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Tectonic deformation in the North Fiji Basin

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University of Hawaii, 1991
TECTONIC DEFORMATION IN THE NORTH FIJI BASIN

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN GEOLOGY AND GEOPHYSICS

DECEMBER 1991

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ACKNOWLEDGEMENTS

Financial support came from many different sources. The Agency for International Development of the US State Department funded the SeaMARC II cruise to the North Fiji Basin. Funding was also in part provided by various ONR and NSF grants given to my advisor, Loren Kroenke, over the years. I am grateful for his financial backing as well as the opportunity to work on the data. The South Pacific Applied Geoscience Commission (SOPAC), especially Don Tiffin and Jim Eade, gave me the opportunity to participate on several cruises to the region and to interact with a number of leading international scientists.

My friends and fellow graduate students, especially Yan, Rick, Bruce, and Glenn, deserve a lot of thanks for their support and help through the years. From their example and experience, I was able to carry on. Lillian Ng patiently and generously helped preparing the text and figures, coordinating my communications, and just generally doing a million and one things that need to be done. Her efforts were instrumental in completing this dissertation. And most importantly, I thank my parents and family who have given me support and encouragement though the years. Without them, this would not have been possible.
ABSTRACT

The North Fiji Basin is a structurally complex marginal basin set between the obliquely converging Australia and Pacific Plates. This study uses recently acquired SeaMARC II imagery and bathymetry and GLORIA imagery as well as other geophysical data to examine the present structure and recent tectonic history of the basin.

Three areas are studied in detail: The first area is the ridge-ridge-ridge triple junction at 17°S, 174°E which shows evidence of a recent realignment in spreading directions. This triple junction formed by a jump eastward from its former location to a site of extension within the proto-Fiji Transform Fault. The current morphological character is that the northern and eastern limbs are deep grabens and the southern limb has typical spreading ridge morphology. The second area is the Fiji Transform Fault north and west of Fiji which shows evidence of transtensional stress. Between 174°E and 176°E, the fault has a wide principal displacement zone and shows evidence of extension in a NW-SE direction. This is compatible with a broad zone of left lateral shear or an overstep in the fault trace but its activity is uncertain. Adjacent to the Fiji Platform, the fault trace proceeds through a series of left-stepping extensional relay zones (ERZ's). One of these ERZs appears to be propagating into the Fiji Platform breaking off a fragment of the island arc crust. The Balmoral Reef and Braemar Ridge are probably older fragments of the Fiji Platform which presumably formed similarly. The third area is the Pandora Ridge at the northern end
of the basin which is undergoing extension and shearing. This area shows evidence of recent faulting and volcanism and probably marks the southern boundary of the Pacific Plate.

The current structural complexity of the North Fiji Basin is the product of frequent changes in the location and nature of its tectonic elements. These changes reflect a history of a rapidly changing stress regime which is probably caused by the ongoing rotations of Fiji and the New Hebrides Arc. Furthermore, while the tectonic elements have undergone rapid evolution, this evolution does not suggest basin-wide non-rigid deformation. Indeed, on a large scale, there does not appear to be any non-rigid behavior. Deformation occurs within, or adjacent to, fairly narrow spreading rifts and faults.
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Chapter 1
INTRODUCTION

The North Fiji Basin, bounded by the New Hebrides Trench, the inactive Vitiaz Trench, the Fiji Platform, and the Hunter Fracture Zone (Fig. 1), occupies a complex tectonic location in the southwest Pacific. This marginal basin is one of several which lie in a buffer zone between the northward moving Indo-Australia Plate, subducting beneath the New Hebrides and San Cristobal-New Britain Trenches, and the northwestward moving Pacific Plate, subducting beneath the Tonga-Kermadec Trench. Situated between these two subduction zones, the North Fiji Basin has been the site of active spreading for more than 5 m.y.

Conflicting hypotheses have been proposed for the mechanism causing seafloor spreading within the basin as well as for the present configuration of the tectonic elements themselves. The idea that nonrigid plate deformation is occurring throughout the basin is arguably the most controversial. The crucial hypothesis here is that the basin is undergoing extreme extensional shearing and is deforming across the entire basin rather than along discrete plate boundaries (Hamburger and Isacks, 1988). Another idea holds that the Fiji Fracture Zone is presently inactive west of 176°E. This hypothesis was advanced by Kroenke et al. (1991) and Malahoff et al. (1991) to explain magnetic anomaly data and the complex
Figure 1: Bathymetry and physiographic setting of the North Fiji Basin. Contour interval is 2500 m. Shaded areas are depths greater than 5000 m.
structures exhibited along the transform fault. Other workers disagree (Lafoy et al., 1987; Auzende et al., 1988a) and argue that activity continues to the central ridge. Still another area of disagreement is the nature of the South Pandora Ridge. This feature has been described as an incipient spreading center by some workers (Kroenke et al., 1991) and as a transform fault by others (Chase, 1971). In this study, I use recently acquired marine geophysical data to identify the tectonic configuration and recent development of the North Fiji Basin. I also relate this development to the motions of the surrounding plates and island arcs.

My interpretation of the principal tectonic elements in the central part of the North Fiji Basin is given in Figure 2. The microplates identified within the basin are named here to facilitate later discussion. Active spreading is occurring along two major north-south oriented spreading centers: the Central North Fiji Basin Ridge (CNFBR) and an eastern rift, the Viwa Rift (VR) as well as along several short spreading segments along the South Pandora Ridge and the Fiji Fracture Zone. Incipient arc rifting is occurring at the Coriolis Trough and the Jean Charcot Troughs (a set of backarc troughs which includes the Vot Tande Trough). The South Pandora Ridge is an extensional transform boundary extending east-west from the Jean Charcot Troughs to the Tripartite Ridge, north of the Fiji Platform.
Figure 2: Tectonic boundaries within the northern North Fiji Basin.

Solid double lines represent spreading centers. Single solid lines are transform faults and dashed lines are incipient rifts.
Marginal basin tectonism

Marginal basin spreading centers share many geological and morphotectonic characteristics with major ocean spreading centers. Yet there are important differences, namely they are commonly short-lived (<15 Ma), have episodic periods of activity, and are related to the subduction process (Taylor and Karner, 1983). To explain these differences, various hypotheses have been advanced. Most of the current ideas regarding the origin of the North Fiji Basin may be considered within the framework of two hypotheses.

One of the earliest explanations for the origin of marginal basins in terms of plate tectonics was given by Sleep and Toksoz (1971). In their model, hydrodynamic forces generated by the subducting slab generate a flow pattern in the asthenosphere. This induced flow in the asthenosphere imparts a tensional stress to the backarc region causing rifting and subsequent seafloor spreading. Episodicity is the result of time variations in the angle of subduction affecting the asthenospheric flow pattern which in turn affects the stress imparted to the overlying backarc region.

An alternative model explains structural variations of island arcs and formation of marginal basins in terms of the motion of the overriding plate and subduction hinge (Moberly, 1972; Dewey, 1980; Carlson and Melia, 1984; Kincaid and Olson, 1987). Relative to a fixed or slowly moving reference frame, extension occurs in an arc where the hinge migrates seaward away from the arc. This theory relies solely on movements in the lithosphere to account for marginal basins.
Previous Work

Chase (1971) first applied plate tectonic theory to the interpretation of the origin of the North Fiji Basin. Using a sparse marine geophysical data set, he identified many of the principal tectonic elements. These include the CNFBR and eastern spreading center (now called the VR), the Hazel Holme Fracture Zone (South Pandora Ridge) and the Fiji Fracture Zone. Chase (1971) was also the first to suggest that the New Hebrides island arc reversed subduction polarity in the Miocene. He postulated that the Solomon Islands, the New Hebrides Islands (the southern part of which is now the nation of Vanuatu), Fiji and the Lau Islands were once joined as part of a continuous northeast facing arc on the Australia Plate. Now, however, Australia Plate lithosphere subducts beneath the New Hebrides Arc and Pacific Plate lithosphere subducts beneath the Tonga Arc. Later workers have supported the idea of a subduction reversal (Mitchell and Warden, 1971; Karig, 1972; Karig and Mannerickx, 1972; Gill and Gorton, 1973; Coleman and Packham, 1976; Jezek et al., 1977; Falvey, 1978; Carney and McFarlane, 1982).

Paleomagnetic data indicate that Fiji and the New Hebrides Arc have been rotating. Following the subduction polarity reversal, Fiji rotated anticlockwise and the New Hebrides Arc rotated clockwise. Falvey (1978) conducted a paleomagnetic study of samples from eight islands in the New Hebrides Arc and concluded that the arc had rotated 30° clockwise commencing 6 Ma. However, many of the samples analyzed were from the island of Malekula and
were not corrected for the tilting of the island. This led to an erroneously young age determination for the start of rotation (Musgrave, pers. comm.) so that the actual start of rotation is probably closer to the 8 Ma reported by Malahoff et al. (1982b).

James and Falvey (1978) had determined that Fiji rotated 21° during the last 4-5 Ma. Malahoff et al. (1982a), however, concluded that Fiji has rotated as much as 90° over the past 7 Ma but some of the older dates have been questioned (Rodda, 1989). Although the amount is controversial, paleomagnetic evidence indicates that Fiji has undergone anticlockwise rotation.

Seismicity has been used to identify active tectonic elements and determine the directions of motion within and around the North Fiji Basin. Hamburger and Isacks (1987) examined the shape of the New Hebrides and Tonga Wadati-Benioff zones and concluded the shape was due to shear flow within the mantle contorting the slab. Furthermore, Hamburger and Isacks (1988), using previous studies of shallow seismicity (Hamburger and Isacks, 1991; Nagumo et al., 1975; Hamburger and Everingham, 1986) and building on ideas suggested by Lawver and Hawkins (1978) and Tamaki (1985), postulated that seafloor spreading was occurring not along discrete spreading ridges but rather over a broad area in the North Fiji Basin. Their justification for this interpretation is that the diffuse seismicity is occurring over a broad area and not in well delineated locations. Hamburger et al. (1990) concurred with Auzende et al. (1986b) that the Viwa Rift is not a spreading ridge but rather a predominantly shearing boundary with a component of extension.
In a series of recent papers, Gill has developed a tectonic history for the North Fiji Basin based on the petrology of lavas erupted on the island arcs (Gill et al., 1984; Gill, 1987; Gill and Whelan, 1989a, 1989b). He and his coauthors relate temporal variations in the composition of the lavas to the timing of the breakup of the Vitiaz Arc and later evolution of the basin. While fundamentally similar to most models, his timing for these tectonic events places him at odds with some other workers (e.g. Kroenke, 1984; Malahoff et al., 1982b). His model has the North Fiji Basin opening around 5 Ma.

