LARGE-SCALE OBLIQUE FEATURES IN AN ACTIVE TRANSFORM FAULT, THE WILKES FRACTURE ZONE NEAR 9°S ON THE EAST PACIFIC RISE

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Abstract. The Wilkes fracture zone offsets the East Pacific Rise about 200 km right-laterally near 9°S. The bathymetric expression of the fracture zone ranges from a simple slope or step along its inactive extension to a 100 km wide zone of oblique structural features in the active portion. A low ridge 200 to 300 m high, 5 to 15 km wide and 185 km long is the dominant oblique structure; it trends 23° north of the main transform trend. A high-amplitude magnetic anomaly trends 097° along the southern part of the active portion and apparently marks the main transform direction. The structurally simple, inactive portions of the Wilkes fracture zone trend 105°. Plots of epicenter locations reveal two groupings of earthquakes, one along an 082° trend in the central part of the fracture zone, and a cluster near the southwestern fracture zone – spreading center intersection.

Taken together the data suggest that some event, other than a shift in the Nazca-Pacific pole of rotation, occurred 0.9 m.y. ago to change the Wilkes fracture zone from a simple fault to a complex zone of shearing. Since that time the long oblique ridge, probably the surface expression of a Riedel shear, was formed. At present the entire 200 km long, 100 km wide region between the offset axes is seismically active, but transform motion may be largely confined to the southern margin of the active zone, coincident with the high-amplitude magnetic anomaly there.

1. Introduction

The Wilkes Fracture Zone (WFZ) offsets the East Pacific Rise (EPR) right-laterally about 200 km near 9°S latitude. This section of the EPR forms the boundary between the Nazca plate to the east and the Pacific plate to the west and extends from the Galapagos triple junction at 2°N to the Easter Island triple junction at 34°S (Figure 1). The most rapid sea-floor spreading rates along the entire world rift system occur along this portion of the EPR with whole rates ranging from 150 mm y^{-1} in the northern portion (Lonsdale, 1977) to 163 mm y^{-1} at 31°S (Rea, 1977). The EPR in this region is a geologically young feature having

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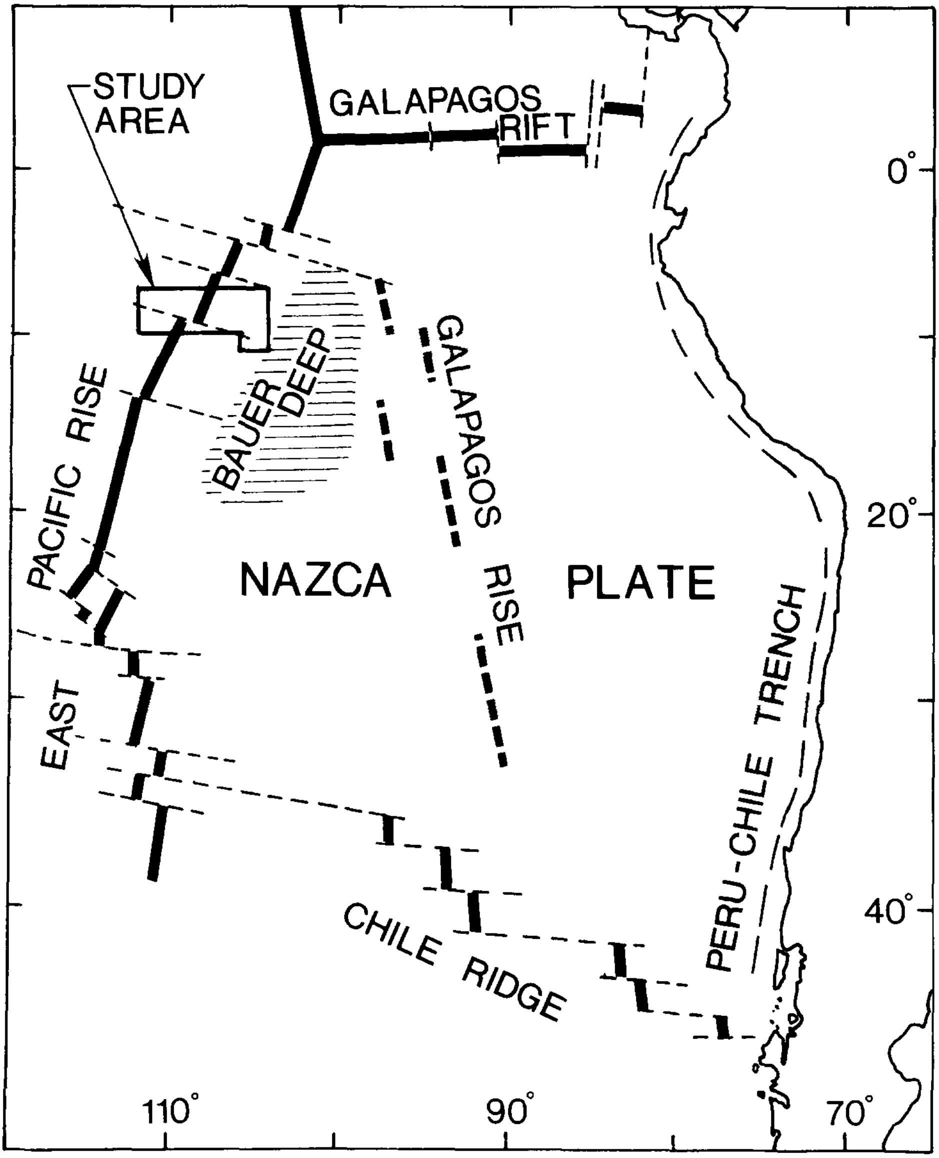

Fig. 1. Index map of the Nazca Plate showing the study area.

formed between about 25 and 6 million years ago (mya) (Herron, 1972; Rea, 1978a; Mammerickx *et al.*, 1980) by westward axis jumps from the now extinct Galapagos Rise.

Most of the information which exists concerning transform faults and their associated fracture zones comes from studies of offsets of slowly or moderately spreading ridges. These features, of which the North Atlantic fracture zone are typical, are characterized by deep linear troughs usually 10 to 30 km wide and bounded by steep walls. The general trough-and-wall morphology of these fracture zones is maintained as spreading directions change (van Andel *et al.*, 1971; Fox *et al.*, 1976). Many of these moderate to large sized fracture zones can be traced as continuous freatures for thousands of kilometers (Phillips and Luyendyk, 1970; Le Pichon and Hayes, 1971). Fracture zones offsetting the fast-spreading portion of the EPR along the western margin of the Nazca plate do not conform to this rather simple picture. Rather, they occur in a variety of forms ranging from barely discernible to 100 km wide zones of broken and blocky topography. The Wilkes Fracture Zone near 9°S is one of the larger ones along the northern part of the Nazca-Pacific plate boundary. The intent of this study is to utilize existing data in the area of the WFZ to map the bathymetry and magnetics in order to accomplish two goals: first, to determine the structure of fracture zones on fast spreading rises and to discover how the thin trailing edges of rapidly accreting plates may deform; and second, to provide a picture of any past spreading direction changes that may have occurred along this plate boundary.

