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Fracture Zone Traces across the North Pacific Cretaceous Quiet Zone and their Tectonic Implications

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We present a new, more complete mapping of the fracture zones as they cross the Cretaceous Quiet Zone in the central north Pacific. We compile and combine observations of lineations from three distinct data bases: deflection-of-the-vertical profiles from GEOSAT altimetry measurements, magnetic and topographic profiles collected on closely spaced north-south ship tracks by the Pioneer survey, and magnetic and Gloria side-scan records from the concentrated Exclusive Economic Zone surveys around the Hawaiian chain and Johnston Island. We adopt and emphasize a northern relocation of the Quiet Zone portion of the Mendocino fracture zone. We find that all the fracture zones from the Surveyor to the Clarion reflect the same plate history; they were all formed on the Pacific-Farallon spreading system by relatively smooth spreading. One or more major ridge jumps are required to explain geometric differences in the Quiet Zone edges; we argue that these occurred early in the Superchron. Most of the fracture zones are seen to consist of groups of multiple strands that widen and narrow appropriately following changing plate motion directions. We contend that the shape of the Mendocino contra-indicates the existence of a Chinook plate in the late Superchron. We explored the fitting of Euler stage poles to our fracture zone shapes and to other Quiet Zone features. We conclude that the youngest Superchron stage pole must lie very near the spin axis. Stage poles for earlier stages of the Superchron probably lie at lower latitudes in the south Pacific but their locations are poorly constrained by the data presently in hand.

INTRODUCTION

The formation of the deep sea floor of the North Pacific basin is summarized, in broad outline, by Atwater [1989]. The seafloor that presently fills the western North Pacific was formed during the Jurassic and early Cretaceous by seafloor spreading between the Pacific plate and at least three others: the Izanagi plate to the north, the Farallon plate to the east, and the Phoenix plate to the south. This history is clearly documented by seafloor magnetic anomaly isochrons of the M-series reversals [Larson and Pitman, 1972; Hilde et al., 1976; Sager et al., 1988; Tamaki and Larson, 1988; Nakanishi et al., 1989, 1992]. Similarly, magnetic isochrons in the northern and eastern North Pacific document its formation during the latest Cretaceous and the Cenozoic by seafloor spreading between the Pacific plate and the Kula and Farallon plates [Grim and Erickson, 1969; Atwater and Menard, 1970; Wilson, 1988; Atwater and Severinghaus, 1989]. In the central North Pacific, between these two sets of isochrons, lies an area that has no

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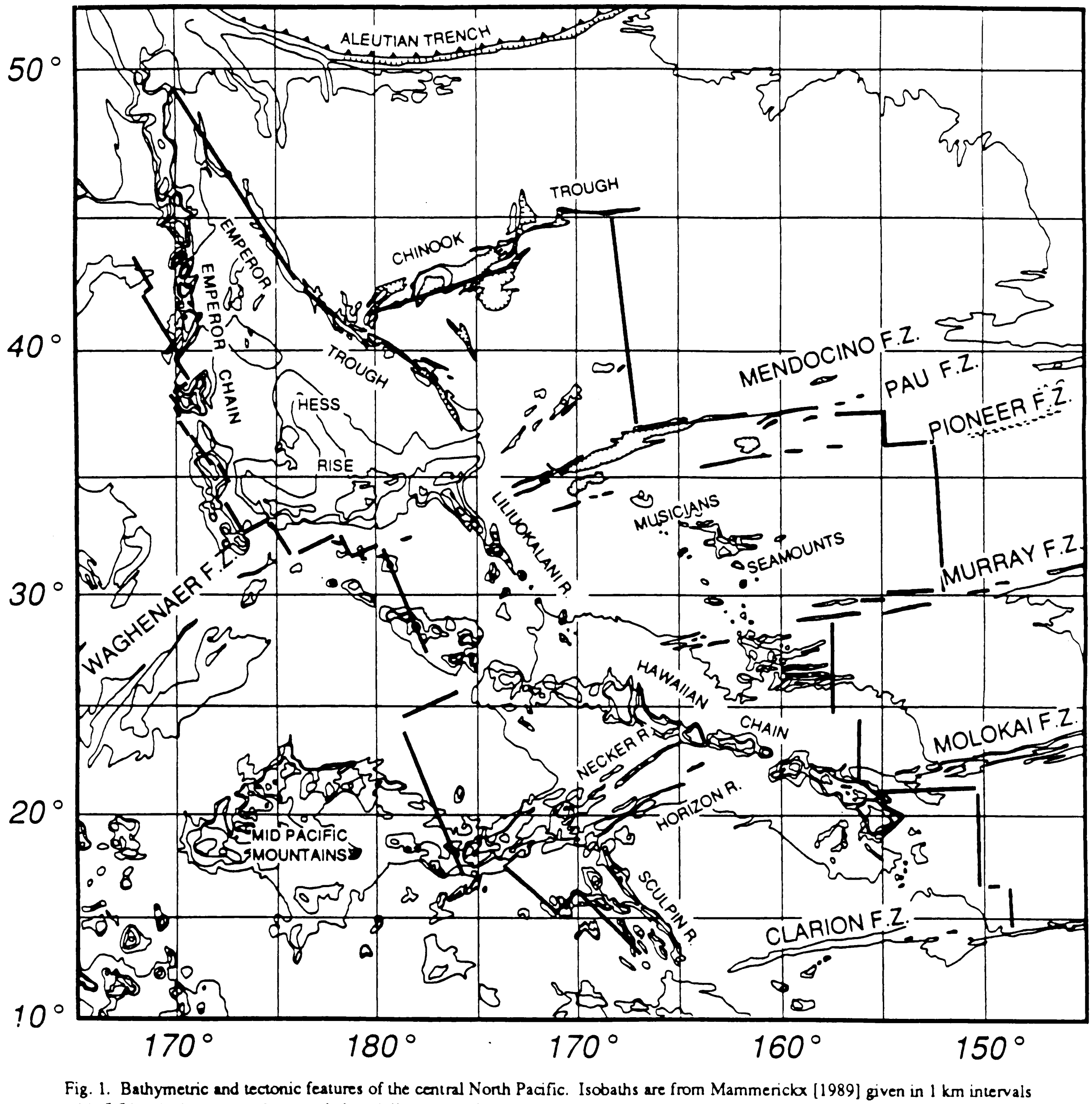

Fig. 1. Bathymetric and tectonic features of the central North Pacific. Isobaths are from Mammerickx [1989] given in 1 km intervals with 5.5 km isobaths added as needed to delineate the fracture zones. Heavy lines mark the edges of the Cretaceous Quiet Zone, seafloor presumed to have been formed during the late Cretaceous Superchron.

known magnetic isochrons, a magnetic "quiet zone", Figure 1. This region was formed during the Cretaceous Normal Superchron when the earth's magnetic field had a stable normal polarity for nearly 40 million years. (In this paper we shall refer to this reversal-free time period as the "Superchron" and to the area of seafloor formed during this time as the "Quiet Zone".) The lack of magnetic isochrons in the Quiet Zone leaves us with relatively little information about the Late Cretaceous tectonic history of the central North Pacific. However, the area is crossed by a set of fracture zones and these contain some information concerning the seafloor spreading system that formed them. In this paper we refine the locations of these fracture zones and examine their tectonic implications.

It is clear that a number of important and interesting events occurred in the North Pacific during the Cretaceous. A number of very voluminous volcanic eruptions occurred (Manihiki Plateau, Ontong-Java Plateau, Hess rise, etc.) leading Larson [1991] to postulate the establishment of a "superplume" in the area. A number of plate tectonic reorganizations also occurred during the Superchron. The Kula plate was formed, probably by the breaking off of the northern Pacific plate near the end of this time period, and other small, short-lived plates may have existed for a time [Mammerickx and Sharman, 1988]. The plate boundary between the Pacific and Farallon plates continued spreading through the Superchron, but offsets across its transform faults were greatly altered by some spreading center jumps of unknown location and timing, and the spreading system was lengthened greatly to the south [Joseph et al., 1992 and this volume]. A major change in Pacific-Farallon relative motion, from nearly east-west to east-northeast-west-southwest, occurred during Chron 33R (the reversed magnetic period preceding Chron 33: about 79-83 Ma according to Cande and Kent, 1992] leaving a distinct bend in all the northeast Pacific fracture zones [Sager and Pringle, 1987b; Joseph et al., 1992 and this volume; Searle et al., this volume]. In the text we shall refer to this feature as the "Chron 33R bend". By tracking the fracture zones from this bend, backward across the North Pacific Quiet Zone and checking their consistency with rigid plate models, we believe we can constrain the timing of the ridge jumps and establish the northern extent of the Pacific-Farallon system.

Fracture zones are the fossil traces of transform faults, and from their transform fault origins they inherit regional and local topographic disturbances, distinctive gravity signatures, and magnetic anomalies. Their topographic traces usually include a regional step, reflecting the original transform fault offset and the resulting juxtaposition of seafloor of different ages on the two sides of the zone [Menard and Atwater, 1969]. This topographic step can be quite large for large offsets in young crust, but the step tends to decay with age since the age-depth curve nearly levels off for seafloor older than about 100 million years age [Parsons and Sclater, 1977; Renkin and Sclater, 1988]. If the fracture zone remains locked during this decline of the regional step, a local step may be preserved, accompanied by a large flexural gravity anomaly over a characteristic scale of about 50 km on either side of the fracture zone [Sandwell, 1984a]. An additional topographic signature common at fracture zones is a narrow (10-20 km wide) strip of ground that was sheared and disrupted while the transform fault was an active plate boundary. The relief associated with this shear zone is relatively small, but it is permanently embedded in the seafloor so that it forms a long-term signal. When a fracture zone is offsetting magnetic isochrons, it can be the site of large block-end magnetic anomalies. Furthermore, transform fault shear zones often contain crushed and metamorphosed rock and serpentine and may have anomalously shallow mantle, creating additional permanent perturbations in the surrounding magnetic and gravity fields.

