Korean Journal of Polar Research 10(2): 117-124

Vector Magnetic Anomalies in the West Enderby Basin

Yoshifumi Nogi and Katsutada Kaminuma

National Institute of Polar Research, 9-10, Kaga-1, Itabashi, Tokyo 173-8515, Japan

ABSTRACT. Vector geomagnetic field measurement has been carried out in the South Indian Ocean since 1988 on board the icebreaker Shirase. Vector magnetic anomalies in the West Enderby Basin obtained between the 30th and the 39th Japanese Antarctic Research Expedition (JARE-30: 1988-89, JARE-39: 1997-1998) were analyzed. Strikes of the two-dimensional magnetic structures at the positions of their boundaries were determined using those data. The magnetic strikes were divided into two groups based on structural change and magnetic polarity change. The two-dimensional magnetic structures associated with magnetic polarity change are observed in the various places. Some of these strikes are identified as magnetic lineation trends, belonging to the Mesozoic magnetic anomaly sequence. The two-dimensional magnetic structures associated with magnetic polarity change and structural trends in the West Enderby Basin suggest that ridge reorganizations occurred during the long Cretaceous normal polarity chron.

Key Words: vector magnetic anomaly, magnetic anomaly lineation, Cretaceous normal polarity chron, Enderby Basin, Mesozoic magnetic anomaly sequence, ridge reorganization

Introduction

Marine magnetic anomalies in the Southern Indian Ocean are key to understanding the seafloor spreading history related to the breakup of Gondwana. However, marine magnetic data are quite sparse and magnetic anomaly lineations remain less well-defined. Recently, major tectonic and topographic features have been revealed by high- density satellite altimetry data in much of the Southern Indian Ocean (e.g. Sandwell 1992; Sandwell and Smith 1992; Marks *et al.* 1993), however, fracture zone trends in the Enderby Basin, the Southern Indian Ocean, especially near Antarctica remain poorly resolved. Since no magnetic anomaly lineation and fracture zone trends have been identified in the vast area of the Enderby Basin, initial seafloor spreading history between India and Antarctica/Australia is still speculative.

*corresponding author (nogi@nipr.ac.jp)

Vector geomagnetic field used in this study have been collected by shipboard three-component magnetometer (STCM; Isezaki 1986) on board the Japanese icebreaker Shirase on her annual cruise between Japan and Antarctica since the 30th Japanese Antarctic Research Expedition (JARE-30) in 1988-1989 in the Southern Indian Ocean. Vector geomagnetic field measurement with STCM has advantage over total intensity measurement with a proton magnetometer in that it allows us to infer the strike of two-dimensional magnetic structures, such as magnetic anomaly lineations and fracture zones, even with single observation line (Seama *et al.* 1993).

Previous studies concerning magnetic anomaly lineations and fracture zones around the West Enderby Basin are summarized as follows. Fracture zone and magnetic anomaly lineation trends have been deduced from the vector magnetic anomaly data from JARE-30 to JARE-33 (1988-1992) in the West Enderby Basin as well as satellite derived gravity anomaly data (Nogi *et al.* 1996). In the east of Gunnerus Ridge, a possible change in the seafloor

