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Magnetic anomaly lineations from Late Jurassic to Early Cretaceous in the west-central Pacific Ocean

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SUMMARY

Late Jurassic to Early Cretaceous (Mesozoic) magnetic anomaly lineations (the Phoenix, Magellan, Mid-Pacific Mountains, Hawaiian and Japanese lineation sets) with fracture zones in the west-central Pacific Ocean were identified more comprehensively than in any previous studies. We fixed 2100 positions of identified magnetic anomalies based on magnetic data of 283 cruise tracks. Two remarkable fracture zones, the Phoenix and Central Pacific Fracture Zones, were mapped and newly named. Our newly identified lineations from M10N to M0 around the Mid-Pacific Mountains, which belong to the Hawaiian lineation set, illustrated that the sea-floor south of the Mid-Pacific Mountains has the same age as that of the north (132–118 Ma). Our analysis of skewness parameters revealed that the older part of the Phoenix set (M17–M29) has skewness different from that of the younger part (M1–M14), implying an effect of magnetic overprints by the Cretaceous volcanism. It was confirmed that the spreading rate of the Mesozoic Pacific spreading system was the fastest in the world in the Mesozoic. A drastic change in spreading rates occurred simultaneously at the period between chrons M21 and M20 (149.5–148.5 Ma) in all the Mesozoic Pacific spreading systems. The event appears to be synchronous with events in other oceans such as the Mesozoic Atlantic and Indian Oceans.

Key words: fracture zone, Late Jurassic to Early Cretaceous (Mesozoic), Mesozoic magnetic anomaly lineation, skewness parameter, spreading rate, west-central Pacific Ocean.

INTRODUCTION

The spreading history of the Pacific plate is revealed by studying magnetic anomaly lineations that chronicle the evolution of the sea-floor. It is well known that there exist Mesozoic (Late Jurassic to Early Cretaceous) lineations in the northwestern Pacific Ocean. Several previous works (e.g., Hilde, Isezaki & Wageman 1976; Sager *et al.* 1988; Handschumacher *et al.* 1988; Tamaki & Larson 1988) repeatedly revised or newly identified Mesozoic lineations in the northwestern Pacific Ocean since Larson & Chase (1972) first identified them. Cande *et al.* (1989) published a map of lineations in the world by compiling previous works. However, no substantial revision of the Mesozoic lineations in the whole northwestern Pacific Ocean has recently been attempted, although available magnetic data are greatly increasing.

Utilizing all available data, we have precisely identified the Mesozoic magnetic anomaly lineations in the whole northwestern Pacific Ocean. Revised lineations in the northwestern Pacific Ocean, the Japanese and Hawaiian lineation sets, were already published (Nakanishi, Tamaki & Kobayashi 1989). We have further extended our identification of Mesozoic lineations southward. As a result, the whole view of the Mesozoic magnetic anomaly lineations in the northwestern Pacific Ocean was revealed. In this article we will describe the results of our identification in the west-central Pacific Ocean and discuss some of their implications (e.g., skewness parameters and spreading rates).

DATA AND METHODS

Geophysical data incorporated in this study consist of 283 cruises including all the available National Oceanic and Atmospheric Administration/National Geophysical Data Center (NOAA/NGDC) cruise data updated in April 1990 (267 cruises). Unpublished cruise data which we newly compiled for this study are composed of six cruises of the Ocean Research Institute, University of Tokyo (ORI) in the

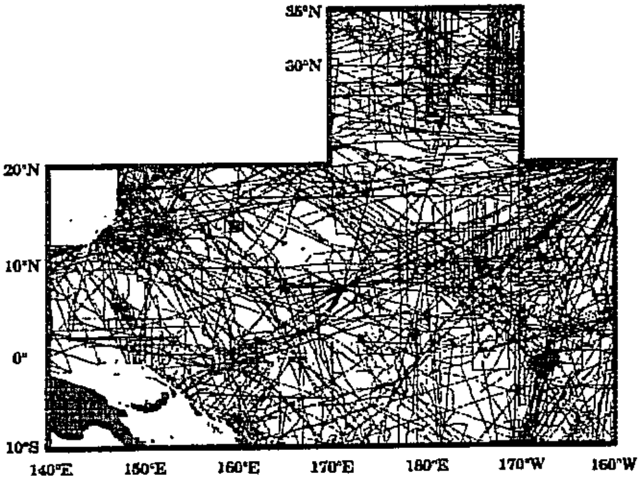

Figure 1. Ship's tracks of 283 cruises with magnetic data in the west-central Pacific Ocean treated in this study. A list of the cruises is shown in Table 1.

period of 1973–1989, one cruise of R/V *Kagoshima-maru* by Kobe University, one cruise of R/V *Tokaidaigaku-maru II* by Tokai University, four cruises by Geological Survey of Japan (GSJ) (Nakanishi, Yamazaki & Ishihara 1992b) and four cruises from Scripps Institution of Oceanography/University of California San Diego (SIO/UCSD).

Tracks of all the cruises are shown in Fig. 1 and listed in Table 1. The term of data spans 30 years from 1960 to 1989. Their density is higher in the eastern half of the studied area than in the western half because of the proximity of ports in Hawaii. Data are diverse in regions west of the Marshall and Gilbert Islands and east of the East Mariana Basin.

Bathymetric data were used as well as magnetic data to fix the positions of fracture zones. The sea-floor in the studied area is mostly flat except for several topographic features such as the Magellan Rise, the Ontong Java Plateau, Line Islands and Mid-Pacific Mountains (Fig. 2). As most of the flat areas are covered with thick (~400 m) sediments (Ludwig & Houtz 1979), we identified fracture zones on seismic reflection profiles as well as bathymetric data. The

Table 1. Inventory and sources of data used for this study.

Institution	Number of Cruises	Data List (Total 283 Files)
Ocean Research Institute, University of Tokyo	21	GDP19, KH67-5, KH68-3, KH68-4-A, KH68-4-D, KH70-2, KH71-4, KH73-4 KH74-2, KH76-1, KH79, KH80-3, KH82-5, KH87-3, KH89-2, UM6402-A, UM64-2-C, UM65-3-A, UM65-3-B, UM66-A, UM67
Geological Survey of Japan	15	GH7405, GH7601, GH7701, GH7801, GH7901, GH801-A, GH801-B, GH805-A, GH805-B, GH814-A, GH814-B, GH824-A, GH824-B, GH833-A, GH833-B
Kobe University	1	KG8101
Tokai University	1	TU8520
Canadian Hydrographic Service	1	PZ72000
Defence Map. Ag.	5	10075, 03973, 17477, 26180, 27474
Hawaii Institute of Geophysics	63	66102601, 66102602, 67102100, 70042201, 70042202, 70042203, 70042204, 70042205, 71042601, 71042602, 71042605, 72110801, 72110808, 73102500, 75072600, 76010301, 76010302, 76010303, 76010304, 76080601, 76080602, 77031701, 77031702, 77031703, 77031704, 77031705, 77031706, 78050400, 78100300, 79080801, 79102901, 80041401, 80041402, 80101002, 81062603, 81062605, 82031601, 82031602, 82031605, 83011602, 83011603, 83011604, 83011605, 84042805, 8516TR, 8612, CK-80-1, CK80-2, KI-80-1, KI81-1, KI81-2, KI81-3, MW8807, MW8808, MW8813, MW8902, PN79-1, PN81-1, PN81-2, SI-79-1, SI81-1, SI81-2, SI81-3
IFREMER (France)	2	85002211, 85002811
Lamont-Doherty Geological Observatory	37	C1006, C1007, C1107, C1204, C1205, C1211, C1301, C1304, C1305, C1712, C2003, C2004, C2006, C2010, ELT30, ELT31, V1907, V2005, V2006, V2105, V2404, V2405, V2407, V2811, V2813, V2814, V3212, V3214, V3312, V3313, V3401, V3403, V3506, V3603, V3610, V3611, V3612
Naval Oceanographic Office	8	SI932005, SI932009, SI933010, SI343722, SI932003, SI343520, SI343613, SI343615
NOAA/NOS	8	CMAPPI5D, CMAPSU5D, CMAPSU6E, CMAPPI6W, CMAPSU6W, CMAPSU7E, CMAPSU7W, CMAPPI7E
NOAA/POL	6	POL6365, POL6501, POL6829, POL6971, POL7004, POL7201
NOAA/U.S. Coast and Geodetic Survey	1	HOECGS
Oregon State University	1	YAQ701
Scripps Institution of Oceanography	90	7TOW06WT, 7TOW3BWT, ANTP14MV, ANTP17MV, ARES04WT, ARES05WT, ARES07WT, BNTH04MV, CATO03MV, CIRC02AR, CRON03WT, DSDP06GC, DSDP07GC, DSDP08GC, DSDP17GC, DSDP20GC, DSDP30GC, DSDP32GC, DSDP33GC, DSDP55GC, DSDP60GC, DSDP61GC, DSDP62GC, DSDP86GC, DSDP89GC, ERDC02WT, ERDC07WT, ERDC09WT, ERDC10WT, ERDC11WT, GECS-BMV, GECS-DMV, GECS-EMV, GECS-FMV, INDP01WT, INDP02WT, INDP03WT, INDP05WT, INDP08WT, INDP09WT, INDP10WT, INDP14WT, JPYN02BD, LUSI01AR, LUSI06HO, LUSI07HO, MARA03WT, MARA05WT, MARA06WT, MARA07WT, MARA08WT, MARA09WT, MARA11WT, MONS01AR, MRTN05WT, NOVA01AR, NOVA02AR, NOVA03AR, NOVA06HO, NOVA09AR, NOVA1AHO, PPTU08WT, PROA3ABD, PROA3BBD, RAMA02WT, RAMA04WT, RAMA05WT, RAMA12WT, RAMA13WT, RNDB10WT, RNDB11WT, RNDB12WT, RNDB13WT, SCAN03AR, SCAN04AR, SCAN05AR, SIXP-1HO, SOTW10WT, SOTW11WT, SOTW12WT, STYX02AZ, STYX03AZ, STYX04AZ, STYX05AZ, STYX06AZ, STYX07AZ, STYX08AZ, STYX09AZ, TETH02BD, TSDY03WT, TSDY08WT, ZTES05AR
South of China Sea Sub-Bureau (China)	3	X05761, X05772, X05783
Texas A&M University	1	ODP124EJ
University of Rhode Island	1	RC2610
University of Washington	1	TT-208
USGS Branch Pacific Marine Geology	17	G179NP, L583HW, L682SP, L782SP, L876NP, L882NP, L884SP, L984CP, DME05-B, DME06, DME09, DME18, DME21, DME24, DME28, V149, VIT51

