Shallow Seismicity and the Classification of Structures in the Lau Back-Arc Basin

A. T. Baxter¹, M. D. Hannington¹,², M. S. Stewart¹,³, J. M. Emberley¹, K. Breker¹, A. Krätschell², S. Petersen⁶, P. A. Brandl², M. Klischies², R. Mensing¹,², and M. O. Anderson⁴

¹Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada, ²GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, ³Department of Earth and Environmental Sciences, Mount Royal University, Calgary, Alberta, Canada, ⁴Department of Earth Sciences, University of Toronto, Toronto, Ontario, Canada

Abstract Back-arc basins open in response to subduction processes, which cause extension in the upper plate, usually along trench-parallel spreading axes. However, global seismic databases reveal that the majority of seismic events in the Lau Basin occur along transcurrent (strike-slip) rather than extensional faults. To better characterize active deformation in this region, we compared centroid moment tensors (CMTs), calculated for large (Mw > 5), shallow (<30 km) seismic events, to the orientations of seafloor lineaments mapped throughout the Lau Basin. Ship-based multibeam and satellite altimetry were combined with vertical gravity gradient data to create the lineament map. By comparing the possible focal planes of the CMTs to the orientations of the lineaments, the most likely fault plane solutions were selected, thus classifying the faults and establishing the nature of the highly variable stress regimes in the basin. We resolved the strike, dip, and dip direction of 308 faults and classified 258 additional structures by fault type. The analysis highlights a stress regime that is dominated by a combination of left-lateral and right-lateral strike-slip faults, large-scale transcurrent motion along rigid crustal-scale fault zones, and nonrigid diffuse deformation along preexisting seafloor structures, with extension mainly limited to the tips of propagating rifts and spreading centers. By resolving many of the uncertain motions on the mapped lineaments of the Lau Basin, the CMT analysis addresses a number of questions concerning basin-scale stress regimes and microplate development, complementing GPS measurements, and providing a more complete picture of the complexities of back-arc basin development.

Plain Language Summary The tectonics of back-arc basins are commonly viewed as a response to rollback of a subducting slab beneath a volcanic arc, with basin opening caused by simple rifting and accretion at a back-arc spreading center. However, detailed analysis of seismicity in the Lau Basin shows a much more complicated history of evolving stress regimes and deformation, with unexpectedly few recently active extensional faults. Instead, both rigid and nonrigid deformation are dominated by strike-slip faulting in response to strong curvature of the trench and widespread microplate and block rotation. The resulting pattern of deformation has significant implications for large-scale crustal permeability and the distribution of magmatic and hydrothermal systems.

1. Introduction

Early plate tectonic theory considered that all plates are rigid and their boundaries narrow (Morgan, 1968; Wilson, 1965). However, some global plate boundaries exhibit mainly diffuse deformation (Gordon, 1998; Gordon & Stein, 1992; Kreemer et al., 2014). Diffuse deformation is particularly evident at curved subduction zones, where tensile stresses promote fragmentation of the upper plate, the development of triple junctions, and the emergence of new microplates (Mallard et al., 2016). Back-arc basins behind curved trenches are subject to both rigid and nonrigid deformation and are inherently unstable. Nonrigid deformation manifests as transform zones at overlapping spreading centers (Hey et al., 1986) and internal deformation or buckling (Gordon et al., 1998; Rangin, 2016), with strongly partitioned seismicity (Engeln & Stein, 1984; Hey et al., 1986). The kinematics of both nonrigid and rigid deformation also has significant implications for the distribution of magmatic and hydrothermal systems, as new crustal-scale faults (e.g., microplate
boundaries) provide pathways for melts and fluids to reach the surface (Hannington et al., 2005). A more rigorous classification of the plate boundaries in a microplate mosaic can help to identify the most likely locations of these pathways. However, the particular stress regimes that lead to the emergence of these structures are difficult to determine, because seismic data alone cannot fully resolve the types of faulting. Here, we combine the data from recorded earthquakes with careful mapping of lineaments in the Lau Basin to better classify the fault architecture at regional and local scales.

1.1. Lau Basin

The Lau Basin is the type example of an intraoceanic back-arc basin and has long been a natural laboratory to understand their evolution. The basin opened in response to rollback of the Pacific slab along the Tonga-Kermadec trench, which caused upper plate extension and eventual separation of the Lau-Tonga paleo-arc between 6 and 5.5 Ma (Hawkins, 1995; Taylor et al., 1996). Back-arc rifting began in the north (Parson et al., 1994) and propagated southwards, with active spreading in the wake of the propagating rifts (Figure 1). Important variations in forearc stresses may have controlled when and where rifting occurred, for example, compression caused by subduction of the Louisville Seamount Chain (Ruellan et al., 2003). Parson and Hawkins (1994) first proposed a model of diffuse strike-slip deformation dominating the Northern Lau Basin, with discrete spreading centers dominating in the south. Geophysical data, including magnetization and GPS measurements, confirm that typical seafloor spreading is occurring in the southern part of the basin, with a total opening rate of 174 mm/yr interpreted from magnetic data (Zellmer & Taylor, 2001) and between 159 ± 10 and 91 ± 5 mm/yr from GPS data (Bevis et al., 1995), decreasing from north to south. More recent studies have focused on understanding the microplate architecture (Conder & Wiens, 2011; Sleeper & Martínez, 2016; Zellmer & Taylor, 2001). However, different models disagree on the positions of the Euler poles and the spreading rates at different microplate boundaries. Some of the plate boundaries are difficult to define, such as the southern margin of the Niuafo‘ou microplate, where there is a lack of seismicity and no clear surface expression of deformation. This has made it difficult to reconcile different estimates of the strain, from 40 mm/yr estimated by Zellmer and Taylor (2001) to as little as 10 mm/yr estimated by Sleeper and Martínez (2016). While the margins of the Niuafo‘ou microplate are still coming into focus (e.g., Conder & Wiens, 2011; Sleeper & Martínez, 2016), in the Northern Lau Basin, numerous other proposed microplate (or nanoplate) boundaries are still largely undefined (Bird, 2003; Conder & Wiens, 2011; Pelletier et al., 2001; Wiens et al., 1995). Focal mechanisms of shallow crustal earthquakes are among the few reliable indicators of the stress regime of the upper lithosphere that can help to resolve these boundaries (Célérier, 2010). Teleseismic data have been analyzed extensively to resolve the deformation and stress history of the Lau Basin (Eguchi et al., 1989; Hamburger & Isacks, 1988; Isacks et al., 1968; Sykes, 1963), highlighting multiple stress regimes with highly variable extension along spreading axes and diffuse or shear-dominated deformation elsewhere. In this study, we examine the global earthquake database and link the recorded motions to observed seafloor structures in order to better understand these relationships.