Heat flow studies have also been conducted and originally served to support the idea of active seafloor spreading. One of the earliest was by Macdonald et al. (1973) who supported the idea that the Hazel Holme Fracture Zone (South Pandora Ridge) was a transform fault plate boundary. Halunen (1979) used a variety of data but relied principally on heat flow values throughout the basin to construct his tectonic model of a complex network of ridges and transform faults.

In recent years there have been a number of marine geological and geophysical studies in the North Fiji Basin undertaken in the search for hydrothermal mineral deposits. In 1982, the Tripartite I cruise, a joint Australia, New Zealand and United States programme with CCOP/SOPAC, surveyed and sampled the South Pandora Ridge and determined it had a significant extensional component of motion (Kroenke and Eade, 1991). In 1985, a German expedition on board the R/V Sonne surveyed the Fiji Fracture Zone.
near the Fiji Platform (Von Stackelberg et al., 1985) and found extensional structures here as well. Also in 1985, French workers during the Seapso III cruise noted the morphotectonic similarities between seafloor spreading on the CNFBR and the East Pacific Rise (Gente, 1987). Beginning in 1987, Japanese and French workers began a number of cruises to the central and southern parts of the basin (Auzende et al., 1988c). This work expanded the earlier ideas of French workers from the Seapso III cruise (Auzende et al., 1986a, 1986b).

Recently collected swath mapping data have provided insight into the tectonic development of the basin. In 1987, the Hawaii Institute of Geophysics' (HIG) R/V Moana Wave surveyed the active rift system in the central and northern parts of the basin as part of the Tripartite II programme conducted for the Committee for Coordination of Joint Prospecting for Mineral Resources in South Pacific Offshore Areas (CCOP/SOPAC, now known as the South Pacific Applied Geoscience Commission SOPAC). In addition to gravity, magnetic, and single channel seismic (SCS) data, we also collected side scan acoustic imagery and swath bathymetry using SeaMARC II, a simultaneous amplitude and phase acquisition system. In 1989, SOPAC conducted a survey cruise within the North Fiji and Lau Basins using the HMAS Cook. Additional side scan acoustic imagery data were collected using GLORIA, an amplitude acquisition system, as well as additional SCS data.
Data Acquisition and Methods

In order to test the validity of the competing theories, it is necessary to characterize the nature of seafloor spreading within the basin. The data used in this study include side scan sonar imagery (SeaMARC II and GLORIA), swath bathymetry (SeaMARC II), analog single channel seismic reflection, gravity, and magnetic data. The side scan imagery together with the standard marine geophysical data allow the classification of the active tectonic elements and accurate descriptions of their recent movements.

Swath mapping systems enable detailed mapping of a wide area of the sea floor in a comparatively short time. Tyce (1986) and Davis et al. (1986) present reviews of many of the swath mapping systems currently available, including SeaMARC II and GLORIA. SeaMARC II and GLORIA both provide side scan sonar imagery but have important differences. SeaMARC II (Blackinton, 1983) has the ability to provide bathymetry as well as side scan imagery. The utility of SeaMARC II lies in the fact that different lithologies and structures have different reflectivity characteristics (Hussong and Fryer, 1983; Reed, 1989). The side-scan imagery depicts rough and specular reflecting surfaces such as recent lava flows and steep escarpments as dark shades of grey and less reflective areas such as heavily sedimented areas as light shades of grey. Thus, recent volcanic centers and faulting are easily delineated in the imagery. The present configuration of SeaMARC II generates a 10 km wide swath section. The theoretical cross-track resolution of SeaMARC II is 5 meters while the along-track resolution can vary to as much as
40 meters. GLORIA (Somers et al., 1978) does not provide bathymetric information, but can generate swath images from 14 to 60 km wide with its present configuration. When towed at 10 knots, its cross track resolution is 30 meters and its along track resolution is 218 meters.

The SeaMARC II side scan data were processed in 1987 using the best methods available at that time. Since then there has been a dramatic improvement in the ability to process SeaMARC II side scan data (Sender et al., 1989). The dynamic range of the SeaMARC II data contain information that is best presented in either one of two ways. One is "age" mapping that allows comparison of relative ages of the seafloor based on the sediment cover. The other is "contrast" mapping and better shows the structure of the seafloor. The data in this study were for the most part processed using the "age" mapping technique. This means that while relative age determinations may be made from the side scan data, there is a degree of uncertainty present in the interpretation. Where there was doubt, other data such as 3.5 kHz were used. If no other supporting data were available, no relative age determination was made.

SCS, magnetic, and gravity data collected during the Moana Wave cruise and other cruises are used to augment the structural analysis. The SCS profiles are all analog records, collected using several different frequency ranges. Magnetic total field strength was measured with a Geometrics proton precession magnetometer. The International Geomagnetic Reference Field for the appropriate
year was subtracted to obtain the residual anomaly. Gravity measurements were made using a Lacoste-Romberg marine gravimeter and standard corrections were applied to determine the free air anomaly (Lacoste, 1967). These measurements were obtained from several cruises and were adjusted to minimize crossover errors following the method of Wessel and Watts (1988).
Introduction

The assumption of rigid plate behavior is valid for a description of the large-scale interactions and kinematics of the major lithospheric plates, such as the Pacific and Indo-Australia Plates. Processes occurring along their boundaries control how they increase or decrease in size and how they move relative to each other. For example, plates can increase in area by crustal accretion at spreading ridges or they can shrink by subduction in subduction zones. Also, changes in plate motion can be accommodated through reorientation of boundaries (Hey, 1977).

At the scale of the North Fiji Basin, however, some workers maintain that this assumption does not hold. Citing the complex magnetic anomalies (Lawver and Hawkins, 1978) and the diffuse regional seismicity (Hamburger and Isacks, 1988), they propose a model for backarc accretion in which classical "seafloor spreading" does not occur along orthogonal ridge-transform fault systems. Instead, accretion occurs through seamount volcanism and along short-lived spreading segments. Hamburger and Isacks (1988) went even further and suggested that the entire basin is being internally deformed within a large shear zone between the Pacific
and Indo-Australia Plates. Auzende et al. (1988a, 1988b, 1988c) reached a similar conclusion on the basis of marine geophysical data from the central and southern basin. While they describe the Central North Fiji Basin Ridge (CNFBR) as similar to the East Pacific Rise, they interpret other parts of the basin, notably the Viwa Rift, as being dissected by several strike slip faults and describe "a distensive type deformation in a strike slip system."

The purpose of this chapter is to examine the structural configuration of a ridge-ridge-ridge triple junction at the northern end of the CNFBR (Fig. 3) and discuss its historical development. The SeaMARC II data acquired during the 1987 Moana Wave cruise reveal the morphotectonic structure of each of the three limbs of this triple junction, and, in conjunction with the single channel seismic, gravity and magnetic data collected during this and other cruises, indicate that seafloor spreading has only recently begun along these limbs. Arguments are developed here which contend that the triple junction has made a discrete jump to its present location from a previous position slightly to the west. Such behavior has produced a complex structural configuration and magnetic anomaly pattern but does not indicate that diffuse, non-rigid plate deformation is occurring on a scale envisioned by others. Rather, deformation and organized spreading centers occur at the edges of what are essentially rigid microplates.
Figure 3: The location and tectonic setting of the newly formed triple junction in the central North Fiji Basin. The stippled area represents the area shown in the SeaMARC II data in Figures 4 and 5.
Data

SeaMARC II Side-scan and Swath Bathymetry

The SeaMARC II side-scan imagery and bathymetry are shown in Figures 4 and 5. The triple junction at 16°55'S, 173°57'E is located at the bottom of the figures as shown in the inset. The three limbs and main volcanic provinces of the triple junction are clearly evident in both the imagery and bathymetry. The northern limb was the first recognized and most extensively surveyed limb.

Beginning at the triple junction, the rift axis of the northern limb strikes N20°W through an en echelon series of narrow, deep grabens (labelled A, B and C in the inset). The grabens lie in the center of a wide (~70 km) zone of extension that trends N10°W. The zone appears to be obliquely rifting through older seafloor fabric. The rift axis grabens terminate around 14°15'S (off the top of Figures 4 and 5). The older fabric striking N50°W may be seen at the northern end of the survey (top of Figures 4 and 5). The northern limb joins the eastern limb at a pronounced right angle bend at 16°45'S, 173°55'E. The eastern limb forms a single, broad and deep graben that trends N60°E. Both the eastern and southern limbs were ensonified by SeaMARC II only in the vicinity of the triple junction. The southern limb, with a more characteristic spreading ridge morphology, is the dark area in the imagery extending southward from the triple junction. This limb trends N10°E and marks the northern termination of the CNFBR. West of the southern limb is a volcanic field having seafloor lineament
Figure 4: SeaMARC II side scan imagery of the triple junction and the northern limb. Dark areas are regions of high reflectivity or backscatter. Inset of figure shows the locations of the three grabens discussed in the text.
Figure 5: Bathymetric map of the triple junction and northern limb based principally on SeaMARC II data but using 3.5 kHz data for extrapolation. The three grabens of the northern limb and the escarpments bounding the eastern limb are especially prominent. Contour interval is 200 m.
trends of N30-60°E and containing individually distinguishable craters. This fabric is not seen on any of the three active limbs and appears to be unrelated to them.

The northern limb, characterized by a broad zone of normal faulting, is marked by only limited amounts of volcanism. The zone of extension is as wide as 70 km near the triple junction and narrows to the north. Normal faults with the characteristic N20°W orientation are seen in the imagery from the triple junction up to 15°S. In general, faulting and volcanic activity seem to gradually decrease northward. Prominent escarpments bound the three en echelon grabens which mark the axis (Figs. 4 and 5).

Graben A begins immediately adjacent to the triple junction at 16°45'S and extends northward to 16°10'S. It is approximately 70 km long and 10 km wide. Along the bounding faults, throw is as much as 1000 m (Fig. 5) and recent, extensive lava flows occur both inside and outside of the axial graben (Fig. 4).

