Spreading process of the northern Mariana Trough: Rifting-spreading transition at 22°N

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[1] We have conducted a geophysical survey of the northern Mariana Trough from 19°N to 24°N. The trough evolves southward from incipient rifting to seafloor spreading within this region. This study aims to clarify the location and time of the rifting-to-spreading transition, which was controversial previously, and processes of seafloor spreading after the transition. The new data set includes swath bathymetry with sidescan images and magnetic vector anomaly. The mantle Bouguer gravity anomaly (MBA) was calculated using the free-air gravity anomaly from satellite altimetry. The rifting-to-spreading transition occurs at about 22°N, which is proved by seafloor-spreading fabric in the bathymetry, clear magnetic lineations, and the bull’s-eye pattern in MBA. Four ridge segments separated by three nontransform discontinuities are recognized between 19°N and 22°N. The northernmost segment has relatively abundant magma supply compared with the other segments, which is estimated from a larger segment length, shallower axial depths with no rift valley, and lower MBA. The next segment to the south is, on the other hand, a magma-starved segment with a prominent rift valley. Two anomalously deep grabens (called the Central Grabens) formed by amagmatic extension occur near the segment ends. The succession of magma-rich, magma-starved, and normal segments with increasing distance from the volcanic arc is the same as the observation in the Lau Basin reported by Martinez and Taylor [2002]. The magnetic anomaly revealed the detailed history of the spreading. The seafloor spreading between 19°N and 20°N began prior to 5 Ma, and that between 20°N and 21°30′N began at about 4 Ma. Spreading half-rates in the western side of the spreading center were 2 to 3 cm/year before 2.58 Ma south of 21°30′N and during the Matuyama Chron north of 21°30′N, but an average during the Brunhes Chron is 1 cm/year or less. Orientations of the ridge axes, which range from −20° to 0° at present, have rotated about 20° clockwise since the start of the spreading. These changes in rate and direction might be associated with changes in the motion of the Philippine Sea plate. Spreading has been asymmetric in the northern Mariana Trough. The spreading rates of the western side of the
spreading center have been significantly larger than the eastern counterpart in general. The asymmetry may have been caused by an interaction of mantle upwelling systems under the volcanic front and the backarc spreading center and would be a characteristic of backarc spreading.

**Components:** 8375 words, 10 figures, 1 table.

**Keywords:** Mariana Trough; spreading; rifting; magnetic anomaly; backarc basin; tectonics.

**Index Terms:** 3035 Marine Geology and Geophysics: Midocean ridge processes; 3005 Marine Geology and Geophysics: Geomagnetism (1550); 3045 Marine Geology and Geophysics: Seafloor morphology and bottom photography.

**Received** 10 December 2002; **Revised** 18 June 2003; **Accepted** 28 July 2003; **Published** 12 September 2003.


1. Introduction

[2] The Mariana Trough (Figure 1) is typical of active backarc basins in the world. It is crescent-shaped with a maximum width of about 250 km near 18°N, located between the Mariana Ridge (active arc) and the West Marina Ridge (remnant arc). The Mariana trench-arc-backarc system along the eastern margin of the Philippine Sea plate has recently attracted a special interest as a target for studying the operation of the Subduction Factory, partly because the system is relatively simple; it has grown on an oceanic crust, and sediments covering the subducting Pacific plate are lithologically uniform and subducts completely. Please refer to Fryer [1995, 1996] and Stern et al. [2003] for thorough reviews of the Mariana trench-arc-backarc system.

[3] The northern Mariana Trough evolves southward from an incipient rifting stage to a mature backarc-spreading stage. Thus the northern Mariana Trough provides us a rare opportunity to study evolution processes of backarc basins. The trough between 22°N and 24°N is in a rifting stage, and structurally and thermally asymmetric [Yamazaki and Murakami, 1998]. The location of the rifting-to-spreading transition was controversial. Yamazaki et al. [1993] inferred from magnetic total-force anomalies and seismic profiles that seafloor spreading occurs to the south of 22°N. Conversely, Martinez et al. [1995] and Baker et al. [1996] proposed that the Mariana Trough north of 20°N is composed of arc lithosphere intruded by arc and backarc-basin magmas, and defined the volcanotectonic zone (VTZ) where rifting and volcanism concentrates. A series of deep half-grabens, about 5700 m at maximum in water depth, is located near the center of the trough between 20°N and 21°N. They were considered to have been formed by amagmatic extension during rifting, and called the Central Grabens [Martinez et al., 1995; Stern et al., 1996]. Martinez et al. [1995] concluded that initiation of seafloor spreading occurs to the south of the Central Grabens at 20°N. Thus prior work on the rifting-to-spreading transition in the northern Mariana Trough has led to different interpretations as to its position: either 20°N or 22°N. The main purpose of this study, then, is to clarify the position of this transition, its relationship to the volcanic arc, and the evolution of the back-arc region over the past few million years using new data.