2. Data and Methods

The movement on a fault during an earthquake can be expressed as a centroid moment tensor (CMT), which represents the magnitude and direction of stress focused on the fault plane. Interpreted motions on three orthogonal axes, $P$ (pressure or compression), $T$ (tension or dilatational), and $N$ (null) identify different types of faulting (e.g., normal dip-slip, strike-slip, and reverse-slip). A complication is that solutions to the orientation and dip of the ruptured surface are nonunique (Figure 2). Additional steps, including inversions of after-shock distribution (Bonnardot et al., 2007), reprocessing seismic wave data to produce higher-degree moment tensors (Dahm & Krüger, 1999), or comparisons with other stress data (e.g., World Stress Map; Heidbach et al., 2010, 2018), can improve the interpretation of the focal mechanisms but cannot distinguish between the two possible focal planes in the CMT. To do this, geological data from the location of the earthquake, such as the orientations of principal structures at the seafloor, are needed to interpret the fault plane solutions. Often, it is not possible because the seafloor structure has not been adequately mapped.

2.1. Mapped Lineaments

We mapped more than 4,000 lineaments in the Lau Basin, which have been manually interpreted and digitized at 1:100,000 to 1:200,000 and assembled in ArcGIS at 1:1 million (Figure 3). The lineaments were
Figure 1. Bathymetric map of the Lau Basin, showing the microplate boundaries and active spreading centers of Bird, (2003). Also shown are the proposed microplate boundaries of Conder and Wiens (2011) and other regional features. GPS velocities (mm/yr) and azimuths (white arrows) are shown for the Tonga Plate, with Australia fixed (Phillips, 2003). Spreading rates (mm/yr) and spreading vectors (green arrows) for the Rochambeau Riffs (RR) and the Northwest Lau Spreading Center (NWLS) are from Lupton et al. (2015), following Bird (2003). Spreading rates for the Central Lau Spreading Center (CLSC), Fonualei Rift and Spreading Center (FRSC), Eastern Lau Spreading Center (ELSC), Valu Fa Ridge (VFR), Mangatolu Triple Junction (MTJ), and the Northeast Lau Spreading Center (NELSC) are from Sleeper and Martinez (2016) and Baker et al. (2019). The spreading rate for the Futuna Spreading Center (FSC) is from Pelletier et al. (2001). CLNP = Central Lau Nanoplate (Conder & Wiens, 2011); PR-LETZ = Peggy Ridge-Lau Extensional Transform Zone. Inset globe shows the position of the Lau Basin in the SW Pacific.
We selected lineaments that correspond to the topographic expressions of faults or ridges formed by magmatic and/or tectonic processes, avoiding other features that are clearly a product of erosion (e.g., channels on the flanks of volcanoes). Profiles were drawn across the lineaments to visualize their geometry. Faults commonly have asymmetric profiles with a constant slope, representing the fault scarp, while volcanic ridges have symmetric profiles. Faults were drawn along a line corresponding to the intersection of the hanging wall with the footwall; volcanic lineaments were drawn along the axis of the ridges. The minimum length of a mapped feature is 500 m; the average length is ~10 km. Throughout most of the back-arc region, the mapped lineaments define a clear spreading fabric, as on mid-ocean ridges (MORs: Macdonald, 1982), with longer and deeper faults at slow spreading centers and active fissures along the spreading axes. Seafloor volcanism, in the form of cones and vents, partly obscures some structures, but typically, the faults or fissures on which the volcanoes have developed can still be mapped (Macdonald, 1982). The depths to which the faults penetrate are difficult to determine, but we assume that fault depth is roughly proportional to the fault length (cf. Nur, 1992).

2.2. CMT Data

The CMT data used in this study are from the open-source Global Centroid Moment Tensor (GCMT) project (www.globalcmt.org; accessed October 2018), which contains data for 49,525 earthquakes that occurred over 42 yr, between the 1 January 1976 and the 31 December 2017 (Dziewonski et al., 1981; Ekström et al., 2012). The database contains moment tensors mostly for earthquakes with Mw > 5.0 with calculated values for the strike, dip, and rake of the two focal planes and an estimate for the focal depth. A subset of the GCMT database east of 180° longitude (east of Fiji), south of 14°S, and north of 26°S was imported into ArcMap (Esri, Version 10.6.1) for analysis. The 20- to 40-km slab depth contours of Hayes et al. (2018) were used for the eastern boundary of the study area, thus avoiding CMTs located on the downgoing Tongan slab that would otherwise interfere with earthquakes on the upper plate (the focus of this study). Elsewhere, earthquakes with depths of >30 km were also excluded. The final subset of 692 CMTs was constructed using the ArcBeachball tool (v2.2) in ArcMap, for comparison with the mapped seafloor lineaments.

2.3. Assigning CMTs to Lineaments

In a previous study, Hamburger and Isacks (1988) used the focal mechanisms of 51 earthquakes to propose that the Lau Basin was dominated by diffuse and mainly shear-related deformation rather than back-arc
spreading. Wetzel et al. (1993) used six CMTs to identify bookshelf faulting in the transfer zone between the Central Lau Spreading Center (CLSC) and the Eastern Lau Spreading Center (ELSC; Figure 1), and Sleeper and Martinez (2016) used the average extensional azimuth ($T$ axes) of 109 CMTs to document Riedel shearing along Peggy Ridge (PR) and adjacent axial volcanic ridges (AVRs). We have used a much larger subset of the GCMT database to classify mapped lineaments across the entire basin.

Lineaments above earthquake hypocenters are assumed to align with, but not necessarily connect to, deeper and similarly orientated structures on which the earthquakes occurred. This assumption is supported by the highly planar nature of strike-slip faults (e.g., Abercrombie & Ekström, 2001), which dominate much of the mapped area. We classified the faults by visually matching one of the focal planes of the CMTs with the orientations of the nearest mapped surface lineaments. However, individual lineaments along which the earthquake occurred could not be identified, owing to the errors associated with locating earthquake hypocenters (e.g., Hejrani et al., 2017; Hjörleifsdóttir & Ekström, 2010; Pan et al., 2002; Valentine &

