(2)

AD-A204 990

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

DTIC FILE COPY

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS: None
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: NORDA; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Naval Ocean Research and Development Activity
6c. ADDRESS (City, State, and ZIP Code): Stennis Space Center, MS 39529-5004	7b. ADDRESS (City, State, and ZIP Code): Stennis Space Center, MS 39529-5004
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: ONR; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code): Washington, DC	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61153N	03105	330	13168C

11. TITLE (Include Security Classification)
Pre-Cretaceous tectonic evolution of the Pacific plate and extension of the geom[illegible]netic polarity reversal time scale with implications fo rthe origin of the Jurassic "Quiet Zone"

12. PERSONAL AUTHOR(S)
D. Handschumacher, W. Sager, T. Hilde and D. Bracey

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Journal Article	FROM ____ TO ____	1988, March	15

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: David Handschumacher	22b. TELEPHONE (Include Area Code): 601-688-5471; 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE: Unclassified

Tectonophysics, 155 (1988) 365–380
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Pre-Cretaceous tectonic evolution of the Pacific plate and extension of the geomagnetic polarity reversal time scale with implications for the origin of the Jurassic "Quiet Zone" *

DAVID W. HANDSCHUMACHER [1], WILLIAM W. SAGER [2], THOMAS W.C. HILDE [3] and DEWEY R. BRACEY [4]

[1] *Naval Ocean Research and Development Activity, NSTL, MS 39529 (U.S.A.)*
[2] *Departments of Oceanography and Geophysics, Geodynamics Research Institute, Texas A & M University, College Station, TX 77843 (U.S.A.)*
[3] *Department of Geophysics, Geodynamics Research Institute, Texas A & M University, College Station, TX 77843 (U.S.A.)*
[4] *Naval Oceanographic Office NSTL, MS 39522 (U.S.A.)*

(Received June 26, 1987; revised version accepted March 13, 1988)

Abstract

Handschumacher, D.W., Sager, W.W., Hilde, T.W.C. and Bracey, D.R., 1988. Pre-Cretaceous tectonic evolution of the Pacific plate and extension of the geomagnetic polarity reversal time scale with implications for the origin of the Jurassic "Quiet Zone". In: C.R. Scotese and W.W. Sager (Editors), Mesozoic and Cenozoic Plate Reconstructions. *Tectonophysics*, 155: 365–380.

Linear magnetic anomalies resulting from seafloor spreading were mapped in the vicinity of the magnetic bight in the western Pacific Ocean. New aeromagnetic data allowed the magnetic bight to be more accurately mapped from M21 to M28 and enabled the identification of low-amplitude magnetic lineations in the Jurassic "Quiet Zone". These lineations were formed by magnetic field reversals prior to M29. A revised Jurassic geomagnetic polarity reversal time scale was constructed with nineteen reversals older than M29, numbered M30–M38. These reversals extend the record of geomagnetic polarity back in time by approximately 8 Ma and are important constraints on the origin of the quiet zone. In particular, they imply that the Jurassic was not a period of constant normal polarity, an explanation offered by some authors. Further, they cast doubt on a model of systematically decreasing geomagnetic field strength with increasing age during this period. The early history of the northern Pacific plate and Pacific–Farallon–Izanagi (P–F–I) triple junction was traced by mapped magnetic isochrons. The Pacific plate seems to have evolved from a small plate that formed near the Phoenix–Farallon–Izanagi triple junction about 180–188 m.y. ago at approximately 17°N, 160°E in present coordinates. Until M21 time the evolution of the northern Pacific plate was relatively simple and the P–F–I triple junction migrated north-northwest with respect to the Pacific.

Introduction

The Vine–Matthews–Morley hypothesis (Vine and Matthews, 1963; Morley and Larochelle, 1964) must rank as one of the most exciting and useful discoveries of the plate tectonic revolution. It states simply that ocean basalts, cooling through the Curie temperature at the axis of a spreading ridge, record the polarity flips of the geomagnetic field. The blocks of opposing polarity created in the crust give rise to linear magnetic anomalies oriented parallel to the ridge axis and represent geologic isochrons. Such anomalies have been

* Geodynamics Research Institute Contribution No. 71.

0040-1951/88/$03.50

measured in all the ocean basins and have made it possible to decipher their tectonic histories. They are also the foundation upon which the geomagnetic polarity reversal time scale, extending back to the Jurassic, has been built.

The western Pacific contains one of the oldest and clearest records of seafloor spreading in the oceans. Here, there are three sets of Mesozoic magnetic anomalies with distinctly different trends, the NE-striking Japanese trend, the NW-trending Hawaiian lineations, and the E–W directed Phoenix lineations (Larson and Chase, 1972). These lineations allowed Larson and Chase to develop the first tectonic model for the early evolution of the Pacific plate—the major features of which have remained unchanged despite continued research on the subject. According to this model, the Pacific plate evolved to the west of two ridge–ridge–ridge (RRR) triple junctions connecting five different spreading ridge systems. As the plate grew, the histories of three of the ridge systems were recorded in its crust as the three lineation sets.

The most studied of the two triple junctions is the northernmost, formed by the intersection of the Pacific, Farallon and Izanagi plates (Hilde et al., 1976; Woods and Davies, 1982), whose ridges created the Hawaiian and Japanese lineations. In the vicinity of the Shatsky Plateau, these anomalies form a Jurassic–Early Cretaceous magnetic bight that preserves many of the details of the early evolution of the Pacific plate (Larson and Chase, 1972; Hilde et al., 1976). The bight has been traced back to M29, the oldest magnetic reversal included in geomagnetic polarity reversal time scales based on the marine magnetic record (Kent and Gradstein, 1985). Farther south, the seafloor is often placed in the Jurassic "Quiet Zone" (JQZ). It evidently formed prior to M29, during a period for which no correlatable magnetic reversal anomalies have been identified.

We conducted a study of the magnetic reversal lineations in the western Pacific to revise existing lineation maps and explore the tectonic evolution of the young Pacific plate. A large part of the impetus for this study was the availability of new aeromagnetic data collected in this region by the U.S. Navy. These data, and the many shiptracks that have accumulated since the last detailed study, yielded a clearer picture of the early history of the Pacific than has previously been possible. Moreover, the aeromagnetic data have allowed linear magnetic reversal anomalies to be identified and correlated in the JQZ, enabling us to revise and extend the record of Jurassic polarity reversals.

This study is presented in two parts. At M21 time the plate boundaries meeting at the Pacific–Farallon-Izanagi (P–F–I) triple junction began a complex reorganization that terminated the relatively simple growth of the northern Pacific plate that had occurred prior to that time. In this article, the implications of magnetic anomalies older than M21 are examined. A companion paper (Sager et al., this issue) discusses the tectonic history of the northern Pacific from M21 to M10.

Previous work

The mapping of magnetic lineations in the western Pacific has been inextricably intertwined with the development of the Mesozoic geomagnetic polarity reversal time scale. A number of workers measured magnetic lineations in the western Pacific (Uyeda et al., 1967; Uyeda and Vacquier, 1968; Hayes and Heirtzler, 1968; Hayes and Pitman, 1970). Although most realized the lineations were Mesozoic in age, and Vogt et al. (1971) even surmised that they corresponded to the Atlantic Keathley anomalies, it remained for Larson and Pitman (1972) to make a correct, detailed, worldwide correlation and establish their age. Their break-through was to realize that negative anomalies in the Pacific sequence correlated with positive anomalies in the north Atlantic because the former were formed at or below the equator and the latter, above. This allowed them to utilize the Hawaiian lineations to construct a reversal time scale for the Late Jurassic and Early–Middle Cretaceous encompassing M1 to M22. Using this time scale, Larson and Chase 1972) demonstrated that the Hawaiian, Japanese and Phoenix lineations in the western Pacific were coeval and developed a model for the early tectonic evolution of the plate. They postulated that the Pacific plate had been surrounded by three others, the Kula to the northwest, Farallon to the northeast, and Phoenix to the south.

In later studies of western Pacific anomalies, Larson and Hilde (1975) added M0 and M23–M25 to the time scale and Hilde et al. (1976) recognized M26 and compiled a map of lineations around the northern magnetic bight. Hilde et al. (1976) further suggested that the Pacific had grown from a small plate spawned at the Kula–Farallon–Phoenix triple junction about 180 m.y. ago. Furthermore, they recognized the tectonic complexity implied by the bight, hypothesizing that the triple junction that formed it had switched after M21 time from a simple RRR configuration to a more complex geometry and that it played a role in the development of the Shatsky Plateau. Woods and Davies (1982) compared the western Pacific magnetic bight with a younger one located in the eastern Pacific and concluded that they were not formed by the same three plates as had been thought. The plate that bounded the Pacific to the northwest in the Jurassic and Early Cretaceous was not the Kula plate defined by Atwater and Grow (1970). Woods and Davies named the older Pacific companion the Izanagi plate.

