JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. B4, PAGES 7539–7556, APRIL 10, 1999

Magnetic lineations within Shatsky Rise, northwest Pacific Ocean: Implications for hot spot-triple junction interaction and oceanic plateau formation

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Abstract. Oceanic plateaus are major ocean features, yet their origins and development are poorly understood. Many are huge piles of basalt, and it is widely accepted that mantle plumes are their source, perhaps from eruptions of the voluminous head of an emerging plume. Shatsky Rise is a basaltic plateau that formed during a period of geomagnetic reversals, unlike many mid-Cretaceous plateaus, so magnetic data can help us understand its tectonic history. In this study, we analyzed magnetic anomaly data from 131 cruises over and around Shatsky Rise and constructed a magnetic lineation chart for tectonic interpretation. A significant finding is that magnetic lineations are traceable through low parts of the rise between volcanic massifs, indicating nearly normal lithosphere, and between large volcanic edifices. Many lineations form bights near the rise axis and show former locations of the Pacific-Izanagi-Farallon triple junction. They indicate that the junction was in a ridge-ridge-ridge (RRR) configuration and closely followed the rise axis from chron M20 (146 Ma) to chron M4 (127 Ma). Lineation and bight geometries indicate that the triple junction jumped northeastward at least nine times, often apparently in response to volcanic activity from the mantle plume. Some jumps, however, appear related to ridge reorientations. Numerous features within the rise are parallel to lineations or lineation offsets, implying that the plateau formed near the triple junction and was modified by ridge faulting. Most of our observations support the hypothesis that Shatsky Rise was formed by a mantle plume that captured a triple junction.

1. Introduction

Oceanic plateaus are enigmatic igneous constructs that occur throughout the ocean basins, especially in the western Pacific Ocean. Their bulk implies unusual volcanic activity, such as that emanating from a mantle plume ("hot spot"). Many geoscientists now think that they are the oceanic counterparts of continental flood basalts and that oceanic plateaus are emplaced by rapid, voluminous eruptions over an emerging plume [e.g., *Duncan and Richards*, 1991; *Coffin and Eldholm*, 1994]. According to this hypothesis, a mantle plume begins with a huge bubble of hot mantle material ("plume head") arising from the D" layer above the core-mantle boundary [*Richards et al.*, 1989]. After ascending through the mantle it impacts the base of the lithosphere where it causes a massive eruption over a short period of time [*Duncan and Richards*, 1991]. For brief periods, plume head eruptions may rival the mid-ocean ridge system in magma flux [*Tarduno et al.*, 1991; *Coffin and Eldholm*, 1994]. What is more, they may affect global climate and environment, perturb mantle convection, shift the magnetic reversal pattern (i.e., outer core convection), and change plate motions [*Larson*, 1991a, b; *Duncan and Richards*, 1991; *Coffin and Eldholm*, 1994].

Plume head eruption consequences and indeed the plume head hypothesis of oceanic plateau formation itself are still largely conjectural. The problem is that oceanic plateaus are large and mostly remote from land, so geophysical data and geologic samples are sparse. As a result, detailed geologic studies of such features have been few.

Shatsky Rise is an oceanic plateau located about 1600 km east of Japan (Figure 1). It is important because it was formed during a time when the geomagnetic field was undergoing reversals, so magnetic lineations can be used to decipher its structure and tectonic history. In contrast, many other oceanic plateaus were constructed during the Cretaceous long normal superchron, and many of those are also on seafloor formed during the superchron. Consequently, it is difficult to determine their tectonic histories. Shatsky Rise is also important because it is a good example of a plateau formed at a triple junction. It has been shown that Shatsky Rise formed at the Pacific-Izanagi-Farallon triple junction during the Late Jurassic and Early Cretaceous [*Larson and Chase*, 1972; *Hilde et al.*, 1976; *Sager et al.*, 1988; *Nakanishi et al.*, 1989]. Curiously, it seems that many plateaus are known or suspected to have been formed at triple junctions or spreading ridges, so the

Paper number 1999JB900002.
0148-0227/99/1999JB900002$09.00

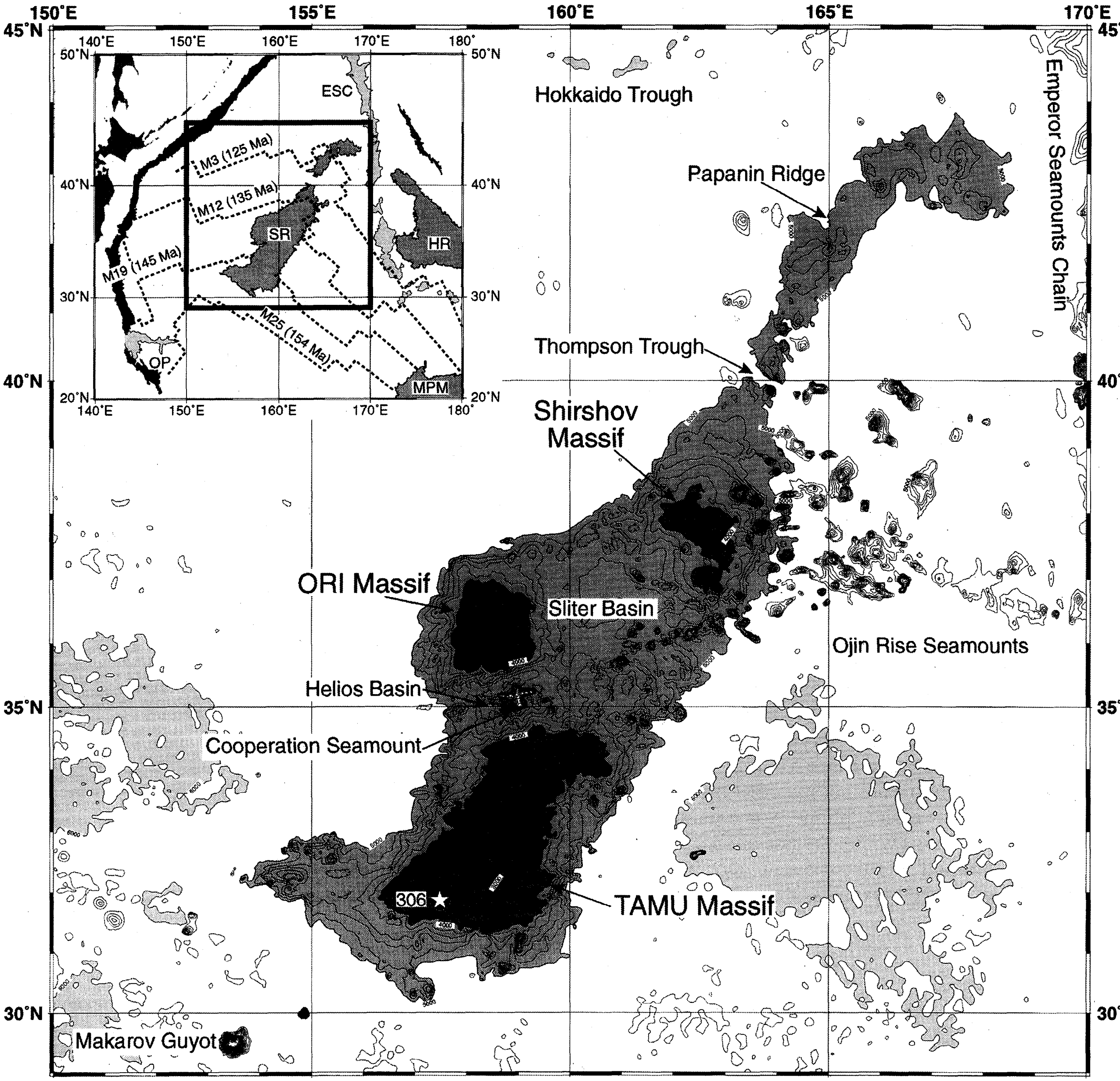

Figure 1. Bathymetric chart of Shatsky Rise. Contours of the rise were made from the bathymetric data grid of *Sager et al.* [1999]. Those in adjacent areas were made from the predicted bathymetry data grid of *Smith and Sandwell* [1997]. Darkly shaded areas are above 5 km depth. Lightly shaded areas are below 6 km depth. The contour interval is 500 m. Bathymetric feature names, used in the text for reference, are from Sager et al. An index map, showing the location of Shatsky Rise relative to northwest Pacific features is shown in the upper left corner. SR, HR, MPM, OP, and ESC denote Shatsky Rise, Hess Rise, Mid-Pacific Mountains, Ogasawara Plateau, and Emperor Seamounts Chain, respectively. The heavy solid line encompasses the study area. Dashed lines show several magnetic lineations [from *Nakanishi et al.*, 1989]. ORI, Ocean Research Institute; TAMU, Texas A&M University.

clues that Shatsky Rise can provide about plume-triple junction interactions can help us understand this link.

In this study, we examine magnetic data collected over Shatsky Rise in an effort to map magnetic lineations within the plateau itself. This was prompted in part by our collection of a large amount of magnetic and other geophysical data over Shatsky Rise during a recent cruise. Also, because the rise formed near spreading ridges with the magnetic field reversing, we expected that magnetic lineations and structure would yield important clues about the plateau's formation [e.g., *Han and Sager*, 1993]. This paper presents a new magnetic anomaly lineation map of Shatsky Rise and discusses its implications for the tectonic history of the rise.

2. Geologic Background

Shatsky Rise is located in the northwest Pacific basin on seafloor formed during the Late Jurassic and Early Cretaceous [e.g., *Larson and Chase*, 1972; *Nakanishi et al.*, 1989]. Because of its great age, the abyssal seafloor surrounding the plateau lies at depths of 6000-5500 m [*Mammerickx and Smith*, 1985]. This part of the Pacific plate has never been near continental sediment sources, so it is covered by a thin blanket of mostly pelagic sediments typically a few hundred meters in thickness [*Ludwig and Houtz*, 1979; *Houtz and Ludwig*, 1979].

Shatsky Rise is elongated southwest to northeast and has an area of 4.8 x 10^5 km^2, about 25% more than islands of Japan. The rise contains three large volcanic constructs (TAMU, ORI, and Shirshov massifs; for place names, see Figure 1) that rise to depths of 3200-2000 m. All three have domes of Cretaceous pelagic sediments up to 1 km thick at their summits [*Karp and Prokudin*, 1985; *Khankishiyeva*, 1989; *Sliter and Brown*, 1993].

The massifs have seismic velocity structures typical of oceanic plateaus: the layers are similar to oceanic crust but several times thicker [*Den et al.*, 1969; *Gettrust et al.*, 1980]. The massifs are separated by areas of low plateau (Helios and Sliter basins) that rise less than 1 km above the surrounding seafloor. On the northeast side of the rise a low, linear ridge (Papanin Ridge) trends to the northeast and bends nearly 90° at 43°N to a southeast trend that projects to Hess Rise. Additionally, a cluster of small to medium seamounts is located around and to the east of Shirshov Massif; it contains a loose chain with a nearly east-west trend (Ojin Rise Seamounts, Figure 1).

After the formation of the plates during Late Jurassic and Early Cretaceous at the Pacific-Izanagi-Farallon triple junction and the construction of the rise itself at about the same time, little of significance seems to have happened to this part of the Pacific plate. Although a widespread mid-Cretaceous volcanic episode formed many seamounts and an extensive intrusive complex in the western Pacific Ocean [e.g., *Schlanger et al.*, 1981], most or all of this activity seems to have occurred to the south of Shatsky Rise. As far as we know, the rise has been quiescent since shortly after its formation.

