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Reorganization of the Pacific-Izanagi-Farallon triple junction in the Late Jurassic: Tectonic events before the formation of the Shatsky Rise

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ABSTRACT

It has been suggested that the Shatsky Rise oceanic plateau formation began simultaneously with a reorganization of spreading at a triple junction bordering the northern Pacific plate, and this coincidence has led to speculation about the connections between the two events. We present new marine geophysical data that constrain the seafloor spreading history of the Pacific-Izanagi-Farallon triple junction just before the birth of the Shatsky Rise. Bathymetric data reveal en echelon, abandoned spreading centers trending northwest-southeast located adjacent to the southwest flank of the Shatsky Rise. Magnetic anomalies and bathymetry are interpreted to indicate that segments of the Pacific-Farallon Ridge near the triple junction propagated northwest from chron M23 (153 Ma) to chron M22 (151 Ma) during a spreading ridge reorganization at the edge of a likely microplate. Our detailed examination of bathymetric and magnetic anomaly lineations also shows that the strike of the Pacific-Izanagi Ridge changed gradually on the west side of the triple junction around chron M22. Our observations indicate that the plate boundary reorganization began several million years before the formation of the Shatsky Rise, implying that the eruption of the plateau did not cause the reorganization.

INTRODUCTION

The Shatsky Rise is located in the northwest Pacific basin on seafloor formed during the Late Jurassic and Early Cretaceous (e.g., Sager et al., 1988, 1999; Nakanishi et al., 1989, 1999b). The abyssal seafloor surrounding the rise is at depths of 6000–5500 m below sea level (Fig. 1). 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).

The Shatsky Rise is elongated southwest to northeast and has an area of 4.8×10^5 km^2, ~25% more than the islands of

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Japan. The rise contains three large volcanic constructs (TAMU, ORI, and Shirshov plateaus; for place names, see Fig. 1) that rise to depths of 3200–2000 m. All three have domes of Cretaceous pelagic sediments as much as 1 km thick at their summits (Karp and Prokudin, 1985; Khankishiyeva, 1989; Sliter and Brown, 1993; Sager et al., 1999). The plateaus 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; Korenaga and Sager, 2012). The plateaus are separated by areas that rise <1 km above the surrounding seafloor. On the northeast side of the rise a low, linear ridge trends to the northeast and bends nearly 90° at 43°N to a southeast trend that projects to the Hess Rise.

The Mesozoic magnetic anomaly lineations with two different strikes were identified around the Shatsky Rise in Nakanishi et al. (1989, 1999b) (Fig. 2). One set has a northeast-southwest strike and belongs to the Japanese lineation set formed at the Pacific-Izanagi Ridge. The other set has a northwest-southeast strike and belongs to the Hawaiian lineation set formed at the Pacific-Farallon Ridge. The two lineation sets younger than M19 (146 Ma; ages for magnetic lineations are taken from the time scale of Gradstein et al., 2012) meet at the Shatsky Rise. Magnetic bights (bent lineations) of anomalies M25 through M22 (156–151 Ma) are found ~800 km southwest of the rise. Magnetic bights from chron M19 to chron M1 (128 Ma) shift to the northeast, following the axis of the Shatsky Rise and indicating a number of ridge jumps (Nakanishi et al., 1999b).

The formation of the Shatsky Rise has been explained by the plume head model (Nakanishi et al., 1989, 1999b). In Nakanishi et al. (1989, 1999b) it was suggested that the emergence of a mantle plume caused a plate boundary reorganization, which included a jump of the Pacific-Izanagi-Farallon triple junction by ~800 km and a strike change of the Pacific-Izanagi Ridge. Although the plume head model seems to explain many facets of Shatsky Rise morphology, observations such as the coincidence of the triple junction and mantle plume and mid-oceanic ridge basalt (MORB)–like geochemistry of basalt samples are not explained easily by this model, indicating that another mechanism may be responsible (Sager, 2005). Because the tectonic history of the spreading ridges near the Shatsky Rise is critical to understand the formation mechanism of oceanic plateaus, it is important to elucidate the tectonic history of the Pacific-Izanagi-Farallon triple junction.

During the summer of 1999, a geophysical survey was conducted near the western end of the Shatsky Rise during a cruise by the R/V *Mirai* (Fig. 3; cruise MR99-K04; Nakanishi et al., 1999a). The seafloor in this location formed at the Pacific-Farallon Ridge

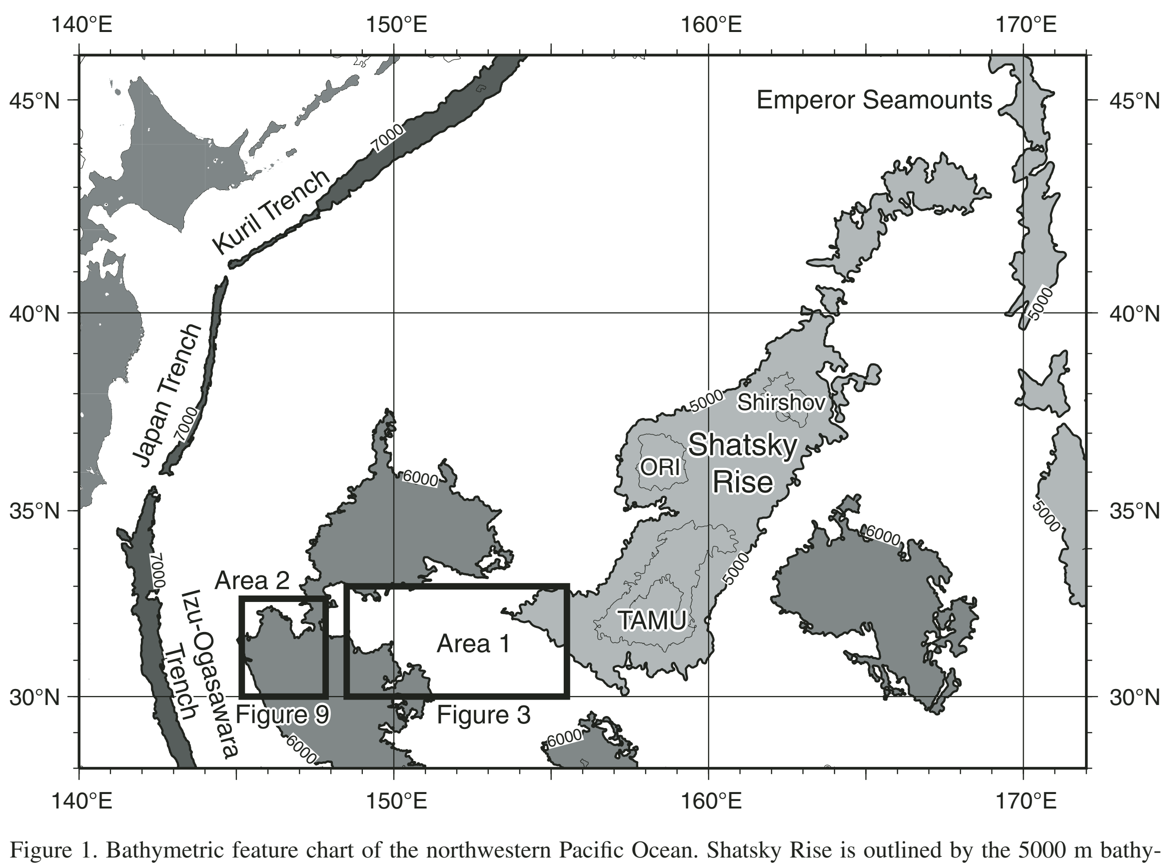

Figure 1. Bathymetric feature chart of the northwestern Pacific Ocean. Shatsky Rise is outlined by the 5000 m bathymetric contour. Rectangles encompass the areas of Figures 3 (area 2) and 9 (area 1). Bathymetric data are from Smith and Sandwell (1997). Dark shaded areas are deeper than 6000 m. Lightly shaded areas are above 5000 m. Kuril, Japan, and Izu-Ogasawara trenches are outlined by the 7000 m bathymetric contour.