[4] Magnetic anomalies are a basic tool for studying seafloor spreading. In the Mariana Trough, however, conventional magnetic total-force anomalies are not very useful because of small anomaly amplitudes, and detailed history of the spreading was not clarified previously. The small amplitudes are due to the geometrical problem of the spreading system in the Mariana Trough: approximately north-south orientation of the spreading axis in low magnetic latitudes. Magnetic vector measurements can overcome this problem, and high-amplitude signals can be obtained regardless of ridge and geomagnetic field geometries [Isezaki, 1986]. Magnetic vector anomalies are hence expected to be quite useful in the Mariana Trough. In the central Mariana Trough, Bibee et al. [1980] succeeded to
correlate only a few magnetic total-force anomaly profiles between 17°30′N to 18°N, and estimated a spreading half-rate of approximately 1.5 cm/year within 50 km (3 Ma) of the spreading axis. Recent magnetic vector anomaly measurements around 18°N have confirmed that seafloor spreading started at about 6 Ma [Yamazaki and Stern, 1997; Seama and Yamazaki, 1998; Iwamoto et al., 2002]. This is consistent with the results of the Deep Sea Drilling Project (DSDP) Leg 60: it was estimated that the rifting began in the latest Miocene, ca. 6 Ma, with a spreading half-rate of 2.15 cm/year [Hussong and Uyeda, 1982].

In this paper, we present swath bathymetry, magnetic vector anomalies, and gravity anomalies in the northern Mariana Trough from 19°N to 24°N. Previously only limited areas of the Mariana Trough, mainly along the spreading center, were covered with swath bathymetry. It is desirable to survey the entire trough to clarify detailed history of evolution because spreading in small backarc basins is usually unstable and spreading rates and directions frequently vary with time. We have mapped most of the trough north of 19°N. On the basis of the new data set, we show that the transition from rifting to seafloor spreading occurs near 22°N, and discuss temporal and spatial changes of spreading in ridge segments between 19°N and 22°N.

2. Data Collection and Analysis Methods

Bathymetric and magnetic data were collected during the KR97-11, KR98-12, KR00-03, and KR02-01 cruises of R/V Kairei, and the Y96-13 cruise of R/V Yokosuka of the Japan Marine
Science and Technology Center. Swath bathymetry data of the R/V Kairei cruises were collected using a SeaBeam 2112 multibeam echo sounder, and those of the R/V Yokosuka cruise were by a Furuno HS-10 system. A shaded-relief topographic map of the northern Mariana Trough between 18°30′N and 24°N is displayed in Figure 2. Side-scan images (Figure 3) were also obtained using the SeaBeam 2112 system. Post processing of the side-scan data, which includes grazing angle correction, low-pass filtering for destriping, on-track pixels cut, and inverse filtering for smoothing, was carried out using the MB-system software [Caress and Chayes, 1995].

A shipboard three-component magnetometer system aboard each vessel was used for magnetic vector anomaly measurements, and a proton precession magnetometer was simultaneously towed for magnetic total-force measurements.
Please refer to Isezaki [1986] for the theory of the onboard magnetic vector measurement and Yamazaki and Stern [1997] and Yamazaki et al. [1999] for the instruments and measurement procedures on R/Vs Yokosuka and Kairei and initial data processing. Magnetic vector anomalies enabled us to identify magnetic lineations more objectively than total-force anomalies; the magnetic polarities and locations of polarity boundaries were determined for each survey line from variation patterns of both vertical and horizontal components and the intensity of spatial differential vectors (ISDV) of Seama et al. [1993]. The ISDV exhibits a peak at a magnetic boundary as an example shown in Figure 4. The amplitudes of the vertical and horizontal components are significantly larger than those of total-force anomalies as expected.

The mantle Bouguer gravity anomaly (MBA), which is assumed to reflect variations in crustal thickness and the temperature and density structure of the mantle, was calculated using the free-air gravity anomaly from satellite altimetry [Sandwell and Smith, 1997] and the multinarrow-beam bathymetry. Following the procedures of Parker [1972] and Kuo and Forsyth [1988], we subtracted attractions of seafloor topography and relief on the crust-mantle interface. We assumed that the crust has constant thickness of 6 km and that densities of the seawater, crust, and mantle are 1030, 2700, and 3300 kg/m³, respectively. We did not correct for

![Figure 3. Side-scan image of the northern Mariana Trough and interpretation of ridge segmentation. Higher backscatter is plotted darker.](image-url)
the effect of density anomalies associated with lithospheric cooling.