A number of investigators have mapped the Mesozoic magnetic anomalies in the vicinity of Shatsky Rise [*Larson and Chase*, 1972; *Hilde et al.*, 1976; *Handschumacher et al.*, 1988; *Sager et al.*, 1988; *Mammerickx and Sharman*, 1988; *Sharman and Risch*, 1988; *Nakanishi et al.*, 1989]. These studies show that two lineation sets, the northeast trending Japanese lineations and the southeast trending Hawaiian lineations, meet at Shatsky Rise. Magnetic bights (bent lineations) of anomalies M25 through M22 (154-150 Ma; ages for magnetic lineations are taken from the timescale of *Gradstein et al.* [1994]) are found about 800 km southwest of the rise. They indicate that the Pacific, Izanagi, and Farallon plates met at a triple junction that was migrating rapidly northwest relative to the Pacific plate [*Handschumacher et al.*, 1988; *Nakanishi et al.*, 1989]. Between chrons M21 and M20 (148-146 Ma) the Japanese lineations reoriented by 25°, indicating a reorganization of spreading on the Pacific-Izanagi ridge [*Nakanishi et al.*, 1989]. They concluded that the appearance of a Shatsky hot spot caused a regional reorganization of the Pacific-Izanagi-Farallon plate boundaries. Simultaneously, the triple junction jumped northeast to the location of Shatsky Rise, annexing a piece of the Farallon plate and causing a short-lived microplate nearby [*Sager et al.*, 1988; *Nakanishi et al.*, 1989]. Subsequently, the triple junction remained near the Shatsky hot spot as shown by the confluence of magnetic lineations along the rise to chron M4 (127 Ma). Shatsky Rise is the trace of the Shatsky hot spot on the Pacific plate [*Nakanishi et al.*, 1989].

Age constraints for Shatsky Rise are few and lack certainty. Although three Deep Sea Drilling Project (DSDP) cruises and one Ocean Drilling Program (ODP) cruise have drilled on top of TAMU Massif, none was able to penetrate basement to recover basalts for radiometric dating. Dredges have recovered basalt from various places on the rise [*Kashintsev and Suzyumov*, 1981; *Sager et al.*, 1999], but all samples have been too altered to yield reliable dates. The best age constraint is early Berriasian fossils recovered approximately 80 m above basement at DSDP Site 306 on the southwest side of the TAMU Massif summit [*Larson et al.*, 1975] (Figure 1). These imply a Late Jurassic or earliest Cretaceous age for that massif. Finding TAMU Massif to be mainly reversed in its magnetic polarity, *Sager and Han* [1993] postulated that it formed rapidly during chron M17 (approximately 142-141 Ma). Because most of the rest of the rise is on younger seafloor, there must be an age progression younging toward the northeast [*Sager and Han*, 1993; *Sager et al.*, 1999]. Analysis of gravity anomalies over the rise indicates isostatic compensation consistent with near-ridge formation [*Watts et al.*, 1980]. Additionally, the topographic features of the rise correlate well with magnetic lineations and fracture zones and indicate that the volcanic edifices were faulted and modified by ridge-crest tectonics [*Sager et al.*, 1999]. Thus virtually all available data point to formation of the rise at about the same time as the seafloor formation.

3. Data and Methods

During 1994 we collected approximately 4500 km of magnetic data over Shatsky Rise during cruise TN037 on board the R/V *Thomas G. Thompson* [*Sager et al.*, 1995] (Figure 2). We combined these data with data from 130 other cruises that have crossed the rise (Figure 2; Table 1). Our data set differs from that analyzed by *Nakanishi et al.* [1989] by the addition of data from cruise TN037, three Japanese cruises (KH-88-3, KH-89-2, and KH-96-3), one ODP cruise (ODP145JR), and an older Russian cruise (DME29). Since the cruises span more than three decades and the total magnetic field data were originally reduced to anomalies using different regional magnetic fields, we recalculated magnetic anomalies using the 1995 International Geomagnetic Reference Field [*IAGA Division V Working Group 8*, 1995].

The magnetic data were analyzed in the usual fashion for magnetic lineation studies: anomalies were plotted as wiggles perpendicular to ship tracks using Generic Mapping Tools (GMT) [*Wessel and Smith*, 1995] and Marine Geophysics Basic Tools (MAGBAT) [*Tamaki et al.*, 1992] and then correlated between tracks by eye. Our analysis began with our previous magnetic lineation map [*Nakanishi et al.*, 1989] and focused on tracing the lineations from the edges through the rise. As with any magnetic lineation identification study, our picks were based on a combination of anomaly shape and spacing, extension from better picks, and constraints imposed by geometry and orientation. To help identify individual anomalies, profiles were compared with a synthetic magnetic model based on the Mesozoic geomagnetic reversal timescale of *Gradstein et al.* [1994].

Many older cruise data are poorly positioned having been navigated with infrequent Doppler satellite fixes or celestial fixes, with the result of navigation errors of several kilometers or greater. Although these errors can be bothersome, they are usually not a problem for our analysis since we correlate anomalies typically several tens of kilometers or more in width. Furthermore, in many places there is enough redundancy of tracks to make it possible to recognize those which are poorly positioned. Nonetheless, in areas where track control is poor, navigation er-

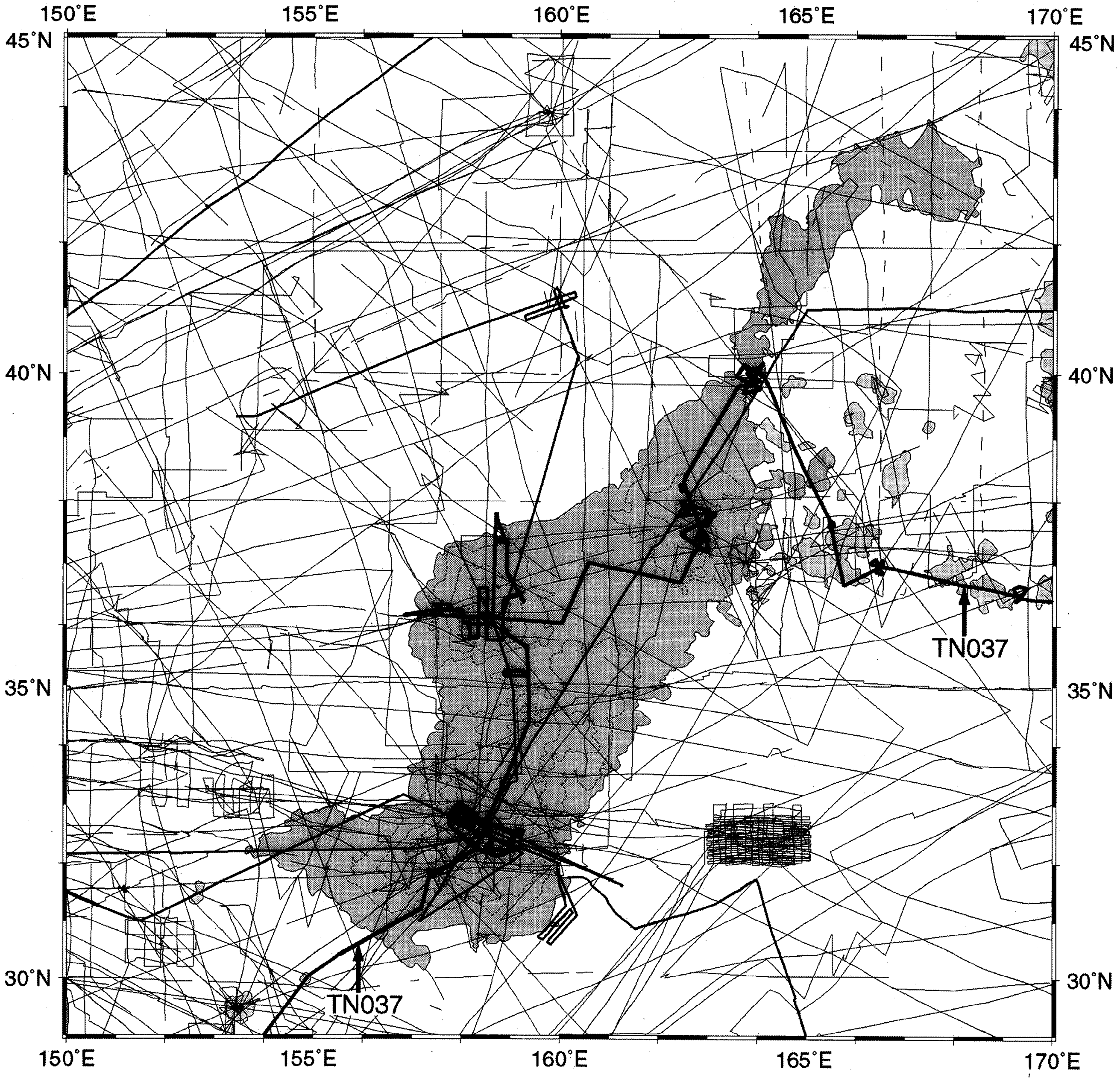

Figure 2. Track chart of cruise data used in this study. The heavy lines represent new tracks added to the data set of *Nakanishi et al.* [1989].

rors can lead to erroneous interpretations of anomaly trends or fracture zones where offsets are apparent but not real.

Figure 2 shows that the distribution of magnetic tracks around Shatsky Rise is uneven. Data are concentrated over the southern part of the rise, especially at the TAMU Massif summit, and sparse elsewhere, particularly in the northeast part of the study area. Additionally, Figure 2 shows that few of the tracks have trends more or less parallel to the rise. This unevenness makes for some uncertainties in anomaly correlations, particularly over the northern half of the rise.

4. Description of Magnetic Anomaly Lineations

We found it possible to trace magnetic lineations within parts of Shatsky Rise, particularly the lower-elevation areas (Figure 3). Figures 4-6 show the anomaly picks and anomalies along most tracks in greater detail for the south, central, and northern parts of the study area. In Figures 7-9, correlations of magnetic anomalies among different cruise tracks and comparison with a synthetic profile are shown.