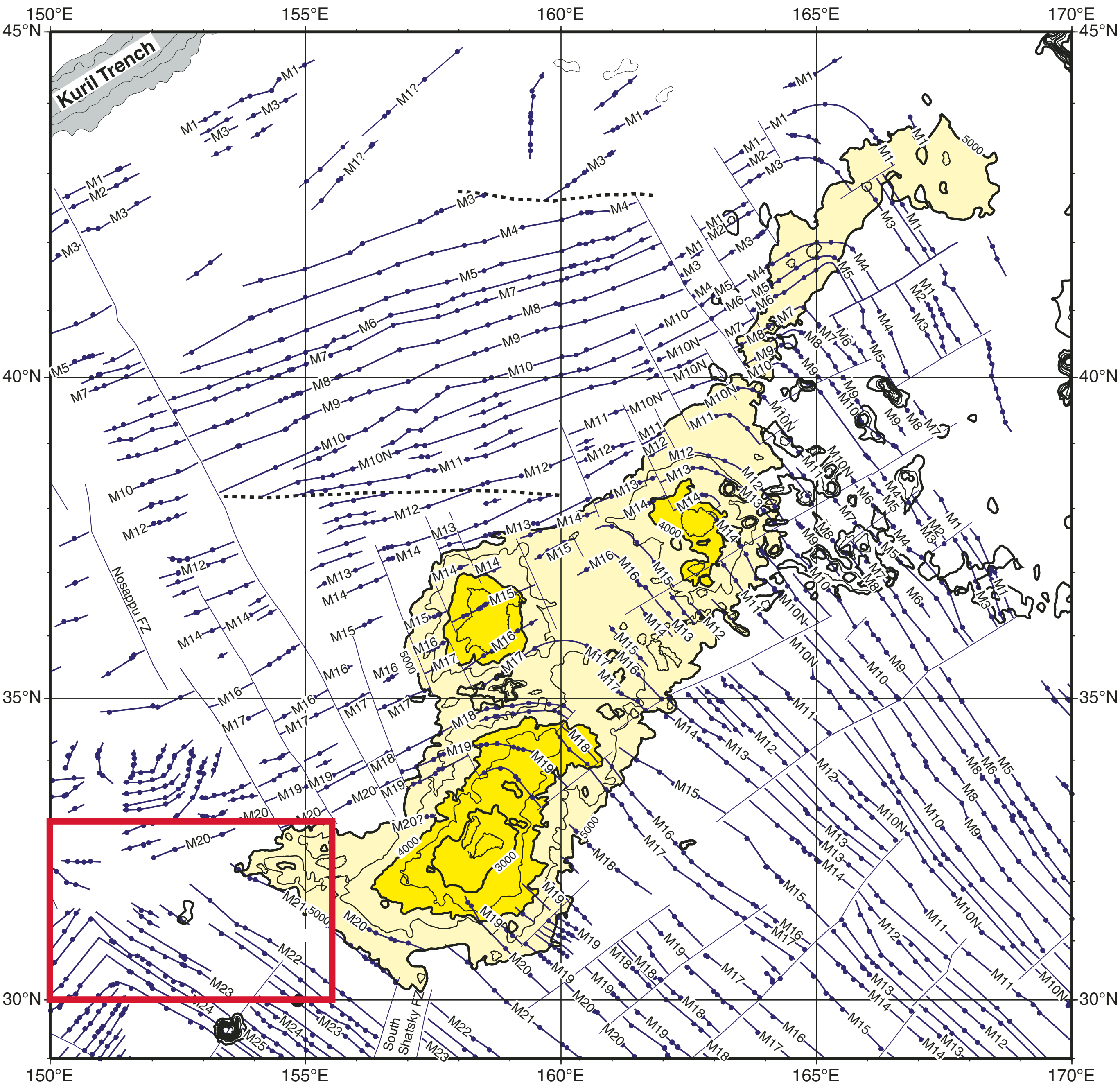

Figure 2. Magnetic anomaly lineations around the Shatsky Rise (after Nakanishi et al., 1999b). The red rectangle encompasses the eastern part of area 1. Blue lines with solid circles and thin lines represent magnetic anomaly lineations and fracture zones, respectively.

near the Pacific-Izanagi-Farallon triple junction before chron M21 (149 Ma). Because this zone is between the locations of the triple junction just prior to and just after the proposed ridge jump, it can provide important clues about the formation of the Shatsky Rise. The free-air gravity anomaly map (Sandwell and Smith, 2009) shows elongated negative anomalies with a northwest-southeast trend northeast of Isakov Seamount in the survey area (Fig. 3). The bathymetric survey during the MR99-K04 cruise discovered elongated and curved troughs, with a depth of ~300 m, corresponding to the linear negative gravity anomaly. In Nakanishi et al. (1999a), it was proposed that a segment of the Pacific-Farallon Ridge connected to the Pacific-Izanagi-Farallon triple junction propagated southeastward before the formation of the Shatsky Rise. The magnetic survey conducted on cruise MR99-K04 was inadequate to identify magnetic anomaly lineations because of the small survey area. To expose the detailed tectonic history, additional geophysical

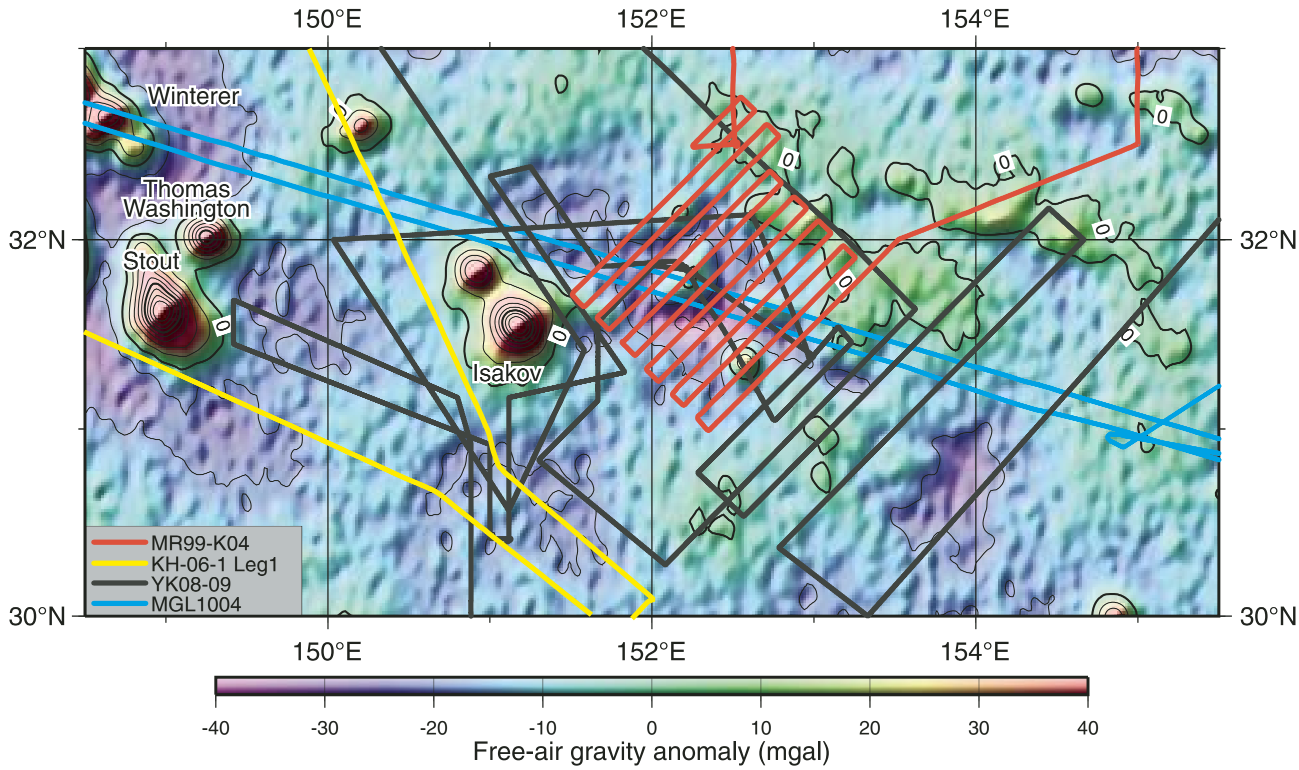

Figure 3. Satellite-derived free-air gravity anomaly map of area 1 showing locations of ship tracks. Gravity anomaly data are from Sandwell and Smith (2009). Contour interval is 20 mgal.

surveys were conducted in the winter of 2006 by R/V *Hakuho-maru* (cruise KH-06-1) and in the summer of 2008 by R/V *Yokosuka* (cruise YK08-09) in area 1 (Figs. 1–3). Bathymetric data were also collected in area 1 during transits of a cruise by the R/V *Marcus G. Langseth* in the summer of 2010 (cruise MGL1004; Fig. 3). We present analyses of the geophysical data collected during these four new cruises as well as preexisting data and use these results to investigate the tectonic event that occurred around the Pacific-Izanagi-Farallon triple junction before the formation of the Shatsky Rise, that is, before chron M21.

TECTONIC SETTING

Junctions between the Japanese and Hawaiian Lineation Sets before Chron M21

Handschumacher et al. (1988) mapped the magnetic bight from M28 to M21 by aeromagnetic data. The configuration of this bight was clarified in Nakanishi et al. (1989). An exact location for the magnetic bight was identified at the junction of lineations between M24B and M23. The lineations from M29 to M25 near the junction are equivocal in the Hawaiian lineation set so that the older part of this bight could not be identified in this period. The Japanese lineations, however, have unequivocal lineations from M29 to M25. The junction between the Japanese and Hawaiian lineation sets from M22 to M21 is indistinct. Anomalies M22 to M21 in both the Japanese and Hawaiian lineation sets become shorter. Magnetic bights for lineations 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 an N70°E trend. This probably indicates that a part of Pacific plate lithosphere was cut off by the reorganization of the plate boundary.

Models of the Formation of the Shatsky Rise

Mesozoic magnetic lineations revealed that the Shatsky Rise is at the confluence of Japanese and Hawaiian lineation sets (Fig. 2; Nakanishi et al., 1989, 1999b). This indicates that the Shatsky Rise formed at the Pacific-Izanagi-Farallon triple junction (Sager et al., 1988; Nakanishi et al., 1989, 1999b). The mean ^{40}Ar-^{39}Ar age from two basalt samples cored at Ocean Drilling Program (ODP) Site 1213 on the TAMU Plateau is 144.6 ± 0.8 Ma (Mahoney et al., 2005), which correlates with chron M18 (145 Ma) in the time scale of Gradstein et al. (2012). Because lineation M18 goes through the northern flank of the TAMU Plateau, and forms a magnetic bight there (Fig. 2), this massive volcano must have formed at the triple junction. Although no reliable dates are available from the igneous rock of the other Shatsky Rise edifices, gravity data imply that the other large volcanoes formed near the age of the seafloor (Sandwell and MacKenzie, 1989). Studies of magnetic lineations and bathymetry conclude that the spreading ridges and plateau volcanoes interacted during formation of the Shatsky Rise (Nakanishi et al., 1999b; Sager et al., 1999).