Figure 3. Map showing the locations of 4,000 digitized lineaments (minimum 500-m strike length) mapped at a 1:100,000 to 1:200,000 and assembled in ArcGIS. These data are compared to the focal planes of centroid moment tensors to derive the fault motions. More than 580,000 km$^2$ of the map area was inspected, including 140,000 line-km of ship tracks.
Trampert, 2012; White et al., 2019). The maximum area of influence used in this study was 10 km from the location of the resolved CMT. The errors for the locations of the earthquake hypocenters were also taken into account, and these data are provided in the supporting information. A numerical filter was also considered (e.g., a cutoff based on a maximum deviation from the focal plane), but this tool is not currently available in ArcMap. By assigning one of the focal planes to nearby lineaments, we infer the type of faulting using the focal plane’s strike, dip, and rake values (Figure 2). If neither of the CMTs focal planes aligned to the mapped surface lineaments, then the CMT was classified as “unresolved”. In some instances, the CMTs were classified as “unresolved” due to the absence of mapped lineaments. This occurred in sedimented areas, where surface lineaments are presumably buried, or in areas with no ship-based bathymetry, where it was difficult to map surface lineaments accurately using the lower-resolution satellite altimetry data. The fault types and corresponding geometries used in the classification are shown in Figure 2e. The CMTs also provide the principal stress directions, including the maximum horizontal stress direction (SHmax), which approximates the orientation of σ1. Where multiple, similarly classified faults are identified, we define nonlinear groupings of similar strain as diffuse zones of deformation or poorly resolved plate boundary segments. Discrete deformation zones or plate boundary segments are defined as linear groupings of similarly classified faults, with little or no deformation observed on either side of the zone or segment. Another limitation is that the cutoff of Mw > 5 could omit many small earthquakes typical of normal faulting. Low-magnitude seismicity along active spreading centers in the Lau Basin has been recorded by ocean bottom seismometers (OBSs) (Eguchi et al., 1989; Conder & Wiens, 2011), and in general, these earthquakes are smaller than Mw = 5.

3. Results

Of the 692 CMTs examined, fault plane solutions were chosen for 308 CMTs where the strike of one of the focal planes clearly aligned with adjacent surface lineaments (Figure 4). In addition, 258 CMTs were classified by their rake values according to a fault type (e.g., normal dip-slip, reverse oblique-slip, and strike-slip), although a preferred fault plane solution could not be selected. The numbers of faults classified according to each type are indicated in Table 1, and their spatial distribution is shown in Figure 5. Overall, the faults in the Northern Lau Basin are dominantly strike-slip, consistent with the deformation reported in other studies (Heidbach et al., 2010, 2018; Pelletier et al., 1998; Wetzel et al., 1993). The movement on the faults is dominantly right-lateral in diffuse deformation zones and left-lateral along the prominent, crustal-scale plate boundary faults. In contrast, the southern Lau Basin has a larger proportion of normal faults, mainly adjacent to the Tofua Arc, some with a component of transtension. Immediately south of PR, the faulting is right-lateral strike-slip, whereas in the transfer zone between the CLSC and the ELSC, the faulting is left-lateral strike-slip.

Grouping similarly classified faults according to their location and proximity to known tectonic features (e.g., spreading centers, propagating rifts, and transform zones) provides a high-resolution image of the different stress domains (cf. “small areas” of Bonnardot et al., 2007). Four different domains or groupings of CMTs are defined in the Northern Lau Basin region (NE Fiji, Central Futuna, Northern Lau, NE Lau, and Tonga forearc: Figure 6). Equal area stereonets, displaying the poles to resolved CMT fault planes, as well as the maximum horizontal stress (SHmax) directions for these stress domains, are shown in Figure 7. Two stress domains are defined in eastern Lau Basin region (Northern Fonualei Rift and Spreading Center [FRSC] and Southern FRSC: Figure 8, with the associated stereonet data displayed in Figures 9a and 9b), two in the central Lau Basin (PR and Central Lau; Figure 10, with the associated stereonet data displayed in Figures 9c and 9d), and two in the southern Lau Basin region (Tofua and Valu Fa: Figure 11, with the associated stereonet data displayed in Figures 9e and 9f).

3.1. NE Fiji

Seismic activity in the NE Fiji domain (Figure 6) occurs along two major tectonic features: (i) the southward propagating Futuna Spreading Center (FSC) (Pelletier et al., 2001) and (ii) the Fiji Transform Zone, a crustal-scale plate boundary just north of the Fiji Platform (Hughes Clarke et al., 1993; Jarvis & Kroenke, 1993; Ruellan & Lagabrielle, 2005). There are 55 CMTs in this area: 25 are correlated with seafloor lineaments, 25 are classified by general fault type and provide general faulting information, and 5 are unresolved. Six left-lateral strike-slip faults are located along the Fiji Transform Zone and have an average strike of 280° and an average dip of 83°. Eight faults are right-lateral, NW-SE-oriented strike-slip faults, subparallel...
to the FSC (Figure 6) and likely formed along the FSC, which has been active since 4.5 Ma (Pelletier et al., 2001). These right-lateral faults appear to be controlled by the same stresses, as indicated by the relationship of SHmax to the plotted poles in the NE Fiji stereonet (Figure 7a). Sleeper and Martinez (2016) proposed that an ESE-trending plate boundary structure extended from the intersection of the Fiji Transform Zone and FSC to PR. Our analysis confirms that an active, crustal-scale strike-slip fault is forming in this region, with one fault clearly identified as left-lateral (Figure 6).

### Central Futuna

The area surrounding the central Futuna Plate of Pelletier et al. (2001) and Bird (2003), including the northern termination of the Northwest Lau Spreading Center (NWLSLC: Figure 6), contains 64 CMTs: 18 are correlated with mapped lineaments, 35 provide general faulting information, and 11 are unresolved (Figure 6). Four of the classified faults occur along the Futuna Deformation Zone (Regnier, 1994) and appear to have transported oceanic crust to the surface to form the Futuna Islands. The poles of the fault planes lie within the dominant SHmax orientation, consistent with a mechanism for thrust faulting (Figure 7b). A group of strike-slip faults, located to the northeast of the NWLSLC, where it intersects a large volcanic zone, could not be correlated with surface lineaments because of the lack of

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**Table 1**

| Fault Classification Scheme Used in This Study, Based on Analysis of Centroid Moment Tensors (CMTs) |
|-------------------------------------------------|
| **Total database** |
| CMTs assessed in the Lau Basin | 692 |
| CMT unresolved | 126 |
| CMTs classified by fault type | 566 |
| Classified by general fault type | 258 |
| Strike-slip | 190 |
| Reverse oblique-slip | 5 |
| Reverse dip-slip | 19 |
| Normal oblique-slip | 21 |
| Normal dip-slip | 23 |
| Classified by specific fault type | 308 |
| Left-lateral strike-slip | 93 |
| Right-lateral strike-slip | 139 |
| Reverse right-lateral oblique-slip | 10 |
| Reverse left-lateral oblique-slip | 6 |
| Reverse dip-slip | 6 |
| Normal right-lateral oblique-slip | 18 |
| Normal left-lateral oblique-slip | 11 |
| Normal dip-slip | 25 |
Figure 5. Map of the entire Lau Basin showing the locations of 692 centroid moment tensors (CMTs) inspected in this study. The compression quadrants of the CMTs are color coded according to the fault types in the key. The identified fault types correspond to the focal planes of the CMT that are most closely aligned to the mapped lineaments. Where no clear focal plane was selected, a general fault type was assigned using the rake values of the two focal planes. CMTs and the $S_{H\text{max}}$ orientations (short black lines) are plotted using the ArcBeachball tool (v.2.2).
bathymetric data in this area. The center of the Futuna microplate (Bird, 2003; Pelletier et al., 2001), in the area referred to by Arculus (2012) as the Central Futuna Zone, contains several CMTs that correspond to structures identified as strike-slip faults (in orange), with three right-lateral strike-slip faults to the north. Volcanic ridges within the plate are oriented parallel to the S\textsubscript{Hmax} (NE-SW) calculated for the CMTs, whereas the Central Futuna Zone is oriented N-S. This is similar to the geometry of the AVRs that define the active plate boundary south of PR (Sleeper & Martinez, 2016: see section 3.1.7).

