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Oligocene-Miocene spreading history of the northern South Fiji Basin and implications for the evolution of the New Zealand plate boundary

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[1] A tectonic model of the evolution of the northern half of the South Fiji Basin, including the Minerva Triple Junction and Cook Fracture Zone, is developed from regional gravity, multibeam bathymetry, and a new interpretation of magnetic anomalies pinned to radiometric dates of oceanic crust in the basin. The geometry and age of a portion of the Minerva Triple Junction and the Cook-Minerva spreading center (the connection from the triple junction to the Cook Fracture Zone, which accommodated coeval opening of the Norfolk Basin), are resolved with multibeam bathymetry and magnetics. The South Fiji Basin opened from about 34 to 15 Ma in an anticlockwise sweep about an Euler pole located at the northern end of the present Lau Ridge. This rotation and a rigidly straight southeastward motion of the Three Kings Ridge were accommodated by the configuration of the triple junction changing from ridge-fault-fault to ridge-ridge-fault to ridge-ridge-ridge. During this evolution the southeastern arm of the system, the Julia Fracture Zone, underwent several transformations and the Cook-Minerva spreading center experienced repeated ridge jumps. The kinematics of the northern South Fiji Basin dictate, to a large extent, the evolution of the southern South Fiji Basin and the Norfolk Basin. This in turn leads to the interpretation of a complex trench-trench-double transform fault framework at the northern New Zealand margin, which explains most aspects of the geology, structure, and arc volcanic history of the margin and provides a radical new setting for the origin of the Northland Allochthon.

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1. Introduction

[2] The South Fiji (SFB) and Norfolk basins occupy the back-arc region between the continental Norfolk Ridge and the Colville-Lau Ridge, a remnant arc west of the active Kermadec-Tonga subduction system (Figure 1). The region is bounded to the north by the active New Hebrides Trench and Hunter Fracture Zone and North Fiji Basin, and to the south by the extinct Vening Meinesz Fracture Zone (VMFZ) [*Herzer and Mascle*, 1996], van der Linden Fault (VLF) [*Sutherland*, 1999] and Northland Plateau (NP) [*Herzer et al.*, 2009] on the New Zealand continental margin. In the center of the region, the Cook Fracture Zone, Bounty Ridge spreading center and Julia Fracture Zone were major interfaces during the evolution of the back-arc basins. They, and the Three Kings Ridge remnant arc, converge near the inferred Minerva Triple Junction (MTJ).

[3] Recent studies of the tectonic history of the southwest Pacific propose that the South Fiji and Norfolk back-arc basins opened in tandem while the Three Kings Ridge and Colville-Lau Ridge moved southeast [*Crawford et al.*, 2003; *Schellart et al.*, 2006; *Mortimer et al.*, 2007]. The timing has been constrained by Ar-Ar dated back-arc basin basalts (BABB) and calc-alkaline volcanics [*Mortimer et al.*, 1998, 2007; *Bernardel et al.*, 2002; *Fraser*, 2002] but the back-arc evolution that accommodated these movements has been unknown until now. We present new results of a multibeam swath bathymetry survey between the Minerva Triple Junction and the Cook Fracture Zone, and a reinterpretation of the regional seafloor spreading magnetic anomalies in the light of recent BABB ages, to reveal how, and in what sequence, elements of the South Fiji–Norfolk Basin system opened.

[4] The intraoceanic Kermadec-Tonga subduction system is rolling back to the east, consuming Pacific crust, and behind the active arc, the Havre-Lau back-arc region has been extending for the past ~5 Myr. Prior to this extension, the North Loyalty–South Fiji–Norfolk back-arc region opened behind the now remnant Colville-Lau Ridge. Arc volcanism is documented on the main islands of Fiji as late Eocene and early Oligocene through early Pliocene [*Rodda*, 1994], and on the Lau Islands as middle through late Miocene [*Woodhall*, 1985; *Cole et al.*, 1985]. A single Ar-Ar age of 16.7 Ma is known from the Colville Ridge [*Mortimer et al.*, 2010]. Arc volcanism is inferred to have extended back to 46–40 Ma on the combined Lau-Tonga Ridge [*Duncan et al.*, 1985], and to at least 25 Ma on the Colville Ridge [*Ballance et al.*, 1999].

[5] The North Loyalty–South Fiji–Norfolk basin extension may have involved the Loyalty–Three Kings Ridge as a west facing arc that collided with the Zealandia margin in the late Eocene–late Oligocene [*Aitchison et al.*, 1995; *Crawford et al.*, 2003; *Schellart et al.*, 2006], though other regional tectonic models are proposed [*Mortimer et al.*, 2007]. On the eastern flank of the Three Kings Ridge there is evidence of a rifted margin [*Herzer et al.*, 2009], where 32 Ma andesite is exposed, and a large field of 20–21 Ma shoshonite volcanoes occurs in the adjacent part of the SFB [*Mortimer et al.*, 2007]. On the western flank is a possible forearc basin [*Kroenke and Eade*, 1982] supported by the presence of 37 Ma boninite [*Bernardel et al.*, 2002]. Evidence that may support collision along the margin ranges from tectonic accretion and obduction in New Caledonia [*Cluzel et al.*, 2001] to broad compression in the Reinga Basin [*Uruski et al.*, 2010]. Serpentinised harzburgites, boninite lavas, and metamorphic rocks containing blue-green amphiboles were reported by *Crawford et al.* [2004] and *Meffre et al.* [2006] from the intervening Norfolk Basin.

[6] The magnetic anomalies in the South Fiji Basin were interpreted as chrons 12 to 7A [*Watts et al.*, 1977; *Davey*, 1982; *Malahoff et al.*, 1982], and chrons 12 to 7N [*Sdrolias et al.*, 2003], entirely Oligocene in age. In the northern SFB (the Minerva Abyssal Plain), paired anomalies point to the presumed Minerva Triple Junction northeast of the Three Kings Ridge. In the southern SFB (Kupe Abyssal Plain), the anomalies are difficult to interpret [*Davey*,1982; *Malahoff et al.*, 1982; *Sdrolias et al.*, 2003]. *Sdrolias et al.* [2003] have proposed a ridge-ridge-ridge (RRR) triple junction in the eastern Kupe Abyssal Plain, connected to the Minerva Triple Junction by a spreading ridge merging with the Julia Fracture Zone.

[7] Oligocene–early Miocene spreading in the SFB is indicated by 26–19 Ma BABB and correlation with the volcanostratigraphy of the Northland Plateau [*Mortimer et al.*, 2007; *Herzer et al.*, 2000, 2009]. Lower Miocene (20 Ma) BABB in the Norfolk Basin [*Mortimer et al.*, 1998] and coeval deformation of the Reinga (VMFZ) margin [*Herzer and Mascle*, 1996; *Herzer et al.*, 1997; *Uruski et al.*, 2010] confirms simultaneous activity in the two basins. Extension and spreading were demonstrated along

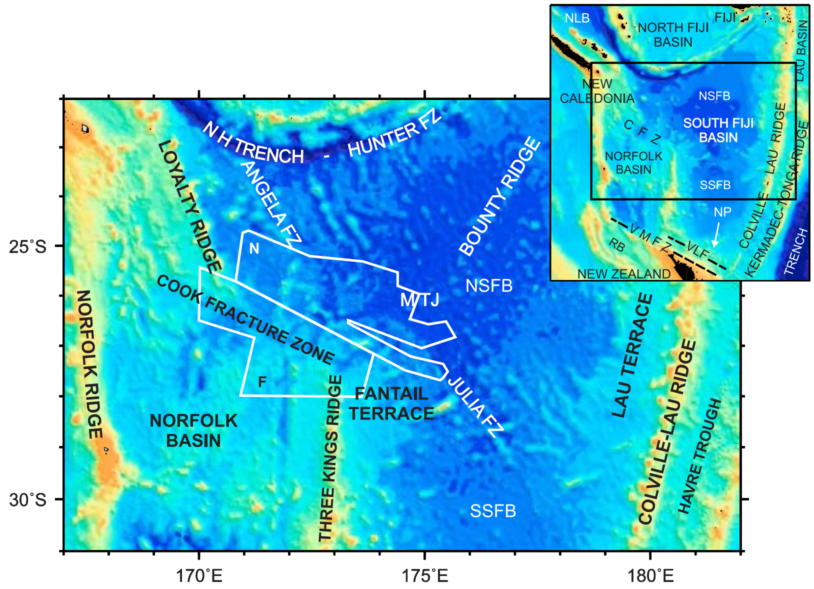

Figure 1. Location, bathymetry and major features. White outlines represent NOUCAPLAC-1 (N) and partial FAUST-2 (F) multibeam boxes shown in Figure 8a. MTJ, Minerva Triple Junction; NLB, North Loyalty Basin; NP, Northland Plateau; NSFB, northern South Fiji Basin (Minerva Abyssal Plain); RB, Reinga Basin; SSFB, southern South Fiji Basin (Kupe Abyssal Plain); VLF, van der Linden Fault; VMFZ, Vening Meinesz Fracture Zone.

both sides of the Cook Fracture Zone [*Mauffret et al.*, 2001; *Bernardel et al.*, 2002].

[8] Extension and spreading may have continued until ~15 Ma. Deformation along the Vening Meinesz Fracture Zone and Northland Plateau lasted into the early middle Miocene [*Herzer et al.*, 1997, 2009], and linear seamounts with ocean island basalt (OIB) dated at 16 and 15 Ma, have been interpreted as short mini–hot spot trails [*Mortimer et al.*, 2007].

2. Methods

[9] The French research vessel *L'Atalante* conducted a survey (NOUCAPLAC-1) with a bathymetric coverage of 80,000 km^2 east of the southern Loyalty Ridge, north of the Cook Fracture Zone and Three Kings Ridge, and as far as the predicted Minerva Triple Junction (Figure 1). Multibeam bathymetry and acoustic imagery were collected along ~2,400 nautical miles of ship track using an EM12D sounder. Six-channel seismic reflection profiles were collected concurrently using a two-gun 300 in^3 GI system operating in harmonic mode at 130 bars and firing every 10 s. Gravity and magnetic data were recorded with a Lockheed Martin BGM5 marine gravimeter and a SeaSPY Overhauser electron spin magnetometer, respectively. The NOUCAPLAC-1 survey adjoins an earlier survey of the northern Norfolk Basin and the Cook Fracture Zone (FAUST-2), using the same vessel and equipment [*Mauffret et al.*, 2001] (Figure 2).

[10] The seismic data allowed us to distinguish thick sedimentary basins from thinly buried seafloor spreading basins, and to differentiate young and old abyssal hill fabric by the thickness of pelagic sediment drape.