Many Pacific fracture zones consist of groups of nearly parallel, linear strands and the detailed geometric relationships among these strands provide clues for the plate motion history during the time they were formed. The multi-strand configuration results from a plate boundary configuration where a ridge-ridge transform system consists of two or more transform fault segments linked by one or more short spreading center segments. This configuration is common in presently active Pacific transform systems [Searle, 1983; Embley and Wilson, 1992; Fornari et al., 1989] and appears to have been the rule during the Cretaceous Superchron. Nearly all of the fracture zones reported in this paper are multi-stranded. We shall use the observed strand relationships to help distinguish among various plate motion models.

The topographic signatures of the fracture zones that cross the Quiet Zone are subtle. Farther east, where they cross the relatively young sea floor of the northeastern Pacific, the major fracture zones dominate the topographic chart [Menard, 1964; Mammerickx, 1989]. The traces of those fracture zones extend westward into the Quiet Zone but they become steadily more subdued as they cross increasingly older crust. The seafloor in the Quiet Zone is believed to be about 83 to 119 million years old [Kent and Gradstein, 1985; Cande and Kent, 1992], so that regional step offsets across the fracture zones have all but disappeared and the local shear topography has been partially smoothed by sediment accumulation. Additional topographic "noise" has been added by other Late Cretaceous features such as the Chinook and Emperor troughs to the north, the Hess rise and Liliuokalani ridge in the center and the Mid-Pacific Mountains and Sculpin ridge to the south. Some of these may be traces of ridge jumps and other non-steady seafloor spreading events, while others are surely the results of off-axis volcanic events. Finally, the Cenozoic Hawaiian/Emperor chain and its associated swells, moats, volcanism and sedimentation have been superimposed upon the older sea floor structures. It is no wonder that traditional attempts to use topography to map the fracture zones through this region have led to a number of ambiguities and controversies.

The fracture zones in the central North Pacific can best be mapped by combining shipboard and satellite data bases. The shipboard geophysical data coverage of the area is patchy. A few regions have been mapped in great detail: by the north-south surveys of the *R/V Pioneer* in the 1960's and by the U. S. Geological Survey Gloria side-scan sonar surveys of the Exclusive Economic Zone (EEZ) around the Hawaiian chain in the 1980's and 1990's. Elsewhere, there are only single, sparsely scattered ship tracks. Fortunately, the fracture zones create a clear gravity signal which is easily discerned on satellite altimetry profiles [Sandwell, 1984b; Haxby, 1985]. These traces tend to be longer wavelength and thus are less precise locators for the fracture zones, but they have the great advantage that the areal coverage is relatively uniform. They give an independent estimate of the locations and offsets of the various fracture zone strands and they allow us to chart them across otherwise uncharted territory.

In this paper we present topographic and magnetic profiles from the Pioneer survey and information from the EEZ magnetic and side-scan sonar surveys. We present deflection-of-the-vertical profiles from the GEOSAT altimeter across the same region. In each of these data sets we identify and trace likely fracture zone lineations. We combine these traces with recent compilations of the surrounding magnetic isochron patterns [Atwater and Severinghaus, 1989; Nakanishi et al., 1992] to provide a revised tectonic chart of the Cretaceous North Pacific. Finally, we use this chart to address some unresolved questions about the tectonic evolution of the Pacific plate.

OBSERVATIONS

Magnetic and topographic profiles from the Pioneer systematic surveys

The marine geophysical profiles that have been collected in the central North Pacific are, for the most part, sparse and unsystematically located. However, a major detailed survey of portions of the area was carried out as part of the U. S. Coast and Geodetic systematic survey by the *R/V Pioneer* in 1961 through 1963 [Elvers et al., 1967]. Many of the lines of this survey run north-south between 175° and 155°W and 40° and 25°N and have a spacing of about one degree of longitude. We present as Figures 2a and 2b the bathymetric and residual magnetic anomaly profiles plotted at right angles to track along these north-south lines.

The major fracture zones can be seen quite clearly crossing the survey lines in Figure 2. On the topographic profiles, Figure 2a, they appear as linear groupings of subtle ridges, troughs and steps. They are small and somewhat discontinuous, presumably due to their age and sediment cover. Ironically, these fracture zones, so named because of their topographic expression, show up much more clearly in the shipboard magnetic profiles in Figure 2b, where the individual strands are marked by high amplitude, short wavelength magnetic anomalies. We traced a number of linear features across the survey, using the magnetic data and cross-checking with the topographic data for "ground truth".

Magnetic profiles and side-scan sonar maps from the Hawaiian/Johnston Island EEZ surveys

In the 1980's and 1990's, the U. S. Geological Survey conducted detailed geophysical surveys of most seabeds within 200 nautical miles of the shores of the United States and its territories (the "Exclusive Economic Zone" or EEZ). This mapping included magnetic profiling and the complete insonification of the seabed with the Gloria side-scan sonar system. The resulting maps present the fabric and texture of the deep seafloor in spectacular detail. For the present study, this data set provides excellent control on the location and character of the multi-stranded Molokai and Murray fracture zones as they approach the Hawaiian ridge and Johnston Island (Figure 3). It provides our only information for location of the Murray fracture zone strands south of the Hawaiian ridge (near 175°W, 25°N).

We used the EEZ data set in several ways. The side-scan sonar technique is excellent for mapping linear seafloor features. We traced the fracture zone strands directly off the photo-montages of the shipboard records (presented in Normark et al. [1987, 1989]; Clague et al. [1988, 1989]; Torresan et al. [1989]; Searle et al. [this volume] and Holcomb [in preparation]). These traces appear as lines and dashes on Figure 3b. In addition, the side-scan technique brings out the ordinary abyssal hill fabric that was formed during seafloor spreading. This fabric is generally aligned perpendicular to the fracture zones, commonly curving as it approaches them. While this fabric is not included on our map, we used it to help distinguish and validate some of the fracture zone traces. The EEZ magnetic profiles, Figure 3a, record the fracture zone locations as sharp linear anomalies. We used these to extend the side-scan fracture zone traces toward the Hawaiian ridge, across regions where their seafloor traces had become buried in debris from the chain. On Figure 3b we present fracture zone traces located by side-scan data as lines and dashes and those located by magnetic profiles as connected dots.

GEOSAT Altimetry

In recent years, fracture zones have been mapped in many parts of the world by tracing their distinct signatures in the records collected by the altimetry satellites SEASAT and GEOSAT. Many authors [e.g., Sandwell, 1984a; Haxby, 1985; Shaw, 1987; Cande et al., 1988, 1989] have used SEASAT altimetry data to trace the positions of fracture zones, and Mayes et al. [1990] averaged GEOSAT repeat orbits to construct detailed deflection-of-the-vertical charts for tectonic mapping of the South Pacific. The validity and accuracy of altimetric fracture zone mapping was tested by Muller et al. [1991] when they compared stacked deflection-of-the-vertical profiles from GEOSAT with detailed topographic mapping of the Kane fracture zone presented by Tucholke and Schouten [1988]. Muller et al. [1991] showed that the main peak (or trough) in the geoid or the deflection-of-the-vertical signature traces the main topographic expression to within $\pm$ 5 km over the entire length of a fracture zone.

GEOSAT data for the central North Pacific are presented in Figure 4. Each profile in the figure represents the average of 44 repeat GEOSAT altimetry profiles [Sandwell and McAdoo, 1990], presented in Figures 4a and 4b as the ascending and descending profiles of the deflection-of-the-vertical (horizontal gravity) along track. To remove random noise and the long wavelength gravity field, we used a Gaussian filter to remove wavelengths shorter than 18 km and the spherical harmonic coefficients of the PGS3337 gravity model of Marsh et al. [1990] to remove wavelengths greater than 4000 km.

The two charts in Figure 4 show signals from all the major topographic features of the area. The Hawaii-Emperor chain runs across the region from the northwest to the southeast; the Mid-Pacific Mountains and the Necker ridge show up in the lower center of the chart; the Emperor trough and Chinook trough appear in the upper center. In addition, a whole suite of less prominent, but strikingly linear features trend east by northeast across the chart. These obviously coincide with the

