Tectonic Reconstruction of the Ellice Basin

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Abstract A geophysical survey of the Ellice Basin, located in the south equatorial Pacific between the Ontong Java and Manihiki plateaus, revealed evidence for an extinct seafloor spreading system between the Pacific Plate and the Manihiki Plate. The spreading occurred during the Cretaceous Normal Superchron, the longest normal period of magnetic polarity from 121 to 83 Ma, and therefore lacks magnetic-isochron-derived age and plate motion constraints. Utilizing high-resolution bathymetric data acquired on survey KM1609 during December 2016–January 2017, morphological and directional analyses were performed on the seafloor spreading fabric. Plate motion between the Pacific Plate and the Manihiki Plate during the Cretaceous Normal Superchron is described by three main stages of spreading. Stage 1 spreading was generally E-W until a clockwise rotation of the spreading direction rotated transform faults by ~15° and lengthened spreading ridges to form Stage 2 zed pattern rhomboids. An offset between Stage 2 fracture zones evidences the presence of a complex and short-lived Stage 3. Reconstructions, with respect to the Pacific Plate, are created for each of the three stages. Our reconstructions show that there was an earlier opening history prior to Stage 1 that ultimately reconstructs the Ontong Java and Manihiki plateaus; its quantification will await high-resolution multibeam bathymetry data closer to the two plateaus.

1. Introduction

A large part of the Pacific Basin formed during the long normal magnetic period known as the Cretaceous Normal Superchron (CNS; 121–83 Ma; Gee & Kent, 2007) and remains poorly understood due to the lack of magnetic reversal identifications. This period coincides with high crustal production rates and the emplacement of many large igneous provinces (LIPs). Of particular interest, the world’s largest LIP Ontong Java Nui (OJN; ~125 Ma) included present day Ontong Java, Manihiki, and Hikurangi plateaus (Taylor, 2006) as well as smaller fragments that were rafted onto the Farallon and Phoenix plates and have since been subducted beneath the South America and Antarctica plates, respectively (Viso et al., 2005). The great extent of this emplacement, an area estimated to have exceeded 1% of the Earth’s surface (Worthington et al., 2006), likely led to the reorganization of the Pacific–Phoenix–Farallon spreading system. The end of OJN formation accompanied the end of Phoenix magnetic lineations shortly after M0 (120 Ma), at the beginning of the CNS. After M0, OJN is inferred to have split by dominantly E-W spreading between the Ontong Java and Manihiki plateaus in the Ellice Basin (Chandler et al., 2012; Taylor, 2006), whereas N-S spreading prevailed between the Manihiki and Hikurangi plateaus whose relict spreading center is the Osbourn Trough (Billen & Stock, 2000; Seton et al., 2012). After the CNS, magnetic anomaly lineations to the east of Manihiki Plateau can be traced from C34n (83 Ma) to present (Figure 1; Nakanishi & Winterer, 1996).

2. The Ellice Basin

Approximately E-W spreading in the Ellice Basin was proposed by Taylor (2006) to separate the Ontong Java and Manihiki plateaus as part of his super-plateau hypothesis supported by gravity-derived fracture zone traces and limited high-resolution multibeam bathymetry. He also recognized a late phase of opening, with fracture zones rotated up to 15° clockwise. Chandler et al. (2012) further developed the two-stage opening model for the Ellice Basin utilizing bathymetric data from a transit survey through the central Ellice Basin by the Korea Ocean Research and Development Institute (now Korea Institute of Ocean Science and Technology, KIOST). Fracture zones, which function as flowlines of past plate motion, were digitized from available bathymetric data in conjunction with satellite altimetry data. The two-stage model of Chandler et al. (2012) identified a central zone where extinct spreading centers not visible from satellite altimetry were inferred to be present. Fracture zones of the first stage trend generally E-W until a clockwise...
rotation of the spreading direction produced WNW-ESE trending fracture zones. This change in spreading direction was likely associated with the collision of Hikurangi Plateau into the Gondwana subduction zone at Chatham Rise, which is considered to have led to the cessation of spreading at the Osbourn Trough (Davy et al., 2008) and a major plate reorganization at ~105–100 Ma (Matthews et al., 2012). Approximately 2,000 km of the full 2,500 km separating Ontong Java and Manihiki plateaus was formed prior to the change in spreading direction, which corresponds to a minimum average full spreading rate of ~10 cm/year if spreading began at 120 Ma. A recent survey and sampling of the Tuvalu seamount chain superimposed on the Ellice Basin oceanic crust obtained anomalously high ages between 95–90 Ma (Finlayson et al., 2018). It is possible that the spreading in Ellice Basin persisted later than spreading at the Osbourn Trough, which is believed to have ceased around 101 Ma (Zhang & Li, 2016). If spreading in the Ellice Basin ceased around 90 Ma, then the average full spreading rate post-reorientation would have been 5–3.3 cm/year. This suggests that spreading between the Ontong Java and Manihiki plateaus was fast until a major reorganization of the spreading center slowed spreading to intermediate-slow rates. This inference is supported by the observed increase in abyssal hill roughness, which can be used as a proxy for spreading rate (Bird & Pockalny, 1994).