Because Shatsky Rise is a large volcanic construct that might be expected to destroy or distort magnetic lineations formed by seafloor spreading, finding lineations within the rise may seem unexpected. However, lineations have been found within other basaltic rises. Lineations can be traced through Iceland, a volcanic edifice formed by a ridge-centered hot spot, as well as the Iceland-Greenland and Iceland-Faeroe ridges that are products of Icelandic hot spot volcanism [*Ryan*, 1990]. Although most of these lineations are somewhat distorted, they are clearly linear. Other magnetic lineations have been mapped within Roo Rise, an extension of the Exmouth Plateau in the eastern Indian Ocean [e.g., *Fullerton et al.*, 1989]. As at Iceland, the lineations are

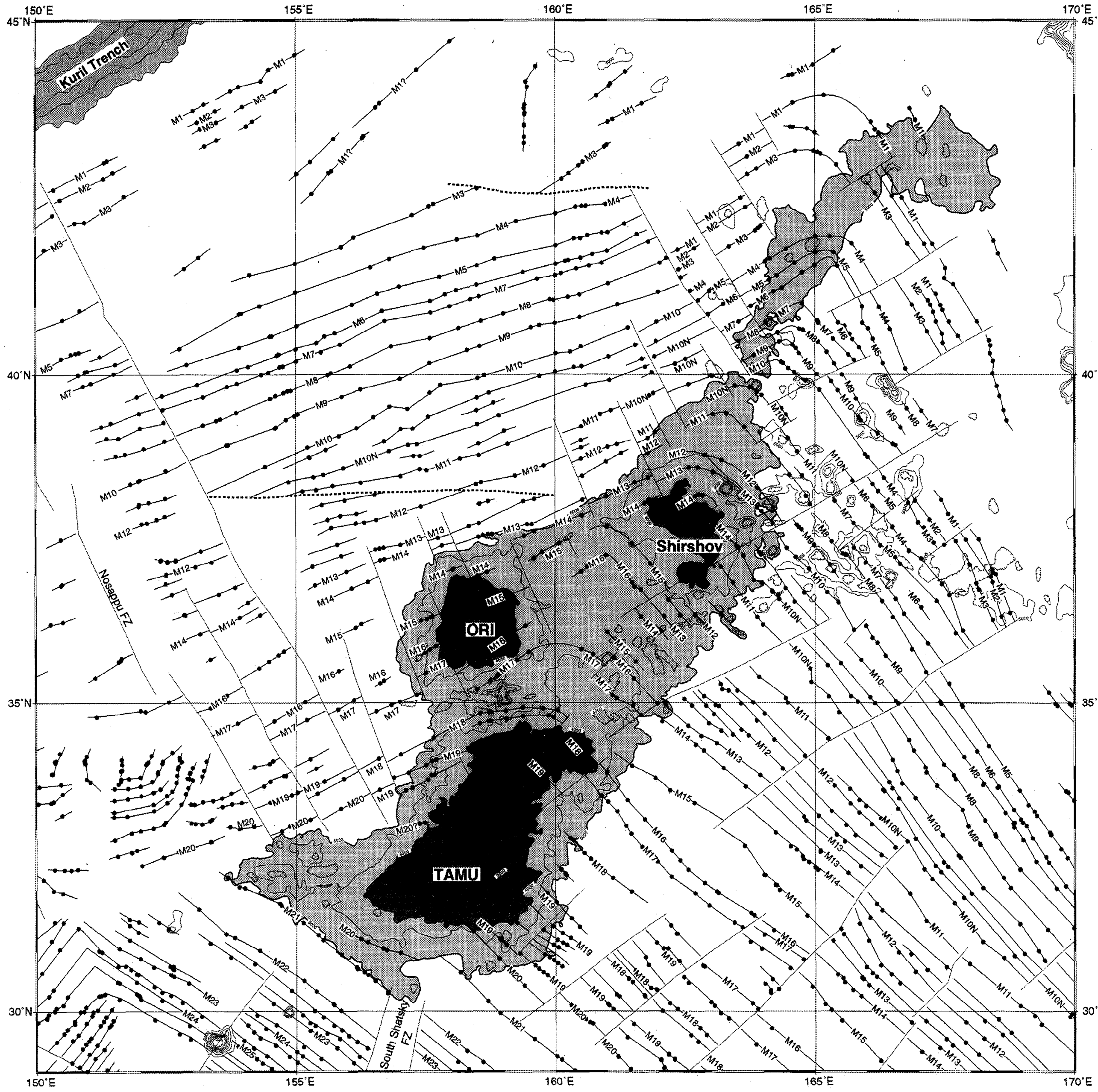

Figure 3. Revised magnetic anomaly lineations around the Shatsky Rise. Heavy solid lines represent lineations and are identified with M numbers. Solid circles are locations where anomalies were identified. Light lines denote fracture zones. Lineations in basins adjacent to Shatsky Rise are from *Nakanishi et al.* [1989]. Dashed lines distinguish possible pseudofaults caused by rift propagation.

somewhat distorted in their shapes but are clearly linear and correlatable from adjacent magnetic track lines. We find a similar situation in Shatsky Rise: there are anomalies that are linear and correlatable between tracks, as demonstrated in Figure 10, even though there is some distortion of the characteristic anomaly shapes.

Although anomaly peaks and troughs correlate reasonably well in many places within Shatsky Rise, the consistency in anomaly spacing and shape is not as good as that for profiles from the adjacent undisturbed abyssal plains. This is undoubtedly a result of volcanic topography and spreading ridge tectonic complexities caused by the formation of the rise. Because of this lesser consistency and the paucity of data in some regions, some of our anomaly picks may be slightly in error. Despite some uncertainties, there is little doubt that the lineations can be traced within the rise, that they are linear, and that they have trends that are the same as those shown in Figures 3-6.

Because the lineations can be traced through the low parts of the rise but not through most of the massifs, these features are probably individual volcanic edifices separated by more or less normal lithosphere that has not been greatly reheated by rise-related volcanism. Interestingly, magnetic lineations run through the northeast flank of the TAMU Massif (Figure 4) and imply that this part of this massif formed at the ridge crest. Lineations

Table 1. Sources of Bathymetric and Magnetic Data Used for This Study

Institution	Number of Cruises	Cruise Identification
Lamont-Doherty Earth Observatory	17	C1007, C1008, C1108, C1207, C1219, C1405, C2004, C2005, V2006, V2106, V2110, V3212, V3213, V3214, V3311, V3312, V3612
Woods Hole Oceanographic Institution	1	A2015L06
National Oceanic and Atmospheric Administration	3	POL6829, POL7004, POL7201
U.S. Army	1	L876NP
School of Ocean and Earth Science and Technology, University of Hawaii	7	73102500, 75072600, 76080601, 76080602, 77031705, 83011605, 70042205
U.S. Navy	18	SI343619, SI343722, SI939006, SI930004, SI931005, SI932005, SI932009, SI933010, SI939012, SI933001, SI343625, SI343613, SI343615, HU931003, HU931005, HU930007, HU939010, BA933001, DSDP88N
Scripps Institution of Oceanography, University of California, San Diego	29	LUSI01AR, SCAN03AR, ZTES2BAR, ZTES03AR, ZTES04AR, ZTES05AR, ANTP03MV, GECS-CMV, GECS-DMV, ARES05WT, ARES07WT, TSDY03WT, INDP01WT, RAMA03WT, RAMA04WT, RAMA13WT, RNDB09WT, RNDB10WT, DSDP06GC, DSDP20GC, DSDP32GC, DSDP55GC, DSDP86GC, DSDP88GC, JPYN02BD, JPYN04BD, HUNT03HT, SILS01BT, SILS02BT
University of Washington	2	TT-168, TN037*
Texas A&M University	2	ODP132JR, ODP145JR*
Institute Physics of the Earth Academy of Science, Russia	8	VIT43, PG30, DME21, DME29*, DME37, DME38, MG21, MG28
National Imagery and Mapping Agency	2	10075, 10375
IFREMER, France	1	85002211
Geological Survey of Japan	15	GH7602, GH771-A, GH771-C, GH7801, GH7901, GH801-A, GH801-B, GH805-A, GH805-B, GH814-A, GH814-B, GH824-A, GH824-B, GH833-A, GH833-B
Ocean Research Institute, the University of Tokyo	21	KH-67-1, KH-67-5, KH-68-3, KH-68-4A, KH-70-2, KH-74-2, KH-74-4, KH-75-3, KH-75-4, KH-78-2, KH-78-3, KH-80-3, KH-82-4, KH-82-5, KH-84-1, KH-88-3*, KH-89-2*, KH-96-3*, UM6503-A, UM6503-B, DELP86KA
Kobe University, Japan	3	JD08, OCEA68, RF72
Chiba University, Japan	1	DELP86WA

* New data that were not used by *Nakanishi et al.* [1989].

IFREMER, Institut Français de Recherche pour l'Exploitation de la Mer.

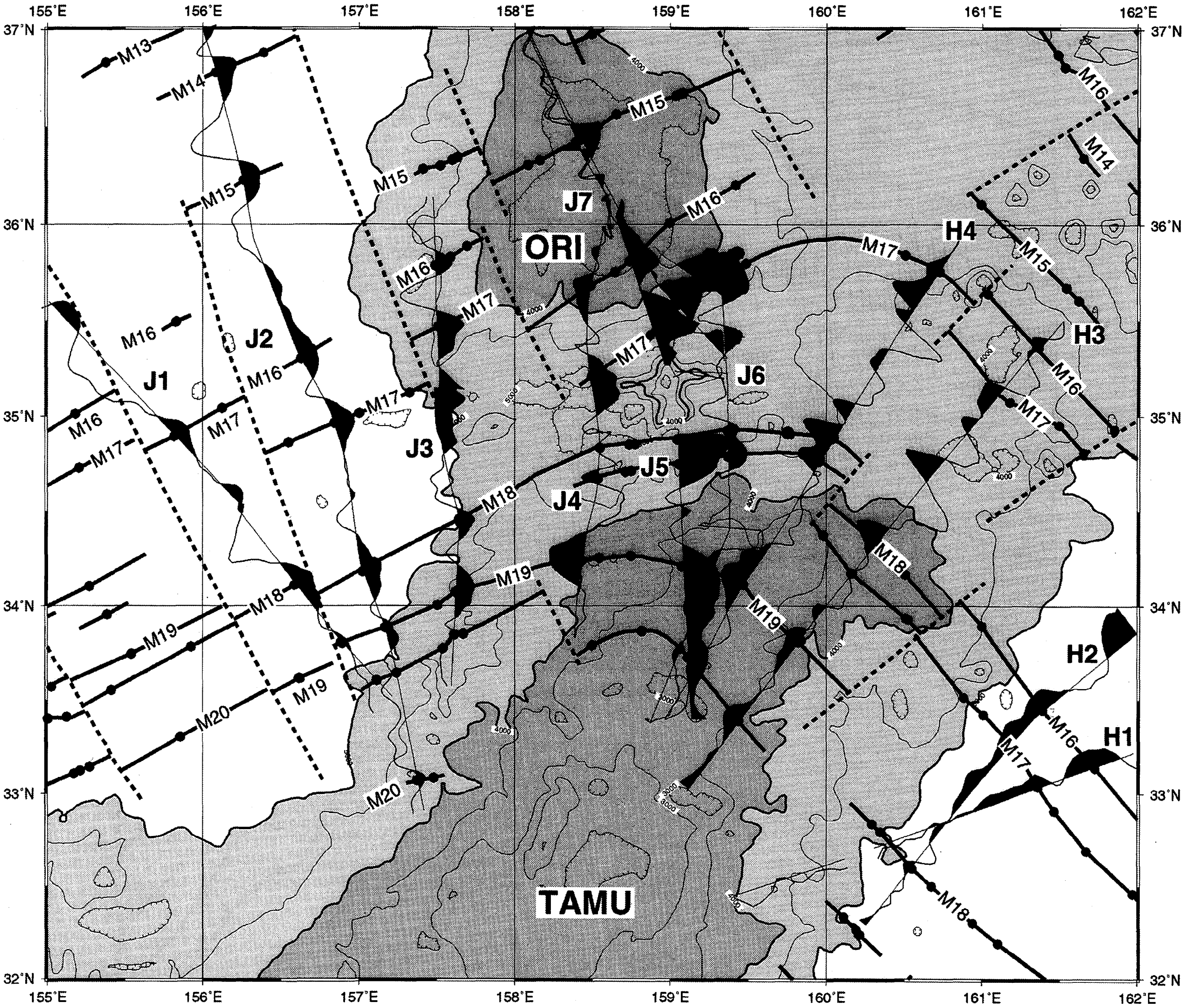

Figure 4. Detail of magnetic anomaly lineations near northern TAMU and ORI massifs. Heavy solid lines are lineations identified with M numbers. Selected magnetic tracks are shown to illustrate anomaly correlations. Bathymetry shallower than 5 km is shaded. Solid circles are the locations of anomaly picks. Letters refer to profiles in Figure 7.

are also traceable through the lower flanks of Shirshov Massif, suggesting that the area of its main volcanic construct is small (Figure 5).