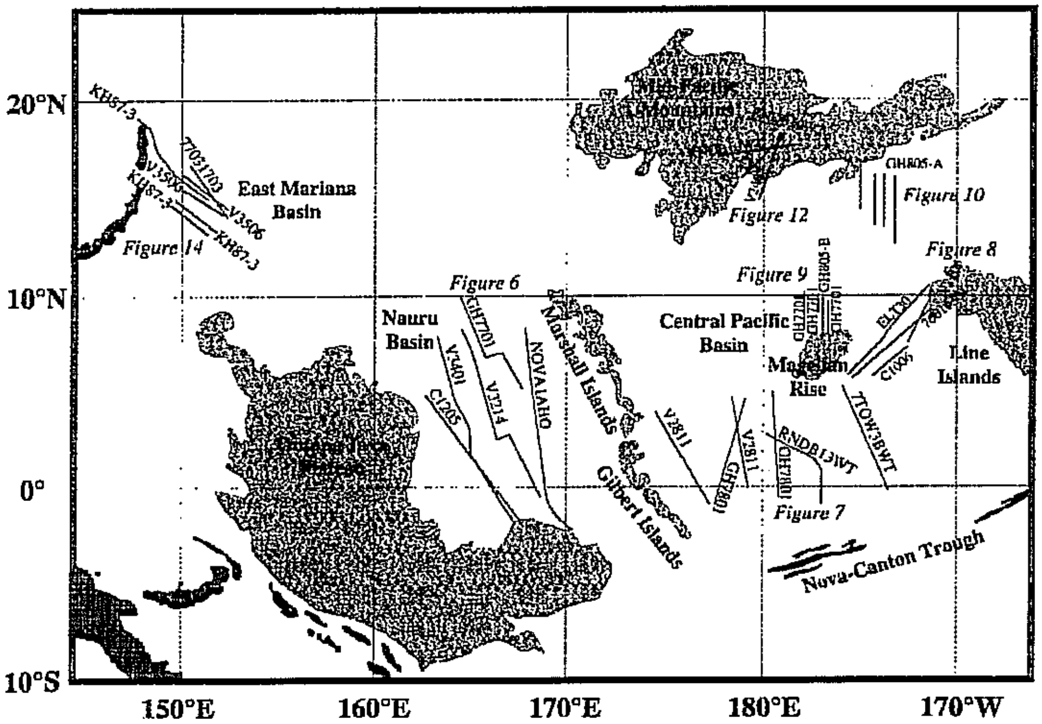

Figure 2. Names of major topographic features in the studied area shown on the 4000 m, 5000 m and 7000 m GEBCO bathymetric contours. Locations of magnetic anomaly profiles used in this article are shown with cruise codes.

seismic data used in this study were 28 cruises from NGDC and one cruise by SIO/UCSD (RNDB10WT).

Magnetic anomalies were calculated referring to the International Geomagnetic Reference Field 1985 (IGRF; IAGA Division I Working Group 1 1985). The geomagnetic reversal time-scale used in this study is that proposed by Kent & Gradstein (1985) with a modification by Tamaki & Larson (1988). The procedure used for identification of magnetic anomaly lineation is essentially the same as those adopted by previous workers, although our method, digitization of magnetic anomalies with assigned age, is new and believed to be the most accurate with positioning of lineations. The detailed procedure was as described in Nakanishi *et al.* (1989). Fig. 3 shows an example of magnetic

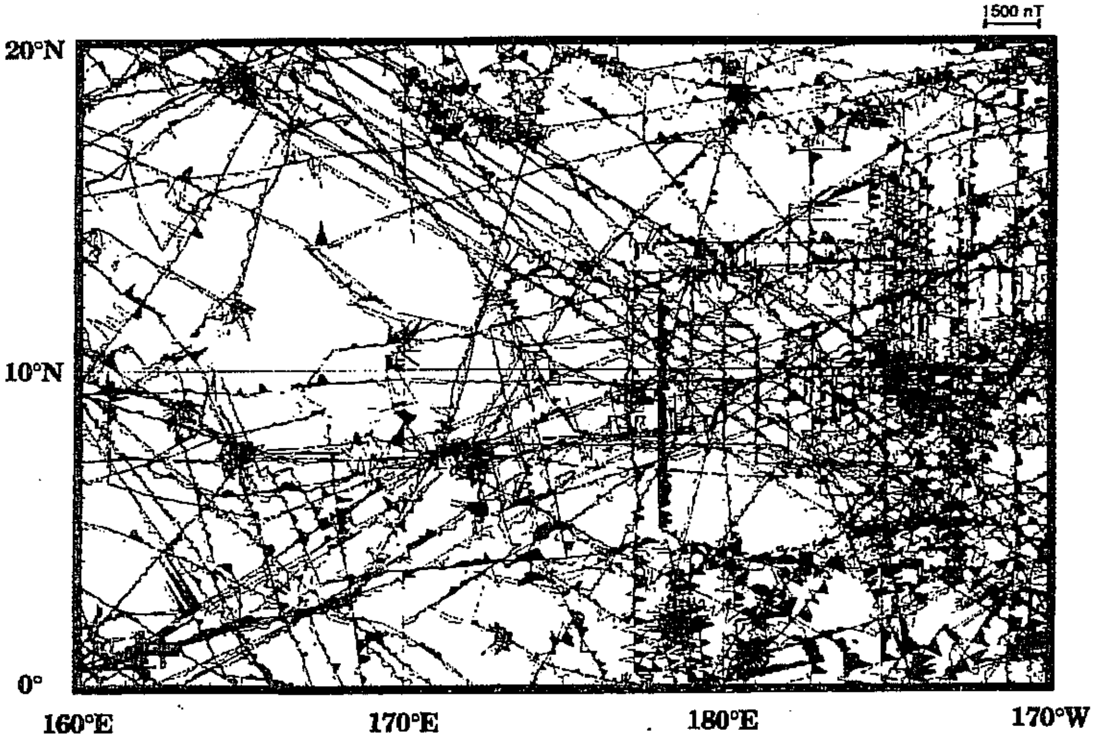

Figure 3. Magnetic anomaly profiles along the ship's tracks in the central portion of the area studied. Scale bar at the top right indicates the amplitude of magnetic anomalies. Positive anomalies are shaded.

anomaly profiles plotted perpendicular to the ship's tracks in the central portion of the studied area. Positive anomalies on the profiles are shaded.

PATTERNS OF LINEATIONS

Fig. 4 illustrates the Mesozoic magnetic anomaly lineations we identified. We fixed about 2100 position of identified magnetic anomalies based on magnetic data of 283 cruises. It has been known that five Mesozoic magnetic anomaly lineation sets exist in the west-central Pacific Ocean; the Phoenix, Magellan, Mid-Pacific Mountains, Hawaiian and Japanese lineation sets. An increased number of cruise files and a new method of analysis have made our results more precise than previous studies. The major configuration of the Mesozoic lineation sets was represented in our chart. Mapping of lineations was particularly improved in the following areas: around the Mid-Pacific Mountains, in the

Figure 4. Summary map of Mesozoic magnetic anomaly lineations and fracture zones in the whole northwestern Pacific Ocean. Heavy solid lines are the lineations identified with M numbers. Anomalies are numbered in accordance with the Mesozoic magnetic anomaly sequence of Larson & Hilde (1975), Cande, Larson & LaBrecque (1978), Handschumacher & Gettrust (1985) and Tamaki & Larson (1988). Positions of fracture zones are indicated with solid lines. The 4000 m, 5000 m and 7000 m GEBCO bathymetric contours are shown for reference.

East Mariana Basin, east of the Ontong Java Plateau and around the Magellan Rise.

Fracture zones are clearly identified at 200 points on the bathymetric and seismic reflection profiles. We propose here nomenclatures of two remarkable fracture zones in the studied area; the Phoenix Fracture Zone and the Central Pacific Fracture Zone in addition to three fracture zones in the northwestern Pacific Ocean (Kashima, Nosappu and South Shatsky Fracture Zones) named previously (Nakanishi *et al.* 1989; Nakanishi 1990). The Phoenix Fracture Zone, which is mostly equivalent to the F.Z.-2 by Larson (1976), has the most remarkable topographic feature among those of the Phoenix lineation set. Its topographic expression is a trough bounded by ridges, which is similar to that of the Kashima Fracture Zone. The maximum height of ridges is 3000 m. The horizontal offset of older lineations than M20 is nearly 600 km, which is about half of that in the Mendocino Fracture Zone in the northeastern Pacific Ocean. The Central Pacific Fracture Zone is situated in the Central Pacific Basin east of the Phoenix Fracture Zone. It had been identified only from offsets of magnetic anomaly lineations (Larson 1976) until we confirmed its existence with bathymetric and seismic reflection data. Its topographic expressions are a ridge with a scarp. The maximum height of ridges is 1000 m. The horizontal offset is nearly 150 km.

Phoenix lineation set

The Phoenix lineation set is distributed in the Nauru and Central Pacific Basins. The area is bounded by the Ontong Java Plateau, Nova-Canton Trough, Line Islands and Mid-Pacific Mountains (see Fig. 2 for location of major topographic elevations). We newly established lineations in the northeastern part of the Ontong Java Plateau and west of Gilbert Islands, while lineations in the other areas were revised or carefully reconfirmed. Ages of identified lineations in the Phoenix lineation set range between chrons M29 and M1 (160–123 Ma). We successfully drew lineations older than M29, but could not assign M numbers to them (Fig. 5).

In the Nauru Basin, lineations from M29 to M10N were identified. Fig. 6 shows selected magnetic anomaly profiles projected approximately perpendicular to the lineations in the Nauru Basin. The maximum peak-to-peak amplitude of anomalies in the Nauru Basin is nearly 400 nT and amplitudes prior to chron M26 are less than 100 nT. Amplitudes of anomalies west of the Marshall and Gilbert Islands increase from 100 to 500 nT as ages become younger. Those between Marshall Islands and Phoenix Fracture Zone are about 300 nT. In the area from east part of the Nauru Basin to the Marshall Islands no lineations from M24 to M19 have been identified yet, probably because there are no tracks trending perpendicular to that of lineations. No lineations appear to exist over the Ontong Java Plateau except for northeastern part of the plateau, whereas lineations were found over the Shatsky Rise.

Lineations M24 to M1 were identified in the Central Pacific Basin (Fig. 7). Amplitudes range from 500 to 1000 nT. There exists a large gap between M20 and M14 in an area east of the Phoenix Fracture Zone where no lineations can be identified (Fig. 5). It is remarkable that the amplitudes from M10N and M1 are so large (about 1000 nT).

Larson & Sager (1991) indicated a possibility that there is a sequence of lineations from M22 to M25 south of the Mid-Pacific Mountains; this is backwards with respect to our sequence. The reversal sequence was identified by only one track. However, our data set indicates that there is a seamount on the sea-floor under the anomalies identified as M23 and M24 by Larson & Sager (1991) that is not mapped in any bathymetric chart. We concluded that the anomalies were due to the seamount and that the reversal sequence by Larson & Sager (1991) was excluded. Moreover, there are no Mesozoic magnetic lineations west of the Mid-Pacific Mountains (Nakanishi *et al.* 1992b). Thus, we rejected the possibility of the existence of the Stealth plate proposed by Larson & Sager (1991).

The Phoenix lineation set has several predominating strikes. Those of lineations in the Nauru Basin west of the Marshall Islands are N65°E from M29 to M18 and N70°E from M17 to M1. Those between the Marshall Islands and Phoenix Fracture Zone are N65°E from M29 to M22A, N70°E from M22A to M18 and N75°E from M18 to M1. Those between the Phoenix and Central Pacific Fracture Zones are N65°E from M24B to M20 and N75°E from M14 to M1. Those of lineations east of the Central Pacific Fracture Zone gradually change from N80°E to N85°E between M10N and M9 but remain constant as N75°E from M8 to M1.

There exist lineations with strike of NE–SW, which are surrounded by the Phoenix, Hawaiian and Magellan lineation sets, although we could not assign their ages. Bathymetry in this area is extremely rough. The strike of the lineations is not the same as those of any other adjacent lineation sets. This implies that an unknown plate boundary, that is, an unknown microplate, once existed near the junction among the Pacific, Farallon and Phoenix plates.

