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"Equator Crossing" of Shatsky Rise?: New insights on Shatsky Rise tectonic motion from the downhole magnetic architecture of the uppermost lava sequences at Tamu Massif

Masako Tominaga,[1,2] Helen F. Evans,[3] and Gerardo Iturrino[4]

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[1] Shatsky Rise is a Large Igneous Province (LIP) currently located in the northwestern Pacific. New downhole magnetic logging data from Integrated Ocean Drilling Program (IODP) Hole U1347A at Tamu Massif of Shatsky Rise captured the magnetic architecture in the uppermost lava sequence, providing a rare opportunity to investigate a time series of the intra-plate volcanism in conjunction with the Pacific plate construction history centered at the triple junction. Logging data results indicate that Tamu Massif was formed during normal polarity periods south of the paleoequator and crossed the equator at some point in the M19–M17 period. Combining these new observations with previous interpretations of the massif's tectonic history, a time series of the latitudinal tectonic motion of a LIP and the underlying Pacific plate during the plateau formation is postulated. **Citation:** Tominaga, M., H. F. Evans, and G. Iturrino (2012), "Equator Crossing" of Shatsky Rise?: New insights on Shatsky Rise tectonic motion from the downhole magnetic architecture of the uppermost lava sequences at Tamu Massif, *Geophys. Res. Lett.*, *39*, L21301, doi:10.1029/2012GL052967.

1. Introduction

[2] Magmatism plays a central role in driving heat, chemical, and water cycles that influence the atmosphere, hydrosphere, lithosphere, and the Earth's interior. LIPs are formed by rapid, voluminous eruption of magma associated with the ascent of a magmatic plume or extended thermal anomalies in Earth's mantle [e.g., *Courtillot et al.*, 2003]. Advancing our knowledge of the origin and evolution of LIPs is thus imperative in our understanding of mantle geodynamics and changes in the Earth's systems over time. In the past, several attempts have been made to address LIP formation dynamics through scientific ocean drilling at the Kerguelen [*Coffin et al.*, 2000] and Ontong Java plateaus [*Mahoney et al.*, 2001]. However, fundamental questions about the role of volcanism in forming LIPs and its evolution over time in the intra-plate tectonic settings remain largely unknown because most LIPs were formed during the Cretaceous Normal Superchron when no distinctive magnetic anomalies were recorded in the basement to trace the formation of LIPs in relation to plate motions [e.g., *Mahoney et al.*, 2001].

[3] Previously identified magnetic lineations around Shatsky Rise suggest that this plateau was formed at the Pacific-Farallon-Izanagi ridge-ridge-ridge triple junction, which expanded the Pacific plate during Late Jurassic to Early Cretaceous before the Cretaceous Normal Superchron [*Nakanishi et al.*, 1989]. The magnetic lineations document the formation of Shatsky Rise with clear age progression from south to north including some ridge jumps [*Sager et al.*, 1988]. Although these magnetic lineations provide the first-order Pacific plate tectonics around Shatsky Rise, how this tectonic evolution coincided with and related to the formation of this LIP is unclear. In this paper, we present a new downhole magnetic architecture from IODP Expedition 324 Hole U1347A for the uppermost lava sequence drilled at Tamu massif. By combining these data with ODP Hole 1213B results, we investigate how the plateau developed over time in relation to the northward motion of the triple junction forming the Pacific plate.

2. Background

[4] Shatsky Rise is a LIP located in the northwestern Pacific, approximately 2000 km east of the Japan Islands (Figure 1). The magma generated at the Rise produced an estimated volume of ~4.3×10^6 km^3 and erupted during a relatively short period of time, during which three massifs were constructed: Tamu, ORI, and Shirshov [*Nakanishi et al.*, 1999]. The tectonic history of Shatsky Rise is known based on the magnetic lineations that surround the plateau and in some places transect the plateau [*Nakanishi et al.*, 1989] (Figure 1). Morphology and apparent age progression of magnetic lineations together indicate that the Rise volcanism was spatially expansive, perhaps owing to rapid movement of the Pacific plate over the source mantle [*Sager*, 2005].