Recently, western Pacific magnetic lineations have generated a renewed interest. Mammerickx and Sharman (1988) examined the magnetic lineations north of the Shatsky Plateau and Sharman and Risch (this issue) as well as Sager et al. (this issue) reevaluated the lineations in the immediate vicinity of the plateau. The latter two articles along with this study form a series devoted to the evolution of the northern Pacific plate and Pacific–Farallon–Izanagi triple junction.

The Jurassic Quiet Zone problem

Studies of oceanic magnetic anomalies have found "smooth zones" or "quiet zones" of Cretaceous and Jurassic age in which it has proven impossible to correlate magnetic isochrons. The Cretaceous Quiet Zone is perhaps the best defined. It lasted from approximately 118 to 84 Ma and is bounded by magnetic anomalies M0 and 34 (Kent and Gradstein, 1985). Evidently, this quiet zone formed because the geomagnetic field stayed in a normal polarity state for the entire period (Helsley and Steiner, 1969; McElhinny and Burek, 1971). Despite years of trying, geoscientists have been able to find only a few possible short reversals during this time interval (e.g., Keating and Helsley, 1978) and even the existence of these is not universally accepted.

The origin of the JQZ is not as clear. Many explanations for its existence have been offered (see reviews by Mascle and Phillips (1972), Poehls et al. (1973), Hayes and Rabinowitz (1975), Barrett and Keen (1976) and Roots (1976)). Authors have called upon equatorial latitudes, remagnetization, alteration and metamorphism, viscous magnetism, low field intensity, rapid reversals, or no reversals at all to account for the JQZ. The most widely accepted ideas are those that involve changes in the character of the geomagnetic field. Perhaps by analogy to the Cretaceous Quiet Zone, many authors assumed that the JQZ resulted from a period of constant normal polarity (Heirtzler and Hayes, 1967; Burek, 1970; Larson and Pitman, 1972). In their worldwide correlation of anomalies, Larson and Pitman (1972) placed the edge of the JQZ at the older side of anomaly M22. It was noted that the amplitudes of anomalies older than about M19 decreased systematically towards the JQZ and the suggestion was made that this "amplitude envelope" showed that the geomagnetic field had increased its intensity in the transition from non-reversing to reversing states (Vogt et al., 1971; Larson and Pitman, 1972; Larson and Hilde, 1975).

As the edge of the JQZ came under further scrutiny, more correlatable low-amplitude anomalies were found. Larson and Hilde (1975) identified anomalies M23–M25 in the Pacific and correlated them with the Atlantic Keathley sequence. Hilde et al. (1976) defined M26 in the western Pacific, but Cande et al. (1978) resolved it into M26–M28 and discovered another isochron, M29. Other authors have found reversals of similar age in the North Atlantic (Barrett and Keen, 1976) as well as some that may be even older in the Pacific (Handschumacher and Kroenke, 1978) and in rock sections on land (Steiner and Helsley, 1975; Irving and Pulliah, 1976; Channell et al., 1982; Ogg and Steiner, 1985). Unfortunately, a definitive worldwide correlation of pre-M25 reversals has proven elusive (Kent and Gradstein, 1985). In the oceans, the primary problem is that these anomalies are difficult to resolve with sea-surface magnetic data over seafloor of Jurassic age in the North Atlantic (Vogt and Einwich, 1979) and western Indian (Rabinowitz et al., 1983) oceans due to the slow spreading rates (1–2 cm/yr).

With the discovery of more possible reversals within the JQZ the extension of the Jurassic reversal time scale must be ranked as one of the most important and exciting frontiers of geomagnetism research. The best location to search for pre-M25 reversal anomalies is the Pacific Ocean because of its higher spreading rates and reduced number of fracture zones. Moreover, the best set of anomalies to examine are the Japanese lineations because they have the highest spreading rate of the three Pacific Jurassic lineation sets. To discover whether pre-M25 anomalies could be correlated over a significant distance, a series of low-level aeromagnetic tracks were flown over the JQZ, perpendicular to the Japanese lineations, by the Naval Ocean Research and Development Activity (NORDA) in the years 1979–1983. Correlatable lineations were indeed found and form the basis for an extension of the Jurassic polarity time scale and many of the tectonic implications presented in this report.

Data

Total field magnetic anomaly data were examined to identify magnetic lineations created by the process of seafloor spreading in the western Pacific. The study area was divided into two subsets for the purpose of discussion: the magnetic bight and the JQZ.

The primary data in the magnetic bight area were collected with proton-precession magnetometers along shiptracks obtained from the National Geophysical Data Center (NGDC) archives. These data were augmented with aeromagnetic data. Four N–S low-level aeromagnetic lines, located near the magnetic bight at 30°–31°N, 151°–152°E, were used to map an extension of the Hawaiian lineations. Two additional low-level aeromagnetic lines, trending perpendicular to the Japanese lineations, were used to trace those anomalies. These six lines were flown with a U.S. Navy P3 Orion at an altitude of 1.5 km and a speed of 250 knots. A few additional aeromagnetic lines from Project Magnet were used for additional constraints in mapping lineations. These data were obtained in a manner similar to the other aeromagnetic lines, except that they were flown at a higher altitude, approximately 3–5 km.

The data used to map and identify the lineations in the JQZ were also U.S. Navy aeromagnetic tracks. These lines were positioned to be closely spaced and perpendicular to the oldest known magnetic isochrons along the Japanese lineations. They were flown to overlap anomalies M25–M28 and extend into the JQZ. Because these older anomalies were known to have low amplitudes, these lines were flown at an altitude of only 305 m in order to reduce the attenuation effect of distance from the magnetic source.

Most of the ship data used in this study were positioned by satellite navigation, whereas inertial navigation was used for the aircraft data. The differences in navigational methods did not prove a problem. Aeromagnetic data were checked for consistency with satellite-navigated shiptracks at crossover points and only small random errors were detected. The largest discrepancies were on the order of 9 km, but 3.5 km was the average crossing error.

Analysis

In both study areas, the magnetic bight and the JQZ, the magnetic data were plotted as total field intensity anomalies perpendicular to the ship or flight tracks. These anomalies were identified and correlated from track to track by characteristic shapes, amplitudes and spacing. A master map of magnetic isochrons was constructed (Fig. 1) and used to constrain our model of the tectonic history of the Pacific plate.

Magnetic bight (M28–M21)

The magnetic bight study area encompassed the region to the southwest of the Shatsky Plateau from 22° to 32°N and 145° to 160°E (Fig. 2). Hilde et al. (1976) mapped a magnetic bight in

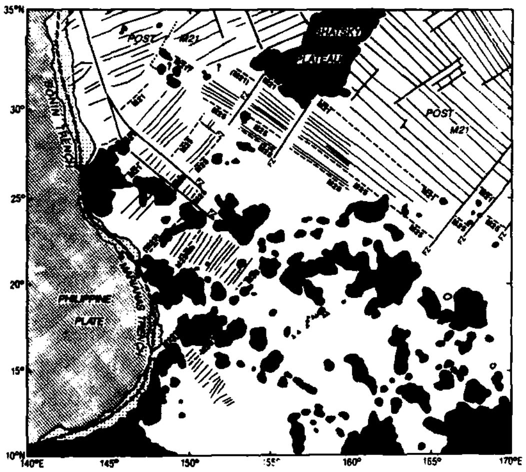

Fig. 1. Summary of magnetic isochrons in the northwestern Pacific. Isochrons including and younger than M21 are discussed in a companion article (Sager et al., this issue). Light continuous lines are magnetic isochrons and heavy continuous lines represent fracture zones. Anomalies M21, M25, M28 and M38 are shown by light dashed lines. Heavy dashed line shows the axis of the Mariana–Bonin trench and stippled regions are bathymetric features. Dotted lines distinguish possible pseudofaults caused by ridge propagation and the dotted pattern shows the deepest parts of trenches. Triangles show the location of possible ancient plate boundary discussed in text.