3. Survey KM1609

A reconnaissance survey of the central area of the Cretaceous Ellice Basin aboard the R/V Kilo Moana during 4 December 2016 to 10 January 2017 revealed further evidence for seafloor spreading and a past plate boundary between the Ontong Java and Manihiki plateaus. Over 7,500 nautical miles of high-resolution bathymetric data were collected for this study (Figure 2). Bathymetric data were processed and gridded using MB-System tools (Caress & Chayes, 1995) in conjunction with the Generic Mapping Tools (Wessel et al., 2013). Additional bathymetric data in the study region were obtained through the National Oceanic and Atmospheric Administration National Centers for Environmental Information Bathymetric Data Viewer.

Figure 1. Age grid (Müller et al., 2019) slightly modified and shaded by predicted bathymetry (Sandwell et al., 2014), with M series (Nakanishi et al., 1992) and younger (Cande et al., 1989) isochrons. Dashed black line represents Tongereva triple junction trace (Viso et al., 2005). White circle is IODP Expedition 329 Site U1365. White box outlines the study area and location of the following figures. OJP = Ontong Java Plateau, MP = Manihiki Plateau, HP = Hikurangi Plateau, EB = Ellice Basin, OT = Osbourn Trough, NCT = Nova Canton Trough.
Figure 2. Vertical gravity gradient (VGG) maps (version 26; Sandwell et al., 2014) overlain with high-resolution (~90 × 90 m pixels) multibeam bathymetry from survey KM1609 and others. Black circles indicate 16 dredge locations. Black arrows point out offsets between fracture zones in the northeast section representing another stage. Red triangles highlight terminated transforms referred to in text. Black dashed lines approximately digitize the dueling, overlapping spreading center trace.

and added to the total compilation grid. Multiresolution images of bathymetric data for viewing in Google Earth can be found in the supporting information (Data S1). In order to provide additional age constraints on the Ellice Basin, we identified and dredged 16 targets (Figure 2 black circles); suitable basalt samples will be 40Ar/39Ar age dated and reported in upcoming work by our colleagues at Oregon State University. Additionally, a gabbro sample was recovered from one dredge location that will be zircon age dated. Due to the Cretaceous age of this basin, a thick layer of sediment has hidden structural details in deep, low-slope areas. Many of the fracture zone valleys that can be inferred from satellite altimetry were thus less prominent when mapped acoustically. In addition, many Cretaceous seafloor features have been overprinted and obscured by tertiary volcanism (i.e., Finlayson et al., 2018).

Initial discoveries included the presence of seafloor spreading fabric between Ontong Java and Manihiki plateaus that involved at least one major change in spreading direction (Chandler et al., 2012; Taylor, 2006). The geometry of the two stages of spreading suggests that there must exist a boundary between the two plateaus. Another in situ discovery was the distinct sediment thickness variation that increased from the northeast to the southwest of the basin. Abyssal hills and fracture zones were digitized in order to distinguish spreading stages needed to describe the evolution of the Ellice Basin. In that process, short left-lateral offsets of WNW-ESE trending fractures were identified (Figure 2 black arrows) evidencing a third stage close to the termination of spreading in the Ellice Basin, though there is no obvious morphological expression of a relict spreading center (unlike others recognized globally; MacLeod et al., 2017). Morphological and directional
analyses of spreading fabric are utilized in lieu of magnetic anomaly identifications to distinguish stages and create pseudo-isochrons. Finite rotations are calculated based on pseudo-isochron selections and applied to bathymetric and satellite altimetry data to reconstruct the basin through time. Transitions between stages appear to have involved a complex interplay of rotating and propagating ridges and the rearrangement (and sometimes elimination) of closely spaced sets of right-stepping transform faults.