[11] The regional coverage of shipborne gravity data is sparse; gravity anomalies derived from satellite altimetry [*Sandwell and Smith*, 1997, V18.1] provide more complete regional coverage (Figure 3). The Three Kings and Loyalty ridges, the Cook Fracture Zone, the zone of gravity anomalies along the Bounty Ridge (BZ), and a series of NW-SE trending lineaments in the eastern and northwestern South Fiji Basin, are prominent features that guided our interpretation.

[12] The magnetic data of the NOUCAPLAC-1 and FAUST-2 surveys were complemented with other shipborne and aeromagnetic data in the region (National Geophysical Data Center (NGDC) GEODAS database, http://www.ngdc.noaa.gov/mgg/geodas/geodas.html) [*Malahoff et al.*, 1982]. These data, collected over a large time period, are of variable quality, and have different navigational accuracies. This paper focuses on relatively short wavelength magnetic anomalies related to seafloor

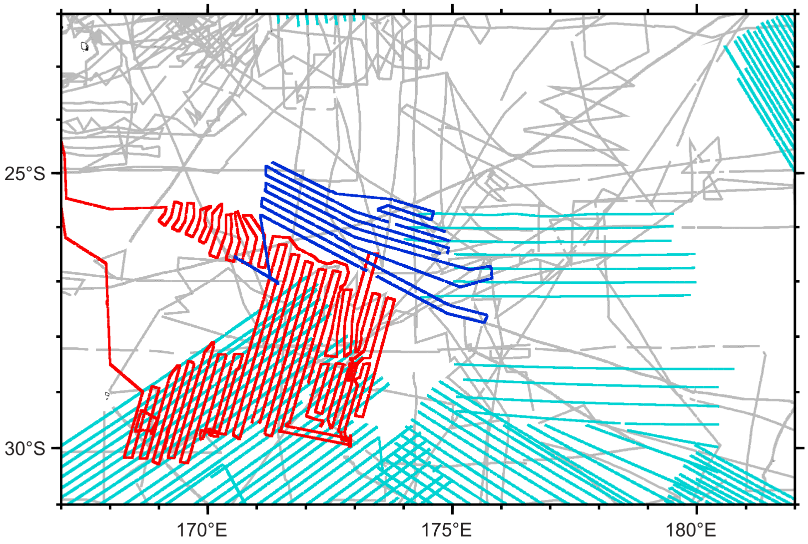

Figure 2. Regional magnetic and multibeam echo sounder data used in this study. For the magnetic data: GEODAS ship tracks are in gray, *Malahoff et al.* [1982] aeromagnetic flight lines are in light blue. The FAUST-2 (red) and the NOUCAPLAC-1 (dark blue) surveys collected both magnetic and multibeam bathymetric data.

spreading; long-wavelength (>100 km) magnetic anomalies were removed from all observations, greatly improving the internal consistency of the merged data set. The data were gridded on a 4 km grid using a minimum-curvature bicubic spline method. Residuals were checked visually to ensure no major magnetic features had been removed by band-pass filtering. Finally, the magnetic anomaly grid was reduced to the pole using present-day inclination and declination (−50° and 15°, respec-

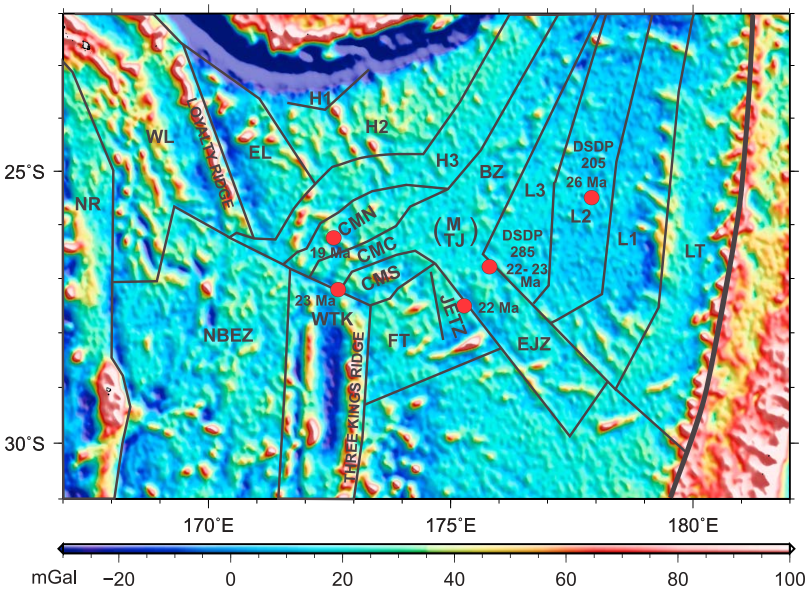

Figure 3. Satellite-derived gravity [*Sandwell and Smith*, 1997, V18.1] illuminated from 0°. Continental, intermediate, and oceanic crustal blocks that behave as rigid or expanding elements in the model (Figure 10) are outlined. Rigid blocks: NR, Norfolk Ridge; WL, Loyalty Ridge–West Loyalty block; WTK, Three Kings Ridge–West Three Kings block; EL, East Loyalty block; FT, Fantail Terrace; LT, Lau Terrace. Transitional areas: JETZ, Julia Extensional Transform Zone. Expanding areas: L1–L3, zones 1 to 3 of the Lau microplate; H1–H3, zones 1 to 3 of the Hunter microplate; NBEZ, Norfolk Basin Extensional Zone; CMN, CMC, and CMS, Cook-Minerva zones north, central and south; BZ, Bounty Ridge Zone; EJZ, East Julia Zone. Red dots are locations of Ar-Ar dated BABB. MTJ, Minerva Triple Junction.

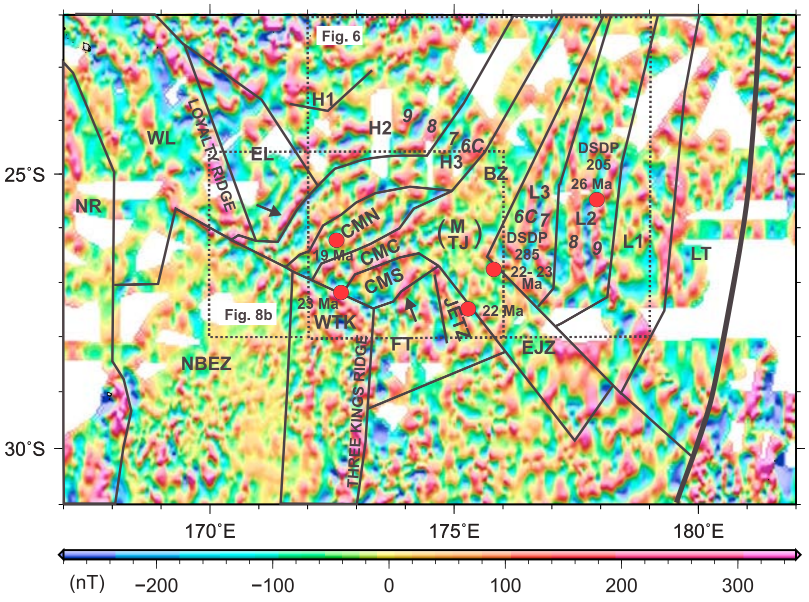

Figure 4. Shipborne and aerial magnetic anomalies (reduced to pole) illuminated from 315°. Outlined are continental, intermediate, and oceanic crustal blocks (refer to Figure 3) that behave as rigid or expanding elements in the model (Figure 10). Dotted lines enclose areas of Figures 6 and 8b.

tively), and assumed values for remanent inclination and declination (−44°and 0°, respectively) (Figure 4).

[13] The most obvious magnetic anomalies include the Loyalty and Three Kings ridges and linear seafloor spreading anomalies in the northern part of the South Fiji Basin. As observed by previous authors, the magnetic anomaly pattern in the Norfolk Basin is very subdued compared to that in the South Fiji Basin.

3. Interpretation

3.1. Gravity

[14] Satellite-derived gravity data (Figure 3) [*Sandwell and Smith*, 1997] reveal the first-order tectonic elements of the South Fiji Basin region, e.g., major ridges, including remnant arcs, basins and associated fault systems, fracture zones, and superimposed seamounts. Marine gravity data record more subtle structure such as the nature of the remnant arcs and their margins with the adjacent basins.

[15] Simple gravity models were constructed from marine gravity profiles across areas of suspected anomalous crust on either side of the South Fiji Basin: to the west, a region informally called the Fantail Terrace beside the Three Kings Ridge, and to the east, the Lau Terrace (Figure 5). Our modeling used ENCOM's ModelVision Pro software. Two-dimensional models were constructed along the profiles, with modeled bodies extending uniformly ±100 km at right angles to the plane of profile and continuing uniformly 100 km beyond each end of the profile. Bathymetric and seismic data along each profile constrained water depth and sediment thickness; there was no adjustment of seafloor depth and sediment thickness. Densities used were water (1,000 kgm^{-3}), sediment (2,300 kgm^{-3}), upper crust (2,670 kgm^{-3}), lower crust (2,900 kgm^{-3}), and mantle (3,400 kgm^{-3}). Each model has the same crustal structure typical of oceanic crust at its basinward end, serving as a reference structure. Thus, the gravity modeling along these profiles accounts for variations in density and/or structure relative to oceanic lithosphere by varying crustal thickness rather than more arbitrary complex changes in crustal densities. Assumptions regarding 2-D treatment of 3-D geometries and simplicity of crustal density structures limit the usefulness of the models' higher-order details, but they do not affect comparison of first-order features across the basin margins.

[16] The gravity models (Figure 5) clearly distinguish ~20–25 km thick crust beneath the Three Kings and Lau ridges and ~8 km thick oceanic crust beneath the SFB. There are well-defined crustal blocks between these ridges and the oceanic basin.