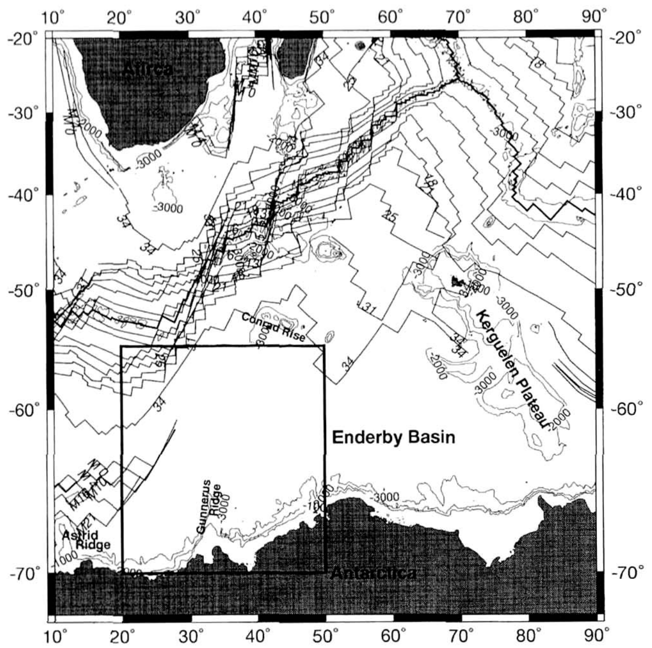

Fig. 1. Isochron data in Southern Indian Ocean (Royer *et al.* 1992) and bathymetric features based on ETOPO5. Isochrons are indicated by thin solid lines labeled with magnetic anomaly number and thick solid lines show the present plate boundaries. Bathymetric features shallower than 3000 m are presented and contour interval is 1000 m. The box indicates the study area.

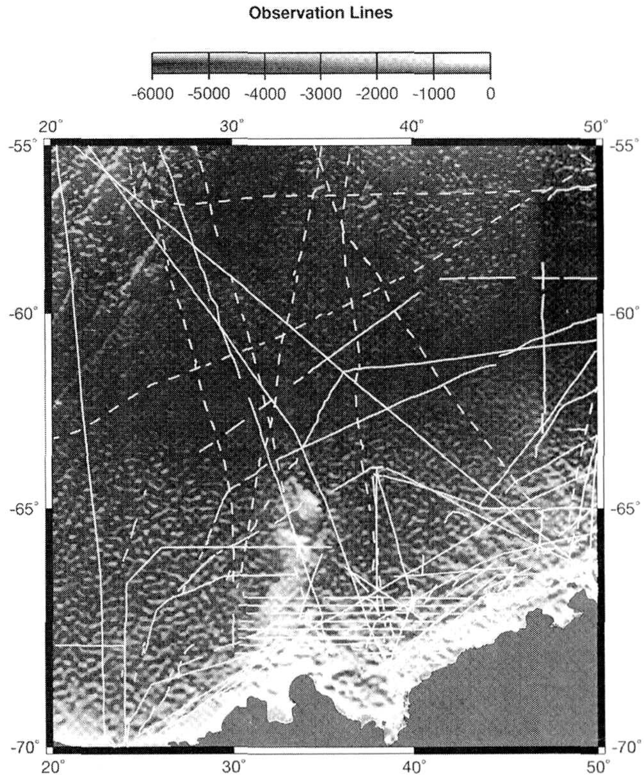

Fig. 2. Observation lines from JARE-30 (1988-1989) to the JARE-39 (1997-1998) (white solid lines) and gray scale image of seafloor topography (Smith and Sandwell 1994). White dashed lines indicate ship tracks, which total intensity magnetic anomalies are obtained from National Geophysical Date Center (1993).

spreading direction occurred from a NW-SE and NNW-SSE trend in the south to a NNE-SSW trend in the north (Nogi *et al.* 1996). The ENE-WSW and E-W magnetic anomaly lineation trends, possibly belonging to the Mesozoic magnetic anomaly lineation sequence, are also reported in the southern part (Nogi *et al.* 1996). Magnetic anomaly No. 34 have been identified around the Conrad Rise (e.g. Schlich 1982; Royer *et al.* 1992). In the east of Astrid Ridge, the WNW-ESE trending magnetic anomaly lineations from M0 to M24 have also been reported (Bergh 1977; Roeser *et al.* 1996).

Previous studies around the West Enderby Basin suggest that oceanic crust created during the long Cretaceous normal polarity chron should be located in somewhere in the West Enderby Basin. Assuming a ridge system with half spreading rate of 10 km Ma^{-1} and using the geomagnetic polarity time scale of Cande and Kent (1995), 700 km width of oceanic crust has to be produced during the long Cretaceous normal polarity chron. The location of the oceanic crust will be the key indicator for seafloor spreading history in the west Enderby Basin.

