Late Jurassic and Early Cretaceous Evolution of the Western Central Pacific Ocean

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The Phoenix lineations are a set of east-west trending magnetic anomalies that recorded sea-floor spreading in the Nauru and Central Pacific Basins of the western Pacific from the Late Jurassic through the Early Cretaceous. The northern portions of these basins near the Marshall-Gilbert Islands are characterized by a magnetic quiet zone that presumably formed in the Late Jurassic prior to M25 (153 m.y.). In the eastern part of the Central Pacific Basin just east of Magellan Rise is a northwest trending M11 (126 m.y.) to M4 (117 m.y.) anomaly sequence. The geometry and spreading rates associated with the east-west trending Phoenix lineations and the Hawaiian lineations to the north suggest that the two patterns met at a fault-fault-ridge triple junction from M25 (153 m.y.) until M14 (131 m.y.) time. This system underwent a readjustment between M14 and M10 time that transferred the Magellan Rise from the Phoenix plate to the Pacific plate and established two triple junctions in place of the previous one. A stable fault-fault-ridge junction formed just southeast of Magellan Rise to connect the east-west and northwest trending Phoenix lineations, while a slow-spreading, ridge-ridge-ridge junction broke the original Pacific plate in two from at least M11 to M4 time and was responsible for the formation of the Mid-Pacific Mountains.

1. Introduction

One of the oldest and best preserved records of sea-floor spreading in the world's oceans is present in the western Central Pacific. In this paper, I shall describe and model correlations of these Late Jurassic and Early Cretaceous magnetic anomalies in the Nauru Basin and the Central Pacific Basin. I shall also discuss fracture zone morphology in that area, variations in sediment distribution that reflect different tectonic histories, and the general structure of the region. These observations combined with the Hawaiian lineation pattern to the north are the basis for a plate tectonic evolution of this area. This evolution includes spreading rate changes and triple junction configurations at various times in the Late Mesozoic. I shall also propose an explanation for the Mid-

Pacific Mountains that results from the geometry of the lineation patterns north and south of this undersea mountain range.

2. Magnetic Anomaly Lineations

The area shown in Figs. 1 and 2 was first studied for magnetic anomaly lineations by LARSON *et al.* (1972) who correlated magnetic anomalies M1 to M10 south of Magellan Rise. They named these features the Phoenix lineations and postulated that the anomalies are Early Cretaceous in age on the basis of Deep Sea Drilling Site (DSDP) 166 where Hauterivian sediments were recovered overlying basalt between anomalies M7 and M8 south of Magellan Rise on Fig. 1 (WINTERER and EWING *et al.*, 1973). LARSON and CHASE (1972) subsequently correlated these anomalies with the Japanese and Hawaiian lineation patterns to the north and derived a paleomagnetic pole location for the Pacific plate during the Early Cretaceous from this correlation. They then proposed a tectonic evolution for the Pacific plate that involved 40° (4,500 km) of net northward motion since the Early Cretaceous and large (5,000–7,000 km) amounts of subduction of oceanic crust at various margins of the Pacific Ocean in the past 120 m.y.

The majority of the lineations shown on Figs. 1 and 2 are correlations made since the initial study of LARSON *et al.* (1972), and are reported here for the first time. The magnetic reversal block models shown in Figs. 3–6 are based on the reversal time scale proposed by LARSON and HILDE (1975) for the Late Jurassic and Early Cretaceous. Spreading rates on the Phoenix lineations are based on that study which assumes that the northern portion of the Hawaiian lineations was generated at a constant rate of about 3 cm/yr. Anomalies M16 to M25 in the Nauru Basin west of the Marshall-Gilbert Islands are the well-preserved result of a Late Jurassic spreading ridge that separated the Pacific and Phoenix plates in that area from 153 to 135 m.y. ago (Figs. 1–3). Anomalies M25 to M21 appear to have formed at 4.7 cm/yr, and the spreading rate slowed to 3.3 cm/yr subsequent to the formation of M21 about 145 m.y. ago. The northern part of the Nauru Basin, north of Kusaie Island, is characterized by very small magnetic anomalies and referred to as the Jurassic Quiet Zone (Figs. 1–3). This area presumably formed by similar spreading processes prior to 153 m.y. during the interval of normal magnetic polarity proposed by LARSON and HILDE (1975). There is a suggestion that Early Cretaceous anomalies M11 to M15 are present between and south of Nauru and Ocean Islands; however, reasonable identifications can only be made on the NOVA profile (Figs. 2 and 3). Other lines west of this profile do not support these correlations.