Before formation of the Shatsky Rise, around chron M21, the Japanese lineations reoriented by 25°, indicating a reorganization of spreading on the Pacific-Izanagi Ridge (Nakanishi et al., 1989, 1999b). In Nakanishi et al. (1989, 1999b) it was concluded that the appearance of a Shatsky hotspot caused a regional reorganization of the Pacific-Izanagi-Farallon plate boundaries. Simultaneously, the triple junction jumped northeast to the location of the Shatsky Rise, annexing a piece of the Farallon plate and causing a short-lived microplate nearby (Sager et al., 1988; Nakanishi et al., 1989, 1999b). Subsequently, the triple junction remained near the Shatsky hotspot, as shown by the confluence of magnetic lineations along the rise to chron M4 (131 Ma). The Shatsky Rise is the trace of the Shatsky hotspot on the Pacific plate (Nakanishi et al., 1989, 1999b). According to this plume model, Shatsky Rise volcanism results from hot mantle material that rose to the base of the lithosphere, where it melted and emplaced the Shatsky Rise. This plume may have originated in the lower mantle as a plume head, explaining the massive initial Shatsky Rise eruptions and the waning of eruptions with time (Nakanishi et al., 1999b; Sager, 2005). According to this model, the coincidence of the plume and triple junction is a result of the heat and uplift from the plume capturing the triple junction.

In addition to the plume explanation for the Shatsky Rise formation, one of us (Sager, 2005) noted that the plume hypothesis does not explain some facts of the Shatsky Rise evolution. An alternative explanation for the Shatsky Rise formation is decompression melting of fertile mantle caused by rapid upwelling near the triple junction (Sager, 2005; Foulger, 2007). One of us (Korenaga, 2005) proposed that Ontong Java Plateau (west-central Pacific Ocean) was formed by the entrainment of dense fertile mantle by strong passive upwelling near a fast-spreading mid-ocean ridge.

Integrated Ocean Drilling Program (IODP) Expedition 324 was conducted in 2009 to investigate the origin of the Shatsky Rise (Sager et al., 2010). Project scientists found that massive lava flows occur on the TAMU Plateau, similar to those found in continental flood basalts and at Ontong Java Plateau, the world's largest oceanic plateau (Sager et al., 2011). Geochemical study of the basement basalts recovered during the expedition shows that the basement basalts have enriched MORB characteristics and compositions that indicate melt at slightly greater depths than typical MORB (Sano et al., 2012). A recent wide-angle seismic refraction survey over the TAMU Plateau indicates that a chemically anomalous mantle may have been responsible for the formation of the rise (Korenaga and Sager, 2012). These new observations suggest that there may be a direct link between the spreading ridges and formation of the Shatsky Rise; therefore, it is more important than ever to examine the tectonic relationships between the two.

DATA AND METHODS

To process the multibeam bathymetric data and shipboard geomagnetic data and to make maps of the data, Generic Mapping Tools (Wessel and Smith, 1998), Marine Geophysics Basic Tools (Tamaki et al., 1992), and MB-System (Caress and Chayes, 1996) were used.

Bathymetric Data

The bathymetric data used to expose topographic features are from 65 cruises (Table 1). In the study area, we conducted bathymetric measurements during the four cruises by R/V *Mirai* (cruise MR99-K04), R/V *Hakuho-maru* (cruise KH-06-1), R/V *Yokosuka* (cruise YK08-09), and R/V *Marcus G. Langseth* (cruise MGL1004; Fig. 3). R/V *Mirai* and R/V *Yokosuka* were equipped with a multibeam echo-sounding system, SeaBeam

TABLE 1. INVENTORY AND SOURCES OF MULTIBEAM BATHYMETRIC DATA USED FOR THIS STUDY, EXCEPT FOR DATA PROVIDED BY HYDROGRAPHIC AND OCEANOGRAPHIC DEPARTMENT, JAPAN COAST GUARD (65 CRUISES)

Institution	Number of cruises	Cruise identification
Acquired by Nakanishi, Sager, and Korenaga (our study)	4	MR99-K04, KH-06-1, YK08-09, MGL1004
ORI, UT	4	KH-89-2 Leg 1, KH-93-1 Leg 1, KH-96-3 Leg 1, KH-03-1 Leg 5
JAMSTEC	51	KH-05-4 Leg 1, KH-10-4 Leg 2, KR02-05, KR02-15, KR06-09, KR06-14, KR07-06, KR08-15, KY05-11, KY09-07, MR98-K01, MR99-K07, MR00-K01, MR00-K02, MR00-K05, MR00-K07, MR00-K08, MR01-K01, MR01-K02, MR01-K03, MR02-K01, MR02-K02, MR02-K03, MR02-K05, MR03-K01, MR03-K02, MR04-02, MR04-04, MR04-06, MR04-07, MR05-01, MR05-02, MR06-01, MR06-03, MR06-05, MR07-01, MR07-03, MR07-05, MR08-03, MR08-06, MR09-04, MR10-01, MR10-02, MR10-06, MR10-07, MR11-02, MR11-03, MR11-05, MR11-06, MR11-02, MR12-03
LDEO, CU	1	EW0204
SIO, UCSD	3	MGLN03MV, RNDB10WT, ZHNG07RR
University of Washington (Seattle)	2	TN037, TN168

Note: Institution abbreviations: ORI, UT—Ocean Research Institute, the University of Tokyo; JAMSTEC—Japan Agency for Marine-Earth Science and Technology; LDEO, CU—Lamont-Doherty Earth Observatory, Columbia University (New York); SIO, UCSD—Scripps Institution of Oceanography, University of California, San Diego.

2112, which operates at 12 kHz with a 2° by 2° beam width. R/V *Hakuho-maru* was equipped with a multibeam echo-sounding system, SeaBeam 2120, which operates at 20 kHz with a 1° by 1° beam width. R/V *Marcus G. Langseth* was equipped with a multibeam echo-sounding system, Kongsberg Maritime EM122, which operates at 12 kHz with a 1° by 1° beam width.

To make a bathymetric grid file of the study area, we compiled and merged the entire multibeam data set collected by the aforementioned cruises with those provided by several organizations. Unpublished bathymetric data collected on six cruises by R/V *Hakuho-maru* were provided by Ocean Research Institute, the University of Tokyo. The Hydrographic and Oceanographic Department of the Japan Coast Guard provided multibeam data collected by their survey vessels from 1998 to 2008 (e.g., Fujisawa, 2009). Multibeam data obtained on the three cruises by R/V *Thomas Washington*, R/V *Melville*, and R/V *Roger Reville*, RNDB10WT, MGLN03MV, and ZHNG07RR, were supplied by the Geological Data Center, Scripps Institution of Oceanography (University of California, San Diego). Additional multibeam data were obtained from the databases of the Japan Agency for Marine-Earth Science and Technology for research cruises (http://www.godac.jamstec.go.jp/darwin/e) and National Oceanic and Atmospheric Administration/National Geophysical Data Center (NOAA/NGDC; http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html).

The first step of multibeam bathymetric data analysis was to construct sound-velocity profiles in order to calculate depths. Data used for this process were of variation of temperature and/or salinity collected by expendable bathythermograph (XBT) or conductivity-temperature-depth (CTD) measurements during the respective cruises. To construct sound velocity profiles for the cruises during which no XBT or CTD measurements were conducted, temperature and salinity data from the 1982 *Climatological Atlas of the World Ocean* (Levitus, 1982) were used. Sound-velocity profiles in the water column were computed per cruise using the equation of Del Grosso (1974).

Where multibeam bathymetric data were stored in the original vendor format, bathymetric data were manually edited using the interactive graphical utility "mbedit" module of the MB-System to remove soundings that are obviously erroneous. After identification of bad soundings, sound-velocity correlation was done if necessary. The depth recorded by any echosounder is strongly dependent on the sound-velocity profile through the water column. We reconstructed bathymetry directly from the traveltime data by full raytracing through an appropriate water sound-velocity profile. After calculation of depths, additional erroneous soundings were manually flagged so that they were not used to make the bathymetric grid. A grid of depth data was calculated, at a 300 m spacing, using all the edited multibeam data.

Geomagnetic Data

The magnetic data used to identify magnetic anomaly lineations are from 73 cruises (Table 2). In addition to previously interpreted data (e.g., Nakanishi et al., 1999b), magnetic data were obtained from the three cruises, MR99-K04, KH-06-1, and YK08-09, using a proton precision magnetometer. The data were incorporated with the data used in Nakanishi et al. (1999b). Additional shipboard geomagnetic data in the study area were obtained from the database of NOAA/NGDC (http://www.ngdc.noaa.gov/mgg/geodas/geodas.html).