Vector magnetic anomalies obtained from JARE-30 to JARE39 (1988-1998) were summarized and the results in the West Enderby Basin were presented in this paper. Possible location of the oceanic crust produced during the long Cretaceous normal polarity chron in the West Enderby Basin were also examined. The study area is indicated by the box in Fig. 1 and the observation lines are shown in Fig. 2.

Data and data processing

An outline of the STCM of the icebreaker Shirase is described by Nogi *et al.* (1990). The status of vector geomagnetic field measurements by STCM on board Shirase are also summarized in Nogi and Kaminuma (1999). In this study, we use three components of geomagnetic field obtained by STCM from JARE-30 to JARE39 on board the Shirase in the West Enderby Basin. The raw data were reduced to vector magnetic anomaly fields according to the method of Isezaki (1986).

Relative changes of vector magnetic anomaly fields is reliable, but absolute values are not reliable at present (Isezaki 1986; Nogi *et al.* 1990; Korenaga 1995). To circumvent this problem, three components of magnetic anomalies along the each observation line were simply determined by filtering out long wavelength anomalies (> 500 km) and subtracting linear trend. Total intensity of magnetic anomalies was also obtained from the vector magnetic anomalies.

The strike of two-dimensional magnetic structure can be determined by using vector data of the geomagnetic anomaly field (Seama *et al.* 1993). The position of magnetic boundary is obtained by searching for the peaks of the intensity of the spatial differential vectors (ISDV; Seama *et al.* 1993). The threshold level of the ISDV is taken as 10 nT/km for determining boundaries. Almost all the major peaks in the variations of ISDV may be picked up using 10 nT/km threshold level.

In this study, we eliminated the strikes of magnetic structures with large inclinations. Large inclinations can result from two possible features of the magnetic structure: one possibility is a dipping two-dimensional structure. The other is a magnetic structure that is close to a three-dimensional body. Three-dimensional magnetic structures also have two possible causes: one cause could be a relatively large and complex geological feature such as a seamount. The other possible cause is the coincidence of two-dimensional structures such as where both a fracture zone and a geomagnetic polarity reversal boundary meet. We took the threshold value of inclinations as 10° in order to extract only the two-dimensional magnetic structures.

The two-dimensional magnetic strikes derived from the vector data were divided into two groups based on structural change and magnetic polarity change using the amplitude of ISDV peaks. The two-dimensional magnetic strikes with the ISDV peak amplitudes less than 50 nT/km were classified as structural in origin, and those with the ISDV amplitudes greater than 50 nT/km as due to magnetic polarity change (Nogi *et al.* 1996). The strikes due to magnetic polarity change reveal either magnetic anomaly lineation or fracture zone trend in an area where fracture zones extend over oceanic crust with both normal and reversed magnetization.

Results

X(northward), Y(eastward) and Z(downward) magnetic anomaly profiles are shown in Figs. 3 (a) - (c). Figure 3 (d) show total intensity magnetic anomaly profiles estimated from vector magnetic anomalies as well as those archived in the National Geophysical Date Center, National Oceanic and Atmospheric and Administration (NOAA/NGDC; National Geophysical Date Center 1993). To level total intensity magnetic anomalies obtained from vector magnetic anomalies, the same data filtering procedure as used for the vector magnetic anomalies was applied to total intensity magnetic anomaly data in National Geophysical Date Center (1993).

Large amplitudes of magnetic anomalies greater than about 300 nT with short wavelength (< 15 km) are observed along almost all the observation lines. It is difficult to identify the location of oceanic crust created in the long Cretaceous normal polarity chron from the magnetic anomaly profiles.