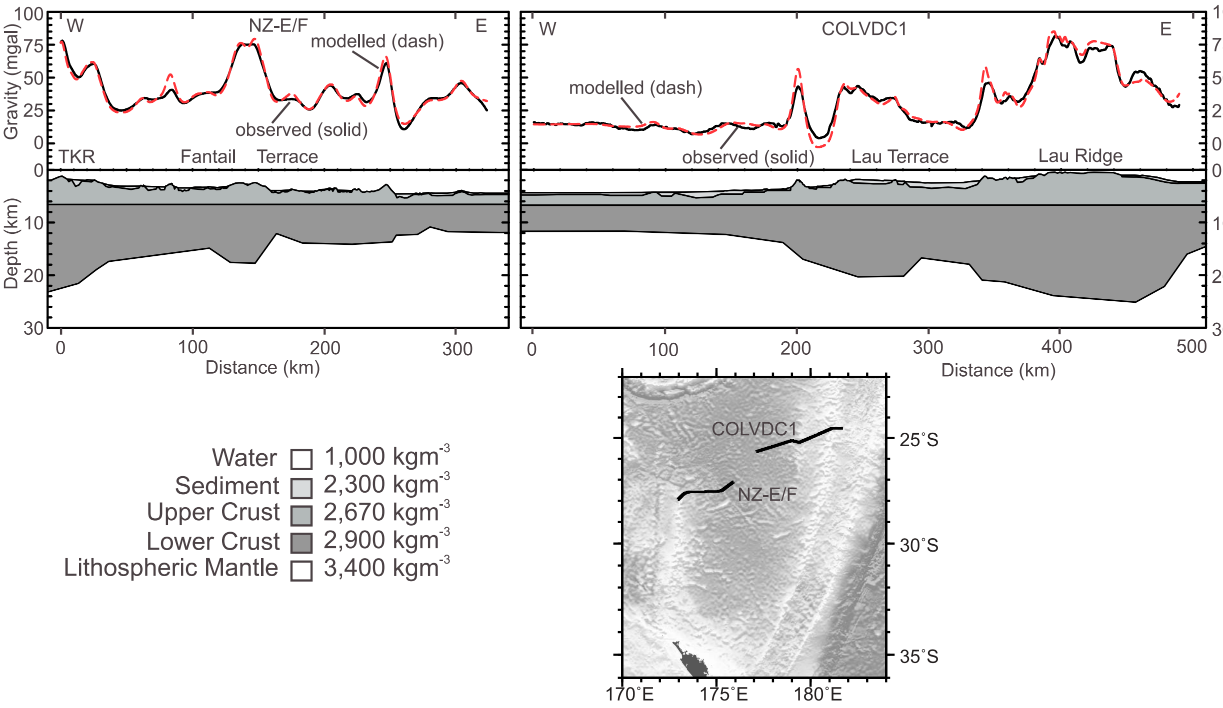

Figure 5. Gravity models of Fantail Terrace and Lau Terrace demonstrate the intermediate crustal thickness of these two features that are interpreted as transitional between continental/arc and oceanic crust.

[17] On the western margin of the basin, profile NZ-E/F shows steps in crustal thickness across the Fantail Terrace: first a step from ~8 km thick oceanic crust to ~10 km thick crust at the Julia Fracture Zone (JFZ) (~260 km along profile), followed by a more complex step (~160 km along profile) to 12–15 km thick crust that extends westward to the Three Kings Ridge. These steps define two domains of intermediate crust across the terrace.

[18] The eastern margin of the basin, illustrated by COLVDC1, shows a zone of thickened and elevated crust between the SFB and the Lau Ridge. Along the gravity profile, this intermediate crustal block, the Lau Terrace, comprises crust 14–18 km thick, intermediate between 8 km thick oceanic crust and 20–25 km thick Lau Ridge. The Lau Terrace is particularly clearly expressed in satellite gravity and bathymetry data, prominent in the north and becoming more subdued southward.

3.2. Magnetics

[19] Mapped magnetic anomalies, reduced to pole, are shown in Figure 4. Although floored by oceanic crust, the South Fiji Basin has few strong seafloor spreading magnetic anomalies. The Norfolk Basin contains extensive plateaus of nonoceanic crust and lacks strong anomalies. In the southern South Fiji Basin (not shown), roughly N-S aligned linear anomalies in the central basin may continue southward into or under the Northland Plateau, where arc rocks between 22 and 15 Ma old have been dredged [*Sutherland*, 1999; *Mortimer et al.*, 2007; *Herzer et al.*, 2009].

[20] Linear magnetic anomaly sets are evident in the eastern and northwestern portions of the northern South Fiji Basin. In the eastern set, well developed N-S trending anomalies north of ~27°S fan to the south, terminating against a less well-developed NW-SE anomaly trend. In the northwestern set, which is less clear due to sparse data coverage, a general NE-SW trend is observed with a deviation to an approximate W-E trend. Between the eastern and northwestern linear anomaly trends, a region of indistinct, poorly constrained, low-amplitude anomalies coincides with generally uneven basement topography and gravity anomalies of the Bounty Ridge. Linear magnetic anomalies have been interpreted as the product of conjugate spreading about a fossil spreading system along the ridge, with a triple junction in the vicinity of ~175°E, 26.5°S [*Weissel and Watts*, 1975; *Watts et al.*, 1977].

[21] Our interpretation of magnetic anomalies in the northern and central South Fiji Basin is based on revised and new dating of oceanic basalts from

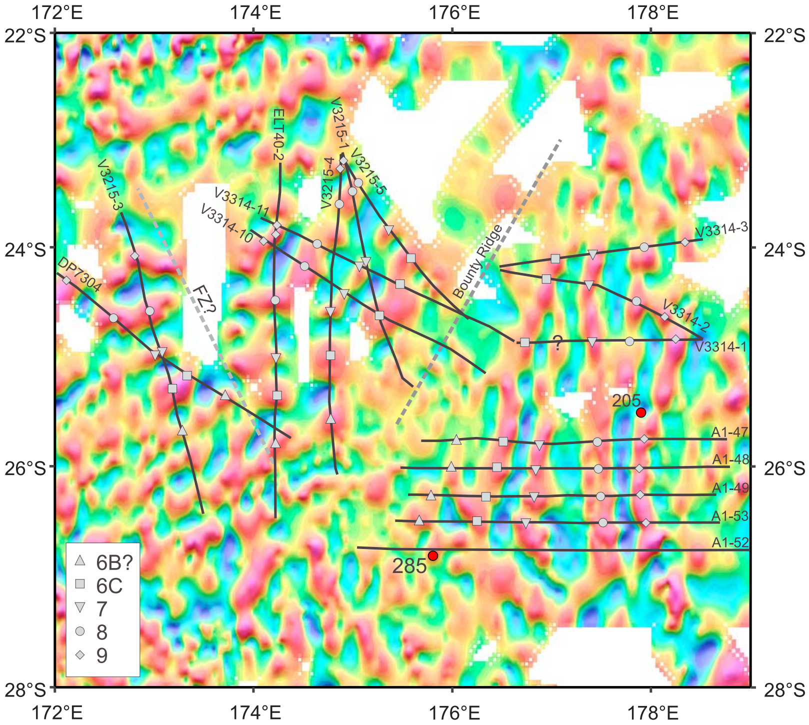

Figure 6. Magnetic profiles used to model seafloor spreading anomalies. See Figure 4 for regional context.

the basin, satellite-derived gravity anomaly data that highlight tectonic trends in basement, and new detailed bathymetric and geophysical data covering an area of the last phases of seafloor opening. The revised interpretation involves conjugate spreading about the ~NE-SW trending Bounty Ridge spreading system (Figure 6), but the timing of spreading is different from earlier models. Ar-Ar ages of samples from DSDP 205 of 26 ± 1.0 Ma and DSDP 285 of 22.8 ± 0.4 and 21.9 ± 0.7 Ma indicate spreading continued well into the Miocene [*Mortimer et al.*, 2007]. These ages correlate with chrons 8r through 7r for DSDP site 205, and chrons 6Br though 6AAr for DSDP site 285 [*Cande and Kent*, 1995].

[22] Selected shipborne and aeromagnetic profiles aligned at a high angle to the mapped anomaly trends were modeled using the MODMAG package [*Mendel et al.*, 2005], a freely distributed set of MATLAB routines that model seafloor spreading magnetic anomalies.

[23] Only simple models were considered practical and useful for this study as there is insufficient a priori information to derive complex spreading histories, and the anomalies are not distinctive enough to discriminate among complex spreading scenarios. Profiles selected for modeling were filtered spatially with a low-cut filter to remove regional trends while preserving the superposed anomaly patterns. All profiles were modeled using coincident bathymetry profiles (collected with the ship-borne anomaly data, or extracted from regional gridded bathymetry [*Smith and Sandwell*, 1997] for aeromagnetic data), fixed source layer thickness of 0.5 km (uppermost crust) and uniform magnetization of 8 A/m. Magnetic inclination and declination were determined for the vintage of data acquisition and location, using the NGDC's IGRF calculator (http://www.ngdc.noaa.gov/geomagmodels/IGRF.jsp). Paleomagnetic parameters used the same values. The synthetic anomaly represents typical values for the location and vintage of profile data illustrated (inclination −43.3°; declination 13.0°). The geomagnetic timescale of *Cande and Kent* [1995] was used.

[24] Crucial to the magnetic profile modeling are the revised ages of oceanic crust rocks from DSDP 205 and DSDP 285 [*Mortimer et al.*, 2007]. Mapped magnetic anomaly data (Figure 4), albeit locally compromised by sparse data coverage, indicate that anomalies are not particularly well organized in the South Fiji Basin. Where anomaly trends can be recognized from mapped data, e.g., in the eastern South Fiji Basin (L1–L3) or, to a lesser

extent, the northwestern South Fiji Basin (H1–H3), the magnetic anomaly profiles lack distinctive short-wavelength characteristics and are difficult to match to either geomagnetic polarity reversal patterns or synthetic anomalies, or even between profiles. Consequently age constraints provided by the DSDP samples determined the portion of the geomagnetic reversal timescale used to model profiles near the drill sites. Profile interpretations were subsequently extended away from the drill sites to adjacent profiles using spatial relationships from mapped anomalies and inferred conjugate spreading history across the Bounty Ridge.

[25] An Oligocene-Miocene spreading history each side of Bounty Ridge is shown on a synthetic model profile together with selected profiles from the South Fiji Basin (Figure 7). Magnetic anomalies that appear coherent in map view often show only moderate similarity on adjacent profiles, even when those profiles are orthogonal to the interpreted anomaly lineations. Potentially distinctive magnetic signatures on the synthetic magnetic anomaly profile are not preserved in the real data, making correlation between acquired profiles and synthetic magnetic profiles difficult. Magnetic anomalies along Bounty Ridge proper have low amplitudes and exhibit no coherent pattern, so the last phase of spreading cannot be defined.

[26] Although the anomaly patterns are not particularly distinctive, the age constraints from dated DSDP samples allow modeling of a select sequence of geomagnetic reversals that best fit the anomaly patterns (Figure 7). The modeled anomalies use the simplest spreading history that is consistent regionally and reproduces the first-order features of the anomaly profiles. A spreading history between chrons 9n and 6Bn is modeled using full spreading rates of 45 mm.a^{-1} to 26.9 Ma (not constrained before ~28 Ma), and ~85 mm.a^{-1} from 26.9 Ma to at least ~22.5 Ma.