Since the cruises span more than four decades and the total magnetic field data were originally reduced to anomalies using

TABLE 2. INVENTORY AND SOURCES OF GEOMAGNETIC DATA USED FOR THIS STUDY (73 CRUISES)

Institution	Number of cruises	Cruise identification
Acquired by Nakanishi	3	MR99-K04, KH-06-1, YK08-09
ORI, UT	13	KH-67-5, KH-68-4A, KH-78-2, KH-80-2, KH-82-4, KH-82-5, KH-84-1, KH-88-3, KH-89-2 Leg 1, KH-93-1 Leg 1, KH-96-3 Leg 1, KH-03-1 Leg 5, UM6503-B
JHOD	9	HS99T43, HT91T253, HT92T261, HT92T262, HT92T271, HT92T272, HT92T273, HT99T442, HT99T452
GSJ	10	GH771-C, GH7901, GH801-A, GH801-B, GH805-A, GH805-B, GH814-A, GH814-B, GH824-A, GH824-A
Kobe University, Japan	1	RF72
SIO, UCSD	17	ANTP03MV, ARES05WT, ARES07WT, DSDP20GC, DSDP32GC, DSDP86GC, GECS-DMV, HUNT01HT, LUSI01AR, RAMA04WT, RNDB10WT, SCAN03AR, SILS02BT, SILS03BT, TSDY03WT, ZTES03AR, ZTES04AR
LDEO, CU	12	RC1007, RC1008, RC1219, RC2004, RC2005, V2106, V2110, V3212, V3214, V3311, V3312, V3612
Texas A&M University	3	ODP132JR, ODP144JR, ODP198JR
U.S. Navy Naval Oceanographic Office	2	SI932005, SI932009
NOAA	1	POL7004
SOEST, UH	1	77031705
University of Washington (Seattle)	1	TN037

Note: Institution abbreviations: ORI, UT—Ocean Research Institute, the University of Tokyo; JHOD—Hydrographic and Oceanographic Department, Japan Coast Guard; GSJ—Geological Society of Japan; SIO, UCSD—Scripps Institution of Oceanography, University of California, San Diego; LDEO, CU—Lamont-Doherty Earth Observatory, Columbia University (New York); NOAA—National Oceanic and Atmospheric Administration; SOEST, UH—School of Ocean and Earth Science and Technology, University of Hawaii.

different regional magnetic fields, we recalculated magnetic anomalies using the 11th International Geomagnetic Reference Field (International Association of Geomagnetism and Aeronomy, Working Group V-MOD, 2010), except for several cruises whose values of total magnetic field were not provided. The geomagnetic reversal time scale used in this study is that proposed by Gradstein et al. (2012). Data from several cruises were excluded for this study because of inaccurate positioning, which were conducted before global positioning system navigation.

RESULTS

Description of Bathymetric Features

The bathymetric data collected by the cruises of MR99-K04, KH-06-1, YK08-09, and MGL1004 with previous data reveal the remarkable topographic features in the study area (Figs. 4 and 5). The depth of the seafloor in this area ranges between 6200 and 5500 m except for the Shatsky Rise and nearby guyots. Seafloor shallower than ~5000 m in the northeastern part of the survey area is the lower flank of the Shatsky Rise. Bathymetry data reveal a linear trough, trending northwest-southeast. The trough has a rhomboidal basin at its center that contains a small uplifted block. Surrounding the trough there are a number of seamounts and guyots of the Japanese Guyots (Vogt and Smoot, 1984; Winterer et al., 1993), including Isakov Seamount, Thomas Washington Winterer, and Stout guyots. Radiometric ages for Isakov Seamount and Winterer Guyot are 103.8 ± 1.8 and 108.3 ± 1.0 Ma, respectively (Winterer et al., 1993).

Our map exposes the topographic expression of the trace of the Pacific-Izanagi-Farallon triple junction before chron M23 (153 Ma). Magnetic lineations in the study area (Fig. 6; Nakanishi et al., 1989; see the following discussion, Description of Magnetic Anomaly Lineations) show that the triple junction drifted north-northwest to the south of Isakov Seamount. Along the path of the triple junction to the south of Isakov Seamount, around 30°35′N and 151°06′E, is a knoll. This knoll is located where seafloor abyssal hill fabric trending southwest-northeast to the west meets similar fabric, trending southeast-northwest, to the east (Fig. 4). The bathymetric map shows that the lineated abyssal hill fabric, which formed at and parallel to spreading centers, is clearly visible except in the vicinity of the guyots and the Shatsky Rise. The abyssal hill fabric mainly corresponds to large rectilinear scarps, most several tens of meters high (Fig. 4). The spacing of abyssal hill fabric is 3–5 km. Two general abyssal hill populations are interpreted in the multibeam data, striking roughly northwest-southeast and roughly northeast-southwest, corresponding to spreading on the Pacific-Farallon Ridge and Pacific-Izanagi Ridge, respectively. The seafloor east of 151°E abounds with northwest-southeast–trending (~N50°W) abyssal hill fabric, assumed to have formed at the Pacific-Farallon Ridge. Seafloor south of Stout Guyot and Isakov Seamount west of 151°E displays abyssal hill fabric with a northeast-southwest trend, which is assumed to have formed at the Pacific-Izanagi Ridge. East-west–striking abyssal hill fabric is mapped on the seafloor north of 32°N, an azimuth that is different from the two directions just described. Larson et al. (2002) and Viso et al. (2005) showed that the trace of the Pacific-Farallon-Phoenix triple junction in the mid-Cretaceous Penrhyn Basin is commonly marked by 500–1000-m-deep trough, but that is not seen in the study area. The discrepancy of topographic expression seems to be attributable to the difference of the triple junction configuration. The configuration of the Pacific-Izanagi-Farallon triple junction was a ridge-ridge-ridge type (Nakanishi et al., 1989), whereas the Pacific-Farallon-Phoenix triple junction oscillated between ridge-ridge-ridge and ridge-ridge-fault types (Larson et al., 2002; Viso et al., 2005). The trough along the trace of that ridge-ridge-fault triple junction seems to correspond to the trace of the transform fault that intersected the triple junction.

We identify a curved trough between Isakov Seamount and the Shatsky Rise (Fig. 5). The trough is elongated in a N50°W direction, which is parallel to the Hawaiian lineation set. The maximum depth of the trough is ~6350 m, in general ~300–400 m deeper than the surrounding abyssal seafloor. The trough is divided into six segments based on topographic discontinuities (T1–T6 in Fig. 5B). At the 6000 m contour, each trough is 80–100 km long and ~20 km wide. The southern side of the segment T1 is bounded by curved northwest-southeast–trending escarpments of adjacent elongated ridges. There is an elongated curved ridge at the center of the segment T1. The segment T2 has a similar elongated curved ridge within. The segment T3 also contains an elongated ridge, but the position is off center in the basin. The segment T3 is oblique to the abyssal hill fabric southeast of the segment. The segment T4 also has an off-center elongated ridge within. The southern side of the segment T5 is bounded by northwest-southeast–trending ridges, some of which are partly concealed by Isakov Seamount. The segment T5 has an elongated central ridge, which has elongated ridges at its both franks. The seafloor of segment T6 deepens northward from 6000 m to 6100 m and is smoother than other segments, as if it is filled with sediment. Isakov Seamount may have supplied segment T6 with debris, causing it to be shallower than the others.

The segments T1, T2, and T5 have an elongated center ridge in common and are parallel to the abyssal hill fabric of seafloor to their south. The morphology of these segments bears a close resemblance to that of the tip of a dying-retreating spreading ridge paired with a propagating ridge, such as observed on the Pacific-Antarctic Ridge near 64°S (Blais et al., 2002). The elongated ridge in the troughs with a depth of 6100–6200 m resembles a neovolcanic ridge in a propagating spreading ridge (e.g., Kleinrock and Hey, 1989; Blais et al., 2002). Similar troughs are often observed in lithosphere formed within zones of overlap between newly formed propagating rifts and dying-retreating rifts (e.g., Hey et al., 1988). We conclude that the complex of curved troughs is a series of abandoned spreading ridges left behind by ridge propagation.

The topographic expression of the segment T3 is similar to that of the segment T4. The segment T3 is oblique to the abyssal