The strikes of two-dimensional magnetic structures derived from vector magnetic anomalies are shown on gray scale image of satellite derived gravity anomaly map (Sandwell and Smith 1997) in Fig. 4. These strikes are classified as structural in origin and that due to magnetic polarity change using the amplitudes of ISDV. White cross indicates the strike due to structural in origin and solid cross indicates that due to magnetic polarity change. Most of the strikes of two-dimensional magnetic structure are the structural in origin and they almost coincide with the structural trends from satellite derive gravity anomaly. Furthermore, most of the strikes are almost parallel to the fracture zone trends. However, the strikes due to magnetic polarity change are also found in the various places. These strikes indicate the presence of normal and reversed magnetized

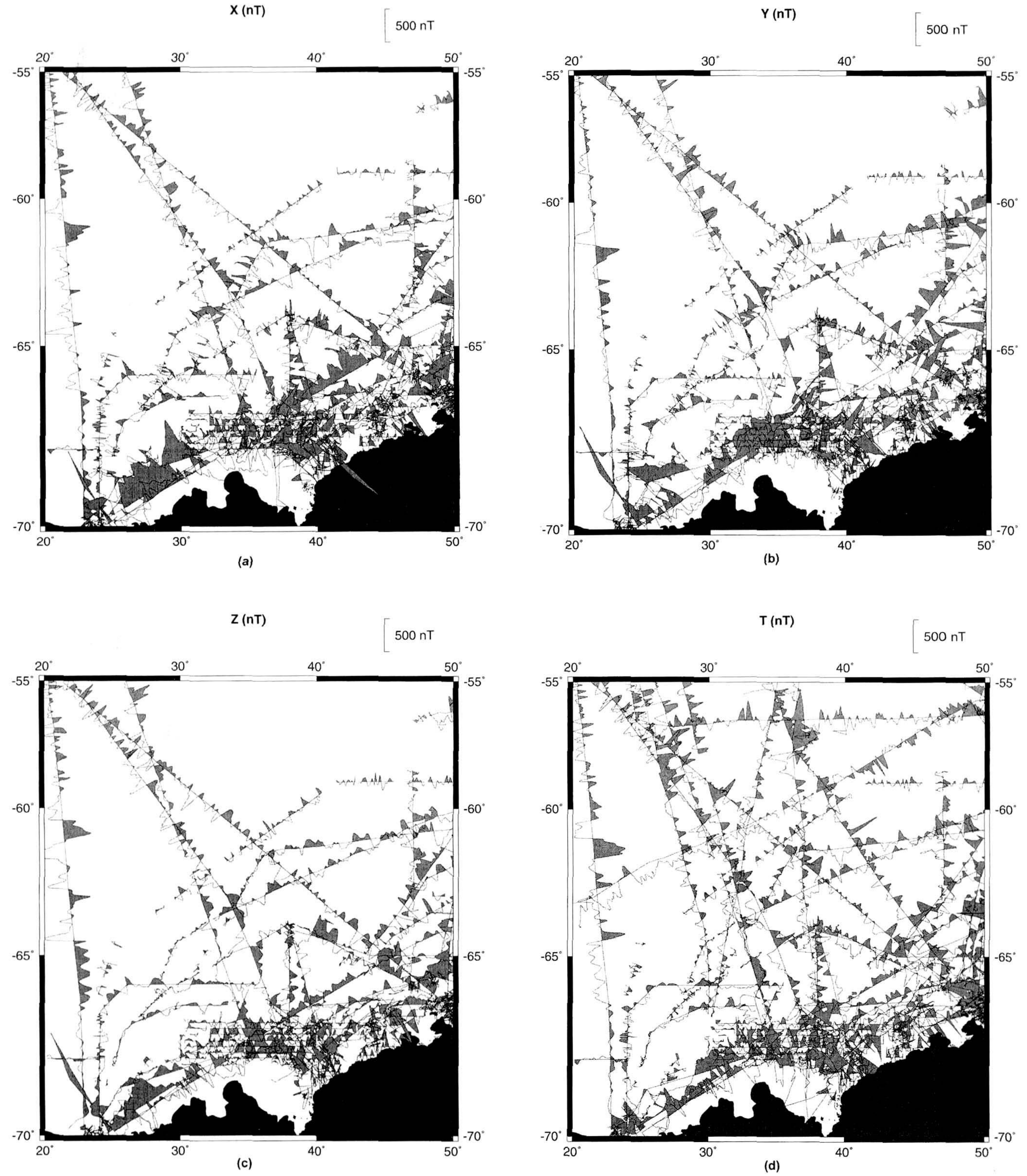