In the Central Pacific Basin, anomalies M11 to M25 are well-established

Fig. 1. Phoenix lineation pattern in the western central Pacific Ocean. Selected contours delineate the Ontong-Java Plateau, Magellan Rise, Nova-Canton Trough and F.Z.-2 (fracture zone -2). Deep sea drilling sites are shown as dots with the site number in parenthesis and the basement age in millions of years (if reached).

Fig. 2. Magnetic anomaly data across the Phoenix lineations shown with correlation lines for selected lineations. Positive anomalies shown in black. Track labels key data to Figs. 3-6 where data are shown in projected form. Short segments of track labeled A, B, C are the locations of the seismic profiles in Figs. 7 and 8.

Fig. 3. Projected magnetic anomaly profiles and model profile for the Nauru Basin. Magnetic reversal block model in this and Figs. 4-6 based on the time scale of LARSON and HILDE (1975). Black blocks are normally magnetized and white blocks are reversely magnetized. Model profile segments were computed for various spreading rates as shown. The magnetic layer is 5,500-6,000 m deep in each of these segments, and the remanent magnetization was varied to match the observed anomaly amplitudes. The cross-sectional shapes (skewness) of these anomalies were matched by varying the skewness parameter, θ (theta), in 10° steps as shown.

on two composite profiles between the Marshall-Gilbert Islands and the fracture zone labeled F.Z.-2 in Figs. 1, 2 and 4. In contrast with the Nauru Basin, the Early Cretaceous portion of the pattern M11 to M15 is obvious on both profiles, and anomaly M10N may be present on profile C1712-3, although basement rises to less than 3,000 m there as the profile crosses the saddle between Beru and Naukunau Atolls in the eastern Gilberts. Late Jurassic anomalies M16 to M22 are obvious on both profiles, and older anomalies M23, 24 and 25 with the Jurassic Quiet Zone to the north are well displayed on profile C1712-2. These older anomalies are not as apparent on profile C1712-1 and the northern continuation of the profile shows much larger anomalies than are usually recorded in a Jurassic Quiet Zone. This may indicate a re-activation of volcanism and/or faulting that is also suggested by the recovery of basalt directly underlying Albian (100 m.y. old) sediments at DSDP 169 (WINTERER and EWING *et al.*, 1973) near profile C1712-1 (Fig. 1). Spreading rates changed in a manner similar to the Nauru Basin, the M25 to M21 sequence having formed at 5.4 cm/yr.

CENTRAL PACIFIC BASIN
NEAR MARSHALL-GILBERTS

Fig. 4. Projected magnetic anomaly profiles and model profile for the Central Pacific Basin near and just east of the Marshall-Gilbert Islands. Conventions are the same as in Fig. 3.

Subsequent to M15 the rate of spreading appears to have continued to decrease to 3.1 cm/yr. The proportionally faster spreading rates for M15 to M25 in the Central Pacific Basin relative to the Nauru Basin indicate that the near pole of rotation for the Pacific-Phoenix plates lies beyond the Nauru Basin to the west relative to the present-day orientation of the anomalies.

