Vector magnetic analysis within the southern Ayu Trough, equatorial western Pacific

Sang-Mook Lee and Seung-Sep Kim

1Marine Geo-Resources Division, Korea Ocean Research and Development Institute, Ansan, PO Box 29, Seoul 425-600, Republic of Korea. E-mail: smlee@kordi.re.kr
2School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, Honolulu, HI 96822, USA. E-mail: sskim@soest.hawaii.edu

Accepted 2003 September 18. Received 2003 September 9; in original form 2003 January 6

SUMMARY
We present the analysis of magnetic field data of the Ayu Trough, a divergent plate margin located in the southern Philippine Sea plate. The survey, which mapped both axial and off-axis regions of the southern Ayu Trough, recorded the total field using a proton precession magnetometer towed behind the ship and the vector magnetic field using a shipboard three-component fluxgate magnetometer together with multibeam bathymetry. The two magnetic field anomalies show good agreement, indicating that the reduction of vector field data was successful. Our inspection of E–W profiles shows that there is little correlation in magnetic anomalies between adjacent profiles and lack of symmetry with respect to the trough axis. However, a careful examination of gridded magnetic anomaly map reveals that symmetry may be found to the north of 1°N along N120E, which is roughly the direction of spreading at this region as revealed by the fine-scale seafloor fabric by our survey. Vector magnetic anomalies exhibit important differences with strike of magnetic boundaries within the inner region between Tobi and Mapia Ridges trending predominantly N–S, whereas in the outer region they are almost E–W. This finding suggests that the outer region appears to retain the magnetization and crustal structure of the old West Philippine Basin, while the inner region is inherited from the E–W seafloor spreading in the Ayu Trough. The short along-axis segmentation and complex seafloor morphology caused by slow oblique spreading may explain the lack of symmetry in the magnetic anomalies with respect to the trough axis and a wider occurrence of 3-D magnetic source crust roughly to the south of 1°N.

Key words: Ayu Trough, divergent margin, vector magnetic field, West Philippine Basin.

INTRODUCTION
The Ayu Trough is a small divergent margin located in the equatorial western Pacific just south of a major subduction system, which extends from Izu–Bonin–Mariana to Yap and Palau Trenches (Fig. 1 inset). The 800-km-long spreading center is marked by a narrow central rift that trends N–S, forming the border between the Philippine Sea and Caroline plates (Fig. 1). The Ayu Trough is the only spreading section along the borders of the Philippine Sea plate with significant length, and as such it has been thought to be a place where seafloor magnetic reversal patterns might provide information on the past motion of the Philippine Sea plate relative to the Caroline plate. However, only a small portion of this region has been mapped and investigated (Weissel & Anderson 1978; Fujiwara et al. 1995), with much of the existing data concentrated on the axial region.

On a regional scale, the Ayu Trough has a triangular or inverted fan shape with its apex pointing to the north and linear ridges extending away from the apex point (Fig. 1). It was based on this shape and variation in sediment thickness that Weissel & Anderson (1978) argued the trough was opening like an inverted fan with the pole of rotation lying just south of the Palau Island. A revised pole of rotation was later proposed by Seno et al. (1993), based on earthquake slip vectors constraining the motion of the Philippine Sea plate while fixing the boundary between the Pacific and Caroline plates. Neither determination of the pole of rotation is constrained by direct geophysical or geodetic measurements along the Caroline plate boundaries. The absence of reliable seafloor age data presents another critical challenge in understanding the evolution of this region. Fujiwara et al. (1995), updating the result of Weissel & Anderson (1978), proposed 4 mm yr⁻¹ as the spreading rate of the Ayu Trough based on sediment thickness. However, the sedimentation rate used in both studies was derived from nearby DSDP site 62 in the middle of the Caroline plate several thousand kilometers away and may not be sufficiently representative.

The Ayu Trough is bounded to the west by the West Philippine Basin whose origin remains controversial (Deschamps & Lallemmand 2002, and references therein). Determining the southern extent of West Philippine Basin is an important in understanding its early
stage evolution. However, the southern boundary is not well defined due to lack of detailed data. A major escarpment exists around 8–10°N and some argue that this feature may be the southern extent of the basin (Mrozowski et al. 1982). However, it is possible that southern boundary of the West Philippine Basin may lie much further south.