3.3. Northern Lau

The Northern Lau Basin, between the Rochambeau Rifts (RR) in the west (Arculus, 2008), the Northeast Lau Spreading Center (NELSC) in the east (Deschamps & Lallemand, 2003), and the Mangatolu Triple Junction (MTJ) in the southeast (Hawkins et al., 1994), together contain 199 CMTs: 73 can be assigned to seafloor lineaments, 103 provide general faulting information, and 23 are unresolved. The classified faults fall into three main groups: (i) left-lateral strike-slip faults along crustal-scale fault boundaries, (ii) right-lateral strike-slip faults on NE-SW-oriented structures that were originally formed at spreading centers, and (iii)
a series of extensional faults on the northern side of the WSW-ESE-trending rift identified within the Futuna Plate (Bird, 2003; Pelletier et al., 2001). Poles to the fault planes of these three groups are shown in Figure 7c. The majority are right-lateral strike-slip faults, particularly along spreading ridge structures in the east that formed at the NELSC (Figure 6). Although the NELSC is an active spreading ridge, significant right-lateral strike-slip faulting is evident in close proximity to the spreading axis where normal faulting would be expected, but it is not recorded in the GCMT database. Extensional faulting is more obvious in a structure within the RR, which is approximately 50 km long and has undergone both normal dip-slip and normal oblique right-lateral strike-slip movement based on the faults classified in this study. To the north, left-lateral strike-slip faults define a zone of deformation that runs parallel to the northern margin of the Lau Basin, and this is interpreted to be the active plate boundary (Hamburger & Isacks, 1988). The faults in this deformation zone dip to the south at an average of 78° (n = 14). Near the island of Niuafo’ou, there is a cluster of CMTs, which suggests that an emerging plate boundary is forming in a geometry similar to that proposed by Conder and Wiens (2011), with a zone of intense deformation to the west of the MTJ now acting as a left-lateral structure and connecting to active faults close to Niuafo’ou Island. These faults also connect to strike-slip faults to the east of the RR (Figure 6).

Figure 7. Equal area stereonets of the stress domains indicated in Figure 6: (a) NE Fiji, (b) Central Futuna, (c) Northern Lau, and (d) NE Lau and Northern Tonga Platform. Poles to the fault planes are plotted colored according to fault type. Rose diagrams in the center of the stereonets show the dominant SHmax orientations of the CMTs within each stress domain.
3.4. NE Lau and Northern Tonga Platform

The NE corner of the Lau Basin is dominated by the NELSC in the west and the northern termination of the Tonga Platform in the east. This area includes the Mata volcanoes (Resing et al., 2011) and the northernmost active volcano of the Tofua Arc (Niua) (Figure 6), both of which appear to have erupted onto extended arc or forearc crust. The area contains 45 CMTs: 10 that can be assigned to seafloor lineaments, 11 that provide general faulting information, and 24 that are unresolved. The northernmost CMTs indicate both left-lateral strike-slip faults and steeply dipping normal dip-slip faults. However, the intense deformation and fragmentation in the region makes it difficult to resolve all of the CMTs. The dominant normal faults are associated with the Mata volcanoes and record the oblique extension of the arc crust east of the NELSC. There is an

Figure 8. (a) Close-up of the eastern Lau Basin showing the locations of 49 centroid moment tensors (CMTs) inspected in this study. Groupings of CMTs that correspond to different stress domains are outlined: (A) Northern FRSC and (B) Southern FRSC. The plate boundaries are according to Bird (2003). The CMTs are colored using the classification scheme in Figure 5. Faults classified only according to general type are semitransparent. (b) Summary structural map with the mapped lineaments in the background. The plate boundary segments are color coded using the classification scheme in Figure 6. The diffuse deformation zones are highlighted as semitransparent polygons. FRSC = Fonualei Rift and Spreading Center; FRSC-PT = Fonualei Rift and Spreading Center propagating tip; MTJ = Mangatolu Triple Junction; NELSC = Northeast Lau Spreading Center. The Northern FRSC is dominated by strike-slip faulting, while the Southern FRSC is dominated by extension at the propagating tip.
abrupt change in the density of CMTs south of the Matas, which corresponds to the northern termination of the Tonga Platform and Tofua Arc.

3.5. Northern FRSC

The CMTs at the northern termination of the FRSC record the propagation of the arc rift into the crust of the Tonga Platform and Tofua Arc (Zellmer & Taylor, 2001). Of the 12 CMTs in this small area, 3 can be assigned to mapped seafloor lineaments, including one right-lateral strike-slip and two left-lateral strike-slip faults, with 7 others providing general faulting information (Figure 8). Almost all of the CMTs are located to the north of the FRSC1 segment (Sleeper et al., 2016). One fault on FRSC1 is classified as a left-lateral strike-
slip fault, consistent with translation between the FRSC and the southern arm of the MTJ (Sleeper et al., 2016). The earthquakes in this area are located at the transition between thicker arc crust in the east and thinner back-arc crust in the west, where the Northern FRSC may eventually connect with the southernmost segment of the NELSC (Figure 8).

3.6. Southern FRSC

The central part of the FRSC and its southern termination (segments FRSC2 to FRSC6 of Sleeper et al., 2016), plus the adjacent Tofua Arc, contain 37 CMTs. Nine can be assigned to mapped seafloor lineaments, 17
provide general faulting information, and 11 are unresolved. A cluster of earthquakes along segment FRSC3 includes two normal dip-slip faults with dips of 54° and 61° to the west. At the southernmost propagating tip of the FRSC, six faults are classified as normal dip-slip, with one normal left-lateral oblique-slip fault. Four of the normal dip-slip faults are located near or within the FRSC, implying that they are actively extending structures. The poles of the normal dip-slip structures are symmetrical around the FRSC spreading orientation (roughly N-S), which corresponds to the S_{\text{max}} for the CMT events (Figure 9b). All but one of the classified faults dips toward the west or WNW. Normal faults are identified both southeast and southwest of the propagating tip of the FRSC, which suggests that a major crustal-scale structure or plate boundary may develop in this area. The lack of seismicity on eastward-dipping faults is perhaps also consistent with the FRSC being mainly in a stage of rifting and not yet active spreading. One possible