1.1. Previous investigations

Spurred by the Wilson's classic paper (1965) on transform faults, many investigators have studied the morphology, pertrology, and tectonics of fracture zones. However, most of them have discussed the large, inactive offsets in the northeast Pacific (cg., Menard, 1964) or offsets of the rifted rises (cf., Sleep and Biehler, 1970; van Andel *et al.*, 1971; Le Pichon and Hayes, 1971; Detrick *et al.*, 1973; Eittreim and Ewing, 1975; Fox *et al.*, 1976; Searle and Laughton, 1977; Choukroune *et al.*, 1978). Some papers address fracture zone geometry as indicators of past plate motions (cf., Phillips and Luyendyk, 1970; Rea, 1970) while others address tectonic processes within these features (Sleep and Biehler, 1970; van Andel *et al.*, 1971 and 1973). Sleep and Biehler (1970) suggested that the trough and elevated wall topography of the Atlantic fracture zones could only occur when rifted rises were offset.

Data from four fracture zones along the moderately-spreading portion of the EPR between the Cocos and Pacific plates reveal a general trough-and-wall morphology for the Tamayo fracture zone at 21°N (CYAMEX, 1978 ; Macdonald *et al.*, 1979), the Rivera fracture zone at 19°N (Gumma, 1974; Prothero *et al.*, 1976), the Orozco fracture zone at 15°N (Lynn, 1976; Lynn and Lewis, 1976) and the Siqueiros fracture zone at 8°N (Crane, 1976). Spreading whole rates for these regions range from 60 mm y^{-1} at 21°N to 120 mm y^{-1} at 8°N. All of these fracture zones offset a spreading center characterized by a small (about 300 m high) axial ridge rather than an axial valley. Still, even at the fairly rapid spreading rate of 120 mm y^{-1} near the Siqueiros fracture zone, the structure of that fracture zone more closely resembles Atlantic-type fracture zones than those found along the Nazca-Pacific plate boundary farther south.

The fracture zones found along the faster spreading (150 to 163 mm y^{-1} whole rates) section of the EPR between the triple junctions at 2°N and 34°S do not display an obvious trough-and-wall structure. A near-bottom survey of part of the Quebrada transform fault near 4°S, which is a series of an echelon faults offsetting the EPR about 390 km right-laterally, indicates a narrow (<200 m wide) furrow about 20 to 50 m deep wherein most of the left-lateral motion appears to be concentrated (Lonsdale, 1978). The longest continuous topographic feature associated with the 55 km right-lateral offset at 6.2°S is a 25 km-long depression, a few hundred meters deep, found between the offset rise crests. In contrast to the discontinuous bathymetric expression, a well-developed high-amplitude magnetic anomaly parallels that fracture zone for about 100 km (Rea, 1976a).

The Wilkes fracture zone, named by Mammerickx and Smith (1978), has been briefly described by Herron (1972) and by Mammerickx *et al.* (1975), who interpreted it as two closely spaced fracture zones, probably because the region between the active rise axes is approximately 100 km wide. Regional bathymetry and magnetic anomalies near the WFZ have been discussed by Rea (1975 and 1976b).

2. Bathymetric, Magnetic and Seismic Data

Data for this study were assembled from 11 cruises between 7° and 11°S and 104.5° and 112°W (Figure 2). Eight of the eleven cruises predated 1972 and the remaining three (*Kana Keoki* 71–8 of Hawaii Institute of Geophysics, *Oceanographer* 73–1 and 73–4 of NOAA) were part of the IDOE Nazca Plate project. Bathymetry was available from all 11 cruises and magnetic data were available on all but the Downwind-*Baird* cruise. Most tracklines were positioned by satellite with an accuracy of at least 1 km and data agreement at line crossings was excellent. Bathymetric observations were conducted using either 12 or 3.5 kHz echo sounders and magnetic data were collected using proton-precession magnetometers. All bathymetric data were corrected for the variation of velocity of sound in seawater by utilizing the Matthews Tables (Matthews, 1939) and an assumed sound velocity of 1463 m s^{-1}. Total intensity magnetic data were reduced to anomaly form using the International Geomagnetic Reference Field (IAGA Commission 2 Working Group 4, 1969).

2.1. Bathymetric Data

Ocean-floor depths in the mapped area range from in excess of 3800 m in the northwestern and southeastern portions of the area to less than 2800 m at the crest of the EPR (Figures 3 and 4). Aside from the fracture zone, the EPR axial ridge, defined by the 3000 m isobath, is the most obvious feature and three sections apprear in the study area (Figure 3). The southwestern section trends

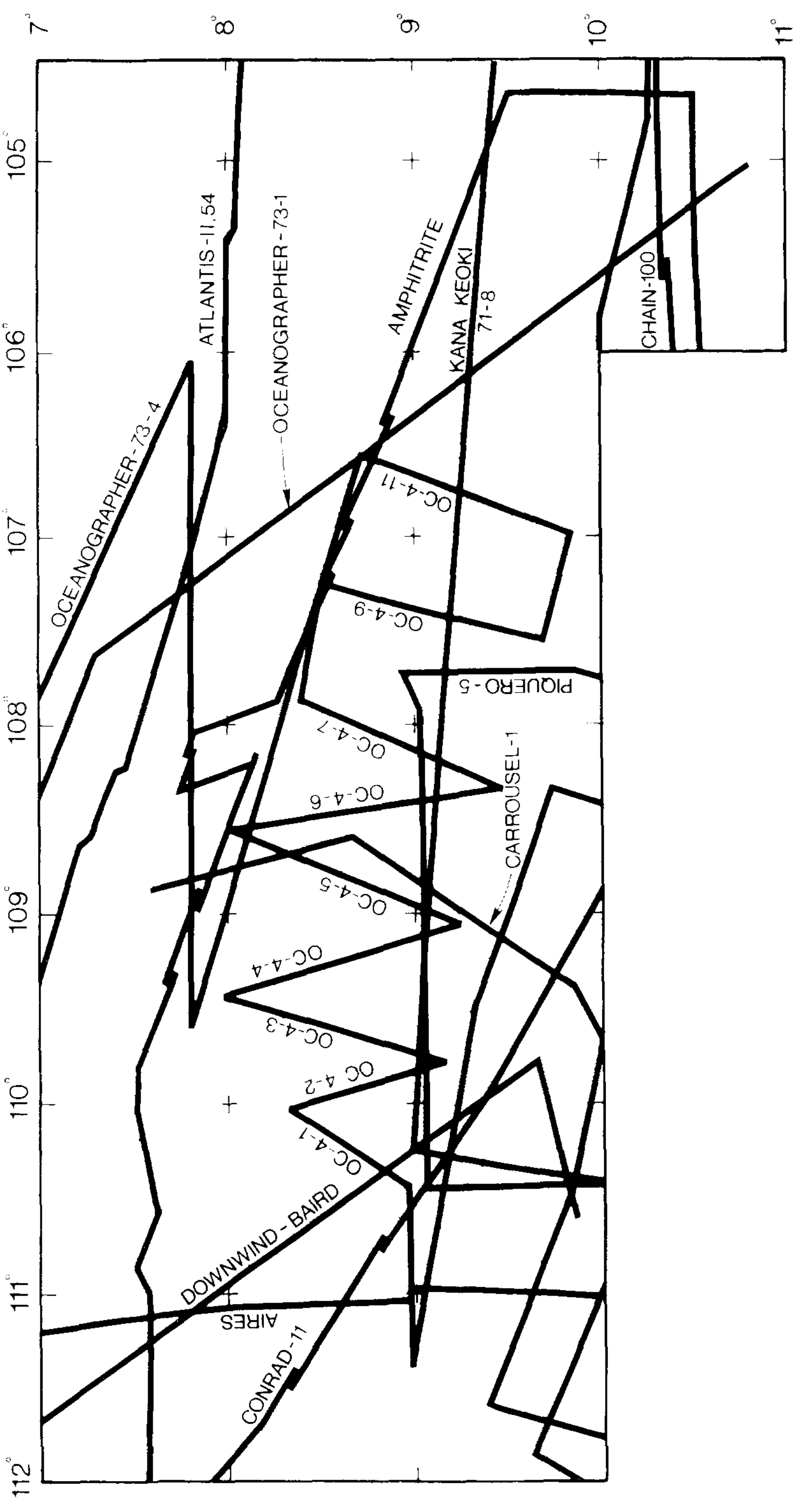

Fig. 2. Tracklines from cruises in the vicinity of the Wilkes fracture zone. Lines OC-4-1, etc. are fracture zone crossings made by the R/V *Oceanographer* on Leg 4 of the 1973 cruise.