The identifications of anomalies M1 to M13 south of the Magellan Rise are shown on Fig. 5. Anomalies M1 to M10 are the same as those shown by LARSON *et al.* (1972) and additional correlations are shown for anomalies M10N, M11, M12 and M13 between fracture zones F.Z.-1 and F.Z.-2. This correlation was facilitated by the recognition of the reversal pattern corresponding to anomaly M10N by LARSON and HILDE (1975) that was not included in the original Late Mesozoic reversal time scale of LARSON and PITMAN (1972). The correlation of these older anomalies (M10N-M13) indicates that substantial spreading rate changes occurred south of Magellan Rise during the Early Cretaceous. Anomalies M14 to M12 were formed at 2.5 cm/yr, the slowest rate observed on the east-west trending Phoenix lineations. Subsequent to M12 the spreading rate increased significantly to 6.4 cm/yr from M10 to M1 time. This spreading rate is greatest between F.Z.-1 and F.Z.-2 and decreases to the east indicating that the rotational pole for the Pacific-Phoenix plates lies relatively east of the Central Pacific Basin during this interval.

A short sequence of northwest-trending lineations labeled M4 to M12 is

Fig. 5. Projected magnetic anomaly profiles and model profile for the Central Pacific Basin south of Magellan Rise. Conventions the same as in Fig. 3.

shown just east of Magellan Rise (Figs. 1, 2 and 6). This lineation trend was mapped, but the anomalies were not identified by LARSON *et al.* (1972). Although this is a short sequence of anomalies present in an area where individual lineations do not persist for more than a few hundred kilometers, the identification of these anomalies as the Early Cretaceous sequence M4 to M12 tentatively appears to be justified (Fig. 6). As is the case on the east-west trending lineations, the recognition of anomaly M10N makes this correlation much more plausible. Furthermore, the extension of both lineation patterns would join common anomalies without large amounts of transform offset. This lineation pattern is remarkable in that it fans drastically to the southwest. The trends of these lineations, including their fan-shaped appearance, is a close approximation of the bathymetric contours of this area (WINTERER, 1973). The profiles in Fig. 6 were projected along 40° , and the model profile was computed for a spreading rate of 4.2 cm/yr. Both of these parameters are intermediate values that vary dramatically across this small lineation pattern. The spreading rate decreases

Fig. 6. Projected magnetic anomaly profiles and model profile for the Central Pacific Basin east of Magellan Rise. Conventions the same as in Fig. 3.

by a factor of two toward the northwest, indicating that the rotation pole for these lineations lies relatively northwest only a few hundred kilometers from this area.

3. Sediment Distribution and Basement Morphology

The deep-sea sedimentary section in the Central Pacific Basin east of F.Z.-2 is well represented by the right-hand side of profile A (Figs. 1 and 7). A thin (~ 500 m) layer of very transparent sediments overlies an opaque acoustic basement about 6,300 m below sea level. There is a suggestion that igneous basement lies slightly deeper than acoustic basement on some profiles. At DSDP 65 (Fig. 7) and 166, the transparent layer corresponds to Eocene to Recent radiolarian ooze overlying a Middle Eocene porcelanite that represents the top of the opaque layer. At DSDP 166, this is underlain by about 100 m of Cretaceous brown clay and zeolitic ash that is in turn underlain by nannofossil mudstones that were deposited on the ridge crest in the Hauterivian (WINTERER and RIEDEL *et al.*, 1971). The hyperbolic echoes and rough character associated with the acoustic basement suggest that true volcanic basement generally lies only a short (~ 100 m) interval beneath this reflector.

The water depth, basement morphology and acoustic character of the sediments change markedly west of F.Z.-2 (Fig. 7). Between F.Z.-2 and the Marshall-Gilbert Islands, the water is shallower, the acoustic basement generally quite smooth, and the overlying sediments thicker and more layered than in

Fig. 7. Seismic reflection profile A (see Fig. 2 for location) made across F.Z.-2 in the Central Pacific Basin. Horizontal scale in kilometers approximates the constant speed of the ship on this profile.

the area east of F.Z.-2. F.Z.-2 usually occurs as one or two well-developed ridges with at least 1,000 m of local relief similar to that observed on Fig. 7. Thus, the most obvious explanation for these different ocean floor characteristics is that the fracture zone acts as a dam that traps carbonate turbidite deposits shed from the Marshall-Gilbert Islands on the west side of the fracture zone and allows only pelagic radiolarian oozes to be deposited to the east. These thick, flat-lying deposits also serve to mask the true volcanic basement that lies deeper than profiler penetration. Turbidites shed from the reefs of the Gilberts were recovered in cores on the V2811 track shown on Fig. 7.