3.3. Morphostructure

[27] New multibeam bathymetry reveals the complexity of the Cook Fracture Zone–Minerva Triple Junction system (Figure 8a). Many morphostructural trends at this scale can be linked to regional geophysical structures. In the southwest, the northern Norfolk Basin comprises rift basins, oriented approximately N-S to north-northeast, and plateaus and terraces. A north-northeast trending seafloor spreading fabric is observed on both sides of the west-northwest trending Cook Fracture Zone. North of the Cook Fracture Zone, an area of complex seafloor (informally named here the Cook-Minerva Zone, is divided into northern, central and southern segments (CMN, CMC, CMS) (Figures 3, 4, and 8a). In the northern Cook-Minerva Zone, the spreading fabric orthogonal to the Cook FZ swings to a predominantly east-northeast trend (Figure 8a) that is in turn orthogonal to north-northwest trending gravity lineaments (Figure 3) and parallel to magnetic trends (Figures 4 and 8b). We have interpreted the gravity lineaments as structures parallel to the spreading vector of the Hunter microplate (Figure 3), and the spreading fabric as belonging to that plate. Seamount chains aligned north to northwest (generally parallel to this vector), in the central northern part of the multibeam box (Figures 8a and 9a), are interpreted as axial and off-axis seamounts, based on BABB recovered in a dredge haul.

[28] Discordant fabric with curved tapered boundaries is present within the northern Cook-Minerva Zone (CMN in Figure 9a). This fabric is repeated in a small area of the southern Cook-Minerva Zone southeast of an east-northeast trending band of perfectly linear spreading fabric, the central Cook Minerva Zone. We interpret the central Cook-Minerva Zone to be the youngest crust in the Cook-Minerva spreading system, and the northern and southern Cook-Minerva zones to contain slightly older seafloor fabric and “failed rifts” (abandoned propagators) (Figures 9a and 9b). Restoration of the seafloor geometry to the configuration prior to creation of the central Cook-Minerva Zone crust, along a vector indicated by small seamount trails parallel to the Cook FZ (large double-headed arrow) (Figures 9a and 9c), reveals a succession of propagator jumps in the northern and southern Cook-Minerva Zone fabric. These propagators alternated between Bounty and Cook-Minerva trends as the triple junction migrated eastward.

[29] At the northeastern end of the central Cook-Minerva Zone, a small graben (propagator?) on the Bounty Ridge trend, containing a small rifted seamount (informally named Pecan Seamount) obliquely cuts across some of the southern and central Cook-Minerva Zone crust (small double-headed arrow) (Figures 8a and 9a). The highs here have limited to no pelagic sediment drape. This is part of the Minerva Triple Junction, and probably the final sliver of crust created by these intersecting spreading directions. It suggests a final brief jump of the triple junction involving the Bounty and East Julia zones that did not include spreading in the central Cook-

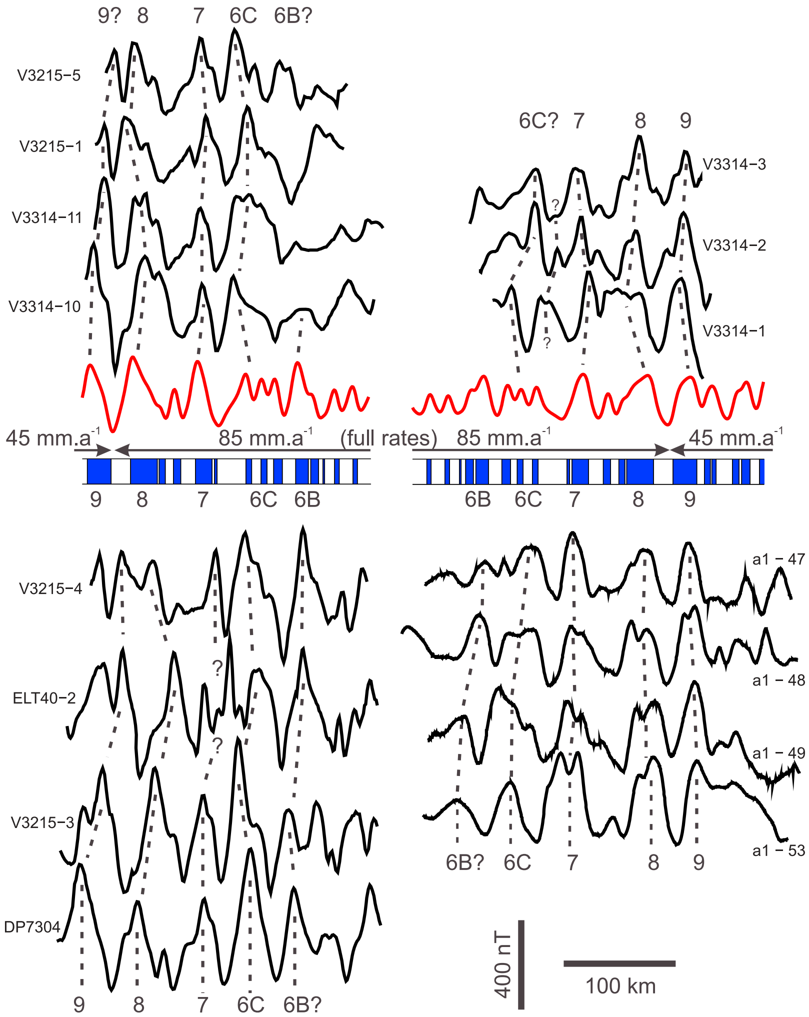

Figure 7. Magnetic profiles from either side of the Bounty Ridge and the reference magnetic model and geomagnetic timescale of *Cande and Kent* [1995]. Dashed lines indicate correlation of anomalies. Magnetic chrons 6C to 9 were modeled; 6B is tentatively identified.

Minerva Zone. Our data do not cover the whole triple junction but suggest oblique spreading in the East Julia Zone (EJZ).

[30] East of the Cook Fracture Zone and northeast of the Three Kings Ridge, the northwestern margin of the Fantail Terrace abuts the northeasterly striking spreading fabric of the southern Cook-Minerva Zone (Figure 8a). The eastern margin of the Fantail Terrace is a north–northwest trending ridge-topped scarp, the Julia Fracture Zone (JFZ). Immediately west of this scarp, southward fanning, north to north–northwest trending lineaments are interpreted as a set of transfer or transform faults, which includes a north–northeast striking rift or spreading fabric. Together they constitute an exten-

Figure 8. (a) Multibeam bathymetry of the Noucaplac-1 (Cook-Minerva Zone) and Faust-2 surveys (Norfolk Basin and Cook Fracture Zone) illuminated from the NW. Dotted circle encloses the present Minerva Triple Junction (MTJ), and solid lines represent the axes of the three intersecting arms. P represents Pecan Seamount. Black crosses represent dredge and drill samples. The other labels are defined in Figure 3. (b) Details of magnetic anomaly data from the Noucaplac-1 (Cook-Minerva Zone) and Faust-2 surveys (Norfolk Basin and Cook Fracture Zone) illuminated from the NW. Dotted circle encloses the present Minerva Triple Junction (MTJ), and thick lines represent the axes of the three intersecting arms. Black crosses represent dredge and drill samples. The other labels are defined in Figure 3. See Figure 4 for regional context.

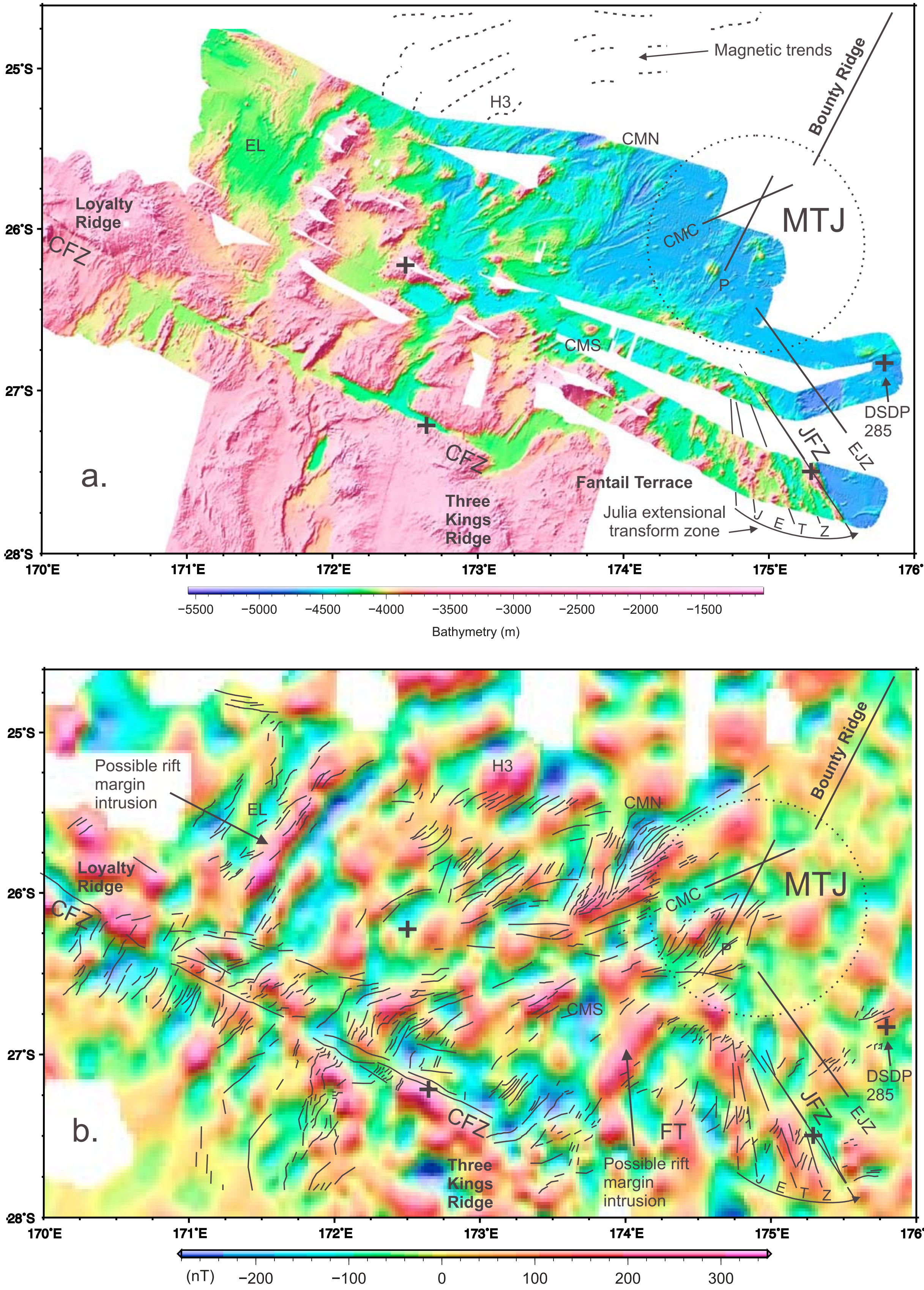
Magnetic trends
Bounty Ridge
H3
CMN
EL
Loyalty Ridge
MTJ
CMC
CFZ
P
CMS
DSDP 285
JFZ
EJZ
a.
Fantail Terrace
Three Kings Ridge
Julia extensional transform zone
J E T Z
25°S
26°S
27°S
28°S
170°E
171°E
172°E
173°E
174°E
175°E
176°E
−5500
−5000
−4500
−4000
−3500
−3000
−2500
−2000
−1500
Bathymetry (m)
Possible rift margin intrusion
b.
FT
(nT)
−200
−100
0
100
200
300