Graben B begins slightly northeast of graben A and extends up to 15°15'S. It is 100 km long and 10 km wide and is the largest of the three axial grabens. The two bounding faults of this graben are prominent in both the bathymetry and imagery. Throw on the faults is as much as 1600 meters. Lava flows within the graben appear hummocky in the imagery and are visible from 16°10'S up to 15°45'S. An off-axis volcano with discernible lava flows occurs at 15°57'S and 173°20'E (Fig. 4). This volcano straddles a normal fault.
West of graben B at the western edge of the survey along 173°10'E, a prominent escarpment striking N05°W is observed between 16°15'S and 15°20'S. This fault has a throw of as much as 1200 meters. While it has a slightly different strike, it is interpreted to be part of the broad zone of extension associated with the northern limb. At approximately 15°15'S, the strike of this fault and the bounding faults of graben B change direction to N50°W. This fabric, although clearly visible, is much more subdued and sedimented than that of the northern limb indicating that it is older. While the N20°W trend typical of the northern limb bounding faults predominates in the imagery, the older seafloor fabric characterized by the N50°W trend seen here is also visible north of and along the western side of the extensional zone (top and left hand side of Figure 4).

Graben C is located 30 km to the northeast of graben B. This graben is 40 km long and 20 km wide. Throw along the bounding faults which strike N20°W is as much as 1200 m. To the north, the strike of these faults merges with that of the old seafloor, i.e., N50°W. Volcanism is not evident in the imagery.

The eastern limb of the triple junction, although not completely ensonified, appears to be formed by a solitary, 25 km wide rift graben bounded on either side by single large escarpments striking N35°E. These escarpments are normal faults with throws of up to 1300 meters. The rift graben narrows away from the triple junction. The northern fault is more prominent and abruptly terminates at 16°45'S, 173°55'E (Figs. 4 and 5) where it abuts
against northern limb fabric in a pronounced right angle. The southern fault has a more irregular trace than the northern fault. The graben structure of the limb is clearly seen in the bathymetry (Fig. 5). The floor of the graben gradually shoals from 3600 m at its eastern end up to 2000 m at the triple junction. The deep floor of the graben has low relief. Recent submersible dives here have reported widespread, slightly sediment covered lava flows which account for the dark appearance in the side scan imagery (Tanahashi, pers. comm., 1990). Small escarpments are visible among the lava flows on the graben floor.

The southern limb of the triple junction is the CNFBR which forms the principal spreading center in the southern half of the North Fiji Basin. Ridge-like in profile and characterized by voluminous recent lava flows, it differs from the northern and eastern limbs which are marked by prominent wide, deep axial grabens and have lesser amounts of volcanic activity. In Figure 4, the CNFBR is marked by the dark band of high reflectivity extending southward from the triple junction, and in the bathymetry of Figure 5, it forms an elongate ridge that shoals along axis to 1900 m at the triple junction. A small axial graben is recognizable in the side-scan imagery and bathymetry at the crest of the ridge. This axial graben is only a few tens of meters in relief and 1 or 2 km wide but is marked by strong reflectivity in the side-scan. The broad dark band in the imagery is caused by very recent and widespread sheet flows and pillow lavas reflecting much of the incident energy (Tanahashi, pers. comm.). These flows appear uniformly dark and
exhibit little internal structure. A bottom camera photograph taken within this dark band shows pillow lavas with little or no sediment (Fig. 6). Hydrothermal vents have been reported nearby (Auzende et al., 1988c).

Numerous circular volcaniform features are visible west of the southern limb in the imagery of Figure 4. This area is the volcanic field mentioned earlier. It is morphologically distinct from the three limbs of the triple junction. Although occurring adjacent to the southern limb, it displays none of the characteristics of southern limb volcanism. Lacking sheet flows, it contains individually recognizable craters and escarpments trending approximately N30-60°E. The dark appearance of the craters in the imagery suggests recent volcanism. At 16° 52'S, 17° 50'E, escarpments of the northern limb appear to cut across escarpments of the volcanic field and curve into the triple junction. This relationship would suggest that the tectonism associated with the volcanic field predates activity along the northern limb. The seafloor of the volcanic field has low relief and gradually rises in the direction of the triple junction (Fig. 5). The northwestern edge of the field is marked by a fairly large escarpment curving from N10°E to N50°E, but only partially mapped at its eastern end by SeaMARC II (Figs. 4 and 5). Further to the west, the seafloor displays little relief marked by a few north trending lineaments. Presumably, this fabric considerably predates the formation of the triple junction.
Figure 6: Bottom camera photograph taken near the axial graben of the CNFBR. Pillow structures and a lack of sediment cover characterize this region which appears homogeneously dark in the side scan imagery.
Gravity

The free air anomaly map is shown in Figure 7. The shape of the anomalies over the limbs mirrors the relief of the seafloor and gives an indication of the structural fabric. The northern limb axis is marked by a negative anomaly centered over each of the three grabens. The offsets between the three grabens, particularly between grabens B and C, are clearly evident. The uplifted rift flanks produce local maxima. At the northern end of grabens B and C, the contours bend and assume the N50°W direction. To the east of the northern limb, the anomalies trend northeast. Away from the northern limb, the free air anomalies are low amplitude and long wavelength indicating undisrupted, low relief seafloor. The eastern limb is also marked by a gravity low centered over the graben. The uplifted rift flank, forming the pronounced bight in the fabric between the northern and eastern limbs, produces a strongly positive anomaly. The southern limb produces a long wavelength positive anomaly extending southward from the triple junction, itself marked by a local maximum.

Magnetic Anomalies

The residual magnetic field is shown in Figure 8. Anomalies with the N20°W trend of the northern limb are obvious from the triple junction up to 15°30'S. Note that the contours do not parallel graben C. Instead, the N50°W trend clearly predominates in this region. This may suggest that although sufficient dike injection and volcanic activity have occurred in grabens A and B to produce magnetic anomalies, insufficient volcanic activity has occurred in
Figure 7: Free air anomaly map over the triple junction and the northern limb. Center of the triple junction and the tilted fault block forming the northern border of the eastern limb are prominent highs. The northern and eastern limbs are characterized by lows centered over their rift grabens.
Free Air Anomaly
Figure 8: Residual total field anomaly map over the triple junction and the northern limb. At the top of the figure, the anomalies are trending N50°W and are the result of a preexisting fabric. The northern limb is breaking through this fabric.
Magnetic Anomaly
graben C. The high amplitude negative anomalies centered over the eastern limb are prominent near the triple junction but terminate about 174° 15'E. The southern limb is marked by a strong positive anomaly consistent with that of a spreading center at this latitude and with this orientation.

Seismic Reflection Profiles

Figure 9 shows a series of single channel seismic profiles across the northern and eastern limbs. The profiles across the northern limb show it to be in the early stages of rifting. Profile KK8 (Fig. 9a) runs from SSW to NNE and obliquely crosses the northern limb about 15°20'S where an offset in the axial rift graben occurs. Sediment accumulations that are as much as 100 meters thick occur only 20 km away from the limb axis, yet there is no detectable sediment evident within the rift graben. Profile KK1 (Fig. 9b) runs south to north along 174°E longitude, crossing the northern escarpment of the eastern limb near the triple junction and closely paralleling the northern limb. Several small abyssal hills with moderate relief are visible on the track paralleling the northern limb. Between the hills are small basins with sediment accumulations of as much as 0.3 seconds, a relatively large amount for this part of the basin. Crossing the eastern limb, the profile shows a tilted fault block which forms the northern boundary of this limb. Profile KK2 (Fig. 9c) crosses the northern limb close to the triple junction. The axis is clearly marked by the narrow rift graben bounded by faults with as much as 1000 m of offset. To the west,
Figure 9: Three SCS lines. (a) Profile obliquely crossing the northern limb shows the structure of grabens B and C and thick sediment accumulations away from the northern limb. (b) Profile shows structure of the eastern limb and to the north, the typical relief of the North Fiji Basin.
Figure 9: (c) Profile across graben A of the northern limb shows its steep escarpments bounding either side.
there are thick sediment accumulations. To the east, however, the profile lies along the northern rift flank of the eastern limb.

**Geological Interpretation**

Based on the SeaMARC II imagery and single channel reflection profiles, five separate geological terrains are recognized (Fig. 10). Three are volcanic while the other two are delineated by sediment thickness and structural considerations. The first terrain is sediment covered with a homogeneous light appearance on the side-scan and marked by significant sediment accumulations. The second terrain is characterized by voluminous sheet flows and pillow lavas, occurring principally along the southern limb. The third terrain, defined on the basis of structural characteristics, is marked by extensive normal faulting. The fourth terrain, also structurally defined, consists of numerous craters and fault escarpments extending over a wide area. The fifth terrain contains isolated volcanoes and discrete flows which are often ponded against escarpments. The distribution of these terrains underscores the differences of the three limbs.

The northern limb comprises the rifted terrain. Extension occurs over a wide area as evidenced by the three axial grabens flanked by a series of subsidiary normal faults. Whereas the three axial grabens are bounded by large escarpments, several subsidiary faults having a substantial throw occur from the triple junction up to 15°S. There are few subsidiary faults at the northern end, however, and the faults bounding graben C are the only indicators of northern limb tectonism. West and north of the limb, the N50°W
Figure 10: Geological interpretation of the area ensonified with SeaMARC II showing the distribution of lithologic units and fault scarps. See text for explanation.
Volcanic flows and off-axis vents overprinted older fabric.
trend is interpreted to represent the pre-existing seafloor fabric. Lineations with this trend appear subdued in the imagery and parallel the magnetic lineations in this area.

Volcanism is not widespread along the northern limb. Individually distinguishable vents and flows occur along the length of the rift axis but diminish towards the north. Flows within the axis of the graben appear hummocky in the side-scan image and emanate from fissures along faults which presumably acted as conduits for the lava to reach the seafloor. At its northern end, the limb is demarcated solely by normal faulting with no evidence of volcanism present.

Similarly, the graben structure and recent volcanism of the eastern limb show it to be undergoing extension (Fig. 4). In contrast with the northern limb, however, two large offset normal faults rather than a series of subsidiary faults delineate the zone of extension. Along the floor of the rift graben, small escarpments are faintly visible among the dark sheet flows. These smaller escarpments have very low relief and are barely visible in the imagery.