West of the Marshall-Gilberts in the Nauru Basin (Fig. 8), the sea-floor is generally smooth, the sediment section contains many internal reflectors, and the water depth is generally shallower than in the Central Pacific Basin to the east. In the northern Nauru Basin, acoustic basement is also smooth over the Jurassic Quiet Zone and anomalies M20 to M25. To the south, the sea-floor rises gently to about 4,000 m over anomalies M16 to M19 and the acoustic basement becomes much rougher. The upper 300–500 m of the acoustic section where the reflectors are more transparent is undoubtedly sedimentary. Piston cores contain radiolarian clays that have lower percentages of radiolaria in the northern part of the basin. The Miocene is often penetrated in the first 15 m. No DSDP sites have been located to date in the Nauru Basin, so the nature of the deeper layers is a matter of speculation. The deeper reflectors within the opaque horizon are generally flat-lying and also likely to be sedimentary. Very occasionally (Fig. 8, profile B) the opaque horizon is penetrated to reveal what obviously is several hundred meters of sediment lying below it. The low frequency channel of profile C (Fig. 8) also shows a suggestion of a deeper base-

Fig. 8. Seismic reflection profiles B and C (see Fig. 2 for location) made in the Nauru Basin. Both profiles made at approximately constant ship speeds, however, the traverse rate on the profiler was doubled during the 24 km and 11 km segments of profile C during sonobuoy runs. Low frequency channel (20–40 Hz) displayed on the 24 km, 50 km, and 11 km segments of profile C may reveal volcanic basement just below 8 seconds reflection time in the Jurassic Quiet Zone. Intermediate frequency channel (60–120 Hz) displayed on 45 km segment of profile C shown for comparison with profile B.

ment at about 8.0 seconds reflection time in the Jurassic Quiet Zone. This hypothesis is supported by sonobuoy results obtained over the Jurassic Quiet Zone and anomalies M17 to M25 in the Nauru Basin. Although these buoys contain high quality reflection data and acceptable noise levels, they are devoid of refractions. This leads immediately to the conclusion that the large acoustic impedance contrast that usually is present at the sediment-volcanic interface in the North Pacific is not present in the Nauru Basin. A T^2/X^2 analysis conducted on two of the sonobuoys by R. Houtz revealed a layer about 1 km thick below the opaque horizon with an interval velocity of about 4 km/sec. Therefore, the lack of refractions is possibly due to unusually small velocity changes across reflecting interfaces.

Refraction velocities of 3–4 km/sec for the uppermost portion of acoustic basement are quite common in ridge crest areas where they are associated with unconsolidated volcanic debris of the uppermost oceanic crust and referred to as layer 2A. This layer thins from about 1 km at ridge crests to near zero at about the 40 m.y. isochron. Beyond 40 m.y., layer 2A is only occasionally detected as a thin (100–300 m) layer often associated with interplate volcanism

such as seamount chains. A 1 km thick layer 2A on undisturbed Late Jurassic magnetic lineations is completely unique.

I suspect that this anomalously thick layer 2A sequence in the Nauru Basin is not volcanic but composed of partially lithified limestones, possibly, but not necessarily, associated with the usual interbedded cherts. This thick sequence of chalks and limestones is probably mainly Late Jurassic in age, having been deposited at a spreading ridge crest located near the equator during the Late Jurassic as recorded by the shapes of the magnetic anomalies. The lithification of this sequence probably increases with depth and age, at least partially in response to increasing lithostatic load. Finally at the bottom of the sedimentary pile, high velocity limestones overlie basalts with similar acoustic properties that make it impossible to obtain refraction arrivals from this horizon. The isostatically compensated depth to basement in the Jurassic Quiet Zone should be approximately 5,900 m (SCLATER and DETRICK, 1973). Neither the velocity or density of the material above 8 seconds on Profile C is known, but if this represents 1,800 m of sediments with an average density of 2.4 gm/cm^3 , then the isostatically compensated depth to the 8 second reflector would be about 5,900 m.