[5] Tamu Massif occupies the southernmost part of the Shatsky Rise (Figure 1), and is thought to have formed during the M21–M16 period by anomalously volumetric magma upwelling [*Sager*, 2005]. Two basement sites were drilled at flanks of this massif: ODP Hole 1213B on the southern flank during ODP Leg 198 [*Bralower et al.*, 2002] and IODP Hole U1347A on the southeastern flank during IODP Expedition 324 [*Sager et al.*, 2010]. The nearest magnetic lineations to ODP Hole 1213B and IODP Hole U1347A are M21 and

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[1] Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.
[2] Now at Department of Geological Sciences, Michigan State University, East Lansing, Michigan, USA.
[3] Department of Marine Geology and Geophysics, Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.
[4] Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.

Corresponding author: M. Tominaga, Department of Geological Sciences, Michigan State University, 206 Natural Science Bldg., East Lansing, MI 48824, USA. (tominaga@msu.edu)

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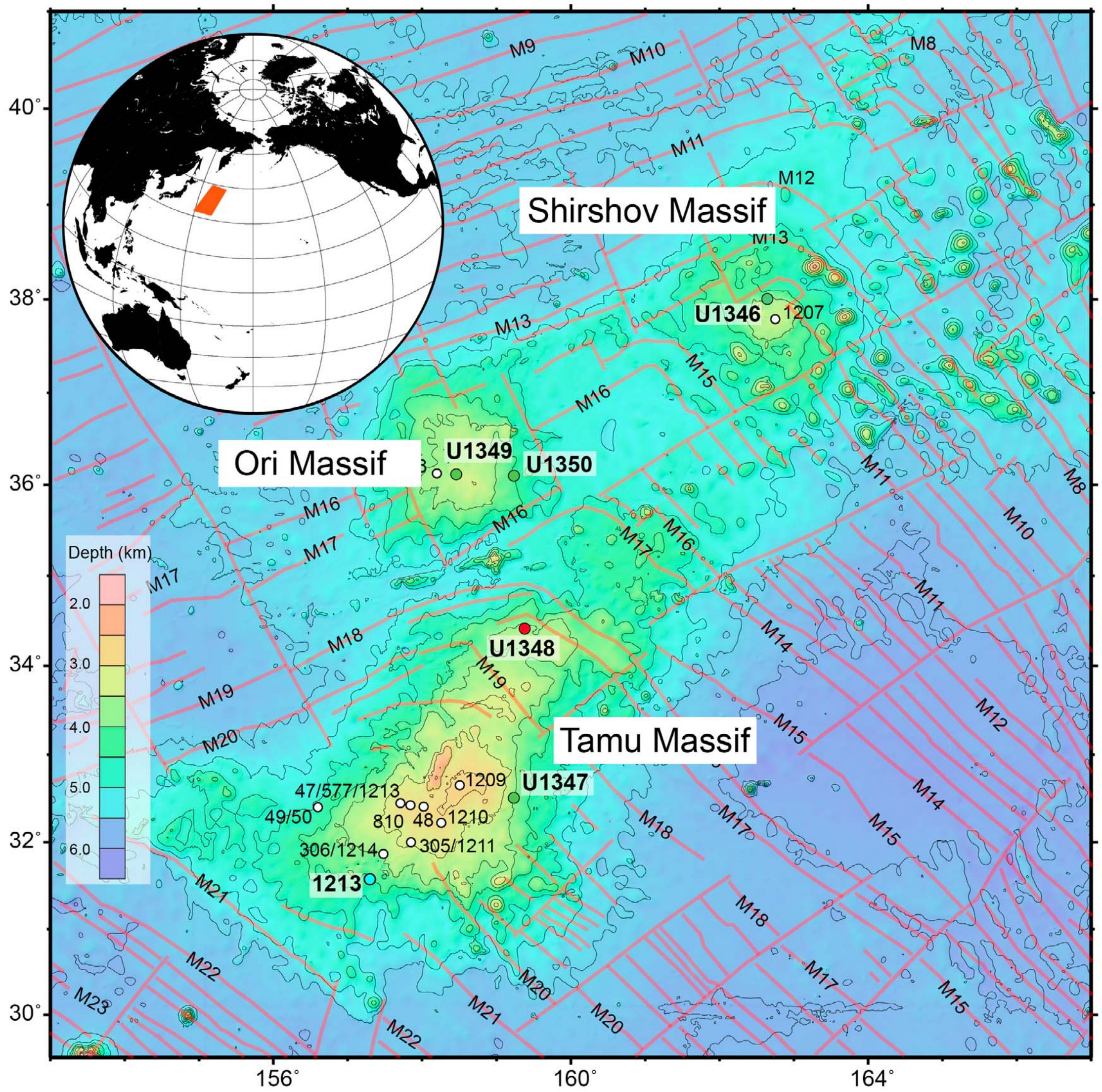