Figure 11. (a) Close-up of the southern Lau Basin showing the locations of 94 centroid moment tensors (CMTs) inspected in this study. Groupings of CMTs that correspond to different stress regimes are outlined: (E) Tofua and (F) Valu Fa. The plate boundaries are according to Bird (2003). The CMTs are colored using the classification scheme in Figure 5. Faults classified only according to general type are semitransparent. (b) Summary structural map with the mapped lineaments in the background. The plate boundary segments are color coded. The diffuse deformation zones are highlighted as semitransparent polygons. There is a zone of compression to the west of Tongatapu Island. Extension at the Valu Fa propagating tip (Valu Fa-PT) shifts to transtension to the southeast, adjacent to the active arc.
3.7. PR and Lau Extensional Transform Zone

PR is a pronounced, >200-km-long NW-SE-oriented ridge in the central Lau Basin (Bertine & Keene, 1975; Chase, 1971; Karig, 1970; Sclater et al., 1972). It has a rugged, irregular topography with volcanoes overlying linear peaks and troughs, consistent with a leaky transform zone (Parson & Tiffin, 1993). To the southeast of PR, there is a zone of left-stepping, en echelon AVRs, crosscut by strike-slip faults, belonging to the Lau Extensional Transform Zone (LETZ) (Figure 10: Sleeper & Martinez, 2016). There are 114 CMTs in this domain: 49 that can be assigned to mapped seafloor lineaments, 48 that provide general faulting information, and 17 that are unresolved. The majority of the classified faults are right-lateral strike-slip faults dipping to the southwest, with the poles clustering tightly 40° to the right of the dominant NNE to SSW S\textsubscript{Hmax} orientations (Figure 9c). The seafloor lineaments have two dominant orientations, one NW-SE, which is subparallel to the orientation of PR and the strike-slip faults in the LETZ, and a second orientated roughly N-S, including the AVRs of Sleeper and Martinez (2016) that likely formed along dilational structures at right angles to the minimum compressive stress direction. The focal planes of the CMTs align more closely to NW-SE strike-slip faults (identified as Riedel shears in Sleeper & Martinez, 2016) with the T axes, approximating the minimum compressive stress directions, at acute angles to the faults. We suggest that the dominant motions correspond to NW-SE right-lateral strike-slip faults rather than N-S normal faults, and the Riedel shears may be accommodating right-lateral translation along the LETZ plate boundary segment.

3.8. CLSC-ELSC Transfer Zone

The complex transfer zone between the CLSC and the northern termination of the ELSC southeast of PR contains 72 CMTs: 49 can be assigned to mapped seafloor lineaments, 18 provide general faulting information, and 5 are unresolved. The dominant fault type is left-lateral strike-slip, as previously documented by Wetzel et al. (1993), and concentrated in the southern and eastern parts of the transfer zone (Figure 10). The majority of the faults dip steeply to the northwest and the poles to the planes cluster approximately 30–45° to the left of the dominant S\textsubscript{Hmax} orientation (NNW-SSE: Figure 9d). The mapped structures define a curvilinear fabric that formed due to rotation as the CLSC has propagated south and overtaken the ELSC (Sleeper & Martinez, 2016). The large cluster of CMTs east of the CLSC was interpreted by Conder and Wiens (2011) as a possible solution to the missing strain between the Australian Plate in the west and the Tonga Platform in the east and possibly marking the southern boundary of the emerging Niuafo’ou microplate. However, there is a conspicuous seismic gap between the northeast corner of this stress domain and the propagating tip of the FRSC, which indicates that a plate boundary segment is not well developed in this region. The normal faults identified directly to the southwest of the FRSC propagating tip suggest that a plate boundary may develop here in the future.

3.9. Tofuа Arc

Near the island of Tongatapu, there are 37 CMTs corresponding to events between 10- and 30-km depth. Because of the lack of high-resolution bathymetry between the active arc and the Tonga trench, only half of the CMTs could be linked to mappable structures: 3 have been assigned to mapped seafloor lineaments, 15 provide general faulting information, and 19 are unresolved (Figure 11). A large number of the faults located close to active arc volcanoes are reverse dip-slip. Closer to the backarc, two left-lateral strike-slip faults are identified, but their significance is unclear.

3.10. Valu Fa

The southernmost tip of the Valu Fa Ridge (VFR) is similar to the FRSC in the north. This area contains 57 CMTs, of which 12 could be assigned to mapped seafloor lineaments, 34 provide general faulting information, and 11 are unresolved (Figure 11). The majority of the faults along the VFR are extensional, parallel to the dominant S\textsubscript{Hmax} direction of the CMTs, and dip toward the spreading axis. On the adjacent arc, to the southeast of the VFR, the faults shift from extensional to transtensional; however, normal faulting is also occurring near the arc as much as 80 km in advance of the propagating tip of the VFR.
3.11. Fault Density Maps

In this study, we resolved the strike, dip, and dip direction of 308 faults in the Lau Basin and 258 additional structures by fault type. The locations and density of similarly classified faults are shown in Figure 12. Using a grid size of 2.5 km and a search radius of 100 km, we contoured the density of similarly classified faults (number of faults per square kilometer). The maps show that most of the active faults lie on the plate boundary segments originally suggested by Bird (2003), but many of the areas of high-density faulting occur within microplates, indicating nonrigid diffuse deformation beyond the plate boundaries. The highest density of

Figure 12. (a–f) Density contours of faults in terms of identified faults per km$^2$, based on a 100-km search area. The highest densities correspond to regions of rigid or nonrigid deformation located along plate boundaries and within microplates. The plate boundaries of Bird (2003) are marked in red and purple.
faults corresponds to areas of major transcurrent faulting (LETZ and Northern Lau Basin). Areas with abundant transtensional faults (e.g., at the north end of the RR) correspond to the areas with the highest spreading rates (120 mm/yr). Another area of diffuse extension occurs where there is an abrupt change in orientation of the Tonga trench in northeast Lau. Along the Tofua Arc and in a zone around the island of Futuna are the highest densities of faults formed under compression. Although only faults associated with large magnitude earthquakes (Mw > 5) are included, the data show the remarkable heterogeneity and patchiness of the dominant stress regimes.

4. Discussion

Our analysis of the structure of the Lau Basin, incorporating all of the classified CMT data, the mapped lineaments, and the current understanding of plate boundaries and microplate dynamics, is summarized as a schematic model of deformation in Figure 13. The data agree well with global stress maps of this region that show the majority of the deformation in the back-arc is strike-slip (Heidbach et al., 2018), but also support more focused studies (Bonnardot et al., 2007; Conder & Wiens, 2011; Crawford et al., 2003; Sleeper et al., 2016; Sleeper & Martinez, 2014, 2016; Zellmer & Taylor, 2001), which highlight the complexity of the stress regimes in the Lau Basin. In particular, different types of faulting that were not previously classified inform the styles of plate deformation and the emergence of new plate boundary segments and microplates (discussed further below). Six different styles of deformation were identified: (i) extension along multiple back-arc spreading centers, (ii) transcurrent motion along crustal-scale fault zones, (iii) slab-induced extension in the forearc, (iv) rotation of crust and nonrigid deformation (i.e., bookshelf faulting), (v) arc rifting, and (vi) compression, including along the active arc front.