4. Termination of Magnetic Lineations

The magnetic lineation patterns are offset internally by fracture zones F.Z.-1 and F.Z.-2, the former occurring only as a magnetic lineation offset and the latter being associated with a large basement ridge as described above. Lineations M11 to M25 are terminated against the Gilbert Islands and Radak chain of the Marshall Islands with the lineations often projecting within 100 km of these atolls. To the west of these island chains, anomalies M16 to M25 terminate in the deep sea of the Nauru Basin considerably west of the Gilbert Islands and the Ralik chain of the Marshalls. Because the combined trend of the Gilberts and Radaks closely parallels the trends of F.Z.-1 and F.Z.-2, it is likely that these atolls also occupy the position of a former fracture zone that was the site of a small lineation offset, similar to that across F.Z.-1. The Ralik chain of the Marshalls and the area devoid of lineations west of the Gilbert Islands is likely to be the site of oceanic crust considerably younger than Early Cretaceous. Because the Nauru Basin anomalies terminate west of the Raliks, it is likely that a subsequent volcanic event reheated the area erasing the magnetic anomalies and forming the Ralik Islands, although evidence for such an event is not obvious in the profiler records. The Radaks and Gilberts may also have been formed by this event, but the possibility exists that their platforms are contemporaneous with the oceanic crust of Late Jurassic and Early Cretaceous age. The only atolls that have been sampled by drilling in this area

are Eniwetok and Bikini in the northern Raliks. The Bikini hole reached the Oligocene but failed to attain basement (EMERY *et al.*, 1954), while Eocene limestone was recovered just above basaltic basement from the Eniwetok hole (LADD *et al.*, 1953).

Anomalies M1 to M10 terminate at about 170°W longitude in the Central Pacific Basin without any obvious change in basement morphology. To the east of these anomalies DSDP 66 recovered 100 m.y.-old sediments overlying basalt that may be a sample of a Mid-Cretaceous volcanic event in this area, as are DSDP 169 and 170 to the north of F.Z.-2. Such an event has been previously proposed by WINTERER (1976) to explain the large number of Mid-Cretaceous volcanic samples from this part of the Pacific.

To the west in the Nauru Basin, anomalies M16 to M25 terminate at the base of the Ontong-Java Plateau. There is no fracture-zone basement expression at this point, although the presence of F.Z.-1 shows that such morphology is not necessary for a fracture zone offset to exist. The anomalies simply die out as the water depth shoals above about 3,800 m on the eastern flank of the Ontong-Java Plateau. This shoaling of the water depth probably occurs as the oceanic crust thickens until it finally reaches 40 km thickness over the main part of the plateau. As postulated by KROENKE (1972) this is probably an extremely thick volcanic pile that is at least Late Cretaceous in age. It may be as old as the anomalies themselves or may also be related to the Mid-Cretaceous volcanic events postulated to the east.

5. Tectonic Reconstruction

The Phoenix lineations, along with the Japanese and Hawaiian patterns to the north, were accreted onto the Pacific plate in the Late Jurassic and Early Cretaceous. I shall now consider the evolution of the southern portion of this system composed of the Hawaiian and Phoenix lineations. This reconstruction will be evolved relative to a fixed Pacific plate without any attempt to place it in a paleolatitude framework. The paleolatitude and orientation of the evolving system are strongly dependent on the skewnesses (cross-sectional shapes) of the magnetic anomalies. A skewness analysis is presently underway and will be presented in a future paper.