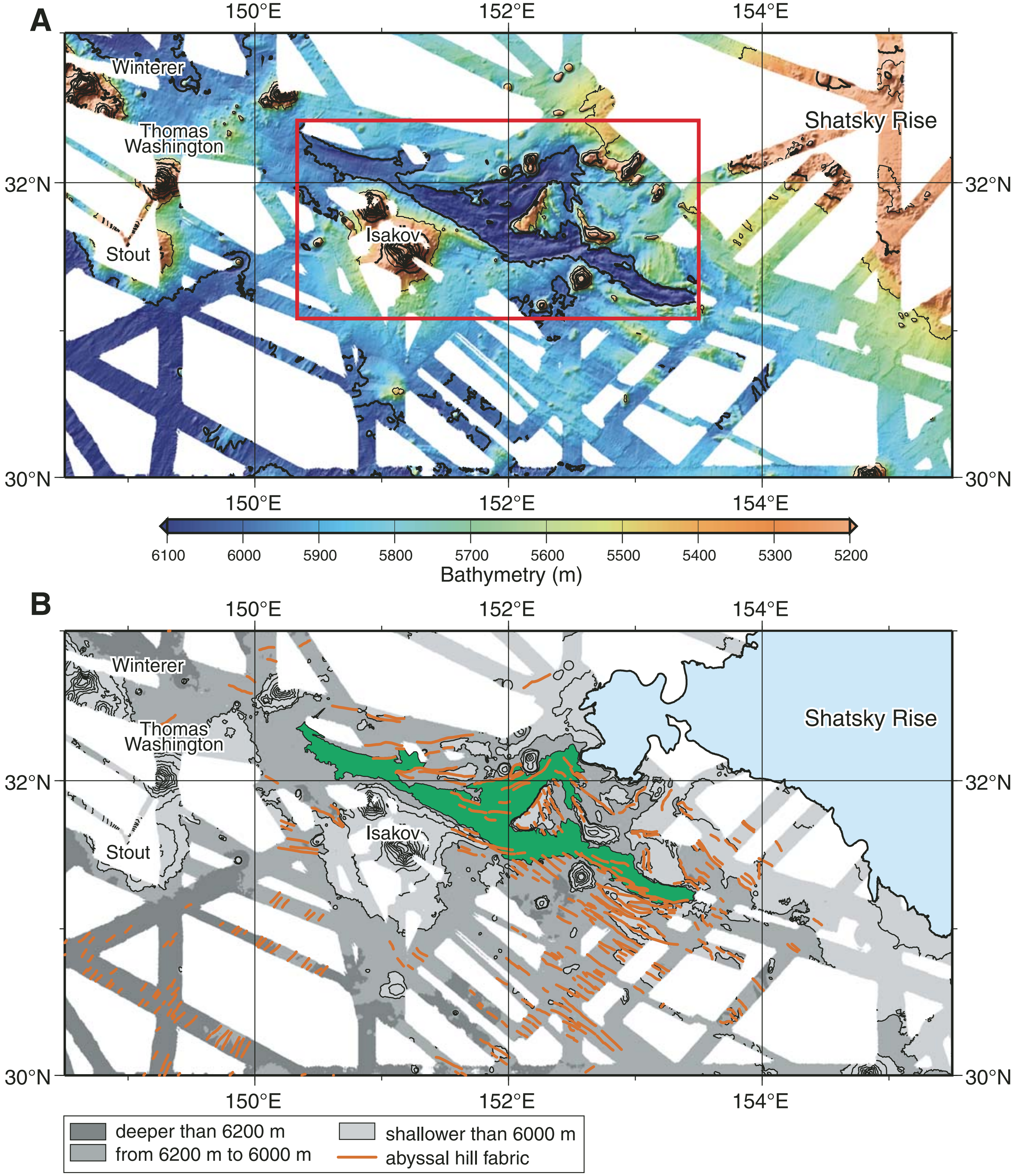

Figure 4. (A) Bathymetric map of area 1 made using swath bathymetry data. Contour interval is 500 m. The red rectangle encompasses the area shown in detail in Figure 5. (B) Abyssal hill fabric. Green colored areas are en echelon curved troughs deeper than 6000 m below sea level. Outline 5000 m contour of the Shatsky Rise is from the 30-arc-second resolution global topography/bathymetry grid (STRM30_PLUS; Becker et al., 2009).

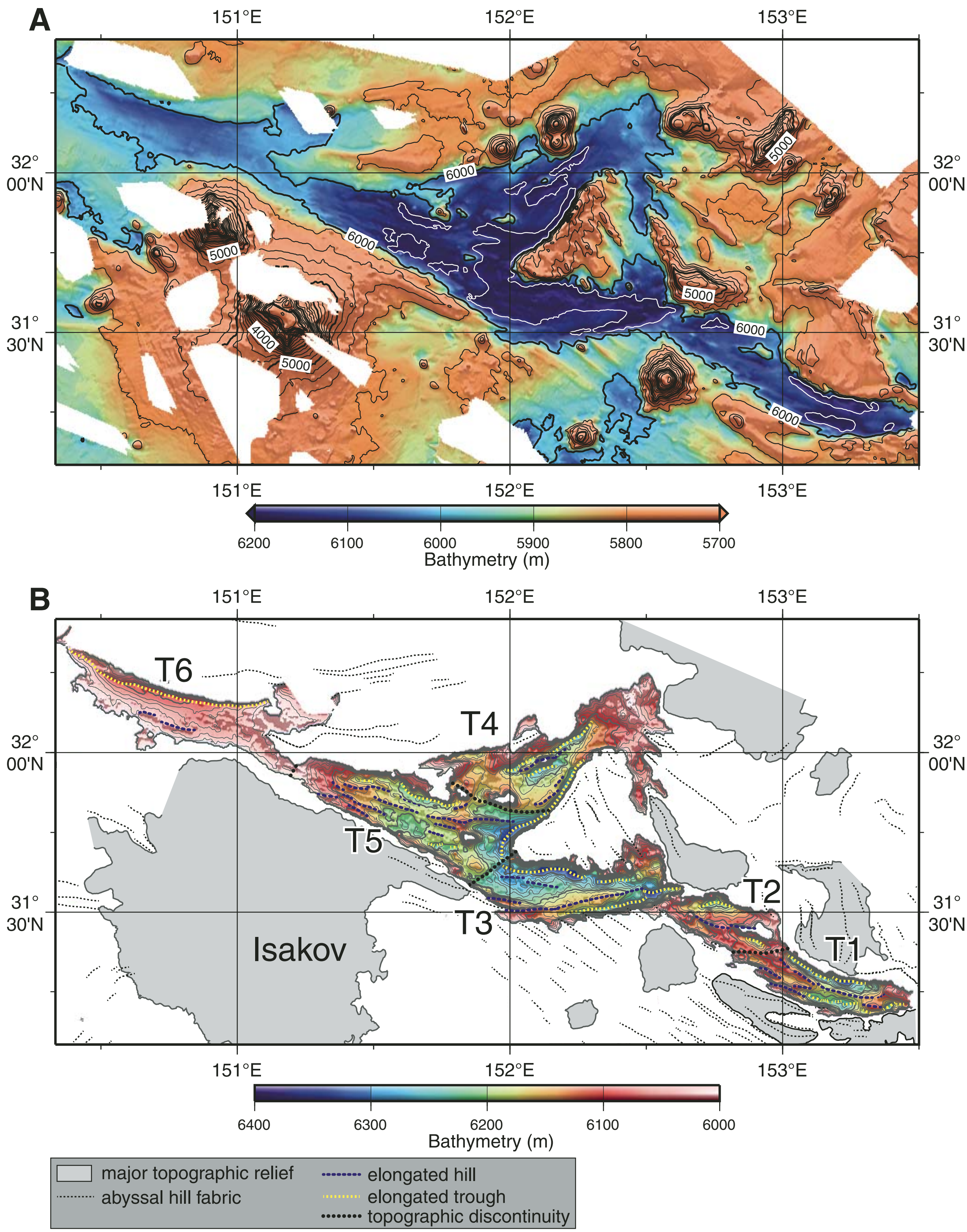

Figure 5. (A) Shaded bathymetric map showing detail of the en echelon curved troughs. Contour interval is 200 m. Contours deeper than 6000 m below sea level are shown in white. (B) Shaded bathymetric map showing only the en echelon curved troughs deeper than 6000 m with abyssal hill fabric. Contour interval deeper than 6000 m is 20 m. Other conventions are as in Figure 4B. The location of the map is shown in Figure 4A.