Figure 8

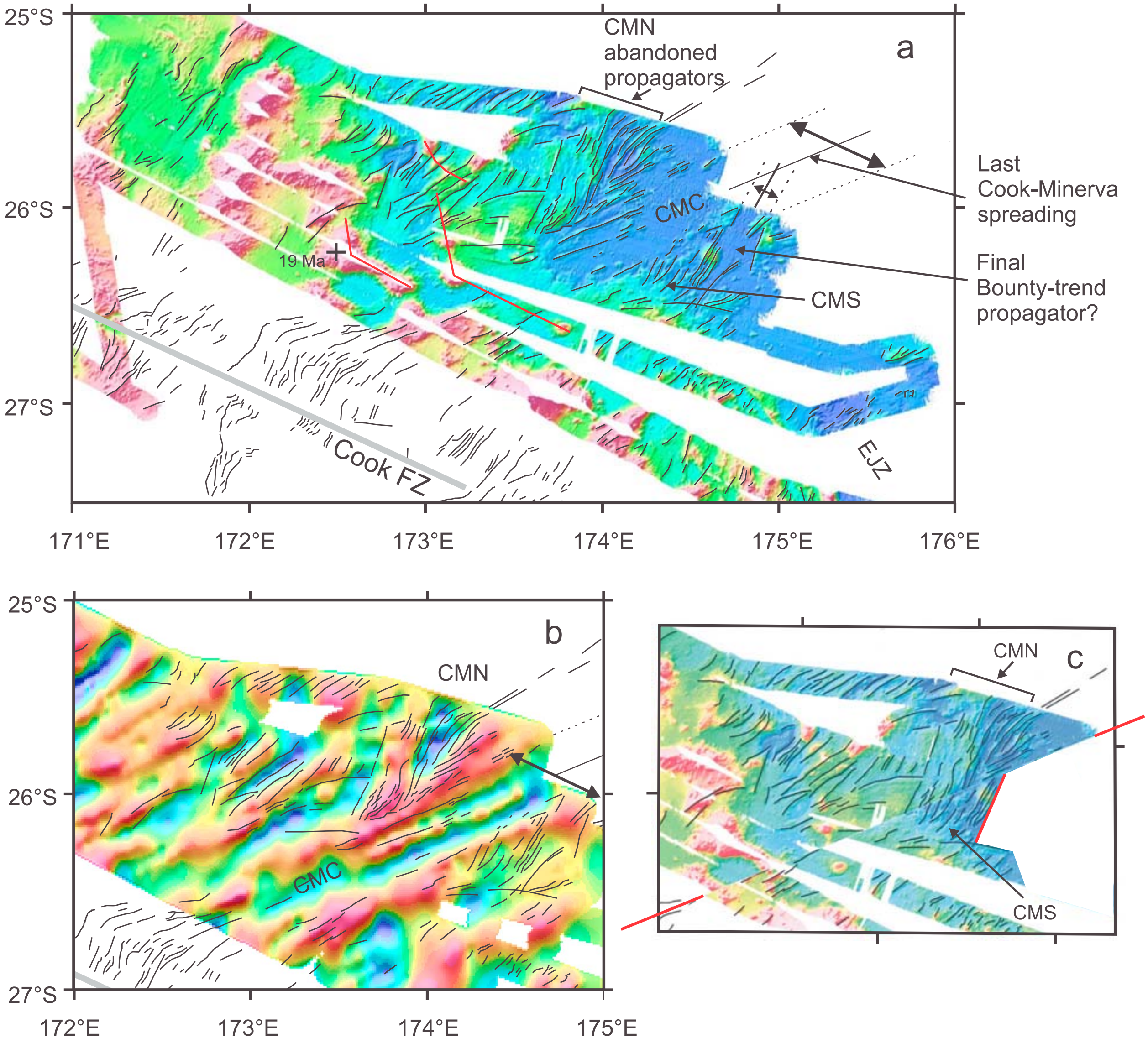

Figure 9. Detail of the youngest spreading episodes (double-headed arrows) in the Cook-Minerva system. (a) Bathymetric interpretation. (b) Magnetic anomalies enhanced to highlight the axial symmetry of the central Cook-Minerva Zone (CMC). (c) A simple palinspastic restoration of the northern and southern Cook-Minerva zones (CMN-CMS) fabric by removing the younger CMC and Bounty trend crust. There is not enough data to interpret the East Julia Zone (EJZ). Red lines in Figure 9a are trails of small axial volcanoes.

sional transform zone [cf. *Taylor et al.*, 1994] (named here the Julia Extensional Transform Zone or JETZ) (Figure 8a). Gravity models suggest that JETZ crust is 10 km thick, relative to presumed 8 km thick oceanic crust in SFB. BABB of 22 Ma age was recovered from the EJZ side of the Julia Fracture Zone [*Mortimer et al.*, 2007].

4. Construction of the Tectonic Model

[31] Five crustal types are interpreted. These help to divide the region into a set of rigid and expanding blocks (Figures 3 and 4). The crustal types are (1) continental (Norfolk Ridge (NR)), (2) arc (Loyalty, Three Kings and Lau ridges), (3) arc flank complexes, the terraces and subordinate ridges and basins that flank arcs (Lau Terrace (LT), Fantail Terrace (FT), West Three Kings (WTK) and West Loyalty (WL) complexes), (4) mixed oceanic/continental (Norfolk Basin Extensional Zone (NBEZ)), and (5) oceanic (areas of the South Fiji Basin with seafloor spreading anomalies).

[32] Arc flank complexes are subdivided into the distinctive ribbon-like ridge-and-basin terrains west

of the Loyalty and Three Kings ridges, and the less distinctive areas of intermediate depth (Lau and Fantail terraces, and East Loyalty Zone (EL)). Gravity models (Figure 5) of the Lau and Fantail terraces indicate that they are underlain by intermediate thickness crust. The subsedimentary basement of the Lau Terrace is back tilted (away from the South Fiji Basin). Normal faulting and block rotation is evident in seismic profiles of both the Lau Terrace (Land Information New Zealand, UNCLOS NZ Continental Shelf Project unpublished data, 1996–2006) and Norfolk Basin [*DiCaprio et al.*, 2009]. Location of the Lau and Fantail terraces adjacent to volcanic arcs makes it likely that they are composed of extended arc, and mixed or intermediate crust. The East Loyalty Zone (EL) is underlain by normal faults and a thick sedimentary basin (Anonymous, Rapport préliminaire Campagne NOUCAPLAC-1, Appendix 2, EXTRAPLAC 05-03, IFREMER, Plouzané, France, 2005).

[33] The crustal types would have behaved or evolved differently during back-arc basin opening, and these differences can be incorporated into a tectonic model (Figure 10). The Three Kings and Loyalty ridges and linear features west of them (that collectively constitute the WTK and WL blocks) align when restored along the Cook Fracture Zone (Figure 3), showing that they formed by tectonism predating motion on the Cook Fracture Zone. Other blocks flanking the fracture zone, the Norfolk Basin Extensional Zone (NBEZ), the Cook-Minerva and H3 blocks, show extension and/or accretion during the motion along the Cook Fracture Zone. Seismic data reveal 8–12 km thick crust and large crescent-shaped normal faults in the Norfolk Basin Extensional Zone [*DiCaprio et al.*, 2009], that, along with isolated plateaus and some abyssal hill fabric, are evidence of oceanic and attenuated, probably continental crust.

[34] The continental Norfolk Ridge (NR), and the West Loyalty (WL) and West Three Kings (WTK) arc–arc flank complexes behave as rigid blocks in the model. The straightness of the Cook Fracture Zone, its parallelism with the Vening Meinesz Fracture Zone, and the parallelism of the Norfolk and Three Kings ridges demonstrate that the Three Kings Ridge–Cook Fracture Zone system behaved rigidly, exerting control on the shape of surrounding less rigid regions. The East Loyalty (EL), Fantail Terrace (FT) and Lau Terrace (LT) blocks, interpreted as rifted arc and/or thick volcanic terranes related to their adjoining arcs, formed early in the basin history. They are mainly rigid in the tectonic model but share some flexible borders such as the Julia Extensional Transform Zone with adjacent blocks. The width of the Lau Terrace is interpreted to have remained constant, implying that it and the Lau Ridge moved as a unit during seafloor spreading in the SFB.

[35] The Pacific trench is assumed to have had a strike parallel to the Lau Ridge, imposed by the subduction zone geometry. The shape and motion of the Colville Ridge, for which there is no data, will most likely have been controlled by the same plunging slab. Motion of the Pacific plate in the Australian plate frame of reference [*Cande and Stock*, 2004] shows that the angle of convergence in the Cenozoic would have been more oblique in the south of the subduction zone than the north. Broadly, southward increasing obliquity would have been matched by increasing slab dip. Hence we have assumed in the north an arc-trench gap approximately equal to that of the modern Tonga arc-trench gap, and in the south a narrower gap consistent with a more steeply plunging slab.

[36] Spreading geometry in the South Fiji Basin was influenced by the interplay of trench rollback and motion along the Three Kings Ridge–Cook Fracture Zone system. The observed complex pattern of seafloor features and magnetic anomalies shows that spreading in some areas would have been in a continual state of readjustment.