Fig. 3. Profiles of the magnetic anomalies. Positive anomalies are shaded.(a) Profiles of X(northward) component. (b) Profiles of Y(eastward) component. (c) Profiles of Z(downward) component. (d) Profiles of total intensity magnetic anomalies. Those obtained from National Geophysical Date Center (1993) are also plotted.

oceanic crust.

Polarity of magnetization of oceanic crust across the strike due to magnetic polarity change was deduced from the variations of total intensity magnetic anomalies. Positive magnetic anomaly side was assigned as oceanic crust with normal magneti-

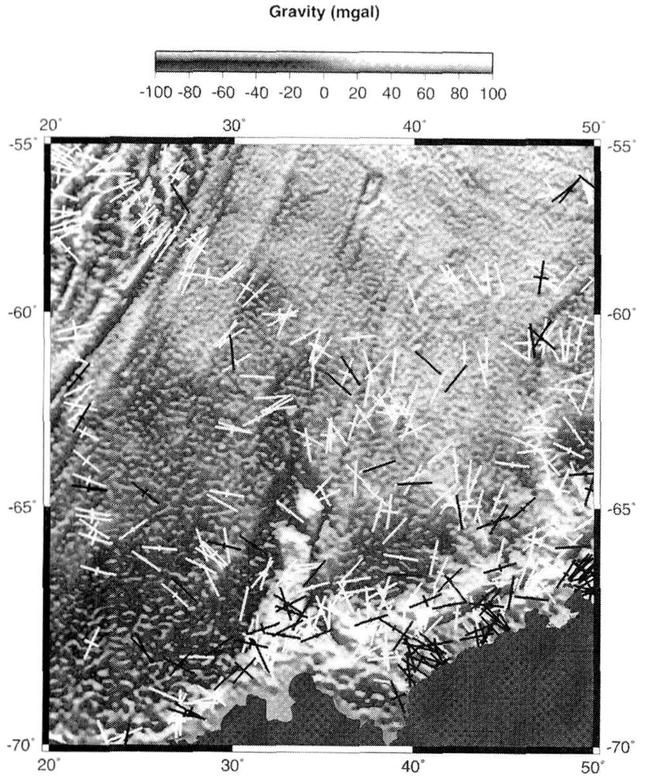

Fig. 4. The strikes of two-dimensional magnetic structures derived from vector magnetic anomalies and gray scale image of satellite derived gravity anomaly map (Sandwell and Smith 1997). Positions (cross) and strike (long line) of magnetic boundaries are shown. The short line of the cross corresponds to twice the standard deviations in the strikes. Black lines indicate the strikes due to magnetic polarity change. White lines show the strikes due to structural in origin.