Because the Ayu Trough lies very close to the magnetic equator and is spreading in an almost E–W direction, the measured magnetic field due to geomagnetic polarity reversals recorded in oceanic crust has subdued amplitudes. The complex tectonic processes as manifested by the rough topography that the Ayu Trough exhibits may also pose an additional obstacle to the identification of geomagnetic reversal patterns. Nonetheless, if careful analysis is employed, one may still derive important information such as the spatial variability of magnetic anomalies. A problem with investigating magnetic anomalies, especially near the magnetic equator, however, is the presence of noise arising from ionospheric activity. Therefore, it is important to correct for the diurnal effect before analysis and interpretation.

Vector magnetic field data provide additional information to the traditional total field measurement. Specifically, we can examine the characteristics of magnetic source layers, such as two-dimensionality of seafloor magnetization, and can constrain the position and structure of magnetic boundaries, including isochrons, pseudo-faults and fracture zones, regardless of the direction of Earth’s field (Isezaki 1986; Seama et al. 1993; Korenaga 1995). As a result, three-component measurements have been fruitful in areas where there are not enough track lines to constrain the magnetic boundary using standard total field measurement (for instance,
Figure 2. Comparison of two total fields, one obtained by PPM measurement (red) and the other calculated from STCM measurement (solid with positive anomaly filled). Seafloor bathymetry obtained by high-resolution swath system is shown in the background with white lines representing the trough axis based on seafloor topography and numbers denoting profile numbers. Every other profile is identified. Black dashed lines trending N–S denote the prominent topographic features in the off-axis region in Fig. 1. White inverted triangle represents an off-axis topographic high discussed in the text. In general, there appears to be a good agreement between the two types of total field measurements.
Figure 3. Vector magnetic anomalies of the southern Ayu Trough. (a) North (X) component; (b) east (Y) component; and (c) downward (Z) component. The positive anomaly is filled. The gray lines represent the trough axis and the numbers next to the profile denote profile number. Black dashed lines trending N–S denote the prominent topographic features in the off-axis region in Fig. 1.
Fujiterra et al. (2001). On the other hand, the correction of three-component magnetic field is more complicated than for total field measurements, and requires accurate attitude information and noise suppression techniques. Furthermore, if the vector magnetic field sensor resides on a research vessel, extra steps are needed to correct for the induced-field effect due to the metallic body of the ship. In this study, we examine the vector magnetic anomaly data collected during a recent research cruise and compare them with morphological and tectonic features of the survey area to gain new insights into the evolution of the Ayu Trough. The detailed reduction steps and analysis routines are described in papers by Isezaki (1986), Seama et al. (1993) and Korenaga (1995) and will not be repeated here.

DATA COLLECTION AND PROCESSING

The data for this study were collected in 2001 May by Korea Ocean Research and Development Institute (KORDI) during a multidisciplinary investigation of the southern Philippine Sea onboard R/V Omuntar as part of the Daeyang Programme. The survey, which covered a section of the southern Ayu Trough from 2° 05'N to the equator (Fig. 1), collected multibeam swath bathymetry, multichannel seismic, gravity, and both total and vector magnetic field. The total field was recorded by a proton precession magnetometer (PPM) towed 200 m behind the vessel while the vector magnetic field was acquired with a ship-mounted three-component fluxgate magnetometer. We also gathered high-precision attitude (roll, pitch, yaw and heading) information to correct the shipboard three-component magnetometer (STCM) data for the influence of the metallic ship.

A total of 18 lines traversed E–W during the 2001 survey of the southern Ayu Trough (Fig. 1). The bathymetric map was produced by combining high-resolution multibeam swath data collected in 2000–2001 with data from ETOPO5 global database (NGDC 1988), which were used to fill the gaps of shipboard measurements (Fig. 2).

An important factor that has to be considered when analysing shipboard measurement is the viscous remnant magnetization (VRM) caused by the ship's body. VRM can cause the measurement to vary from profile to profile and is noticeable when the ship makes a sudden turn. To investigate the effect of VRM, we examined a finite length of record before and after ship turn for each profile and found that difference between two sections is significantly reduced approximately 30 km (or 1.5 hr) after the turn, although it varies somewhat from profile to profile. We excluded from the analysis the portion of the record after ship turn that shows significant difference with the adjacent profile (shown as white dashed lines in Fig. 1).