No Mesozoic magnetic anomaly lineations are seen immediately south of the lineation M1. Chron M0 was not identified in an area south of M1. There lies a peculiar topographic feature called the Nova-Canton Trough that is apparently like a fracture zone. This deep lineated crack is nearly parallel to the Phoenix lineation set. Larson, Smith & Chase (1972) claimed that the Nova-Canton Trough is an extension of the Clipperton Fracture Zone situated east of this trough. On the other hand, Rosendahl *et al.* (1975) and Winterer (1976) postulated that this trough is an abandoned Pacific–Phoenix Ridge. Joseph *et al.* (1990) suggested based on the side-scan data that the Nova-Canton Trough originated from a fracture zone in its east. They show that strike of the tectonic fabric north of this trough is N67°E and that of its south is N42°W. We infer that a reorganization of the Pacific–Phoenix Ridge from which the Phoenix lineation set was formed occurred between chrons M1 and M0 which may probably be correlatable to the origin of this trough. A reversed sequence from M3 (south) to M1 (north) exists with repeated appearance of M1 in an area near the Gilbert Islands. Similar conjugate lineations from M1 to M3 have been obtained by R. Jarrard (personal communication, 1990). It appears to have resulted from a plate reorganization at the period from chron M1 to chron M0 (Nakanishi *et al.*, in preparation).

Taylor (1978) identified lineations from M12 to M19 in the Lyra Basin west of the Ontong Java Plateau. His identification indicated that the age of the sea-floor west of the Ontong Java Plateau is the same as that of its east.

Figure 5. Mesozoic magnetic anomaly lineations (the Phoenix, Magellan, Mid-Pacific Mountains, and Hawaiian lineation sets) with fracture zones in the central Pacific Ocean. The 4000 m, 5000 m and 7000 m GEBCO bathymetric contours are shown for reference.

However, our identification suggests that the age of the sea-floor west of the Ontong Java Plateau is not the same as that east of the plateau. Recently, Mahoney & Spencer (1991) proposed that the origin of the Ontong Java Plateau is a sequence of ridge migration or rift propagation, which may result in synchronous distribution of ages relative to the plateau. Our identification could not confirm whether their proposal is correct. Further magnetic surveys on and around the Ontong Java Plateau and more detailed analysis will expose its origin.

Magellan lineation set

This lineation set was first discovered by Tamaki, Joshima & Larson (1979) and revised by Tamaki & Larson (1988). The present study further revised their identification. Selected anomaly profiles in a region east of the Magellan Rise are shown in Fig. 8. The Magellan Trough is situated along double lineations M9 (Tamaki & Larson 1988). Peak-to-peak amplitudes of magnetic anomalies north of the Magellan Trough (700 nT) are larger than those in its south (400 nT). Amplitudes south of the Magellan Trough decrease with decreasing ages. Strikes of the northern lineations of the Magellan Trough change from E–W to N45°W. Those of the southern lineations vary from N20°W to N45°W.

In the eastern part of the Central Pacific Basin situated east of the Phoenix lineation set, we identified the Magellan lineations from M11 to M1. Strikes of the lineations are N55°W, N40°W and N35°W. Orwig & Kroenke (1980) indicated that there were magnetic anomalies with strike of E–W in this area. They concluded that the sea-floor in the eastern part of the Central Pacific Basin was spreading from 100 to 85 Ma (Late Cretaceous). Ishihara & Yamazaki

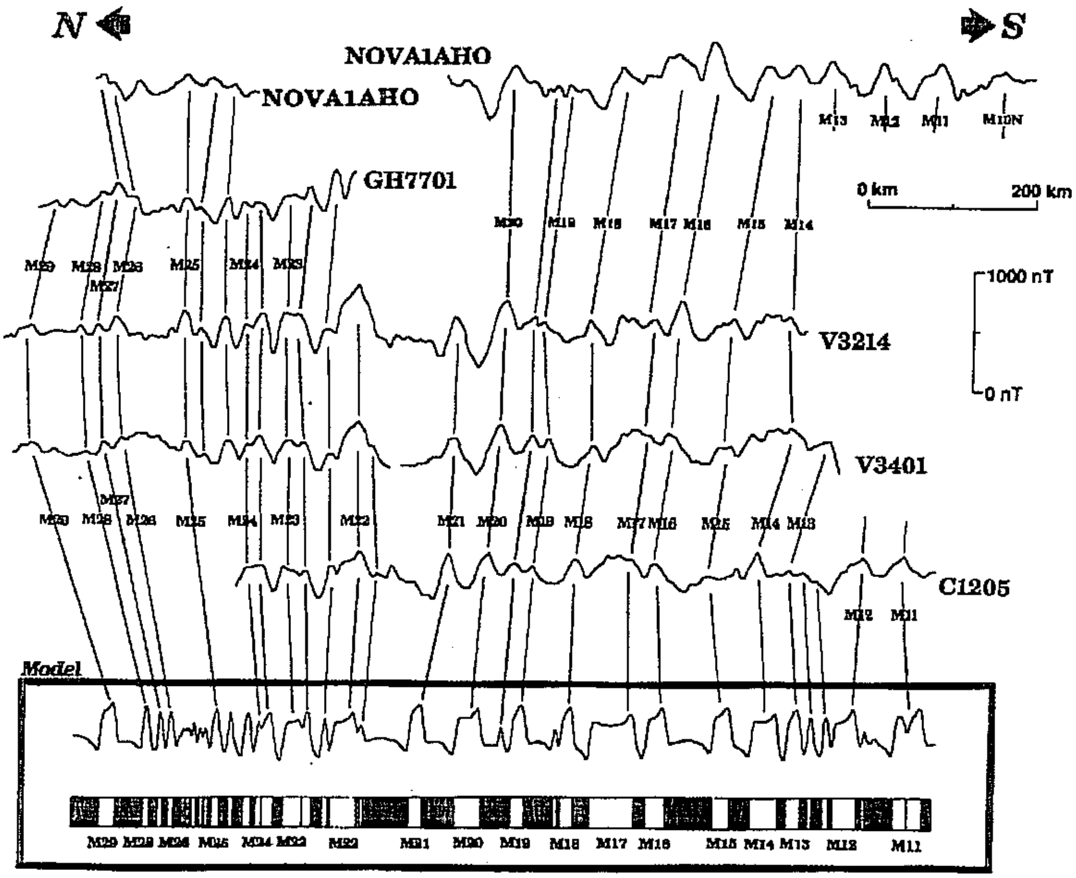

Figure 6. Selected magnetic anomaly profiles of the Phoenix lineation set in the Nauru Basin projected normally to the lineations and arranged from east (top) to west (bottom). The annotations of the magnetic profiles indicate cruise codes. The magnetic reversal sequence is from Larson & Hilde (1975) and Cande *et al.* (1978). Normally magnetized blocks are solid black. The skewness parameter for calculation of the model profile is −160°. FZ shows a fracture zone indicated by dashed lines.

(1986) tentatively identified lineations M4 and M3 trending NW–SE in this area. Our identification is similar to the identification by Ishihara & Yamazaki (1986), but does not agree with that by Orwig & Kroenke (1980). The sea-floor west of the Line Islands is older than the islands in a similar manner to the Central Pacific Basin (Early Cretaceous).

Lineations west of the Magellan Rise were revised and extended from M21 to M12 (Fig. 9). Lineations from M19 to M15 identified by Tamaki & Larson (1988) are younger southward, but those in the present identification are reversed and older southward. Their strikes gradually change from E–W (M21) to N40°W (M12). The strike of lineation M12 (N40°W) in them is the same as that of M12 in the Hawaiian lineation set. There exist lineations M20 and M21 trending E–W on the Magellan Rise. The basement surface of the Magellan Rise has considerably rough relief. Its basement highs are interpreted to be E–W trending narrow ridges. It seems likely that the Magellan Rise was formed near the ridge causing the E–W lineations. Palaeontological evidence based on shipboard study of the DSDP site 167 samples in the Magellan Rise gave an age of the oldest sediment to be either Berriasian or Tithonian (Winterer *et al.* 1973). This age, 140–150 Ma, corresponds to a period between chrons M16 and M21 and is consistent with our identification.

Mid-Pacific Mountains lineation set

The Mid-Pacific Mountains lineation set was named by Tamaki & Larson (1988), as it is surrounded by the Mid-Pacific Mountains and the Line Islands (Fig. 10). Lineations older than M12 are very short, whereas lineation M11 is long. We newly identified lineations near the Magellan Rise, in the area surrounded by the Magellan and Mid-Pacific Mountains lineation sets. The oldest lineation is M14, although a few lineations may exist in the area older than M14.

We found that strikes of the Mid-Pacific Mountains lineation set have two predominant directions, although Tamaki & Larson (1988) identified it with only one strike. Strikes of lineations south of the Mid-Pacific Mountains gradually change from N135°W to N70°W from M14 to M11, whereas they are constant at N55°W after M11. The strike of lineation north of the Line Islands is N45°W. Lineations younger than M10 existing between latitudes 174°W and 170°W were found to be different from the results of previous identification. For instance, we identified lineation M10 that was identified as M10N by Tamaki & Larson (1988). We could not confirm the existence of lineation M0 near the Line Islands which was identified by Tamaki & Larson (1988).

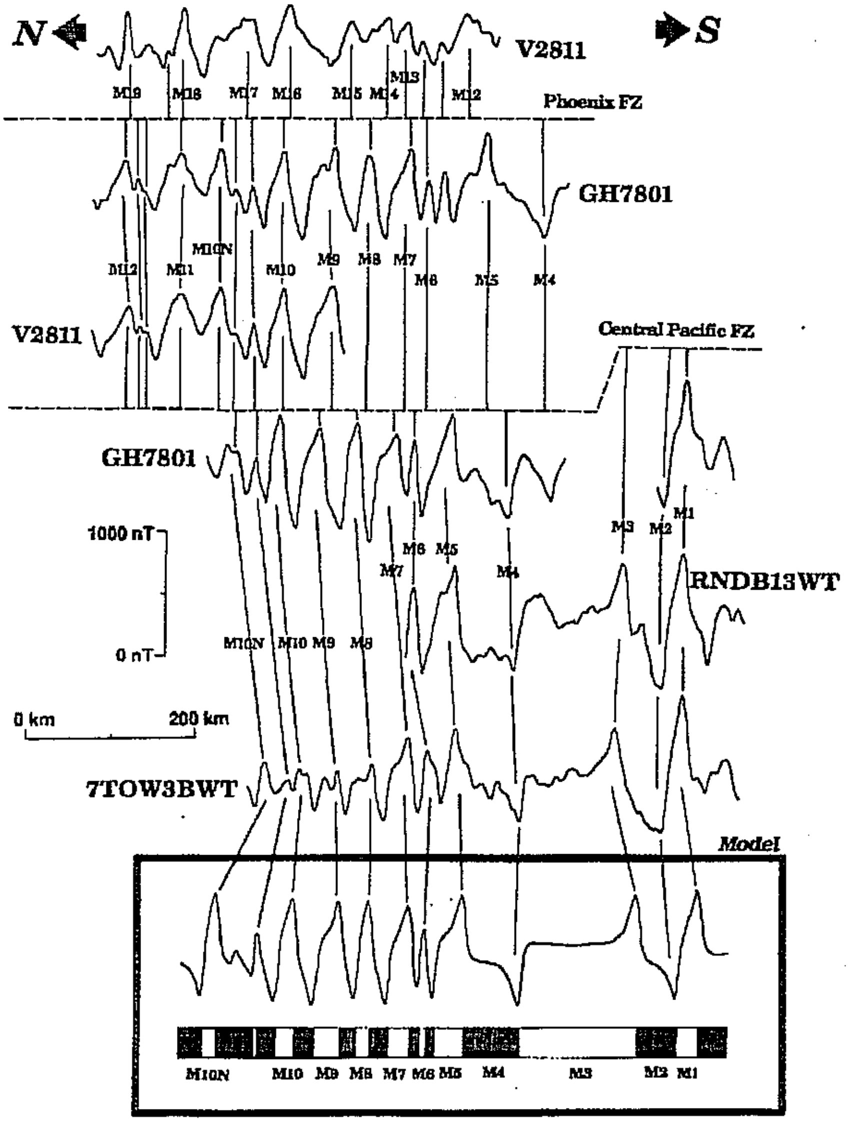

Figure 7. Selected magnetic anomaly profiles of the Phoenix lineation set in the Central Pacific Basin projected normally to the lineations and arranged from east (top) to west (bottom). The annotations of the magnetic profiles indicate cruise codes. The magnetic reversal sequence is from Larson & Hilde (1975) and Tamaki & Larson (1988). Normaly magnetized blocks are solid black. The skewness parameter for calculation of the model profile is −130°. FZ shows a fracture zone indicated by dashed lines.