4. Morphological Features

High-resolution multibeam bathymetric data allow for a detailed description of first-order morphological features of the seafloor spreading in the Ellice Basin. These features provide noteworthy examples of processes that occur during changes of spreading direction that are applicable globally.

4.1. Fracture Zones and Abyssal Hills

Our mapping documented long fracture zones that can be traced point-symmetrically about the central zone of the basin. These fracture zones bound abyssal hill fabric and confirm seafloor spreading in Ellice Basin that involved at least one major change in spreading direction from ~E-W to WNW-ENE (Chandler et al., 2012; Taylor, 2006). Reorientation of the spreading ridges during a change in spreading direction can occur by rotation or propagation (Hey et al., 1980; Menard & Atwater, 1968; Menard & Atwater, 1969) or synchronously as observed at the Woodlark Basin spreading system (Goodliffe et al., 1997). Reorientation by rotation involves the gradual rotation of spreading centers as observed in the early transition between stages in most of the basin (Figure 2; Menard & Atwater, 1969; Menard & Atwater, 1968). Reorientation by propagation involves the formation of a new spreading center with the new orientation propagating into older lithosphere with the old orientation and results in oblique pseudofaults that form a characteristic V shape (Hey et al., 1980). The primary mode of reorientation in the Ellice Basin is by rotation, but reorientation by propagation is also observed in some abyssal hill fabric. The detailed survey revealed an offset between the WNW-ENE-trending fracture zones (Figure 2 black arrows), suggesting a late third stage of spreading that appears to have reoriented synchronously; therefore, the Ellice Basin holds evidence for all known modes of seafloor spreading reorientation.

4.2. Abyssal Hill Deflections

Near-transform abyssal hill deflections are observed at the outside and inside corners of ridge-transform-intersections of both slow- and fast-spreading ridges (Croon et al., 2010; Sonder & Pockalny, 1999). Abyssal hills in the Ellice Basin exhibit J-shaped deflections opposite of inside corner highs (i.e., approximately −179°/−6° & −177.5°/−7.5°). In two cases within the basin, J-shaped abyssal hill deflections appear to overshoot the fracture zone (Figure 3, Rhomboid 4). Additionally, sigmoidal abyssal hill fabric deflecting on both the outside and inside corners is observed in the Ellice Basin between closely spaced fault strands.

4.3. Rhomboids

The geometric structure of a spreading system provides direct evidence of changes in past plate motions (Searle et al., 1993). Changes in spreading direction are recorded by transform faults and preserved as fracture zones. When the spreading system experiences a change in spreading direction, the resulting geometry is usually a “Z” or “S” pattern of rhomboids depending on the trend of the offset of the spreading ridges (i.e., left or right stepping) and the direction of rotation in relative plate motion (i.e., clockwise or counterclockwise; Atwater et al., 1993). The system can then be further characterized as transtensional or transpressional, depending on the regime created by the change in spreading direction. Based on the curvature of near-fracture abyssal hill fabric, we conclude the ridges in the Ellice Basin to be primarily right stepping. A clockwise rotation in relative plate motion caused extension across transforms resulting in the “lazy-Z” pattern rhomboids (Figure 3) and a transtensional system. The Molokai and Siqueiros fracture zones are two other transtensional systems similar to the Ellice Basin system, though left stepping (Pockalny et al., 1997; Searle et al., 1993). Survey KM1609 mapped evidence of at least 11 rhomboids (Figure 3), with numeric labels increasing from northeast to southwest. Rhomboid limbs are point-symmetrically conjugate about the relict spreading center.

Atwater et al. (1993) and Searle et al. (1993) both found that north Pacific fracture zones, such as the Molokai, Mendocino, and Pau fracture zones, tended to consolidate transforms and lengthen spreading ridges when the spreading reorientations were tranpressional and created new transforms and decreased
the length of spreading ridges when the spreading reorientations were transtensional. In the transtensional Ellice Basin, the geometry is a mirror image of Molokai fracture zone, but several transforms, at least eight in our mapped area (Figure 2 red triangles), were eliminated when the spreading direction changed, thereby increasing the length and decreasing the number of spreading centers. Propagation of the spreading ridges associated with termination of these transforms (Figure 2 red triangles) occurred late in, or after, the transition to WNW‐ESE opening.