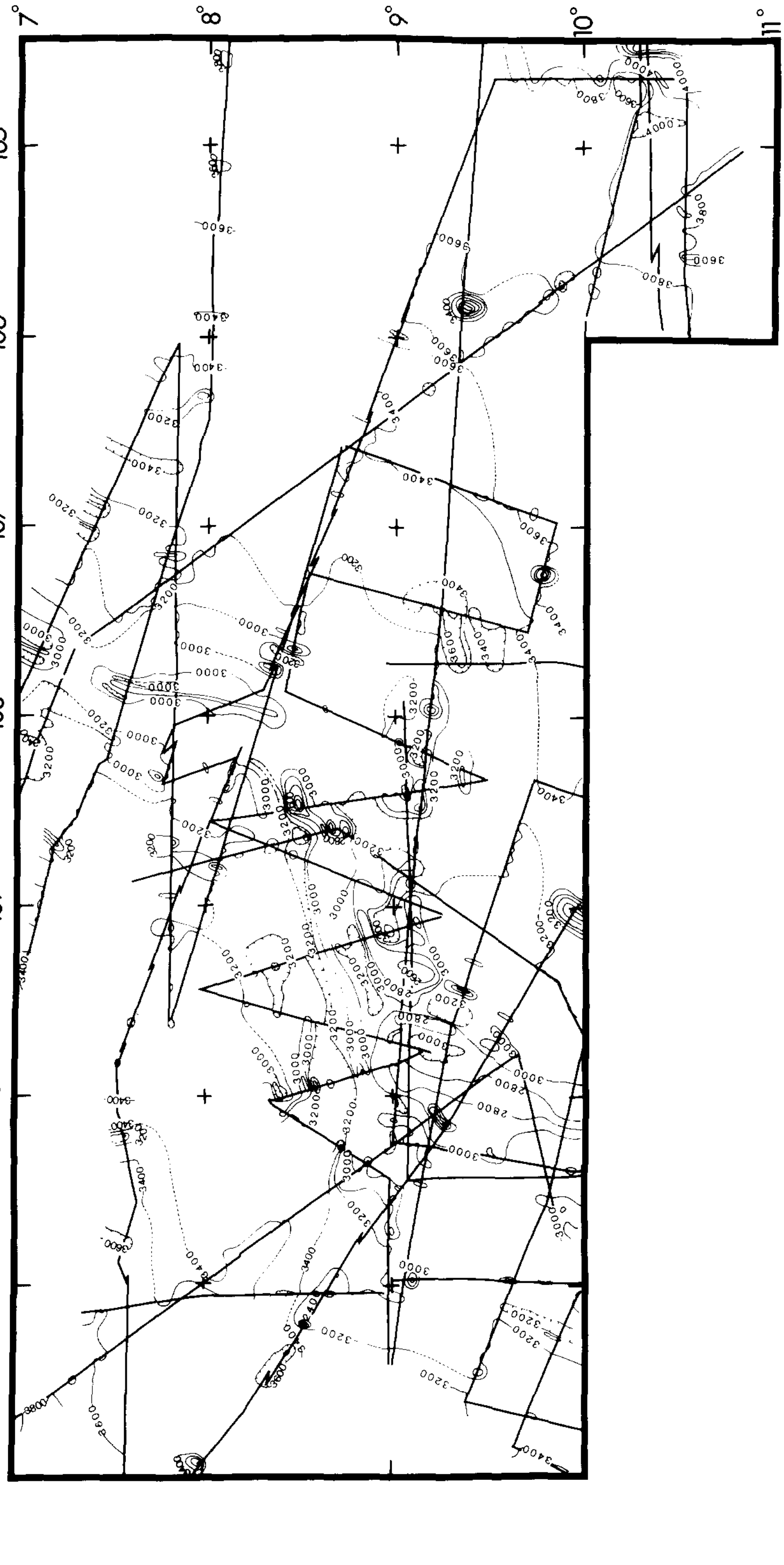

Fig. 3. Bathymetric map of the Wilkes fracture zone. Contour interval is 200 m. Location of EPR axis shown on Figure 7.

012° south of about 9°S, 109.8°W. The central section, offset about 200 km right-laterally along the WFZ, trends about 012° and extends from 8.5°S, 108°W to 7.5°S, 107.8°W. There is an unexplained 15 to 20 km wide gap at 7.3°S between the central section and the northern section of the EPR axis which extends to the north out of the study area (Rea, 1975). These sections of the EPR are characterized by a typical axial ridge about 300 to 350 m high and 15 to 20 km wide at the base. The usual abyssal hills of 100 to 200 m relief occur on the flanks of the EPR, but these are not well defined on the map (Figure 3) because the contour interval is 200 m.

The bathymetry of the WFZ ranges from simple to complex. In the westernmost portion, the WFZ is characterized by a simple north facing step of about 500 m (lines CON-11, AIRES, DWD in Figure 4) in a manner similar to fracture zones in the northeast Pacific (Menard, 1964). About 75 km west of the southwestern section of the EPR axis, the WFZ becomes more complex. Here the fracture zone changes from a distinct step trending 105° to a 100 km-wide zone of ridges and troughs. A low ridge 200 to 300 m high, 5 to 15 km wide, and 185 km long trends about 074° from the northern end of the southwestern section of the EPR axis toward the southern end of the central axis segment. Associated with this ridge, and parallel to it on the northern side, is a narrow trough (2.5 km to 10 km wide) 200 to 700 m deep and about 75 km long. The regional base level offset from lines CON-11 through CAR-1 at 109°W (Figure 4) is down to the north; it is uncertain on line OC-4-6, and is down to the south east of 108.2°W on lines OC-4-7 through OC-1-1.

East of the southern end of the central section of the EPR the bathymetry of the WFZ again changes character. A trough extending east from 108.3°W can be traced to a 400 m deep depression at 9.3°S, 107.5°W where it loses bathymetric expression. The eastern extension of the WFZ is less obvious east of line OC-4-7, but there are bathymetric indications of its existence east to the Amphitrite trackline at 104.8°W (Figure 4). These features have a trend of about 105° which agrees with the trend of the western extension of the WFZ. Thus, the WFZ can be traced for about 750 km through the study area from about 111.5°W to 104.8°W.

The WFZ bathymetry can be described briefly in terms of three sections: western, central, and eastern. The western and eastern sections are similar in that they both show the expected base level offsets and trend about 105°. However, the western section is characterized by simple 500 m step while the 600 m base level offset of the eastern section is across a broad slope. The central portion of the fracture zone is characterized by the trough-ridge sequence trending 074° and some lesser ridges and depressions which occur along the southern edge of the WFZ between 108.5°W and 107.4°W.