3. Results and Interpretation

3.1. Seafloor Topography and Side-Scan Image

[9] The seafloor topography shows contrasts in depth and seafloor texture between north and south of a boundary at 22°N near the Shoyo Seamount (a white broken line in Figure 2). The seafloor to the north of the boundary is much shallower than the south of it, and characterized by fault-controlled volcanic edifices such as the one at 22°C176°40'E, 142°30'E. A row of rift basins occurs along the eastern margin of the trough, which includes the basins northwest and southeast of the Nikko Seamount at 23°N. The trough north of the boundary consists of rifted and subsided island arc crust [Martinez et al., 1995; Baker et al., 1996; Yamazaki and Murakami, 1998]. To the south of the boundary, the trough is dominated by the seafloor-spreading fabric, narrow ridges and troughs, of nearly NNW-SSE trend. The two deeps centered at 21°00'N, 143°25'E and 20°05'N, 144°05'E are called the Central Grabens [Martinez et al., 1995; Stern et al., 1996]. Their water depths are about 5300 m and 5700 m at maximum, respectively. The latter is the deepest in the Mariana Trough.

[10] The positions of ridge axes (Figure 2) are determined from the topography, zones of high backscatter on a side-scan image (Figure 3), and magnetic anomalies (Figure 5). We can recognize three significant left-stepping nontransform discontinuities at about 20°35'N, 19°55'N, and 19°20'N. The first two are clear on the side-scan image. The last one is ambiguous on the image, but clearly recognized by an offset in magnetic lineations. MBAs also support the interpretation, which will be shown later. We call Segment 1 for the ridge between 22°10'N and 20°35'N, Segment 2 between 20°35'N and 19°55'N, Segment 3 between 19°55'N and 19°20'N, and Segment 4 south 19°20'N. The segment boundaries can be traced off axis as ridge-normal or oblique bathymetric depressions, which form irregular discordant zones. Characteristics of the four segments and their boundaries are summarized in Table 1.

[11] There is a possibility that the southernmost
30 km of the Segment 1, south of 20°50′N, belongs to a separate segment. A zone of high backscatter corresponding to the ridge axis does not appear on the side-scan image between 20°50′N and 20°35′N; instead a series of narrow NNW-trending streak of high backscatter occurs in a broad area between 143°25′E and 143°55′E (Figure 3). This suggests that spreading may have taken place in a diffuse manner; it may not be focused at the axis along 143°25′E but occur widely in the area east of it. This might be an undergoing eastward ridge jump. This disorganized spreading, if it occurs, has began recently because the topographic fabric to the west of the axis exhibits organized spreading, and there is no off-axis trail extending from the possible segment boundary at 20°50′N. No offset was observed in the magnetic lineations either (Figure 5). We hence consider that the discontinuity at

Figure 5. Isochrons and ridge segmentation based on magnetic anomaly interpretation. Profiles of magnetic anomaly vertical (Z) component (positive downward is hatched) superimposed on the topographic relief map, and location of spreading center (yellow) and magnetic polarity boundaries: Brunhes-Matuyama boundary (0.78 Ma), top of the Olduvai Subchron (1.77 Ma), Matuyama-Gauss boundary (2.58 Ma), Gauss-Gilbert boundary (3.58 Ma), and top of Chron 3n.3 (4.80 Ma). White broken lines show segment boundaries. Anomaly features annotated by purple broken ovals are discussed in the text. Parameters used for calculation of the model profile are as follows: spreading half-rate of 1.0 cm/year during the last 1.77 m.y., half-rate of 2.5 cm/year before 1.77 Ma for the western side of the axis, ridge-axis orientation of −20°, magnetized layer thickness, depth, and intensity of 1 km, 4 km, and 5 A/m, respectively.
Table 1. Summary of the Features of Ridge Segments and Segment Boundaries in the Northern Mariana Trough