The Phoenix and Hawaiian lineation patterns present today in the western Pacific are shown in Fig. 9D. The evolution of this system is shown at critical times in Figs. 9A, 9B and 9C. The situation present during the formation of the oldest anomaly, M25 at 153 m.y., is shown in Fig. 9A. This, and subsequent references to absolute ages of the anomalies (LARSON and HILDE, 1975), are meant to allow the calculation of approximate amounts of offset and time

Fig. 9. Reconstruction of the Late Jurassic, Early Cretaceous spreading patterns in the western central Pacific Ocean relative to a fixed Pacific Plate (in the case of Fig. 9C, a fixed South Pacific Plate). Double lines on plate boundaries denote spreading centers, and single lines are transform faults. Dashed lines are magnetic anomaly isochrons plotted on the only remaining (Pacific) plate. Arrows on spreading centers indicate both the directions and rates of spreading with the lengths of the arrows proportional to rates as measured on the scale in Fig. 9A. Relative velocity triangles in Figs. 9A, 9B and 9C represent the relative velocities at the triple junctions of the plates. (9A): Spreading pattern at M25 time (153 m.y.) showing the three plate boundaries joined at a fault-fault-ridge triple junction. (9B): Spreading pattern at M14 time (131 m.y.) showing a similar triple junction to that at M25 time and a relatively simple evolution of the plate boundaries in the intervening period. Contour enclosing M.R. denotes the Magellan Rise. (9C): Spreading pattern at M4 time (117 m.y.) after a more complicated evolution from M14 time. The lineations east of Magellan Rise require the formation of a second (northern) triple junction that was the site of 200 km of northwest offset between the Hawaiian lineations (N. Pacific plate) and the Phoenix lineations (S. Pacific plate) from M11 to M4 time in the vicinity of the Mid-Pacific Mountains. (9D): Present-day magnetic lineation-fracture zone patterns in the western central Pacific showing the Phoenix lineations selected from Fig. 1 of this paper, the Hawaiian lineations selected from Fig. 1 of LARSON and HILDE (1975), and the intervening isochrons (dashed lines) that result from the evolution outlined in Figs. 9A, 9B and 9C. Volcanic platform of the Mid-Pacific Mountains indicated by a generalized contour at about 4,000 m.

passage and do not connote ages accurate to one m.y. Figure 9A shows the Pacific, Phoenix, and Farallon plates separated by three spreading ridges. Of these three plates only the Pacific plate remains in its entirety, the majority of the latter two having been subducted beneath North America, South America and Antarctica. The Farallon plate probably evolved into the Gorda, Cocos, and Nazca plates present in the eastern Pacific today, while the Phoenix plate evolved into the Antarctic plate in the South Pacific (LARSON and CHASE, 1972). The boundaries between these three plates are shown connected at a fault-fault-ridge triple junction. The southern fault is an extension of F.Z.-2 through the Phoenix lineations, while the northern fault is a proposed offset of the Hawaiian lineations in the vicinity of the Mid-Pacific Mountains. The spreading rates at the southern and eastern ends of the Hawaiian and Phoenix lineations, respectively, are used to calculate the velocities at the triple junction and determine the trend and rate of spreading on the auxiliary ridge that separates the Farallon and Phoenix plates. The small offset in the ridge separating the Phoenix and Pacific plates is the site of the present-day Marshall Islands. Note that the spreading vectors on either side of this offset are slightly non-parallel and, strictly speaking, require a slight amount of opening at this offset. While this may have been in part responsible for the initiation of the Marshall Islands, the difference in trends is small at M25 time and is often negligible (at M20 time).

The condition for stability of the fault-fault-ridge triple junction at M25 time is that the spreading rates across the Pacific-Farallon and Pacific-Phoenix plate boundaries are identical (McKENZIE and MORGAN, 1969). Since the Phoenix lineations measure 5.4 cm/yr and the Hawaiian lineations measure 3.0 cm/yr near the triple junction, this condition is not met, and some tendency towards instability will result. It is not well understood geologically how much instability is necessary to produce a new triple junction geometry, although it is likely that the system will evolve towards a more stable ridge-ridge-ridge configuration. Large changes in the triple junction geometry are not required by the evidence, and the situation shown in Fig. 9B for M14 time at 131 m.y. is very similar to that in Fig. 9A.