Figure 10. Tectonic model of the South Fiji–Norfolk basin region based on kinematics of the northern SFB. The Australian plate is fixed. Estimates of relative motion of the Pacific plate from *Cande and Stock* [2004]. The crustal blocks defined in Figures 3 and 4 are outlined. Blue outlines represent continental and Loyalty–Three Kings crust; orange outlines represent Hunter microplate oceanic crust; green outlines represent Lau microplate oceanic crust; yellow shading represents intermediate crust; pink shading represents newly formed crust. Red double-headed arrows represent active spreading or extension. Parallel lines passing through the WL and WTK are the Loyalty and Three Kings Ridges (wide lines) and their associated ridge-and-basin terrain (thin lines) seen on bathymetry and gravity (Figures 1 and 3). Dashed wide line represents main volcanic chain of Northland Plateau and van der Linden Fault. Ar-Ar ages are shown for andesitic rocks (solid green dots), BABB (solid red dots), and alkalic basalts (solid blue dots). Green chevrons represent Miocene andesites. Red chevrons represent shoshonites. Large circle represents Resultant Euler pole for Lau Ridge–Tonga Trench. Small circles represent Euler poles for successive Hunter and Lau microplate spreading stages.

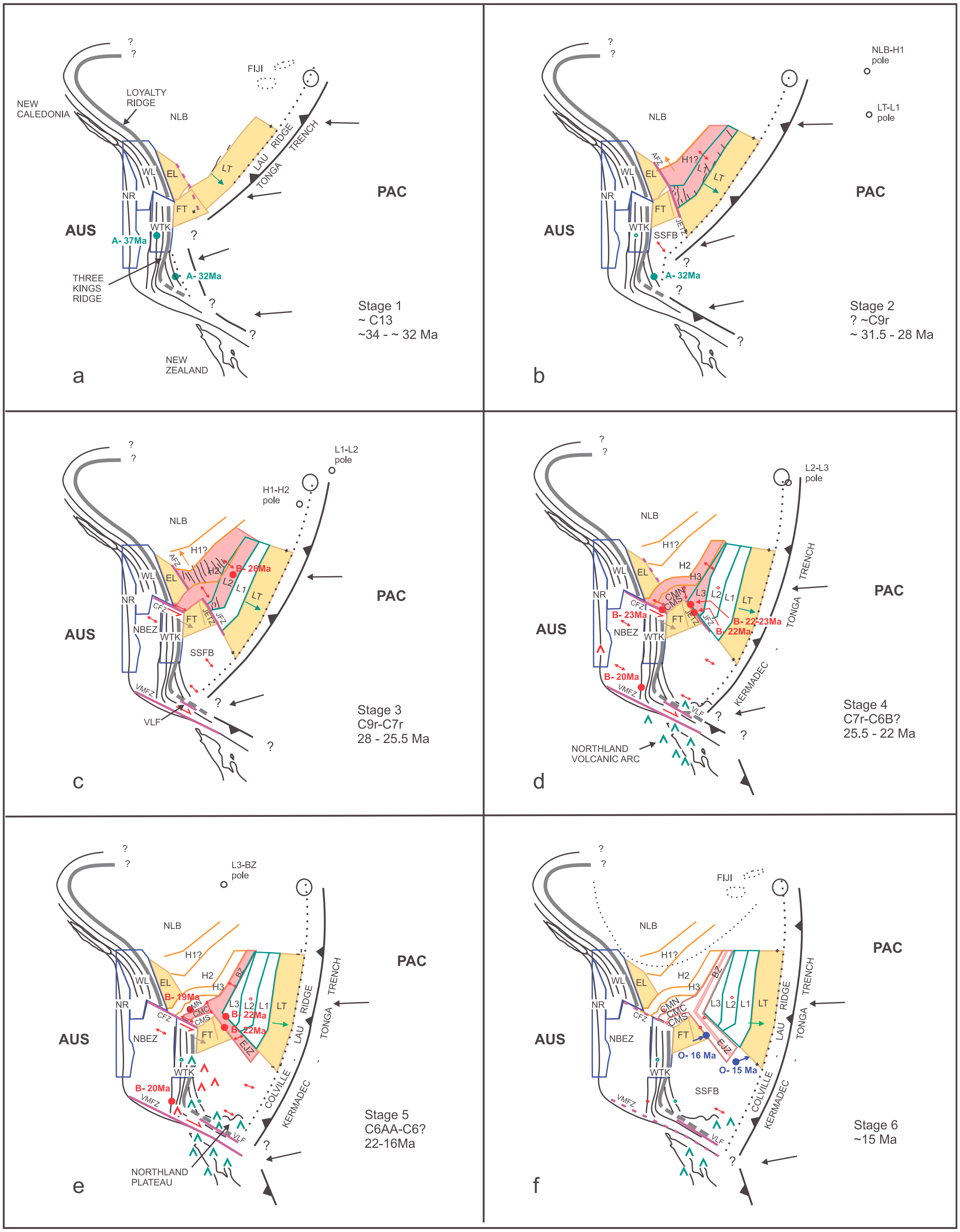
a
NEW CALEDONIA
LOYALTY RIDGE
NLB
FIJI
LT
LAU RIDGE
TONGA TRENCH
WL
EL
NR
FT
WTK
AUS
PAC
A- 37Ma
A- 32Ma
THREE KINGS RIDGE
NEW ZEALAND
Stage 1
~ C13
~34 - ~ 32 Ma
b
NLB-H1 pole
LT-L1 pole
NLB
AFZ
H1?
L1
LT
WL
EL
NR
FT
WTK
SSFB
JEFZ
A- 32Ma
AUS
PAC
Stage 2
? ~C9r
~ 31.5 - 28 Ma
c
L1-L2 pole
H1-H2 pole
NLB
AFZ
H1?
H2
L2
L1
LT
B- 26Ma
WL
EL
NR
CFZ
NBEZ
FT
WTK
JEFZ
JFZ
SSFB
VMFZ
VLF
AUS
PAC
Stage 3
C9r-C7r
28 - 25.5 Ma
d
L2-L3 pole
NLB
H1?
H2
H3
CMN
CMS
L3
L2
L1
LT
TRENCH
TONGA
KERMADEC
WL
EL
NR
CFZ
B- 23Ma
NBEZ
FT
WTK
EJFZ
JFZ
B- 22-23Ma
B- 22Ma
B- 20Ma
VMFZ
VLF
NORTHLAND VOLCANIC ARC
AUS
PAC
Stage 4
C7r-C6B?
25.5 - 22 Ma
e
L3-BZ pole
NLB
H1?
H2
H3
BZ
WL
EL
B- 19Ma
CMN
CMC
CMS
L3
L2
L1
LT
B- 22Ma
B- 22Ma
EJFZ
NR
CFZ
NBEZ
FT
WTK
B- 20Ma
VMFZ
VLF
LAU RIDGE
TONGA TRENCH
COLVILLE
KERMADEC
NORTHLAND PLATEAU
AUS
PAC
Stage 5
C6AA-C6?
22-16Ma
f
FIJI
NLB
H1?
H2
H3
BZ
CMN
CMC
CMS
L3
L2
L1
LT
EJFZ
WL
EL
NR
CFZ
NBEZ
FT
O- 16 Ma
O- 15 Ma
WTK
SSFB
VMFZ
VLF
LAU RIDGE
TONGA TRENCH
COLVILLE
KERMADEC
AUS
PAC
Stage 6
~15 Ma

Figure 10

[37] The oceanic area of the northern SFB is divided into blocks based on seafloor spreading magnetic anomalies and fracture zone trends interpreted from gravity anomaly lineaments. The blocks (Figures 3 and 4) are (1) H1 to H3, the Hunter microplate, (2) L1 to L3, the Lau microplate, (3) BZ, the Bounty Ridge Zone, (4) CMN, CMC and CMS, the north, central and southern parts of the Cook-Minerva spreading zone, and (5) EJZ, the East Julia Zone. Area L1 lacks identifiable spreading anomalies and is distinguished by strong linear gravity anomalies projecting from the Lau Terrace (LT) (Figure 3).

[38] The Norfolk Basin Extensional Zone (NBEZ) and the southern SFB (with few distinct seafloor spreading anomalies) are undifferentiated and left to expand freely in the model. Areas H2 and H3 and L2 and L3 contain matching interpreted magnetic anomalies 9 through 6C, supported by the Ar-Ar age on BABB of 26 Ma [*Mortimer et al.*, 2007] (Figure 4). The 22–23 Ma BABB in DSDP hole 285 on the edge of L3 matches a 22 Ma BABB on the eastern scarp of the Julia Fracture Zone. Between them, the East Julia Zone has a weak magnetic signature and is interpreted as crust of that age and younger. The BABB in DSDP285 was originally interpreted as a doleritic sill [*Stoeser*, 1976] and therefore not a true representation of the age of the crust. *Mortimer et al.* [2007] suggested that it could be a thick flow, a lava lake for example, and we have used their new Ar-Ar age from it. The location of the hole on the boundary of two crustal blocks L3 and EJZ allows both sill and thick flow interpretations to make sense, the age being that of the beginning of East Julia Zone magmatism. The Bounty Ridge Zone, the axis of symmetry between the Hunter and Lau microplates, is correlated with the East Julia Zone and the central Cook-Minerva Zone, the three completing the triple junction. A complex gravity pattern in the Bounty Ridge Zone suggests that in detail the pattern of spreading and corresponding basement structure in this zone are not simple, which may explain the lack of linear magnetic anomalies. The northern and southern parts of the Cook-Minerva Zone are interpreted from multibeam bathymetry and magnetic anomaly data to be older than the central Cook-Minerva Zone (Figure 9). The northern Cook-Minerva Zone contains BABB of Ar-Ar 19 Ma age [*Mortimer et al.*, 2007] on a seamount (Figure 8a). A BABB of 23 Ma Ar-Ar age at the northern end of the Three Kings Ridge, in the Cook Fracture Zone [*Bernardel et al.*, 2002], may belong to southern Cook-Minerva Zone or H3 crust.

5. Tectonic Model

[39] The tectonic model (Figure 10) is derived by removing the youngest back-arc crustal block BZ-CMC-EJZ, and then successively older blocks. The Norfolk Ridge and West Loyalty blocks are fixed to the Australian plate. The Lau Ridge remains attached to the eastern side of the Lau Terrace, assumed to have formed before oceanic block L1 and younger elements. The Lau Ridge and Kermadec-Tonga Trench move west as the South Fiji Basin closes. When the South Fiji and Norfolk basins are closed, blocks FT and LT, the Fantail and Lau terraces, are restored to a position adjoining block EL, the East Loyalty Zone, all three flanking a space that is interpreted to have been part of the North Loyalty Basin that was much later subducted beneath the North Fiji Basin. In this tectonic model, the North Loyalty Basin (NLB) must have opened to the present longitude of Fiji **before** the SFB began to open.