Many lineations form magnetic bights in the middle of the rise. These bights indicate past locations of the triple junction. Magnetic bights from M22 and older are found southeast of Shatsky Rise (Figure 3) [*Sager et al.*, 1988; *Nakanishi et al.*, 1989]. Magnetic bights of lineations M19-M14 are found near the rise axis between TAMU and Shirshov massifs (Figures 4 and 5). Large gaps between some, such as lineations M17-M16 and M15-M14, imply northeastward triple junction jumps. Magnetic bights of lineations M13 through M4 follow Papanin Ridge to the northeast, but bights for lineations M3 though M1 diverge from the northern end of the ridge (Figure 6).

4.1. Lineations Older Than M21

Lineations older than M21 on our chart are unchanged from *Nakanishi et al.* [1989] (Figure 3). They show magnetic bights older than chron M23 southwest of Shatsky Rise. We were able to closely map magnetic bights for chrons M24B and M23. In contrast, magnetic bights for chrons M22 and M21 are missing, and these magnetic lineations within the Hawaiian set appear to be truncated. Just a little farther north, long Japanese lineations appear with the postreorganization N70°E trend. This probably indicates that some Pacific plate lithosphere was cut off by the spreading ridge reorganization (see section 6).

4.2. Lineation M20

The configuration of anomaly M20 is problematic because of changing plate boundaries and the TAMU Massif. The strike of the Japanese lineation set changes 25° clockwise from N45° to N70°E between chrons M21 and M20 [*Sager et al.*, 1988; *Nakanishi et al.*, 1989]. Lineation M20 trending N70°E is identified in the area at 32°N between 151° and 153°E, directly north of the older magnetic bights. Farther north are several curved lineations with odd and inconsistent trends [*Nakanishi et al.*,

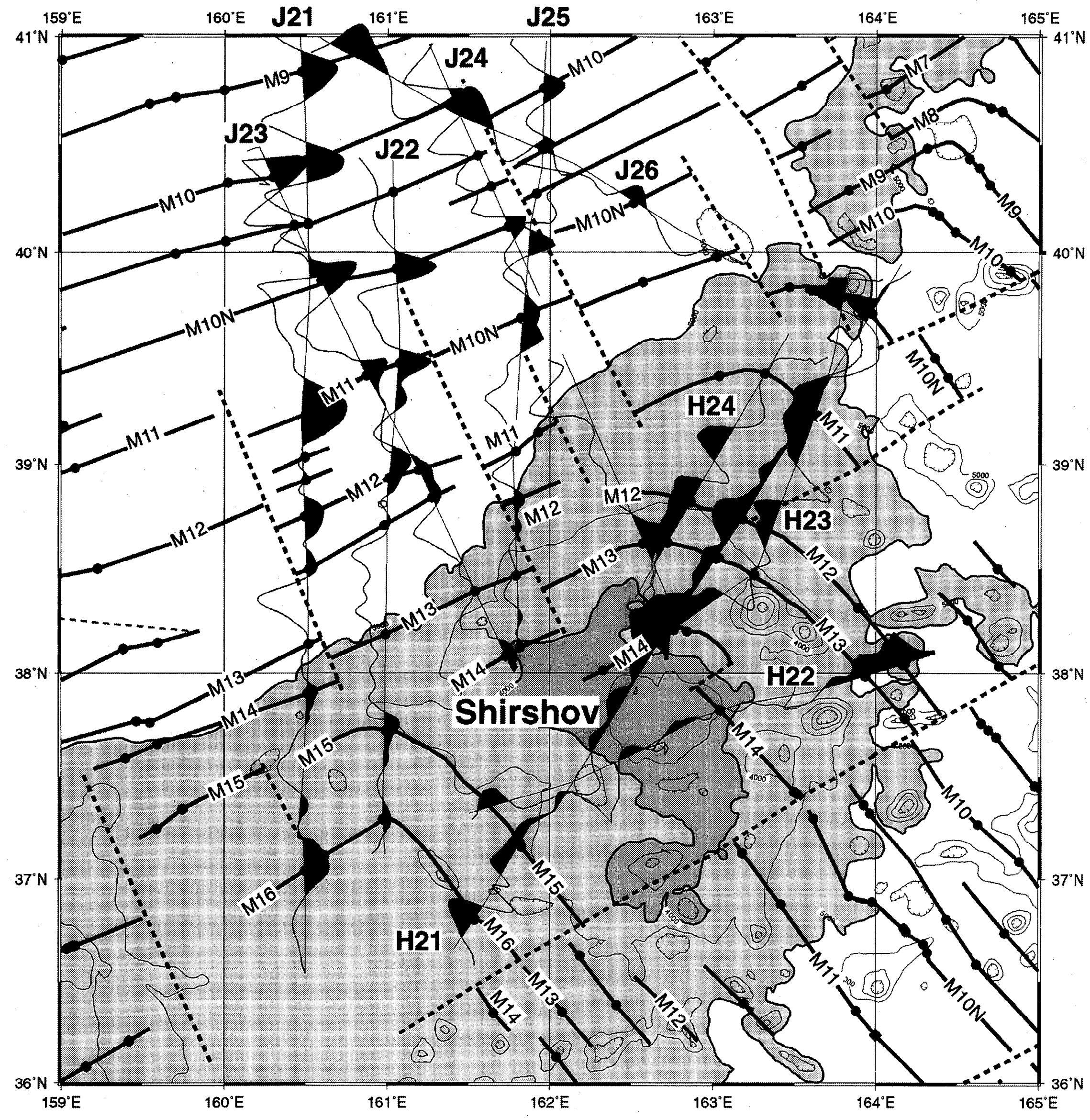

Figure 5. Detail of magnetic anomaly lineations near Shirshov Massif. Conventions are identical to those in Figure 4. Letters refer to profiles in Figure 8.

1989]. These are believed to have been formed on a microplate that existed briefly near the triple junction [*Sager et al.*, 1988; *Nakanishi et al.*, 1989].

Lineation M20 can also be traced northwest in the Hawaiian lineations to the south flank of TAMU Massif, but the connection to the Japanese lineation is obscured by TAMU Massif. There is a short lineation slightly northeast of and nearly parallel to lineation M21 on the south edge of the rise, and it is spaced about right to be lineation M20 if the South Shatsky Fracture Zone [*Nakanishi,* 1993] extends past chron M21 (Figure 3). On the other hand, we mapped several unidentified anomalies south of M19 on the north flank of TAMU Massif (about 158°E). One of these could also be lineation M20. Any way one looks at it, the offset between M20 on the south side and M19 on the north side of TAMU Massif indicates that there must have been a northeastward jump of the triple junction [*Sager et al.*, 1988; *Nakanishi et al.*, 1989].

4.3. Southeast of TAMU Massif

Lineations close to the southeast side of TAMU Massif are difficult to identify because they do not match the expected spacings. Anomalies M21 and M20 are easily recognized as is the M17-M16 pair, but in between some anomalies seem to be repeated. This probably resulted because several small eastward ridge jumps occurred at different times in different spreading segments along the Pacific-Farallon ridge [*Nakanishi et al.*, 1989].

We carefully examined how far into the southeast flank of the rise we can trace these magnetic lineations. They go only as far as about the 3500 m contour, probably owing to the volcanism associated with the rise. Although *Glebovsky et al.* [1995] claim to have identified lineations from M19 and M15 farther toward the center of TAMU Massif, we did not agree with their interpretations, which are based on fewer data.

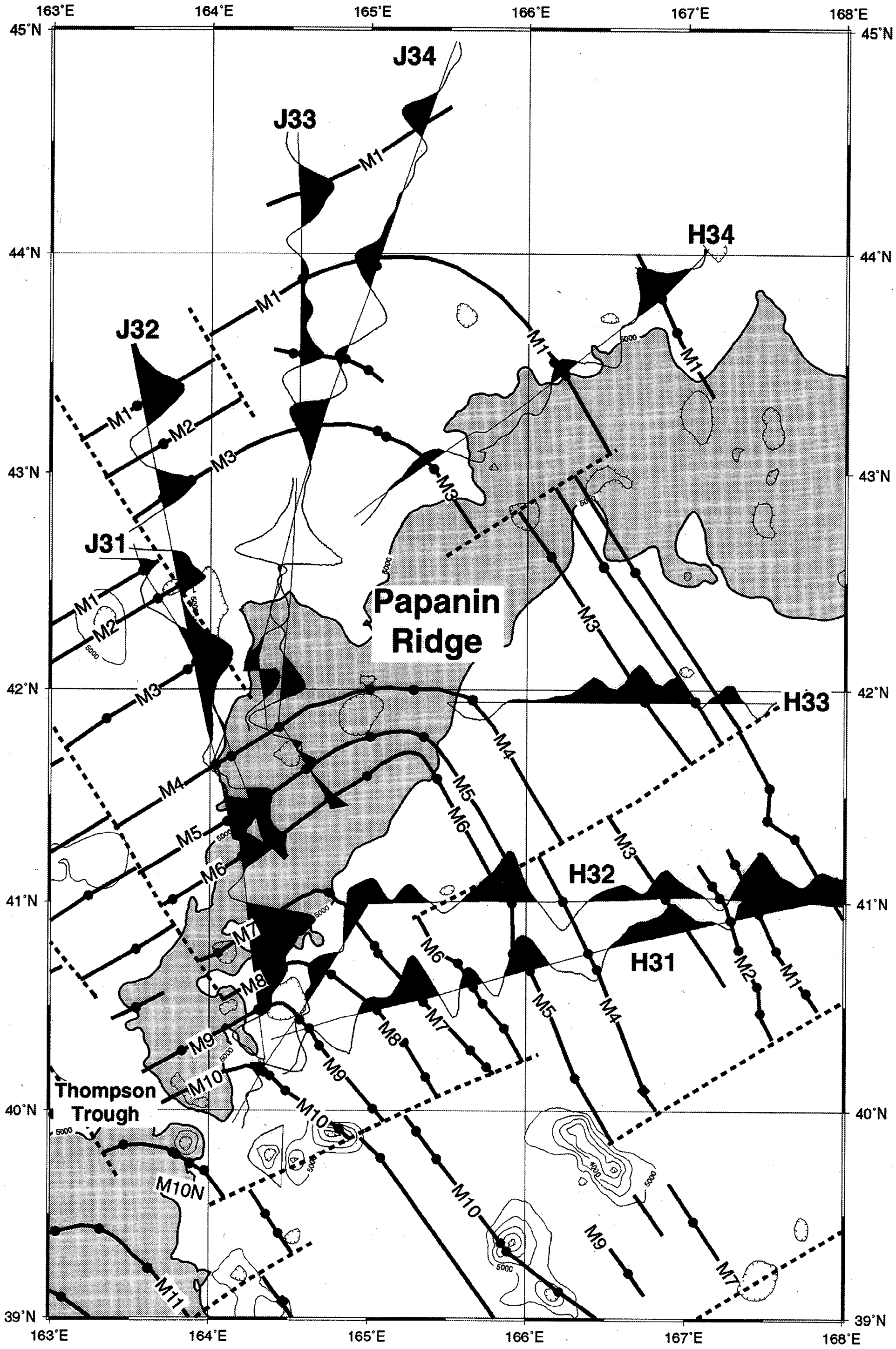

Figure 6. Detail of magnetic anomaly lineations near Papanin Ridge. Conventions are identical to those in Figure 4. Letters refer to profiles in Figure 9.