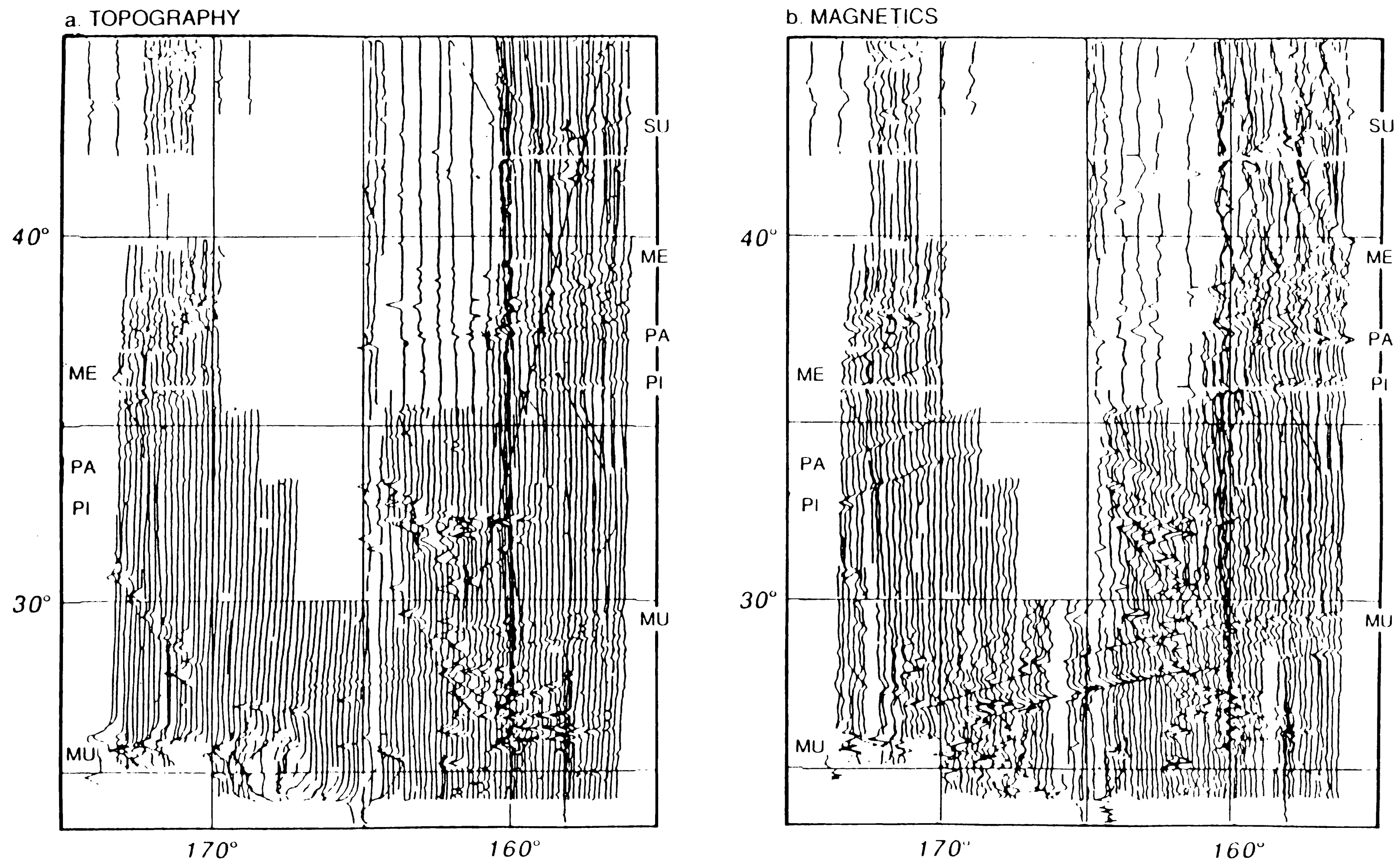

Fig. 2. Profiles of shipboard data from the *R/V Pioneer* systematic survey [Elvers et al., 1967]. Labeled fracture zone traces are SU: Surveyor, ME: Mendocino, PA: Pau, PI: Pioneer, and MU: Murray fracture zones. (a) Topographic profiles; positive elevations are plotted to the west. (b) Magnetic anomaly profiles; positive magnetic anomalies are plotted to the west.

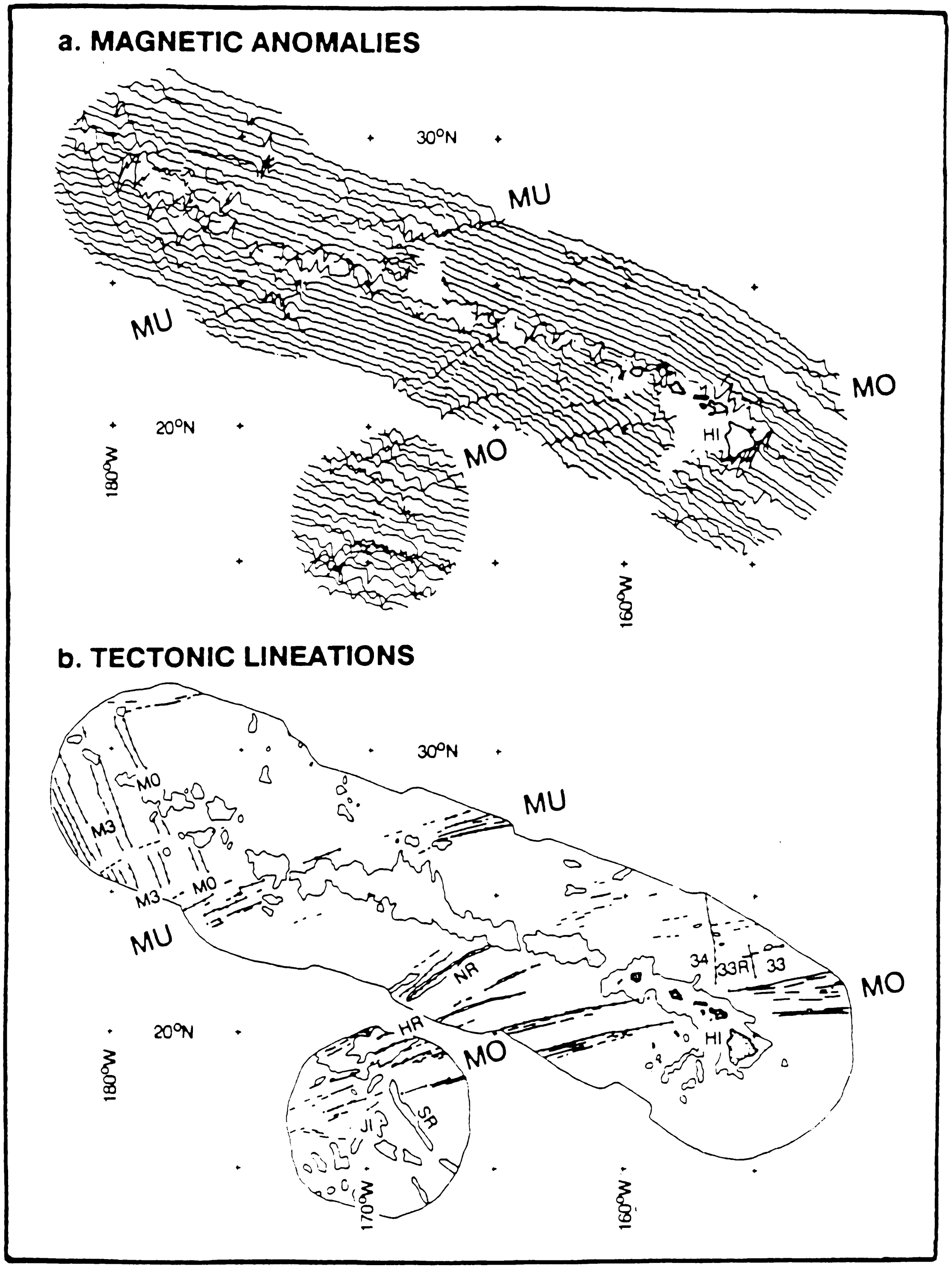

Fig. 3. Data from the Hawaiian and Johnston island Exclusive Economic Zone surveys (EEZ SCAN) from Normark et al. [1987, 1989], Clague et al. [1988, 1989], Torresan et al. [1989], and Searle et al. [this volume]. Labeled features are MU: Murray fracture zone, MO: Molokai fracture zone, NR: Necker ridge, HR: Horizon ridge, SR: Sculpin ridge, HI: Hawaii and JI: Johnston Island. (a) Magnetic anomalies collected along survey ship tracks. (b) Tectonic lineations. Solid lines are lineations traced from EEZ SCAN side-scan records; lines with dots are lineated features crossing the magnetic profiles, with the dots at ship track crossings. 4 km isobath from Mammerickx [1989].