The Ayu Trough exhibits rough seafloor topography with numerous segments along the axis and evidence of oblique spreading in the N120°E direction (Fig. 2) (Jung & Lee 2002). Away from the axis, a number of linear ridges can be seen. These off-axis ridges extend roughly N–S but their distance from the axis increases to the south. The three ridges noted in the study area are referred to as Outer and Inner Tobi Ridges and Mapia Ridge from west to east (Figs 1 and 2). If the Ayu Trough did open by splitting the old remnant arc, Palau–Kyushu Ridge, there should be conjugate ridges on both sides of the Ayu Trough. Interestingly, there is only one linear ridge, Mapia Ridge, on the Caroline plate side. The outer Tobi Ridge has no apparent conjugate on the east side. For convenience, we refer to the area between Inner Tobi and Mapia Ridges as the ‘inner region’ and that beyond as the ‘outer region.’

The vector magnetic field data were processed using the method formulated by Isezaki (1986). To calibrate the magnetic field produced by the ship, ‘figure eight’ turns were performed 14 times in the survey area. The measurement of the magnetic field during these turns allows us to construct a set of coefficients that can be applied to the data to compensate for the ship's effect. For each component of the vector magnetic field, the long-wavelength regional field calculated using the International Geomagnetic Reference Field (IGRF) (IAGA Division V 2000) was removed.

To correct for the effects of large diurnal variations, we used the magnetic field record from a reference station in Guam, the nearest geomagnetic station, which substantially improved the quality of survey data. For instance, the rms misfit at crossover points for PPM data was reduced from 65 to 20 nT after the correction. The vector field measurements from Guam during the survey period were also applied to the STCM data.

RESULTS

Processed vector magnetic field anomalies in the study area are shown in Fig. 3 with north, east and downward components denoted as X, Y and Z, respectively. The validity of the reduction can be examined by comparing the STCM total field with total field measured by the PPM. The comparison shows a good agreement (Fig. 2) and thus suggests that the reduction of STCM data was quite successful. For profiles 1–3 on the western flank, however, there is some offset between the two total fields. The probable cause of this is unclear.

![Figure 4](image-url)

Figure 4. Forward calculation of 2-D magnetic reversal on the seafloor for lineations striking in N–S direction (solid) and 30° clockwise from the north (dashed). (a) Total field; and (b) north (X); (c) east (Y); and (d) downward (Z) components. (d) The seafloor is magnetized according to geocentric axial dipole hypothesis (Merrill & McElhinny 1983) in which case the magnetization would have inclinations of ±2° at this location. Magnetization intensity of 10 A m⁻¹ and source layer thickness of 1 km were assumed in this calculation.
but may be due to the difference in the compensation of the ship's permanent and induced fields by figure eight turns between the inner and outer regions of the study area.

The north component of magnetic anomalies has smaller amplitudes than the other two components (Fig. 3). A simple forward model predicts that perfectly 2-D magnetic lineations striking N–S at this location will have zero anomalies in the north component. Fig. 4 is a simple block model of seafloor magnetization showing the magnetic anomalies resulting from lineations that strike perfectly N–S (solid) and those that deviate from perfectly N–S (dashed). A case where lineations strike 30° from the north is shown as an example. It predicts that a perfectly 2-D magnetic reversal pattern on the seafloor striking N–S at this location will have no anomaly in the north component (solid line in Fig. 4b). The presence of a north component anomaly in the observed data therefore suggests that the magnetic lineations are not perfectly 2-D or that they do not strike exactly in N–S direction. The model also predicts that magnetic lineations striking 30° has little effect on the east component (Fig. 4c), whereas a significant phase shift results in the vertical component (Fig. 4d).

We examined the individual profiles to see if there is symmetry with respect to the trough axis and correlation between adjacent profiles. Despite our careful analysis, however, there does not appear to be strong evidence for symmetry in the magnetic field anomaly with respect to the axis (Fig. 2). To a certain extent, this may be due to the fact that we ran track lines in E–W direction, whereas

---

**Figure 5.** Gridded STCM total field anomaly map produced by data from individual track lines. The contours represent seafloor bathymetry drawn at 500-m interval. The white lines along the center is the trough axis and the black lines cross-sectional profiles along which magnetic field anomalies were sampled for further analyses (Fig. 6).

