: plume versus plate

Oceanic plateaus, the largest of the large igneous provinces (LIPs) in the deep ocean basins, are broad, more or less flat-topped undersea mountains that typically cover areas of millions of square kilometers, have volumes of millions of cubic kilometers, and rise thousands of meters above surrounding seafloor [1]. Such broad, giant volcanic edifices are mostly formed by basaltic volcanism and associated igneous intrusions, which implies massive eruptions of magma from the mantle to the lithosphere [1,2]. The formation of oceanic plateau can therefore be important to indicate both regional tectonic events and mantle behavior and geodynamics [3]. Unfortunately, oceanic plateau volcanic processes are still poorly understood because oceanic plateaus are hidden beneath the sea in remote locations far from land and are often covered by thick sediment layers, all of which make it difficult to sample and study oceanic plateaus in great detail.

Oceanic plateaus are such large volcanic features that must have formed from some anomalous mantle process, such as a mantle plume [3], but there is ongoing debate about their origins. Several mechanisms have been proposed for the formation of oceanic plateaus, but none explains all observed features [4]. One class of mechanisms is based on the mantle plume hypothesis. Many workers think that a nascent plume ascends from deep in the mantle and arrives at the base of lithosphere to form an oceanic plateau (the plume head hypothesis) [1,5–7]. Although this widely-accepted model can explain some features of large oceanic plateaus, it still needs further modification and alternative development to incorporate additional complexities. For example, the bulk of the Ontong Java Plateau never reached sea level contrary to the expectation from the dynamic uplift of a plume head [8]. The other class of mechanisms, the plate model, involves decompression melting of fertile upper mantle material at plate boundaries or cracks in the plates, such as leaky transform faults [9], spreading ridge reorganizations [4,10] and where changes in plate

* Corresponding author.
E-mail address: jchen@scsb.gov.cn (J. Chen).

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stress weaken the lithosphere [11]. It is, however, hard to explain the huge volumes of magma required for building large oceanic plateaus.

1.2. Shatsky Rise: a large oceanic plateau formed at a mid-ocean-ridge triple junction

Among oceanic plateaus all around the world, the Shatsky Rise in the northwest Pacific Ocean (Fig. 1), is unique because it has a combination of factors that make it important for studying the problem of plateau formation. Firstly, it is the third largest oceanic plateau on Earth (after the Ontong Java Plateau and the Kerguelen Plateau), and has an area of 4.8×10^5 km^2 [3], which makes it big enough for a good example of large oceanic plateaus, but not so large as to be extremely difficult to study. Its original size may have been approximately double its current size because it was formed at a spreading ridge triple junction [14], so half may have been carried away on other plates that are now subducted. Secondly, the Shatsky Rise formed at a time of magnetic reversals, during the Late Jurassic and the Early Cretaceous. This means that the evolution of coeval oceanic spreading ridges, near which it formed, can be traced through time [14]. In contrast, many other oceanic plateaus in the Pacific Ocean were formed during the Cretaceous Normal Superchron or the Cretaceous Quiet Period, a time during which the magnetic field ceased reversing, making it impossible to reconstruct the tectonic history of those plateaus from magnetic anomalies. Thirdly, it was created at a ridge–ridge–ridge triple junction [9,14,20,21], suggesting a link to a plate boundary (spreading ridge) and allows tests of the mantle plume versus the plate boundary processes as mechanisms of oceanic plateau formation. In addition, volcanism on the Shatsky Rise is laterally spread out and sediments deposited on the flanks are thin, which makes it easier to sample volcanic basement and to see the morphology of the plateau from bathymetry data. Thus, the Shatsky Rise combines several salutary situations that make it an important plateau to study for understanding its formation.