4.4. Northern TAMU Massif

We traced magnetic bights on the north flank of TAMU Massif (Figures 3 and 4). On the basis of their shapes, we identify them as M19 and M18. A notable feature of these anomalies is that they can be traced through the northeast TAMU Massif above 3500 m. In this region, topography is rough, and there are bathymetric features elongated parallel to the lineations, implying ridge crest faulting [*Sager et al.*, 1999].

As stated in section 5, spacing between lineations M20 and M19 implies that the lithosphere beneath much of TAMU Massif was annexed to the Pacific plate by a northeastward ridge jump. Because magnetic lineations are found only on the northeast side of TAMU Massif summit, presumably much of the massif existed prior to the ridge jump. Thus the massif probably formed before M19. Our observations suggest that the initial, large eruptions of Shatsky Rise approximately coincided with the Jurassic-Cretaceous boundary (M19 in the timescale of *Gradstein et al.* [1994]). Whether the two events are related is open to conjecture.

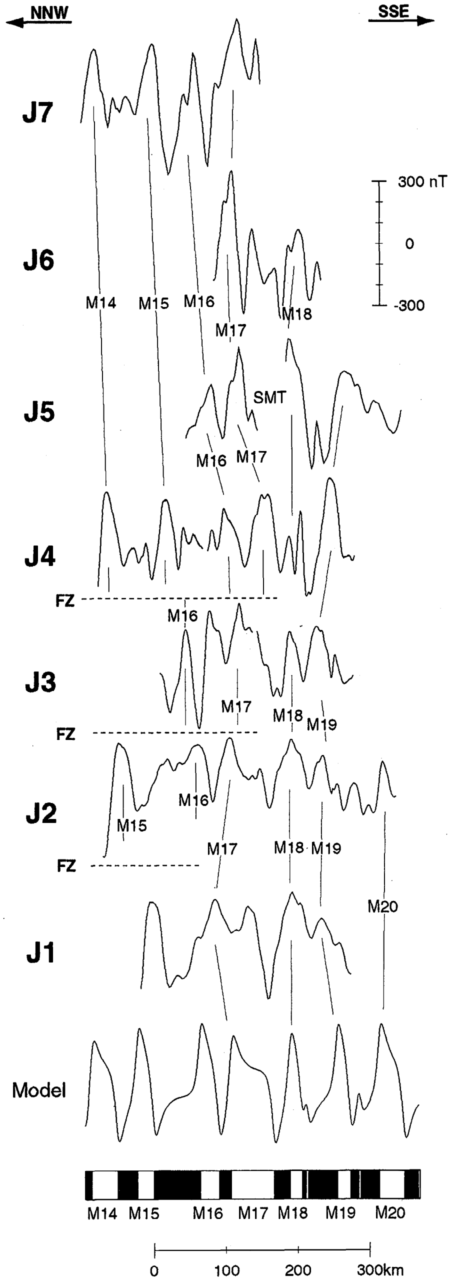

Figure 7a. Selected magnetic anomaly profiles from the Japanese lineations in the area of TAMU and ORI massifs, projected approximately normal to lineations. Profile locations are shown in Figure 4. Magnetic anomaly reversal sequence is from *Gradstein et al.* [1994]. Normally magnetized blocks are solid. The modeled anomaly skewness parameter is -230°. FZ denotes a fracture zone.

4.5. ORI Massif Region

Anomaly M17 is traced south of ORI Massif to a magnetic bight near the rise center (Figure 4). The gap between lineations M18 and M17 suggests another northeast ridge jump. Interestingly, lineation M17 has a different trend from that of lineation M18 in the Helios Basin, perhaps owing to the ridge jump. The spacing between the M17 and M16 bights is also large and suggests yet another jump moving the triple junction farther northeast along the rise axis.

ORI Massif is bracketed by lineations M16 and M15 (Figure 4), and the spacing between these two anomalies is greater through the center of the edifice than elsewhere. This observation implies that a northwest jump of the Pacific-Izanagi ridge occurred between M16 and M15, annexing most of ORI Massif to the Pacific plate. Because this occurred immediately after the M18-M16 triple junction jumps, it is tempting to conclude that the massif eruption occurred on the Izanagi plate coincident with those jumps.

4.6. Shirshov Massif Region

Lineations M15 and M14 surround Shirshov Massif, the former forming a bight to the west and the latter forming, a bight to the north (Figures 3 and 5). The distance between lineations M15 and M14 in the Hawaiian lineations is longer than expected, implying another ridge jump that accreted much of the lithosphere beneath Shirshov Massif to the Pacific plate. Although we do not know when Shirshov Massif formed, it seems most plausible that the eruption coincided with the ridge jump, and the two are therefore linked.

4.7. Lineations M13 and Younger

Lineations M13-M1 are situated on the northeastern end of Shatsky Rise, and magnetic bights are mapped or can be inferred for most (Figures 3, 5, and 6). The progression of the magnetic

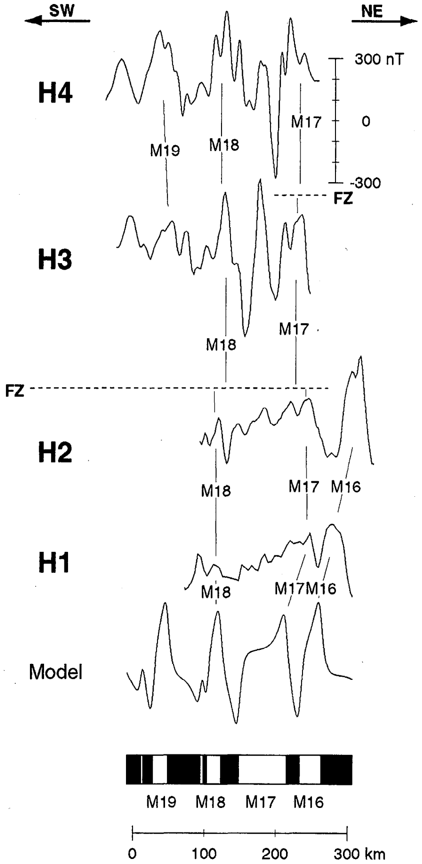

Figure 7b. Selected magnetic anomaly profiles from the Hawaiian lineations in the area of TAMU and ORI massifs, projected approximately normal to lineations. Conventions are identical to those in Figure 7a. The modeled anomaly skewness parameter is -130°.

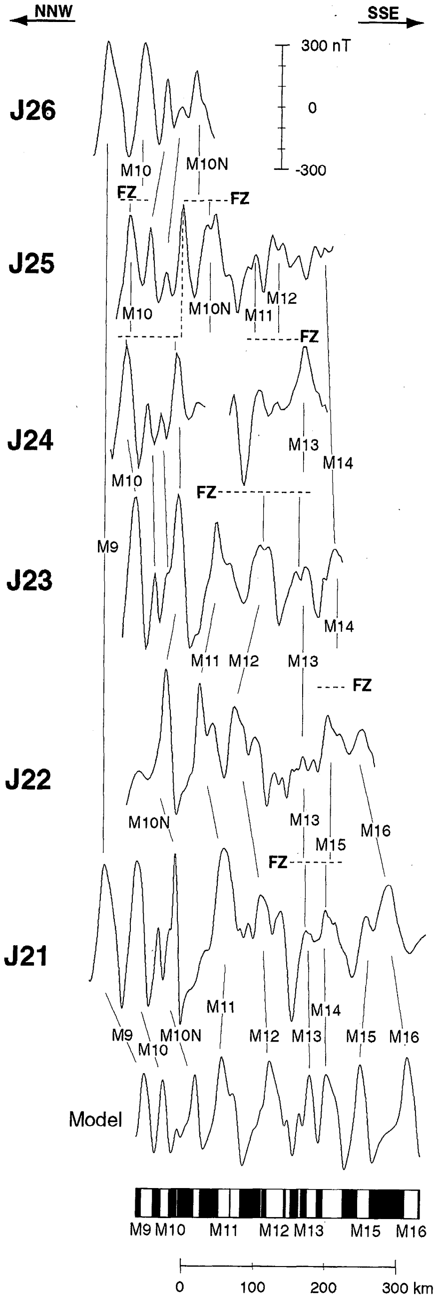

Figure 8a. Selected magnetic anomaly profiles from the Japanese lineations in the area of Shirshov Massif, projected approximately normal to lineations. Profile locations are shown in Figure 5. Other conventions are identical to those in Figure 7. The modeled anomaly skewness parameter is -230°.

bight has a variable trend: N10°W from M14 to M12, N20°E from M12 to M8, N15°W from M8 to M7, and N10°E from M7 to M1 (Figures 3 and 6). It also appears that the bight jumped several times: about 60 km eastward between chrons M10N and M10, 110 km westward between chrons M5 and M4, and 55 km eastward between chrons M4 and M3.

Anomalies of the Hawaiian lineations south and east of Shirshov Massif are somewhat problematic owing to interference from anomalies of the Ojin Rise Seamounts and the poor distribution of ship tracks over this highly segmented ridge. Having more complete bathymetric mapping of the seamounts [*Sager et al.*, 1999], we found that several previously identified lineations were, in fact, caused by seamounts. Also, we reinterpreted some of the anomalies around 36°N, 163°E and found that the spacings suggest several small eastward ridge jumps.

North of Shirshov Massif, the bathymetric expression of the rise is small, so anomalies are more easily identified. Unfortunately, ship tracks in this area are few. Nevertheless, we identified anomalies M10-M1 in the vicinity of the Papanin Ridge, and we note that the magnetic bights appear to deviate from the ridge axis, especially after M4 (Figure 3). *Sharman and Risch* [1988] and *Mammerickx and Sharman* [1988] both mapped the magnetic bights in this area and identified a bight from M6-M2. Our identification is closer to that of Sharman and Risch , which postulates fewer fracture zones than Mammerickx and Sharman do. Our identification of the jump between chrons M4 and M3 is, however, the same as that of Mammerickx and Sharman.

The Japanese lineations between M13 and M9 show a change from a segmented ridge to a single long ridge segment between about 152° and 162°E (Figure 3). This observation implies a series of short-lived ridge propagation events that eliminated fracture zones.