© 2003 RAS, *GJI*, 156, 213–221
However, as mentioned earlier, there is a great deal of uncertainty associated with this estimate. In fact, the sedimentation rate of Ayu Trough may be much higher than that of the DSDP site 62 due to its proximity to land, and therefore the actual spreading rate may be higher than 4 mm yr$^{-1}$. In order to produce the synthetic magnetic anomaly profiles, we employed a 2-D model where magnetic lineations strike 30° from the north and took 10 A m$^{-1}$ as the magnetization intensity and 1 km as the thickness of uniformly thick magnetic source layer that follows the undulation of seafloor topography. In addition, the geomagnetic polarity timescale by Cande & Kent (1995) was applied to model the magnetic reversal pattern on the seafloor. The magnetization was assumed to have declination and inclination according to the geocentric axial dipole hypothesis (Merrill & McElhinny 1983). The comparison between the observed and modelled anomalies clearly shows a large discrepancy (Figs 6b and d). In particular, there is a significant offset between the presumed axis of symmetry and the trough axis, marked as gray vertical bar and filled inverted triangle in Figs 6(b) and (d), respectively.

Another important observation from Figs 2 and 5 is that there are both positive and negative anomalies along the trough axis. If there were Brunhes anomaly associated with spreading, the axis should have uniformly negative total field (Fig. 4). One interpretation for the presence of both positive and negative anomalies along the axis is that spreading has stopped and therefore the present trough axis is a relict feature. For example, as the spreading comes to a halt, there may be a significant variation in the supply of magma along the trough axis, which may lead to substantial changes in the magnetization intensity and magnetic source layer thickness along the axis.

As mentioned earlier, vector magnetic field data can provide important information about the magnetic source including the nature of magnetization contrasts within oceanic crust. One approach that has been widely adopted is to construct a magnetic boundary strike diagram (MBSD) (Seama et al. 1993; Korenaga 1995). Fig. 7 is the MBSD of our study area showing the strikes of magnetic boundaries and their magnetization contrast, assuming that the magnetic source layer has a uniform thickness of 1 km. The most important feature in Fig. 7 is the difference in the strike of inferred magnetic boundaries between different areas. In the inner region of the Ayu Trough, the predominant direction of strike is N–S, whereas in the outer region, it is almost E–W.

Another useful piece of information that can be obtained from vector magnetic anomalies is the dimensionality of magnetic sources (Isezaki 1986; Seama et al. 1993; Korenaga 1995). 2-D magnetic sources produce no magnetic field parallel to their long axis (as shown in Fig. 4b), and in that case, the vertical field component can be transformed to a calculated horizontal component. This quantity can then be compared with the observed horizontal component to discriminate between 2-D and 3-D sources. The deviation between the downward components defines a 3-D index; values greater than 1 are assumed to be generated by 3-D sources. In general, the three-dimensionality appears to be greater in the southern portion of the study area than area roughly north of 1°N (Fig. 7).

**CONCLUDING REMARKS**

An important finding of this study is that magnetic field anomalies exhibit much higher degree of symmetry along the presumed direction of seafloor spreading (N120E) than in the E–W direction. This is consistent with the direction of spreading as revealed by fine-scale seafloor fabrics from detailed bathymetric survey (Fig. 2). However, this symmetry only appear to be present to the north of 1°N; to the
south of 1° N, there is very little sign of symmetry even in the inferred
direction of spreading (Fig. 5).

In the area where we see some symmetry, a large discrepancy
between the presumed axis of symmetry for the magnetic anomaly
and topographic axis exists. The discrepancy is quite notable along
profile B2 (Fig. 6d). However, it is unclear at this stage whether this
is due to our misidentification of magnetic anomaly symmetry axis
or if the present trough axis is a relict feature.

In general there does not appear to be much correlation between
adjacent tracks, even along the presumed direction of spreading
(N120E). However, this observation can be biased by the extent of
our coverage. For instance, profiles A1 and B1 transect geological
different sections of the segment as shown by the topography. In
order to better resolve the magnetic structure of this complex area,
we may need to conduct an additional survey but this time in N120E
direction.