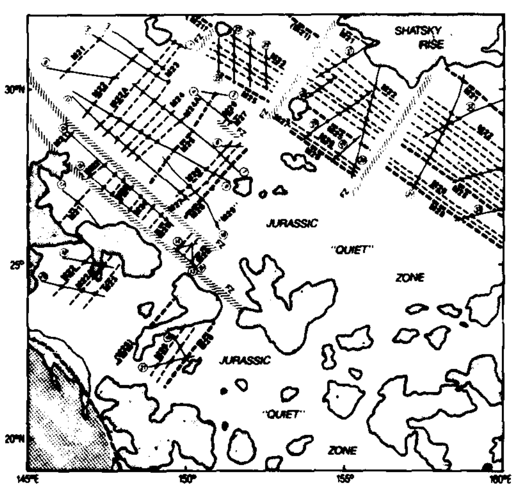

Fig. 2. Magnetic isochrons in the vicinity of the magnetic bight. Dashed lines are the isochrons. Heavy dashed lines represent M25 and M28. Light continuous lines show selected shiptracks and dots indicate magnetic anomaly picks. Diagonal shading represents fracture zones and bathymetric highs are shown by the stippled pattern. Circled numbers identify tracks in other figures and in text. Other symbols and notations as in Fig. 1.

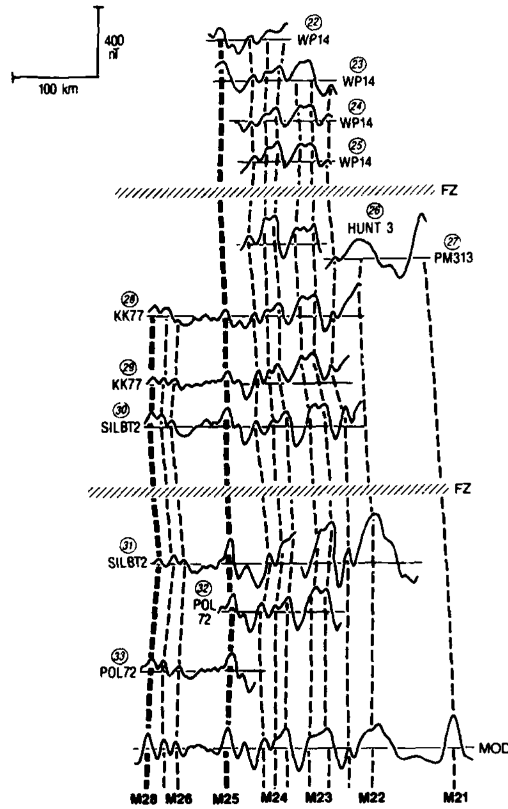

Fig. 3. Stack of magnetic anomaly profiles from the Hawaiian lineations (formed at the P–F ridge). Anomalies M21–M28 are shown on selected tracks from Fig. 2. Dashed lines show the anomaly correlations. M25 and M28 are shown by heavy dashed lines. Diagonal shading represents fracture zones. Lowermost anomaly profile was calculated from a magnetic reversal model. Northeast is to the right; southwest to the left. Location of survey tracks shown in Fig. 2.

this region showing the merger of the Late Jurassic–Early Cretaceous Hawaiian and Japanese lineations from M21 to M26 time. We used over 30 ship and aeromagnetic tracks to delineate the isochrons defining the bight.

Isochrons M21–M28 were identified in the region of the bight (Figs. 2–4). In the northwest corner of Fig. 2, north of 26°N and west of 150°E, the magnetic lineations were particularly well defined as they were mapped as part of a detailed marine magnetic survey conducted by the U.S. Navy (Handschumacher et al., 1988). The tracks examined in our study overlapped the U.S. Navy survey, allowing us to extend the lineation identifications to the east and south.

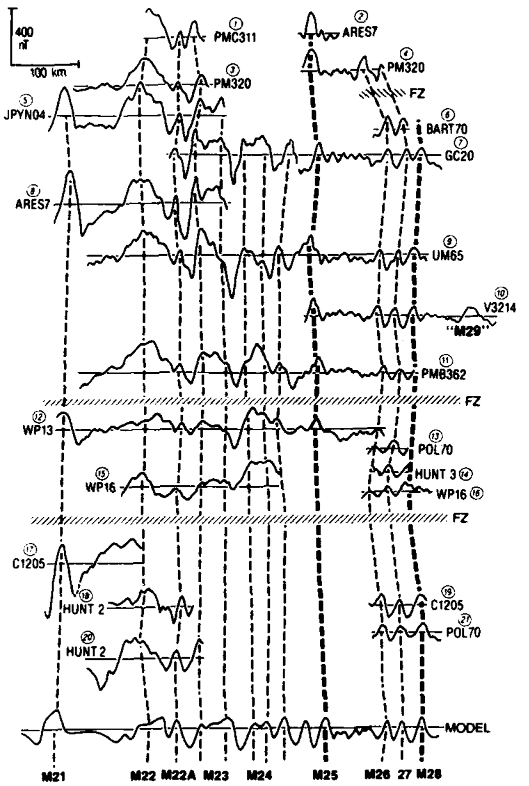

Fig. 4. Stack of observed magnetic anomaly profiles from the Japanese lineations (formed at the P–I ridge). Southeast is to the right; northwest to the left. Location of survey tracks shown in Fig. 2. Other symbols and notations as in Fig. 3.

The pre-M20 Japanese lineations have a strike of N42° E and the Hawaiian lineations have a trend of N43° W, so the two isochron sets meet nearly at right angles (actually, 95°). A half-spreading rate of 5.2 cm/yr was found on the former, and 3.1 cm/yr on the latter (Fig. 5), based on the polarity reversal time scale of Larson and Hilde (1975).

Our lineation map is different from previous work in several respects. The location of the bight and positions of fracture zones are far better constrained than in the study of Hilde et al. (1976), primarily because of our larger data set. Although Hilde et al. drew a relatively broad bend of the lineations at the bight, Fig. 2 shows that the bight is tightly constrained and that the bend must be relatively sharp. The four new aeromagnetic lines in the vicinity of 31° N, 152° E showed previously undiscovered isochrons of the Hawaiian lineations. These isochrons, identified as M22–M25 (Fig. 3), moved the location of the M25 bight 180 km to the northwest of the position mapped by Hilde et al. (1976).

Figure 2 shows five fracture zones, with offsets of 60–170 km, in the vicinity of the bight, whereas Hilde et al. (1976) found evidence for only two, one cutting each lineation sequence. A new fracture zone offsetting the Hawaiian lineations and trending from the western tip of the Shatsky Plateau was required on the basis of the aeromagnetic data that located M25–M23 near the bight. The fracture zone previously postulated in the Japanese lineations (Hilde et al., 1976) was resolved into two offsets. Tracks 12 and 15 (Fig. 4) show that the anomalies in between the two fracture zones were easily identified. Although the trend of these anomalies was not well constrained by the two closely spaced tracks, the detailed U.S.

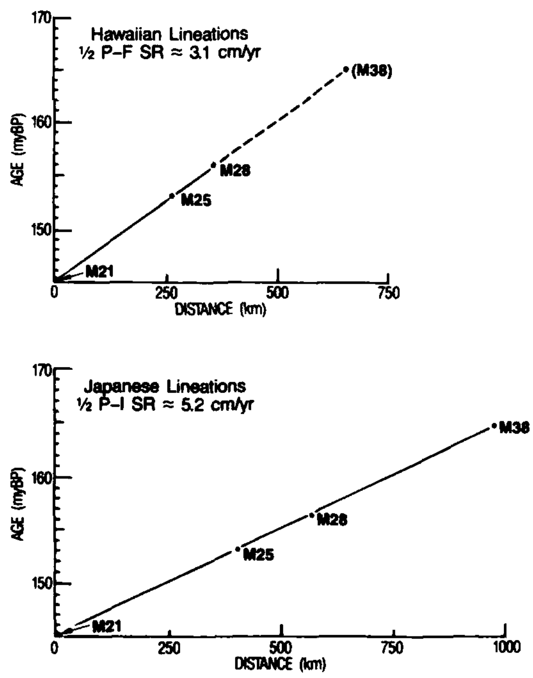

Fig. 5. Spreading rates on the P–I (below) and P–F (above) ridges, M38–M21. Rates from M25 to M21 were based on the geomagnetic reversal time scale of Larson and Hilde (1975) and were extrapolated to derive ages for older anomalies of the Japanese lineations (Table 1). An estimation of the expected position of M38 in the Hawaiian lineations is shown.

Navy magnetic survey did enable a good control (Handschumacher et al., 1988). An additional small-offset fracture zone was found cutting anomalies M26–M28 in the Japanese lineations near the bight. This fracture zone was constrained to be between tracks 4 and 6 (Figs. 2 and 4). The most interesting feature of the fracture zones around the bight is that they all have sinistral offsets. Perhaps this common trait implies something of the mechanism that formed them.