Figure 1. A map of Shatsky Rise with previously identified magnetic lineations [*Nakanishi et al.*, 1989] and locations of drilled holes. The bathymetry used in the figure is modified from Global Topography v. 14.1 (ftp://topex.ucsd.edu/pub/global_topo_1min) [*Smith and Sandwell*, 1997].

M19, respectively. The sea-surface magnetic anomaly track lines are sparse over Tamu Massif, making it difficult to decipher the exact juxtaposition of the drilled site with magnetic lineations, which could provide chronological information [*Tominaga et al.*, 2005].

[6] Paleomagnetic results from ODP Hole 1213B suggest that a massive single lava flow from this hole erupted during a single reversed polarity chron at slightly north of the paleoequator. The radiometric age of 144.6 ± 0.8 Ma (2σ [*Mahoney et al.*, 2005]) has been documented in cores, which can range from M17r (142.73 Ma) to M19r1 (145.43 Ma) [*Tominaga and Sager*, 2010]. The oldest sediment recovered within 10–20 m of the sediment-basement interface was dated as Berriasian, which ranges 140.2–145.5 Ma [*Bralower et al.*, 2002], and paleomagnetic measurements on these sediments suggest that the plateau was located ~5° north of the equator during the post-volcanic deposition [*Evans et al.*, 2005].

[7] IODP Hole U1347A is located at 3450 m water depth and penetrated 158 m of sediments and 160 m of basaltic basement, coring through several lava flows [*Sager et al.*, 2010]. The uppermost crustal section was interpreted as layers of massive flows and pillow lavas [*Sager et al.*, 2010]. Physical properties and degrees of alteration change slightly from one flow to another, but the lava flows are chemically identical. Several post-eruption sediment layers of varying thickness (50 cm–5 m) interbed these basaltic flows, indicating that there were a series of hiatuses between lava eruptions [*Sager et al.*, 2010]. The deepest recovered part of the sediment section has an age 140–133 Ma (Berriasian - Valanginian) based on shipboard biostratigraphy (Table 4 in "Paleontology" [*Sager et al.*, 2010]).

3. Methods

[8] We analyzed the three-axis magnetic data acquired by the General Purpose Inclinometry Tool (GPIT) that provide the intensity and x-, y-, and z-direction of the magnetic signals recorded within the adjacent borehole wall rocks