4.4. Multi‐Strand Fracture Zones
Survey KM1609 revealed early fracture zones (trending ~E‐W) to consist of multiple, closely spaced fault strands. The fault strands bound short, sigmoidal abyssal hills that are not orthogonal to the fractures. Many Pacific fracture zones formed as multi‐strand transform systems, so understanding how they evolve following changes in plate motion is vital to unraveling the history of the Pacific basin at large. Multi‐strand fracture zones are common on fast spreading and fast slipping systems due to the easy migration of the spreading system on a thin, young plate (Fox & Gallo, 1984; Searle, 1983). This feature can also be formed as a result of extension on an active transform producing a pull‐apart basin and oblique intra‐transform spreading centers like at Siqueiros fracture zone (Pockalny et al., 1997). In the Ellice Basin, observed multi‐strand fracture zone trends differed between satellite altimetry data and high‐resolution multibeam bathymetry by about 5° because satellite altimetry captures longer wavelengths and cannot resolve the

Figure 3. (a) Vertical gravity gradient (VGG) map (version 26; Sandwell et al., 2014) overlain with multibeam bathymetry. (b) Line drawing interpretation of bathymetric data collected during survey KM1609. Rhomboids identified are labeled 1–11. Blue lines show east limb fracture zones, purple lines show west limb fracture zones, red lines show east limb abyssal hills (AH), orange lines show west limb AH, dark red lines show Stage 3 AH, gray polygons show seamounts, green lines show stage borders. Line colors correspond to slice colors of inset rose diagrams.

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small en echelon basins between the closely spaced fault strands. Mapped multi-strand fracture zones in the Ellice Basin trend 75–105° (~E-W) and contain up to nine fault strands spaced 3–20 km apart. When the change in spreading direction occurred, spreading ridges extended in length, and single fault transforms spaced 20–140 km apart were created (Figure 3).

4.5. Dueling, Overlapping Spreading Center

In the case of Rhomboid 4, the conjugate limbs differ slightly due to a dueling, overlapping spreading center that propagated to the southwest and left a path of accreted transferred crust on the east limb, which has a pseudofault conjugate of symmetric trend on the west limb (Figure 2 black dashed lines). This discontinuous propagation of the spreading center eventually took over spreading from the adjacent Rhomboid 5 to the south. Prior to the initiation of the dueling, overlapping spreading centers, the ridge reoriented and propagated north, eliminating multiple transforms in the process. This evolution was complex, and resolving the accreted, transferred, and rotated pieces of crust is difficult without magnetic reversal identifications. Though it is not entirely clear where the center of Rhomboid 4 is located, it is clear that the dueling, overlapping spreading center never created new transforms but eliminated neighboring transforms instead (Figure 2).

4.6. Inside Corner Highs

Inside corner highs form on the corner between a spreading ridge and an active transform as a result of decoupling along the transform that is associated with normal faulting and outside corner tilting; they have not been observed on fast spreading ridges (Severinghaus & Macdonald, 1988). In the Ellice Basin, inside corner highs are most commonly observed associated with the change in spreading direction from Stage 1 to Stage 2—being not observed beforehand (consistent with fast spreading) and infrequently much thereafter. The abyssal hill topography indicates that, as the spreading ridges in the Ellice Basin rotated to the new spreading direction, the outside corners between the spreading ridge and the inactive fracture zone were relatively starved during their attempt to reorient and lengthen while inside corners received a robust magma supply. This could be explained by conjugate asymmetric spreading about the ridge center during reorientation.

5. Spreading Stages

Analysis of fracture zones and abyssal hills determines three main stages of spreading in the Ellice Basin: an easterly Stage 1, a WNW-ESE Stage 2, and a late easterly Stage 3 evident by offsets from collinearity between the eastern and western limbs of Stage 2 fractures (Figures 3 & 4). To aid in the reconstruction of the basin,
Table 1
Table of Stage Poles Relative to Fixed Pacific Plate and Total Finite Relative Rotations Utilized in Reconstructions

| Stage Poles | Latitude (°) | Angle (°) |
|-------------|--------------|-----------|
| Pacific Plate fixed | Longitude (°) | 178.9 | 19.8 |
| Stage 1 | -174.2 | 9.5 |
| Stage 2 | -178.0 | 17.7 |
| Total finite relative rotations | Longitude (°) | 11.6266 | 2.5429 |
| End Stage 1 | 12.7303 | -11.6266 |
| Begin Stage 2 | 11.5723 | -5.9434 |
| End Stage 2 | 16.2406 | -2.5429 |