The southern limb is the site of well developed seafloor spreading complete with a small axial graben at the crest of the spreading ridge. The spreading rate reported by Auzende et al. (1988a) was 35 mm/yr half rate. A dredge taken during the Moana Wave 1987 cruise recovered very fresh pillow basalts having a MORB (mid ocean ridge basalt) composition typical of volcanism at mid-ocean ridge spreading centers (Price et al., in press). The sheet
flows form the predominant unit along the southern limb and are located on the rift graben floor of the eastern limb. They are marked by high reflectivity and exhibit little internal structure.

In contrast, the volcanic field immediately west of the southern limb is characterized by a number of volcanic cones among small isolated escarpments, all of which are sediment covered. The fabric within this volcanic field apparently curves from N30°E at its southern end to N60°E near its northern end, trends that are distinct from those of the adjacent southern limb. Because its appearance on the side-scan imagery is so different from the three currently active limbs, particularly the trend of the seafloor fabric, I suggest that the volcanic field represents an older episode of volcanism resulting from a pre-existing extensional relay zone along the proto-Fiji Transform Fault.

Tectonics of the North Fiji Basin

Any explanation for the tectonics of the basin must account for at least four primary features of this triple junction. First, the northern limb has become active recently, is predominantly marked by faulting, and exhibits limited volcanism. The faulting occurs over a wide zone with volcanic activity lessening northward. Second, the eastern limb is also rifting with basalt effusion occurring across the floor of the broad, deep rift graben. Third, the southern limb has a profile much like the East Pacific Rise and is the most volcanically active limb. Fourth, the volcanic field has structural and volcanic characteristics unlike those of the three active limbs and is not
apparently associated with any of the active limbs. I interpret these observations as indicating that the present arrangement is a recent occurrence which is overprinting older seafloor fabric.

Based on magnetic studies over the entire basin, previous workers suggested that the triple junction has recently (<1 Ma) changed position (Malahoff et al., 1991; Auzende et al., 1988b). These studies identified the previous location of the CNFBR as being west of the area surveyed with SeaMARC II but differ with regard to the previous configuration of the triple junction. Auzende et al. (1988b) place the paleo-triple junction near 15°S, 173°E while Malahoff et al. (1991) place it further south around 17°S. One reason for this discrepancy is that north of 18°S the magnetic anomalies become highly complex. However, from the side scan imagery it is doubtful that much recent activity has occurred at the location suggested by Auzende et al. (1988b).

This older triple junction connected the CNFBR with now extinct spreading centers in the northwestern and northeastern parts of the basin (Fig. 11a). The northwestern limb has been reliably identified on the basis of magnetic anomalies and seafloor morphology and was active until at least 2 Ma (Malahoff et al., 1991). The old northeastern limb is identified mainly on the basis of seafloor morphology and its age is less well constrained. However, it could not have existed for much of the history of the basin because seafloor morphology and sediment thickness show this to be an older part of the basin (Kroenke et al., in press).
Figure 11: A before and after sequence showing the development of the triple junction. (a) The older triple junction is identified on the basis of magnetic anomalies. (b) As the opening of the basin commences, the present day volcanic field was active at this time as a zone of extension within the proto-Fiji Transform Fault. (c) The triple junction has jumped eastward and is now situated within the now inactive volcanic field.
After this stage, the Fiji Transform Fault developed and connected the triple junction with the Lau Basin (Fig. 11b). It is proposed that the old northeastern limb had a component of shearing which gradually became more prominent as the North Fiji and Lau Basins opened. (How this occurred is discussed more fully in the next chapter.) This configuration preceded the present arrangement.

The Fiji Transform Fault today is not a straight through-going transform fault but is instead a "leaky" transform fault having a significant extensional component. This extension is accommodated by short discrete spreading segments occurring within offsets along the trace of the fault. Similarly in the past, the fault had this same structure with a significant extensional component.

The volcanic field was probably a short spreading segment which connected the Fiji Transform Fault with the triple junction. The evidence for this is mainly inferential. The volcanic field occurs on one side of the southern limb while on the opposite side is fairly thick sediment. The fabric of the volcanic field curves to the east at its northern end much like the present short spreading segments occurring along the trace of the Fiji Transform Fault. Using these as an analogue, it is easy to identify the volcanic field as a relict spreading center.

An alternative interpretation might be that the volcanic field represents off-axis volcanism associated with the southern limb but I discount this possibility for the following reasons. First, as stated above, it occurs on only one side of the southern limb axis rather
than on both. Off axis volcanism would be unlikely to occur on only one sided of the ridge crest. Second, the borders of the volcanic field are very sharply defined. There is a distinct break between the volcanic field and the southern limb and between the volcanic field and the older fabric. And third, the fabric of the northern limb is clearly overprinting the fabric of the volcanic field implying a definite age relation.

The final step in the formation of the triple junction was a discrete jump in its location from its former site in the southwest to its present site (Figure 11c). This happened fairly quickly for the seafloor around the three limbs is comparatively old and was not apparently produced by any of the three limbs. Only short distances away from the ridge the fabric is no longer ridge parallel. Furthermore, the jump happened fairly recently for all three limbs show signs of being recent phenomena.

This model for the development of the triple junction is dependent on the previous location of the triple junction being where other people say it was. Yet this is not as serious a problem as it might first appear. From the SeaMARC II data, two important points may be deduced. We know where the triple junction is today and we know it hasn't been there very long. We can then say that the paleo-triple junction lay elsewhere. Its previous location cannot be pinpointed but it is certain that it lay outside the surveyed area.

The question arises as to what is the cause of this jump and how does it relate to the question of rigid plate behavior. Such a jump is not at odds with "traditional" plate tectonic models for
backarc accretion. The North Fiji Basin is dominated by the motion between the Pacific Plate and the backarc. In such an environment, plate boundaries can migrate and jump frequently as the New Hebrides Arc rotates and the geometry of the basin's boundaries changes. This does not require non-rigid plate behavior, however. All observed deformation occurs along the three limbs of the triple junction and there is no evidence for internal plate deformation occurring away from the three limbs. The motion of the Pacific Plate past the microplates of the North Fiji Basin is accommodated by rapidly migrating boundaries rather than by isolated volcanoes and short-lived spreading centers within a large scale pull-apart basin.

Conclusions

1) All three limbs of the triple junction are active but have unique characteristics. The northern limb is an incipient rift and is characterized by normal faulting with minor amounts of volcanism. The eastern limb is a wide rift graben extending from the triple junction to its terminus at the Fiji Fracture Zone. The southern limb is an active spreading ridge with voluminous sheet flows emanating along a small axial graben.

2) I propose that the triple junction jumped northeastward from its former location to a site within a spreading segment in the Fiji Transform Fault. The northern limb then began to break through older crust and is now propagating northward. The northern and
eastern limbs are presumably in the early stages of rifting, splitting apart older oceanic crust.
Introduction

The Fiji Transform Fault (FTF) is an active sinistral transform fault extending across the northern end of the Fiji Platform and into the North Fiji Basin (Fig. 12). Transform faults are a particular type of strike-slip fault which mark the boundary between two lithospheric plates. Classical plate tectonic theory provides a good first order description of the behavior of transform faults. However, to gain further insight into their tectonic expression, we must turn to modern seafloor swath mapping devices. In this chapter, I present a tectonic analysis of recently acquired swath mapping imagery and bathymetry as well as other marine geophysical data of the FTF and discuss how the complex structures associated with it were produced. This is of fundamental importance to describing the development of the North Fiji Basin.

There is considerable literature detailing the structural behavior of strike-slip faults, especially in continental settings (Christie-Blick and Biddle, 1985; Crowell, 1974; Mann et al., 1983; Freund, 1974; Withjack and Jamison, 1986). Strike-slip faults seldom have a perfectly linear trace. Bends or other irregularities occur along strike giving rise to areas having a localized component of extension or compression in addition to shear. Harland (1971)
Figure 12: Tectonic map showing the locations of the SeaMARC II survey (dark, dotted pattern) and the GLORIA survey (dashed lined pattern) along the Fiji Fracture Zone. The SeaMARC II survey is shown in Figures 13 and 14 and the GLORIA survey is shown in Figure 18A.
first defined the terms "transtension" and "transpression" to refer to the stresses produced in such areas. Sedimentary basins are a common product of transtension and are frequently sites of hydrocarbon accumulation.

In an oceanic environment, areas of localized extension may also develop. A number of studies have detailed the smaller scale structures of transform faults (Fox and Gallo, 1984; Madsen et al., 1986; Kastens, 1987; Gallo et al., 1986; Searle, 1986; Macdonald et al., 1979; Macdonald et al., 1986). Fox and Gallo (1984) have shown that the morphotectonic behavior of transform faults is sensitive to the lithospheric age contrast across the fault which in turn depends on the slip rate and offset between ridges. Yet transform fault morphology is affected by more than these factors. Menard and Atwater (1968) first suggested that small changes in spreading direction and magnitude could lead to "leaky" transform boundaries by producing a small component of extension. Small extensional relay zones (ERZ's), or intratransform spreading centers, can offset segments of the fault. Lonsdale (1989) hypothesized that a change in Pacific-Nazca spreading direction has led to the development of ERZ's within many of the transform faults along the East Pacific Rise. Alternatively, Fornari et al. (1989), in a study of the Siqueiros Transform Fault, believe that ERZ's are a by product of the interaction of melt anomalies in the mantle with fractures along the transform fault.

In the following discussion, I argue that the complex structures observed along the FTF are a consequence of the fault
geometry and of the propagation of short spreading segments into the Fiji Platform. The intersection of the FTF with the Viwa Rift (VR) is examined first. This intersection marks the boundary between two contrasting structural styles along the FTF. From the VR to about 180°E, the FTF is offset as its trace steps around the Fiji Platform. Contained within these offsets are short spreading segments. I argue that one of these spreading segments has recently propagated southward into the Fiji Platform and transferred a portion of Fiji lithosphere onto the Balmoral Plate. I also postulate that such a mechanism is responsible for the formation of the Balmoral Reef and Braemar Ridge. Between the central basin triple junction and the VR, the history and location of the FTF is problematic and the area comprises elongate ridges and basins occurring over a 40 km swath. An argument is made that this section of the FTF was inactive but is now in the process of adjusting to the new spreading directions following the change in location of the triple junction.