Another important finding of this study is that the general strike
of magnetic boundary differs between the inner and outer regions
(Fig. 7). In the inner region, the predominant strike direction is
N–S, whereas in the outer region, it is nearly E–W. The N–S strike
within the inner region is consistent with the detailed seafloor fabric,
which suggests oblique spreading in the N120 direction. Thus much
of the strike data represent simple magnetic reversal boundaries
or ‘stripes’ produced by seafloor spreading. There are small areas
within the inner region where notable deviation can be observed. For
example, in the southwestern corner of our survey area, magnetic
boundaries with large contrast (>4 A m⁻¹) strike nearly E–W. The
seafloor topography map shows a large block of shallow seafloor
(denoted as inverted triangle in Fig. 2) which coincides with the
E–W strike, indicating the influence of local topographic relief on
the MBSD.

In general, a greater deviation in strike and higher value of 3-D
index can be observed in the southern portion of the study area
(Fig. 7). This contrast may be related to the segmentation or linearity
of the spreading axis. The exact boundary between the two regions
is not so clear. However, roughly north of 1° N, the trough axis is
fairly long and straight (>100 km), indicating well-behaved 2-D
seafloor spreading (Fig. 2). In contrast, the segment length are much
shorter (<50 km) to the south and the trough axes occur in an en
echelon manner. Hence, the deviation from two-dimensionality at
the spreading axis may explain the increase in 3-D index south
of 1° N.

The second main result from our study of MBSD is the tectonic
contrast between the Ayu Trough and West Philippine Basin. The
presence of E–W trending magnetic strike in the region west of Inner
Tobi Ridge suggests that the region may belong to West Philippine
Basin, the oldest backarc basin within the Philippine Sea plate. Mag-
netic investigations carried out since the 1970s have been analysed
in the West Philippine Basin, but north of 5° N (Shih 1980; Hilde
& Lee 1984); the area just west of Ayu Trough has not been exten-
sively surveyed. According to Hilde & Lee (1984), the basin began
opening along the Central Basin Ridge from approximately 59 Ma
(anomaly 25) to 26 Ma (anomaly 7A). The magnetic boundary strike
in the outer region thus appears to be roughly consistent with the
E–W trending magnetic anomalies of this basin. However, it is un-
clear whether the magnetic boundaries that we observe are the old
magnetic lineations produced during seafloor spreading or tectonic
features produced during the basin rifting.

Figure 7. Magnetic boundary strike diagram (MBSD) together with magnetization contrast information plotted on top of 3-D index map. Direction of bar represents the declination of magnetic boundary strike and its length varies with the cosine of the inclination. The length of the cross bar corresponds to the magnitude of the angular standard deviation with longer cross bar representing larger uncertainty. Only strikes with angular standard deviation of less than 15° are shown. Thickness of the bar corresponds to the intensity of magnetization contrast at the boundary. The bars in the legend box correspond to magnetization intensity contrast from 1 to 11 A m⁻¹. Black dashed lines trending N–S denote the prominent bathymetric ridges off axis. White lines represent the trough axis as in Fig. 2.
We conclude that the MBSD reveals that the exact boundary between the younger Ayu Trough and the older West Philippine Basin lies along the Inner Tobi Ridge (Fig. 7). This would explain the absence of a conjugate feature to the Outer Tobi Ridge on the eastern flank of the Ayu Trough. For example, if the trough initially formed by splitting the Palau–Kyushu Ridge, our vector magnetic anomaly result suggests that the division produced the Inner Tobi and Mapia Ridges. This is consistent with our multichannel seismic observation on the western flanks of the Ayu Trough (Hong & Lee 2002), which show no evidence of large faulting along the profile in the outer region.

ACKNOWLEDGMENTS

This cruise to Ayu Trough was funded by the Korea Ocean Research and Development Institute under Daeyang Programme 2000–2002. We would like to thank Jun Korenaga and Nobukazu Seama for offering the programme and technical assistance for STCM data processing. We also thank Allegra Hosford, Toshiya Fujiwara and Maurice Tivey for constructive review. Pan-Mook Lee graciously provided the Seatex motion reference unit so that comparisons can be made with HIPPY 120 during 2001 campaign. Digital magnetogram of station in Guam was provided by Don Herzog of US Geological Survey. Marine scientific research application within Indonesian EEZ could not have been granted in time without the service of Indroyono Soesilo and Safri Burhanudin of Ministry of Marine and Fisheries, Indonesia. The GMT software (Wessel & Smith 1991) was used for the figures. Finally, we would like to express our gratitude to the crew of R/V Onnuri for their effort.

REFERENCES