Papanin Ridge is separated from the north flank of Shirshov Massif by northwest trending Thompson Trough, which was mapped with a multibeam echosounder during cruise TN037

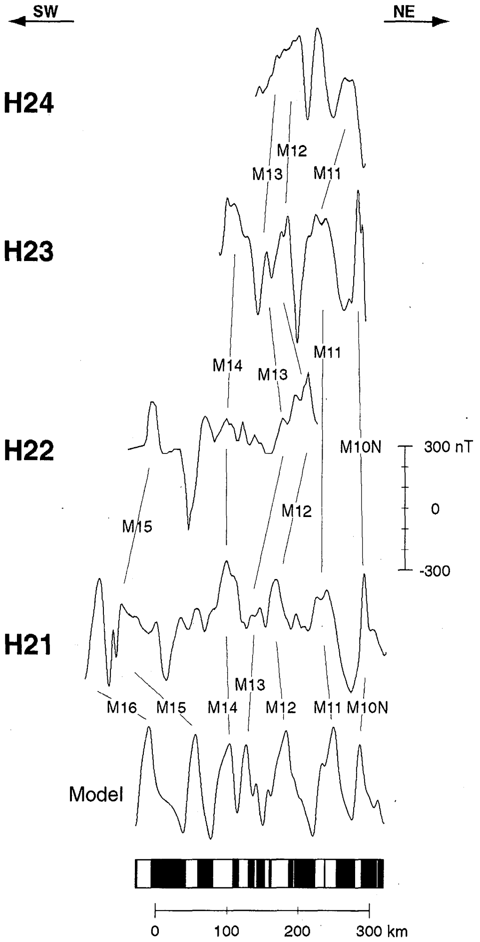

Figure 8b. Selected magnetic anomaly profiles from the Hawaiian lineations in the area of Shirshov Massif, projected approximately normal to lineations. Other conventions are identical to those in Figures 7 and 8a. The modeled anomaly skewness parameter is -130°.

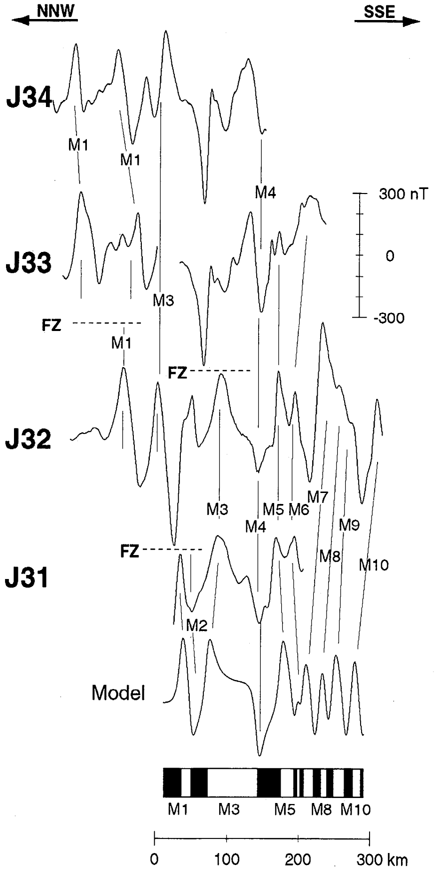

Figure 9a. Selected magnetic anomaly profiles from the Japanese lineations in the area of Papanin Ridge, projected approximately normal to lineations. Profile locations are shown in Figure 6. Other conventions are identical to those in Figure 7. The modeled anomaly skewness parameter is -230°.

(Figure 11). Shipboard seismic data indicate that the trough is a graben, and the multibeam soundings show that its bottom is at 5400 m, about the same as abyssal seafloor around the rise [*Sager et al.*, 1999]. It is also situated slightly northeast of the M10N magnetic bight (Figure 11). Because of the similarity in trend of the trough and lineation M10N, we conclude that the trough is an abandoned ridge crest graben, formed at or near the triple junction after the triple junction jump between chrons M10N and M10.

The lineation pattern between 160° and 165° E north of 42° N appears discontinuous (Figure 3). Anomalies to M3 (west of 161°E) and M1 (east of 161°E) fit with the pattern to the south, but to the north several short lineations with different trends are observed. The different lineation azimuths imply that a reorganization of the Pacific-Izanagi ridge occurred between chrons M4 and M0 as *Nakanishi et al.* [1989] suggested. A similar reorganization does not seem to have occurred on the Pacific-Farallon ridge because lineation M0 has been mapped without an obvious change of trend in the Hawaiian lineations to the southeast of our study [*Nakanishi et al.*, 1992a].

We identified a magnetic bight for chron M1, but lineations north and northeast of this bight also look like M1. This implies another major triple junction jump between M1 and M0. At the same time, the Pacific-Farallon-Phoenix triple junction also changed its configuration [*Joseph et al.*, 1993; *Nakanishi et al.*, 1992a; *Nakanishi and Winterer,* 1996], and the coincidence suggests a widespread plate reorganization.

5. Drift of the Triple Junction

Early analyses of magnetic lineations around Shatsky Rise noted apparent large lineation offsets and proposed that the triple junction was in a ridge-ridge-fault (RRF) [*Hilde et al.*, 1976] or ridge-fault-fault (RFF) configuration [*Sharman and Risch*, 1988; *Sager et al.*, 1988; *Nakanishi et al.*, 1989]. Both are only stable under restricted geometric conditions. *Sager et al.* [1988] noted that neither a ridge-ridge-ridge (RRR) or RFF configuration was consistent with the triple junction having remained at the Shatsky Rise axis from chron M20 to chron M10; if in an RRR configuration it should have drifted northward away from Shatsky Rise or if in a RFF configuration, it should have drifted northeast faster than that observed. They postulated that the triple junction shifted back and forth between the two configurations to keep it at the center of the rise. *Nakanishi et al.* [1989] concluded that the configuration of the triple junction alternated between RRR and RFF configurations several times during the formation of Shatsky Rise.

Our map shows magnetic bights throughout Shatsky Rise, and these bights imply that within the resolution of our data, the triple junction was in an RRR configuration virtually the entire time covered by our study. We identified nine jumps from observing

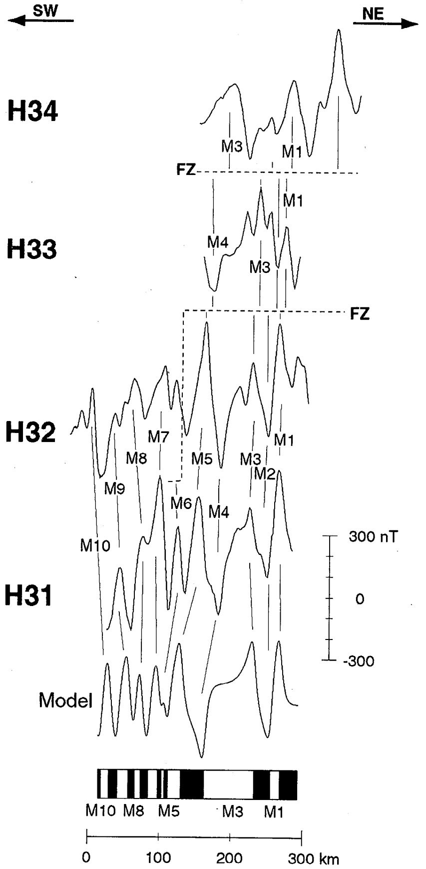

Figure 9b. Selected magnetic anomaly profiles from the Japanese lineations in the area of Papanin Ridge, projected approximately normal to lineations. Other conventions are identical to those in Figures 7 and 9a. The modeled anomaly skewness parameter is -130°.

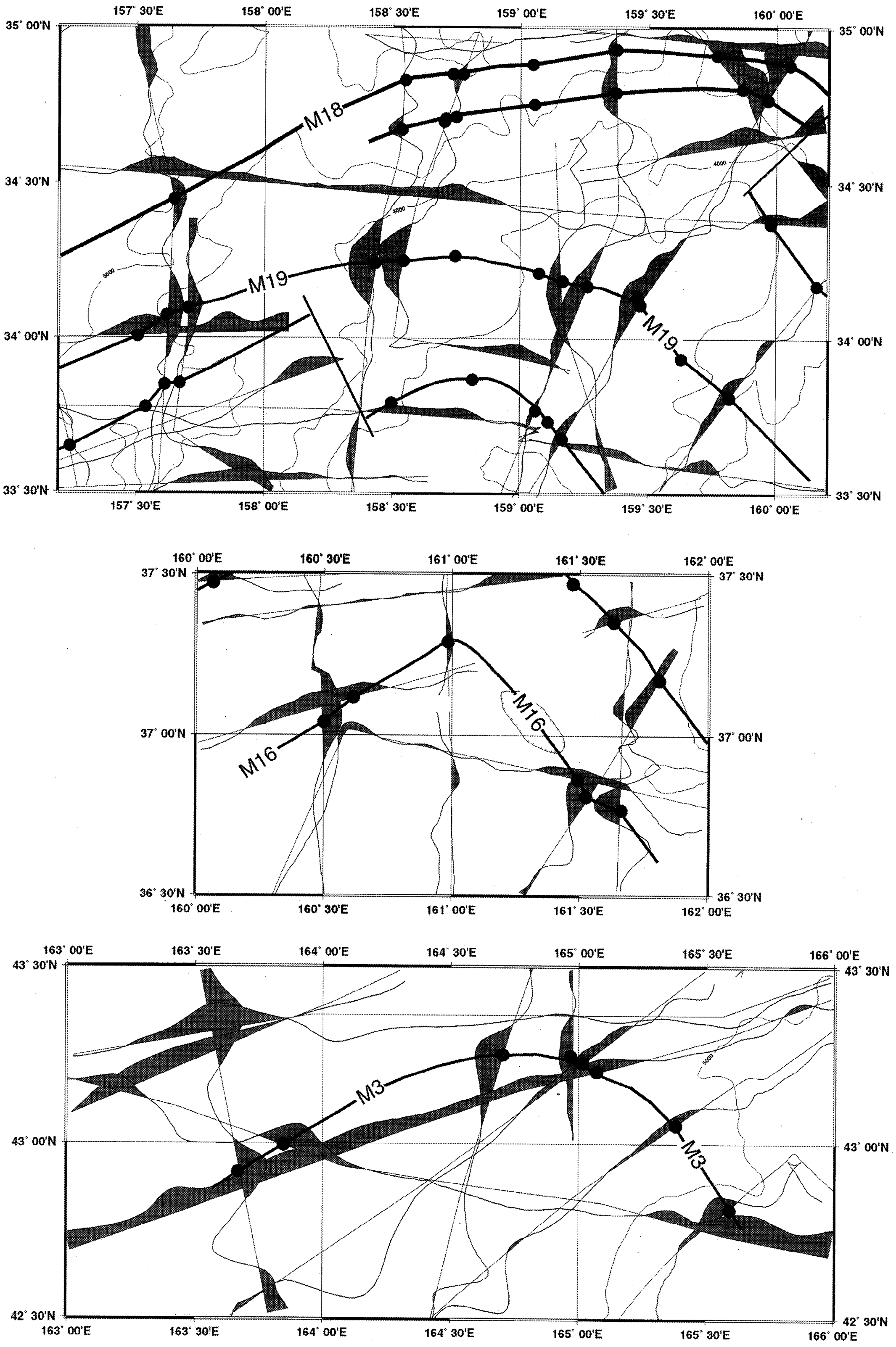

Figure 10. Detail of magnetic anomaly correlations in three areas demonstrating the linearity and trends of the magnetic lineations near some magnetic bights. Conventions are identical to those in Figure 4.