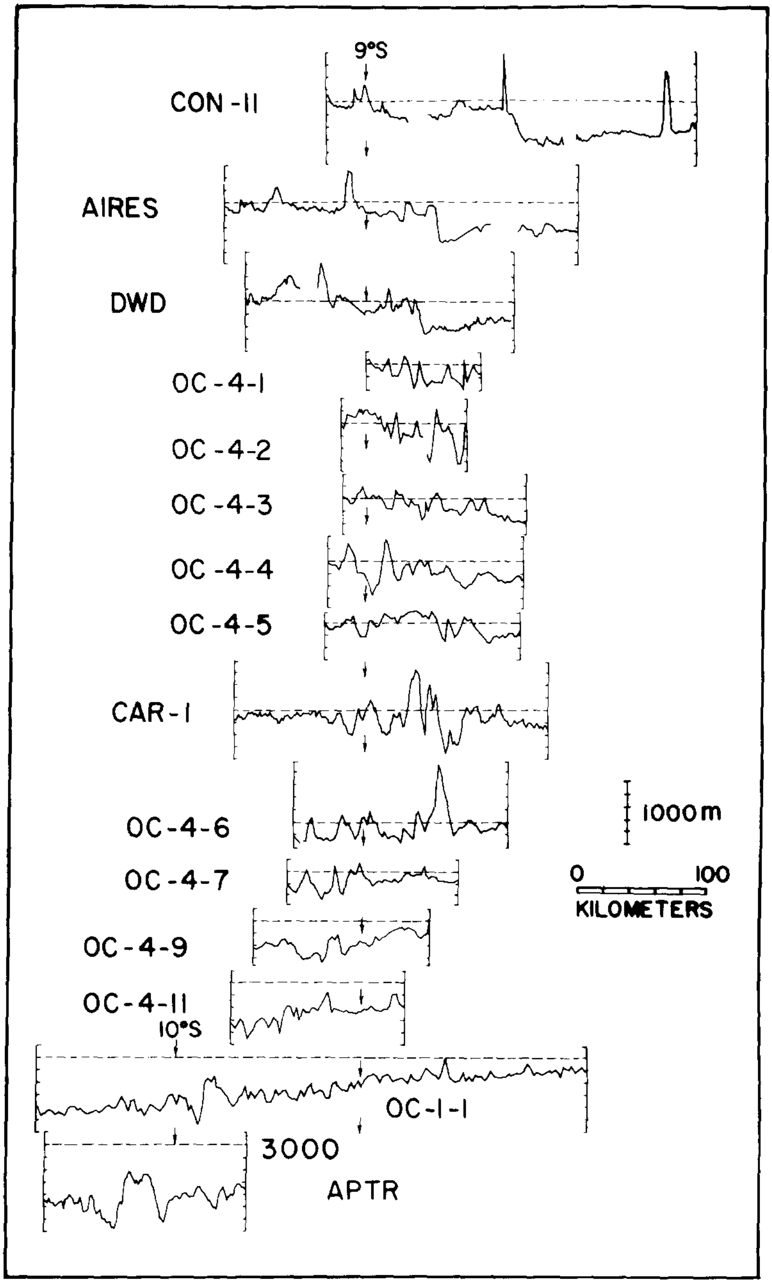

Fig. 4. Bathymetric profiles across the Wilkes fracture zone. Profiles are arranged west-to-east from top to bottom, north is to the right. Small arrows show where profiles cross 9° and 10°S. Abbreviations are: CON, *Conrad*; DWD, *Downwind-Baird*; OC, *Oceanographer*; CAR, *Carrousel*; APTR, *Amphitrite*.

2.2. Magnetic data

In contrast to the complex bathymetry associated with WFZ, the magnetic anomalies appear more straightforward (Figures 5 and 6). Spreading anomalies are difficult to identify in the area as a result of its proximity to the magnetic equator and the orientation of the EPR axis (Schouten, 1971), although near 10°S Rea (1976b) was able to identify and correlate anomalies associated with the Brunhes-Matuyama reversal and the Jaramillo and Olduvai events with some success. The most striking feature of the fracture zone magnetic anomaly pattern is the large negative magnetic anomaly along the southern part of the WFZ. Although this anomaly does not appear to extend farther west than the southwestern section of the EPR axis, it may in subdued form extend as far east as the eastern boundary of the study area. The anomaly appears to be offset about 20 km to the south at 107.5°W from where it continues east (Figures 6 and 7). The anomaly trend along the active portion of the WFZ, 097°, parallels the small trough-like feature mentioned above, but lies 7 km north of it. The high amplitude of this anomaly system would be the natural consequence of an easterly trending magnetic source body situated near the magnetic equator (Schouten, 1971).

There is a small positive anomaly up to 300 gammas in amplitude associated with, and parallel to, the trough-ridge feature trending 074° between the offset rise axes. A dipole anomaly associated with a seamount at 9.5°S, 108.7°W is positive to the north, which would indicate normal polarity for this hemisphere.

2.3. Seismic data

Locations of 55 earthquake epicenters reported by the World Wide Standardized Seismic Network (WWSSN) to have occurred in the vicinity of the Wilkes F. Z. between 1963 and 1977 are plotted on a map of structural features of the area (Figure 7). Although a few earthquakes do occur away from the main fault zone, most (48) of the epicenters are associated with the active portion of the WFZ. These occur as two groups: one is a cluster located at 9°S, 109.8°W. Three epicenters are located on the 074°-trending oblique structure between the offset EPR segments (Figure 7).

The first group, or western cluster, is at the approximate location of the intersection between the WFZ and the southwestern section of the EPR axis and may denote the change from divergent to transform motion. The second group, or eastern line, trends about 082° and ends almost exactly where it would intersect the southern extension of the central axis section. This trend is about 15° off the 097° trend of the WFZ in this zone as determined by the bathymetric and negative magnetic anomaly trends. Such deviation between seismic and bathymetric trends has been noted elsewhere (Crane, 1976; Prothero *et al.*, 1976; Choukroune *et al.*, 1978).