For the most part, anomalies M26–M28 were easily identified and correlated in the region of the bight. Although Cande et al. (1978) identified them on only seven tracks in this area, Figs. 3 and 4 show that they stand out quite well on many tracks crossing both lineation sets. In contrast, M29 proved difficult to pick in the region north of 25°N. Much of the problem resulted from the scarcity of properly oriented and positioned shiptracks as well as from the presence of seamounts near the expected position of M29 in the bight. However, the definition of anomaly M29 also poses problems for reasons discussed in the following sections.

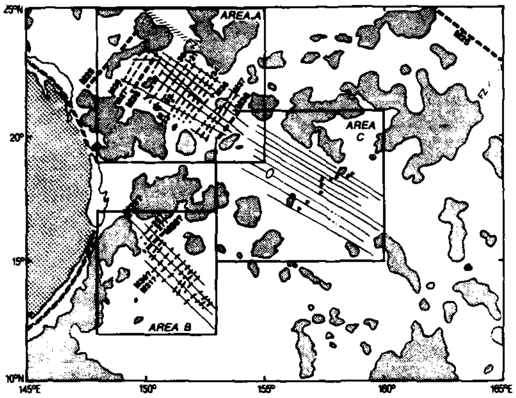

Fig. 6. Location map of aeromagnetic tracks used to trace magnetic lineations in the Jurassic Quiet Zone (JQZ). Dashed lines indicate magnetic reversal lineations. Heavy dashed lines represent M25 and M28. The magnetic data from areas A–C are shown in detail in Figs. 7–12 and discussed in the text. Stippled areas are bathymetric highs. Other symbols and notations as in Figs. 1 and 2.

Jurassic Quiet Zone

The JQZ study area included the region to the south of the magnetic bight, from 13° to 24°N, and from 145° to 160°E (Fig. 6). In this region we examined NORDA aeromagnetic survey data flown specifically to search for low-amplitude magnetic anomalies within the JQZ. To simplify the description and discussion of this data, we have further subdivided the area into three smaller sections, A–C (Fig. 6).

The survey is composed of closely spaced tracks oriented perpendicular to and overlapping the Japanese lineations. This lineation set was chosen because it displays the fastest spreading rate and would therefore provide the best resolution. Survey sites were thus chosen to be adjacent to the Japanese lineations, to avoid the many seamounts in the region, to steer clear of the potentially complex area of the triple junction, and to avoid the magnetic equator (approximately 10°N at this longitude) because of its enhancement of the amplitude of diurnal variations. Diurnal variations can be a problem because they create anomalies difficult to distinguish from crustal anomalies in marine magnetic data; the aeromagnetic data were therefore collected at much higher speeds which tend to smooth out variations caused by the external field. Furthermore, the NORDA aeromagnetic tracks were flown at times other than the hours around local noon, the latter being the period of the most significant diurnal changes.

Although most published magnetic polarity time scales portray the Jurassic as a period of constant normal polarity (e.g., Harland et al., 1982; Kent and Gradstein, 1985), the eight aeromagnetic lines in area A, oriented NW–SE, show correlatable low-amplitude magnetic lineations on JQZ seafloor (Fig. 7). Anomalies M26–M28 were easily identified. To the southeast was found a series of low-amplitude (20–75 nT) magnetic lineations with a trend identical to those of M26–M28 and the rest of the pre-M21 Japanese lineation set. Because their coherence and length are unlike that of any other known seafloor magnetic source these appear to be magnetic reversal anomalies recorded by seafloor spreading. Furthermore, because of their trend, low amplitudes, and the fact that they cannot be matched to a younger series of reversals, these lineations are most likely Jurassic magnetic isochrons formed before M28. We modeled

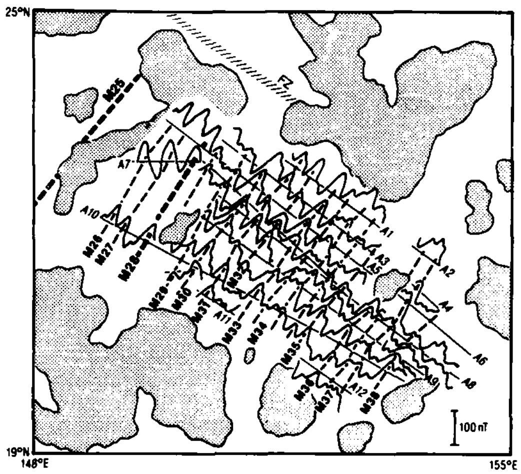

Fig. 7. Magnetic anomalies plotted perpendicular to aeromagnetic tracks in JQZ study area A. Correlations of magnetic anomalies, identified as isochrons M26–M38, are shown by dashed lines. Heavy dashed lines show M25 and M28. Numbers prefixed with "A" are survey tracks. Other symbols and notations as in Figs. 1 and 2.

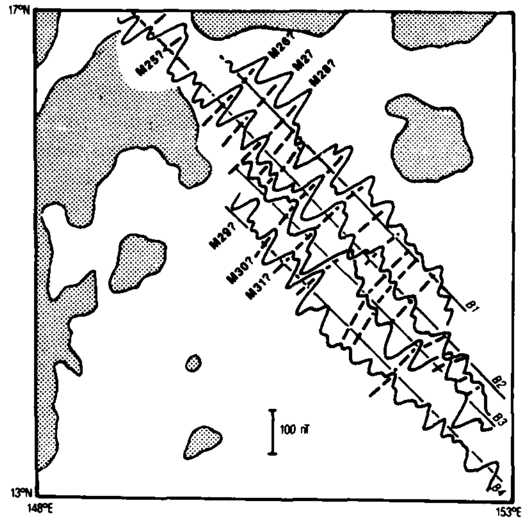

Fig. 9. Magnetic anomalies plotted perpendicular to aeromagnetic tracks in JQZ study area B. Numbers prefixed with "B" are survey tracks. Bathymetric features shown stippled.

these magnetic anomalies (Fig. 8) and tentatively numbered them M30–M38 (Handschumacher and Gettrust, 1985a,b).

It is curious that these lineations were not identified in the northern part of the JQZ. In the more northerly Japanese anomalies their absence may be a result of interference by bathymetric features and poor data distribution. However, these lineations may have been missed in the Hawaiian lineations because of the rapidity of the reversals and their low amplitude combined with the slower spreading rate on the P–F ridge.

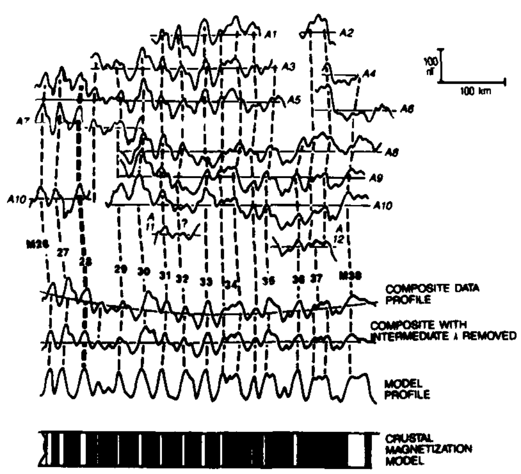

Fig. 8. Stack of observed and model magnetic anomaly profiles from JQZ study area A. Observed profiles are those along survey tracks A1–A12 (see Fig. 7 for location). A composite profile, a composite profile with regional anomaly (λ) removed, a model profile and a polarity block model (see Table 1) are also shown.

In area B four aeromagnetic lines approximately parallel to those in area A were examined. These tracks are located to the east of the Mariana trench between 13° and 17° N and between 148° and 153° E (Fig. 9). Positioned to the southeast of lineations previously identified as M22–M25 (Hussong and Fryer, 1982), they also appear to show low-amplitude magnetic anomalies similar to those in area A. Unfortunately, these anomalies did not correlate from line to line as well as those in area A. Nevertheless, the anomalies at 15°–17° N, 150°–151° E appeared to follow the familiar sequence of M26 to M28. Making this assumption, M29–M31 were tentatively identified to the southeast (Figs. 9 and 10). Other anomalies suggestive of M32–M38 were noted, but because of the uncertain correlation, we declined to identify them.

Figure 11 shows ten additional aeromagnetic lines in area C located to the southeast of area A,

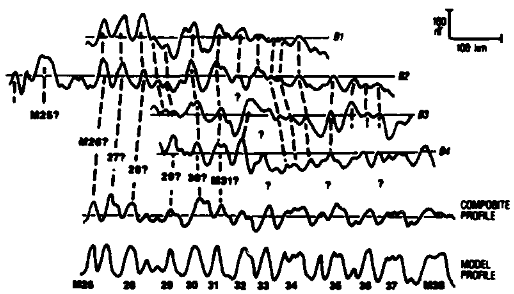

Fig. 10. Stack of observed and model magnetic anomalies from JQZ study area B. Location of observed profiles shown in Fig. 9.