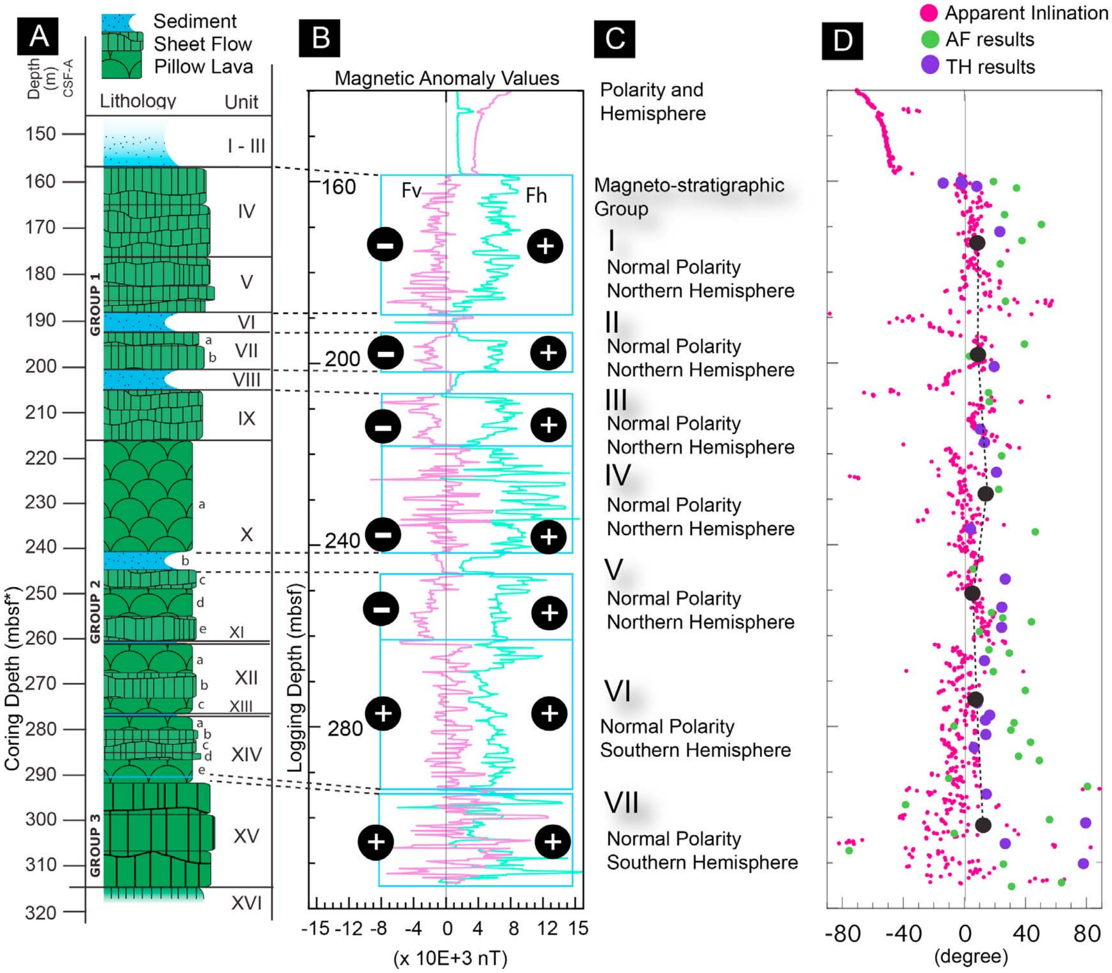

Figure 2. (a) downhole volcanic stratigraphy [*Sager et al.*, 2010]. (b) downhole magnetic anomaly values (IGRF corrected). Pink and green curves show vertical and horizontal components, respectively. (c) Determined polarity and hemisphere origins (see the text). (d) Shipboard descrete sample measurements (green dots: alternating field demagnetization; purple dots: thermal demagnetization) and calculated apparent inclination from GPIT data (red dots). Black dots are the mean values of apparent dip of fractures in each magnetic group.

[*Ito et al.*, 1995; *Tivey et al.*, 2005]. Cross-check of multiple up- and down-log GPIT passes shows the accuracy of the depth-matched GPIT data is <4%, thus the data are reliable for further interpretation.

[9] To extract crustal magnetic signals, we first subtracted x-, y-, and z- values of the Earth's magnetic field at the drilled site from the raw GPIT data. The GPIT logs clearly show steel drill pipe joints as well as the induced magnetic field from the bottom of the pipe (Figure S2 in the auxiliary material) similar to results reported in previous studies [e.g., *Hamano and Kinoshita*, 1990].[1] Weakly magnetized intervals are observed within sediment interbeds (Figure 2a) and the GPIT sediment-basalt interface data show diagnostic curves at the top and bottom of sediment intervals, suggesting that these contacts are influenced by the induced magnetic field from the more strongly magnetized basaltic rock layers [cf. *Tivey et al.*, 2005].