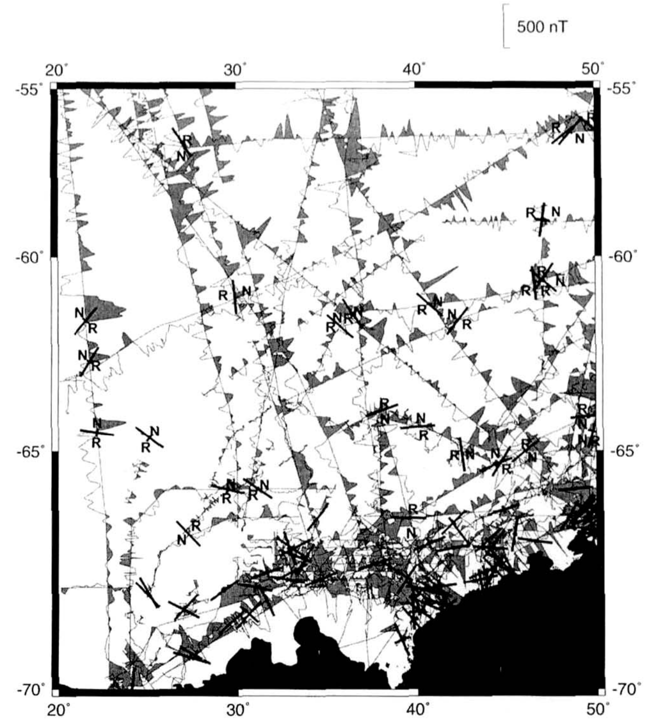

Fig. 5. The strikes of two-dimensional magnetic structures associated with magnetic polarity change (solid lines) and profiles of total intensity magnetic anomalies. Positive anomalies are shaded. N and R indicate normal and reversed magnetized oceanic crust across the magnetic boundaries respectively.

zation and negative anomaly side as that with reversed magnetization. The strikes obtained close to the Antarctic coast and Gunnerus Ridge were not used, because we were dealing with only the strikes due to seafloor spreading in oceanic basin. Polarity of magnetization across the strikes are shown in Fig. 5. The polarity of magnetization is also summarized superimposed on gray scale image of satellite derived gravity anomaly map (Sandwell and Smith 1997) as well as global set of isochron data (Royer *et al.* 1992) in Fig. 6.

In the area A3 in Fig. 6, E-W and ENE-WSW strikes most likely indicate the magnetic anomaly lineation trends and NNW-SSE strike possibly shows the fracture zone trend in an area where fracture zones extend over oceanic crust with both normal and reversed magnetization. NW-SE strikes in the area A2 in Fig. 6 possibly indicate magnetic anomaly lineation trends and N-S and NNE-SSW strikes show the fracture zone trend as observed in satellite derived gravity anomaly map. These results are consistent with the fracture zone and magnetic anomaly lineation trends in the West Enderby Basin suggested by Nogi *et al.* (1996). In the area A1 in Fig. 6, south of Conrad rise, normal and reversed magnetized oceanic crust with NNE-SSW and NE-SW strikes are also found. These areas (the areas A1, A2 and A3 in Fig. 6) at least contain reversed magnetized oceanic crust.

Discussion

Some strikes classified as structural in origin are almost parallel to the strikes of magnetic anomaly lineations (N-S and NNE-SSW directions in the area A2 and E-W and ENE-WSW directions in the area A3 in Fig. 6). One possible cause for these strikes is the structure which is parallel to the ridge axis such as normal fault, and the strikes simply indicate