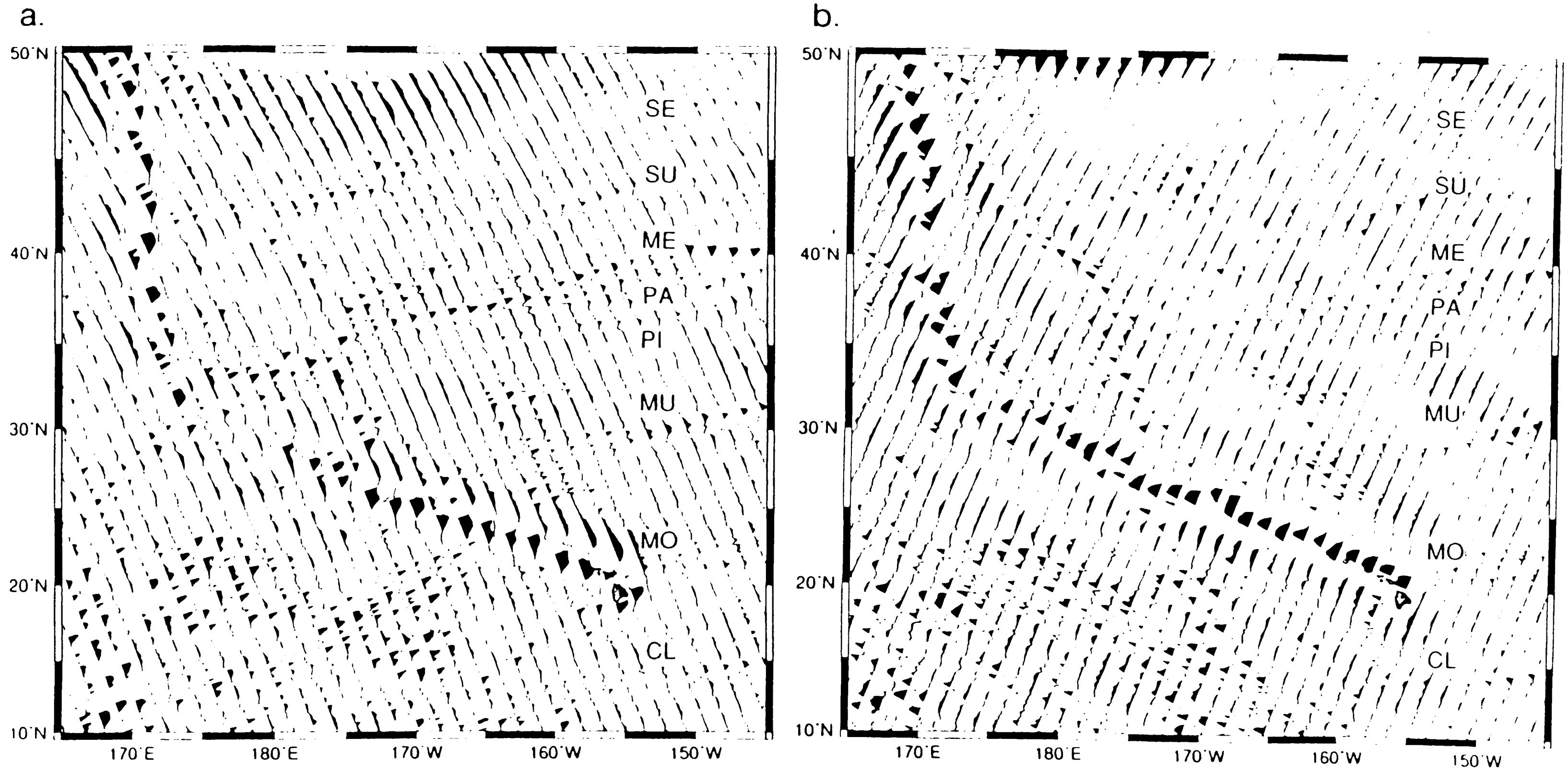

Fig. 4. Profiles of the deflection-of-the-vertical at right angles to track from the GEOSAT altimeter. Labeled fracture zone traces are SE: Sedna, SU: Surveyor, ME: Mendocino, PA: Pau, PI: Pioneer, MU: Murray, MO: Molokai, and CL: Clarion fracture zones. (a) Ascending profiles. These tracks ascend to the northwest. (b) Descending profiles. These tracks descend to the southwest.

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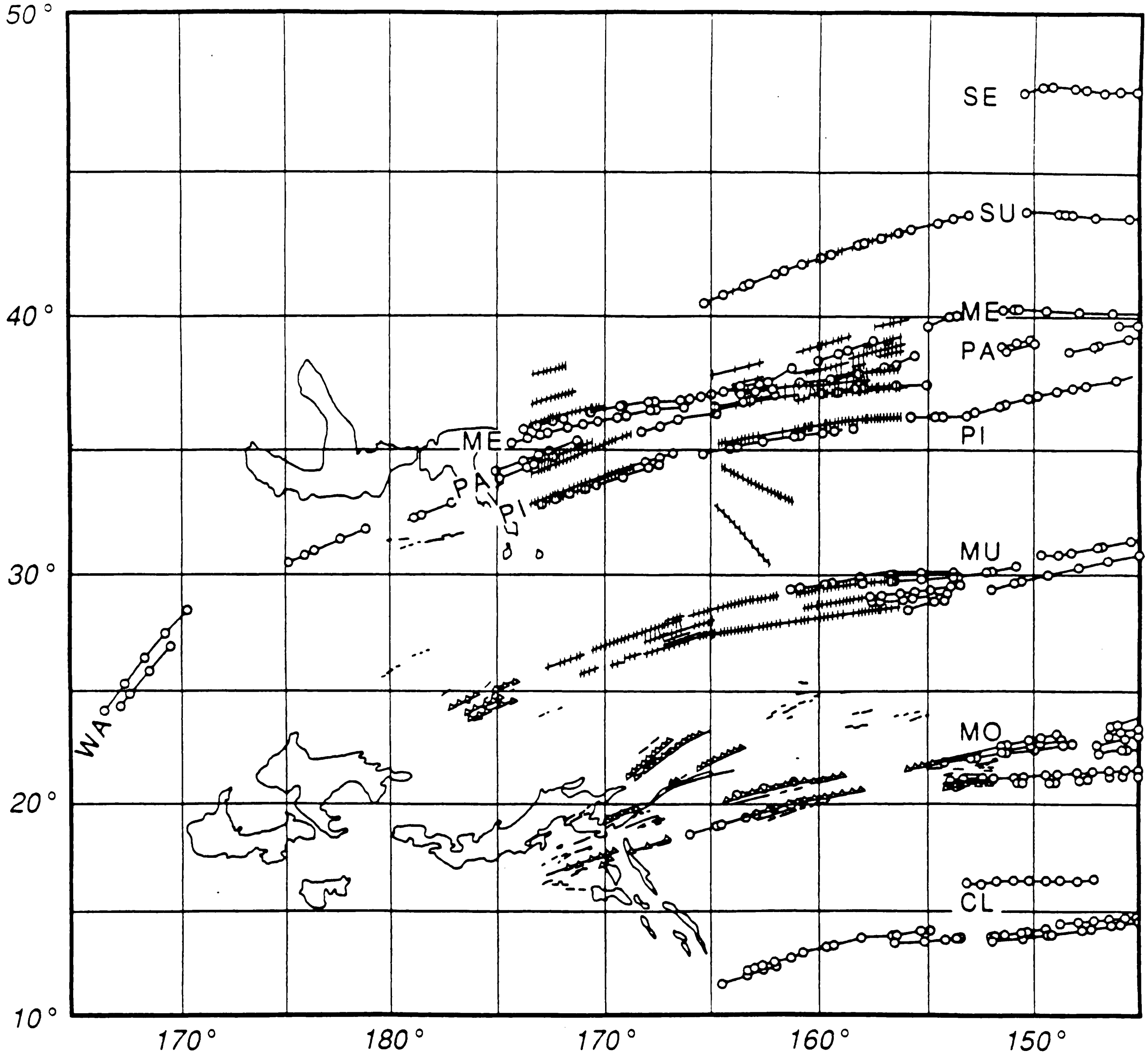

Fig. 5. Compilation of observed fracture zone traces in the central North Pacific. Hatched lines are fracture zone locations from the Pioneer survey magnetic and topographic profiles in Figure 2; each hatchure represents a ship track crossing point. Plain lines and dashes are side-scan traces and lines with open triangles are magnetic lineations, both from the EEZ SCAN data in Figure 3; each triangle represents a track crossing point. Lines with open circles are fracture zone locations from the GEOSAT altimetry data in Figure 4; each cicle represents the crossing of an averaged line. Labeled fracture zone traces are SE: Sedna, SU: Surveyor, ME: Mendocino, PA: Pau, PI: Pioneer, MU: Murray, MO: Molokai, and CL: Clarion fracture zones.

major fracture zones where they are known from shipboard data and they provide the means to continue the fracture zones across areas where they were not previously surveyed. For our compilation, we picked both peaks and troughs in the deflection-of-the-vertical profiles, mapping several sub-parallel strands for each fracture zone. The traces can be followed across most of the Quiet Zone, although they disappear near the Hawaiian ridge, presumably because they have been overprinted.

Fracture zone compilation

Our various determinations of the locations of the fracture zones, described above, are compiled in Figure 5 with a different symbol for each different data set. The lineations

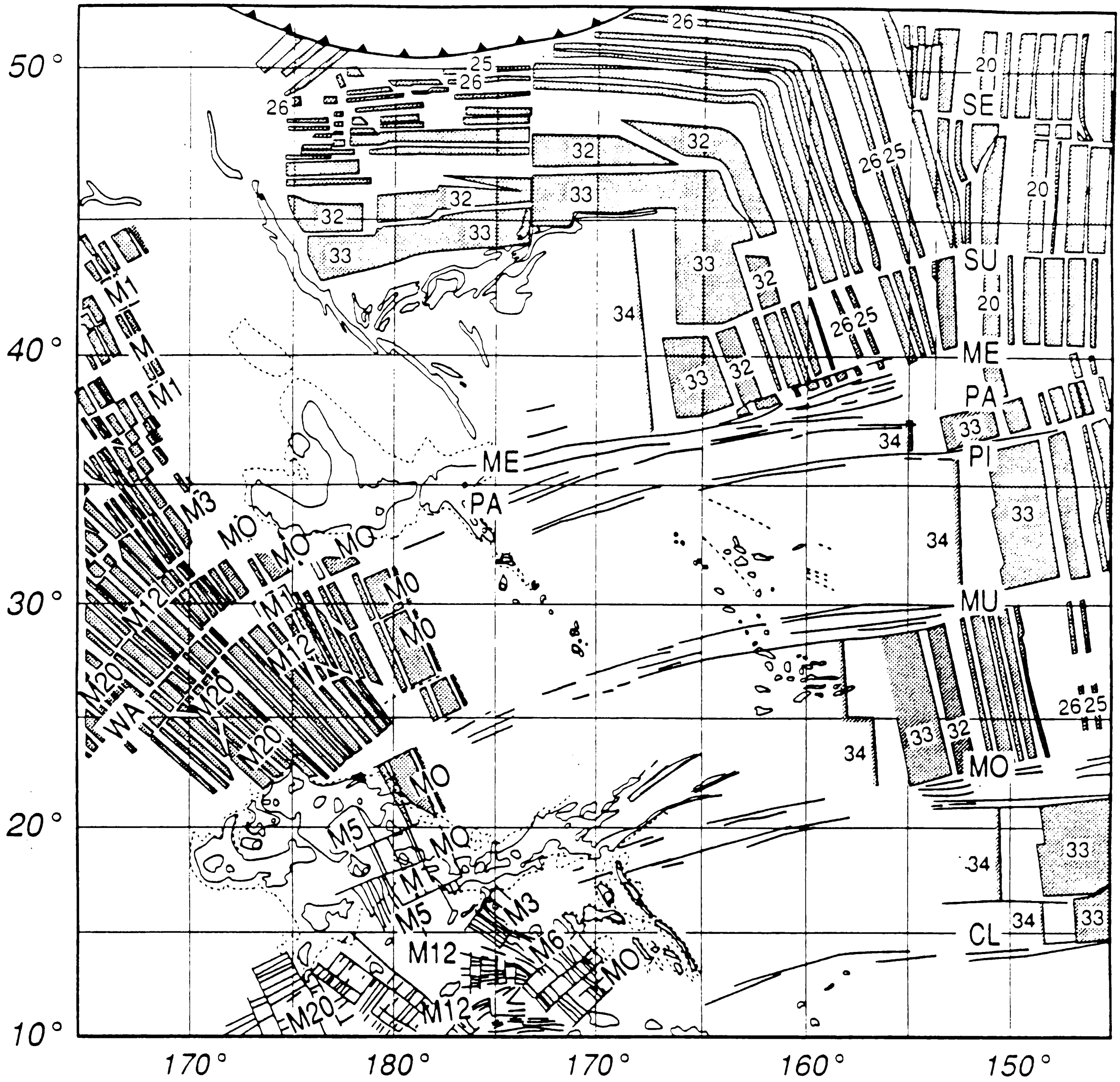

Fig. 6. Tectonic chart of the Cretaceous North Pacific. The numbered, shaded areas represent identified magnetic isochrons from Atwater and Severinghaus [1989] modified using EEZ SCAN magnetic data from Figure 3. Line pattern in the lower left are M-series isochron locations from Nakanishi et al. [1992]. Locations of fracture zone strands are simplified from Figure 5. The light continuous lines represent the 2 and 4 km contours, the light dashed line portions of 5 km contour. The contours of the Hawaiian-Emperor chain have been omitted to emphasize that this feature was superimposed upon the Mesozoic seafloor during the Cenozoic.