Hawaiian lineation set

Lineations from M10 to M0 are well established in an area around the Mid-Pacific Mountains (Fig. 11) and connected to the Hawaiian set with a strike of N25°W by a fracture zone. No previous works have revealed this pattern of lineations around the Mid-Pacific Mountains. New cruise data after 1980, RNDB10WT and L984CP, have made it possible for us to identify them (Fig. 12). A broad positive anomaly M3 is a key for the identification. Kroenke, Kellog & Nemoto (1985) proposed that the sea-floor south of the Mid-Pacific Mountains, which is younger than that of the sea-floor north of it (from Hauterivian to Aptian, 132–118 Ma), started to spread in early Albian time (110 Ma). Our identification, however, demonstrates that the age of the sea-floor south of the Mid-Pacific Mountains is the same as that of the north. The result imposes a restriction on the formation of the Mid-Pacific Mountains.

Japanese lineation set

In the East Mariana Basin, lineations from M21 to M33 exist (Fig. 13). Selected magnetic anomaly profiles are shown in Fig. 14. A research cruise KH87-3 of the *Hakuho-maru* provided a crucial data set for identification of the lineations. Their strikes are N45°E and amplitudes are less than 100 nT. Hussong & Fryer (1982) indicated there are lineations from M23 to M25 in the East Mariana Basin near the Mariana Trench. Handschumacher *et al.* (1988) identified lineations from M25 to M31 in an area further south by aeromagnetic data. Identification by Tamaki *et al.* (1987) is different from theirs. Our result is similar to that of Tamaki *et al.* (1987). Five short events between M28 and M29 are clearly recognized in two V3506 and two KH87-3 profiles except for one of KH87-3. We also identified lineations southeast of M33, although their ages could not be assigned (Fig. 13).

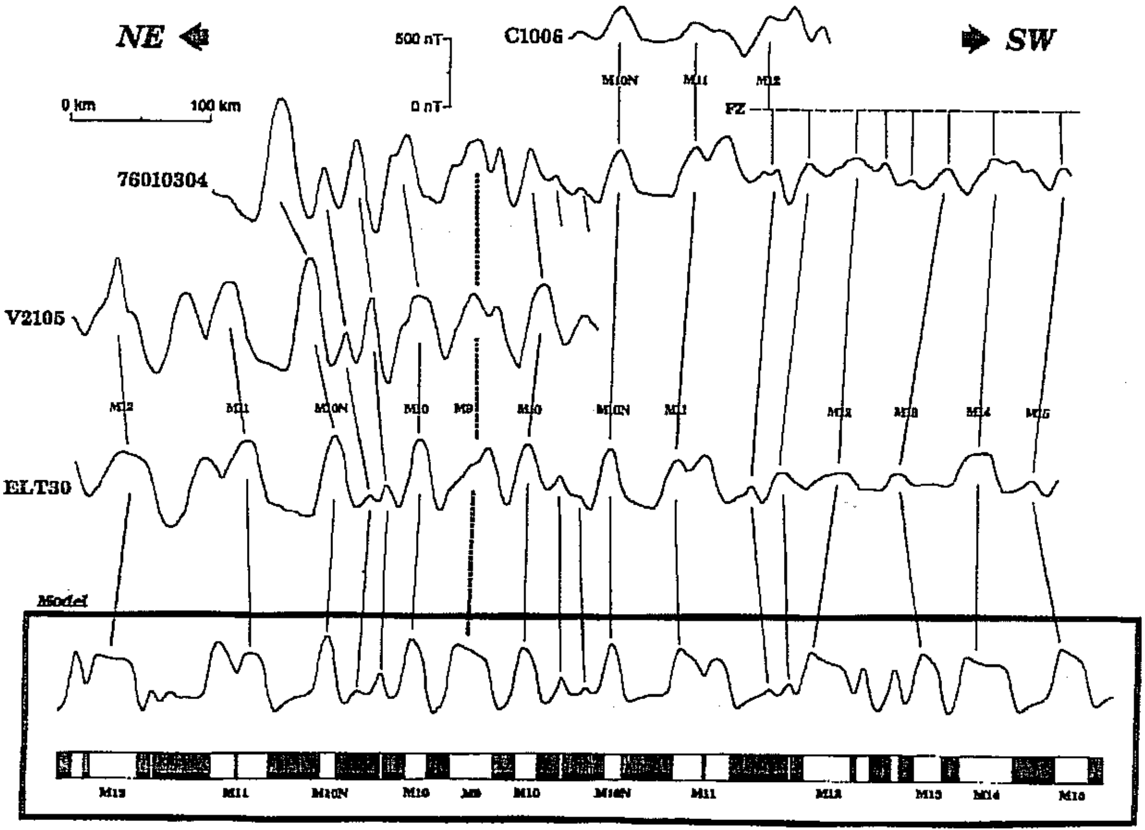

Figure 8. Selected magnetic anomaly profiles of the Magellan lineation set east of the Magellan Rise projected normally to the lineations and arranged from southeast (top) to northwest (bottom). The annotations of the magnetic profiles indicate cruise codes. The magnetic reversal sequence is from Larson & Hilde (1975) and Tamaki & Larson (1988). Normally magnetized blocks are solid black. M9 is the past spreading centre. The skewness parameter for calculation of the model profile is −190°. FZ shows a fracture zone indicated by dashed lines. The Magellan Trough is represented by heavy dashed lines.

The ODP hole 801B in the Pigafetta Basin penetrated pillow basalts immediately below sediments containing radiolarian fossils of Callovian/Bathonian of middle Jurassic age (~170 Ma) (Lancelot *et al.* 1990). This result seems to be quite consistent with the age extrapolated from our identification of lineations, as the hole is situated roughly 500 km southeast of an identified lineation M29 (Nakanishi, Tamaki & Kobayashi 1992a).

Junction between the Hawaiian and southern lineation sets (Phoenix, Magellan and Mid-Pacific Mountains lineation sets)

Junctions between the Hawaiian and southern lineation sets, Phoenix, Magellan and Mid-Pacific Mountains lineation sets, are not as simple as the junction between the Japanese and Hawaiian lineation sets that was described by Nakanishi *et al.* (1989). The Mid-Pacific Mountains are situated in the junction between Hawaiian and Phoenix lineation sets. No lineations older than M10 were identified in the Hawaiian and Phoenix lineation sets over the Mid-Pacific Mountains. Lineations from M19 to M15 in the Phoenix lineation set are obscured in an area east of the Phoenix Fracture Zone.

A junction between the Hawaiian and Magellan lineation sets is more complex than that between the Hawaiian and Phoenix lineation sets. Lineations from M15 to M12 situated west of the Magellan Rise have similar strikes to those of the same period in the Hawaiian lineation set. It was, therefore, concluded that these lineations from M15 to M12 were formed from the Pacific–Farallon ridge from which the Hawaiian lineation set was formed. The junction of the Hawaiian and Magellan lineation sets seems to be situated west of the Magellan Rise.

The distance between the Hawaiian and Mid-Pacific Mountains lineation sets is too small to identify any lineations at their junction. The strike of the Hawaiian lineation set is N25°W, whereas that of the Mid-Pacific Mountains lineation set is N55°W with a difference of 30°. It seems that there was a triple junction between these two lineation sets. Larson (1976) proposed that the Pacific plate was divided into two portions from chron M11 to chron M4, although there is no definite evidence in favour of his proposal. Another explanation for the junction is the past existence of an obliquely spreading ridge there. In this case it is not necessary to divide the Pacific plate into two portions. Our identification prefers the latter case.

A junction between the Phoenix and Magellan lineation sets seems to be situated west of the Line Islands. It is unlikely that magnetic bights existed in a period older than M5, because older lineations of the Magellan lineation set than those of the Phoenix lineation set are situated at the junction between the Phoenix and Magellan lineation sets. We cannot confirm the existence of a magnetic bight younger than M5, because corresponding lineations are not identified at the site.

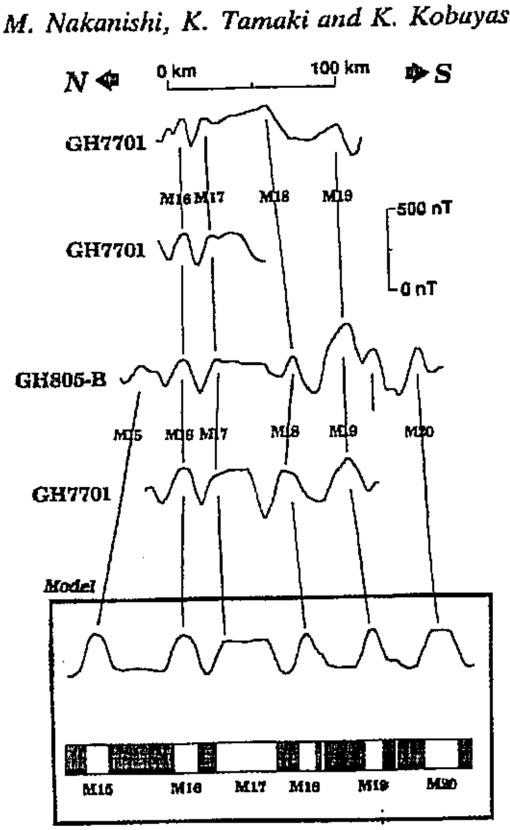

Figure 9. Selected magnetic anomaly profiles of the Magellan lineation set west of the Magellan Rise projected normally to the lineations and arranged from west (top) to east (bottom). The annotations of the magnetic profiles indicate cruise codes. The magnetic reversal sequence is from Larson & Hilde (1975) and Cande *et al.* (1978). Normally magnetized blocks are solid black. The skewness parameter for calculation of the model profile is −180°.