5.1. Stage 1, ~34 to ~32 Ma

[40] In the earliest Oligocene, at the time that the East Loyalty (EL), Fantail Terrace (FT) and Lau Terrace (LT) blocks were conjoined, the Loyalty and Three Kings ridges were a continuous feature lying along the continental margin, with arc volcanism recorded at 37 and 32 Ma on the Three Kings Ridge (Figure 10a). Three Kings Ridge was later overprinted by early Miocene arc volcanism [*Mortimer et al.*, 1998], and the axis shown in Figure 10a, derived from present-day bathymetry, may not be precisely that of the early ridge. Northeast striking fault fabric in the deep sedimentary basin of the East Loyalty Zone (Figures 8a and 9a) and extensional faults in the Lau Terrace suggest southeastward migration of the Lau Ridge and Tonga Trench. Motion necessary for migration to continue required either rifting the Fantail Terrace from the East Loyalty Zone or shearing the Lau Terrace from the Fantail Terrace along a transform fault. Fault structure on the northwestern Fantail Terrace (Figures 8a and 9a) and matching large magnetic anomalies (possibly signifying intrusions and volcanics) on both the northwestern Fantail Terrace and southeastern East Loyalty Zone (arrows in Figures 4 and 8b) support rifting, but the kinematics of Figure 10b suggest that transform

motion predominated and significant displacement of the Fantail Terrace came later. There would have been Pacific subduction along the Tonga Trench, reflecting combined back-arc spreading and Pacific-Australian plate convergence, which fed arc volcanism in Fiji, and probably the Lau Ridge. There may have been slower paced, oblique convergence and a developing Northland Trench along the Northland margin of New Zealand at this time.

5.2. Stage 2, ~31.5–28 Ma

[41] The Tonga Trench rolled back about a pole near Fiji, taking the Lau arc and Lau Terrace with it, and in the early Oligocene the first oceanic crust of the South Fiji Basin began to form (Figure 10b). New crust (H1 and L1) was formed in the northern SFB on either side of a northeast trending, arc-parallel spreading ridge, the Bounty Ridge, as both the Hunter and Lau microplates moved apart along a transform system comprising the Angela Fracture Zone (AFZ) (informal new name) and the Julia Extensional Transform Zone (JETZ). For the model to preserve a sensible subduction geometry, the JETZ would have linked with spreading in a nascent southern SFB where rifting of the Three Kings Ridge exposed the 32 Ma andesite. Expansion in the JETZ accounts for some of the anomalous crustal block overlap between the Fantail and Lau terraces seen in Stage 1. There was as yet no motion of the Three Kings Ridge or displacement on the Cook and Vening Meinesz fracture zones. Subduction of the Pacific plate along the Tonga Trench continued under the Lau Ridge, and expanded southwestward forming a new ridge, the Colville Ridge. Oblique subduction probably became well established along the Northland margin. The age of Stage 2 is taken as ca. 31.5 to 28 Ma, based on the exposure of 32 Ma andesite and the age of chron 9r at the end of L1-H1 spreading.

5.3. Stage 3, 28–25.5 Ma

[42] In the late Oligocene complexity of the back arc increased enormously with the development of multiple fracture zones and initiation of wholesale drift of the Three Kings Ridge and Fantail Terrace as a new mobile block (Figure 10c). New crust (H2 and L2) continued to be formed along the Bounty Ridge spreading center as Tonga Trench rollback continued about the Euler pole near Fiji. Clockwise rotation of the Hunter microplate continued, with northwesterly transform displacement relative to the fixed Australian plate probably concentrated on the Angela Fracture Zone. The Lau microplate moved southeastward with the retreating subduction zone while the anticlockwise rotation was taken up by the JETZ extensional component of the Julia Fracture Zone. The ridge-fault-fault (RFF) configuration of the Minerva Triple Junction changed to a complex geometry with spreading propagating across the Angela-Julia fracture zone and through the East Loyalty–Fantail Terrace crust (EL/FT) to a newly forming Cook Fracture Zone (CFZ). The West Three Kings Ridge complex (WTK) and Fantail Terrace began to migrate as a block southeastward along the Cook and Vening Meinesz fracture zones toward the rapidly retreating southern part of the subduction zone. Back-arc expansion in the south was accommodated by new rifting and extension in the Norfolk Basin (NBEZ) as well as significant spreading in the southern South Fiji Basin (SSFB). The new strike-slip/transform geodynamics extended to the New Zealand continental margin [*Mortimer et al.*, 2007; *Herzer et al.*, 2009]. Pacific subduction continued along the Tonga Trench and northern New Zealand margin, and the Colville Ridge/arc continued to lengthen southwestward. The age of Stage 3 is taken as 28 to 25.5 Ma based on the 26 Ma basalt in DSDP 205 and the ages of chrons 9r and 7r, identified in blocks L2 and H2.

5.4. Stage 4, 25.5–22 Ma

[43] In the earliest Miocene, the back-arc basin continued to expand as new crust was generated along the Bounty spreading ridge (H3 and L3) and Cook-Minerva spreading center (CMN-CMS) (Figure 10d). The Hunter microplate, however, stopped moving at the end of Stage 3 and the Angela Fracture Zone ceased to function. With the Hunter microplate now part of the Australian plate, motion of blocks in the back arc was all toward the southeast, including migration of the accreting Bounty and Cook-Minerva spreading centers. The West Three Kings Ridge–Fantail Terrace (WTK–FT) block continued to move southeast along the Cook and Vening Meinesz fracture zones, with the southern SFB and the Norfolk Basin expanding ahead of and behind it, respectively. The difference between the vectors of the WTK–FT block and the Lau microplate was accommodated by the JETZ. The Minerva Triple Junction became established as a ridge-ridge-fault (RRF) feature with a stable Bounty spreading arm, an enduring Julia Fracture Zone with its extensional component, and a complex Cook-Minerva spreading arm that constantly

adjusted to the migration of the rigid crustal blocks and the changing dynamics of the Minerva Triple Junction. Pacific subduction continued along the Kermadec-Tonga and Northland trenches, but as the former rolled back, it progressively captured the latter. It was during Stage 4 that the Northland Allochthon was emplaced and volcanism began in the Northland arc. The age of Stage 4 is interpreted to be 25.5 to 22 Ma based on the age of chron 7r and possible chron 6Br, identified in blocks L3 and H3, and 22–23 Ma BABBs in DSDP 285. The ages of BABB dredged in the Cook FZ and Julia FZ (23 Ma and 22 Ma, respectively) support this interpretation.

5.5. Stage 5, 22 to ~16 Ma

[44] During the apparent final stages of expansion, before the active back arc jumped to the Havre-Lau system, the geometry of the Minerva Triple Junction became RRR (Figure 10e). This new configuration was in response to the increasingly eastward directed movement of the Lau microplate, brought about by continued anticlockwise rotation of Tonga trench rollback. This involved spreading in the Bounty Ridge and central Cook-Minerva zones, and a change of the Julia FZ to a spreading ridge, the East Julia Zone. The West Three Kings–Fantail Terrace block continued to migrate southeastward along a straight trajectory as the Norfolk and southern South Fiji back-arc basins widened. The Kermadec-Tonga subduction zone finally consumed the Northland subduction zone, and became linked directly to the Hikurangi subduction zone to the south. During Stage 5, calc-alkaline volcanism was widespread in the Northland arc and Northland Plateau. Stage 5 lasted from about 22 Ma to approximately 16 Ma, based on 22 Ma BABB on the edges of the East Julia Zone (EJZ), 20 Ma BABB in the Norfolk Basin, 19 Ma BABB volcano in the northern Cook-Minerva Zone, bathymetric evidence for even younger crust in the central Cook-Minerva Zone, and continued tectonism on the Northland margin [*Herzer et al.*, 1997, 2009].

5.6. Stage 6, 16–15 Ma

[45] Precisely when the South Fiji and Norfolk basins stopped spreading is not known as the youngest crust (that in the CMC and that associated with the rifted Pecan Seamount) has not been sampled. If the large, linear, east–northeast, trending seamounts with 16 and 15 Ma OIB are minihot spot trails [*Mortimer et al.*, 2007] then spreading could have continued until 15 Ma (Figure 10f). This age for the end of spreading is supported by waning tectonism on the Northland Plateau [*Herzer et al.*, 2009] and elsewhere on the northwest New Zealand margin [*Herzer et al.*, 1997]. By 16 to 15 Ma, volcanic activity in the Northland arc and Northland Plateau was confined to the southeast where the Kermadec and Hikurangi subduction zones were active.

6. Discussion

[46] The mode in which the northern South Fiji Basin opened provides a keystone in the Eocene-Miocene tectonic framework of the surrounding SW Pacific region, in particular that of the northern New Zealand plate boundary. In the early Oligocene the North Loyalty Basin was open, and an active Three Kings arc was in a pericontinental position. Plate convergence at the Tonga Trench, accelerated by back-arc spreading, would have been much faster than at the Three Kings–New Zealand margin. Plate convergence at the Three Kings Ridge (Figure 10a) begs the existence of a west dipping Pacific subduction zone beneath it, but this is inconsistent with dredge samples; the 37 Ma arc lava in the West Three Kings Zone is a boninite and the 32 Ma lava on the eastern flank is an andesite. Although these are extremely sparse data, the samples imply that the Three Kings Ridge may have been a west facing arc whose forearc collided with the Norfolk Ridge, a scenario supported by observations of obducted rocks in New Caledonia. This geometry would require a Three Kings subduction flip between Stages 1 and 2.

[47] New back-arc spreading is interpreted to have begun in the southern SFB south of the Fantail Terrace and Julia FZ as the Pacific plate boundary began to retreat from the Three Kings Ridge (red double-headed arrows, Figure 10b). At this stage, the rift margin exposing the 32 Ma andesite would have formed as the southern SFB began to open. Subduction under the southern SFB led to formation and southwestward growth of the Colville arc. There are few samples from the Colville Ridge [*Ballance et al.*, 1999; *Mortimer et al.*, 2010], but our model predicts that its history as a ridge began later than that of the Lau Ridge.