<table>
<thead>
<tr>
<th>Segments</th>
<th>1</th>
<th>1’</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment length, km</td>
<td>140</td>
<td>30</td>
<td>75</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>Ridge-axis orientation</td>
<td>$-22^\circ$/$-0^\circ$</td>
<td>$-15^\circ$</td>
<td>$-9^\circ$</td>
<td>$-21^\circ$</td>
<td>$-17^\circ$</td>
</tr>
<tr>
<td>Min. axial depth, m</td>
<td>2964</td>
<td>3936</td>
<td>4146</td>
<td>3650</td>
<td>3694</td>
</tr>
<tr>
<td>Min. MBA, mgal</td>
<td>$-28$</td>
<td>$32$</td>
<td>$27$</td>
<td>$9$</td>
<td>$14$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Segment Boundaries</th>
<th>1/1’</th>
<th>1’/2</th>
<th>2/3</th>
<th>3/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude, N</td>
<td>$20^\circ$50’</td>
<td>$20^\circ$35’</td>
<td>$19^\circ$55’</td>
<td>$19^\circ$20’</td>
</tr>
<tr>
<td>Max. axial depth, m</td>
<td>5034</td>
<td>4708</td>
<td>5038</td>
<td>4700</td>
</tr>
<tr>
<td>Max. MBA, mgal</td>
<td>46</td>
<td>42</td>
<td>47</td>
<td>39</td>
</tr>
<tr>
<td>Axial offset at 0 Ma, km</td>
<td>0</td>
<td>45</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Axial offset at 2.58 Ma, km</td>
<td>0</td>
<td>13</td>
<td>7</td>
<td>10</td>
</tr>
</tbody>
</table>

$^a$ North of $21^\circ$25’N.
$^b$ South of $21^\circ$25’N.

20°50’N is less significant than the three major discontinuities mentioned above, and call this portion Subsegment 1’.

Segments 2, 3, and 4 show a typical morphology of slow-spreading ridges like the Mid-Atlantic Ridge [Ramberg et al., 1977; Severinghaus and Macdonald, 1988; Sempere et al., 1990; Tucholke and Lin, 1994, Gente et al., 1995]. The lengths of the segments are from 60 to 75 km (Table 1). These segments have well-developed rift valleys, and neo-volcanic zones within the valleys are partly observed, particularly in Segment 2 (Figure 6). The floor of the valley is shallowest near the center of each segment, and becomes deeper toward nodal basins at the segment ends with increasing relief of the rift valley. The rift valleys have asymmetric structure: inside corners are higher elevation than

Figure 6. Detailed topographic map of Segment 2. Topographic contours are at 100m intervals. Location of this box is shown in Figure 2. Neovolcanic zone is recognized in the rift valley between two red arrows. IC: inside corner.
outside corners. For example, the western flank of the ridge Segment 2 is shallowest near the northern segment boundary, whereas the eastern flank is shallowest near the southern segment boundary (Figure 6). Water depths of the rift valley of Segment 2, about 4100 m near the segment center, are deeper than those of Segment 3, about 3700 m near the center. The rift valley at the southern end of Segment 2 (the southern Central Grabens) has particularly large relief which exceeds 3000 m: the water depth of the valley reaches to 5700 m, whereas the top of the inside corner is about 2500 m (Figure 6).

[13] Segment 1, on the other hand, has no clear rift valley except for the segment ends, which morphologically resembles ridges with intermediate spreading rates [Macdonald, 1982]. Its large segment length, about 140 km excluding Subsegment 1’, is also characteristic of intermediate to fast spreading ridges [Macdonald et al., 1991]. Water depths of the ridge axis of this segment, about 3000 m near the segment center, are shallower than other segments. This segment may be divided into two by a minor discontinuity at 21°25’N, which is suggested by a change of the ridge orientation, slightly deeper ridge axis, and an off-axis trace of the depressions from the point. The southern part of Segment 1 near the boundary between the Subsegment 1’ has a prominent rift valley (the northern Central Graben) with a shallow inside corner, which resembles the southern end of Segment 2.

### 3.2. Magnetic Vector Anomaly

[14] Interpretation of magnetic polarity boundaries is based on all three components and the ISDV, although only vertical component anomalies are shown in Figure 5. The anomalies are somewhat skewed, and thus positive vertical-component anomaly does not exactly correspond to normal-polarity magnetization, as shown by a forward model in Figure 5. This is because azimuths of the ridge axis more or less deflect westward from the north. The magnetic anomaly patterns can be correlated to the polarity reversal sequence from the Brunhes Chron (the last 0.78 m.y., hereafter based on the timescale of Cande and Kent [1995]) to the Gilbert Chron (3.58 to 5.89 Ma). Even shorter polarity subchrons in the timescale fit the anomaly patterns well, although only isochrons that correspond to the major polarity boundaries are displayed in Figure 5. For example, the positive anomalies in the vertical component between the isochrons of 2.58 and 3.58 Ma (the end and beginning of the Gauss Chron) consist of two peaks (Figure 5), which reflect the presence of short reversed subchrons (C2An.1r and C2An.2r) in the middle of the Gauss Chron. Further, the two minor peaks between the isochrons of 3.58 Ma (Gauss/Gilbert boundary) and 4.80 Ma (top of C3n.3n) in Segment 3 would correspond to the two normal subchrons (C3n.1n and C3n.2n) in the Gilbert Chron. The variation patterns are identical to those near 18°N [Yamazaki and Stern, 1997; Iwamoto et al., 2002], where organized seafloor spreading is believed to take place.