[10] We identified 7 magneto-stratigraphic groups in the Hole U1347A crust based on wavelength characteristics and the truncation of the signals by sediment layers (Figure 2). For each group, we determined the remanent magnetization polarity and hemisphere origin by inspecting the signs from the horizontal and vertical components of the anomalies [*Ito et al.*, 1995] (Figure S1). The signs of the anomalies are simply exhibited by how today's regional magnetic field in Hole U1347A (positive polarity in northern hemisphere, i.e., downward, northward inclination) interacts with magnetic signals produced by the magnetized rock formation at the borehole wall (Figure S1). If the direction of the regional magnetic field is the same as that of the remanent magnetic field, we set a positive anomaly. We set a negative anomaly when these two magnetic fields point in opposite directions [*Ito et al.*, 1995].

4. Results

[11] The polarity and hemisphere origins of the 7 magneto-stratigraphic groups were uniquely determined (Figure 2b). The apparent inclinations calculated from the GPIT data generally agree with shipboard alternating field and thermal demagnetization results from hand-specimens, suggesting that the corrected GPIT anomaly data are valid for interpretation

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL052967.

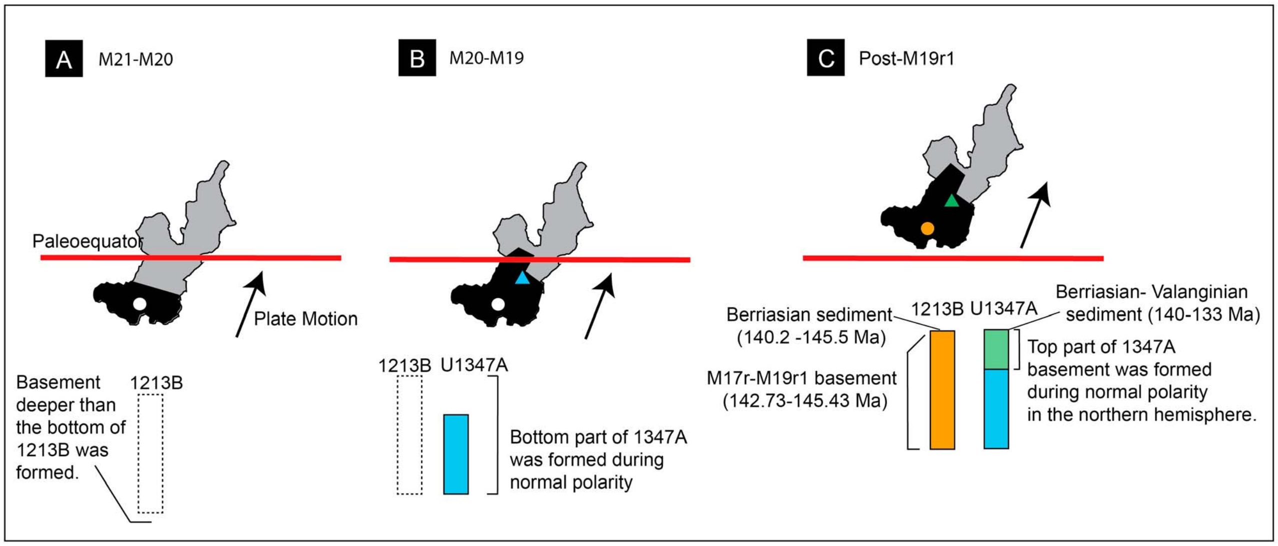

Figure 3. A series of maps showing early Shatsky Rise formation at Pacific-Farallon-Izanagi triple junction [*Expedition 324 Scientists*, 2010]. Red solid lines show positive magnetic anomaly correlations [*Sager et al.*, 1999]. The age of the M-anomalies are based on *Tominaga and Sager* [2010]. Black filled parts of Shatsky Rise sketch indicate the basement already formed whereas gray shaded parts show today's Shatsky Rise basement. (a) M21–M20. period. Tamu massif is located at the southern hemisphere. The primary basement, including the basement deeper than the bottom of ODP Hole 1213B, of Tamu massif was formed; (b) M20–M19 period. The bottom part of IODP Hole 1347A basement was formed during a normal polarity. Tamu massif is located at the southern hemisphere, then crosses the paleoequator after this period; and (c) M19r1–M17r and post eruption period. Tamu massif is located in the northern hemisphere. ODP Hole 1213B and the top part of the IODP Hole 1347A basement were formed.

(Figure 2c). Groups VI and VII, located at the bottom of IODP Hole U1347A, show that the remanence was acquired during normal polarity in the southern hemisphere (negative inclination). Groups I–V, located above these units, show the magnetic remanence was acquired during normal polarity in the northern hemisphere.