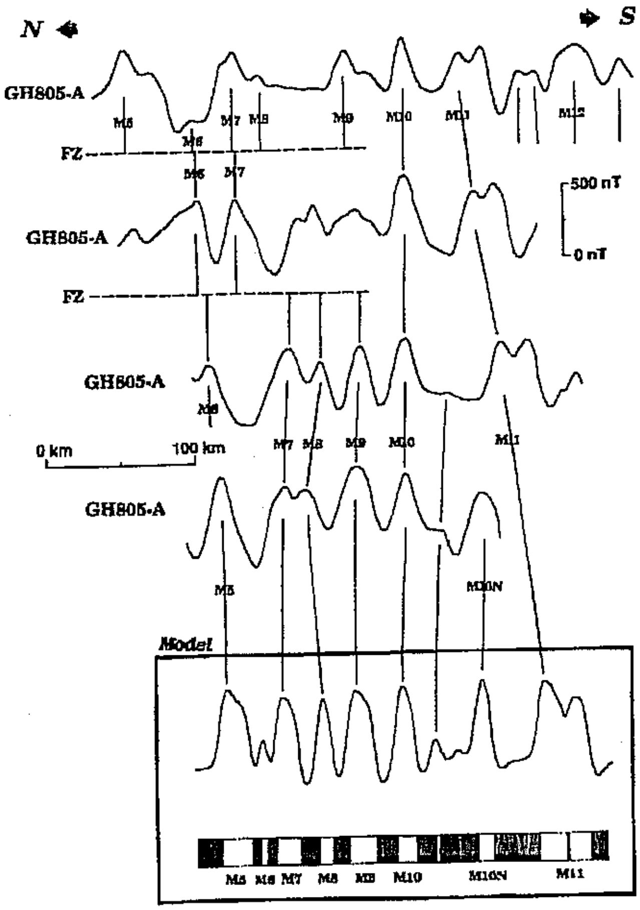

Figure 10. Selected magnetic anomaly profiles of the Mid-Pacific Mountains lineation set projected normally to the lineations and arranged from west (top) to east (bottom). The annotations of the magnetic profiles indicate cruise codes. The magnetic reversal sequence is from Larson & Hilde (1975) and Cande *et al.* (1978). Normally magnetized blocks are solid black. The skewness parameter for calculation of model profile is −190°. FZ shows a fracture zone indicated by dashed lines.

SKEWNESS PARAMETERS

Skewness parameters of the lineation sets were determined by deskewing analyses of several profiles in each lineation set as described in Nakanishi *et al.* (1989). Typical observed profiles of magnetic anomalies with those deskewed in 10° increments are shown in Figs 15–18 for the western part of the Phoenix lineation set (Nauru Basin), the eastern part of the Phoenix lineation set (Central Pacific Basin), Magellan lineation set (south and north flanks of the Magellan Trough) and Mid-Pacific Mountains lineation set, respectively. The results of deskewing are summarized in Table 2. These values will provide an important clue to reconstruct the past configuration of each spreading system as the source of the lineations, as the skewness parameter is affected by three factors; direction (inclination and declination) of the present magnetic field at the observed site, direction of natural remanent magnetization (NRM) of the sea-floor and strike of the lineation (Schouten 1971). The skewness discrepancy (about 30°) between the south and north flanks of the Magellan lineation set was observed. The skewness discrepancy can be accounted for by non-rigid plate motion of the Magellan microplate.

It should be mentioned here that skewness parameters of anomalies from M17 to M29 and from M1 to M14 in the Phoenix lineation set are significantly different from eachother (Fig. 15). Those of anomalies M16 and M15 do not belong to either group. A similar difference in skewness parameters was reported by Larson & Sager (1991). The boundary of their difference of skewness parameters is M10N and is different from ours. They suggested that the difference in skewness parameters is due to an undiscovered plate (Stealth plate) between the Pacific and Phoenix plate from chron M29 to chron M10N or due to time-varying anomalous skewness in the period owing to a change in the Earth's magnetic dipole field intensity. However, the existence of the Stealth plate is unlikely as we described in the section 'Pattern of lineations' of this article. The results of the skewness analysis of the Japanese and Hawaiian lineation sets (Nakanishi *et al.* 1989) showed that there is no such clear difference of skewness parameters for the same anomalies in the Japanese and Hawaiian lineation sets as seen in the Phoenix lineation set. If the Earth's magnetic dipole field intensity changed during the period, the change of skewness parameters should be observed in other lineation sets contemporary to the Phoenix lineation set. The non-existence of the equivalent changes in other areas

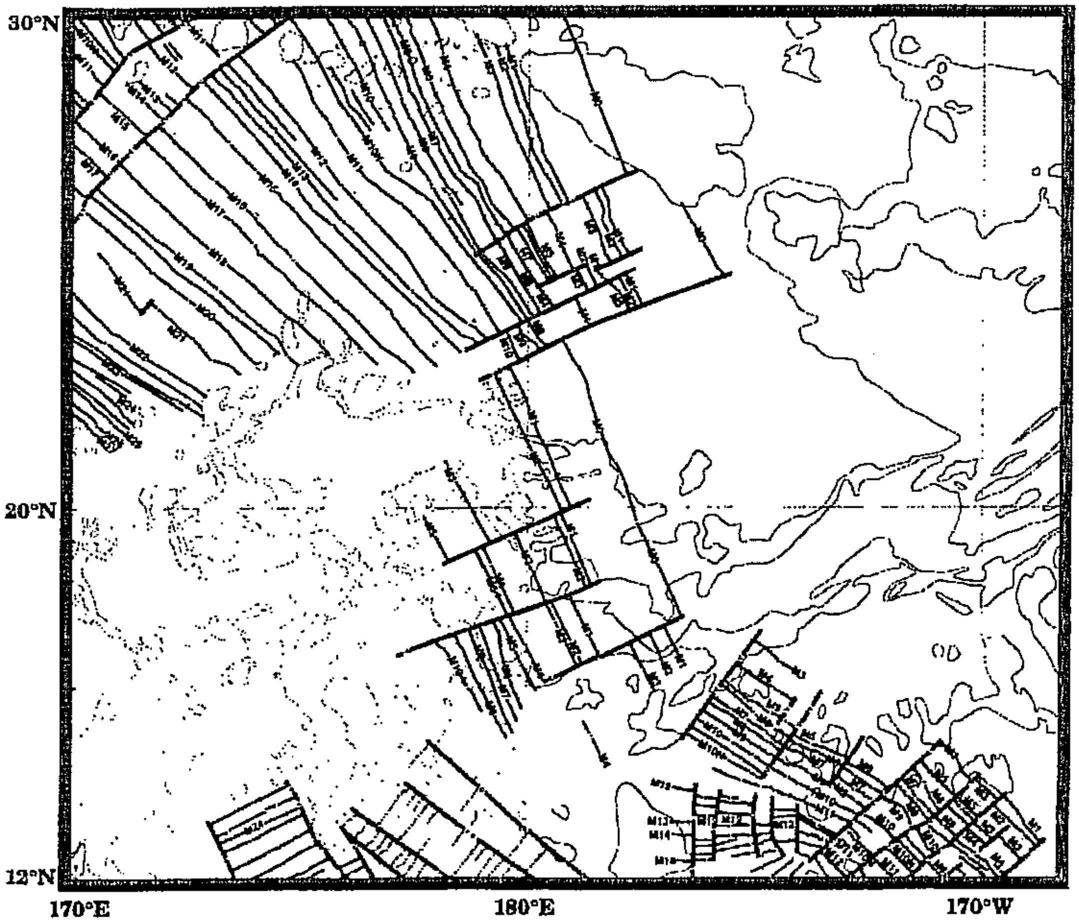

Figure 11. Mesozoic magnetic anomaly lineations with fracture zones (the Hawaiian lineation set) around the Mid-Pacific Mountains. The 4000 m, 5000 m and 7000 m GEBCO bathymetric contours are shown for reference.

seems to exclude the change in the Earth's magnetic dipole field intensity as a cause of the difference of skewness parameters. We would like to postulate that difference in skewness parameters was caused by that in directions of NRM of the sea-floor by other mechanisms.

The difference in directions of NRM of the sea-floor may be caused by either of the following two factors; one is relative motion between the areas older than chron M17 and those younger than chron M14. Observed difference in skewness parameters, 30°, corresponds to that in declination of NRM, 70°, assuming that the relative motion has only a horizontal component. It corresponds to difference in inclination, 30°, if the relative motion has only a vertical component. As strikes of magnetic lineations do not change very much, horizontal motion causing changes of 70° in declination is unlikely. It is also unrealistic to tilt a part of the large Phoenix plate by 30°.

An alternative explanation is a change in direction of NRM of the basement rocks in the Nauru Basin. A Cretaceous volcanic complex was discovered in the Nauru Basin (Larson *et al.* 1981). Such a post-spreading volcanism has not completely destroyed the Late Jurassic to Early Creataceous magnetic lineations from M29 to M11 as observed there. Larson & Schlanger (1981) postulated tension cracks caused by thermal uplift or magma wedging to provide pathways for Cretaceous magma through the Jurassic basement without disrupting the Jurassic magnetic structure. The Jurassic basement was kept cool by cold sea water circulating in the cracks to keep its magnetic layer below the blocking temperature for a period of volcanic intrusion. The Jurassic magnetic polarity has thus been mostly preserved in the layer. Magnetization of the Cretaceous intrusives is wholly normal, as it was formed in the magnetic quiet period. Superposition of the Jurassic and Cretaceous layers still causes magnetic lineations observed on the sea surface.

Palaeomagnetic measurement of cores recovered from holes 801A and 801B in the Pigafetta Basin (Lancelot *et al.* 1990) indicated that the Pacific plate moved northward in the Early Cretaceous, causing an inclination of normal magentization in the intrusives higher than those of the Jurassic basement rocks. Several previous studies showed that the area where a Cretaceous volcanism occurred almost agrees with the area older than chron M17, whereas the areas younger than chron M14 were free from post-spreading volcanism. If intrusions by a Cretaceous volcanism caused a change in the direction of the NRM, the difference of skewness parameters seems to be explained by

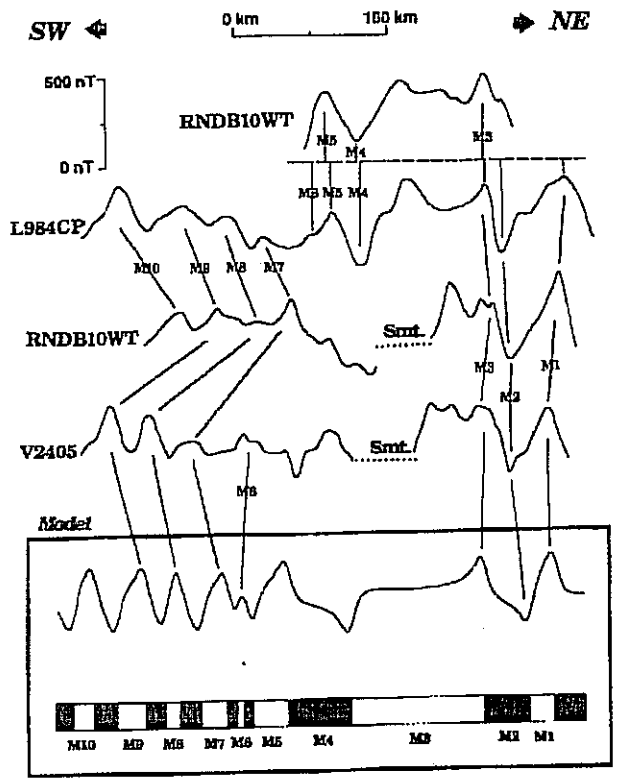

Figure 12. Selected magnetic anomaly profiles of the Hawaiian lineation set in the south part of the Mid-Pacific Mountains projected normally to the lineations and arranged from north (top) to south (bottom). The magnetic reversal sequence is from Larson & Hilde (1975) and Cande *et al.* (1978). Normally magnetized blocks are solid black. The skewness parameter for calculation of the model profile is −130°. FZ shows a fracture zone indicated by dashed lines.

overprints of chemical or partial thermoremanent magnetization with higher inclination caused by Cretaceous post-spreading volcanism.