[15] Locations of ridge-axis discontinuities at present and their changes in the past can be known from offsets of the magnetic anomaly isochrons, and such information was used for identifying the ridge segments mentioned in the previous section. No displacement in magnetic lineations is recognized at the boundary between Segment 1 and Subsegment 1’. In the zone to the east of the ridge axis of the Subsegment 1’, magnetic lineations older than the Brunhes Chron are obscure. This is consistent with the idea of diffuse spreading there. The length of Segment 3 has decreased with time; it was 110 km at 4.8 Ma but now 65 km. Magnetic lineations are disrupted at a block in the western margin of the trough between 19°50’N and 20°20’N. The block has small volcanoes and no spreading fabric. We estimate that it consists of rifted arc crust.

[16] The identification of magnetic lineations revealed spatial and temporal variations of spreading rates, directions, and initiation of seafloor spreading. Seafloor spreading of Segment 3, between 19°N and 20°N, started a little prior to 5 Ma, which was extrapolated from the oldest magnetic isochron identified (4.8 Ma) and its distance from the West Mariana Ridge. Segments 1 and 2 began spreading at about 4 Ma, more than 1 m.y. after the initiation of Segment 3. It is estimated that the two segments between 20°0’N and 21°25’N started spreading simultaneously without northward prop-
agation of the spreading, because the 3.58 Ma isochron is almost parallel to the West Mariana Ridge. In the northern part of Segment 1, north of 21°25'N, the spreading started during the Gauss Chron. The age is younger than the southern part of this segment, and hence northward propagation is suggested here. Recent magnetic vector measurements have confirmed that the central Mariana Trough around 18°N began seafloor spreading at about 6 Ma [Seama and Yamazaki, 1998; Iwamoto et al., 2002]. These observations indicate that the start of the seafloor spreading becomes later according as the trough narrows northward. The northward propagation of the spreading was stepwise, but not continuous in general.

[17] The magnetic lineations show that the spreading has been asymmetric in the northern Mariana Trough. Spreading rates of the western side of the spreading center are much larger than the eastern counterpart in general (Figure 7), although magnetic lineations of the eastern side are not as clear as the western side partly because of volcanic overprints such as the Kasuga Seamount Chain (Figure 2). An exception is the spreading during the Brunhes Chron in Segment 2, where the eastern side is faster. The asymmetry of the spreading in the Mariana Trough is also derived from the fact that the location of the spreading center is not at the center of the trough but biased toward the volcanic arc. The asymmetry is observed also in the central and southern part of the Mariana Trough [Iwamoto et al., 2002; Seama et al., 2002].

[18] Spreading rates have decreased with time (Figure 8). The western side of the spreading center shows clearer evidence for the spreading rate change as follows. The half-rate was 2 to 3 cm/year in average before 2.58 Ma (Gauss/Matuyama boundary) south of 21°30'N. In the northern part of Segment 1, north of 21°30'N, where the initiation of spreading was later, the half-rate of 2 to 3 cm/year continued during the Matuyama Chron. These rates were reduced to be about 1 cm/year or less during the Brunhes Chron. An exception is part of Segment 1 between 21°15'N and 21°45'N: the rate during the Brunhes Chron is a little higher, 1.5 to 2.0 cm/year. This part corresponds to the ridge without axial rift valley. Changes in spreading half-rate in the eastern side of the spreading center are not clear, but the rates are slower than the western side in general as mentioned above, and there is no evidence for any increase associated with the decrease in the western side. This implies a decrease of spreading full-rate.

[19] Spreading directions can be estimated from strikes of magnetic anomaly isochrons. The trends of the isochrons agree with those of topographic
fabric in general (Figure 5). Spreading directions have changed with age. In each segment, this can be recognized visually from a difference in trend between the oldest isochron and the present spreading center in Figure 5. Orientations of the spreading center, which range from $-20^\circ$ to $0^\circ$ at present (Table 1), have rotated about $20^\circ$ clockwise since the start of the spreading (Figure 8). This clockwise rotation resulted in increases of ridge-axis offset with time at the segment boundaries. The magnetic isochrons indicate that the offset at the boundary between Subsegment 1 and Segment 2 was about 13 km at 2.58 Ma but is about 45 km now (Table 1). The offset at the boundary between Segments 2 and 3 increased from 7 to 30 km within the same period of time.