[12] One aspect to consider is the possibility of a systematic tectonic block rotation over time due to lava loading that affected the steepness of the magnetic field inclination values shifting the vertical component of the magnetic signals to a positive sign (Figure 2b) [*Tivey et al.*, 2005; *Schouten and Denham*, 2000]. Both shipboard core observations [*Sager et al.*, 2010] and our analyses of FMS downhole structural orientations show no systematic rotations (Table S1 and Figure 2d). Even if we assume that a moderate 15° dip fault steepened the original inclination value as have been previously suggested [*Hamano and Kinoshita*, 1999], additional rotation in inclination values for both normal and reverse polarity cases can only be as high as −30°, which is not what we observe in the group VI and VII apparent inclinations. Thus, we propose that there was no significant rotation of the originally acquired magnetic direction in Hole U1347A and the polarity as well as hemisphere origins observed in GPIT data are intact.

5. The Implications of the Different Hemisphere Origins Observed in the Magnetic Architecture of the Hole U1347A Lava Sequence

[13] Our study of the crustal magnetization of Tamu Massif provides two significant results for understanding the formation and evolution history of Shatsky Rise. First, all the uppermost lava sequences drilled at this site were formed during normal polarity periods. Second, the lava sequences have different hemisphere origins between the bottom and upper part of the sequences. This is a striking new result, which reveals a unique, important insight for reconstructing the Shatsky Rise plateau formation history and for Pacific plate reconstruction modeling [e.g., *Gurnis et al.*, 2012].

[14] The first-order Shatsky Rise tectonic reconstruction model based on plate motions, magnetic lineations [*Nakanishi et al.*, 1989], and apparent polar wonder paths [*Sager et al.*, 2005] of the triple junction area show that Shatsky Rise was formed at the triple junction while the Pacific plate was moving north and northeastward. Based on this tectonic model, surface magnetic lineations as well as paleomagnetic results, stratigraphic records, and GPIT results from ODP Hole 1213B and IODP Hole U1347A, we propose an eruptive time series model for the Rise formation with respect to the northeastward Pacific plate motion (Figure 3).

5.1. In the Southern Hemisphere

[15] The oldest part of the Tamu massif is the southern end of its basement that is marked by magnetic anomaly M21 (Figure 1). Combining new downhole magnetic results from IODP Hole U1347A and the interpretation of the magnetic lineations, we suggest that Tamu massif's primary igneous basement, where magnetic anomalies M21–M20 (southern flank, ODP Hole 1213B) to M19 (southeastern flank, IODP Hole 1347A) emerge, was initially formed in the southern hemisphere (Figure 3a). Then, the lava sequences from the bottom of IODP Hole U1347A (southeastern flank of the Tamu massif) were formed during a normal polarity period,

probably coinciding with the formation of M19, when this site was still in the southern hemisphere (Figure 3b).