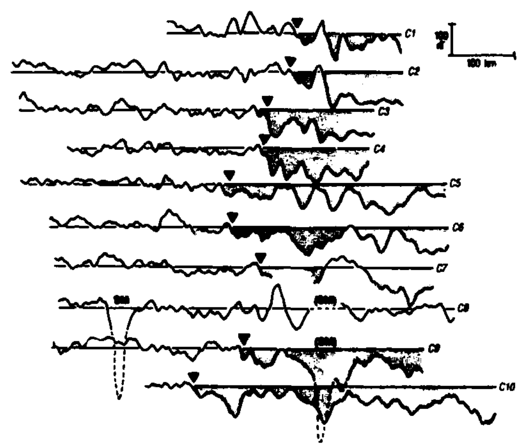

Fig. 12. Stack of observed magnetic anomalies from JQZ study area C. Although low-amplitude anomalies are observed, they cannot be reliably correlated across a significant number of tracks. Note the change in anomaly character at the triangle on each line. The anomalies to the right (southeast) have longer wavelengths, higher amplitudes, and a lower base level. The lineament denoted by the triangles may denote a fossil plate boundary or a change in spreading direction or rate. Location of profiles shown in Fig. 11. *SM*—seamount.

covering 15°–21° N, 153°–160° E. These lines are roughly perpendicular to anomalies M29–M38 in area A and traverse seafloor that should be older than M38. Although small amplitude anomalies were noted on all tracks, we were unable to correlate more than a few of them between lines. We did, however, note a distinct change in anomaly character between the northwest and southeast parts of this survey (Fig. 12). The anomalies in the southeast part of area C are different from those to the northwest in two ways (Figs. 11 and 12). First, the southeastern anomalies have larger amplitudes and generally longer wavelengths. Second, the base level to the southeast is lower and the anomalies there are predominantly negative. Both changes occur at roughly the same place on each line. Moreover, the locations of the changes are consistent from line to line forming a "boundary" that trends NE–SW across the survey (Figs. 11 and 12). The origin of this boundary is unclear. It may represent a change in spreading rate or direction, or even an earlier plate boundary.

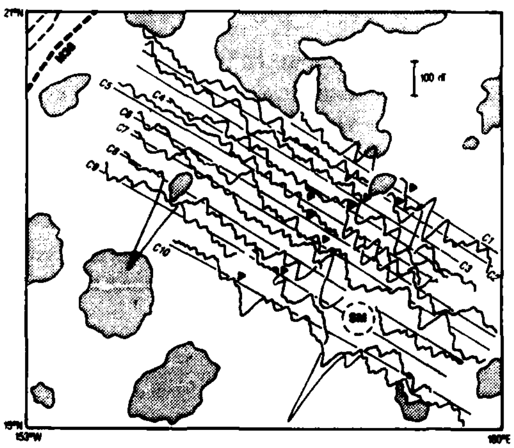

Fig. 11. Magnetic anomalies plotted perpendicular to aeromagnetic tracks in JQZ study area C. Dashed lines in upper left corner indicate positions of isochrons M37 and M38 from JQZ study area A. Triangles show boundary between anomalies of different character as discussed in text. *SM*—seamount. Bathymetric features shown stippled.

Interpretations and discussion

Jurassic polarity reversal time scale

Figures 7 and 9 show magnetic lineations on JQZ seafloor. Although these lineations display low amplitudes, they are easily correlated from track to track in area A (Fig. 7). Their trends are clear and parallel to M21–M28 in the Japanese lineations. Furthermore, their shapes, amplitudes and spacing are inconsistent with any other known sequence of Jurassic or younger reversals. Therefore, we believe that these lineations record reversals of the geomagnetic field that occurred prior to M28. If this interpretation is correct, it casts doubt upon explanations of the JQZ as a period of constant polarity.

It is difficult to prove beyond doubt that these low-amplitude lineations represent reversals rather than fluctuations of the magnetic field or even some other geologic phenomenon. To do so, it would be necessary to measure the same sequence of reversals in oriented paleomagnetic samples from a rock section of the appropriate age or to find them recorded in the seafloor of another ocean. However, several workers have found evidence of magnetic reversals in Jurassic sediments (Steiner and Helsley, 1975; Channell et al., 1982; Ogg and Steiner, 1985). Unfortunately, it is not yet possible to confidently correlate these reversals between land sites; nor is it yet possible to tie them to marine magnetic lineations. Nonetheless, we prefer geomagnetic field reversals as an explanation for the pre-M28 anomalies as they are a well-documented source of similar anomalies elsewhere.

A simple, two-dimensional magnetism model (Talwani and Heirtzler, 1964) was constructed to represent pre-M25 lineations (Fig. 8). A uniform thickness magnetic layer with vertical boundaries between blocks of opposite polarity was assumed and magnetic parameters appropriate for Jurassic seafloor in this region of the Pacific were adopted (Hilde et al., 1976).

In the construction of this extended Jurassic geomagnetic polarity time scale, the ten reversals in the sequence M25–M28 were carried over from published sources (Cande et al., 1978) and nineteen reversals older than M29 were added (Figs. 8 and 13). The M25–M29 segment had to be expanded slightly (about 10%) to fit the observed spacing of anomalies in the Japanese lineations (Fig. 13). This was because Cande et al. (1978) assumed a lineation trend about 15°–20° in error when they constructed their reversal time scale. In the pre-M28 sequence, numbers were assigned to significant magnetic anomaly peaks, formed either by longer reversals or clusters of reversals (Fig. 8).

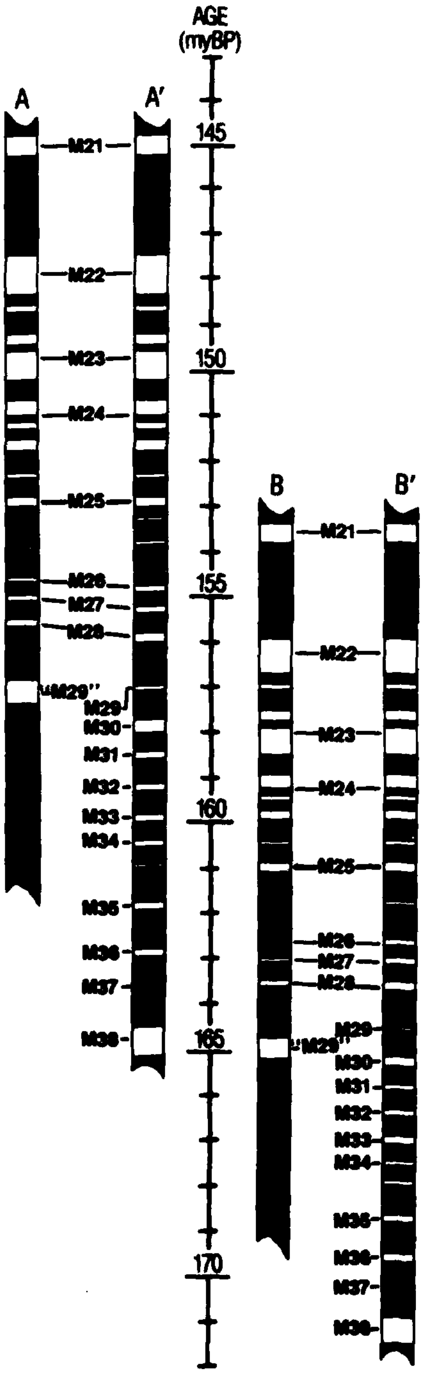

Fig. 13. Extension of the Jurassic geomagnetic polarity reversal time scale. Black indicates normal polarity; white is reversed. Column A is the time scale of Larson and Hilde (1975) with M25–M29 from Cande et al. (1978). Column A' shows an extension of the Larson and Hilde time scale with new reversals M30–M38 and revised ages for M25–M29. Column B is the time scale of Harland et al. (1982) and Column B' shows the new reversals added to that time scale with revised ages for M25–M29.

M29 in our model is not the same as that published by Cande et al. (1978). In order to match the observed anomalies, they had to make M29 wider than it should be because it is the end reversal of their magnetic model. We had to do the same for M38. Consequently, it was difficult to decide which pre-M28 reversal should correspond to previous interpretations of M29, particularly considering that the trend of the Japanese lineations used by Cande et al. (1978) was in error and some of their tracks may have crossed a fracture zone unknown to them. In our model, M29 is simply the first significant anomaly older than M28.