from these very different sources are in close agreement wherever they overlap, demonstrating the validity of the individual methods and the power of their combination. By combining the data sets we were able to map the fracture zones and their separate strands across much of the central North Pacific.

Revised Mesozoic Tectonic Chart

We have created a revised Mesozoic tectonic chart of the central North Pacific (Figure 6) by combining our new fracture zone traces with the other major topographic features of the area from Mammerickx [1989] and with the magnetic isochrons compiled by Nakanishi et al. [1992] and by Atwater and Severinghaus [1989], modified using EEZ isochrons from Figure 3a and Searle et al. [this volume]. We have deliberately excluded the Hawaiian-Emperor chain from this map in order to concentrate on the possible Mesozoic sea floor spreading elements. The primary contribution of this chart is a more complete and consistent mapping of the fracture zones than has previously been presented. In the next sections we present the details of each fracture zone, working from north to south.

Surveyor Fracture Zone

The Surveyor fracture zone is recorded very clearly in both shipboard and satellite data bases. In the Pioneer topographic profiles it appears as a linear ridge and trough; in the magnetic data it creates a linear high-amplitude disturbance and an offset of identified isochrons; in the deflection-of-the-vertical profiles it is a linear anomaly. This fracture zone appears to have been created as part of the accommodation of the Farallon-Pacific spreading system to the change in relative plate motion direction, described above, that occurred during Chron 33R. None of the data bases shows any evidence of its existence before that time.

Mendocino, Pau and Pioneer Fracture Zones

Our most important departure from traditional interpretations concerns the identification of the Mendocino fracture zone and its relationship to the Pau and Pioneer fracture zones. Most previous workers [e.g., Menard, 1964; Engebretson et al., 1984; Mammerickx, 1989] did not recognize the Chron 33R bend in the Mendocino fracture zone but, rather, traced it approximately straight to the west-southwest. We adopt the new location for the Mendocino fracture zone proposed by Atwater and Severinghaus [1989], following a more northerly strand westward across the eastern Quiet Zone and west-southwestward near the southern edge of the Hess rise. To emphasize this important difference, Atwater and Severinghaus renamed the more southerly strand that was formerly labelled as the Mendocino. They named it the Pau fracture zone. While this reinterpretation may seem to be a minor alteration, it has significant implications for the kinematic history of the area, described below.

The Atwater and Severinghaus [1989] reinterpretation of the Mendocino and Pau fracture zones is driven primarily by differences in the signatures of these features in the satellite altimetry data in the eastern Quiet Zone. The Mendocino, Pau, and Pioneer fracture zones and several additional intermittent strands can all be mapped across the shipboard magnetic and topographic profiles around 170°W, Figures 2a and 2b. Their traces in this traditional data set all look about the same, so that they do not help us to distinguish the huge-offset Mendocino from its relatively minor-offset relatives. However, there is no ambiguity in the deflection-of-the-vertical profiles crossing these features, Figures 4a and 4b. The Pioneer and Pau traces are barely visible in this data, whereas the northern strand, the newly labelled Mendocino, has a very large anomaly, presumably reflecting its much greater offset.

These new fracture zone identifications are also supported by some tectonic considerations. This new interpretation brings the shape of the Mendocino fracture zone into agreement with the shapes of the other fracture zones that were formed during the same period of time and that might have been reacting to the same plate motion changes. The fracture zones that we identify as the Pioneer and Pau fracture zones can be seen in both the satellite and Pioneer data sets. They trace out very similar shapes and are nearly parallel on the map. A similar shape is seen on the Mendocino but the entire pattern is shifted more than 1000 km to the west so that adjacent segments of the Pau and Mendocino are rarely parallel. Indeed, they approach and depart from one another with each change in direction, until the Pau meets its demise when the Mendocino runs over it (near 142°W) following a particularly abrupt change in plate motion direction.

Murray Fracture Zone

Five hundred kilometers to the south, the Murray fracture zone shows up as several distinct strands crossing the deflection-of-the-vertical profiles (Figure 4) and the Pioneer survey magnetic profiles (Figure 2b). It can also be detected on the Pioneer topographic profiles (Figure 2a), but it is more difficult to follow the individual strands as they are obscured by topographic noise and sedimentary cover. The combined data permit the tracing of this fracture zone all the way from the easternmost North Pacific to just north of the Hawaiian ridge. On the south side of the Hawaiian ridge it is not detectable in the deflection-of-the-vertical profiles but can be clearly seen in the EEZ magnetic records, Figure 3a. The Gloria side-scan records of this region are quite smooth, but they do contain an intermittent group of linear features in the vicinity of the traces in the magnetic records, Figure 3b. They also contain a widely scattered set of lineations perpendicular to the first, not shown, suggesting occasional glimpses of ordinary sea floor spreading fabric. On this basis, we trace the Murray fracture zone across the Hawaiian ridge to this location and to the major offset in the M-series isochrons, farther to the west.

Molokai Fracture Zone

The next fracture zone to the south is the Molokai. It is clearly traced in the deflection-of-the-vertical profiles and spectacularly laid out in the Gloria side-scan records [see Searle et al., this volume]. It has a complex multi-strand nature which increases in width and complexity to the east, in response to the Chron 33R change. To the west it encounters the Hawaiian Islands at the latitude of Molokai, hence its name. When it emerges from the south side of the chain, its location and multi-strand nature is again discernible in both the satellite and side-scan data sets. It becomes increasingly obscure and intermittent as it crosses the Sculpin ridge and approaches the M-series isochrons, but it is not clear if this is due to hot-spot overprinting or to original tectonic reorganizations. The Horizon ridge lies along the northern edge of the fracture zone and is sub-parallel to its trend, so that it may be part of it. Farther to the north, the Necker ridge lies oblique to all the other structures and seems to require a separate explanation.

Clarion Fracture Zone

The most southerly of the fracture zones in the region, the Clarion, shows up clearly in the deflection-of-the-vertical profiles. It appears to have a simpler structure than the Quiet Zone fracture zones to the north, consisting of only one or two strands. It forms a continuous feature from the easternmost North Pacific to the southern end of the Sculpin ridge.

IMPLICATIONS FOR TECTONIC HISTORY

The Pacific/Farallon Plate Boundary and its Reorganizations

Perhaps the most important result of our new tectonic map is the fact that the shapes of the various fracture zones are all quite similar. From west to east, i.e. from old to young, all are concave south, gradually changing trend from east-northeast to nearly east, then all abruptly shift back to east-northeast at the Chron 33R bend. The similarity suggests that all were formed along transform faults of a single plate pair (the Farallon and Pacific plates) and that those two plates experienced changes in relative plate motion direction that were recorded simultaneously by all the transform faults.

Unfortunately, although it seems clear that most of the central Pacific Quiet Zone was formed by Pacific-Farallon spreading, it is equally clear that the spreading was not symmetrical and continuous but, rather, that the system suffered major ridge crest jumps sometime during the Superchron. This is required by the fact that the fracture zone displacements offsetting magnetic isochron M0 are distinctly different from those offsetting isochron 34 (Figures 1 and 6). The timings of these jumps is not established, but several lines of evidence suggest that they occurred early in the Superchron. The similarities in the fracture zone shapes, described above, are particularly distinctive in the eastern part of the Quiet Zone. Since a major spreading center jump would be likely to change the shape of its adjoining fracture zone segments, this shape-similarity suggests that the jumps occurred in the western (older) part of the Quiet Zone. Furthermore, there are a number of topographic anomalies of unknown origin that could be the results of spreading center jumps. These occur primarily in the western part of the Quiet Zone. Finally, the proposed timing fits with the larger observation that the western Pacific region was the site of numerous, extremely voluminous volcanic outpourings that began at the beginning of the Superchron [Larson, 1991]. Such an event might facilitate plate boundary reorganizations by weakening the lithosphere on the flank of a spreading center. Engebretson et al. [1991] and Joseph et al. [this volume] postulate such a relationship between the Manihiki plateau volcanism and a southward jump of the Pacific-Farallon-Phoenix triple junction, for example.

In general, spreading center "jumps" are accomplished when a new propagating rift tears off a piece of one plate, creating a microplate between it and the old, established ridge. If activity on the old ridge then dies, the microplate has been transferred to the other plate and the spreading center has "jumped". In some well-documented cases of such transfers, the extinct ridge is marked by a topographic high while the rift propagation line (i.e. the initiation site) is a trough. Such features are seen around the Mathematician plate [Mammerickx et al., 1988] and around the Murray-Molokai "disturbed zone" [Malahoff and Handschumacher, 1971, as modified by Atwater and Severinghaus, 1989].