Data

SeaMARC II data

The SeaMARC II side-scan imagery and bathymetry of the intersection of the FTF with the VR are shown in Figures 13 and 14. In the imagery, the VR is the dark band trending southward from the intersection located at 16° 35'S, 176° 10'E. The approximately north-south aligned seafloor fabric evident in the imagery is produced by the parallel alignment of fault escarpments on both
Figure 13: SeaMARC II side scan imagery of the Viwa Rift and its intersection with the Fiji Fracture Zone.
Figure 14: SeaMARC II bathymetry of the Viwa Rift and its intersection with the Fiji Fracture Zone. The location of the survey area is shown in Figure 12.
sides of the VR. These escarpments are prominent within and adjacent to the VR but become more subdued away from it. Two well developed, yet slightly different, patterns of spreading fabric can be distinguished. To either side of the VR, the fabric is ridge-parallel trending about N10 to 15E. However, beyond 10 km to the west of the VR, the fabric becomes more nearly north-south. Furthermore, east of the VR the ridge-parallel lineaments occur out to 35 km, but beyond this the only identifiable lineaments have a roughly northeast trend and are presumed to be much older. West of 175° 50'E, the escarpments that form the fabric are more subdued, but still appear to trend north-south curving to the northeast at the northern end.

In the bathymetry (Fig. 14), the VR is a long, 10 km wide trough that is more than 3000 m deep and deepens close to the FTF. There are differences between the two sides of the VR. The sides of the rift shoal to 2100 m on the west and 1300 m to the east. Near the intersection, this eastern side is similar to the morphology observed at ridge-transform intersections (Fox and Gallo, 1984; Macdonald et al., 1986; Macdonald et al., 1979) with the 1300 m shallow area being the "high inside corner." Also, fault escarpments and bathymetric contours are ridge-parallel south of the intersection but gradually become more oblique near the transform fault as the principal stress directions change. Off-axis volcanoes may be seen in both the imagery and bathymetry near 16° 55'S, 175° 55'E.
The intersection of the FTF with the VR marks a change in its morphotectonic character. Westward from the VR, the FTF appears as a shallow ridge trending east-west. At 175° 50'E, the trend of the FTF changes to N80°E. It is marked in the imagery (Fig. 13) as ENE trending escarpments and in the bathymetry (Fig. 14) as a shallow (<800 m) ridge. The ridge and adjoining seafloor appear in the imagery to be sediment covered.

Eastward from the VR, the Yasawa Trough marks the location of the FTF. It appears in the imagery in Figure 13 as a broad light band bounded to the north and south by broad dark bands and appears in the bathymetry in Figure 14 as the 5000 m trough trending eastward from the intersection. It is 70 km long and 15 km wide but gradually narrows at either end. The light band in the imagery is caused by ponded sediment along the trough axis, and the flanking dark bands are caused by the steep, rough sides of the trough causing high backscatter. The northern escarpment bounding the trough is steep, fairly straight and continuous whereas the southern escarpment is noticeably less steep, more irregular and has a variable slope. Evidently, slumping and/or rotational block faulting has played a more prominent role along the southern escarpment than along the northern escarpment. North of the Yasawa Trough, a series of shallow ridges lie on the same ENE trend as the FTF does west of 175° 50'E.

Figure 15 shows a geological interpretation of the SeaMARC II data. The areas of recent volcanism are marked by the dotted pattern. The two patterns of spreading fabric lineaments are
Figure 15: Geological interpretation of the SeaMARC II data shows the location of recent volcanism (stippled area) and the Fiji Fracture Zone. The Viwa Rift is the broad zone of volcanism in the center of the figure. The solid line marks the location of the active portion of the fault. The dashed line west of the Viwa Rift shows the approximate location of the FFZ. The dashed lines at the top right hand side of the figure show the trend of ridges which may be a remnant section of the FFZ.
readily apparent. Although the data are sparse, the lack of spreading fabric beyond 35 km east of the VR appears real. A few lineaments trending N45°E are present in this area, but this may be only due to the proximity of the Fiji Platform. West of the VR, the FTF lineaments are nearly east-west but change to a more northeast direction west of 175° 50'E. East of the VR, the location of the FTF is marked by a single solid line running from the northern end of the VR eastward through the Yasawa Trough. North of the Yasawa Trough, the dashed line in the figure marks the ridges having the same ENE trend as the ridge.

The complexity of structures between the VR and the CNFBR can be seen in a single swath of SeaMARC II side-scan data (Fig. 16). This is the only side scan data from this part of the FTF and together with single channel seismic lines (discussed below), provides the basis for the interpretation of this area. The ENE trending ridge terminates around 175°E where a few volcaniform features may be seen. To the west the FTF is characterized by NNW trending ridges and intervening basins occurring over a 40 km wide zone. Nearer the triple junction, especially around 174° 30'E, the seafloor fabric has a NW trend. The regional bathymetry (Fig. 17) shows the major structures in the area. The ENE ridge extending westward from the VR is the most conspicuous feature east of 175°E. West of 175°E, however, although bathymetric data is sparse, the regional morphology is aligned north-south.
Figure 16: A single swath of SeaMARC II imagery along the FFZ between the Viwa Rift and the triple junction. This area is south of the GLORIA survey shown in Figure 18A. Profile A-A'–A" shown in Figure 21A was taken along this track.
Figure 17: Regional bathymetry of the Fiji Fracture Zone between the Viwa Rift and the triple junction. Data taken from single swath of SeaMARC II bathymetry as well as 3.5 kHz records from older cruises.
GLORIA Data

The GLORIA imagery is shown in Figure 18A. The imagery is the reverse of SeaMARC II imagery in that highly reflective surfaces appear white and less reflective surfaces appear black. The imagery covers much of the FTF between 174°E and 180°E (Fig. 12). As stated previously, the intersection of the FTF with the VR marks a change in the morphotectonic character of the fault. To the west, the trace of the FTF from the eastern limb of the central basin triple junction to the VR is uncertain. East of the VR, between 176° 10'E and 176° 45'E, the fault is marked by the narrow, deep Yasawa Trough. The southern escarpment bounding the Yasawa Trough dipped toward the GLORIA towfish and shows up as a prominent white band in the imagery. The northern escarpment dipped away from the towfish and appears as a black shadow zone in the imagery because, due to the "look angle", the GLORIA towfish could not image it.

Between the triple junction at 174°E and the VR at 176°E, there are a number of ridges and basins oriented obliquely to the direction of motion along the fault (Fig. 18A and 18B). Fewer earthquakes occur here than the area east of the VR (Fig. 18B) and those that do are widely scattered (Hamburger et al., 1991). The eastern limb of the triple junction is a wide (~30 km) rift graben floored by recent lava flows and small faults as discussed in the previous chapter. This graben extends approximately 70 km northeast from the triple junction where it narrows and terminates, obliquely abutting against a northwest trending ridge which appears
Figure 18(a): GLORIA side scan imagery of the Fiji Transform Fault.

The locations of the seismic lines as well as some of the principal physiographic features are indicated.
Figure 18(b): Bathymetry of the Fiji Transform Fault. Earthquake epicenters are indicated by solid circles.
as the prominent white band at 16° 40'S, 174° 30'E. This ridge can also be seen in the bathymetry of Figure 18B.

Besides this ridge, there are no significant structural trends visible in the GLORIA imagery between 174° 30'E and 175° 30'E. Most of this area is heavily sedimented and is interpreted to be old compared with the rest of the North Fiji Basin. The only prominent feature is a large volcaniform structure at 16° 20'S, 175° 10'E. The absence of any recent deformation in this area suggests that the active PDZ of the FTF, if present, lies south of the GLORIA survey in the vicinity of the SeaMARC II survey described earlier (Fig. 16).

The most prominent structures visible in the imagery are the FTF-VR intersection and the Yasawa and Yadua Troughs. The VR, running roughly north-south along 176° 10'E and intersecting the fault at 16° 35'S, was better surveyed with SeaMARC II (Figs. 13 and 14). Balmoral, Braemar and Bligh Ridges (new name) are the most conspicuous features in the bathymetry shown in Figure 18B. Note that the trend of the Balmoral Ridge is slightly east of north, whereas the trend of Braemar Ridge, north of the Yasawa Trough, is more northeast. Adjacent to Yadua Trough, Bligh Ridge trends nearly east-west.

Three left-stepping offsets occur along the FTF resulting in short extensional basins. The obvious spreading segments within two of these basins are denoted as ERZ A and B in the GLORIA imagery shown in Figure 18A. The third offset is the Yadua Trough. East of the VR along the FTF, the structures are typically transtensional. This section of the fault is better demarcated and
shows clear evidence of shearing and extension. The seismicity in this area is confined to a fairly narrow band (Figure 18B). Focal mechanisms are predominantly left lateral strike-slip (Hamburger et al., in press). The trace of the fault runs eastward from the Yasawa Trough (Fig. 18A) but is offset by the ERZ's in a left-stepping sense.

ERZ A appears as a highly reflective area centered at 16° 25'S, 177° 25'E. Very fresh basalt was dredged from this location (Von Stackelburg et al., 1988). The spreading fabric related to this ERZ appears slightly arcuate. Pull-apart basins commonly have such an arcuate shape between the two master faults (Mann et al., 1983). Furthermore, the spreading fabric does not extend very far to either side of the axis suggesting that the ERZ has not been active for very long. ERZ A is abruptly truncated at its southern and northern ends by prominent east-west trending lineaments marking the active sections of the transform fault.

East of ERZ A, the location of the fault trace is poorly defined in the imagery but is postulated to extend eastward through the Yadua Trough, a depression reaching depths greater than 4000 meters and which is presumably the second offset in the fault trace. This is supported by the relatively large number of earthquakes occurring within the Yadua Trough. No volcanism within the Yadua Trough is evident in the imagery. This trough separates the Fiji Platform from the shallow Bligh Ridge.

ERZ B, the third offset, appears as the highly reflective area centered at 15° 30'S, 178° 40'E. From this point, the location of the
fault lies north of the area imaged with GLORIA. The fabric associated with this ERZ has a highly irregular appearance. If the spreading axis coincides with the area of greatest backscatter, it has a trend of N45°E, highly oblique to the nearly east-west trend observed for the fault trace. Furthermore, the spreading fabric west of the spreading axis has a slightly arcuate shape and changes trend from northwest to northeast gradually becoming more ridge-parallel. An east-west trending lineament west of the arcuate fabric occurs at the same latitude as the southern end of the spreading fabric. The fabric east of the spreading axis is also arcuate but is abruptly truncated by the neovolcanic zone. Both older sets of spreading fabric do not extend much further south then 15° 30'S. However, the neovolcanic zone does extend below 15° 45'S. An extensive lava field occurs at the southern end of this ERZ centered at 15° 45'S, 178° 35'E and can be seen in the imagery as the broad white area.