HALF SPREADING RATES

We computed half spreading rates in the entire area studied by applying a linear regression analysis to ages and distances between lineations including the results by Nakanishi *et al.* (1989). We used the skewness parameter in each lineation set for calculation as shown in Table 2. Spreading rates thus obtained are shown in Fig. 19. The values vary from 1.84 to 7.87 cm yr^{-1}. Spreading rates of the Japanese lineation set range from 2.90 to 7.87 cm yr^{-1}. The range of the Hawaiian lineation set is 3.15–5.64 cm yr^{-1}. That of the Phoenix lineation set is 2.86–7.22 cm yr^{-1}. The Magellan lineation set has a range of spreading rates 2.53–6.61 cm yr^{-1}. The range of the Mid-Pacific Mountains lineation set is 1.84–5.89 cm yr^{-1}.

The largest spreading rate obtained by this study is 7–8 cm yr^{-1} at the lineations from M29 to M25 in the Japanese lineation set. On the other hand, the oldest part of the Hawaiian lineation set shows a rate of about 5 cm yr^{-1} that is slower than most of the Japanese lineation set. The oldest part of the Phoenix lineation set shows an intermediate value of 5–7 cm yr^{-1}. The younger part of the Phoenix lineation set in the Central Pacific Basin has spreading rates faster than those of other lineation sets. Spreading rates east of the Phoenix Fracture Zone after chron M5 (greater than 6 cm yr^{-1}) are quite different from those in its western part (smaller than 5 cm yr^{-1}).

Variations in spreading rates of the Pacific spreading systems for Mesozoic ages 160–123 Ma (M29–M1) are shown in Fig. 20. Distinct changes in spreading rates simultaneously occurred at the period between chrons M21

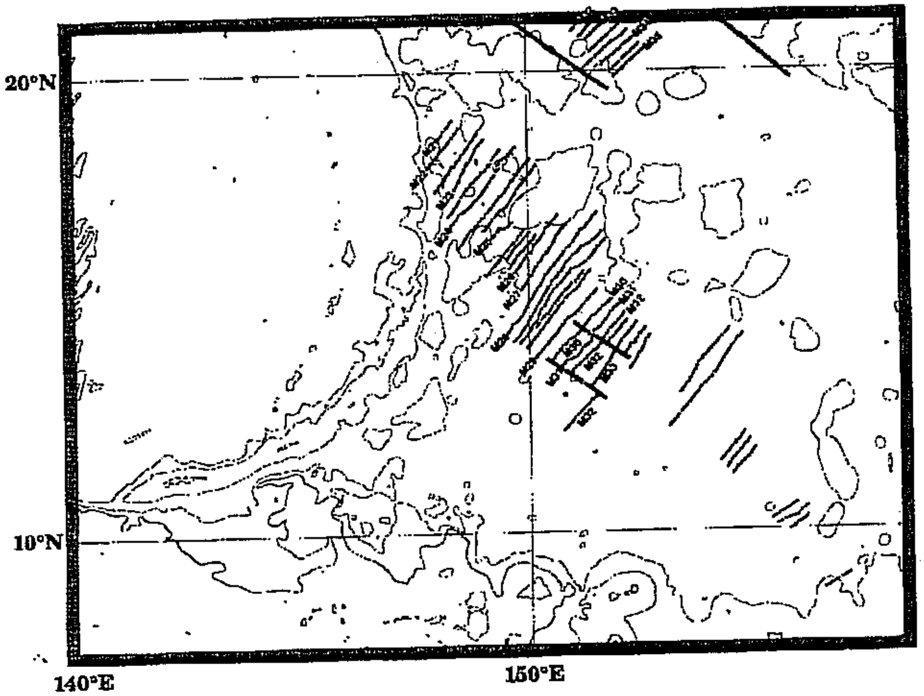

Figure 13. Mesozoic magnetic anomaly lineations with fracture zones (the Japanese lineation set) in the East Mariana Basin. The 4000 m, 5000 m and 7000 m GEBCO bathymetric contours are shown for reference.

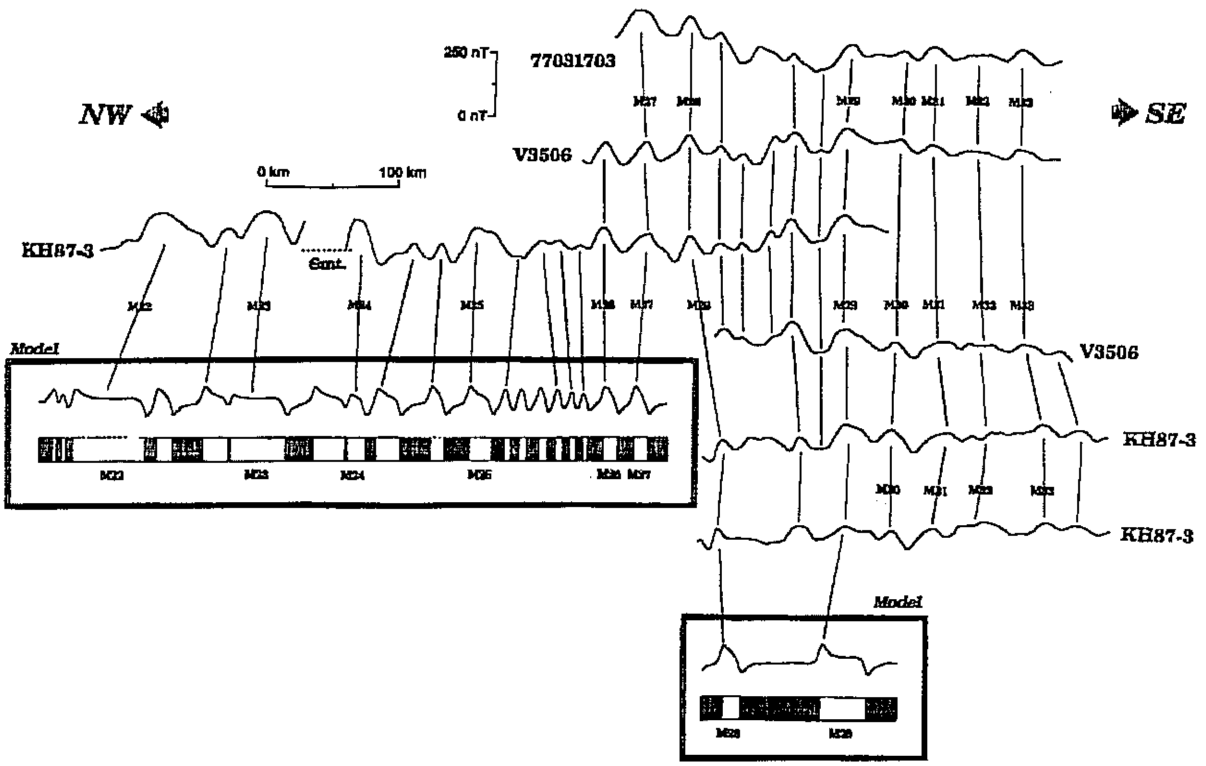

Figure 14. Selected magnetic anomaly profiles of the Japanese lineation set in the East Mariana Basin projected normally to the lineations and arranged from east (top) to west (bottom). The magnetic reversal sequence is from Larson & Hilde (1975) and Cande *et al.* (1978). Normally magnetized blocks are solid black. The skewness parameter for calculation of the model profile is −230°. FZ shows a fracture zone indicated by dashed lines.

and M20 in all three lineation sets. Synchronous changes in spreading rates were reported with the Keathley sequence in the Atlantic at chron M21 (Sundvik & Larson 1988) and with lineations in the Argo Abyssal Plain in the Indian Ocean between chrons M22A and M20 (Fullerton, Sager & Handschumacher 1989). Reorganization of the plate configuration in the Pacific Ocean appears to have occurred at the same time as changes in continental rifting in other parts of the world. An apparent change of the spreading rates at 155 Ma (M25) in the Japanese and Hawaiian lineation sets was not in harmony with that in the Phoenix lineation set, which does not seem to be a worldwide phenomenon.

Mesozoic spreading rates in the Japanese, Hawaiian and Phoenix lineation sets are 4–8, 3.5–6 and 2.7–7.5 cm yr^{-1}, respectively, comparable to those of the present East Pacific Rise (4–9 cm yr^{-1}). Those in the Mesozoic lineation sets in the Atlantic, Arctic and Antarctica are less than 3 cm yr^{-1} (Atlantic: Sundvik & Larson 1988; Rabinowitz, Cande &

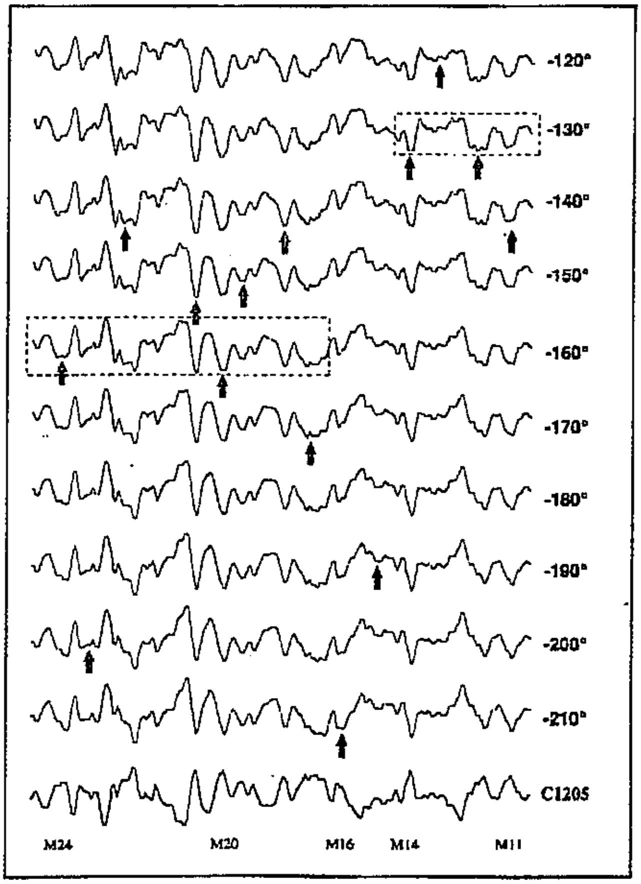

Figure 15. Deskewed magnetic anomaly profiles from the Phoenix lineation set in the Nauru Basin with an observed profile at the bottom. The method of deskewing is by Schouten & McCamy (1972) and Schouten & Cande (1976). Numbers on the right-hand side are assumed skewness parameters with 10° increments. Solid arrows on the bottom of anomalies indicate anomalies with symmetric shape that is completely deskewed. A profile best-fitted to the model is enclosed by a dashed rectangle and regarded to be completely deskewed. The skewness parameter of lineations older than M17 thus obtained is −160° ± 20°. That of lineations younger than M14 is −130° ± 10°.