There are several anomalous topographic features in the western Quiet Zone, Figure 1, that might have been formed by ridge jumps. The Hess, Liliuokalani, and Sculpin ridges might all be extinct spreading centers, although each could, rather, have been superimposed on the crust later by off-axis volcanic events. The southern Emperor trough could be an initiation site, though it also may have been superimposed later, during the breakoff of the Kula plate, as described next. Initiation troughs are not observed in the other segments, but these may have been diminished by the flattening of the age-depth curve. Given the ambiguous origins of all these features, we are left concluding only that if they were formed by ridge jumps, the jumps occurred early in the superchron.

One group of topographic features that does not correspond to any common explanation is the Necker ridge and adjacent, parallel ridges near 22°N, 165°W on Figure 3b. These features are extremely linear, narrow and high and they lie oblique to the nearby Molokai fracture zone and to the seafloor topographic grain. Thus, they resemble neither common seafloor spreading features nor common superimposed volcanic features. In some ways they resemble a series of ridges reported by Winterer and Sandwell [1987] that run east-southeastward from Christmas Island. Winterer and Sandwell propose that those features formed along leaky tension cracks. If the Necker ridge group formed in some similar way, it is of great interest for plate stress considerations at its origin time, but it was probably superimposed on aged lithosphere so does not impact our Cretaceous seafloor spreading scenarios.

Development of the Kula Plate (and Chinook Plate?)

The patterns and relationships shown in Figure 6 and discussed above have implications for the history of the Kula plate. We agree with both Rea and Dixon [1983] and Mammerickx and Sharman [1988] that spreading on the Kula-Pacific boundary initiated in the Chinook trough. Magnetic isochrons north of the trough mapped by Mammerickx and Sharman [1988] and by Atwater and Severinghaus [1989] are shown in Figure 6. They demonstrate that Kula-Pacific spreading initiated along a break that propagated from west to east during Chron 33R (i.e., after the Superchron), breaking off a northern piece of the Pacific plate. If the northern Emperor trough and the Chinook trough are assumed to have been formed as the breaks along the western and southern edges of the new Kula plate, it is possible that the southern Emperor trough may have been formed during this same rifting event, as a third arm or "failed arm" similar to those formed during continental breakups [Burke, 1976].

The breakoff of the northern part of the Pacific plate has important ramifications for plate driving forces. The break would have dramatically reduced the northward pull on the Pacific plate from north Pacific subduction zones. Given its timing, the breakoff is the likely cause for the major change of spreading direction observed in Pacific/Farallon motion corresponding to the Chron 33R bend.

It has been suggested by various authors that the region between the Chinook trough and the Mendocino fracture zone was occupied by another plate, the Chinook plate [Rea and Dixon, 1983; Mammerickx and Sharman, 1988]. However, our contention that the Mendocino was a fracture zone in the Pacific-Farallon system implies that the region to the north of it was part of the Pacific plate, not some other. We are firmly convinced of this interpretation for the eastern part of the Quiet Zone because of the similarity of fracture zone shapes approaching the Chron 33R bend. Furthermore, the sea floor between the Mendocino fracture zone and the Chinook trough lacks any indication of an abandoned plate boundary, such as a north-south ridge, and Chron 34 is extremely straight, lacking the usual offsets and mismatches that indicate a recent reorganization. Thus, we conclude that, if the Chinook plate existed at all, it was deactivated before late Superchron time.

Variations in fracture zone widths

One of the more interesting aspects of transform systems is the process by which they accommodate changes in relative plate motion directions. The geometric problem is illustrated for a flat earth case in Figure 7. During steady spreading periods (Figure 7: steps 1-3) transform systems generate fracture zones with strands following parallel straight lines (or concentric small circle paths on a sphere). When there is a change in spreading direction (steps 3-4), the transform faults must take on the new direction and the resulting fracture zones are widened and narrowed, depending upon their senses of offset (step 7).

The fracture zones in our area have large offsets in both senses and they change widths in a manner similar to that illustrated in Figure 7. These width changes are particularly clear at the Chron 33R bend, where the Molokai and Mendocino-Pau-Pioneer systems become significantly wider from west to east while the Murray and Clarion systems become narrower. Some subtle width changes that are in the opposite senses from those just described can be detected going from west to east (from old to young) across the Quiet Zone. Particularly clear is a widening of the Murray system, but width changes can be seen or inferred on the others as well. These changes in width provide an important constraint for plate kinematic models, as will be described next.

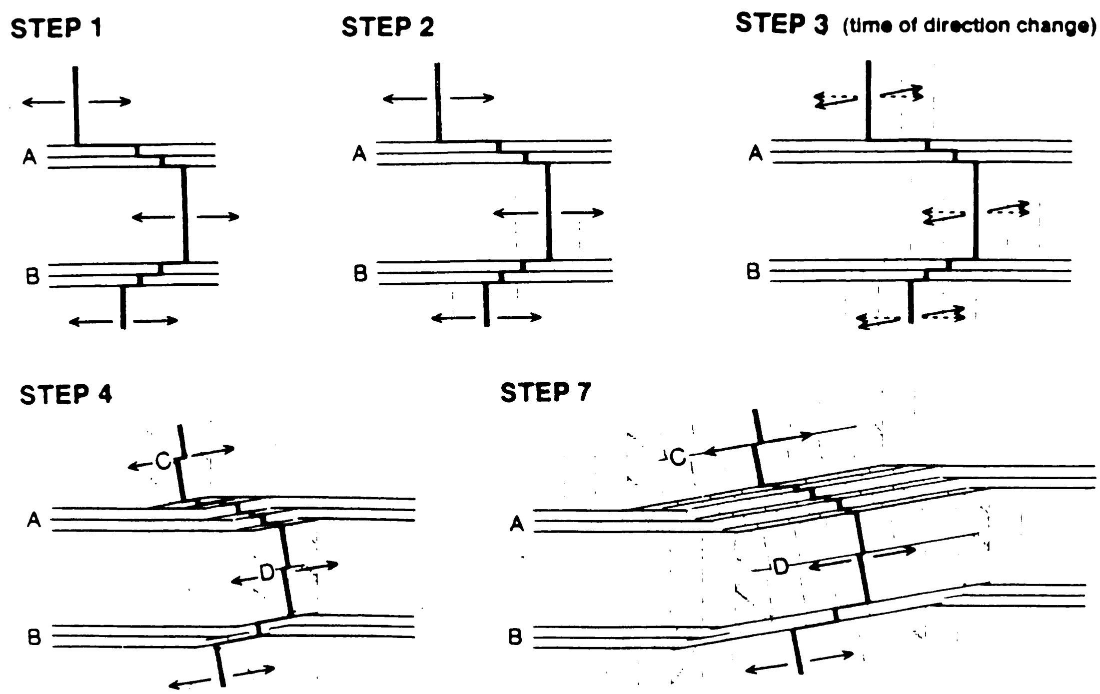

Fig. 7. Theoretical sea floor patterns formed when a spreading system containing two multi-stranded fracture zones (A and B) suffers an abrupt change in direction of relative plate motion. Heavy double lines are active spreading centers; heavy single lines are active transform faults; light lines are fracture zone traces; vertical dashed lines are seafloor isochrons. Numbers represent equal time steps. From step 1 to step 3 spreading was steady E-W. At the time of step 3, the relative plate motion changed by 10° to east-northeast-west-southwest. From step 3 to step 4 the the spreading centers and transform faults adjusted to the new direction, as follows: transform A narrowed and consolidated its strands; transform B widened and created additional strands; propagating rifts (traced by oblique dotted lines) gradually established spreading centers perpendicular to the new direction, creating new transform faults when they stalled (fracture zones C, D, and E). Steady spreading continued in the new direction through steps 5 and 6 (not shown) to step 7.

Stage pole descriptions of Pacific-Farallon relative motions

The relative spreading directions between plates during the formation of oceanic lithosphere can be described by rotations about Euler "stage poles". Stage poles have been fit to the Pacific-Farallon isochron patterns that were formed during the M-Series reversals by Engebretson et al. [1984] and to the patterns formed during the early Heirtzler scale reversals by Francheteau et al. [1970], Engebretson et al. [1984] and Rosa and Molnar [1988]. Some of these poles are listed in Table 1 and are plotted on Figure 8. For the Quiet Zone, some poles have been published that describe the entire Zone as one single stage [Francheteau et al., 1970; Engebretson et al., 1984; Sager and Pringle, 1987a; Joseph et al., 1992 and this volume] but none have been published for multiple stages within the Quiet Zone.

This lack of poles for stages during the Superchron is a direct result of the lack of datable magnetic reversals during this time period. The procedures employed for fitting stage poles use fracture zones to measure spreading directions and magnetic reversal isochrons to choose the appropriate segments of the fracture zones and to measure half-spreading distances. Without isochrons the process is severely hampered. However, if there were significant Euler pole shifts, the fracture zone shapes alone could contain age information since fracture zone segments formed during each given stage should all follow concentric small circles about the pole for that stage. We explored this possibility for the Quiet Zone fracture zones with mixed results. In the next sections we describe our attempt to fit the fracture zones with a series of seven high latitude stage poles, an attempt by Joseph et al. [1992] to fit them with a single low latitude pole and a possible compromise between these approaches.

TABLE 1.
Stage poles for Cretaceous Pacific-Farallon relative plate motions.