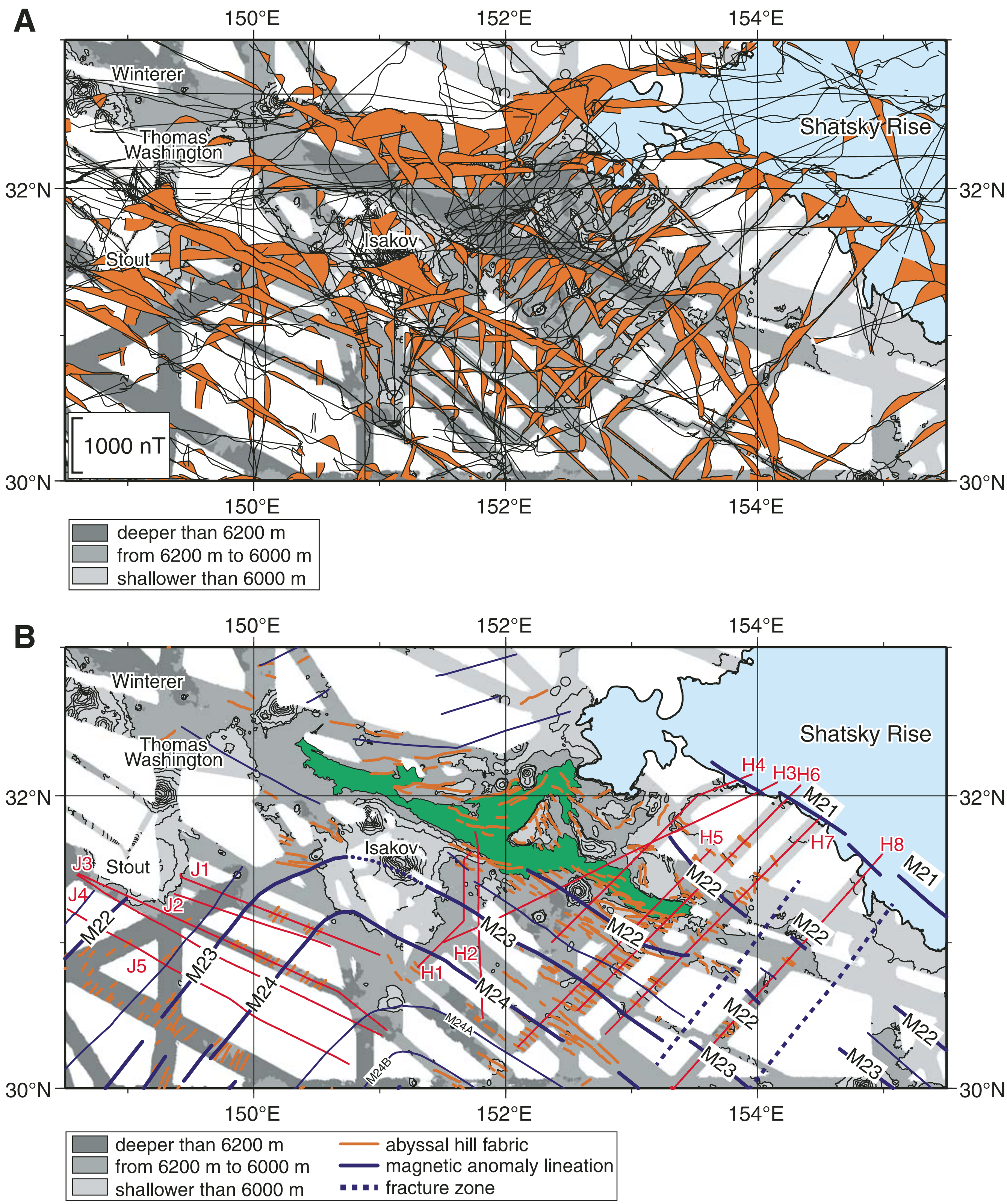

Figure 6. (A) Magnetic anomaly profiles along ship tracks in area 1. Positive anomalies are shaded orange. (B) Revised magnetic anomaly lineations with abyssal hill fabric. Red solid lines represent the positions of magnetic anomaly profiles shown in Figure 7. Other conventions are as in Figure 4B.

hill fabric farther south. The top of the triangular elevation around 31°45′N and 152°15′E has an abyssal hill fabric with a north-northwest–south-southeast strike. The difference in strikes of abyssal hill fabric between the top of the elevation and the seafloor southeast of T3 is ~15°–20°. Thus, a counterclockwise rotation of the triangular elevation of ~15°–20° can explain the difference in strike of abyssal hill fabric. We propose that the segment T3 is a fissure made by the counterclockwise rotation of the triangular elevation. If so, the segment T4 is a deformed zone caused by the rotation of the triangular elevation.

The abyssal hill fabric on the northern side of the segments T1 and T2 has various directions, unlike the coherent northwest-southeast trends of faults on the southern side. The discordant abyssal hill fabric in this area is inconsistent and does not fit with expected spreading directions for either the Pacific-Izanagi Ridge or the Pacific-Farallon Ridge. A sheared zone with discordant abyssal hill fabric is produced when lithosphere is progressively transferred from one plate to the other between dueling ridges in propagating rift systems (Hey et al., 1988). If the trough was formed by a propagating ridge, as we suggest, then the discordant abyssal hill fabric north of segments T1 and T2 may be a result of the sheared zone between the dueling rifts. Shearing between dueling rifts also occurred during the counterclockwise rotation of the triangular seamount.

Description of Magnetic Anomaly Lineations

Maximum peak-to-peak amplitudes of anomalies are nearly 400 nT, except for those around seamounts (Fig. 6A). The Mesozoic magnetic anomaly lineations from anomaly M24B to anomaly M21 are identified within the study area (Fig. 6B). Lineations older than M24 are the same as those identified in Nakanishi et al. (1989). We identify lineations from M24B to M21 with a northwest trend east of 151°E that belong to the Hawaiian lineation set. We also identify lineations with an N45°E strike west of 151°E that belong to the Japanese lineation set. Figure 7 illustrates the correlation of the magnetic anomalies among selected cruise tracks and comparison with a synthetic profile calculated from the geomagnetic reversal time scale of Gradstein et al. (2012). In general the anomalies fit the expected shapes well, except for some discrepancies due to the roughness of bathymetry. The skewness parameters of the calculated profiles in Figure 7 are the same as those in Nakanishi et al. (1989).

Duplicate lineations M22 are identified in the Hawaiian lineation set between 152°E and 154°E (Figs. 6B and 7). The southeastern tip of the southern lineation M22 is curved. The duplicate and curved lineations M22 are situated around the southeastern tip of the curved trough and indicate that the trough is a spreading center abandoned by a ridge jump that allowed M22 to be duplicated. The position and shape of curved abyssal hill fabric parallel to the lineations indicates that rift propagation started during chron M22 (151 Ma).

In spite of good magnetic data coverage, we could not assign ages to any lineations north of the duplicate lineation M22, close to the western tip of the Shatsky Rise. The relief of the bathymetry in the area is very rough due to the sheared north side of the rhomboid basin (Fig. 5). The lack of identified magnetic anomaly lineations east of 154°E, however, is due to the dearth of cruise magnetic data. Lineations M21 just south of the Shatsky Rise are shorter and more discontinuous than previous work (Nakanishi et al., 1989).

The magnetic bights between anomalies M24B and M23A were shown in Nakanishi et al. (1989, 1999b). Careful restudy with newly collected data reveals the magnetic bights in more detail, especially around the junction of northeast- and northwest-trending lineations. Magnetic bights from anomaly M24B to M23 are traceable (Fig. 6B). A part of lineation M23 is hidden by the Isakov Seamount, but we believe that the lineation continues northwest beneath the seamount. Previous work indicated that the absence of magnetic bights from anomalies M23 to M21 resulted from the spreading ridge reorganization cutting off the some Pacific plate. Our new identification elucidates the existence of magnetic bights up to anomaly M23 between Stout Guyot and Isakov Seamount (Fig. 6B), and their lack after anomaly M22. Lineations younger than M23 in the Japanese lineation set shorten to the east of Stout Guyot. We could not find the northwestward extensions of lineations M22 and M21 in the Hawaiian set in spite of good data coverage (Fig. 6A).

We identified a magnetic anomaly lineation with a northwest-southeast strike northwest of Isakov Seamount (Fig. 6B), which is similar to the strike of the Hawaiian lineation set. Because it is isolated, we cannot identify the lineation and assign its age and decide whether it belongs to the Hawaiian lineation set. The increased data show a curved magnetic lineation north of troughs T4 and T5, although previous work (e.g., Sager et al., 1988; Nakanishi et al., 1989) identified it as a straight lineation. Sager et al. (1988) and Nakanishi et al. (1989) identified it with lineations M21 and M20, respectively. In Nakanishi et al. (1989) it was concluded that it is a part of the Japanese lineation set after chron M20 (148 Ma) by similarity of the strike. In Sager et al. (1988) it was identified with lineation M21, formed at the plate boundaries of a microplate that existed near the Pacific-Izanagi-Farallon triple junction. Because of the anomaly curvature, we cannot endorse either interpretation. Instead, this anomaly may belong to a set of curved anomalies around 33°N, 152°E (Fig. 2) that may have formed around a microplate (Nakanishi et al., 1989, 1999b). The curved lineation is almost parallel to the segments T4–T6 of the curved trough. This implies that the curvature of the lineation could be due to the deformation between dueling spreading centers, although its age cannot be assigned.

DISCUSSION

Two models for the formation of the Shatsky Rise have been proposed: in Nakanishi et al. (1989, 1999b) a plume head model was proposed and it was indicated that the reorganization of the Pacific-Izanagi-Farallon triple junction, the reorientation of the Pacific-Izanagi Ridge, and a jump of the triple junction occurred