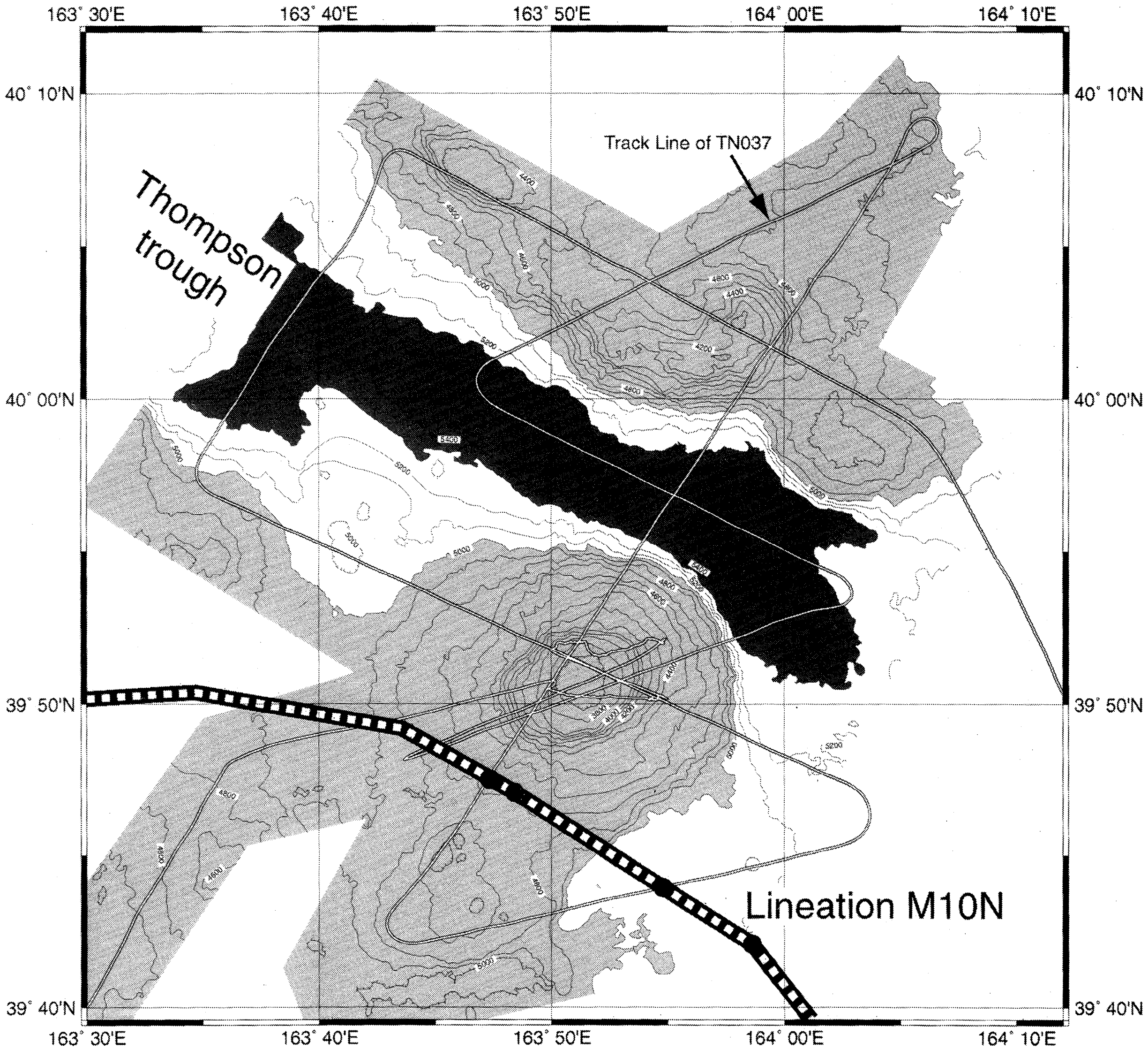

Figure 11. Comparison of Thompson Trough bathymetry [*Sager et al.*, 1999] with magnetic lineation M10N. Bathymetric contour interval is 100 m. The heavy dashed line denotes lineation M10N. Darkly shaded areas are below 5.3 km depth. Lightly shaded areas are above 5 km depth.

gaps in the lineations or deviations in the triple junction path (M21-M20, M20-M19, M18-M17, M17-M16, M15-M14, M12-M10N, M10N-M10, M7-M6, and M4-M3), beginning with the large 800 km eastward jump that brought the junction to the rise and ending with the small northward jump that caused the Papanin ridge and junction to separate their ways (Figure 3).

At least two of the jumps seem to have brought the triple junction to the probable plume location. The large M21-M20 jump put the junction at TAMU Massif whereas the M15-M14 jump put the junction at Shirshov Massif. Several other jumps had the effect of keeping the triple junction at the rise axis. These coincidences suggest that plume activity caused many jumps. Some jumps, however, such as the M10N-M10 and M4-M3 jumps, seem a response to broader ridge reorganizations. The former is coincident with a change in both the Pacific-Farallon and Pacific-Phoenix ridge trend changes [e.g., *Sager et al.*, 1988; *Joseph et al.*, 1993; *Nakanishi et al.*, 1992a; *Nakanishi and Winterer,* 1996]. The latter is inferred from the apparent Pacific-Izanagi shift noted in section 4.7.

6. Shatsky Rise Tectonic Evolution and Plume-Ridge Interactions

Prior to the formation of Shatsky Rise, the Pacific-Izanagi-Farallon triple junction was southwest of the current plateau location and was moving north or northwest (Figure 12a). Between chrons M21 and M20 (148-146 Ma), the ridges at the triple junction reorganized and the junction jumped 800 km eastward and apparently shaved off a triangle of northern Pacific plate that was lost to the Izanagi plate (Figure 12b).

6.1. Formation of TAMU Massif

From our data set we cannot state conclusively which event caused which: did the TAMU Massif eruption cause the ridge re-

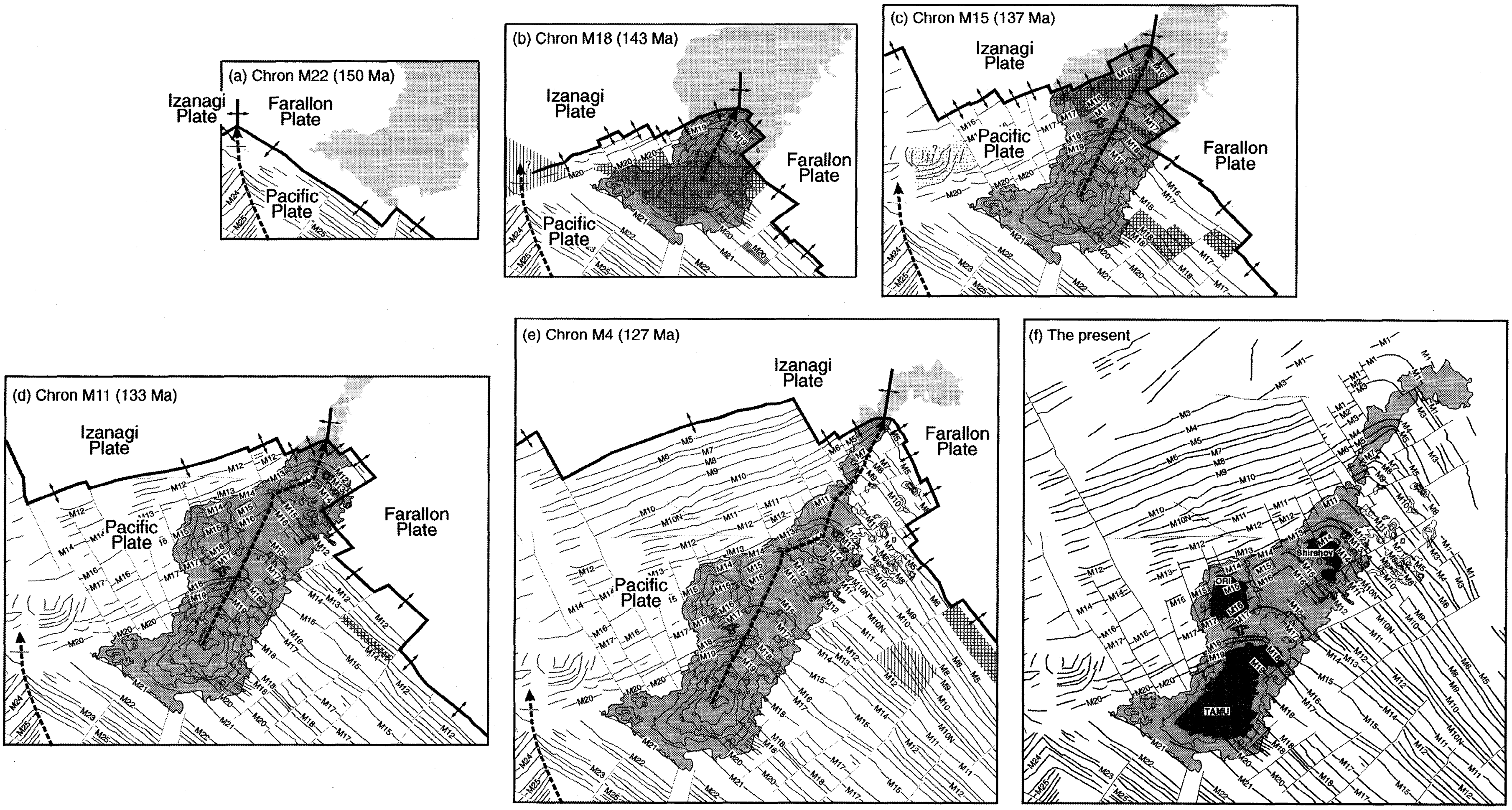

Figure 12. Tectonic history of Shatsky Rise inferred from the magnetic lineation pattern. Five stages are shown at times 4-7 m.y. apart, at the times of (a) chron M22 (150 Ma), (b) chron M18 (143 Ma), (c) chron M15 (137 Ma), (d) chron M11 (133 Ma), (e) chron M4 (127 Ma), and (f) in the present. Only features remaining on the Pacific plate are shown, since the plates to the northwest (Izanagi) and northeast (Farallon) have been subducted, making features on those plates speculative. Medium lines are magnetic lineations and fracture zones; some are labeled with chron numbers for reference. Thin lines are bathymetry contours at 500 m intervals, shown only on the part of the Pacific plate that existed at the time represented each stage. Bathymetry shallower than 5 km is shaded. The outline of Shatsky Rise to the northeast of the magnetic bight is shown for reference but did not exist at the time represented each stage. The thick line with a small arrow shows the spreading ridges, with the small arrow representing the direction of seafloor spreading. Thick dashed lines show the progression of the Pacific-Izanagi-Farallon triple junction relative to the Pacific plate. Hatched areas show plate fragment pieces accreted to the Pacific plate by ridge jumps in the time between one stage and the next. Areas with vertical ruling show pieces of plate sliced off the Pacific plate by ridge jumps.

organization or vice versa? The implications, however, are important in understanding the formation of oceanic plateaus and hot spots. Lineations through the north side of TAMU Massif imply that the triple junction jumped to that location and that this part of the rise formed at the ridge (Figure 12b). However, no lineations can be traced through the bulk of the massif. Moreover, *Sager and Han* [1993] note that TAMU Massif has a simple magnetic anomaly that can be explained by a predominantly reversed polarity. The asymmetry of the TAMU Massif center relative to the magnetic lineations on its northeast side suggest that its bulk did not form at the ridge. We believe this evidence points to an eruption that began off ridge but caused the triple junction to jump to its location.