Magnetic Anomalies

Figure 19 shows a magnetic anomaly profile across the western side of the VR. Assuming a magnetic layer thickness of 1 km, a residual magnetic anomaly was calculated and compared with the observed anomaly. A reasonable match was obtained for a half rate spreading velocity of 25 mm/yr with an increase to 37 mm/yr beginning at 1.1 Ma. Although the timing of the increase in spreading velocity is poorly constrained, a medium spreading velocity is required to generate the observed Jaramillo and Brunhes
Figure 19: Observed magnetic anomaly profile over the Viwa Rift is shown along with a model calculated for a constant spreading rate. The SeaMARC II profile along this track is given for comparison.
anomalies. The appearance of the VR in the side scan imagery and its magnetic anomaly record indicate that the VR has been continually spreading for at least the past 1.7 Ma. It should be noted here that some authors argue that the VR is not a spreading axis at all but is instead one of several small extensional basins located within a complex shear zone (Auzende et al., 1988b). This controversy is addressed below.

Gravity

The free air anomaly over the FTF between 174° and 177°E is shown in Figure 20. This map was compiled from several different cruise data sets. The GLORIA survey covered the northern portion of this region. The principal structural trends are immediately evident in this figure. The high amplitude anomalies associated with the Yasawa Trough are between 176° and 177°E. These are the result of the high seafloor relief along the active transform fault. On the left hand side of the figure, the eastern limb of the triple junction is marked by a gravity low centered over the graben at 16°45'S, 174°15'E. Between these two areas, although based on less data, anomalies have lower amplitudes and longer wavelengths than those observed over the spreading center or along the active FTF. The general trend is northwest-southeast such as the gravity low centered at 17°S, 175°E.

Seismic lines

Although the SeaMARC II and GLORIA surveys did not obtain complete coverage of the FTF, single channel seismic reflection
Figure 20: Free air anomaly over the Fiji Fracture Zone between the triple junction and the Yasawa Trough. Areas without data points are masked out and appear white.
profiles collected by previous cruises provide a more complete
determination of structural relationships (Fig. 21). Profile A-A'-A''
shows the structure of the FTF between the triple junction and the
VR. This profile was collected along the track of the single SeaMARC
II swath shown in Figure 15. Between A and A', the profile follows
the ENE trending ridge and is marked by a thin sedimentary cover.
At about 175°E, however, a 750m deep separates this area from a
region of thick sedimentary cover which continues all the way to the
CNFBR. Profile B-B' in Figure 21C shows a profile across the
northern flank of Balmoral Ridge. The sediment cover is markedly
thicker on the presumably older northwestern side of the ridge.
Also, the northwestern flank of the ridge itself is marked by steep
escarpments and rotated fault blocks. Profile C-C' (Fig. 21B), an
interpreted section taken along one of the GLORIA tracks, shows
ERZ's A and B and the northwestern flank of the Bligh Ridge. The
ERZ's are floored by sediment-free crust and are characterized by
small escarpments and rough terrain. Bligh Ridge rises more than
1000 m above the adjacent ERZ's along steep escarpments and
contains pockets of thick sediment.

Discussion

Is the VR a Spreading Ridge?

In his seminal work on the tectonics of the North Fiji Basin,
Chase (1971) identified the VR as a spreading ridge. His
interpretation relied on sparse geophysical data and some later
workers have disputed this finding. Based on a Seabeam survey
Figure 21: Single channel seismic profiles. (a) Profile A-A'-A'' over the Fiji Fracture Zone taken along the SeaMARC II swath shown in Figure 16. (b) Profile C-C' shows the structure across ERZ A and B and Bligh Ridge.
Figure 21(c): Profile B-B' shows the structure across the Balmoral Ridge and the contrasting sediment thickness on either side of it.
along part of the VR, Auzende et al. (1988b) describe a "distensive type deformation" wherein the area is subject to transtension resulting in the observed volcanism.

The data presented here support Chase's original interpretation. The neovolcanic zone of the VR is confined to the axis of the VR, and magnetic modelling suggests that spreading has been continuous for the past 1.7 Ma. The east-west trending lineaments are produced by tectonism along the FTF and are confined to a zone about 15 km wide along the trace of the fault. This morphology suggests that the PDZ of the FTF is fairly narrow. South of the PDZ, the seafloor fabric is very nearly ridge-parallel and can be attributed to seafloor spreading along the VR. Oblique deformation hypothesized for the VR is not in evidence in the SeaMARC II imagery. Furthermore, the discontinuity in the VR axis shown in the Seabeam map of Auzende et al. (1988b; their Fig. 14) may indicate the presence of a propagating ridge with the western ridge propagating southward. Its morphology is very nearly indistinguishable from that of the Galapagos propagating rift (Hey, 1977).

The history of the FTF may also be inferred from the structural patterns evident in the SeaMARC II imagery. The change in orientation of the VR fabric shows a discrete change from north to slightly northeast. The ENE ridge to the west possibly represents an older section of the FTF abandoned in favor of the present east-west trend.
How did the Balmoral and Braemar Ridges Form?

North and east of the VR, the FTF and adjoining areas comprise several complex structures (Fig. 18A). The area has some of the greatest relief within the North Fiji Basin. The active fault runs close to the Fiji Platform and the ERZ's occur within offsets in its trace. Northwest of the Fiji Platform, the Balmoral, Braemar and Bligh Ridges are prominent shallow features standing above seafloor with depths typical of the rest of the North Fiji Basin. Explanations for the complexity of this area are conspicuously absent in the literature although Kroenke et al. (1991) attribute the Balmoral Ridge to overthrusting based on seismic reflection data.

East of the Yasawa Trough, the section of the transform fault that is currently active lies between Bligh Ridge and the Fiji Platform. The east-west lineaments, marking the northern end of the neovolcanic zone of ERZ A, extend into the southern end of the Yadua Trough joining ERZ A with Yadua Trough. This along with the seismicity (Fig. 18B) suggests that the Yadua Trough may be an incipient ERZ within the FTF. Furthermore, the southern end of the neovolcanic zone of ERZ B extends south to around 17°S, nearly to the northern end of Yadua Trough. Finally, while the seismicity of the area is somewhat dispersed, most of the epicenters are concentrated between the Bligh Ridge and the Fiji Platform (Hamburger et al., in press). In my interpretation, a transform fault links the Yadua Trough and ERZ B.

The recent structural history of the ERZ's as deduced from the GLORIA imagery suggests that ERZ B has propagated into the Fiji
Platform slicing off Bligh Ridge. Evidence for the propagation of ERZ B into the Fiji Platform may be observed in the orientation of spreading fabric. The spreading fabric of both ERZ's is not very wide suggesting that they have not been active for very long. Furthermore, while the fabric of ERZ A is ridge-parallel indicating spreading orthogonal to the ridge axis, the fabric of ERZ B is highly arcuate and does not parallel the present neovolcanic zone. This older fabric also does not extend as far south as the neovolcanic zone. While the recent volcanic activity is observed along ERZ B down to 15° 55'S, the older fabric terminates at 15° 30'S. The neovolcanic zone of ERZ B is marked at its southern end by a large lava field. The absence of volcanic activity or of a significant sedimentary sequence in the Yadua Trough suggests that recent extension has occurred.

Figure 22 shows the proposed model for the development of this area. The active section of the FTF was originally located north and west of the Bligh Ridge, which was then part of the Fiji Platform (Fig. 22A). The proto-ERZ B axis was shorter when it generated the older fabric. The southern end of the proto-ERZ B ended at the active transform fault and produced the east-west lineament seen west of the ERZ. The reason for the change in trend of the fabric west of ERZ B is not clear. Rotation of the active spreading center could produce such curvature but the eastern side of the ERZ does not exhibit a similar pattern. Propagation of the ERZ with a new azimuth into the Fiji Platform was probably responsible.
Figure 22: Proposed model for the development of the Bligh Ridge.

(a) Bligh Ridge is interpreted to have once been attached to the Fiji Platform. (b) Following propagation of ERZ B and rearrangement of ERZ A, Bligh Ridge separated from the platform and the Yadua Trough is now a transtensional area within the FFZ.
This model provides an explanation for the formation of the Balmoral and Braemar Ridges. Like the Bligh Ridge, it is possible that they were once attached to Fiji but have been rifted away from it through ridge propagation into the arc lithosphere. My interpretation of the few available reflection profiles predicts that the seafloor is significantly older to the west of Balmoral Ridge than it is to the east. This explanation implies that all three ridges are the product of island arc volcanism which occurred while they were still part of the Fiji Platform, rather than derived from back arc basin volcanism. It also implies that the FTF has been active for a good portion of the history of the North Fiji Basin. Thus, I believe that the FTF has been active for a long time for more than 1 Ma and perhaps more than 2 Ma and has changed orientation from northeast to east-west through progressive, discrete jumps in its location.

Is the FTF active west of the VR?

The nature and extent of the FTF between the triple junction and the VR are problematical primarily due to a lack of data from this area. The seismicity is widely dispersed and less frequent than it is along the FTF east of the VR. Structural trends vary. Based on a few Seabeam tracks in the area, Lafoy et al. (1987, 1990) described the region as being cut by several en echelon strike-slip faults. Unfortunately, the SeaMARC II and GLORIA surveys did not cover enough of the area for any definitive models to be advanced. Figure 23A shows what can be determined from the data. From the
Figure 23: Schematic illustration showing structure of the Fiji Fracture Zone between the triple junction and the Viwa Rift.
(a) Connection is uncertain but the major physiographic features are a north-south oriented ridge near the eastern limb and a NNE oriented ridge. (b) One interpretation is that the eastern limb is offset to the south and propagating eastward. (c) Another interpretation is that the NNE ridge is part of the old fault which is now being abandoned following triple junction reorganization.
triple junction, the eastern limb extends toward the northeast. From the VR - FTF intersection, there is a narrow ridge extending toward the west-southwest. Between these two features, it is not certain what occurs but two models may be advanced.