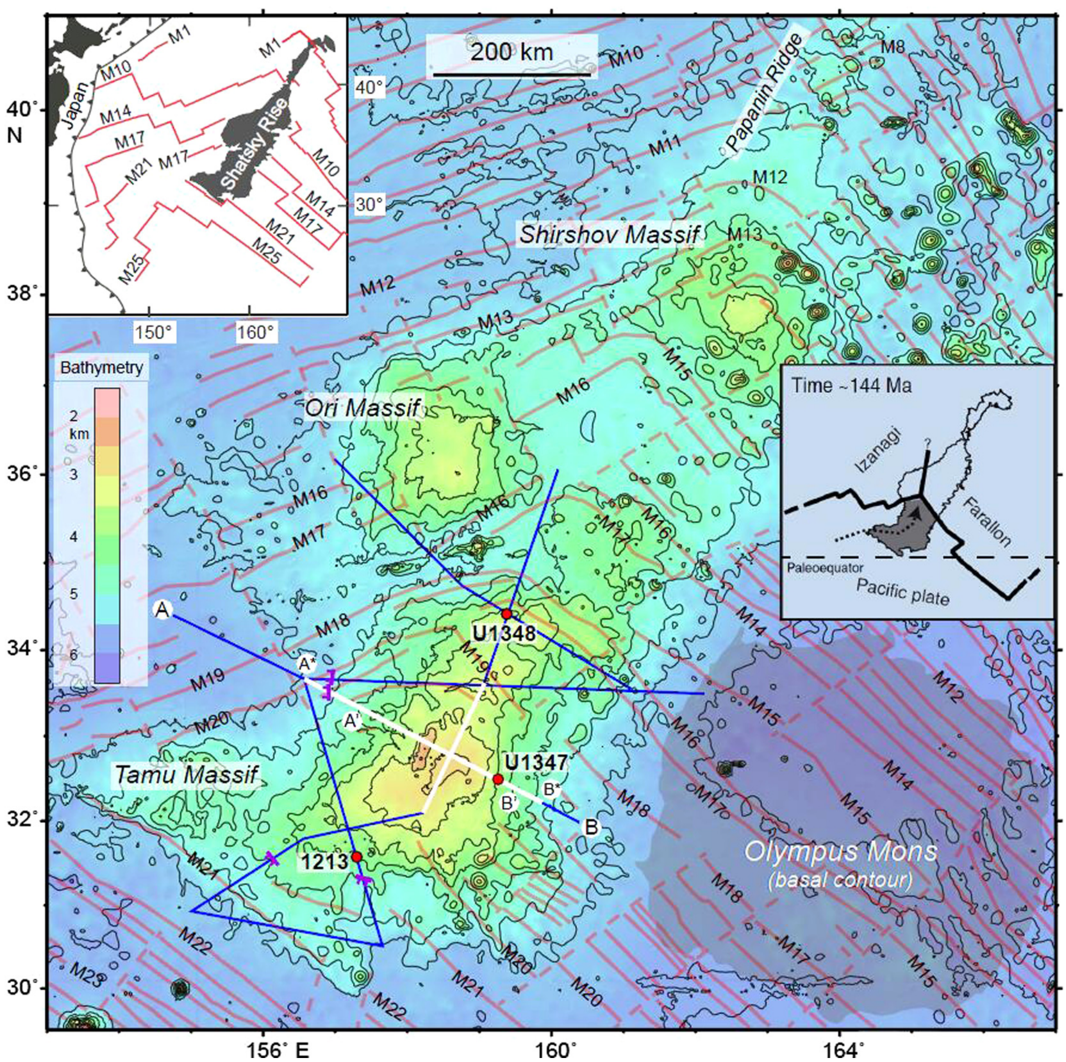

Fig. 1. Bathymetry and tectonic map of southern Shatsky Rise, modified from Sager et al. [12]. Bathymetry is from satellite-predicted depths with 500 m contours [13]. Red lines denote magnetic lineations and red dashed lines denote fracture zones [14]. Blue lines show MCS reflection profiles, whereas white lines show wide-angle refraction sections. Filled red circles denote locations of ODP and IODP drill sites. Inset in upper left depicts the location of Shatsky Rise relative to Japan and nearby subduction zones (toothed lines) and the wider magnetic pattern. Inset in middle right shows reconstructed location in the central Pacific with respect to plate boundaries at ~144 Ma during the time when Tamu Massif was formed (gray infill), and triple junction separates Izanagi, Farallon and Pacific plates with stippled arrow illustrating the triple junction migration path [15–17]. Gray area in lower right shows the footprint of Olympus Mons on Mars at the same scale. Heavy purple tick marks (ticks on downthrown side) show the locations of large down-to-basin faults seen on multi-beam bathymetry and MCS profiles [18]. The fault strikes are estimated from bathymetry data [19]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)