Time Interval			Stage Pole Parameters		
Pole	Chrons	Ma.*	Lat,°S	Lon,°W	Rot,°c
Final M-Series Stage [Engebretson et al., 1984]					
M_f	M11-M0	131-119	9	164	15
Superchron Alternative 1 [this paper]					
S_1	M0 - ?	119 - ?	64	114	4.0
S_2	?	?	70	114	4.0
S_3	?	?	74	114	3.0
S_4	?	?	77	114	3.0
S_5	?	?	80	114	2.0
S_6	?	?	84	114	2.0
S_f	? - 33R	? - 81	87	114	2.1
Superchron Alternative 2 [Joseph et al., 1992]					
S_J	M0 - 33R	119-81	30	152	25
Superchron Alternative 3 [this paper]					
S_J	M0 - ?	119 - ?	30	152	15
S_6	?	?	84	114	2.0
S_f	? - 33R	? - 81	87	114	2.1
First Heirtzler Series Stage [Engebretson et al., 1984]					
H_1	34 - 25	83 - 56	66	116	21

*absolute ages from time scales of Kent and Gradstein (1985) and Cande and Kent (1992)

A crucial decision one must make before searching for Quiet Zone stage poles is whether to include the new configuration of the Mendocino fracture zone in the analysis. The special importance of the Mendocino for the pole fitting process arises from the fact that it is significantly offset in longitude from the other fracture zone traces. When the Mendocino is included, the stage pole for the youngest part of the Superchron (just preceding the Chron 33R bend) must lie near the spin axis in order to fit the nearly east-west trends of all the fracture zones over such a wide longitudinal spread. For reasons described in an earlier section, we assume that it must be included for the youngest part of the Superchron. Thus, we conclude that the pole for the final Superchron stage is relatively well constrained to lie near the spin axis: pole S_f in Table 1 and filled circle on Figure 8.

We found that we could fit flow lines to the Quiet Zone fracture zones using a series of high latitude stage poles. We fit poles to the fracture zones working westward (backwards in time) from our late Superchron stage pole S_f. The fracture zones curve quite smoothly and we fit them using a series of six stage poles, S_6-S_1, that drift smoothly from S_f to S_1. This series is listed under Superchron Alternative 1 in Table 1 and is plotted as open and filled circles on Figure 8. However, this is not the only approach for fitting Quiet Zone poles.

Joseph et al. [1992 and this volume] consider features in the equatorial and southern central Pacific and propose a southern Quiet Zone history and kinematic model. They elaborate on the model of Engebretson et al. [1991] to suggest that the Pacific-Farallon-Phoenix triple junction, shown to lie near 2°N, 167°W by the M1 isochrons of Nakanishi et al. [1992], jumped south to about 20°S. They suggest that this occurred near the beginning of the Superchron when the Manihiki Plateau (M on Figure 8) erupted and broke the seafloor along its eastern edge. This transferred a microplate (the region outlined by the dotted line on Figure 8) to the Pacific plate and created a new southern segment of the Pacific-Farallon Quiet Zone spreading system. Joseph et al. [1992] propose an elegantly simple kinematic model for the relative motion that created all of this greatly extended Quiet Zone: a rotation about a single, low latitude pole, S_J, at 30°S, 152°W (Superchron Alternative 2 in Table 1 and circle with dot in Figure 8).

One obvious test of these alternative kinematic models is to construct theoretical flow lines about the poles and compare [redacted] 151 [redacted]

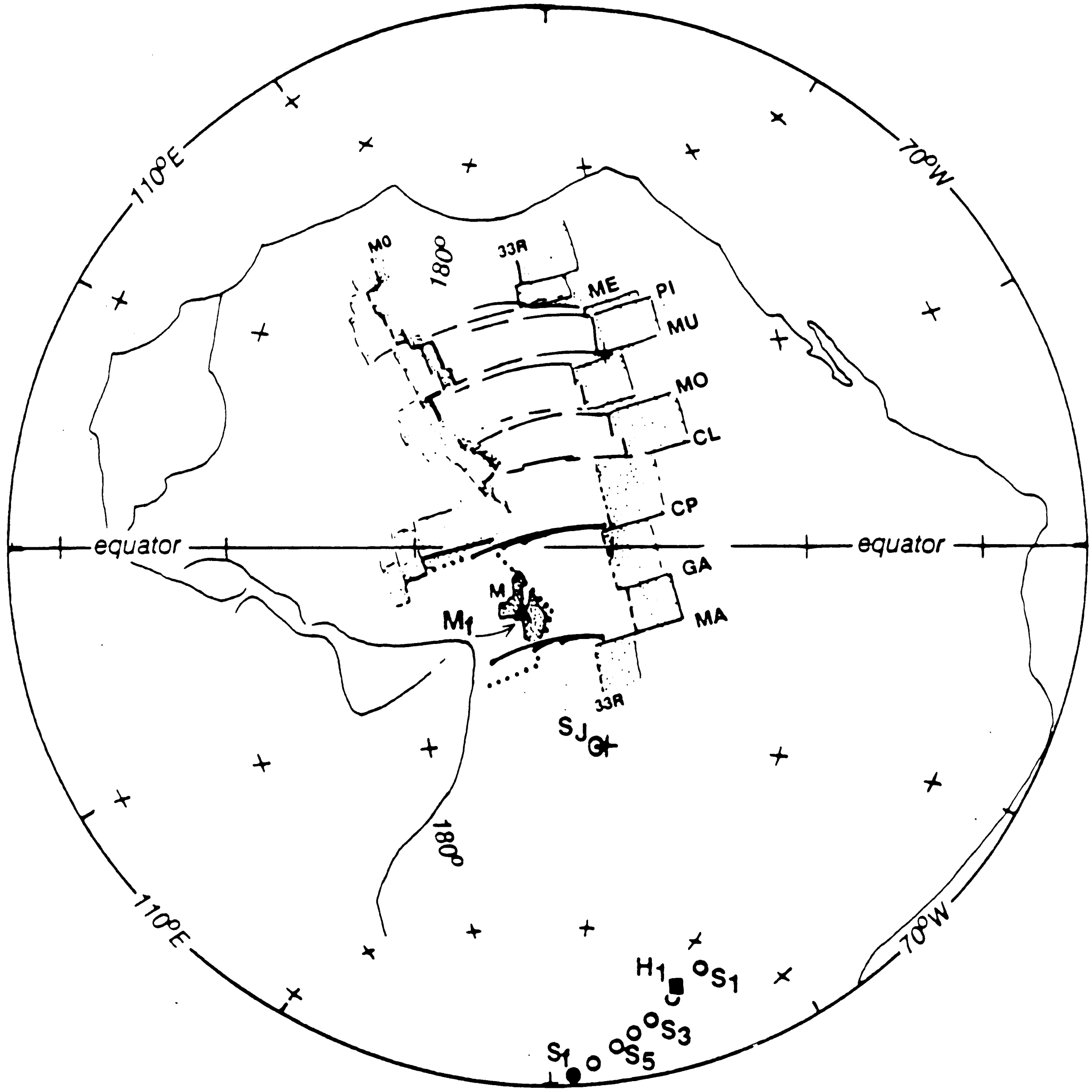

Fig. 8. Configuration of the central Pacific Quiet Zone and possible Euler pole descriptions of the Pacific-Farallon relative plate motions during the Cretaceous. Western and eastern stippled regions are approximate areas of seafloor formed preceding the Superchron (chrons M11-M0) and following the Superchron (chrons 33R-25), respectively. Heavy dotted line shows approximate outline of Phoenix mini-plate, postulated by Engebretson et al. [1991] and Joseph et al. [1992] to have been transferred to the Pacific plate about M0 time. Euler pole locations are M_f (filled triangle) describing the final M-series motions and H_1 (filled square) describing early Heirtzler-scale motions, both from Engebretson et al. [1984], and Superchron alternatives: S_J (circle with dot) - single low latitude pole of Joseph et al. [1992] and S_1-S_6, S_f (open and filled circles) - high latitude series. Two sets of nested curves each include Superchron flowlines predicted by the three alternative plate kinematic models listed in Table 1: longest curves are predicted by Alternative 1; shortest curves are predicted by Alternative 2; intermediate length curves are predicted by Alternative 3. Labelled features are ME: Mendocino, PI: Pioneer, MU: Murray, MO: Molokai, CL: Clarion, CP: Clipperton, GA: Galapagos, and MA: Marquesas fracture zones and M: Manihiki Plateau. Western stippled region is bordered by Chron M11 and M1 or M0 where known after Nakanishi et al. [1992], Atwater and Severinghaus [1989] and Figure 3 (details of Magellan plate patterns have been omitted). Eastern stippled regions are bordered by approximate locations of Chrons 33 and 25 (dashed where extrapolated) and fracture zone traces after Mayes et al. [1990], Eittreim et al. [submitted], Atwater and Severinghaus [1989], Candy et al. [1989], Haxby [1987], and Figures 3 and 6. Light lines outline features of the present Pacific rim, for orientation. Stereo projection is centered on 160°W and the equator.

them to our north Pacific fracture zones. We have done this in Figure 9. Since we believe that most of the ridge jumps in the Quiet Zone occurred early in the Superchron, we constructed flow lines working backward in time (from east to west) starting at the Chron 33R bend. We note that, since the bend locations are not perfectly known and, in any case, were probably shifted somewhat by propagating rifts at the time of the bend, we made minor adjustments in the bend location to maximize the fit for each kinematic model that was tried. Predicted flow lines from the two models are presented in Figures 9a and 9b, as theoretical lines on the left and as grey curves overlain on the observed fracture zone lineations on the right. The predicted patterns are quite similar to each other except for two aspects, as follows.

One important difference between the two kinematic models concerns the fitting of the Mendocino fracture zone. Flow lines constructed for pole S_J, Figure 9b, miss it entirely. Joseph et al. do not claim to fit this fracture zone; they extend their analysis only as far north as the Pau fracture zone. If we accept S_J as the single pole to describe the entire Quiet Zone creation, then we must postulate a non-Farallon-Pacific origin for the Mendocino fracture zone right up to Chron 33R time or else we must abandon the Atwater and Severinghaus [1989] mapping of it. As described in earlier sections, we find both of these alternatives to be unlikely.