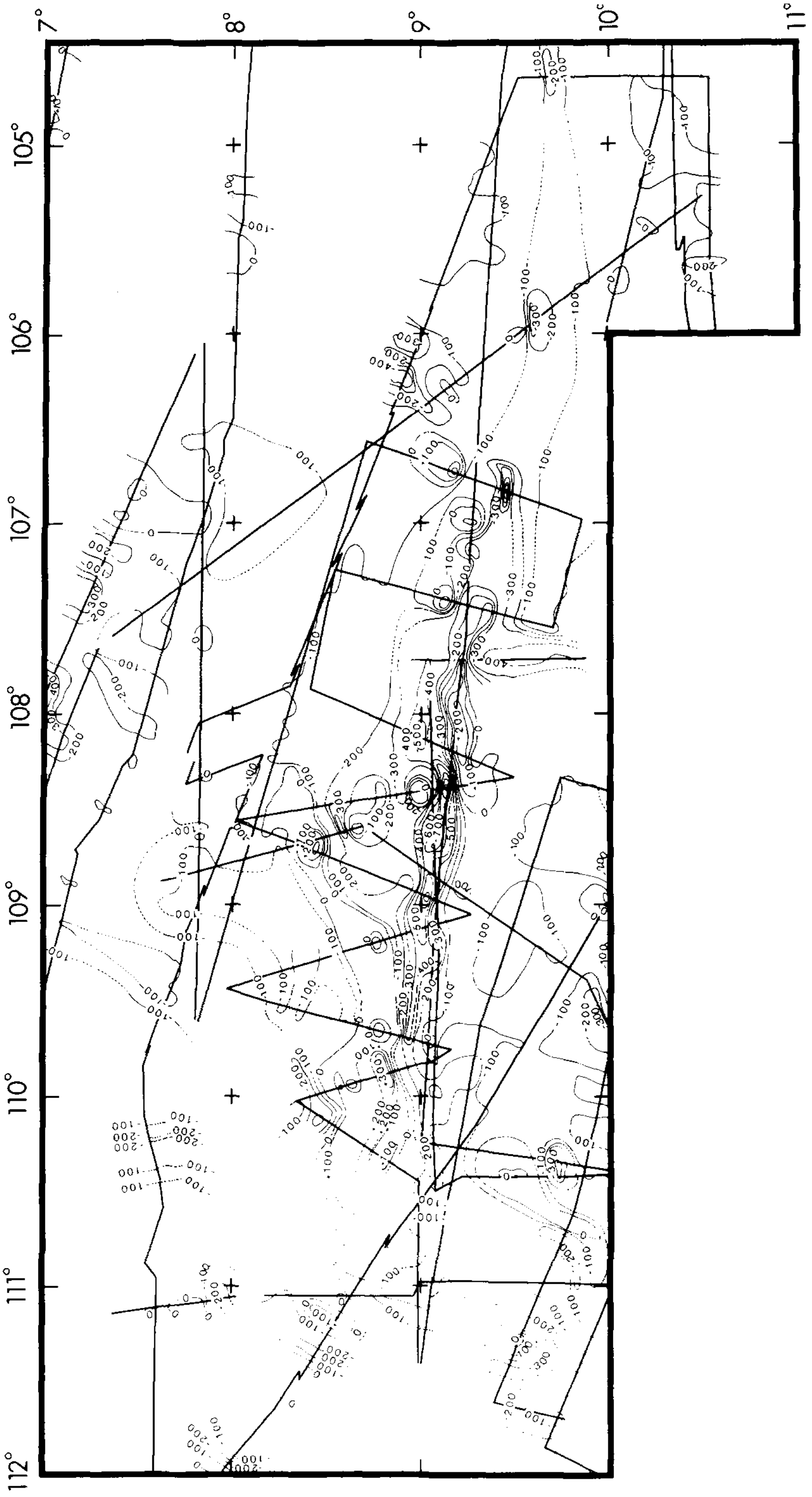

Fig. 5. Magnetic anomaly map of the Wilkes fracture zone. Contour interval is 100 gammas. Location of EPR axis shown on Figure 7.

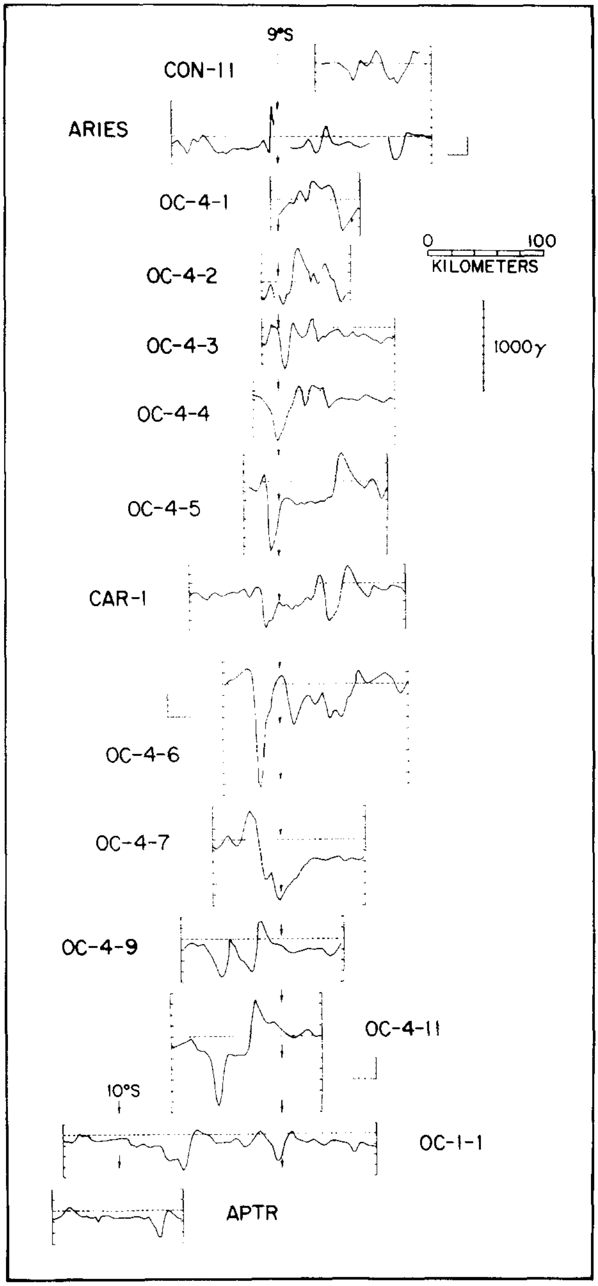

Fig. 6. Magnetic anomaly profiles across the Wilkes fracture zone. Profile arrangement and annotation as in Figure 4.