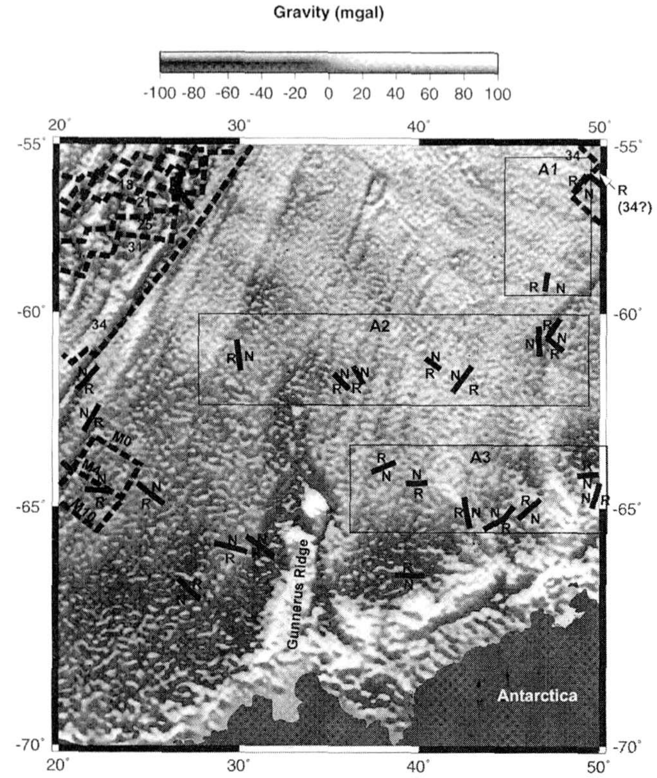

Fig. 6. The strikes of two-dimensional magnetic structures associated with magnetic polarity change (solid lines) and isochron data in Southern Indian Ocean (Royer *et al.* 1992) on gray scale image of satellite derived gravity anomaly map (Sandwell and Smith 1997). Isochrons are indicated by dashed lines labeled with magnetic anomaly number. N and R are same as in Fig. 5. The boxes indicate the areas A1, A2 and A3 described in text.

structural trends. However, the other possibility is magnetic anomaly lineation caused by slow spreading rate. The distance between the boundaries of magnetic polarity change become short due to slow spreading rate and thus some of the magnetized blocks may appear as short polarity interval . In this case, the resolution of ISDV method would become worse (Seama *et al.* 1993) and the amplitudes of ISDV peaks may also be reduced. Therefore, a part of the strikes of structural in origin, which is almost parallel to the magnetic anomaly lineation trends, may indicate magnetic anomaly lineation trends.

Magnetic anomaly lineations obtained in the areas A2 and A3 in Fig. 6 belong to the Mesozoic magnetic anomaly sequence. Magnetic anomaly No. 34 have been identified around Conrad Rise (e.g. Schlich 1982; Royer *et al.* 1992). In the east of Astrid Ridge, WNW-ESE trending magnetic anomaly lineations from M0 to M24 have been reported (Bergh 1977; Roeser *et al.* 1996). The origin of the Kerguelen plateau are considered to be hot spot. The Southern Kerguelen Plateau was formed before or during Albian time (114 ± 1 Ma) (Leclaire *et al.* 1987; Whitechurch *et al.* 1992). Oceanic basin near the Southern Kerguelen Plateau have to be formed before or during the formation of the Southern Kerguelen plateau. Paleomagnetic results of the South Kerguelen Plateau basalts suggest that no major relative tectonic movement took place between the Kerguelen Plateau and Antarctica since formation of the basalts (Inokuchi and Heider 1992). It is inconvincible that seafloor spreading occurred after chron 34 in the West Enderby Basin. These indicate the magnetic anomaly lineations in the West Enderby Basin belong to the Mesozoic magnetic anomaly sequence.

In the south of the Conrad rise, reversed magnetized oceanic crust possibly indicate the Mesozoic magnetic anomaly sequence. In the area A1 in Fig. 6, the two-dimensional magnetic structures associated with magnetic polarity change can be recognized. In the north of the area A1, WNW-ESE strikes with magnetic polarity change possibly indicate magnetic anomaly No. 34, although the strike shift northward to global isochron data from Royer *et al.* (1992). N-S and NNW-SSE strikes in the area A1 also show two-dimensional magnetic structures associated with magnetic polarity change and, in the west of these strikes, reversed magnetized oceanic crust are found. These strikes are obtained in the south of the area where magnetic anomaly No. 34 is identified. Therefore reversed magnetized oceanic crust in the south of the Conrad Rise should be formed before the long Cretaceous normal polarity chron. We interpret that reversed magnetized oceanic crust with N-S and NNW-SSE strikes in the south of the Conrad Rise also belong to the Mesozoic magnetic anomaly sequence.