Pseudo-isochrons are identified for each stage based on conjugate features on either side of the assumed relict spreading center. Pseudo-isochrons and fracture zones are then used to calculate total finite relative rotation poles (Table 1) for each stage of spreading mapped. Lineations were selected based on continuity and extent of the lineaments and how well the fabric represents the spreading stage. Some abyssal hills were not digitized in entirety as their near-transform deflections do not directly exemplify the spreading direction (Fox & Gallo, 1984). Additionally, fabric formed during the transition between stages or fabric relocated by propagators was excluded from directional analyses. Lineations are further divided between the northeast region and the southwest region to illustrate the differences due to proximity to the pole.

5.1. Stage 1

The most distinguishable features of Stage 1 are the multi-strand fracture zones. Mapped multi-strand fracture zones are bundles of five or more fault strands and are connected by long spreading ridges 100 km and 176 km in length (Figure 3). Spacing between fault strands within the bundles ranges from 3 to 10 km, but the abyssal hill fabric between them is sigmoidal and does not accurately represent the spreading direction. In the northeast region, the average fracture azimuths are 78° and 85° for the east and west limbs, respectively, with an angular separation of 7°. In the southwest region, the average azimuth of east fractures is 86° and west fractures is 99° with an angular separation of 13°. However, if we only compare conjugate east and west limbs, the angular separation is consistently 13°. This is simply due to data availability; we mapped more Stage 1 west limb fractures in the northeast. The only mapped abyssal hill fabric that accurately represents Stage 1 is found in the east limb of Rhomboid 4 before the overlapping spreading center initiates. The average azimuth of these abyssal hills in the northeast region is 347°.

5.2. Stage 2

The transition from Stage 1 to Stage 2 opening incorporated the transition from multi-strand to single-strand fracture zones. Each Stage 1 fault strand splayed and rotated ~15° (along approximately ~5° and ~8° latitude) as spacing between transforms increased, and in three cases, transforms were eliminated as the new stage developed. The elimination occurred well into the transition at the beginning of orthogonal Stage 2 fabric development. This transition lengthened and reoriented spreading ridges mostly by rotation of the spreading ridge. Stage 2 spreading ridges range from 24–57 km in length, not including the discontinuous propagator that is composed of longer, dueling spreading centers (Figure 2 black dashed lines). The average azimuth of Stage 2 fractures in the northeast region are 104° and 105° for the east and west limbs. In the southwest region, the average azimuth of east fractures is 116° and west fractures is 120°. The angular separation between the northeast set and the southwest set progresses from 1 to 4 as a result of proximity to the pole (Table 1). However, the uncertainty on fracture selections in the southwest region is greater due to a thick layer of sediment hiding the details of the faults. The population of representative abyssal hill fabric for Stage 2 is greater than any other population of lineations. In the northeast region, Stage 2 abyssal hills have average azimuths of 14° and 17° for the east and west limbs, respectively. Stage 2 abyssal hills in the southwest region have average azimuths of 28° for the east limbs and 32° for the west limbs. The angular separation between Stage 2 abyssal hill fabric progresses from 3° to 4° from the northeast to southwest due to the presence of Stage 3.

5.3. Stage 3

In the northeast region, Stage 3 can be identified by the systematic left-lateral offsets of Stage 2 fractures, but the organization of the spreading system appears to not be entirely rigid with elements of distributed deformation. Short ~N-S-trending abyssal hills can be identified in the southwest region, but fracture zones cannot be identified. Stage 3 abyssal hills in the southwest region have an average azimuth of 353° and are represented roughly by a stage pole at 178.0°W, 17.7°N. The only configuration fitting the observed abyssal hill fabric suggests the abrupt change in spreading direction returned the system to be dominated by short spreading ridges with long transform offsets in the faster spreading southwest region further from the pole of rotation (Table 1). Spreading ridges are 10–20 km in length and are spaced up to 150 km apart. The net
6. Results