In one model (Figure 23B) this area is interpreted as an inactive section of the FTF into which the eastern limb is propagating (Kroenke, pers. comm.). This would require that the FTF be presently inactive in this area, i.e., a true fracture zone. The eastern limb is regarded as a short spreading segment which is offset to the south by a transform fault. Between this point and the VR - FTF intersection, it is not clear what happens. Perhaps the WSW ridge is the product of this propagation. One implication of this model is that the sequence of events in Figure 11 would require another stage. It would mean that the FTF form, be active for a time and then cease activity in this area.

In another model, this part of the FTF is interpreted to be as active but with left lateral shear occurring over a broad zone (Fig. 23C). The various trending ridges and basins in this area are considered the products of this deformation. This model might be plausible if the area were still adjusting to the recent change in spreading directions. Following the change in triple junction location, the shearing associated with the FTF would have to be accommodated along a different area. The WSW ridge is interpreted to be part of the old trace of the FTF but now the fault has changed location in response to the triple junction jump. The master fault is
offset around 175° leading to compression and a "push-up" structure.

Conclusions

1) The Viwa Rift is an active spreading center and has been spreading for at least the past 1.7 Ma and probably longer.
2) Adjacent to the Fiji Platform, the FTF consists of a series of left-stepping segments bounding short spreading segments.
3) These spreading segments propagate into the Fiji Platform and at times break off sections of lithosphere transferring them to another plate. This is believed to be the origin of Balmoral Reef, Braemar Ridge, Bligh Ridge and the arcuate fabric.
4) Between the central basin triple junction and the VR, the FTF exhibits a complex structural pattern but the tectonic nature of this area is uncertain.
Chapter 4

PLATE BOUNDARIES IN THE NORTHERN NORTH FIJI BASIN

Introduction

Defining the boundary of the Pacific Plate is crucial to a full understanding of the tectonic development of the North Fiji Basin. Tectonic interpretations are often at odds regarding the location and nature of this boundary. Before the use of side scan sonar devices, efforts to fully understand this boundary were hampered by a lack of an adequate means to identify it. Few earthquakes are recorded here and those that have been are widely scattered. Magnetic anomalies are complex and have led to widely varying interpretations. This inability to precisely identify the boundary has contributed to the development of multiple models for the origin of the basin.

Most interpretations of the tectonic configuration of the North Fiji Basin (Figure 24) place the boundary between the Pacific Plate and the western half of the basin along the South Pandora Ridge (SPR). The SPR is characterized by very high relief along its length and early workers (Chase, 1971; Macdonald et al., 1973) interpreted the SPR as a left lateral transform fault extending from the New Hebrides Arc to somewhere near Rotuma Island. Some workers (e.g., Malahoff et al., in press) have regarded the SPR as an incipient spreading ridge based on the occurrence of relatively young basalt
Figure 24: Location of the GLORIA and SeaMARC II surveys of the South Pandora Ridge and Tripartite Ridge superimposed on the tectonic map. The GLORIA survey of Figure 25 is indicated by the dashed pattern and the SeaMARC II surveys of Figures 27-30 are indicated by the dotted pattern. The dotted line through Tripartite Ridge indicates the location of the seismic profile shown in Figure 31B.
(Sinton et al., in press; Price et al., in press; Price and Kroenke, in press), offset ridge morphology (Kroenke et al., in press) and magnetic anomaly patterns consistent with seafloor spreading (Malahoff et al., in press). Another model interprets the SPR as one, albeit an important one, of several strike-slip faults in the region (Hamburger and Isacks, 1988).

The boundary of the Pacific Plate and the eastern half of the basin is also controversial. Most authors interpret the FFZ as the southern boundary of the Pacific Plate in this region. This interpretation relies primarily on the high seismic activity observed along it. Brocher (1985) postulated a progressive reversal of the paleo-Vitiaz Arc and identified a fossil east-west trending spreading center north of the Fiji Platform. However, he still regarded the Fiji Transform Fault as the present day Pacific Plate boundary. Some workers have suggested that the actual boundary lies to the north along the Tripartite Ridge (TR). Malahoff et al. (in press), for example, identified the TR as an active spreading center on the basis of magnetic anomalies. Arguments in favor of this hypothesis also can be made on plate motion considerations (Louat and Pelletier, 1989).

In this chapter, I interpret newly acquired side scan sonar imagery from the SPR and the TR. Only three small portions of the northern boundary have been ensonified with the side scan sonar (Figure 24). Nevertheless, these three small surveys coupled with older data (Kroenke et al., in press) go a long way toward revealing
the nature of the boundary. This boundary is shown to be much more complex than indicated by earlier studies.

Finally, I present a model of the tectonic history of the basin. From the structures revealed in the side scan imagery, the recent history of the basin's tectonic elements can be determined. By taking the processes leading to their present configuration and extrapolating them back in time, it's possible to construct a model which accounts for several previously unexplained features.

**Data**

**GLORIA Side Scan Imagery**

GLORIA imagery was obtained along an oblique traverse across the western end of the SPR (Figure 25A). This section of the SPR is characterized by a wide zone of high relief comprising curvilinear escarpments that trend primarily N70°E and appear as the white bands in the imagery. Outside of this zone, seafloor relief appears somewhat more subdued and the escarpments have a different trend. The bright areas in the imagery are predominantly due to steep escarpments. The greatest concentration of escarpments occurs around 170° 45'E. A few isolated volcaniform features are present at this location (e.g., 170° 30'E, 14° 10'S) but no extensive volcanic fields are apparent. East of 171°20'E, the dark appearance of the imagery is due to a reduced transmit power supply rather than the presence of a thick sedimentary cover.

In the bathymetry of Figure 25B, the SPR is distinguishable as the region of maximum relief trending N70°E. It can be traced from
Figure 25A: GLORIA imagery across the South Pandora Ridge. Near the middle of the figure, the profile crosses the ridge which is marked by a zone of ENE trending lineaments with little volcanic activity. Note that GLORIA imagery is the reverse of SeaMARC II imagery in that reflective areas appear white.
GLORIA Imagery of the SOUTH PANDORA RIDGE
Figure 25B: Bathymetry of the South Pandora Ridge in the area that was partially imaged with GLORIA. The location of the seismic profile of Figure 31A is indicated by the dashed line.
the northeast corner of the figure into the GLORIA survey area on the basis of its morphology, passing through a few small basins reaching deeper than 4000 m. These basins are arranged in a relay pattern and have the same ENE trend as the SPR.

Figure 26 shows a geological interpretation of the GLORIA imagery. The N70°E trend of the escarpments which is interpreted to be the center of the SPR occurs in the middle of the swath. About 169°45'E, the escarpments have widely varying trends. This may be due to the proximity of the New Hebrides Arc and the Jean Charcot Troughs. Also indicated are a few isolated volcaniform features.

Superimposed on this interpretation are the locations of dredge samples and sediment cores recovered during previous cruises. A short distance to either side of the SPR, free fall cores recovered more than a meter of light brown calcareous mud (Kroenke et al., in press). Dredges recovered altered basalt and lithified mudstone (Sinton et al., in press). Although most samples suggest that this area is relatively old, some volcanic activity has occurred recently. One dredge haul at 172°E recovered very fresh looking basalt identified as a transitional tholeiite Sinton et al. (in press). Bottom photographs have also shown that recent volcanism has occurred (Kroenke et al., in press).

Nagumo et al. (1975) reported very intense microearthquake activity in the area based on a single OBS station located at 15°01'S, 172°25'E. Although exact epicenter positions could not be obtained, using the difference in arrival times of P and S waves, they could
Figure 26: Geological interpretation of the GLORIA swath showing trend of escarpments and the locations of previously recovered bottom samples. Dashed line shows the trend of the South Pandora Ridge through the area. Dashed circles within the imaged area demarcate volcaniform features. Dredge RD19 recovered very fresh basalt from the SPR.
narrow down the epicenters to within a 50 km radius from the station. These events, therefore, could have occurred either on the SPR or on the northern limb of the triple junction. Hamburger et al. (in press) using a seismic network on Fiji, reported six strike slip focal mechanisms from the area but the fault plane solutions were oblique to the strike of the SPR.

SeaMARC II Side Scan Imagery and Bathymetry

SeaMARC II imagery and bathymetry of the eastern end of the SPR reveal recent volcanism and faulting (Figures 27 and 28). Recent volcanic activity characterizes the SPR in the western half of the survey (Figure 27). The dark pattern in the imagery is produced by 2 large volcanic fields comprising numerous satellite cones and associated lava flows. Their appearance in the imagery is similar to that of the volcanic field described in chapter 2. Areally extensive lava flows can be traced to their source vents as at 13° 37'S, 173° 34'E. The individual volcanoes and flows occur on two active or recently active volcanic edifices reaching depths shallower than 1600m and 1400m (Figure 28). To the north, a third edifice reaching 1400 m occurs at 13° 15'S, 174° 05'E, is covered by sediment and is relatively older. It is also separated from those volcanic fields to the south by a southward-dipping, large offset normal fault. East-west striking lineaments occur to the north and south of the volcanic edifice.

Steep escarpments bounding a deep trough define the SPR in the eastern half of the survey. The highly reflective lineaments in
Figure 27: SeaMARC II side scan imagery from the South Pandora Ridge. Numerous volcaniform features are common in the western half of the survey while several large escarpments occur in the eastern half.
Figure 28: SeaMARC II bathymetry of the South Pandora Ridge.
The western half has large volcanic edifices and the eastern half has large steep escarpments.
the imagery (Figure 27) correspond to the high angle, anastomosing escarpments evident in the bathymetry (Figure 28). The trough is oriented roughly east-west and reaches depths greater than 4600 m. Volcaniform structures occur here but are probably older based on their appearance in the imagery.

Figures 29 and 30 shows the SeaMARC II imagery and bathymetry of the northern flank of Cakabau seamount (named during the cruise) located along the TR ridge axis. The center of this seamount is located at 13° 37'S, 175° 53'E. A few small offset escarpments occur north of the seamount and have a N60°W trend but for the most part, the seafloor surrounding this seamount has little relief and is covered by sediment. The most prominent features in the imagery are the dark, recent lava flows and numerous small satellite craters surrounding the main volcanic edifice.