Using the spreading rate determined for M25–M21 in the Japanese lineations northwest of area A, the ages of the pre-M25 reversals were extrapolated (Fig. 13, Table 1). We assumed a constant spreading rate from M39 to M21 (Fig. 5) because this was the simplest possible assumption. The estimated age of any of these reversals depended on the geomagnetic reversal time scale employed. If the pre-M28 reversals were attached to the time scales of Larson and Hilde (1975) and Cande et al. (1978) an age of about 165 Ma was predicted for M38 (Table 1); however, if they were added to that of Harland et al. (1982), an age of about 172 Ma was implied (Fig. 13). In either case, the extension of the reversal time scale was about 8 m.y.

Compared to the rest of the M-sequence reversal anomalies mapped in the Pacific, the pre-M25 anomalies stood out in two respects. Their amplitudes are much lower (compare Figs. 3 and 4 with Fig. 7) and the reversal rate was much higher. Both the anomaly amplitudes and reversal frequency appear to have undergone a virtually simultaneous transition around anomaly M24–M22 time. Considering the first point, between M22 and M11 the average length of a period of normal polarity was 0.69 m.y., and for a reversed period, 0.53 m.y. However, in the interval between M38 and M25 it was much shorter, 0.12 and 0.21 m.y for normal and reversed periods respectively (Table 1, Fig. 13). Although the Jurassic reversal rate was high, it was not extraordinarily so. Indeed, these values of polarity period length are remarkably similar to those around anomaly 6–5 time in the Cenozoic when the average normal and reversed periods were 0.21 and 0.15 m.y. in length.

TABLE 1

Pre-M25 polarity interval boundary ages, extrapolated from Larson and Hilde (1975). All values expressed as Ma

Normal	Length	Reversed	Length	Chron
152.03–153.24	0.21	153.24–153.34	0.10	25
153.34–153.48	0.14	153.48–153.58	0.10	
153.58–153.77	0.19	153.77–153.91	0.14	
153.91–154.05	0.14	154.05–154.15	0.10	
154.15–154.25	0.10	154.25–154.35	0.10	
154.35–154.45	0.10	154.45–154.52	0.07	
154.52–154.77	0.25	154.77–155.07	0.30	26
155.07–155.32	0.25	155.32–155.60	0.28	27
155.60–155.85	0.25	155.85–156.10	0.25	28
156.10–156.34	0.24	156.34–156.42	0.08	28a
156.42–156.70	0.28	156.70–156.74	0.04	28b
156.74–154.92	0.18	156.92–157.05	0.13	29
157.05–157.61	0.56	157.61–157.95	0.34	30
157.95–158.00	0.05	158.00–158.09	0.09	30a
158.09–158.27	0.18	158.27–158.45	0.18	31
158.45–158.90	0.45	158.90–159.11	0.21	32
159.11–159.17	0.06	159.17–159.24	0.07	32a
159.24–159.52	0.28	159.52–159.75	0.23	33
159.75–160.08	0.33	160.08–160.26	0.18	34
160.26–160.35	0.09	160.35–160.47	0.12	34a
160.47–160.53	0.06	160.53–160.68	0.15	34b
160.68–161.05	0.37	161.05–161.18	0.13	34c
161.18–161.39	0.21	161.39–161.58	0.19	35
161.58–161.65	0.08	161.65–161.74	0.09	35a
161.74–162.04	0.30	162.04–162.10	0.06	35b
162.10–162.28	0.18	162.28–162.51	0.23	36
162.51–162.85	0.34	162.85–162.97	0.12	37
162.97–163.03	0.06	163.03–163.16	0.13	37a
163.16–163.24	0.08	163.24–163.35	0.11	37b
163.35–163.60	0.25	163.60–163.62	0.02	37c
163.62–163.85	0.23	163.85–164.56	0.71	38

Concerning the second point, the western Pacific anomalies formed after M22 time have typical amplitudes of 250–500 nT (Figs. 3 and 4), whereas those older than M25 have typical amplitudes of about 50–70 nT (Fig. 8). Between about M25 and M22 intermediate anomaly amplitudes are found. This difference has been attributed to an increase of the magnetic field strength from a low value during the Jurassic Quiet Period to a normal higher value during a later period of reversals (Vogt et al., 1971; Larson and Hilde, 1975; Cande et al., 1978). However, the observed magnetic data do not appear to show the lengthy (M21–M29) systematic decrease hypothesized by Cande et al. (1978).

The low amplitudes may be a result of several factors. Normal Jurassic seafloor is deep, so anomalies measured at sea level are attenuated by distance from their source. Furthermore, the rapid Jurassic reversal rate created narrow, closely spaced crustal blocks of opposing polarity whose magnetic anomalies tend to partially cancel when measured from the sea surface. However, we conducted a modeling study using the extended reversal time scale with the aforementioned two-dimensional technique and a source geometry typical of many used for the study of magnetic isochrons (i.e., a thin source layer 0.5 km thick with vertical polarity boundaries). The results suggested that these factors cannot fully account for the observed amplitude difference.

This problem has led others to suggest that the dipole strength of the geomagnetic field was low during the Jurassic (Vogt et al., 1971; Larson and Hilde, 1975; Cande et al., 1978). Although this explanation is possible, it is also plausible that a complex source geometry is part of the cause. The magnetization of layer 2 basalts and dikes near the surface of the ocean crust is degraded with time and lower source layers are thought to play an increased role in causing the magnetic anomaly measured at sea level (Blakely, 1976, 1983). Moreover, many models of the geometry of the polarity blocks within the crust suggest that they have significant transition zones, sloping boundaries, or both (Blakely, 1976; Kidd, 1977). Nonvertical or indistinct polarity boundaries such as these tend to accentuate the cancellation effect of the rapid reversal rate, reducing the amplitudes of the magnetic anomalies recorded at the sea surface.

Without definitive data, provided perhaps by drilling into the magnetic source bodies or deep-tow magnetometer measurements, any model of these anomalies and the cause of their different character is inherently nonunique. It appears that either the Jurassic magnetic field had two stable states of intensity, linked in some manner to the reversal rate, or the magnetic source bodies of opposing polarity in Jurassic Pacific crust have significant transition widths. We prefer the latter hypothesis because it seems the simplest explanation.

Our results suggest that explanations of the JQZ in terms of the source geometry are the most viable. In particular, it appears that models of the Jurassic as a period of constant normal polarity were incorrect. Additionally, models of the amplitude envelope of increasing geomagnetic field strength after the period of Jurassic constant polarity are cast into doubt. Not only is there no evidence of a constant polarity interval, but the transition from low to high anomaly amplitudes occurred over a much shorter period than previously thought.

Tectonic evolution

In order to investigate the early tectonic history of the Pacific plate we extrapolated the Phoenix (from Larson and Schlanger, 1981), Japanese, and Hawaiian isochron trends back in time into the Jurassic period assuming constant spreading rates (Fig. 14). This exercise suggests that the young Pacific plate was roughly triangular in shape and that its oldest crust is currently located at about 17° N, 160° E. The age of the oldest crust should be about 180–188 Ma. Hilde et al. (1976) used similar reasoning to suggest that the Pacific plate formed at a RRR triple junction between the Phoenix, Farallon and Izanagi plates at 180 Ma and at 150° N, 155° E in present-day coordinates. Our results are in general agreement except that they imply that the oldest point on the Pacific plate is 600 km farther to the east-northeast. The shape and size of the young Pacific plate brings to mind that of microplates, both current and ancient, found elsewhere in the Pacific (Handschumacher et al., 1981; Rea and Dixon, 1983; Anderson Fontana et al., 1985; Mammerickx and Sharman, 1988; Tamaki and Larson, 1988). In general, microplates are formed at or near triple junctions or large transform faults in areas of relatively rapid spreading. These factors suggest that the Pacific plate may have had such a beginning. Most microplates of this nature evolve separately for only a short time before being incorporated into one of the larger, surrounding plates; although

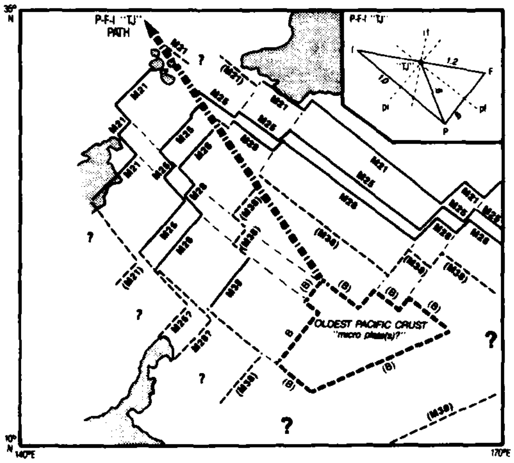

Fig. 14. Tectonic history of the northern Pacific plate and extrapolation of the boundaries of the oldest Pacific crust. Continuous lines trace isochrons M21–M38. Light dashed lines show predicted positions of isochrons not identified. Medium dashed lines labeled "B" outline oldest Pacific crust. Arrow and heavy dashed line show path of P–F–I triple junction. Bathymetric features shown stippled. Velocity diagram of P–F–I junction shown in inset for M28 time. Dot represents the velocity of the triple junction. Heavy continuous lines are relative velocity vectors between the plates. Dashed lines are the loci of points that remain on the plate boundaries; they are labeled with lower case letters (e.g., "pf" corresponds to the Pacific–Farallon ridge). Numbers are spreading rates normalized to the velocity of the P–I ridge.