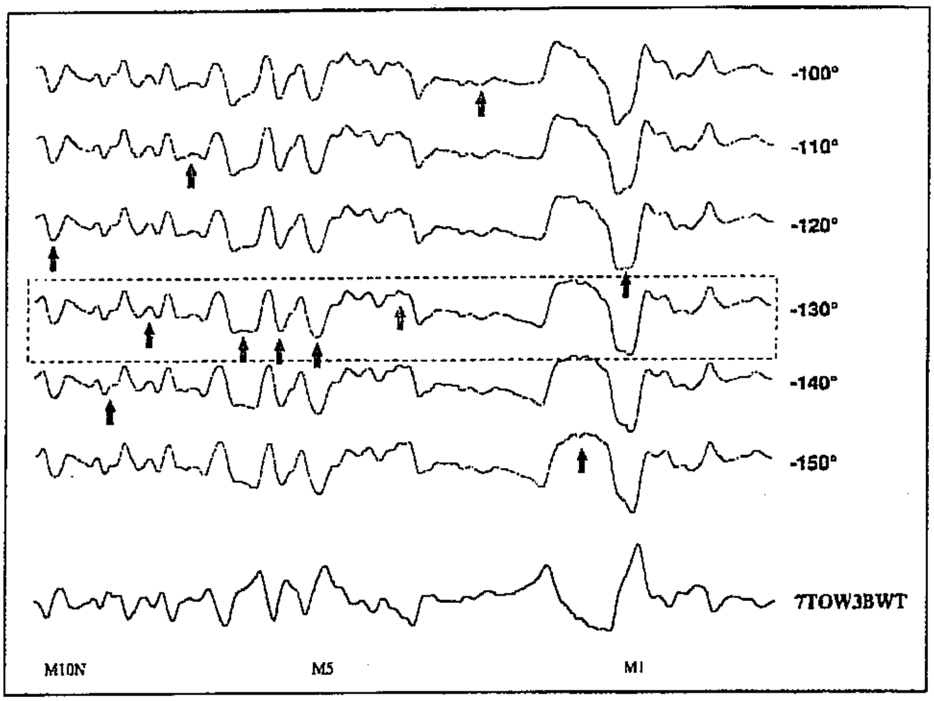

Figure 16. Deskewed magnetic anomaly profiles from the Phoenix lineation set in the Central Pacific Basin compared with an observed profile. The skewness parameter of the observed profile was determined to be −130° ± 10°. Other conventions are the same as in Fig. 15.

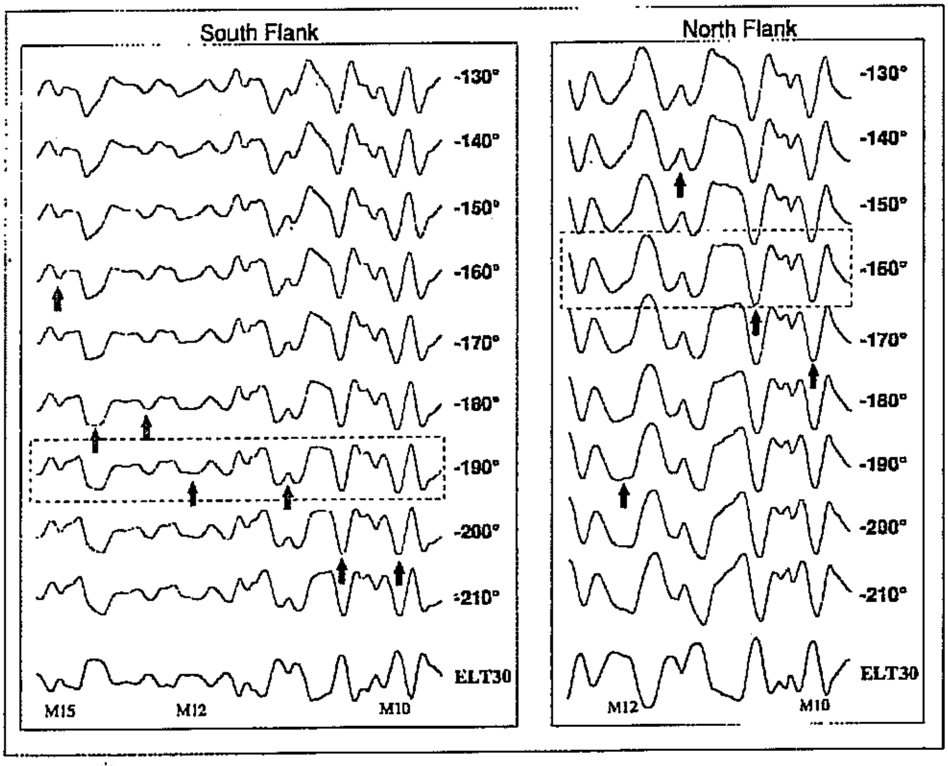

Figure 17. Deskewed magnetic anomaly profiles from the Magellan lineation set with an observed profile. The left part is the south flank of the Magellan Trough. The right one is the north flank. The skewness parameter of the observed profile in the south flank is determined to be −190° ± 10°. That in the north flank is determined to be −160° ± 20°. Other conventions are as in Fig. 15.

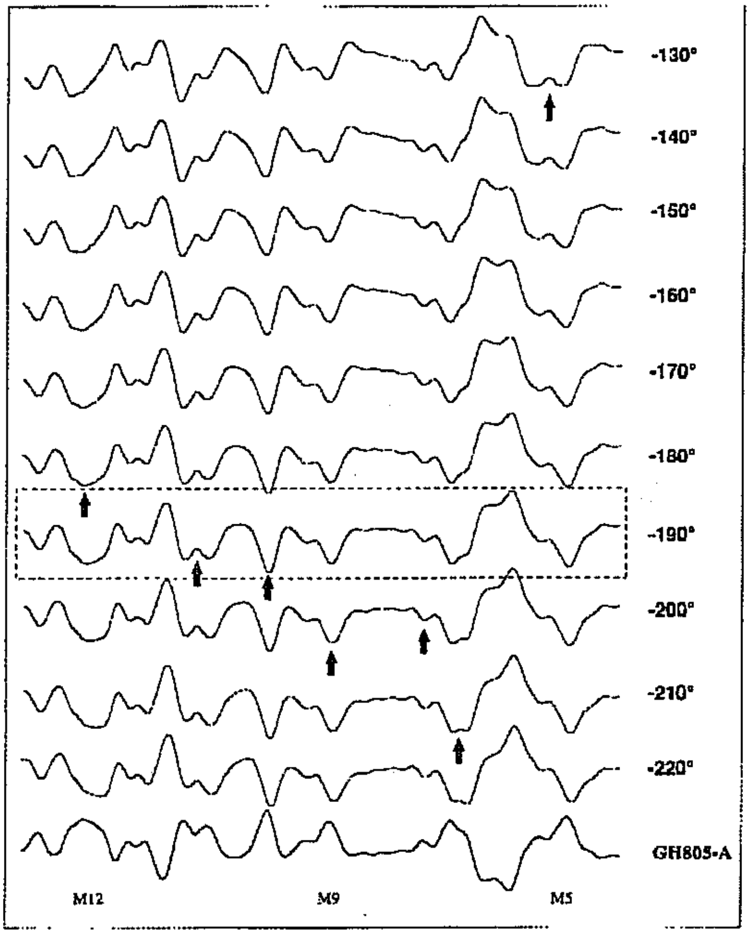

Figure 18. Deskewed magnetic anomaly profiles from the Mid-Pacific Mountains lineation set with an observed profile. The skewness parameter of this lineation set is −190° ± 20°. Other conventions are as in Fig. 15.

Hayes 1979; Rabinowitz & LaBrecque 1979; Arctic: Taylor *et al.* 1981; Antarctica: Bergh 1977, 1987). Thus, the spreading rates in the Mesozoic Pacific lineation sets were the fastest among the presently existing Mesozoic lineation sets (Fig. 21).

We compared spreading rates in several major spreading systems (East Pacific Rise and Pacific–Antarctic Ridge in the Pacific, north and south Mid-Atlantic Ridge and ridges in the Indian Ocean) since the Middle Cretaceous (80 Ma) until the present (Fig. 22). The fast spreading rate exceeding 10 cm yr^{-1} is observed in the Indian Ocean for a short time span. Larson & Pitman (1972) indicated that the spreading rates of the Pacific spreading system in the Cretaceous quiet period are two or three times faster than those in other periods. However, Larson (1991) concluded that the spreading rate in the Cretaceous quiet period was not abnormally rapid compared with those in the other ages.

CONCLUSIONS

We identified Mesozoic magnetic anomaly lineations in the western-central Pacific Ocean more comprehensively than in any previous works. Newly obtained cruise data extended the studied areas where Mesozoic magnetic anomaly lineations were identified (e.g., around the Mid-Pacific Mountains, in the East Mariana Basin, east of the Ontong Java Plateau and around the Magellan Rise).

The principal results of the present investigation are summarized as follows.

(1) The configuration of three Mesozoic lineation sets, the Phoenix, Magellan and Mid-Pacific Mountains lineation sets, was precisely revealed in the west-central Pacific Ocean. We newly identified a part of the Magellan lineation set east of the Phoenix lineation set. We identified lineations from M10 to M0 around the Mid-Pacific Mountains, which are a part of the Hawaiian lineation set.

(2) The strike of the Phoenix lineation set is E–W (from N65°E to N85°E). There is a large gap from M20 to M14 in the Phoenix lineation set east of the Phoenix Fracture Zone. The Magellan lineation set has a strike of NW–SE. The strike of the Mid-Pacific Mountains lineation set is NW–SE (N45°W and N55°W).

(3) There exist lineations older than lineation M29 in the East Mariana Basin. A NE–SW trending lineation set was found in an area south of the Mid-Pacific Mountains surrounded by the Phoenix, Hawaiian and the Magellan lineation sets, although age of these lineations has not yet been assigned.

(4) The skewness parameters of these lineation sets were

Table 2. Skewness parameters of magnetic lineation sets in the northwestern Pacific Ocean.

Japanese	Hawaiian	Phoenix M16-M29	Phoenix M1-M14	Magellan (south flank)	Magellan (north flank)	Mid-Pacific Mountains
-230°±20°	-130°±10°	-160°±20°	-130°±10°	-190°±10°	-160°±20°	-190°±20°

determined. The difference between the younger (M1–M14) and older (M17–M29) lineations of the Phoenix lineation set seems to be due to overprints of chemical or partial thermoremanent magnetization caused by Cretaceous post-spreading volcanism.

(5) By combining the present results with our previous ones with the Japanese and Hawaiian lineation sets, spreading rates in various ages and different areas were compared. The spreading rates of the Mesozoic Pacific lineation sets seem to be the largest in the world. A change in the spreading rates occurred at the period between chrons M21 and M20 (149.5–148.5 Ma) in all the Mesozoic Pacific spreading systems and appears to be correlatable to a synchronous event in other oceans.