[20] No magnetic lineation of seafloor-spreading origin is observed north of the boundary at 22°N (Figure 5). The magnetic anomaly profiles there are correlative neither with each other nor with the magnetic polarity reversal sequence back from the Brunhes Chron. These observation is consistent with the idea that the trough north of 22°N consists of rifted arc crust [Yamazaki et al., 1993; Martinez et al., 1995; Yamazaki and Murakami, 1998]. Dominant positive anomalies in the vertical component north of 22°N (Figure 5) are associated with volcanoes in general: for example, a row from 22°30’N, 142°35’E to 22°45’N, 142°25’E (eastern purple broken oval in Figure 5). A pair of positive and negative anomaly bands in the western margin of the trough between 22°25’N and 22°45’N (western purple broken oval in Figure 5) is probably caused by an intrusive body.

3.3. Mantle-Bouguer Gravity Anomaly

[21] By a first look of the MBA map (Figure 9), we can recognize a contrast between lows along the Mariana and West Mariana Ridges and highs in the trough south of 22°N. Steep gradients in MBA...
occur along the topographic and magnetic boundary near 22°N, as well as in the northernmost part of the trough near 23°N and along flanks of the Mariana and West Mariana Ridges facing the trough. This indicates a large contrast in crustal thickness at the boundary near 22°N: rather abrupt thinning southward. This supports the idea that the rifting-to-spreading transition takes place here.

South of 22°N, the MBA is lowest near the center of each segment, and increases toward the segment ends (Figures 9 and 10). It is anti-correlated with the water depth of the spreading center (Figure 10). This variation pattern, the so-called “bull’s-eye,” is known to occur commonly along slow-spreading ridges like the Mid-Atlantic Ridge (MAR) [Kuo and Forsyth, 1988; Lin et al., 1990], and is interpreted to represent thicker crust near the segment center than at the ends caused by focused magmatic accretion. The ridge axis of Segment 1 has lower MBAs and shallower water depths than the other segments. The center of Segment 1 is located on the slope of MBA decreasing toward the Mariana Ridge, but not on an enclosed low like the other segments. A drop in MBA with a corresponding peak of axial depth at about 20°45′N (Figure 10) suggests that the southern part of Segment 1 between 20°50′N and 20°30′N probably belong

Figure 9. Mantle Bouguer gravity anomaly map calculated using the Free-air gravity anomaly from satellite altimetry. Contours are at 10 mgal intervals. Thick lines show location of ridge axis. Grid interval about 3700 m.
to a separate short segment (Subsegment 1’), as inferred from the topography and side-scan image mentioned above. Segments 2, 3, and 4 have axial MBA amplitudes of 20 to 30 mgal and axial depth relief of about 1000 m (Figure 10 and Table 1), which agrees with the relationship between the two observed along the MAR between 15°N and 40°N [Thibaud et al., 1998].

The low MBAs along the West Mariana Ridge protrude into the trough between 19°50’N to 20°20’N, which corresponds to the remnant arc crust estimated from the topography and magnetic lineations. High MBAs are observed along the western margin of the trough between 21°N and 22°N. Similar tendency, although weak, is recognized south of 19°50’N. This could represent the thermal effect of lithospheric cooling. On the other hand, such highs in MBA are absent in the eastern margin of the trough, probably because of a thermal effect of the hot volcanic arc.

4. Discussion

We have presented the occurrence of spreading fabric in the swath bathymetry, clear lineations in the magnetic vector anomalies, and the bull’s-eye pattern in the MBAs associated with ridge segmentation to the south of the boundary near 22°N. We thus conclude that seafloor spreading has already started south of 22°N. We consider that it is not necessary to define a rifting-to-spreading transition zone in the south of 22°N like the Volcano-Tectonic Zone (VTZ) of Martinez et al. [1995]. In contrast, such spreading features are not observed north of the boundary, which indicates that the trough north of 22°N is in a rifting stage. The VTZ model of focused rifting and volcanism would be applicable here, which can explain the occurrence of the magnetic anomaly bands in the western margin of the trough between 22°25’N and 22°45’N.

A major reason for the conclusion of Martinez et al. [1995] that the trough between 20°N and 22°N is underlain by rifted arc crust was that broad, positive and negative magnetization bands were commonly observed north and south of 22°N on their results of a three-dimensional inversion of magnetic total-force anomaly data. A possible cause of the different conclusion from ours is that fine features, which are useful for the identification of magnetic lineations, seem to have been reduced.