there is no reason to suggest that a microplate cannot grow to a large size, like the Pacific,

Figure 14 implies that the genesis of the Pacific plate may have been roughly coincident with the formation of two major fracture zones. One cuts the Japanese lineations and trends northwest until it disappears into the Japan trench. The other is the long Mendocino Fracture Zone that crosses most of the Pacific Basin and terminates at the California coast. The trends of these fracture zones intersect nearly at the spot where the oldest Pacific plate is found. These results are intriguing because they suggest that the two large persistent fracture zones were generated by the formation of the Pacific plate.

Although such extrapolations as these make for interesting speculation, we highlight their potential dangers by noting two pieces of evidence that do not appear to fit our model. The first is the boundary shown by the abrupt change in magnetic anomaly character in area C of the JQZ. This feature may represent a change of spreading rate or direction, or a fossil plate boundary. Second, a detailed geophysical survey of a small area centered at 14° N, 159.5° E (Peterson et al., 1986), undertaken as a site survey of the Deep Sea Drilling Project, delineated aligned abyssal hills parallel to the Hawaiian lineations. If these were formed parallel to the spreading ridge, then they are at odds with our extrapolation of the Phoenix ridge in Figure 14. It is quite possible that the growth of the Pacific plate prior to M38 was more complex than implied by our simple model. If this model fails, the problem probably occurs prior to M38 because the parallelism of M38–M21 implies that no major plate boundary reorganization occurred during the intervening time.

From M28 onward, we can trace the formation of the northern boundary of the Pacific plate and in particular the behavior of the P–F–I triple junction using magnetic lineations (Fig. 14). The location of the triple junction was plotted by extrapolating each magnetic isochron of the Japanese and Hawaiian lineations to their intersection.

Using the spreading rates from Fig. 5 and the isochrons in Figs. 1 and 2, a velocity-space diagram of the P–F–I triple junction was constructed corresponding to anomaly M28 time (Fig. 14). This analysis indicates several important features of the P–F–I ridge system. The location of the junction in velocity space is close to the F–I velocity vector, implying that the triple junction could have assumed either a RRR or RRF configuration. The latter would have been stable only as long as the velocity of the junction lay on the F–I velocity vector and thus a small change in spreading rates or directions would have caused it to revert to the RRR geometry. Additionally, the diagram implies that both the P–I and P–F ridges were growing in length and that the triple junction should have drifted to the north-northwest with respect to the Pacific plate. The increasing lengths of the P–I and P–F ridges are evident in Fig. 14. The figure also shows that the triple junction did indeed drift north-northwest with respect to the Pacific plate.

Overall, the Jurassic evolution of the Pacific plate and P–F–I triple junction appears to have been relatively simple. This situation changed abruptly at M21 time as the spreading direction on the P–I ridge rotated by 24° and large ridge jumps occurred on the P–F ridge. Some evidence suggests that a microplate formed between the Pacific, Farallon and Izanagi plates. These topics are discussed in a companion article (Sager et al., this issue).

Conclusions

Jurassic magnetic reversal lineations were mapped in the vicinity of the magnetic bight in the western Pacific. New aeromagnetic data extended the length of the known Hawaiian lineations and allowed the magnetic bight to be located more accurately from M28–M21. Other aeromagnetic data show coherent, low-amplitude magnetic lineations on seafloor older than M28 in the region east of the Mariana trench. These lineations were apparently formed by rapid magnetic reversals that occurred in the Jurassic period. We have proposed an extension of the geomagnetic time scale and numbered the new anomalies M30–M38. M38 is predicted to be approximately 8 m.y. older than M29. These anomalies cast doubt on hypotheses of the Jurassic Quiet Zone that involve a period of constant polarity. In addition, they do not appear to show a significant systematic transition from periods of low to high geomagnetic field strength during the Late Jurassic. We prefer the hypothesis that the quiet zone is the result of rapid reversals combined with a crustal source geometry that has the effect of creating transitions of significant width between blocks of opposing polarity.

The early history of the northern Pacific plate and the P–F–I triple junction was traced with observed magnetic lineations where possible and by the extrapolation of the observed lineations to older seafloor. The Pacific plate seems to have grown from a small plate that appeared at the triple junction between the Phoenix, Farallon and Izanagi plates about 188–180 m.y. ago at a point currently located at about 17°N, 160°E. A long fracture zone which cuts the Japanese lineations, together with the Mendocino Fracture Zone which offsets the Hawaiian lineations, can be traced to the oldest part of the Pacific. Evidently they formed at the time the Pacific plate was born. The magnetic isochron data also imply that the evolution of the northern Pacific and the P–F–I triple junction was relatively simple from M38–M22 time. The triple junction drifted north-northwest with respect to the Pacific plate to a position presently near the southwest tip of the Shatsky Plateau.

Acknowledgements

We wish to thank the flight crews of the NAVOCEANO support squadron VXN-8 and NRL special project squadron stationed at NATC Patuxent River, Maryland for their assistance in aeromagnetic data collection. We also thank Steve Madosick III and Eugene Morganthalier for their assistance in data processing. This work was supported by Office of Naval Research program element number ONR-61153N under the direction of Herbert C. Eppart Jr. We would also like to express our appreciation to J. Channell, M. Steiner, J. Ogg, G. Sharman, P. Vogt, S. Cande, R. Larson and J. Gettrust for their helpful discussions, suggestions and reviews.

References

Anderson-Fontana, S., Engeln, J.F., Lundgren, P., Larson, R.L. and Stein, S., 1986. Tectonics and evolution of the Juan Fernandez microplate at the Pacific–Nazca–Antarctic triple junction. J. Geophys. Res., 91: 2005–2018.

Atwater, T. and Grow, J.G., 1970. Mid-Tertiary tectonic transitions in the Aleutian arc. Geol. Soc. Am. Bull., 81: 3715–3722.

Barrett, D.L. and Keen, C.E., 1976. Mesozoic magnetic lineations, the magnetic quiet zone, and sea floor spreading in the northwest Atlantic. J. Geophys. Res., 81: 4875–4884.

Blakely, R.J., 1976. An age-dependent, two-layer model for marine magnetic anomalies. In: G.H. Sutton, M.H. Manghnani and R. Moberly (Editors), Geodynamics of the Pacific Ocean Basin and its Margin. Am. Geophys. Union, Geophys. Monogr., 19: 227–235.

Blakely, R.J., 1983. Statistical averaging of marine magnetic anomalies and the aging of oceanic crust. J. Geophys. Res., 88: 2289–2296.

Burek, P.J., 1970. Magnetic reversals: their application to stratigraphic problems. Am. Assoc. Pet. Geol. Bull., 54: 1120–1139.

Cande, S.C., Larson, R.L. and LaBreque, J.L., 1978. Magnetic lineations in the Pacific Jurassic Quiet Zone. Earth Planet. Sci. Lett., 41: 434–440.

Channell, J.E.T., Ogg, J.G. and Lowrie W., 1982. Geomagnetic polarity in the Early Cretaceous and Jurassic. Philos. Trans. R. Soc. London, Ser. A, 306: 137–146.

Handschumacher, D.W. and Gettrust, J.F., 1985a. Mixed polarity model for the Jurassic "Quiet Zones": new oceanic evidence of frequent pre-M25 reversals. Eos, Trans. Am. Geophys. Union, 66: 867.

Handschumacher, D.W. and Gettrust, J.F., 1985b. Marine geophysics at NORDA: seafloor investigations. Nav. Res. Rev., 37: 24–30.

Handschumacher, D. and Kroenke, L., 1978. An extended time scale of Mesozoic geomagnetic reversals. Eos, Trans. Am. Geophys. Union, 59: 266 (Abstr.).

Handschumacher, D.W., Pilger, R.H., Foreman, J.A. and Campbell, J.R., 1981. Structure and evolution of the Easter plate. In: R. Roderick (Editor), Nazca Plate: Crustal Formation and Andean Convergence. Geol. Soc. Am. Mem., 154: 63–76.