Seismic reflection data

Seismic reflection profiles from various cruises reveal the variable structure exhibited along the SPR and the TR. Profile A-A' (Figure 31A) was obtained along the length of the GLORIA track (Figure 25) and shows the structure of the SPR at its western end. The SPR is marked by a great number of escarpments having various offsets and occurring across a wide zone. Localized areas of sediment accumulation occur along the length of the profile, and even within the SPR, but are thicker and more prominent away from the it. Because of the New Hebrides Arc's proximity, the
Figure 29: SeaMARC II side scan imagery of the northwestern flank of Cakabau Seamount. Summit is located at 13° 35'S, 175° 54'E. Numerous volcanic craters occur on the flanks of the seamount while away from the edifice, sediment and older structures are observed.
Figure 30: SeaMARC II bathymetry of the northwestern flank of Cakabau Seamount. Contour interval is 100 m. The seamount rises more than 2500 m above the seafloor.
Figure 31A: Interpretation of a single channel reflection profile over the South Pandora Ridge. High relief and areas of thick sediment accumulations typify this area. Location is shown in Figure 25B.
Figure 31B: Interpreted seismic reflection profile across the Tripartite Ridge. The location is shown in Figure 24.
sediment cover at the western end of the profile is probably made up of arc-derived volcanics as well as pelagic sediment. The eastern end is predominantly pelagic sediment.

Profile B-B' (Figure 31B) is an interpreted record across the TR near Cakabau Seamount. The TR appears to be a nascent rift in this profile. Two high ridges labelled rift flank uplifts are symmetrically placed about a central ridge. Sediment thicknesses more than 200 m are seen outside of these ridges and significant sediment accumulations occur within the rift as well. There is no observable sediment at the center of the ridge.

Gravity

The free air gravity anomaly map over the region is given in Figure 32. The SPR is marked by high amplitude anomalies with lows centered over the troughs occurring on the axis. These are the grabens that Kroenke et al. (in press) interpreted as indicating that the SPR is an incipient rift. The trend of these anomalies correspond to the trend of the basins and not the SPR itself. To either side of the SPR are very low amplitude anomalies indicative of the low relief associated with the older parts of the basin. At the western end of the SPR (left hand side of Figure 32), the anomalies become gradually more subdued and around 171°E become indistinguishable from the surrounding seafloor anomalies. The troughs also cease here. Similarly, there is a change in character around 175°E where the SPR and TR meet. The strong, high amplitude anomalies apparently cease eastward of this point.
Figure 32: Free air gravity anomaly map over the northern North Fiji Basin. The SPR is marked by high amplitude anomalies and by prominent lows coinciding with the graben structure. In contrast, the TR does not have much of a signature. The location of the SeaMARC surveys are indicated by the dashed lines while the GLORIA survey is indicated by the dotted line.
Free Air Anomaly
Over the TR (Figure 32) there are no high amplitude anomalies, but this may be due to the sparse data set. Cakabau seamount occurs at 176°E and is the most notable feature on the TR. The prominent low occurring at 175°E is the result of the deep trough visible in Figure 28 and marks the eastern termination of the SPR. Generally, however, the TR does not have a notable gravity signature.

Discussion

Activity along the SPR and TR

The data presented here confirm that the SPR is currently tectonically active. This is in agreement with the results of earlier workers (Chase, 1971; Macdonald et al., 1973). At its western end, it is marked almost exclusively by highly faulted terrain. Steep escarpments and high relief typify its morphology (Figures 25 and 31A). Between 171°E and 173°E, the SPR is marked by deep graben structures containing some recent volcanics. However, thick sediment accumulations are common in this region suggesting that it is an older part of the basin. At the eastern end, the SPR is marked by some volcanism and faulting. About 174°E, it intersects the Rotuma Ridge and the TR which has a trend of ESE.

In its central and eastern portions, the SPR bears more resemblance to an incipient rift than it does to a transform fault. In fact, in many ways it is morphologically similar to the northern limb of the triple junction (chapter 2). Steep escarpments, offset deep
grabens and recent volcanism characterize both. At its western end, the escarpments all have approximately the same N70°E trend as the grabens of the SPR. Just as the northern limb is believed to be propagating northward, it is possible that the SPR is propagating westward.

The nature of the activity on the TR is more problematic however. Based on the seismic reflection profiles and the SeaMARC II results, it is clear that some recent volcanism has occurred there. This is in accordance with the results of Malahoff et al. (in press) who reported high amplitude magnetic anomalies. East of 176°E, however, there is no strong evidence for recent activity. Activity along the TR is limited but may be produced by the same mechanism causing activity along the SPR. The precise location of the Pacific Plate’s southern boundary is uncertain north of the Fiji Platform. Recent GLORIA work from the area shows that the Fiji Transform Fault does not extend as far as the northern Tonga Trench (Hughes-Clark et al., in press). Instead, the northern Lau Basin contains several complex spreading centers with various orientations. The connection between this area and the fault is not certain. However, it is certain that the complex ridge system extends from the Lau Basin to north of the Fiji Platform.

Development of the North Fiji Basin

This and previous chapters have detailed the complex structural history of several parts of the basin. In all of these places
there is evidence of ongoing changes in orientation and location of the tectonic elements.

At the triple junction in the central part of the basin, there has been a recent change in the location of the three limbs of the triple junction. The northern limb is now propagating northward through older crust. The eastern limb extends a short distance away from the triple junction and is now or soon will be connected to the Fiji Transform Fault. The southern limb moved from a north-south orientation to a slightly northeast orientation. These changes probably occurred within the past 1 Ma.

Along the Fiji Transform Fault, there is evidence that it has progressively changed from a northeast trend to an east-west trend. One of the spreading segments situated within an offset in the fault trace appears to have propagated into the Fiji Platform and "flaked" off a portion of it. Other shallow ridges in the area probably formed in a similar fashion.

The SPR appears to be quite young and forming within a much older part of the North Fiji Basin. Parts of the SPR exhibit rift morphology and recent volcanism. Other places show faulted seafloor with very high relief but no volcanism. Thick sediment occurs in many places along the SPR. Similarly, the TR shows some volcanism and rift-like morphology but these are much less marked than on the SPR.

From these observations, we may construct a model for the opening of the North Fiji Basin. From paleomagnetic evidence (Musgrave, pers. comm., 1990) and from the timing of volcanism on
Fiji and the New Hebrides (Kroenke, 1984), it appears the basin began forming between 8 and 10 Ma. It formed when backarc rifts of the newly formed New Hebrides Subduction Zone began rifting apart the pre-existing Vitiaz Arc. Figure 33A schematically depicts this phase with the solid double line representing nascent rifts. The history of tectonic activity of the Vitiaz Arc is disputed (see Kroenke (1984) and Gill (1987) for a useful review of ideas), but it had been inactive for some time prior to the formation of the New Hebrides Arc. Portions of this ancient arc are preserved in the New Hebrides (Carney and Macfarlane, 1982) as well as in the modern, inactive Vitiaz Arc at the northern end of the basin.

When the Lau Basin began opening between 5 to 7 Ma, the limbs began to change in response to the new orientation of the New Hebrides Arc and the rotation of Fiji (Figure 33B). At this point, seafloor spreading is occurring along organized spreading centers and magnetic anomalies are easily identified from many parts of the basin. This triple junction was the precursor of the present triple junction. The magnetic anomalies from the northeastern part of the basin are highly complex and not easily correlatable. This northeastern limb extended north of the Fiji Platform but this area soon began to undergo shearing and the development of the Fiji Transform Fault.

As the rotation of the New Hebrides Arc continued, the limbs began to change in response to the arc's new orientation (Figure 33C). The Fiji Transform Fault is active at this point. Although depicted in the figure as a straight through-going fault, it probably
Figure 33: Schematic illustration showing the development of the North Fiji Basin. A: The NFB began opening soon after the formation of the New Hebrides Subduction Zone. B: Soon after this, the Lau Basin began opening and a three limbed triple junction is active. C: As the opening proceeds, the northeastern part of the basin becomes dominated by shearing motion rather than extension and Balmoral Ridge is separated from the Fiji Platform.
Figure 33: (D) Spreading in the northwestern part of the basin becomes inactive. (E) Orientation of the spreading centers rotates and Braemar Ridge becomes separated at this time. The Viwa Rift has formed by this period also. (F) The present configuration of the North Fiji Basin.
was nowhere near being so ideal. Small, localized areas of extension occurred within the principal displacement zone of the fault. These contributed to the present complex magnetic signature of the area as well as facilitating "flaking off" parts of Fiji. Balmoral Ridge separated from the Fiji Platform about this time and was transferred to a different microplate on the opposite side of the fault.

Subsequent to this, the spreading center in the northwestern part of the basin began to die (Figure 33D). The oldest anomaly recognized from this part of the basin dates the area at about 2 Ma. Also at this point, the Viwa Rift had just begun forming. The southern limb of the triple junction has changed orientation somewhat.

Figure 33E depicts the configuration of the basin at approximately 1 Ma. The Viwa Rift is now well established. The Fiji Transform Fault has changed orientation from trending northeast to become more nearly east-west. In the process of changing, Braemar Ridge has separated from the platform and the predecessors of the present ERZ A and B were active. In the central part of the basin, the southern limb has changed orientation to become north-south. It is joined to proto-FTF by a short extensional segment, namely the volcanic field discussed in chapter 2.

The present configuration developed soon after this (Figure 33F). In the northern part of the basin, the SPR has become active. The northern limb has begun rifting in a new location but its northern termination does not extend as far as the SPR itself.
Presumably this is a temporary condition. The southern limb has changed orientation to slightly northeast although further south along its axis, its trend has remained north-south. The connection between the eastern limb and the Fiji Transform Fault is uncertain. The Bligh Ridge has recently become detached from the Fiji Platform.

This model describes a great number of the features present in the North Fiji Basin. Furthermore, it does so without having to rely on highly episodic activity occurring throughout the basin. Through a continuing pattern of reorientation, a few tectonic elements have produced the complex structural configuration of the North Fiji Basin.

**Conclusions**

1) Tectonic activity continues on the SPR and the TR from the Jean Charcot Troughs to at least 176°E. Activity is characterized by widespread faulting and localized areas of volcanism.

2) The SPR shows strong indications of being an extensional boundary. Normal faulting predominates along its length.

3) The FTF had long been the boundary of the Pacific Plate but following the recent spreading reorganization, the SPR and the TR are now the present boundary.

4) The North Fiji Basin developed through a continuing process of rotation of its major tectonic elements. Throughout the development of the basin, these elements have changed orientation and varied in their levels and types of activity. However, other
parts of the basin were relatively stable while the activity on these elements continued.
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