4.1. Extension Along Multiple Back-Arc Spreading Centers

Extension in the Lau Basin occurs along six different spreading centers (FSC, RR, NWLSC, NELSC, CLSC, and ELSC), two arc propagating rifts (FRSC and VFR), and one triple junction (MTJ) (Conder & Wiens, 2011; Zellmer & Taylor, 2001). The lack of seismicity associated with the spreading centers is partly due to the high spreading rates in some cases (e.g., along the ELSC), which are associated with lower magnitude earthquakes (<5 Mw; Macdonald, 1982). Data from OBSs (Eguchi et al., 1989; Conder & Wiens, 2011) and from land seismographs (SPASE array) on Tonga and Fijian islands (Wiens et al., 1995) have recorded lower magnitude seismic events, but there are no associated CMTs. More than 300 shallow earthquakes have been recorded in the LETZ at the southeastern end of PR and in the area north of the ELSC (Conder & Wiens, 2011), confirming significant earthquake activity with Mw < 5 in the central Lau Basin. However, this study suggests that normal faults may be widely reactivated as strike-slip faults particularly at the NELSC and in the transfer zone between the CLSC and the ELSC.

4.2. Transcurrent Motion Along Crustal-Scale Faults and Fault Zones

Three major, crustal-scale deformation zones in the Lau Basin are dominated by strike-slip motion: the Fiji Transform Zone in the west, the NW-SE oriented faults of the LETZ and PR (Bertine & Keene, 1975; Hamburger & Isacks, 1988), and a transform boundary encompassing the northern margin of the Lau Basin. We identify mainly left-lateral strike-slip faults along the main fault zone of the Fiji Transform. North of the transform zone, right-lateral strike-slip faults occur along reactivated spreading structures that were presumably formed along the FSC. Major left-lateral motion across the transform zone has resulted in right-lateral displacement of the smaller reactivated faults. The reactivation of normal faults, originally formed at a spreading axis, is similar to the mechanism proposed to explain deformation within the South Iceland Seismic Zone (Einarsson et al., 1981), at the 95.5°W Galapagos propagating ridge (Morgan & Kleinrock, 1991) and the Savanco fracture zone, offshore Vancouver (Cowan et al., 1986). In contrast, motion in the central Lau Basin is dominated by right-lateral motion along a short segment of PR and the LETZ. The LETZ is considered the active plate boundary, which connects PR to the CLSC (Sleeper & Martinez, 2016) and includes both extensional and strike-slip components, with extension accommodated by the AVRs south of PR. Our results indicate that the majority of the major earthquakes in this area occur along the Riedel shear structures as defined by Sleeper and Martinez (2016). Smaller, more frequent events (Conder & Wiens, 2011) are occurring along the AVRs, but they are not included in the GCMT database.
Figure 13. Revised structural model of the Lau Basin, showing previously proposed and potentially new microplate boundary segments and the main areas that are experiencing diffuse deformation. The structural map highlights where plate boundaries have yet to develop or may emerge in the future. The CMTs are synoptic examples for the different stress regimes, colored using the scheme in Figure 5, and the curved arrows indicate clockwise or anticlockwise rotation. Classifying faults by assigning CMTs to seafloor lineaments provides a method to characterize plate boundary segments in complex arc-back-arc systems where new microplates are emerging.
The northern margin of the Lau Basin is dominated by the transition from subduction to transform faulting. Here, a slab tear, which is manifested on the Pacific Plate as a Subduction-Transform Edge Propagator or STEP fault (Govers & Wortel, 2005), is causing significant internal deformation of the upper plate. This is evident in the region to the west of the NELSC as a diffuse deformation zone characterized by a high density of right-lateral strike-slip faults. The dynamics correspond to a ridge-trench-fault (RTF) triple junction, where the Tonga trench, transform fault, and the NELSC converge, similar to what has been proposed for the Southern Marianas (Martinez et al., 2018) and along the Matthew-Hunter Ridge to the south of the North Fiji Basin (Patriat et al., 2019). The current plate boundary in the north of the Lau Basin runs through an intensely deformed zone of forearc crustal blocks, dominated by left-lateral strike-slip faulting and extends to the northernmost RR. Counterclockwise rotation accommodates the left-lateral movement along the STEP fault as observed in other similar settings (Govers & Wortel, 2005).

4.3. Slab-Induced Extension in the Forearc

The mapped faults also highlight local extension of the forearc crust between the Vitiaz Fracture Zone, the Tonga trench, and the NELSC. This is the location of the Mata volcanoes, a group of volcanically active cones and ridges erupting onto the extended forearc crust (Embley et al., 2014; Resing et al., 2011). The classified faults in this area are primarily steeply dipping normal faults, but the complicated nature of deformation and active faulting suggests that crustal permeability must be high in this region, which is supported by the abundant hydrothermal venting observed (Baker et al., 2019). The region is further complicated by the change in orientation of the Tonga subduction zone and the close proximity of an RTF triple junction and a STEP fault (Govers & Wortel, 2005).

4.4. Rotation of Crust and Nonrigid Deformation

Wetzel et al. (1993) showed that (left-lateral) bookshelf faulting is an important mechanism to accommodate (clockwise) rotation of faults in the overlap zone between the CLSC and ELSC. Our analysis confirms that the mapped lineaments are best explained by left-lateral strike-slip faults, with clockwise rotation caused by strike-slip motion in the LETZ (Figure 10). The average dip of these faults is 76.6°, with dip directions mainly to the east. In the northeast Lau Basin, rotation by bookshelf faulting is also indicated by the prevalence of right-lateral strike-slip faults. Here, the rotation is anticlockwise, caused by the STEP fault to the north, which may have reactivated preexisting spreading structures as right-lateral strike-slip faults. Anticlockwise rotation and northwestwards extension at the NELSC results in shortening in the west, which may explain why there is a lack of extensional faulting throughout much of the Northern Lau Basin, except in the northern part of the RR.

4.5. Arc Rifting

The active arc is currently being rifted in at least two places: the southward propagating FRSC in the northeast and the Valu Fa Rift in the southeast. The CMTs within the FRSC correlate mainly with normal faults that are clearly related to the rifting. Two seismically active segments are observed: one in the central FRSC and the other at the propagating tip. The direction of propagation is ambiguous as normal faults are located to the southeast and southwest of the propagating rift tip. The faults that extend to the southeast may link with the Fonualei discontinuity (Bonnardot et al., 2007; see also Brandl et al., 2019). The faults that extend to the southwest of the rift tip, in the direction of the ELSC and CLSC, may be an indication of a new plate boundary fault system (Figure 8). The northern termination of the FRSC where it overtakes the SE arm of the MTJ appears to be propagating toward the southern tip of the NELSC; however, the absence of normal faulting at this location suggests a more complicated situation, dominated instead by strike-slip motion. The crust in this location is mapped as sedimented arc crust intruded by off-axis volcanoes (Mensing, 2019) and may be in excess of 25 km thick (which is inferred from the focal depths of the CMTs), and may be more difficult to rift than arc crust closer to the FRSC and VFR (e.g., Crawford et al., 2003). Identifying the precise location of the propagating tips is also complicated by the thickness of the crust, as observed in oceanic rift propagators (e.g., Hey et al., 1977). Remnants of arc crust located north of the FRSC1 segment also may contribute to the overall crustal thickness.