As in Figs. 9A and 9B shows the Pacific, Farallon and Phoenix plates separated by three plate boundaries that meet at a fault-fault-ridge triple junction. The southern fault is an extension of F.Z.-1 through the Phoenix lineations and the northern fault is a proposed offset through the Mid-Pacific Mountains. It is not known if Fig. 9A evolved to Fig. 9B through a gradual change of the M25-triple junction to a ridge-ridge-ridge configuration or if the unstable nature of that triple junction persisted until M14 time when the Pacific-Phoenix and Pacific-Farallon plate boundaries extended abruptly into the Phoenix and Farallon plates, respectively, forming a new fault-fault-ridge triple junction. This

latter triple junction is stable at M14 time (Fig. 9B) because the spreading rates on both the Phoenix and Hawaiian lineations have slowed to the identical value of 2.5 cm/yr half-rate at the triple junction. This stable condition is only a transient phenomenon, as the spreading rate on the Phoenix lineations increased by nearly a factor of three in less than five million years, while the spreading rate on the Hawaiian lineations remained approximately constant. This dramatic change in triple junction stability was accompanied by large changes in the plate boundary geometry shown in Fig. 9C.

Figure 9C shows four plates separated by five ridges that join at two triple junctions at M4 time (117 m.y.). The Pacific plate has been broken into two plates separated by a northwest trending plate boundary that meets the northern triple junction in the Mid-Pacific Mountains. The evidence that requires this second triple junction is the fan-shaped M4 to M11 lineation pattern east of Magellan Rise. These lineations were recognized by LARSON and CHASE (1972) but not correlated as M4 to M11, so that their tectonic significance was ignored. Because this fan-shaped pattern opens to the southeast in the opposite sense as the M4 to M11 Hawaiian lineations, they cannot be a simple extension of the Hawaiian lineations that has suffered subsequent rotation. They are required to be a different plate boundary that separates the South Pacific and Farallon plates in Fig. 9C. This in turn requires opening in the vicinity of the Mid-Pacific Mountains from M11 to at least M4 time that is probably largely responsible for the presence of this huge volcanic outpouring. It is difficult to predict the direction of relative motion between the North and South Pacific plates, but it must have occurred at a slow rate. This is because the M11 to M4 lineations east of Magellan Rise and on the Hawaiian patterns are both converging rapidly toward the triple junction. In calculating the triple junction velocities, I have linearly extrapolated these rate changes, which will produce slight overestimates of triple junction velocities, since the true situations must resemble sine curves as the poles of rotation are approached. This results in spreading across the North Pacific-South Pacific plate boundary at a 1.2 cm/yr half-rate with slip in a northwest direction. This maximum rate of spreading will produce about 200 km of opening from M11 to M4 time at a rate usually associated with slow spreading ridges that generate rough topography. It is logical to assume that much of the present relief of the Mid-Pacific Mountains was formed during that period. As WINTERER (1976) pointed out, the Mid-Pacific Mountains consist of two bathymetric levels, a lower plateau level at about 3,500 m from which the guyots and seamounts rise to about 1,500 m. A generalized contour of this lower volcanic platform (Fig. 9D) shows it to have a roughly orthogonal shape. I suspect that this is a relic of the trends of the fracture zone-ridge crest system that separated the North and South Pacific

plates from M11 to M4 time. The 200 km of opening calculated for this plate boundary closely resembles the width of the Mid-Pacific Mountains.

Reef limestones with Middle Cretaceous ages were first dredged from the Mid-Pacific Mountains by HAMILTON (1956). LONSDALE *et al.* (1972), WINTERER *et al.* (1973) and MATTHEWS *et al.* (1974) have all confirmed this approximate age with subsequent samples. MATTHEWS *et al.* (1974) summarized all of the available information and concluded that there are no reefs that are demonstrably younger than Turonian or older than Aptian. I suspect that the oldest reef limestone places an approximate minimum age on the northern triple junction in Fig. 9C because widespread reef growth will not start until volcanism associated with the triple junction ends and subsidence begins. Thus, the northern triple junction could have persisted about 5 m.y. after the formation of M4 in the early Barremian.