Figure 10. Along-axis variations of mantle Bouguer gravity anomaly (MBA) and depth in the northern Mariana Trough between 19°N and 22°N.
in their inversion solution, because they applied a band-pass filter which suppresses wavelengths less than 12 km. Short-wavelength signals that correspond to the Olduvai Subchron and two subchrons within the Gauss Chron may have been affected by the filtering. It can also be pointed out that our results from the magnetic vector anomalies would have higher resolution than theirs on the basis of the total-force anomalies. The latter has inevitably small anomaly amplitudes in the Mariana Trough as mentioned before. Moreover, their inversion assumption may not be valid in some points. They assumed the source layer thickness of 1 km for their inversion. This assumption is commonly used for magnetic anomaly inversions of seafloor-spreading origin [e.g., Macdonald et al., 1980; Grindlay et al., 1992; Pariso et al., 1996], but may not be applicable for arc crust north of 22°N. The upper part of arc crust would consist of thick volcaniclastics, which contributes little to the magnetic anomalies. Instead, middle and lower crusts may have strong magnetization associated with intrusion and underplating of magmas. Their inversion includes the Mariana and West Mariana Ridges, where deep-seated plutonic bodies may contribute significantly to the magnetic anomalies. The importance of such anomaly sources beneath oceanic island arcs is suggested by the occurrence of long-wavelength magnetic anomalies over the Izu-Ogasawara (Bonin) Arc and the Kyushu-Palau Ridge [Yamazaki and Yuasa, 1998]. Thus the inversion which included altogether the Mariana and West Mariana Ridges and the trough from 20°N to 24°N but assumed the constant 1 km source-layer may not be valid; they have different crustal structures and hence should have different source-layer depths and thicknesses. Furthermore, the assumption is not consistent with their model. If the trough south of 22°N is underlain by rifted arc crust with volcanic intrusions as they postulated, the sources of the anomalies could be deeper and thicker than surface 1 km, in particular in the western part of the trough where the crust should be cooler and have experienced relatively small extension.

[27] The two deeps near the center of the trough between 20°N and 21°N, the Central Grabens, have been formed by amagmatic extension at the segment ends. The southern one near 20°N occurs at the southern end of Segment 2, and the northern one near 21°N is located at the southern end of Segment 1 if we introduce Subsegment 1’. They were previously thought to have been formed by concentration of rifting [Martínez et al., 1995] or be enigmatic [Stern et al., 1996], but can well be explained in the context of seaﬂoor spreading. The topographic asymmetry of the deeps, the prominent eastern scarps vs. the gentle western slopes, can be explained by tectonic thinning of the inside corners by low-angle detachment faults [Tucholke and Lin, 1994; Tucholke et al., 1998]. Gabbros and ultramafic rocks were recovered from the deep at 20°N [Stern et al., 1996, 1998; Ohara et al., 2002]. Exposure of lower crust and upper mantle at inside corners is common in the MAR [Tucholke and Lin, 1994; Cannat et al., 1995; Gracia et al., 1997]. The great depths of the Central Grabens were emphasized previously and thought to be anomalous compared with the MAR, where maximum depths of some second-order segment boundaries are close to 5000 m. But the maximum depth of 5700 m of the Central Grabens are not quite anomalous, considering that depths of backarc basins in the Philippine Sea plate including the Mariana Trough is about 700 m deeper in average
than expected from the age-depth curve of major oceans [Park et al., 1990].

Segment 1 shows the characteristics of the ridges with intermediate spreading rates, those are the larger segment length and the shallower depths of the ridge axis without rift valley, even though the spreading rate during the Brunhes Chron is only slightly larger than the southern segments. Furthermore, this segment has much lower MBAs than the other segments in the bull’s-eye pattern, suggesting thicker crust and/or hotter mantle. Since this segment is closest to the volcanic arc and the MBA low of the segment center continues to the Mariana Ridge, these observations lead us an interpretation that this segment receives extra magma delivery from the volcanic front. Similar changes of topography and gravity are observed in segments of the MAR approaching to the Azores hot spot [Detrick et al., 1995; Thibaud et al., 1998] and the Iceland hot spot [Bell and Buck, 1992; Searle et al., 1998]. On the basis of chemical compositions of basalts obtained from the northern part of the trough between 21°C176N and 22°C176N, Stern et al. [1990] estimated a mixing of 50–90% Mariana arc component with a mid-ocean ridge basalt (MORB) component. Subsegment 1’ and Segment 2 are, on the contrary, cold, magma-starved segments. The centers of the segments are deeper than Segment 3 as well as Segment 1, and they accompany the deep grabens near the segment ends. Segments 3 and 4 show normal morphological features for slow-spreading ridges. The succession of magma-rich, magma-starved, and normal segments with increasing distances from the volcanic arc is the same as the observation in the Lau Basin, from the Valu Fa Ridge to the Central Lau spreading center, as proposed by Martinez and Taylor [2002]. Presence of the volcanic arc would be a fundamental difference of backarc spreading from mid-ocean ridges. The asymmetry in spreading rates also suggests that an interaction between mantle upwellings under the backarc spreading center and the volcanic front may control the distance between the two.