Handschumacher, D.W., Bracey, D.R. and Sager, W.W., 1988. Detailed magnetic anomaly chart of the western Pacific. (Geological Society of America Map and Chart Series.) Geol. Soc. Am., Boulder, Colo., in press.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R., 1982. A Geologic Time Scale, Cambridge Univ. Press, Cambridge, 131 pp.

Hayes, D.E. and Heirtzler, J.R., 1968. Magnetic anomalies and their relation to the Aleutian island arc. J. Geophys. Res., 76: 4637–4646.

Hayes, D.E. and Pitman III, W.C., 1970. Magnetic lineations in the north Pacific. In: J.D. Hayes (Editor), Geological Investigations of the North Pacific Ocean. Geol. Soc. Am. Mem., 126: 291–314.

Hayes, D.E. and Rabinowitz, P.D., 1975. Mesozoic magnetic lineations and the magnetic quiet zone off northwest Africa. Earth Planet. Sci. Lett., 28: 105–115.

Heirtzler, J.R. and Hayes, D.E., 1967. Magnetic boundaries in the north Atlantic Ocean. Science, 157: 185–187.

Helsley, C.E. and Steiner, M.B., 1969. Evidence for long intervals of normal polarity during the Cretaceous period. Earth Planet. Sci. Lett., 5: 325–332.

Hilde, T.W.C., Isezaki, N. and Wageman, J.M., 1976. Mesozoic seafloor spreading in the north Pacific. In: G.H. Sutton, R. Moberly and M. Manghanani (Editors), The Geophysics of the Pacific Ocean Basin and its Margin. Am. Geophys. Union, Geophys. Monogr., 19: 205–226.

Hussong, D.M. and Fryer, P., 1982. Structure and tectonics of the Mariana arc and fore-arc: drillsite selection survey. In: D.M. Hussong, S. Uyeda et al., Initial Reports of the Deep Sea Drilling Project, Vol. 60, U.S. Gov. Print. Off., Washington, D.C., pp. 33–44.

Irving, E. and Pullaiah, G., 1976. Reversals of the geomagnetic field, magnetostratigraphy and relative magnitude of paleosecular variation in the Phanerozoic. Earth Sci. Rev., 12: 35–64.

Keating, B.H. and Helsley, C.E., 1978. Magnetostratigraphy of Cretaceous age sediments from site 361, 363 and 364. In: H.M. Bolli, W.B.F. Ryan et al., Initial Reports of the Deep Sea Drilling Project, Vol. 40, U.S. Gov. Print. Off., Washington, D.C., pp. 459–468.

Kent, D.V. and Gradstein, F.M., 1985. A Cretaceous and Jurassic geochronolgy. Geol. Soc. Am. Bull., 96: 1419–1427.

Kidd, R.G.W., 1977. The nature and shape of the sources of marine magnetic anomalies. Earth Planet. Sci. Lett., 33: 310–320.

Larson, R.L. and Chase, C.G., 1972. Late Mesozoic evolution of the western Pacific Ocean. Geol. Soc. Am. Bull., 83: 3627–3644.

Larson, R.L. and Hilde, T.W.C., 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic. J. Geophys. Res., 80: 2586–2594.

Larson, R.L. and Pitman III, W.C., 1972. World-wide correlation of Mesozoic magnetic anomalies and its implications. Geol. Soc. Am. Bull, 83: 3645–3662.

Larson, R.L. and Schlanger, S.O. 1981. Geological evolution of the Nauru basin, and regional implications. In: R.L. Larson, S.O. Schlanger et al., Initial Reports of the Deep Sea Drilling Project, Vol. 61. U.S. Gov. Print. Off., Washington, D.C., pp. 841–862.

Mammerickx, J. and Sharman, G.F., 1988. Tectonic evolution of the north Pacific during the Cretaceous Quiet Period. J. Geophys. Res., 93: 3009–3024.

Mascle, J. and Phillips, J., 1972. Smooth zones in the south Atlantic. Nature, 240: 80–84.

McElhinny, M.W. and Burek, P.J., 1971. Mesozoic paleomagnetic stratigraphy. Nature, 232: 98–102.

Morley, L.W. and Larochelle, A. 1964, Paleomagnetism as a means of dating geological events. R. Soc. Can. Spec. Publ., 8: 39–50.

Ogg, J.G. and Steiner, M.B., 1985. Jurassic magnetic polarity time scale-current status and compilation. In: O. Michelson and A. Zeiss (Editors), Jurassic Stratigraphy. Dan. Geol. Surv. Spec. Publ., pp. 1–16.

Peterson, L.D., Duennebier, F.K. and Shipley, T.H., 1986. Site surveys in the western Pacific conducted aboard the Kana Keoki, cruise KK810626, Leg 4. In: R. Moberly, S.O. Schlanger et al., Initial Reports of the Deep Sea Drilling Project, Vol. 89. U.S. Gov. Print. Off., Washington, D.C., pp. 603–628.

Poehls, K.A., Luyendyk, B.P. and Heirtzler, J.R., 1973. Magnetic smooth zones in the world's oceans. J.Geophys. Res., 78: 6985–6997.

Rabinowitz, P.D., Coffin, M.F. and Falvey, D., 1983. The separation of Madagascar and Africa, Science, 220: 67–69.

Rea, D.K. and Dixon, J.M., 1983. Late Cretaceous and Paleogene tectonic evolution of the north Pacific Ocean. Earth Planet. Sci. Lett., 65: 145–166.

Roots, W.D., 1976. Magnetic smooth zones and slope anomalies: a mechanism to explain both. Earth Planet. Sci. Lett., 31: 113–118.

Sager, W.W., Handschumacher, D.W., Hilde, T.W.C. and Bracey, D.R., 1988. Tectonic evolution of the northern

Pacific plate and Pacific–Farallon–Izanagi triple junction in the Late Jurassic and Early Cretaceous (M21–M10). In: C.R. Scotese and W.W. Sager (Editors), Mesozoic and Cenozoic Plate Reconstructions. Tectonophysics, 155 (this issue): 345–364.

Sharman, G.F. and Risch, D.L., 1988. Northwest Pacific tectonic evolution in the Middle Mesozoic. In: C.R. Scotese and W.W. Sager (Editors), Mesozoic and Cenozoic Plate Reconstructions. Tectonophysics, 155 (this issue): 331–344.

Steiner, M.B. and Helsley, C.E., 1975. Late Jurassic magnetic polarity sequence. Earth Planet. Sci. Lett., 27: 108–112.

Talwani, M. and Heirtzler, J.R., 1964. Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape. In: G.A. Parks (Editor), Computers in the Mineral Industries. Stanford Univ. Press, Stanford, pp. 464–480.

Tamaki, K. and Larson, R.L., 1988. Mesozoic tectonic history of the Magellan microplate in the western central Pacific. J. Geophys. Res., 93: 2857–2874.

Uyeda, S. and Vacquier, V., 1968. Geothermal and geomagnetic data in and around the island of Japan. In: L. Knopoff, C.L. Drake and P.J. Hart (Editors), The Crust and Upper Mantle of the Pacific Area. Am. Geophys. Union, Geophys. Monogr., 12: 349–366.

Uyeda, S., Vacquier, V., Yasui, M., Sclater, J., Sato, T., Lawson, J., Watanabe, T., Dixon, F., Silver, E., Fakao, Y., Sudo, K., Nishikawa, N. and Tanaka, T., 1967. Results of the geomagnetic survey during the cruise of the R/V Argo in the western Pacific, 1966 and the compilation of magnetic charts of the same area. Bull. Earthquake Res. Inst. Tokyo, 45: 799–814.

Vine, F.J. and Matthews, D.J., 1963. Magnetic anomalies over oceanic ridges. Nature, 199: 947–949.

Vogt, P.R. and Einwich, A.M., 1979. Magnetic anomalies and sea-floor spreading in the western north Atlantic, and a revised calibration of the Keathley (M) geomagnetic reversal chronology. In: B.E. Tucholke, P.R. Vogt et al., Initial Reports of the Deep Sea Drilling Project, Vol. 43, U.S. Gov. Print. Off., Washington, D.C., pp. 857–876.

Vogt, P.R., Anderson, C.N. and Bracey, D.R., 1971. Mesozoic magnetic anomalies, sea-floor spreading, and geomagnetic reversals in the southwestern north Atlantic. J. Geophys. Res., 76: 4796–4823.

Woods, M.T. and Davies, G.F., 1982. Late Cretaceous genesis of the Kula plate. Earth Planet. Sci. Lett., 58: 161–166.