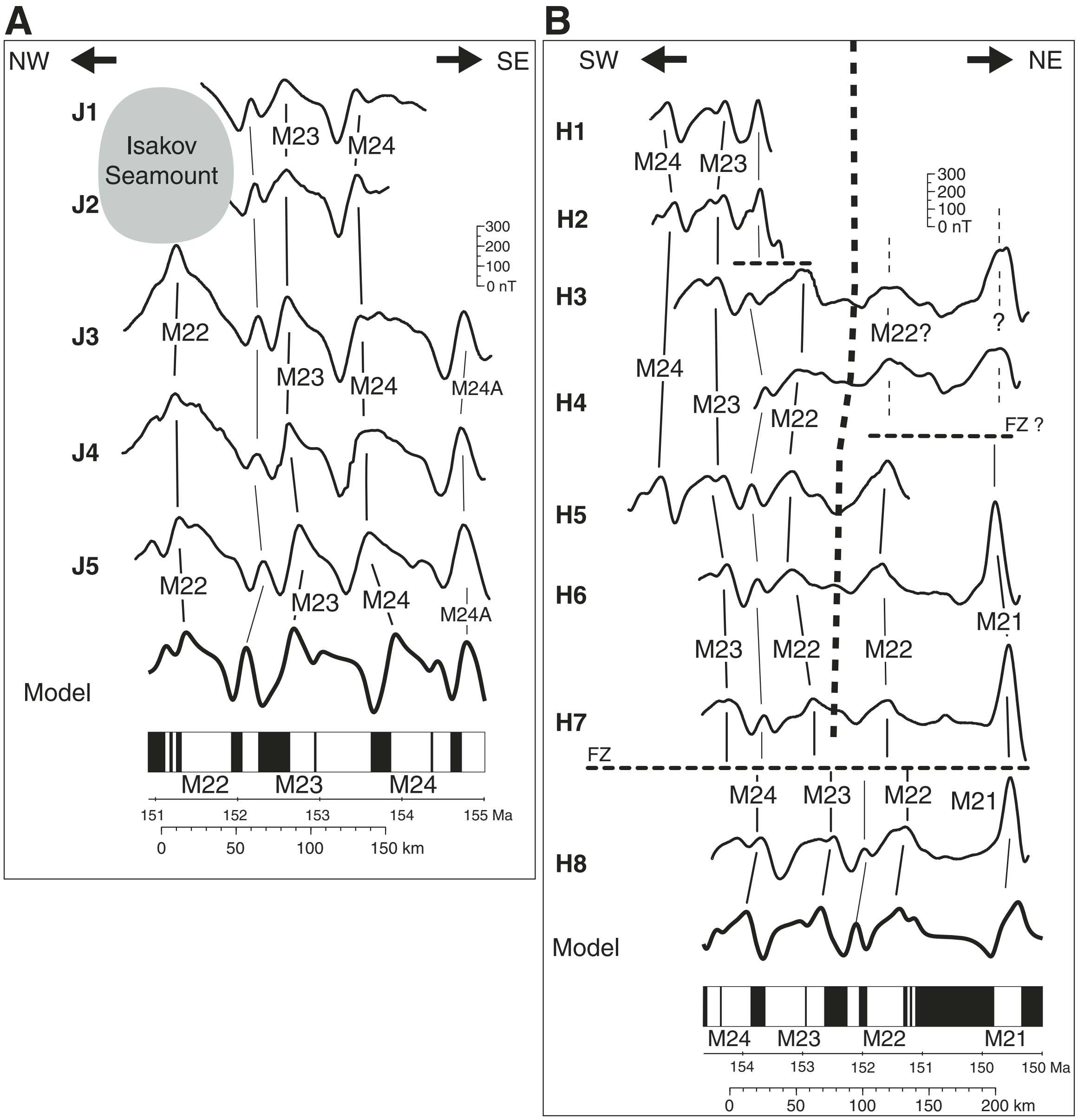

Figure 7. (A) Selected magnetic anomaly profiles from the Japanese lineation set projected approximately normal to the lineations. Profile locations are shown in Figure 6B. Magnetic anomaly reversal sequence is from Gradstein et al. (2012). Normally magnetized blocks are solid black. The modeled anomaly skewness parameter is –230°. The constant half-spreading rate of the model is 5.5 cm/yr. (B) Selected magnetic anomaly profiles from the Hawaiian lineation set projected approximately normal to lineations. The modeled anomaly skewness parameter is –130°. The constant half-spreading rate of the model is 4.0 cm/yr. FZ—fracture zone. The heavy dashed line denotes an abandoned spreading center.

simultaneously with the initiation of the Shatsky Rise. In contrast, in Sager (2005) it was noted that some evidence does not fit the mantle plume head hypothesis and considering models based on decompression melting of fertile mantle was recommended. Important observations that do not fit the plume head hypothesis are (1) the low probability of a mantle plume rising near a triple junction and the frequent occurrence of this coincidence in the Pacific and (2) the MORB-like geochemistry and isotopic signatures of rocks samples obtained from the Shatsky Rise (Mahoney et al., 2005; Expedition 324 Scientists, 2010; Sano et al., 2012). Furthermore, seismic refraction results from the TAMU Plateau imply a crustal velocity-thickness relationship compatible with formation from chemically anomalous mantle (Korenaga and Sager, 2012). All of these discrepancies invite a reappraisal of tectonic data. In particular, the relationship between the Pacific-Izanagi-Farallon triple junction evolution and the Shatsky Rise formation is critical. In the following we reexamine tectonic models based on new evidence from this study.

Reorganization of the Pacific-Izanagi-Farallon Triple Junction

Previously (e.g., Handschumacher et al., 1988; Nakanishi et al., 1989) it was concluded that the configuration of Pacific-Izanagi-Farallon triple junction was ridge-ridge-ridge. Our mapping of magnetic bight before chron M23 is consistent with this conclusion (Fig. 8A). Although a record of the third plate boundary (Izanagi-Farallon) is not preserved on the Pacific plate, a ridge-ridge-ridge junction is the most likely to be stable and to fit the observed kinematics. The existence of the curved trough in the seafloor between repeat M22 lineations indicates ridge propagation on the Pacific-Farallon Ridge toward the triple junction. The propagation was occurring just after chron M22 just southwest of the Shatsky Rise. The dying segment of Pacific-Farallon Ridge was connected to the triple junction, implying that the reorganization of the triple junction occurred around chron M22 (Fig. 8B). Figure 8B indicates a succession of propagating rifts and possibly a short-lived microplate forming, developing, and dying, although the model of the configuration of the plate boundaries is uncertain because aspects of the propagating rift and the microplate evolution are unclear. The formation of a microplate in this location is strengthened by the curved, unidentified magnetic lineations with oblique trends located west of the Shatsky Rise (Fig. 2). Our model implies that an abrupt jump of the triple junction synchronous with the commencement of Shatsky Rise formation, as proposed in Nakanishi et al. (1989, 1999b), is incorrect. A reorganization of the Pacific-Farallon Ridge was accompanied by ridge propagation and occurred several million years before the formation of the TAMU Plateau. Based on the trend of the trough and surrounding magnetic lineations and the location of the curved magnetic lineations west of the Shatsky Rise, the triple junction propagation direction was north, rather than toward the Shatsky Rise. Later reorganizations must have brought the triple junction to the middle of the Shatsky Rise.

Similar ridge propagation near a triple junction is found at the Bouvet triple junction in the South Atlantic Ocean (Ligi et al., 1997, 1999). Ligi et al. (1997, 1999) proposed that the Bouvet triple junction region is affected by one or more hotspots; they suggested that a major magmatic pulse by a hotspot has recently built a new, swollen segment of the Southwestern Indian Ridge (Spiess Ridge) that is propagating toward the Mid-Atlantic Ridge at a rate of 4–5 cm/yr, disrupting a former ridge-ridge-ridge triple junction. If the propagation of Pacific-Farallon Ridge around chron M22 were to be due to a similar type of volcanic activity, the propagation might indicate that the volcanism of the Shatsky Rise started around chron M22, although previous work (e.g., Nakanishi et al., 1989, 1999b) proposed that the volcanism started just after chron M21. If the massive volcanism that formed the TAMU Plateau began at chron M22, long before the lava flows at the summit were emplaced at 144.6 ± 0.8 Ma (Mahoney et al., 2005), then the Shatsky Rise took much longer to form (~6 m.y.) than is currently thought. Clearly, additional radiometric dating of the Shatsky Rise would help determine this temporal relationship.

Rotation of the Pacific-Izanagi Ridge

In Nakanishi et al. (1989) it was suggested that the Pacific-Izanagi Ridge rotated simultaneously with the initiation of Shatsky Rise volcanism. The magnetic anomaly lineation map (Nakanishi et al., 1989) shows that the strike of magnetic anomaly lineations changed from N45°E to N70°E between chrons M21 and M20 in area 2. Figure 9 illustrates a bathymetric map (Fig. 9A), magnetic anomaly profiles along selected ship tracks (Fig. 9B), and abyssal hill fabric with magnetic anomaly

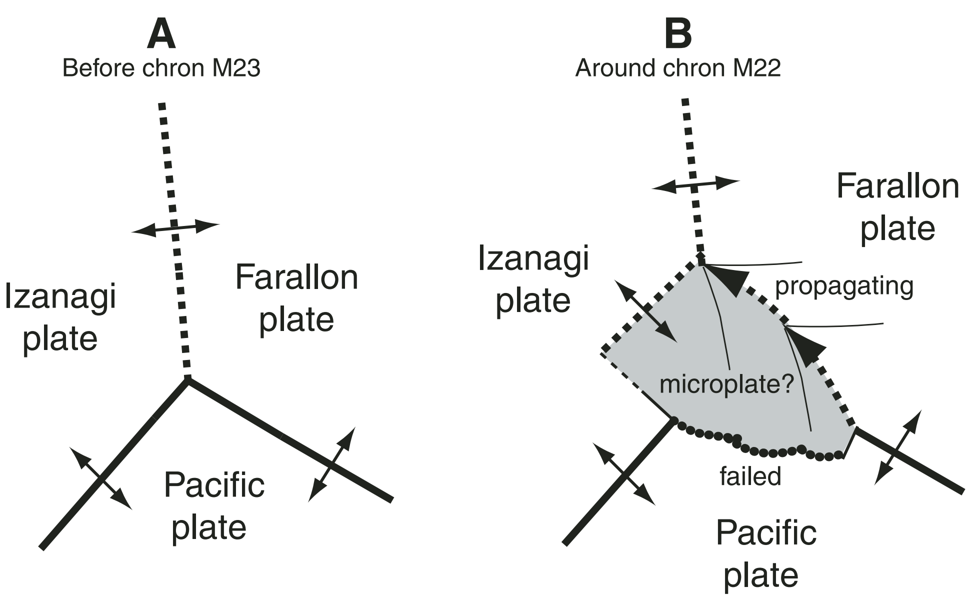

Figure 8. Tectonic history of the Pacific-Izanagi-Farallon triple junction before chron M23 and around chron M22 inferred from the magnetic lineation pattern and bathymetric features. (A) before chron M23, (B) around chron M22. The thick lines with a small arrow show spreading ridges; the small arrow represents the direction of seafloor spreading. The dashed lines with arrowheads represent propagating ridges. The dotted lines denote failed ridges. The features on the Izanagi and Farallon plates are speculative because of subduction.