As evidenced by the lineations, the formation of TAMU Massif was mostly finished by chron M18 (143 Ma), at odds with the interpretation of *Sager and Han* [1993] that it formed during chron M17. Their assignment of TAMU Massif formation to M17 was based on this being the longest period of reversed polarity in the Early Cretaceous polarity timescale [*Sager and Han*, 1993]. If TAMU Massif formed predominantly during a period of reversed geomagnetic polarity, as they concluded, then it must have been during an earlier chron. Chrons M21 through M19 have durations of 0.37-0.68 Ma, 31-57% of the duration of M17. If these interpretations are correct, they indicate an eruption rate several times greater than 1.75 km^3yr^{-1} estimated by Sager and Han. This is an extraordinarily large emplacement rate.

Apparently coincident with TAMU Massif formation, a series of small ridge jumps occurred on the Pacific-Farallon ridge southeast of the rise. The first jump, closest to the rise, occurred shortly after chron M19 (145 Ma). Subsequent jumps, after chrons M18 and M17 (143-142 Ma), occurred progressively farther down the ridge to the southeast. These small jumps suggest that the ridge was trying to adjust to the new tectonic regime and the formation of the TAMU Massif.

Between the TAMU and ORI massifs lies Helios Basin, a deep, rectangular trough with lineated topography at its center and normal fault scarps along the south flank of ORI Massif and the north flank of TAMU Massif. Its bathymetry suggests that Helios Basin was caused by rifting [*Sager et al.*, 1999]. However, it does not appear to be the result of a simple ridge jump because it does not appear to be the center of a set of mirrored anomalies, and there is a slight difference in trend between lineation M18 on its south side and lineation M17 on its north side (Figure 3).

6.2. Formation of ORI and Shirshov Massifs

The separation of TAMU and ORI massifs by deep seafloor indicates that ORI formed from a second large plume eruption. The triple junction jumped northeastward by 170 km between chrons M17 and M16 (142-140 Ma), and ORI must have formed at about the same time (Figure 12c). Between chrons M15 and M14 (137-136 Ma) the triple junction jumped again, about 160 km northeast, ending up bracketing the Shirshov Massif, which may represent a third large plume eruption [*Sager et al.*, 1999]. Once again, we do not know the age of this volcanic construct, but it seems logical that its formation and the ridge jump are related. By M14-M13 time (136-135 Ma), the junction was moving north again, and contours of the northern Shirshov flanks follow it. This parallelism implies that the ridges bounded either the volcanic activity or sediment apron construction. Seismic profiles collected on cruise TN037 show nearly 1 second (two-way travel time) of sediment on the Shirshov north flank. Consequently, we think most of the volcanic activity was short lived, that it built the higher, central part of that massif, and that the lower flanks consist mainly of a sediment apron.

6.3. Formation of Papanin Ridge

The Papanin Ridge may represent the waning eruptions of the Shatsky plume [*Sager et al.*, 1999] (Figure 12e). After a small jump between chrons M10N and M10 (132-131 Ma) that correlates with a slight shift in orientation of the Pacific-Farallon ridge [*Larson*, 1976; *Sager et al.*, 1988; *Tamaki and Larson*, 1988; *Nakanishi et al.*, 1992a, b], the triple junction stayed near the ridge until chron M4 (127 Ma). Thompson Trough, the gap between Shirshov Massif and Papanin Ridge, formed as an abandoned rift at the time of the M10N jump.

The Ojin Rise Seamounts, located east of Shirshov Massif, are located on seafloor from about chron M14 and younger. Many are elongated parallel to magnetic lineations, and this coincidence implies formation at the ridge crest. Further evidence in favor of a near-ridge formation comes from the positive magnetic anomaly of one of these seamounts that we surveyed at 37.0°N, 165.5°E. Its anomaly indicates a reversed magnetic polarity, and it sits on chron M6; therefore it most likely formed between chrons M6 and M0 (128-121 Ma). The morphologies of these seamounts are distinctly different from the main rise features, suggesting a difference in source. It is not clear whether they are related to Shatsky Rise volcanism or not.

The final chapter in Shatsky Rise evolution was the separation of the triple junction and Papanin Ridge. A reorganization of Pacific-Izanagi ridge started at about chron M4, and the triple junction was located northwest of the ridge thereafter (Figure 3).

Interestingly, the triple junction and plume may have gotten back together during the Cretaceous long normal superchron. The Papanin Ridge bends to a southeast trend at 43° and trends toward the northwest extension of Hess Rise [*Sager et al.*, 1999]. It has been postulated that Hess Rise formed from a secondary head of the plume that formed Shatsky Rise [*Bercovici and Mahoney*, 1994]. Moreover, even though the evolution of the ridges during the Cretaceous long normal superchron is unclear, it appears as if the triple junction jumped to the southeastward to the vicinity of Hess Rise [*Larson and Chase*, 1972; *Mammerickx and Sharman*, 1988].

6.4. Was Shatsky Rise Formed by a Plume Head?

Although many Earth scientists embrace the plume head hypothesis of ocean plateau formation [e.g., *Coffin and Eldholm*, 1994], it is not universally accepted [e.g., *Anderson et al.*, 1992]. Does Shatsky Rise fit this model? Many elements of Shatsky Rise evolution are consistent with the plume head hypothesis, but a few are not.

Shatsky Rise looks like a feature that was built by an episodic eruption that started off big, forming TAMU Massif, and ended small, forming Papanin Ridge. In the transition, ORI and Shirshov massifs were constructed. TAMU Massif represents an enormous volcanic output, and the bulk of it seems to have formed rapidly. Although our age constraints are weak, we know of little evidence to suggest that any of the rise massifs formed over an extended time. The scenario of a massive, rapid eruption that trails off into a smaller plume fits the plume head hypothesis. Isotopic data from Shatsky Rise dredge samples suggest contributions from both plume and ridge sources [*Tejada et al.*, 1995], as would be expected from a hot spot at a triple junction. Moreover, some element ratios in these samples can be interpreted as indicative of lower mantle involvement [*Tatsumi et al.*, 1998].

This conclusion is weakened, however, by an imperfect understanding of mantle chemical segregation and by the fact that the samples interpreted as indicative of lower mantle affinities come from a seamount between TAMU and ORI massifs and that the relationship of this volcano to the main Shatsky Rise edifices is unclear.

Complicating the plume head picture are a two observations. First, the jump that brought the triple junction to Shatsky Rise occurred at the time of a major ridge reorganization [*Sager et al.*, 1988; *Nakanishi et al*, 1989]. Although it might be expected that the triple junction would jump to a nearby source of heat and uplift, as would result from a plume head, the eruption occurred near the trailing edge of the plate. If oceanic plate motions are largely a result of slab pull, it is difficult to understand how this eruption would cause the plate motion to change. Indeed, it seems that many ocean plateaus formed at ridges or triple junctions (e.g., Magellan Plateau [*Tamaki and Larson*, 1988]; Manihiki Plateau [*Winterer*, 1976]; Hess Rise [*Mammerickx and Sharman*, 1988]; Kerguelen Plateau [*Royer and Sandwell*, 1989]; Ontong Java Plateau [*Winterer and Nakanishi*, 1995]; Agulhas Plateau [*LaBrecque and Hayes*, 1979]; and Iceland [*Vink*, 1984]). This pattern suggests a link. However, most hypotheses that postulate flood basalt eruptions resulting from plate boundary tectonics require thick, cold crust, such as continental crust, to induce upwelling [e.g., *Anderson et al.*, 1992; *Anderson*, 1994; *White and McKenzie*, 1995]. The lithosphere near oceanic ridges is thin, so it seems probable that it would have little effect on underlying mantle convection.

Another complicating factor is that the Ojin Rise Seamounts appear more or less contemporaneous to the rise, and some of their members form a loose linear chain that implies a second hot spot [*Henderson*, 1985; *Sager et al.*, 1999]. Was there more than one plume? Without more data we cannot be certain of the relation of these seamounts to Shatsky Rise; however, they appear distinct from Shatsky Rise edifices both in morphology [*Sager et al.*, 1999] and in isotopic composition [*Tejada et al.*, 1995]. Conceivably, they are unrelated to the main Shatsky Rise eruptive activity. This is true of seamount chains and groups south of Shatsky Rise, where it is thought that volcanic chains have crisscrossed owing to the combination of numerous plume sources and plate motion changes. In conclusion, we believe the plume hypothesis explains many of the features of Shatsky Rise, but concede that many aspects of Shatsky Rise tectonic history are still poorly known.

7. Conclusions

Our examination of Mesozoic magnetic anomaly lineations within Shatsky Rise revealed lineations in the low parts of the plateau between volcanic massifs. When the lithosphere in these areas formed, the spreading ridges must not have been greatly affected by Shatsky Rise volcanism. In contrast, linear magnetic anomalies were not found over most of the area of volcanic massifs, implying that the higher rise was constructed as three large, discrete eruptions. Lineations are traced through the ridge that forms the northeast extension of the rise, so it appears to have formed near the ridge crest without significantly disrupting spreading, much like the formation of the Iceland-Faeroe and Iceland-Greenland ridges formed from the Iceland hot spot.

At least nine reorganizations of the triple junction occurred during the formation of Shatsky Rise: between chrons M21 and M20 (148-146 Ma), M20 and M19 (146-145 Ma), M18 and M17 (143-142 Ma), M17 and M16 (142-140 Ma), M15 and M14 (137-136 Ma), M12 and M10N (135-132 Ma), M10N and M10 (132-131 Ma), M7and M6 (129-128 Ma), and M4 and M3 (127-125 Ma). Each time, either the Pacific-Farallon ridge, the Pacific-Izanagi ridge, or both jumped, adding new lithosphere to the Pacific plate. The magnetic bights bracket parts of the topographic massifs, and the ridge jumps often brought the ridge or triple junction to a location near a topographic massif. This implies that the ridges jumped to the location of the hot spot when it erupted to form the massifs. Moreover, it appears the triple junction repeatedly reorganized to remain near the rise axis, which was presumably the location of the hot spot.

A change of relative movement of the Pacific-Farallon plates occurred between chrons M10N and M10 (132-131 Ma). After this the Shatsky hot spot diminished in its output and formed the low northeast ridge. The triple junction stayed near the ridge until chron M4 (127 Ma), when the Pacific-Izanagi ridge underwent a reorganization. After M1 the triple junction jumped farther away from the rise, approximately coincident with a 90° change in the azimuth of Papanin Ridge. Like other bends in hot spot seamount chains, this may signify a large-scale change in plate motion relative to the mantle.

Most evidence from Shatsky Rise fits the plume head hypothesis for oceanic plateau formation. It appears that the initial rise formation was rapid and large, as if from a plume head, forming the largest massif and causing the largest triple junction jump. The final eruptions were smaller, forming the ridge, as if from a plume tail. The two smaller massifs may represent transitional eruptions.

Acknowledgments. We thank the captain, technical staff, and crew of the R/V *Thomas G. Thompson* who made it possible to collect data on cruise TN037. We acknowledge K. Sayanagi, N. Seama, and J. Segawa for their permission to use the magnetic data of the KH-88-3 cruise. We appreciate the efforts of National Geophysical Data Center, whose efforts to create the GEODAS system has greatly facilitated compilations such as ours. WS and cruise TN037 were funded by NSF grant OCE93-14229. We thank R. L. Larson, the associate editor, and anonymous reviewers for their constructive reviews.

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(Received May 14, 1998; revised November 10, 1998;
accepted December 17, 1998.)