Reversed magnetized oceanic crust in the south of Conrad Rise implies that ridge reorganization occurred before or during the long Cretaceous normal polarity chron. If a ridge system formed immediately after the breakup of Gondwana and succeeded until chron 34, oceanic crust formed during Cretaceous normal polarity chron could exit just south of the Conrad Rise. However, reversed magnetized oceanic crust are found in the area A1 in Fig. 6 and these possibly belong to the Mesozoic magnetic anomaly sequence. Ridge reorganization is necessary to explain the reversed magnetized oceanic crust just south of Conrad Rise. The strikes of the two-dimensional magnetic structures in the area A1 show N-S and NNW-SSE directions. WNW-ESE trending structural trends can be recognized from a satellite derive gravity anomaly map in the south of the Conrad Rise, although origin of these structural trends is unknown. N-S and NNW-SSE strikes in the area A1 are almost perpendicular to these structural trends. If the WNW-ESE structural trends are fracture zone trends, N-S and NNW-SSE strikes in the area A1 indicate magnetic anomaly lineation trends. WNW-ESE trending structural trends in the south of the Conrad rise are similar to the structural trends obtained in the east of Gunnerus Ridge near Antarctic Continent (Nogi *et al.* 1996). Moreover, in the east of Gunnerus Ridge, a change in the seafloor spreading direction is indicated, from a NW-SE and NNW-SSE trend in the south to a NNE-SSW trend in the north (Nogi *et al.* 1996).

WNW-ESE structural trends in the south of Conrad Rise may indicate fracture zone trends formed by the same ridge system which created NW-SE and NNW-SSE fracture zone trends east of the Gunnerus Ridge near the Antarctic Continent and then following seafloor spreading history in the West Enderby Basin are proposed. First stage, NW-SE and NNW-SSE directional seafloor spreading were occurred east of the Gunnerus Ridge near the Antarctic Continent since before the long Cretaceous normal polarity chron immediately after the breakup of Gondwana. Second, NNE-SSW directional seafloor spreading evolved north of the Gunnerus Ridge before the long Cretaceous normal polarity chron. This new ridge system divided into two plates formed by NW-SE and NNW-SSE directional seafloor spreading. The north side of the plates which was divided into two plates was trapped by this new ridge system. Third, the trapped plate was shifted northward by NNE-SSW directional seafloor spreading to the present position of the Conrad Rise before or during the long Cretaceous normal polarity chron. Finally, ridge reorganization reoccurred and ridge axis jumped to the north of the Conrad Rise before or during chron 34.

Ridge reorganizations may prevent us from inferring the location of oceanic crust produced during the long Cretaceous normal polarity chron. If the seafloor spreading history in the West Enderby Basin which is mentioned above is correct and the ridge reorganizations occurred during the long Cretaceous normal polarity chron, oceanic crust formed in the long Cretaceous normal polarity chron may be divided into some segments, at least two segments. The Mesozoic magnetic anomaly sequence which accompanied with reversed magnetized oceanic crust are observed in the area A1, A2 and A3 in Fig. 6. These suggest that ridge reorganizations in the West Enderby Basin occurred during the long Cretaceous normal polarity chron. The location of oceanic crust formed during the long Cretaceous normal polarity chron may be difficult to identify by segmentation of oceanic crust due to ridge reorganization in the long Cretaceous normal polarity chron.

Conclusions

Two-dimensional magnetic strikes associated with magnetic polarity change can be observed in various places in the West Enderby Basin. Magnetic anomaly lineation trends belonging to Mesozoic magnetic anomaly sequence are also found. However, the location of the oceanic crust created in the long Cretaceous normal polarity chron can not be identified. Ridge reorganizations during the long Cretaceous normal polarity chron are suggested by two-dimensional magnetic strikes associated with magnetic polarity change and structural trends in the West Enderby Basin. However, the location of oceanic crust produced during the long Cretaceous normal polarity chron may be difficult to identify because of ridge reorganizations in the long Cretaceous in the West Enderby Basin.

Acknowledgment

The authors thank the JARE members and crews of the icebreaker Shirase for their kind help during operations from JARE-30 to JARE-39. Y. N. thanks Prof. N. Isezaki and Dr. N. Seama , Chiba University, for numerous discussion.

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Received 23 July 1999
Accepted 18 September 1999