The southward propagating tip of the VFR is one of the few regions of shallow seismicity in the GCMT data set that is dominated by extensional faults. Seismicity is occurring in front of the propagating tip in older rifted back-arc crust (“ridges and knolls” region). The seafloor lineaments in this area are interpreted to...
be NNE-SSE-trending normal faults (Ruellan et al., 2003), although transtensional faulting is also recognized (Fujiiwara et al., 2001). Approximately 100 km to the southeast of the Valu Fa propagating tip, there is a conspicuous cluster of earthquakes in the CMT database along the active arc front that indicate both extensional and transcurrent motions. One possible explanation for these earthquakes is that they are precursors of a ridge jump as the VFR migrates south and east into the arc crust. Alternatively, upper plate extension may be related to the collision of the Louisville Seamount Chain with the Tonga trench (Ruellan et al., 2003).

4.6. Compression, Including Along the Active Arc Front

Several regions of compression are identified in the CMT data. The most obvious is along the active arc front west of the island of Tongatapu (Figure 11). The classified reverse fault dip direction is to the northeast, perpendicular to the convergence direction of the Pacific Plate. Active faulting may be related to magma emplacement along a preexisting plane of weakness or back-arc thrusting induced by forearc compression. Another region of compressional faults surrounds the island of Futuna (Figure 6). Here, reverse dip-slip faulting, previously recognized by Regnier (1994), appears to dominate. He suggested that these faults occurred within relay zones of the North Futuna Transform Zone (NFTZ). The average dip of the faults is 31° (n = 4), and the fault planes are orthogonal to the SHmax (Figure 7b), confirming that they are mainly low-angle thrusts. Accretion on the east side of the FSC may also induce oblique compression north of the deformation zone that has contributed to the uplift at Futuna Island.

4.7. Implications for Microplate Boundaries

Weissel (1977) first proposed that the Lau Basin contained three microplates, with a triple junction in the center of the basin. Subsequent studies have debated the number of plates, their dimensions, the location of the boundaries, and the plate boundary types. The presence of both rigid and diffuse deformation zones and numerous stress fields acting on the basin has further complicated previous interpretations, which can be broadly split into three models: (i) an oblique extensional system of intraplate deformation with no microplates (Hamburger & Isacks, 1988), (ii) a rigid microplate mosaic (Weissel, 1977; Zellmer & Taylor, 2001), and (iii) a diffuse plate boundary tectonic model (Bonnardot et al., 2007; Sleeper & Martinez, 2016). Our results are consistent with the structure of the Northern Lau Basin being controlled by both diffuse plate boundaries and intraplate deformation, whereas the southern Lau Basin is defined by more rigid plate and plate boundary processes. The northern region is dominated by shear stresses along major (rigid) crustal-scale faults and within-plate strike-slip faults that have reactivated spreading ridge structures, such as those formed along the NELS. The southern Lau Basin is controlled by more typical back-arc spreading extensional stress driven by subduction along the Tonga-Kermadec trench. Ruellan et al. (2003) suggested that subduction of the Louisville Seamount Chain has caused compression in the upper plate, with the southward migration of the seamount chain reflected in the likely southward migration of the A-T and N-T Euler poles proposed by Sleeper and Martinez (2016). In the central Lau Basin, the active segment of PR acts as a rigid transform plate boundary while more diffuse deformation occurs in the transfer zone between the CLSC and ELSC. Here, we also identify the boundaries of the three dominant microplates in the north (Tonga Platform, Niuafo’ou, and Futuna) and classify them according to the CMT data (Figure 13).

4.7.1. Niuafo’ou Plate Boundaries

The Niuafo’ou microplate, as described by Zellmer and Taylor (2001), is a refinement of the Northern Lau microplate proposed by Pelletier and Louat (1989). Rigid boundaries occur along the FRSC, a short segment of PR and along the NWLSC. Diffuse boundaries are identified among the AVRs and Riedel shears of the LETZ and in the overlap between the CLSC and ELSC. Sleeper and Martinez (2016) first suggested that right-lateral strike-slip faulting along the Riedel shears to the southeast of PR account for the oblique extension in this zone. Although there is clearly an extensional component on the AVRs, it is not recorded in the CMT data. Therefore, we conclude that the majority of the recent motion along this plate boundary segment is strike-slip.

Conder and Wiens (2011) reported over 600 locally recorded seismic events in the LETZ within a 3-month period, which suggests that the AVRs are clearly active but that the earthquakes have magnitudes <5 Mw. Conder and Wiens (2011) proposed that a small plate, the Central Lau Nanoplate (CLNP), also may be forming in the area of intense deformation between the CLSC and ELSC. Here, the CMTs indicate that
left-lateral strike-slip motion dominates. However, Sleeper and Martinez (2016) concluded that the abundant seismicity and deformation are not consistent with a rigid plate. Our analyses are also more consistent with a diffuse deformation zone rather than a rigid nanoplate.

Two boundaries of the Niuafo’ou microplate are less well constrained: (i) in the southeast, between the northern ELSC and the southern tip of the FRSC, and (ii) in the north between the MTJ and the NWLSC. In the southeast, the observed strain (Conder & Wiens, 2011) is too small to account for the relative motion between the Niuafo’ou and Tongan microplates (Zellmer & Taylor, 2001). To account for this, Conder and Wiens (2011) proposed that the Euler pole was located closer to the southern tip of the FRSC, which would result in significantly lower plate velocities and account for the lack of deformation seen in this area. The location of the Euler pole was subsequently revised by Sleeper et al. (2016), to be consistent with their interpretation of the magnetic data, and they noted that significant nonrigid plate behavior would be required to accommodate the strain. They concluded that the deformation is dominated by transtension on strike with normal faults propagating to the southwest from the tip of the FRSC (Figures 8 and 10). We also identify normal left-lateral oblique-slip faults in this area that coincide with the anticlockwise rotation of $S_{\text{max}}$ (from N-S in the northwest corner of the domain, Figure 9b, to NW-SE in the northeast corner, Figure 9c). The northern boundary of the Niuafo’ou microplate extends from the western arm of the MTJ through a deformation zone that is dominated by left-lateral strike-slip faulting (Figure 6). This portion of the plate boundary, however, is obscured by a volcanic flow field north of Niuafo’ou Island. The CMT data also indicate a new plate boundary forming between the RR and the RTF triple junction in the north (Figure 13).