Based on the extent of the basin and formation age constraint within CNS, spreading in the Ellice Basin was fast (~10 cm/year) until a transtensional change in the opening kinematics decreased spreading to intermediate-slow rates (5–3.3 cm/year). This decrease in spreading is supported by an increase in abyssal hill roughness. Near the extinction of the spreading system, a synchronous counterclockwise change in the spreading direction put the system into a brief period of transpression. One key difference observed in the Ellice Basin compared to other Pacific fracture zones is the elimination of fault strands (Figure 2 red triangles) accompanying a transtensional change in spreading direction, resulting in longer and fewer spreading segments. The reason for this difference is not clear and perhaps is stochastic. Our Stage 1 reconstruction indicates that there exists a prior opening event that ultimately reconstructs Ontong Java and Manihiki plateaus together, in part due to apparent crustal stretching (Hochmuth et al., 2015). Therefore, this interpretation may be further improved with additional high-resolution bathymetric data closer to the plateaus.

6.1. Reconstructions

Chandler et al. (2012) advanced the Taylor (2006) hypothesis by solving for spherical rotations based on inferred plateau boundaries of Ontong Java, Manihiki, and Hikurangi plateaus. New high-resolution bathymetric data provide tighter constraints on the finite rotations that describe part of the opening of the Ellice Basin. Pseudo-isochrons, in conjunction with their offsetting fracture zones, were utilized with the “Hellinger1” program from the Ted Chang software suite (Kirkwood et al., 1999) to calculate the best-fit reconstruction by minimizing the Hellinger (1981) criterion for the sum of the misfits of the conjugate sets with respect to individual great-circle segments. A series of finite rotations (Table 1) was calculated and applied to bathymetric and satellite altimetry data for Stage 1–Stage 3 to reconstruct the central basin through time. Unlike actual magnetic isochrons, the pseudo-isochrons are not guaranteed to represent the exact same age, though they do represent great-circle segments about the stage pole that are equidistant from the spreading axis; hence, the uncertainty in the rotation poles is simply a relative measure of misfit. In the following total reconstructions, the Pacific Plate with Ontong Java plateau (the western plate) remains fixed.
Figure 4 presents all pseudo-isochrons that were utilized in the following reconstructions. Spreading centers of the late Stage 3 are identified, and the assumed ridge-transform configuration is presented (white line). The transpressional system created by the counterclockwise rotation of the spreading direction forced transforms to cut across the existing configuration. The transition from Stage 2 to Stage 3 was rapid, synchronous, and poorly organized. Stage 3 is removed (Figure 5) to the youngest distinguishable Stage 2 fabric (blue lines) to align the conjugate Stage 2 fracture zones and therefore likely includes significant late Stage 2 opening. These blue pseudo-isochrons are estimated to be approximately 94 Ma, based on available rock sample age constraints (Finlayson et al., 2018) and the age bounds of CNS. Stage 2 spreading ridges are offset by transforms 44–87 km in length, which are generally shorter than their preceding Stage 1 transforms.

Figure 6. Map of vertical gravity gradient (version 26; Sandwell et al., 2014), bathymetry and interpretation reconstructed to the beginning of Stage 2 around 98 Ma with all younger seafloor removed and the Pacific Plate fixed. Brown polygons on the left represents Ontong Java Plateau. Black dashed lines represent possible rift boundaries, red lines represent Stage 1 pseudo-isochrons, thin black lines represent flowlines of Stage 1, Magenta line represent Stage 2 beginning pseudo-isochron, Magenta dashed lines represent boundaries of the rotation that were not interpreted.

Figure 7. Map of vertical gravity gradient (version 26) (Sandwell et al., 2014), bathymetry and interpretation reconstructed to the end of Stage 1 around 102 Ma with all younger seafloor removed and the Pacific Plate fixed. Brown polygons on the left and right borders represent Ontong Java and Manihiki plateaus, respectively. Black dashed lines represent possible rift boundaries, thin black lines represent flowlines of Stage 1, red line represents Stage 1 pseudo-isochron, Red dashed lines represent boundaries of the rotation that were not interpreted.
In the next reconstruction (Figure 6), we removed all Stage 2 fabric that is formed after the completed transition from Stage 1. These pseudo-isochrons (magenta lines) are estimated to correspond to a time around 98 Ma. This removal allowed for the analysis of the extended transitional period from Stage 1 to Stage 2. This stage represents the period of transtension for the spreading system when the number of transforms decreased as spreading ridges lengthened, as observed from fracture zone traces. As the spreading system adjusted to the new spreading direction and rate, the outside corners of the ridge-transform intersection formed low basins as the spreading ridges attempted to reorient and lengthen while the inside corners formed highs possibly due to differences in local spreading rate along the reorienting ridge. Analogous to a marching band executing a turn, the inside corner abyssal hills asymmetrically spread more slowly (“marking time”) than the outside corner abyssal hills (stepping quickly to complete the turn)—see section 7.