[48] As the southern SFB took shape during the Oligocene, the plate boundary is interpreted to have developed a cusp at the junction with the Northland margin (Figures 10b and 10c). The relative motion of the Pacific plate suggests that the Northland margin developed into a subduction zone, which

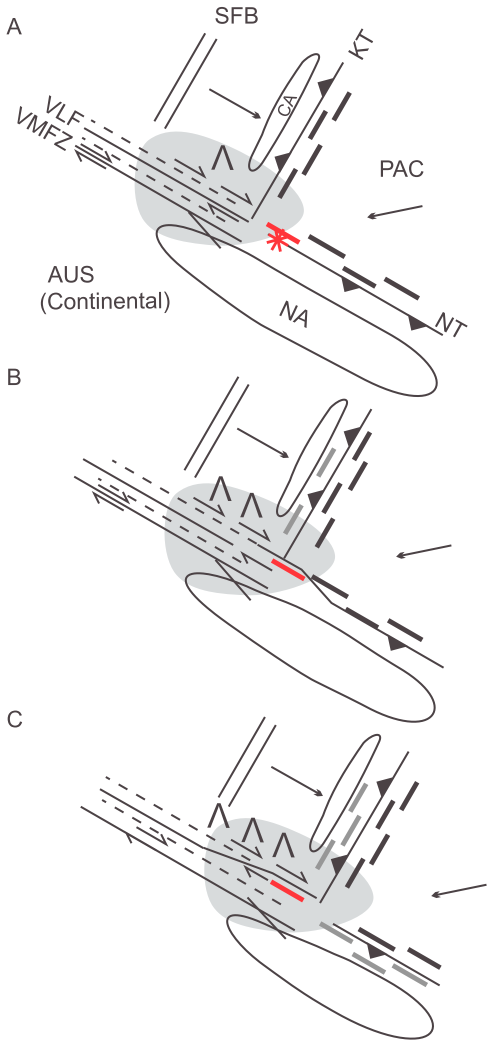

Figure 11. Schematic model of the migrating trench cusp (TTF triple junction). Subduction at the Kermadec Trench is much faster than at the Northland Trench. This simple hypothetical sequence illustrates how (1) arc volcanism extending into the back arc above a zone of shallow dipping slab forms the Northland Plateau (chevrons) and (2) basalt from a jammed horst (red block) of Pacific crust in the cusp is transferred to the upper plate in the strike-slip/transform zone. Shaded area represents region of warped lower plate with shallow dip; black blocks represent outer trench-wall horst-and-graben structure; gray blocks represent subducted horsts; red asterisk represents impacting horst. AUS, Australian plate; CA, Colville arc; KT, Kermadec Trench; NA, Northland arc; NT, Northland Trench; PAC, Pacific plate; SFB, South Fiji back-arc basin; VLF, van der Linden Fault; VMFZ, Vening Meinesz Fracture Zone.

eventually led to arc volcanism in Northland. The first appearance of the Northland volcanic arc about 23 Ma is consistent with subduction beginning about 32–28 Ma. The progressive NW to SE extinction of the arc from 18 to 15 Ma [*Hayward et al.*, 2001] is consistent with the demise of subduction along the Northland Trench due to rollback of the Kermadec-Tonga Trench, while the continuation of volcanism in the southeast is consistent with the eventual linkup of the Hikurangi and Colville (Kermadec) subduction zones.

[49] Parallelism of the Northland Plateau with the continental margin suggests a volcanic and structural relationship with the migrating trench cusp. The model predicts that in the region north of the Northland margin, Cretaceous crust on the Pacific plate was progressively replaced in the late Oligocene and early Miocene by new SFB back-arc crust as the Kermadec trench swept past. During this episode, the volcanic Northland Plateau with its arc volcanoes, was constructed. If the magnetic anomalies of the Northland Plateau do reflect seafloor spreading processes then the SFB back-arc crust must have formed either shortly before overprinting by arc rocks of the plateau, or simultaneously with them as *Herzer et al.* [2000] and *Mortimer et al.* [2007] infer (cf. arc-like constructions within the actively extending southern Havre Trough back arc [*Wright et al.*, 1996]).

[50] We propose the following model for the origin of the Northland Plateau (Figure 11). The greatly divergent strikes of the Colville (Kermadec) and Northland subduction zones would have necessitated a warp with shallow dip in the downgoing slab at the intersection. The warp would have followed in the wake of the migrating triple junction, possibly deflected by the linear continental margin. Arc volcanism would thus have extended further northwest along the shallow-dipping warp than elsewhere behind the Colville Ridge, erupting in the back arc, and this, combined with possibly effusive leaky transform volcanism, created the Northland Plateau.

[51] It was at this time that the Northland and East Coast allochthons were emplaced, and tectonism involved in the change from subduction to transform may have initiated and controlled this event. The third arm of the triple junction that developed at the cusp consisted of the crustal strike-slip and transform faults of the van der Linden and Vening Meinesz systems. The geology and structure of the continental margin at the southern end of the SFB [*Herzer et al.*, 2009] indicates some partitioning of the transform motion; the van der Linden Fault in the outer Northland Plateau acted as a continent-ocean transform for SFB seafloor spreading, while the Vening Meinesz Fracture Zone on the continental shelf edge and inner Northland

Plateau acted as a crustal strike-slip fault (Figures 10d and 10e).

[52] We suggest that trench capture in a migrating TTF triple junction, where the pericontinental trench being consumed is replaced by a colinear, wide, continent–back arc transform/strike-slip complex, is a potential setting to transfer pieces of subducting-plate crust in undeformed blocks to the upper plate, and that Pacific basalt was thus entrained.

[53] In our example, a horst block of the Pacific plate becomes jammed in the Northland trench at the cusp, where the slab abruptly becomes shallower (Figure 11a). The block becomes part of the upper plate (Figure 11b) and is incorporated into the rapidly advancing transform zone (Figure 11c). We propose that the continental margin sediments, Pacific basalt, South Fiji Basin basalt, and even arc lavas of the Northland Plateau and rocks inherited from the possible Three Kings collision, were entrained in the transform zone, and that uplift of this complex allowed nappes to slide off forming the Northland Allochthon. This hypothesis has the attraction that it explains some of the diverse and contentious ages and compositions of the ophiolite bodies in the allochthon [e.g., *Nicholson and Black*, 2004; *Whattam et al.*, 2004] and, if arc collision is accepted, the mix of near and distant reported paleolatitudes of the ophiolites [e.g., *Cassidy*, 1993; *Rait*, 2000; *Whattam et al.*, 2005].

7. Conclusions

[54] Within the region of the South Fiji Basin, areas of continental and volcanic arc (20–25 km thick), transitional (10–18 km thick), and oceanic (~8 km thick) crust are identified from analysis of satellite and marine gravity anomaly data. As seafloor spreading proceeded in the back arc, these elements behaved as rigid and partly rigid blocks and freely expanding oceanic domains, respectively. Magnetic anomalies have been identified in the oceanic domain as chrons 9 to 6c by association with radiometrically dated back-arc basin basalt and dolerite samples. Regional geophysics and multibeam bathymetry around and northeast of the Cook Fracture Zone identify key fracture zones and define the seafloor spreading geometry. The opening of the basin is described in six stages.

[55] Stage 1 is in the early Oligocene. Before SFB spreading or Norfolk Basin extension, the North Loyalty Basin was apparently fully open as far east as Fiji. The Tonga Trench lay east of the Lau Ridge. The Three Kings and Loyalty ridges were connected as a single volcanic arc that may have collided in the late Eocene with the New Caledonia–Norfolk Ridge.

[56] Stage 2 is in the middle Oligocene. The Tonga Trench began rolling back about an Euler pole near Fiji, and the South Fiji Basin began to form as two basins, north and south, linked by a single fracture or extensional transform zone, the Julia Fracture Zone.

[57] Stage 3 is in the late Oligocene. As the two basins continued to open, the northern spreading center propagated across the Julia Fracture Zone to the Loyalty–Three Kings Ridge which began to shear along the newly forming Cook Fracture Zone. The Three Kings Ridge began to move southeastward, and the Norfolk Basin began to open. A complex transform/strike-slip boundary combining the van der Linden Fault and Vening Meinesz Fracture Zone developed on the New Zealand margin to accommodate this opening.

[58] Stage 4 is in the very late Oligocene–very early Miocene. The late Oligocene dynamics continued into the Miocene but the northern segment of the Julia Fracture Zone (the Angela Fracture Zone) died; net back-arc motion was now all toward the southeast in the wake of the migrating Kermadec-Tonga Trench. The Minerva Triple Junction was now linked to the Cook Fracture Zone by an unstable and continually repropagating spreading ridge.

[59] Stage 5 is in the early Miocene. The three-basin geodynamics continued, with the spreading systems linked by the Cook and Julia fracture zones, and the Three Kings Ridge still migrating southeastward along the Cook and Vening Meinesz fracture zones. But, as the anticlockwise sweep of the Tonga Trench became increasingly easterly, the Julia Fracture Zone became a spreading ridge and the northern SFB became a ridge-ridge-ridge system.

[60] Stage 6 is in the early middle Miocene. Final spreading in the Bounty and East Julia zones and southern South Fiji Basin may have occurred at this time, coinciding with waning tectonism on the northern New Zealand margin.

[61] A tectonic model for the evolution of the northern South Fiji Basin provides a framework for the development of the northern New Zealand plate boundary. It agrees with the offshore geology and explains many of the diverse and often conflicting observations of onshore geology. The back-arc and Australian-Pacific plate motions imply that from the early Oligocene a trench-trench-fault triple junction was present at the Northland margin. The Kermadec-Tonga trench was almost orthogonal to

the Reinga-Northland margin and, as it rolled back along the margin, it consumed the stationary Northland Trench. Behind the Kermadec-Tonga Trench (on the back-arc side) the margin became a continent-ocean transform/strike-slip complex that accommodated the opening of the Norfolk and South Fiji basins. Disposition of the trenches and timing of trench migration predicted by the model have three important implications: (1) the Northland volcanic arc was generated by subduction of the Pacific plate under Northland (possibly following Three Kings arc collision and subduction flip) and was progressively extinguished by the passage of the triple junction, (2) the Northland Plateau was generated in the South Fiji Basin back arc above a narrow zone of shallow dipping slab and should include a mix of oceanic crust and arc volcanics, and (3) the allochthon was generated in the migrating triple junction and growing transform where complex trench-transform interactions sliced and delaminated the crust, and caused differential uplift and subsidence, leading to eventual large gravity slides. The Northland ophiolites of multiple ages, chemistries and paleolatitudes were sourced from Pacific crust excised and obducted in the trench cusp, South Fiji Basin back-arc crust excised from the Northland Plateau in the transform, including even Northland Plateau arc volcanics, and possibly rocks inherited from Three Kings arc collision.

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