4.7.2. Tonga Plate Boundaries

The boundaries of the Tonga Plate include the Tonga trench in the east and the FRSC in the west. Similar to the Niuafo’ou plate, the northern and southern boundaries are less well constrained. The northern boundary is complicated by the strong curvature of the Tonga trench and the inferred STEP fault, multiple overlapping spreading centers (including the NELSC, MTJ, and Northern FRSC), and the strike-slip faulting between the Northern FRSC and the southward propagating tip of the NELSC. The latter suggests that these two features may connect in the future and form a more continuous northwestern Tongan plate boundary. However, extensional faulting is limited in this area. GLORIA sidescan data show that many of the NELSC spreading ridges are sedimented, suggesting slow spreading rates (Tiffen, 1993). Bird (2003) suggested that the southern boundary segment connects with the propagating tip of the Valu Fa Rift through the active arc, but seismic and other geophysical evidence for this is lacking (Figure 11). Instead, recent data on the rift morphology at the propagating tip of the FRSC support an emerging connection to the Fonualei discontinuity (Hannington et al., 2019), passing through a cluster of oblique-slip faults on the arc front (Figure 8). This may be an indication of the future breakup of the north Tongan platform (Conder & Wiens, 2011; Sleeper & Martinez, 2016). Several of the large earthquakes are located on the nearby arc Volcano “F,” which erupted spectacularly in early August 2019 (Brandl et al., 2019).

4.7.3. Futuna Plate Boundaries

The Futuna Plate of Pelletier et al. (2001) was included in the model of Bird (2003) but assigned to the “New Hebrides Fiji Orogen.” The northern margin of the Futuna Plate is defined by the Futuna Transform and deformation zone (Regnier, 1994), a pop-up structure passing through the island of Futuna and corresponding to the faults classified in this area as low-angle thrusts. This boundary intersects the FSC in the west, where a well-developed spreading center has operated for 4.5 Ma (Pelletier et al., 2001). The proposed southern boundary of Bird (2003) follows a discontinuous zone of seismic events but cuts across large intact crustal blocks that can be identified in high-resolution bathymetry. Instead, the compiled CMT data and mapped lineaments suggest a plate boundary originating at the intersection of the FSC and the Fiji Transform Zone and connecting to the westward extension of the PR along structures dominated by left-lateral strike-slip faults (Figures 6 and 13). The eastern boundary of the Futuna microplate is the NWLSC, but the northeast corner is covered by a large volcanic flow field surrounding Niuafo’ou Island. Here, the inferred plate boundary is interpreted to offset to the east, where it connects to the RR spreading axes, marked by a cluster of strike-slip faults.

4.7.4. Other Deformation Zones and Emerging Microplate Boundaries

Conder and Wiens (2011) suggested that up to four microplates could be emerging north of the Niuafo’ou microplate, and this is supported by our interpretation of the CMT data (Figure 6). A number of other within-plate deformation zones and possible emerging microplate boundaries are indicated by the
compiled CMT data and mapped lineaments, consistent with the continuing breakup of the Northern Lau Basin. In the center of the Futuna Plate, between the FSC and NWLSC (Figures 6 and 13), a zone of strike-slip earthquakes corresponds to the Central Futuna Zone of Arculus (2012). Conder and Wiens (2011) also suggested that a microplate boundary is located underneath the volcanic flow field in this area, and the classified faults in our study confirm that the Futuna Plate is actively deforming at this location. Effusive volcanic activity may have weakened the crust and facilitated the emergence of this boundary, or the volcanism is centered on preexisting structures. At the northeast corner of the Futuna microplate, the plotted CMTs show a large normal fault that may be an arm of the RR. This may have been an unstable triple junction (Rochambeau Triple Junction) abandoned as opening of the Northern Lau Basin increased and extension was taken up by multiple, new spreading centers. This scenario may be analogous to the failed west arm of the MTJ (Mensing, 2019). The northernmost RR connects to the active plate boundary between the Pacific Plate and the Lau Basin, which crosses the ancient forearc along a major left-lateral deformation zone. The orientations of all the spreading centers in the Northern Lau Basin (i.e., NELSC, RR, NWLSC, and northern arm of the MTJ) are parallel or subparallel to the S_{1max} orientations of the plotted CMTs and suggest that the same broad stress regime that first opened the basin persists today.

5. Conclusions

We compared the two possible focal planes of CMTs to mapped seafloor lineaments in the Lau Basin to identify fault planes deeper in the crust and classify them according to the type of fault slip experienced during earthquake events. The most abundant large earthquakes (Mw > 5) occur in the Northern Lau Basin, along structures, initially formed at spreading centers such as the NWLSC, RR, and the NELSC, which have been reactivated as strike-slip faults. The CMT analysis shows an unexpectedly small number of normal faults, partly explained by the low magnitude of the associated earthquakes, but it highlights the overwhelming dominance of strike-slip-faulting in the opening of the basin. We suggest that structures formed at spreading axes may be reactivated as strike-slip faults (shears and extensional transforms) soon after developing. These structures accommodate back-arc stresses as diffuse, nonrigid deformation that may be an important mechanism for channeling melts and fluids through the crust.

The probability of reactivating older structures is strongly influenced by rotation of the nonrigid portions of the crust, and the development of bookshelf faulting, a key feature of this region. Right-lateral strike-slip faults accommodate anticlockwise rotation; left-lateral strike-slip faults accommodate clockwise rotation. Anticlockwise rotation in the northern part of the Lau Basin is most likely a response to the STEP fault, which is propagating along the Pacific Plate slab tear. In contrast, the central Lau Basin is dominated by right-lateral strike-slip faulting, first along a short segment of PR and then transitioning into a more diffuse transform plate boundary in the LETZ, with extension also occurring along the AVRs. Strain in the deformed crust between the CLSC and ELSC is strongly partitioned into left-lateral strike-slip faults that accommodate clockwise rotation within the associated deformation zone.

Based on the distribution of CMTs examined in this study, we propose that the northern boundary of the Niuafo’ou microplate corresponds to a transform zone connecting the west arm of the MTJ, through the Niuafo’ou flow field, to the RR. The southeast boundary of Niuafo’ou appears to be still emerging. A new boundary may also be forming in the Tonga Plate between the southern tip of the FRSC and the Fonualei discontinuity to the southeast, which would create a new triple junction in this region. We show that before a microplate forms, the plate deforms internally and does not move independently of adjacent crust (nonrigid deformation). Once the plate boundaries become more focused (i.e., narrow) and deformation is restricted to those boundaries, then the microplate moves independently of adjacent crust. Our findings confirm that prolonged periods dominated by one type of stress are probably a major oversimplification of the tectonic history of back-arc basin development and are unlikely to produce the complex microplate mosaics that can be found in arc-back-arc systems.

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