The reconstruction of Stage 1 removes all zed pattern rhomboids such that three main multi-strand fracture zones remain in the surveyed region (Figure 7). Spreading ridges in these sections of closely spaced transforms range from 3 to 10 km in length. Longer spreading ridges separate the multi-strand fracture zones and are 20–140 km in length. Stage 1 pseudo-isochrons (red lines) are estimated to be around 102 Ma. This reconstruction brings Ontong Java and Manihiki plateaus closer together but illustrates that the full opening history is more extended and complicated. Hochmuth et al. (2015) found the breakup of OJN to be complex including tectonic shearing and crustal stretching. Specifically, the western margin of Manihiki Plateau displays many features of crustal stretching based on the analysis of seismic data, and this history can explain the asymmetry between suspected rift boundaries (black dashed lines).

7. Discussion

7.1. Reorientation

The Ellice Basin provides an opportunity to expand our understanding of plate motion change and the associated reorientation of spreading centers. The transition from Stage 1 to Stage 2 was the result of a clockwise rotation of the spreading direction that resulted in a transtensional system where ridge segments lengthened and zed pattern rhomboids formed (Figure 8). This transition also included an increase in abyssal hill roughness, suggesting slowing of the spreading rate (by ~6.7–5 cm/year) and the change from multi-strand fracture zones to single strand fracture zones. This transition initiated the formation of inside corner highs and outside corner lows by point-symmetric spreading about the ridge segments. As the ridges rotated to the new spreading direction, spreading was slower at the inside corners and faster at the outside corners (Figure 9).

7.2. Conflicting Ideas

The confirmation of spreading in Ellice Basin conflicts with previous works that have recognized N-S fracture zones in the basin (Hochmuth et al., 2015; Nakanishi et al., 1992). In particular, Hochmuth et al. (2015) present a magnetic anomaly map (their Figure 5) that appears to have involved the insertion of assumed fracture zones from Nakanishi et al. (1992) to render an image that results in a false N-S trend through the middle of Ellice Basin. Our newly acquired data from survey KM1609 rule out such a trend.

8. Conclusions

A Survey KM1609 revealed seafloor spreading fabric evidencing a past plate boundary between the Pacific Plate with Ontong Java Plateau and the Manihiki Plate with the Manihiki Plateau. However, this
boundary is poorly resolved due to a change in plate motion near the extinction of the spreading system. B Fast spreading rates (−10 cm/year full rate) are inferred for the early opening of the Ellice Basin based on the great extent of the basin and plateau age constraints within the CNS. Spreading rates slowed to intermediate-slow (−4 cm/year full rate) after a pronounced change in the spreading direction, which we suspect to be a result of the extinction of Osbourn Trough spreading. Morphological features such as multi-transform fracture zones and abyssal hill roughness support these inferences. Age dates presented by Finlayson et al. (2018) allow spreading in the Ellice Basin to persist later than spreading at the Osbourn Trough. We estimate the extinction of the Ellice Basin spreading system around 90 Ma. C The Ellice Basin spreading system is described by three main spreading stages as depicted from analysis of the fracture zones and abyssal hill fabric. Finite rotations were utilized to reconstruct Ellice Basin through time and revealed that the total tectonic history of the Ellice Basin cannot be described by three stages alone. Seismic data interpreted by Hochmuth et al. (2015) suggest significant crustal stretching on the western margin of Manihiki Plateau that could explain the asymmetry observed between the plateaus in our Stage 1 reconstruction. Therefore, this interpretation can be further improved with additional high-resolution bathymetric data closer to the plateaus. D Inside corner highs are primarily observed in the Ellice Basin during the transition from Stage 1 to Stage 2 and appear to be involved with reorientation (Figure 9). Their rare presence post-reorientation aligns with our estimate of intermediate-slow spreading for Stage 2.

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