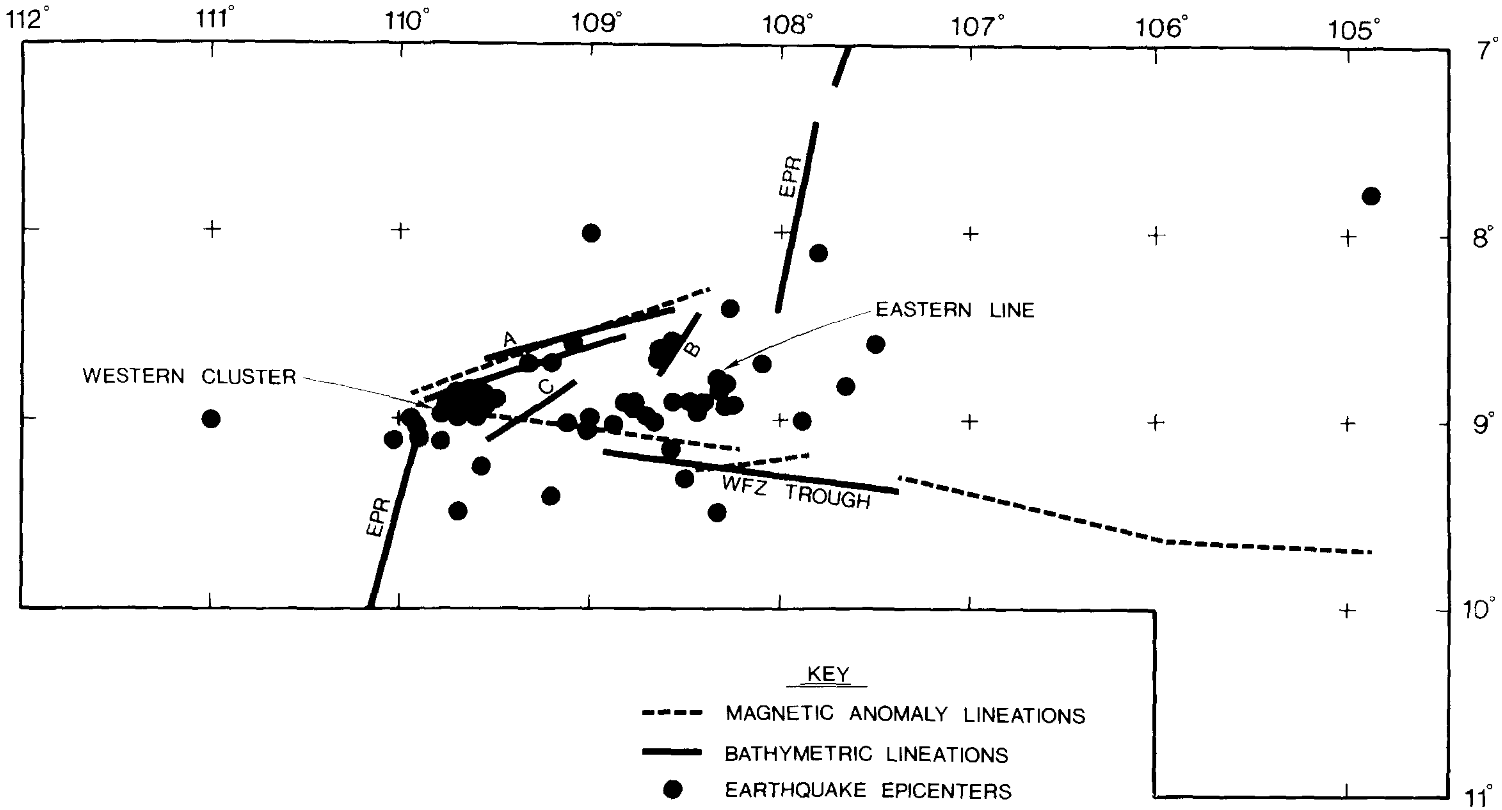

Fig. 7. Tectonic elements of the Wilkes fracture zone. Ridges A, B, and C, discussed in text, are shown. Western cluster and eastern line refer to epicenter groupings.

3. Discussion

3.1. Transform-Fault Tectonics

The eastern extension of the WFZ trends 105°, then changes to 097° about 75 km east of the spreading axis. The western extension also trends approximately 105° to within about 75 km of the spreading axis. A distance of 75 km corresponds to an age of approximately 0.9 my at the present spreading half-rates of about 80 mm y^{-1} (Rea, 1976b). The change in fracture zone orientation implies a westerly shift in the Nazca-Pacific pole of rotation which should be reflected along the entire length of the plate boundary. However, there is evidence of only minor adjustments of the EPR axis since 2 mya (Rea, 1976a, b, 1977, 1978b), and none involve an apparent change in spreading direction.

The active portion of a transform fault is a variety of wrench fault as defined by Wilcox *et al.* (1973) who found two sets of fractures located 10 to 30°, and 70 to 90° from the wrench strike. The 10 to 30° set has the same sense of displacement as the main wrench zone (synthetic) while the 70 to 90° set has the opposite sense of displacement (antithetic) (Wilcox *et al.*, 1973). The synthetic and antithetic faults are conjugate to each other and are termed Riedel shears and conjugate Riedel shears, respectively. As slip along the main wrench continues, slip diminishes on the other faults and the wrench zone predominates.

Normal faulting may also occur obliquely to strike-slip motion in transform faults. Normal faulting on these oblique trends is described from deep tow studies of the Tamayo F. Z. (Macdonald *et al.*, 1979) and the Quebrada transform fault (Lonsdale, 1978) on the EPR as well as on Fracture Zone A of the FAMOUS area on the Mid-Atlantic Ridge (MAR) (Choukroune *et al.*, 1974). Crane (1976) and Searle and Laughton (1977) report oblique structures on the Siqueiros transform fault of the EPR and Kurchatov F. Z. of the MAR respectively.

On the Tamayo F. Z. the average trend of the normal faults is about 50° relative to the main transform trend (Macdonald *et al.*, 1979) which should be approximately normal to the least compressive stress. Macdonald *et al.* (1979) note further that the formation of normal faults along oblique shears is promoted when there is a component of tension across the strike-slip fault zone (which may result either from thermal contraction of the lithosphere or acceleration to regional spreading velocities). However, they observed neither Riedel shears nor conjugate Riedel shears in their study area.

Normal faults associated with oblique shears are found on the young side of the Tamayo transform (Macdonald *et al.*, 1979). Lonsdale (1978) reports similar structures on the old side of the more rapidly-slipping Quebrada transform fault. These features are oriented about 45° relative to the 098° trend of that fault. In addition, he reports finding no evidence for conjugate Riedel shears. Lonsdale (1978) attributes the observed structures to extension across the strike-slip fault caused by thermal contraction as the lithosphere cools. He also suggests two mechanisms for intrustion and volcanism along a transform: a change in trend of the rise axis with respect to the orientation of the least compressive stress and/or oblique tension caused by the shear couple. Sinuosity of a fracture zone can also create localized zones of tension which would permit intrusion.

Thus, oblique shears and associated normal faulting are not uncommon along moderate to fast slipping transform faults. In addition, there appear to be at least five possible mechanisms that allow volcanic intrusion and/or extrusion: (1) thermal contraction of the lithosphere causing tension across the fracture zone; (2) change in relative plate motions; (3) sinuosity of the shear creating a local zone of tension and providing a conduit for material from below; (4) distribution of lateral shear stresses across a wide zone; and (5) oblique tension caused by the shear couple.

The central portion of the EPR is offset about 85 km to the north (measured from the present trend of the WFZ) from where it would be expected to intersect the southern margin of the WFZ (Figures 3 and 7). Similar situations occur along the Tamayo F. Z. (Macdonald *et al.*, 1979) and on the Quebrada-Gofar system (Lonsdale, 1978). A 'relay zone' is proposed to explain this for the Tamayo F. Z. (Macdonald *et al.*, 1979) and an echelon faults for the Quebrada-Gofar system (Lonsdale, 1978).

The large oblique ridge and trough (A on Figure 7) has the proper orientation (Table I) to represent a zone of synthetic shears (left-lateral movement) or possible a highly oblique spreading center. The possibility of an oblique spreading center is suggested by the need to create crust somewhere and the south western section of the EPR does not appear to extend far enough north nor the central section of the EPR far enough south. Conversely, if this were a spreading center,

TABLE I

Significant bathymetric and magnetic anomaly trends

Feature	Location	Trend	
		Relative to N	Relative to WFZ (097°)
EPR: SW Section		012°	085°
EPR: Central Section		012°	085°
Ridge A	108°W-110°W	074°	023°
Trough A	108°W-110°W	074°	023°
Ridge B	108.5°W	035°	062°
Ridge C	109°W	060°	037°
WFZ Trough	107-108°W	097°	——
WFZ Step	West of 110.5°W	105°	008°
WFZ Magnetic Anomaly		097°	——

there would be much less transform motion at this location and larger and sharper magnetic anomalies might be expected because of the easterly trend of any resulting magnetic source bodies. Thus, synthetic shearing appears to be the most likely cause of the large oblique features. Unfortunately there are no focal mechanism solutions published for the Wilkes fracture zone, so we can not test this proposed synthetic shearing.

There are at least two possible explanations for the origin of ridge B (8.5°S, 108.5°W; Figure 7). The position and orientation of this ridge would indicate that it may be a normal fault with associated extrusion similar to structures described by Macdonald *et al.* (1979) and by Lonsdale (1978). Extrusion is suggested by the 1000 to 1300 m high seamounts on the ridge. A second explanation for the origin of ridge B is that it may be located in a bend in ridge-trough A; gaps for extrusion can be provided by the curvature of strike-slip faults. Such features have been described on the Tamayo F. Z. (Macdonald *et al.*, 1979), and Siqueiros F. Z. (Crane, 1976) on the northern EPR, and Fracture Zone A (with microfaults, Choukroune *et al.*, 1978) on the Mid-Atlantic Ridge.