A second, more subtle test of the Figure 9 flow line fits is to note the extent of widening and narrowing of fracture zones as they cross the Quiet Zone. Our drifting, high latitude poles, S_1-S_f, predict distinct width changes, as the individual strands converge or diverge, Figure 9a. The single pole, S_J, predicts constant-width fracture zones with concentric strands, Figure 9b. While the observational data is fragmentary, it is clear that the observed fracture zones do widen or narrow, depending on their offsets, in concert with one another. However, the width changes do not seem to be as pronounced as those predicted by the flow lines in Figure 9a.

We constructed a compromise solution that incorporates the more successful attributes of both the models just discussed. It adopts S_J for the older two-thirds to three-quarters of the Quiet Zone and S_6 and S_f for the youngest stages (Superchron Alternative 3 in Table 1). Flow lines for this compromise model are shown in Figure 9c. They predict modest width changes and they fit the Mendocino trend.

We also compared predictions from the three alternative kinematic models for Quiet Zone features in the equatorial and south Pacific. Predicted flow lines are illustrated by the two sets of nested curves crossing the Quiet zone on Figure 8. Each set includes three curves, one for each of the three alternative models. A possible test would be to compare the observed fracture zone curvatures to the curves predicted by the models. Joseph et al. [1992 and this volume] present a test similar to this for pole S_J, showing a fair match to the traces of the fracture zones in the SEASAT data. Unfortunately, as shown by the nested curves, the other kinematic models predict quite similar curvatures. Furthermore, the SEASAT data for the southern Quiet Zone fracture zones are somewhat indistinct and ambiguous, so that the predicted subtle differences are not likely to be distinguishable.

A simpler test of the kinematic models concerns the breadth of the southern Quiet Zone. If the history proposed by Engebretson et al [1991] and Joseph et al. [this volume] is accepted, the eastern edge of the Manihiki plateau (eastern dotted lines on Figure 8) should approximately correspond to the M0 isochron. Approximate locations for the Chron 33R bend can be found from SEASAT traces and from isochron mappings and extrapolations. Thus the breadth of the Quiet Zone is approximately known, as shown on Figure 8. The theoretical breadths predicted by the three kinematic models for the southern Quiet Zone are dramatically different from one another. In each set of nested curves on Figure 8, the shortest curve corresponds to the low latitude pole S_J, and the longest to the high latitude poles S_1-S_f. The former clearly underestimates the breadth of the southern Quiet Zone while the latter clearly overestimates it. Several major additional ridge jumps would be required to fit either of these models. The compromise model (Superchron Alternative 3 in Table 1) predicts the intermediate length curves and is more compatible with the observed breadth.

The most obvious conclusion from all these pole fitting exercises is that the kinematic description of the Quiet Zone is still very poorly constrained. We were hard-pressed to distinguish among poles that were nearly sixty degrees apart on the globe! A final kinematic description, if we ever are able to find one at all, will probably have a high latitude pole for the late Superchron (to fit the Mendocino), shifting poles (to fit the variable fracture zone widths) and lower latitude poles for earlier stages (to fit the southern Quiet Zone breadth). While the compromise model, Superchron Alternative 3, has these characteristics, it is by no means unique.

CONCLUSIONS

We have combined shipboard topographic and magnetic profiles, Gloria side-scan data, and satellite altimetry data to refine the chart of fracture zone traces in the central North Pacific. Adding the known magnetic isochrons to these fracture zone traces and leaving out the Hawaiian/Emperor chain, we have produced a new Cretaceous tectonic chart.

The mapped fracture zone and isochron patterns shed new light on various aspects of the spreading history that created the sea floor in the central Pacific Quiet Zone. They support the idea that all of this area was formed by spreading between the Pacific and Farallon plates and they cast doubt on the existence of the Chinook plate, at least in the late Superchron. They show that one or more major ridge jumps occurred, probably early in the Superchron. They document smooth spreading with relative direction gradually changing from east-northeast to east, then a sudden change back to east-northeast during Chron 33R. They show patterns of fracture zone widening and narrowing, intricately following the geometric constraints imposed by plate direction changes.

When combined with data and ideas from Joseph et al. [1992 and this volume] for the Quiet Zone in the equatorial and

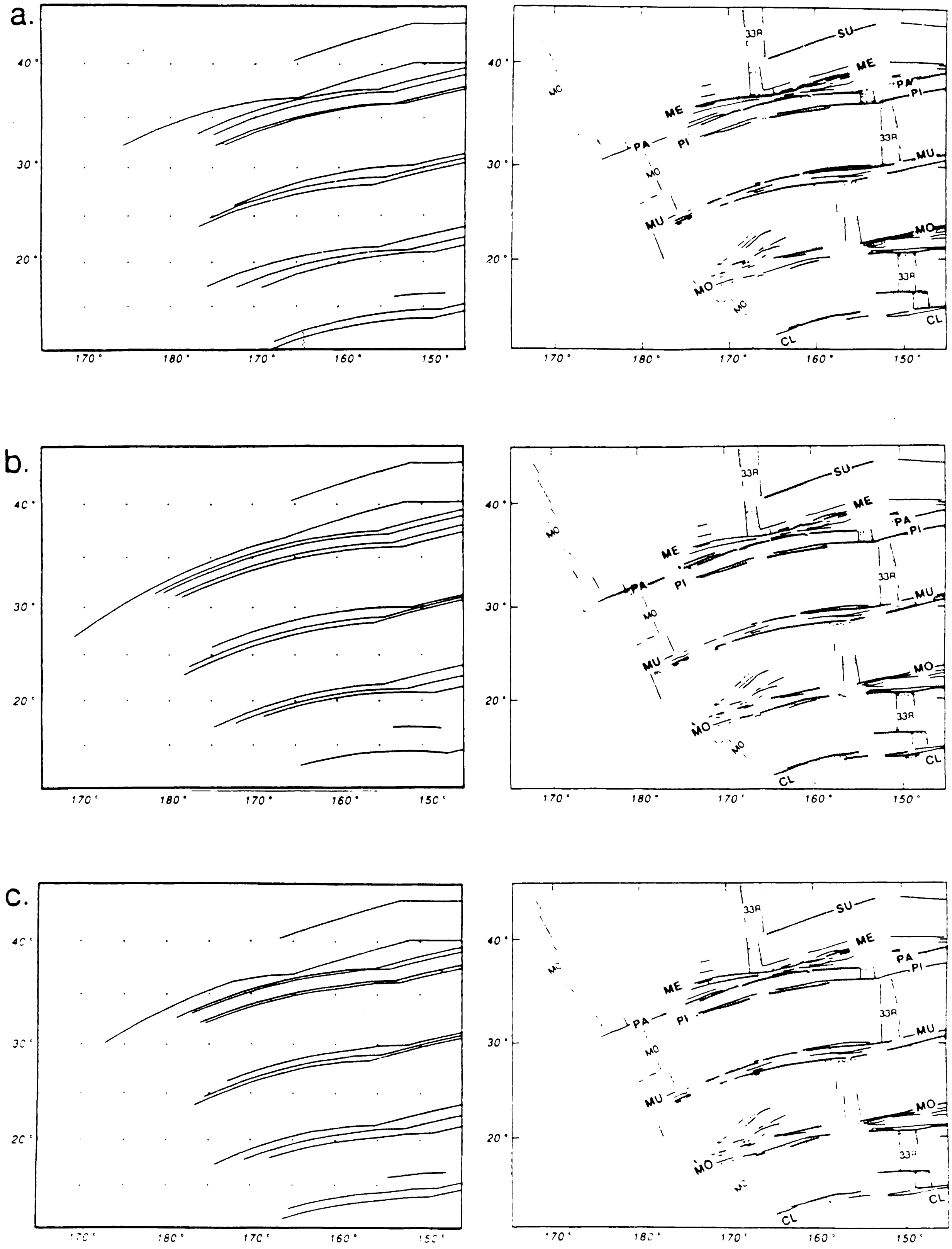
a.
b.
c.
40°
30°
20°
170°
180°
170°
160°
150°
SU
ME
PA
PI
MU
MO
CL
33R
MO

Fig. 9. Comparison between fracture zone traces mapped in the central north Pacific and synthetic flow lines predicted by alternative kinematic models. Black lines and dashes are observed linear features; M0 lines show observed or extrapolated locations of Chron M0; coarsely stippled areas are Chron 33R regions (polarity reversal between between Chrons 34 and 33), all from Figure 6. Fat grey lines show flowlines constructed starting at points near the Chron 33R bends; as described in the text, these points were slightly adjusted to maximize each fit. The flow lines were constructed eastward using pole H_1 and westward using the three alternative Superchron kinematic models described in Table 1 and the text. Labelled fracture zones are SU: Surveyor, ME: Mendocino, PA: Pau, PI: Pioneer, MU: Murray, MO: Molokai, and CL: Clarion fracture zones. (a) Flowlines predicted by Superchron Alternative 1: high latitude series of poles, S_7-S_6-S_5-S_4-S_3-S_2-S_1. (b) Flowlines predicted by Superchron Alternative 2: single low latitude pole of Joseph et al. [1992], S_J. (c) Flowlines predicted by Superchron Alternative 3 (compromise model): S_7-S_6-S_J.

south Pacific, our north Pacific tectonic patterns supply some constraints for Superchron plate kinematic models. The changing widths of our fracture zones imply that there were several distinct stage poles (as opposed to a single pole for the whole Superchron). The fracture zone trends for the late Superchron (immediately pre-Chron 33R), when the Mendocino is included, require a stage pole very near the spin axis. The narrowing breadth of the Quiet Zone in the south Pacific implies lower latitude, south Pacific poles for the earlier stages of the Superchron. Locations for the various stage poles (except, perhaps, for the youngest stage) are poorly constrained by the present data sets. Future shipboard mapping of the Quiet Zone traces of the Marquesas and Galapagos fracture zones will be particularly important for this problem, since these features lie quite near the likely locations of the early Superchron stage poles.

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