The southern triple junction in Fig. 9C is shown as a fault-fault-ridge connection of the South Pacific, Farallon and Phoenix plates that was originally interpreted as a ridge-ridge-ridge junction by LARSON and CHASE (1972). With the identification of M11 to M4 east of Magellan Rise, the geometry of such an intersection becomes unreasonable because the M4 lineations south and east of Magellan Rise are close to parallel. The fault-fault-ridge junction is a stable pattern from M11 to M4 time because both lineation patterns recorded spreading at 4.8 cm/yr half-rate at the triple junction. Moreover, this geometry explains why no remnant of a bight exists between the two lineation patterns that are instead both truncated abruptly across the strike of the anomalies.

It is likely that the plate boundary reorganization from Fig. 9B to 9C occurred about 125 m.y. ago (M10N to M11 time) because these are the oldest anomalies mapped south and east of Magellan Rise. Figure 9 was constructed with the assumption that the reorganization occurred exactly at M11 time. This is exactly coincident with the large spreading rate increase recorded on the Phoenix lineations between F.Z.-1 and F.Z.-2 (Fig. 5). This reorganization probably occurred abruptly by the Phoenix-Pacific plate boundary breaking through to "capture" the Magellan Rise portion of the Phoenix plate (Fig. 9B) and weld it to the South Pacific plate (Fig. 9C). This would force the Farallon-Phoenix plate boundary in Fig. 9B to assume the new role of the Farallon-South Pacific plate boundary in Fig. 9C. Thus, the Magellan Rise formed as a volcanic pile on the Phoenix plate in the Late Jurassic and was transferred to the Pacific plate by the plate boundary reorganization 125 m.y. ago. Lineations M14 to M11 formed at the Phoenix-Farallon plate boundary (Fig. 9B) north of Magellan Rise would also have been transferred to the Pacific plate by this reorganization of plate boundaries. These lineations with an east-southeast trend presently should be located in the poorly surveyed area between Magellan Rise

and the Mid-Pacific Mountains (Figs. 9C and 9D). If these lineations can be mapped by future surveys, they would pinpoint the age of the ridge jump and would locate the Pacific-Farallon-Phoenix triple junction that was present prior to this reorganization.

It is unknown if the second (northern) triple junction persisted beyond M4 time although it is unlikely to have done so for more than 5 m.y. as previously discussed. The present-day situation in Fig. 9D shows only the 200 km of slip that occurred between the North and South Pacific plates from M11 to M4, although more may exist. It also shows selected isochrons in the vicinity of the Mid-Pacific Mountains which would result from the evolution described above. The portions of these isochrons that mark former spreading centers can be used to test the above hypotheses. It is quite possible that lineations M14 to M11 still exist as a recognizable set of anomalies generated at about 4 cm/yr half rate north of Magellan Rise. However, a similar test for the presence of M11 to M4 in the vicinity of the Mid-Pacific Mountains will be difficult because these hypothetical spreading centers probably occurred as short segments of ridge crests that generated rough topography at slow spreading rates. It is well known that magnetic anomalies generated under such conditions are relatively poor records of the spreading process.

6. Summary

The following features have been mapped and conclusions subsequently drawn in the preceding text and illustrations.

1. Early Cretaceous and Late Jurassic magnetic anomalies are present trending east-west in the Nauru and Central Pacific Basins of the western Pacific Ocean. The Jurassic Quiet Zone is present in the northern parts of these basins near the Marshall Islands.

2. A northwest-trending, fan-shaped M11 to M4 anomaly sequence is present east of Magellan Rise.

3. The sedimentary sequence in the Central Pacific Basin is a few hundred meters of radiolarian ooze, porcelanite, brown clay and nannofossil mudstone, while the upper portion of the Nauru Basin sequence is hypothesized to be similar to this and underlain by about 1 km of Mesozoic carbonates and limestones.

4. The plate tectonic reconstruction implied by these magnetic anomalies and the Hawaiian lineations to the north is a ridge-fault-fault triple junction from M25 to M14 time that separates the Pacific, Farallon and Phoenix plates.

5. Between M14 and M10 the plate boundaries reorganized to form two triple junctions in place of the original one and break the Pacific plate in the vicinity of the Mid-Pacific Mountains.

6. This additional triple junction was active from M11 to M4 time and was responsible for the formation of the Mid-Pacific Mountains at a slow-spreading plate boundary.

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