Ridge C (9°S, 109°W, Figure 7) is properly oriented to be a tension related feature (Table I) and may be the result of the oblique tension caused by the shear couple. This ridge, considering its proximity to the EPR axis, could also be due to lateral thermal contraction of the lithosphere resulting in normal faulting as suggested by Lonsdale (1978).

3.1. Transform-Fault Magnetics

Many fracture zones have associated with them characteristic magnetic anomalies. Examples include the Molokai, Murray, and Mendocino fracture zones in the northeast Pacific (Rea, 1970), 6.2°S fracture zone in the south-east Pacific (Rea, 1976a), and Ascension fracture zone in the Atlantic (van Andel *et al.*, 1973). Amplitudes of the anomalies are a function of the orientation and latitude of the magnetic source bodies (Schouten, 1971). At the latitude of this study area (9°S) and with a generally northerly trending rise crest, Schouten predicts that the sea floor spreading anomalies will have small amplitudes, be anti-symmetrical, and difficult to distinguish. This is indeed the case (Figure 5; Rea, 1976b). Conversely, an east-west oriented structure at the same latitude would produce a large amplitude anomaly (Schouten, 1971; Rea, 1972). An 1100-gamma anomaly is associated with the 6.2°S fracture zone (Rea, 1976a) and a similar situation occurs along the WFZ where a 400 to 1000-gamma amplitude negative anomaly trends 097° along the southern edge of the fracture zone. This anomaly extends from about 110°W to 107.5°W at 9°S, is offset about 20 km to the south and continues east along a trend of approximately 105° (Figure 5).

The source of the anomaly apparently is an intrusive body rather than end effects of sea-floor spreading anomalies (cf. Twigt *et al.*, 1979) as the anomaly is of uniform sign along its entire length and there is no bathymetric expression of extrusive structures associated with it. This negative anomaly apparently extends as far east at 104.8°W, yet it does not extend farther west than the southwestern section of the EPR axis at about 110°W, suggesting that the southwestern EPR axis exerts some control on the intrusion processes. The active shear may extend to the magma chamber under the southwestern axis thereby providing an injection conduit. In any case, the large amplitude magnetic anomaly apparently marks the present fracture zone trend and serves to identify the eastern extension of the WFZ well beyond obvious bathymetric features.

3.2. Seismicity

The WFZ has 48 epicenters in two groupings associated with it, one generally along the fracture zone trend (the eastern line) and the other at the junction of the fracture zone with the EPR axis (the western cluster, Figure 7). Data scatter may be associated with triangulation problems resulting from the relationship among the WWSSN stations in this area of the world, but the expected errors are not large enough to discount the trends seen.

The eastern line trends 082° from about halfway between the EPR axis southwestern and central sections to a point south of the central section (Figure 7). Three possible explanations exist for this trend. It might indicate that the fracture zone is reorienting to a new trend, although there is no supporting evidence for this in either the magnetics or bathymetry. The second explanation is that these earthquakes are associated with a series of small en-echelon faults. Oblique trends are associated with other transform faults; e.g., the Siquieros (Crane, 1976), Tamayo (Macdonald *et al.*, 1979) and Quebrada (Lonsdale, 1978) fracture zones and therefore are not unexpected here. The third explanation is that this trend represents the initiation of an oblique feature similar to ridge-trough A as this structure may no longer be active. Although the present data are insufficient to distinguish between the last two explanations; the second appears to be most likely.

The western cluster involves 16 epicenters at the intersection of the present WFZ trend and the southwestern section of the EPR axis at about 110°W (Figure 7). Prothero *et al.* (1976) conducted a seismic study along the Rivera fracture zone and discussed a cluster of earthquakes at the western intersection between that fracture zone and the EPR axis whose source depths are < 5 km. They also noted the abrupt termination of the epicenters at the rise crest. This appears to be the situation with the WFZ and probably records the change of motion from the transform mode to the spreading mode. Thus, the western epicenter cluster probably records transform motion as the Nazca plate moves away from the EPR axis and the abrupt termination of activity reflects the coupling of the plates north and south of the WFZ and west of the southwestern EPR axis.

4. Summary and Conclusions

The Wilkes Fracture Zone differs from fracture zones on slower spreading rises in that it is not characterized by a well defined trough-and-wall structure. Instead, the WFZ is a broad zone of shearing with significant geologic structures both parallel and oblique to the main transform trend of 097°.

The WFZ region is characterized by four major trend directions: (1) the EPR axis at 012°, (2) the western and eastern extensions of the WFZ at 105°, (3) the large magnetic anomaly along the southern portion of the fracture zone at 097°, and (4) the central zone with the oblique ridge of 074°. The oblique ridge A (Figure 7) appears to have the trend of a synthetic shear feature. Ridge B may be the result of enhanced tension and ensuing volcanic extrusion caused by sinuosity in ridge-trough A.

The large amplitude magnetic anomaly trending 097° identifies trend and location of the WFZ transform fault. The anomaly terminates rather abruptly at the southwestern EPR axis, but may extend far east as 104.8°W. Sea floor spreading anomalies in the area are low amplitude and antisymmetric (Schouten, 1971) while the seamounts have south-negative dipoles suggesting recent formation.

The WFZ appears to have two distinct zones of seismic activity. The eastern line of epicenters trend 082° from the mid-point of the active zone of the WFZ to a point south of the central section of the EPR axis where it abruptly ends. This group may reflect present transform activity or the initiation of a feature similar to the large oblique ridge. A western cluster of epicenters at the junction of the EPR axis and the WFZ probably results from initiation of the transform motion associated with the Nazca plate as it moves away from the rise crest.

The change in trend of the WFZ from 105° to 097° could imply an 8° westward shift in the Nazca-Pacific pole of rotation. However such a shift in the pole of rotation should be reflected along the entire Nazca-Pacific plate boundary and this does not appear to be the case. Hence, it seems more likely that this change in trend is a local adjustment in response to some undetermined stimulus.

The sequence of events during the last 1.0 mya appears to be as follows:

(1) about 0.9 mya some event, as yet unknown, occasioned an 8° change in the trend of the WFZ (from 105° to 097°) and caused the shear zone to broaden from a narrow step to a 100 km wide zone;

(2) shortly after the change, synthetic shearing began along a trend of 074° and tension associated with this shearing provided a conduit for the extrusion of oblique ridge A;

(3) about 0.2 mya sinuosity in oblique ridge A resulted in localized tension and extrusion of ridge B.

In summary, the magnetic data suggests that the main zone of decoupling is along the southern margin of the fracture zone associated with the major magnetic anomaly, the seismic data suggests that the entire region is active and the bathymetric data show major oblique features. Although the event 0.9 mya broadened the shear zone from a simple step to a region 100 km wide, the resulting bathymetric features appear to be locally induced and controlled by shearing and tensional forces related to ordinary strike-slip motion. Furthermore, it appears that the thin trailing edges of fast spreading plates are readily broken and deformed.

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References

Choukroune, P., Francheteau, J., and Le Pichon, X.: 1978, *In Situ* 'Structural Observations Along Transform Fault A in the FAMOUS Area, Mid-Atlantic Ridge', *Geol. Soc. Am. Bull.* **89**, 1013–1029

Cochran, J. R.: 1973, 'Gravity and Magnetic Investigations in the Guiana Basin, Western Equatorial Atlantic', *Geol. Soc. Am. Bull.* **84**, 3249–3268.