Seafloor spreading in small backarc basins is considered to be unstable in general compared with mid-oceanic ridges in major oceans because the former may be affected by kinematics of surrounding plates more easily, and changes in spreading direction and rate may be frequent. Recent GPS measurements revealed that both the Philippine Sea plate and the Mariana Ridge are moving westward relative to the Eurasia [Kato et al., 1998; Sella et al., 2002], and the opening of the Mariana Trough occurs because the movement of the former is faster than the latter. This observation is not consistent with the opening model assuming a trench rollback [Martinez and Fryer, 2000]. Spreading of the Mariana Trough predicted from the GPS measurements is almost east-west with a full-rate of about 4.7 cm/year, which was measured in its southern part (Guam). It is not inconsistent with those in the northern Mariana Trough estimated from the magnetic anomalies of Brunhes age, considering that the rates would decrease northward with decreasing width of the trough. The reducing spreading rate and the clockwise rotation of ridge-axis strike observed in the northern Mariana Trough during the last ca. 1 to 2 m.y. should reflect a change in the motion of the Philippine Sea plate. Some evidences suggest that the convergence along the Nankai and Sagami Trough subduction zones in the northern margin of the Philippine Sea plate changed from the north to northwest at ca. 1 Ma [Nakamura et al., 1984; Yamazaki and Okamura, 1989]. It is, however, difficult to construct a plausible model of the past Philippine Sea plate motion only from these constraints, and further accumulation of data concerning a detailed spreading history in the central and southern part of the Mariana Trough, internal deformation of the Mariana arc, and convergence along margins of the Philippine Sea plate are required.

5. Conclusions

This study revealed following characteristics of the spreading in the northern Mariana Trough between 19°N and 24°N.

(1) Transition from rifting to seafloor spreading occurs near 22°N. Four ridge segments sepa-
rated by three nontransform discontinuities are identified between 19°N and 22°N. Seafloor spreading between 19°N and 20°N began prior to 5 Ma, and that between 20°N and 21°30'N began at about 4 Ma. The northward propagation of the spreading was stepwise, but not continuous. The bull's-eye pattern of MBA, which is a characteristic of slow-spreading ridges, occurs along the ridge.

[32] (2) The northernmost segment is morphologically similar to ridges with intermediate spreading rates: a large segment length and shallow water depths without rift valley. The MBAs near the segment center are lower than the other segments. This suggests an abundant magma supply to this segment. The next segment is, on the contrary, a magma-starved segment with a prominent rift valley. Two anomalously deep grabens (the Central Grabens) occur near the segment ends between 20°N and 21°N, and were formed by amagmatic extension. The succession of magma-rich, magma-starved, and normal segments with increasing distances from the volcanic arc is the same as the observation in the Lau Basin reported by Martinez and Taylor [2002].

[33] (3) Spreading rate has decreased with time. The spreading half-rates in the western side of the spreading center were 2 to 3 cm/year before 2.58 Ma south of 21°30’N and during the Matuyama Chron north of 21°30’N, but an average during the Brunhes Chron is 1 cm/year or less. Direction of spreading has also changed with time. Orientations of spreading ridges, which range from −20° to 0° at present, have rotated about 20° clockwise since the start of the spreading. These changes might be associated with changes in the motion of the Philippine Sea plate.

[34] (4) The seafloor spreading has been asymmetric. The spreading rates of the western side of the spreading center have been significantly larger than the eastern counterpart in general. We estimate that diffuse spreading occurs in the eastern side of the axis between 20°35’N and 20°50’N, which may be an undergoing eastward ridge jump. The asymmetry may have been caused by an interaction of upwelling systems under the volcanic front and the backarc spreading center, and would be a characteristic of backarc spreading.

Acknowledgments

[35] We thank Naoki Wakabayashi, Yuichi Hasegawa, and Hisanori Iwamoto for their help of the measurements and data processing, and Robert J. Stern, Makoto Arima, Makoto Yuasa, and Takemi Ishihara for discussion. We also thank all onboard scientists, officers and crew of the cruises of R/V Kairei and R/V Yokosuka for cooperation, and Hajimu Kinoshita, Kiyoshi Suyehiro, and other JAMSTEC personnel related to the cruises for their support. The manuscript was greatly improved by comments from two anonymous reviewers and an associate editor, Bruce Anderson. The GMT software [Wessel and Smith, 1995] was used for producing the figures. This study was partly supported by the Grant-in-Aid for Scientific Research (B)(2) No. 12440116 of the Japan Society for the Promotion of Science.

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