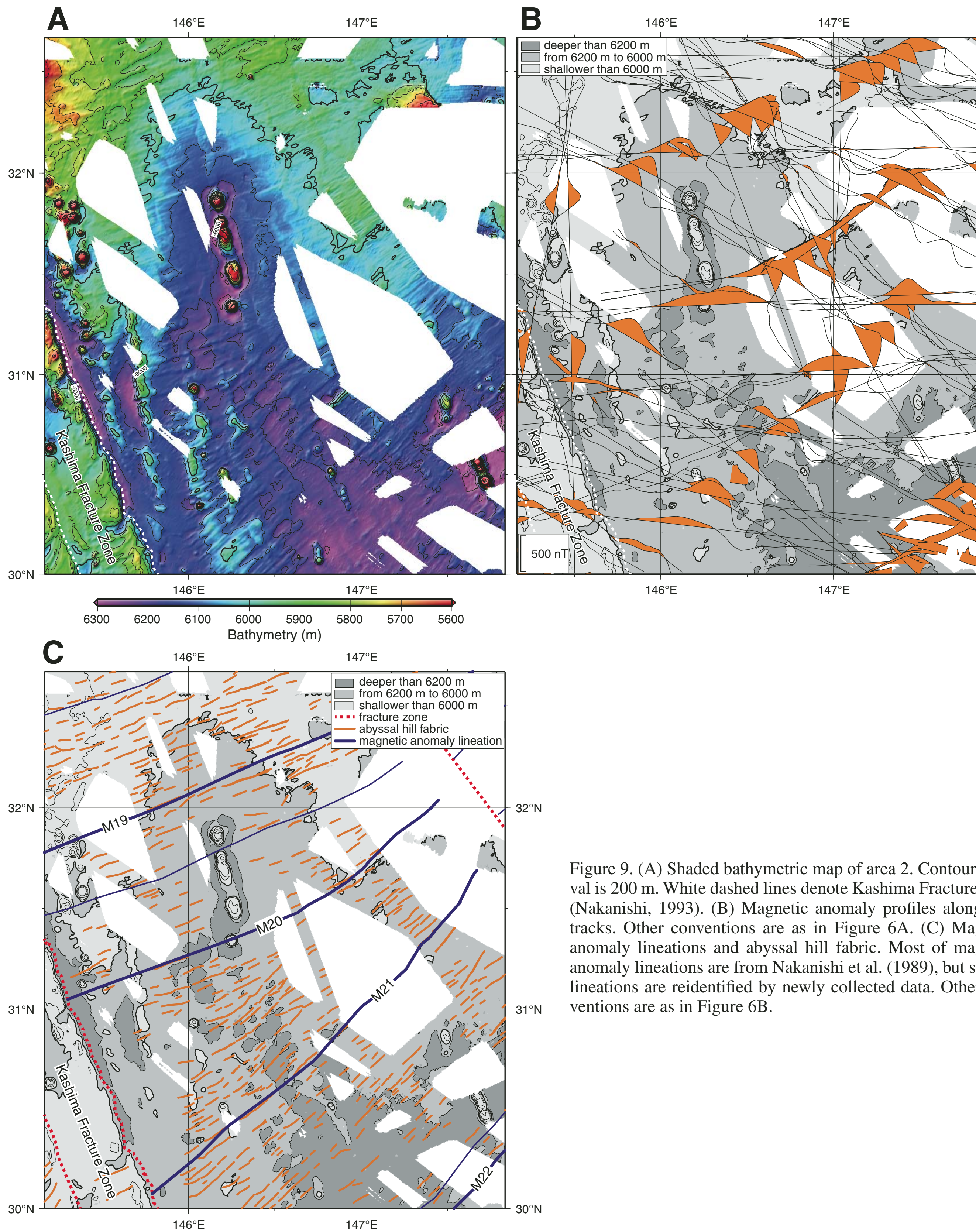

Figure 9. (A) Shaded bathymetric map of area 2. Contour interval is 200 m. White dashed lines denote Kashima Fracture Zone (Nakanishi, 1993). (B) Magnetic anomaly profiles along ship tracks. Other conventions are as in Figure 6A. (C) Magnetic anomaly lineations and abyssal hill fabric. Most of magnetic anomaly lineations are from Nakanishi et al. (1989), but several lineations are reidentified by newly collected data. Other conventions are as in Figure 6B.

lineations (Fig. 9C) within this area. The Kashima Fracture Zone (Nakanishi, 1993) is located in the southwestern part of this area. Two strikes of abyssal hill fabric east of the Kashima Fracture Zone are shown in Figure 9A. The dominant strike of abyssal hill fabric in the southern part of the area is N45°E, and that in the northern part of the area is N70°E. Magnetic anomaly profiles in Figure 9B show that magnetic anomaly lineations have two different strikes. The strike of the abyssal hill fabric gradually changes from N45°E to N70°E between lineations M21 and M20 (Fig. 9C). The inflection point of the abyssal hill fabric is located around 30°45′N and 146°20′E. That of lineation M20 is located at 31°30′N and 146°40′E. These observations imply the progressive propagation of the strike change of the Pacific-Izanagi Ridge on the west side of Pacific-Izanagi-Farallon triple junction. The strike of lineation M20 around the Ogasawara Plateau west of the Kashima Fracture Zone is N70°E (Nakanishi et al., 1989). The Kashima Fracture Zone changed in strike between lineations M22 and M21 (Nakanishi, 1993; Nakanishi et al., 1989). The spreading rate of the segment of Pacific-Izanagi Ridge near the triple junction changed after chron M22 (Nakanishi et al., 1989). Thus, the relative motion between the Pacific and Izanagi plates changed in direction between chrons M22 and M21. These observations also suggest that a reorientation of the Pacific-Izanagi Ridge was not due to the birth of the Shatsky Rise, which probably occurred later. The relative motion change between the Pacific and Izanagi plates occurred after that of the Pacific-Izanagi-Farallon triple junction around chron M22 and was likely a part of a large plate reorganization that occurred over several millions of years. Ridge propagation and microplate formation are thought to be plate boundary responses to changes in spreading direction, and such reorganizations can take millions of years (Hey et al., 1988).

Can a Plume Head Initiate the Reorganization of the Plate Boundaries?

A mantle plume head could have caused uplift of the lithosphere ~5 m.y. before eruption of voluminous basalts (Griffiths and Campbell, 1991; Campbell, 2005). The area of the reorganization of the plate boundaries exposed in this study is within the radius of a large plume head (e.g., radius ~1000 km; Campbell, 2005). Such uplift might have resulted in the reorganization. However, we could not find any topographic features resulting from uplift and ensuing subsidence in the study area. Moreover, no remarkable tectonic events were recognized by previous studies (e.g., Nakanishi et al., 1989). Spreading rates and strikes of the Pacific-Farallon Ridge except in this study area did not change from chron M23 to chron M20 (Nakanishi et al., 1989). Had widespread uplift occurred in the vicinity of the Pacific-Izanagi-Farallon triple junction around chron M22, it should have produced more widespread disruption of the anomaly pattern. Existing data imply only the formation of a microplate coincident with reorganization of the Pacific-Izanagi spreading direction. Given these limitations a plume head is not required to explain the reorganization of the plate boundaries exposed in this study.

CONCLUSIONS

Our bathymetric and geomagnetic analyses, using new data collected southwest of the Shatsky Rise, combined with preexisting multibeam bathymetric data and geomagnetic data, lead to the following conclusions.

1. The magnetic bights between Japanese and Hawaiian lineation sets between M24B and M23 are now identified. Previous studies concluded that these bights were missing.

2. The curved troughs mapped in area 1, adjacent to the southwest flank of the TAMU Plateau, are interpreted as a series of abandoned spreading ridges left behind by ridge propagation.

3. The ridge-ridge-ridge configuration of the Pacific-Izanagi-Farallon triple junction was broken after chron M23. Rift propagation along the Pacific-Farallon Ridge near the triple junction between chrons M23 and M22 caused the reorganization of the plate boundaries around the triple junction.

4. Segments of the Pacific-Izanagi Ridge connected to the Pacific-Izanagi-Farallon triple junction started a rotation from N45°E to N70°E far away from the triple junction between chrons M22 and M21, slightly later than the ridge propagation event on the Pacific-Farallon Ridge.

5. The synchronization of the triple junction and plate boundary reorganization with the formation of the Shatsky Rise proposed in Nakanishi et al. (1989) is questionable. This implies that the reorganization predated the formation of the Shatsky Rise by several million years. Although this suggests that the plume head model may not be appropriate, with our data we cannot rule it out.

Our study suggests a difference in timing between the tectonic reorganization of the spreading ridges, likely caused by regional changes in plate motion. The significance and duration of this time gap are poorly known because of the lack of radiometric ages for Shatsky Rise basalts and sparse coverage of the Shatsky Rise by bathymetry and magnetic data. Future studies of the connection between the triple junction reorganization and Shatsky Rise formation would benefit from dating of existing and new samples from the Shatsky Rise as well as the collection of densely spaced tracks with marine geophysical data around the TAMU Plateau.

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