Crane, K.: 1976, 'The Intersection of the Siqueros Transform Fault and the East Pacific Rise', *Mar. Geol.* **21**, 25–46.

Cyamex: 1978, 'First Submersible Study of the East Pacific Rise: RITA (Rivera-Tamayo) Project 21°N, *Trans. Amer. Geophys. Union* **59**, 1198.

Detrick, R. S., Mudie, J. D., Luyendyk, B. P., and Macdonald, K. C.: 1973, 'Near-bottom Observations of an Active Transform Fault (Mid-Atlantic Ridge at 37°N)', *Nature Phys. Sci.* **246**, 59-60.

Eittreim, S. and Ewing, J.: 1975, 'Vema Fracture Zone Tránsform Fault', *Geology* **5**, 555–558.

Fox, P. J., Schreiber, E., Rowlett, H., and McCamy, K.: 1976, 'The Geology of the Oceanographer Fracture Zone: A Model for Fracture Zones', *J. Geophys. Res.* **81**, 4117–4128.

Gumma, W. J.: 1974, *An Interpretation of the Gravity and Magnetic Anomalies of the Rivera Fracture Zone, East Pacific Ocean*, Unpub. M. S. Thesis, Oregon State Univ., Corvallis, 50 p.

Herron, E. M.: 1972, 'Sea-floor Spreading and the Cenozoic History of the East-Central Pacific', *Geol. Soc. Am. Bull.* **83**, 1671–1692.

I.A.G.A. Commission 2 Working Group 4, Analysis of the Geomagnetic Field: 1969, 'International Geomagnetic Reference Field 1965.0', *J. Geophys. Res.* **74**, 4407–4408.

Le Pichon, X. and Hayes, D. E.: 1971, 'Marginal Offsets, Fracture Zones, and the Early Opening of the South Atlantic', *J. Geophys. Res.* **76**, 6283–6293.

Lonsdale, P.: 1977, 'Structural Geomorphology of a Fast-Spreading Rise Crest: The East Pacific Rise Near 3°25′S', *Mar. Geophys. Res.* **3**, 251–293.

Lonsdale, P.: 1978, 'Near Bottom Reconnaissance of a Fast-Slipping Transform Fault at the Pacific-Nazca Plate Boundary', *J. Geology* **86**, 451–472.

Lynn, W. S.: 1976, *A Geophysical Analysis of the Orozco Fracture Zone and the Tectonic Evolution of the Northern Cocos Plate*, Unpub. M. S. Thesis, Oregon State Univ., Corvallis, 80 p.

Lynn, W. S. and Lewis, B. T. R.: 1976, 'Tectonic Evolution of the Northern Cocos Plate', *Geology*, **4**, 718–722.

Macdonald, K. C., Kastens, K., Spiess, F. N., and Miller, S. P.: 1979, 'Deep Tow Studies of the Tamayo Transform Fault', *Mar. Geophys. Res.* **4**, 37–70.

Mammerickx, J., Anderson, R. N., Menard, H. W., and Smith, S. M.: 1975, 'Morphology and Tectonic Evolution of the East-Central Pacific', *Geol. Soc. Am. Bull.*, **86**, 111–118.

Mammerickx, J. and Smith, S. M.: 1978, 'Bathymetry of the Southeast Pacific', *Geol. Soc. Am. Map and Chart Series* MC-26.

Mammerickx, J., Herron, E., and Dorman, L.: 1980, 'Evidence for Two Fossil Spreading Ridges in the Southeast Pacific', *Geol. Soc. Am. Bull.* **91**, 263–271.

Matthews, D. J.: 1939, *Tables of the Velocity of Sound in Pure Water and Sea Water for Use in Echo-Sounding and Sound Ranging* (second ed.), Hydrographic Dept., Admiralty, London, 52 p.

Menard, H. W.: 1964, *Marine Geology of the Pacific*, McGraw-Hill, Inc., New York, 271 p.

Phillips, J. D. and Luyendyk, B. P.: 1970, 'Central North Atlantic Plate Motions Over The Last 40 Millions Years', *Science* **170**, 727–729.

Prothero, W. A., Reid, I., Reichle, M. S., and Brune, J. N.: 1976, 'Ocean Bottom Seismic Measurements on the East Pacific Rise and Rivera Fracture Zone', *Nature* **262**, 121–124.

Rea, D. K.: 1970, 'Changes in Structure and Trend of Fracture Zones North of the Hawaiian Ridge and Relation to Sea-Floor Spreading', *J. Geophys. Res.* **75**, 1421–1430.

Rea, D. K.: 1972, 'Magnetic Anomalies Along Fracture Zones', *Nature Phys. Sci.* **236**, 58–59.

Rea, D. K.: 1975, *Tectonics of the East Pacific Rise 5° to 12°S*, Unpub. Ph. D. Thesis, Oregon State Univ. Corvallis, 139 p.

Rea, D. K.: 1976a, 'Changes in the Axial Configuration of the East Pacific Rise Near 6°S During the Past Two Million Years', *J. Geophys. Res.* **81**, 1495–1504.

Rea, D. K.: 1976b, 'Analysis of a Fast-Spreading Rise Crest: The East Pacific Rise, 9° to 12° South', *Mar. Geophys. Res.* **2**, 291–313.

Rea, D. K.: 1977, 'Local Axial Migration and Spreading Rate Variations, East Pacific Rise, 31°S', *Earth and Planet. Sci. Lett.* **34**, 78–84.

Rea, D. K.: 1978a, 'Evolution of the East Pacific Rise Between 3°S and 13°S Since the Middle Miocene', *Geophys. Res. Lett.* **5**, 561–564.

Rea, D. K.: 1978b, 'Asymmetric Sea-Floor Spreading and a Nontransform Axis Offset: The East Pacific Rise 20°S Survey Area', *Geol. Soc. Am. Bull.* **89**, 836–844.

Schouten, J. A.: 1971, 'A Fundamental Analysis of Magnetic Anomalies Over Oceanic Ridges', *Mar. Geophys. Res.* **1**, 111–144.

Searle, R. C. and Laughton, A. S.: 1977, 'Sonar Studies of the Mid-Atlantic Ridge and Kurchatov Fracture Zone', *J. Geophys. Res.* **82**, 5313–5328.

Sleep, N. H. and Biehler, S.: 1970, 'Topography and Tectonics at the Intersections of Fracture Zones with Central Rifts', *J. Geophys. Res.* **75**, 2748–2752.

Twight, W., Slootweg, A. P., and Collette, B. J.: 1979, 'Topography and a Magnetic Analysis of an Area South-East of the Azores (36°N, 23°W), *Mar. Geophys. Res.* **4**, 91–104.

van Andel, T. H., von Herzen, R. P., and Phillips, J. D.: 1971, 'The Vema Fracture Zone and the Tectonics of Tranverse Shear Zones in Oceanic Crustal Plates', *Mar. Geophys. Res.* **1**, 261–283.

van Andel, T. H., Rea, D. K., von Herzen, R. P., and Hoskins, H.: 1973, 'Ascension Fracture Zone, Ascension Island, and the Mid-Atlantic Ridge', *Geol. Soc. Am. Bull.* **84**, 1527–1546.

Wilcox, R. E., Harding, T. P., and Seely, D. R.: 1973, 'Basic Wrench Tectonics', *Am. Assoc. Pet. Geol. Bull.* **57**, 74–96.

Wilson, J. T.: 1965, 'A New Class of Faults and Their Bearing On Continental Drift', *Nature* **297**, 343–347.