[16] If the primary basement of Tamu massif was formed in the southern hemisphere, the inversion of the magnetic anomalies over the massif represents a normal polarity, which differs from conclusions reached in previous studies [*Sager and Han*, 1993; *Tominaga et al.*, 2005]. We think that *Sager and Han* [1993] conclusion still remains equivocal for several reasons. Magnetic anomaly tracks are sparsely spaced hence the inversion results from such data over a large region with significant bathymetrical variations may erroneously estimate the distribution of the magnetized source. Moreover, sparse data distribution and the resulting large grid map make it difficult to locate the edges of magnetized bodies with opposite polarities. Finally, even if the inversion results are feasible, Tamu massif is not entirely mapped with reverse polarity [*Sager and Han*, 1993]. From previously observed magnetic lineations and ^{40}Ar/^{39}Ar age data, the ODP Hole 1213B lava sequence was formed between anomalies M21 and M18 [*Mahoney*, 2005; *Sager*, 2005]. During this period, there were a total of 6 normal and reverse periods, which range from 0.22 to 0.58 m.y. and from 0.15 to 0.72 m.y., respectively [*Tominaga and Sager*, 2010]. However, magnetic anomalies that have been mapped around Tamu massif do not have enough resolution to discern these polarities. With all these uncertainties and new data, we suggest an alternate conclusion from that of *Sager and Han* [1993], which is, that the Tamu massif primary basement marked by M21–M19 was formed in the southern hemisphere and the magnetic anomalies with negative inclination in previous studies indicate normal polarity (Figure 3a).

5.2. After Crossing the Paleoequator

[17] The triple junction that formed the Pacific platen and Shatsky Rise basement then moved to the northern hemisphere crossing the paleoequator prior to the deposition of lava sequences found in Holes 1213B and U1347A (Figures 3b and 3c). During this move, Tamu Massif crossed the equator at some point in the M19-M17 period (Figures 3b and 3c). This timing can provide a new constraint for refining Pacific plate construction model, for which very few of age and plate configuration data are available [e.g., *Gurnis et al.*, 2012]. Crossing the paleoequator covering a few hundred kilometers in a northward direction over several million years most likely would have required fast plate motion. This seems reasonable especially when we look at the 80 km/ m.y. average Pacific plate velocity due to slab pull at subduction zones over past 70 Ma [*Faccenna et al.*, 2012]. This suggests that even if Tamu massif had traveled over 400 km comprising the M21-M17 period in approximately 4 m.y. to cross the paleoequator, this is still within reasonable velocity ranges especially when taking into account the large volume of magma involved in the generation of Shatsky Rise.

[18] After the equator crossing, ODP Hole 1213B basement and the rest of the IODP Hole U1347A basement had been formed (Figure 3c). This part of the lava sequence was emplaced with some eruption hiatuses during normal polarity periods from M19 to the deposition of the oldest sediment (140-133 Ma) in the northern hemisphere (Figure 3c). The ODP Hole 1213B single lava flow with reverse polarity (144.6 ± 0.8 Ma, *Mahoney et al.*, 2005) was emplaced in the northern hemisphere (*Tominaga et al.*, 2005)(Figure 3c). If the sediments recovered from IODP Hole U1347A and ODP Hole 1213B have preserved an intact sedimentation record at both sites, then lava flows at Hole 1213B ceased being active first followed by the deposition of Berriasian sediments (140.2–145.5 Ma [*Bralower et al.*, 2002]), while U1347A lava flows were still active. Finally, lava flows at Hole U1347A ceased activity and 140–133 Ma sediments were deposited (Figure 3c). This is our proposed eruptive time series model of the latitudinal tectonic motion of a LIP during a volcanic plateau formation period.

6. Conclusions

[19] We draw the following conclusions from this study: (1) Tamu Massif of Shatky Rise was formed during normal polarity periods south of the paleoequator and crossed the equator at some point in the M19-M17 period based on GPIT data interpretations from IODP Hole U1347A. This result can provide a new constraint for refining Pacific plate construction model, for which very few of age and plate configuration data are available; and, (2) Combining downhole GPIT, marine magnetic and paleomagnetic data interpretations of the Tamu massif tectonic history allowed us to reconstruct an eruptive time series of the latitudinal tectonic motion of a LIP and the underlying Pacific plate during the plateau formation.

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