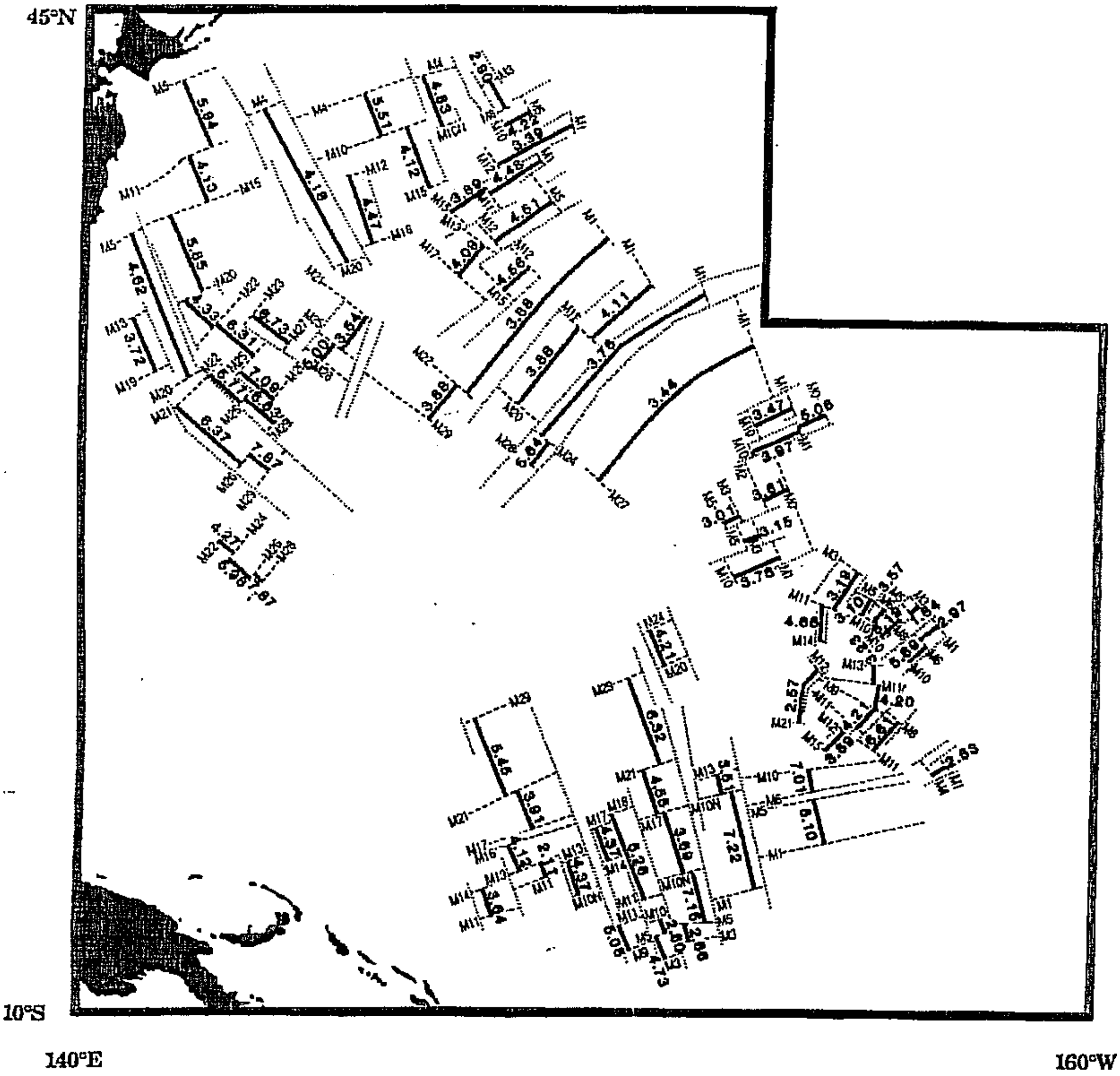

Figure 19. Variations in the half spreading rates of the studied area calculated by a linear regression analysis for age and distance on the basis of the lineation map (Fig. 4). Dashed lines show lineations with M numbers. Dotted lines are fracture zones. Numerical figures on thick lines represent spreading rates in cm yr^{-1}.

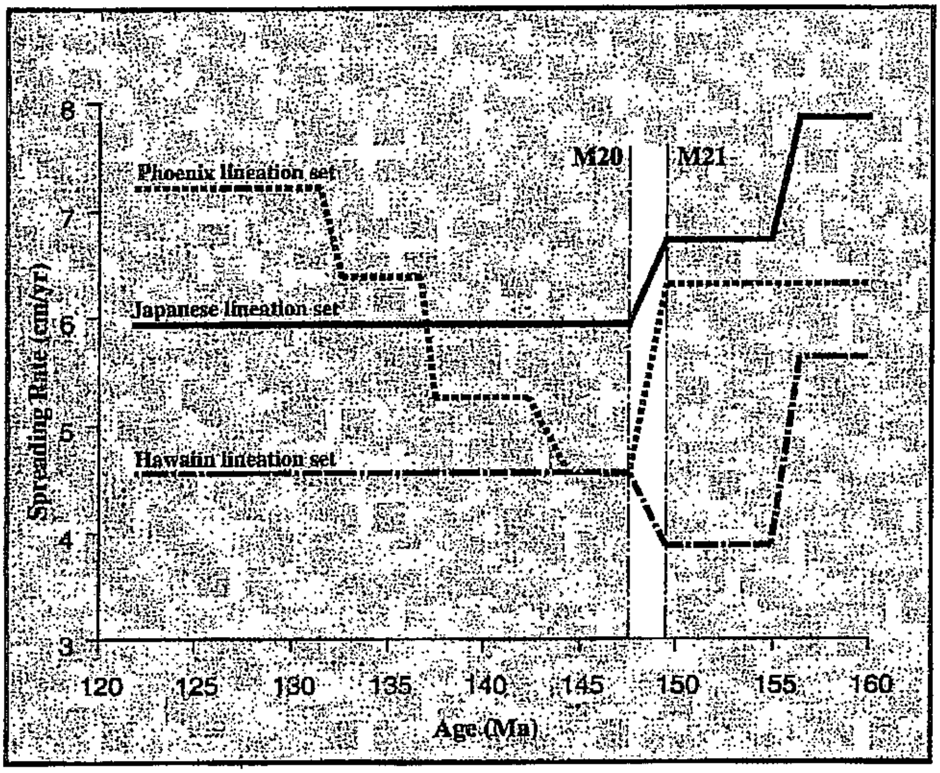

Figure 20. Variations in spreading rates of the Mesozoic Pacific spreading systems.

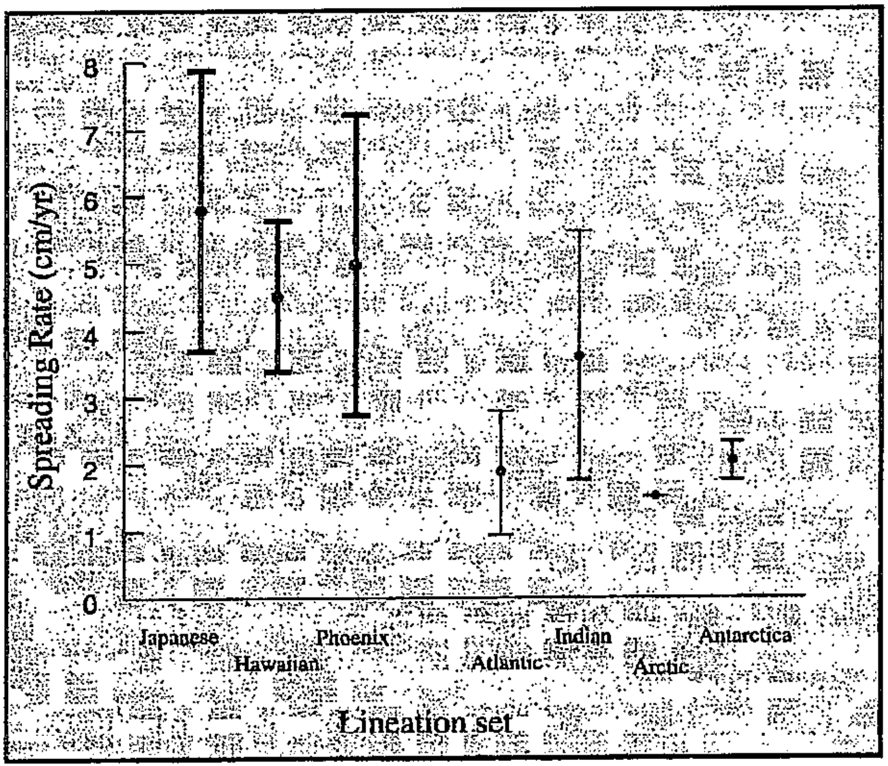

Figure 21. Ranges of spreading rates in the Mesozoic spreading systems observed in the present world oceans.

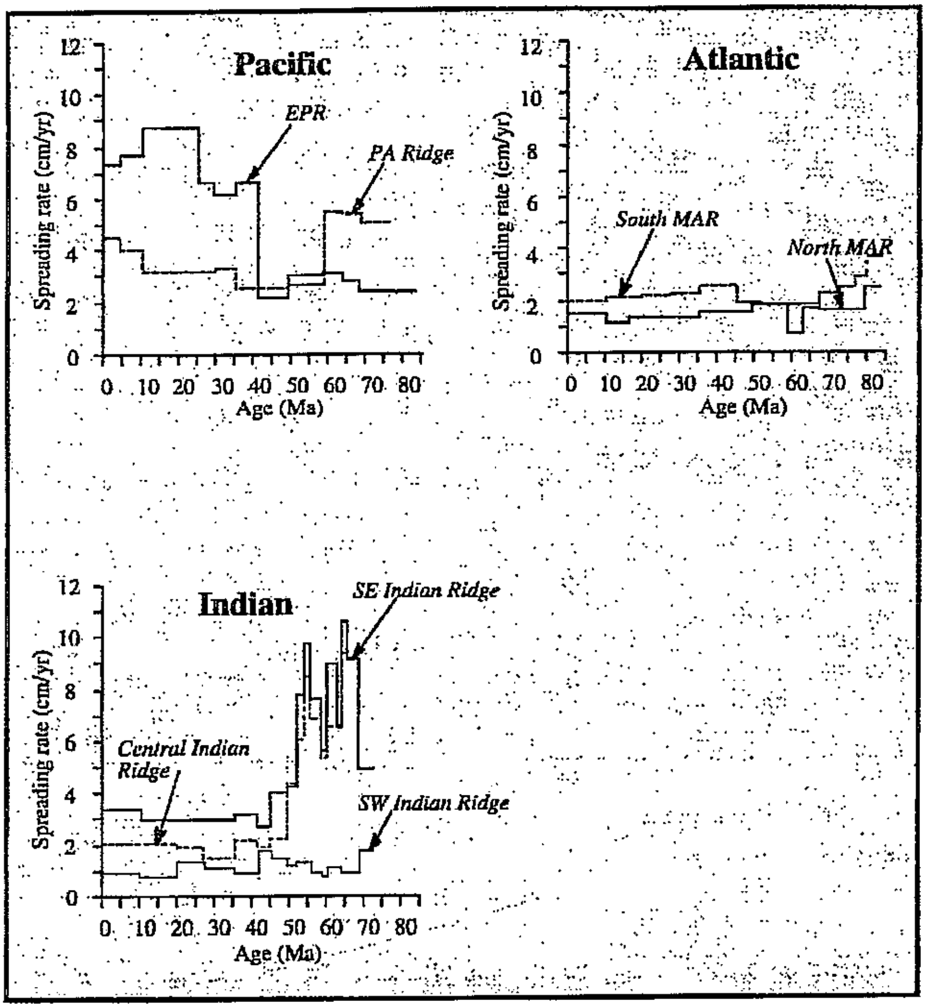

Figure 22. Variations in spreading rates of the Pacific, Atlantic and Indian spreading systems after 85 Ma. Spreading rates of the Pacific spreading systems are based on Mayes, Lawver & Sandwell (1990). Those of the Atlantic spreading systems are from Klitgord & Schouten (1986) and Cande, LaBrecque & Haxby (1988). Those of the Atlantic spreading systems are from Patriat & Segoufin (1988).

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