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The Strike-Slip West Wishbone Ridge and the Eastern Margin of the Hikurangi Plateau

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Key Points:

- The West Wishbone Ridge is recognized as having been a dextral strike-slip fault during the Cretaceous
- The present-day eastern margin of the Hikurangi Plateau between 42-43°S is located using seismic reflection data and gravity modeling
- We identify over-thickened oceanic crust north of, and proximal to the Hikurangi Plateau

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Abstract The West Wishbone Ridge (WWR), east of New Zealand, has previously been interpreted as a Cretaceous plate boundary, although both the nature and timing of motion along this feature have been disputed. Here, using recently acquired seismic reflection data from the region of the intersection of the WWR with the Chatham Rise, we show that the WWR was primarily a dextral strike-slip fault during the Late Cretaceous. The WWR first propagated along the eastern margin of the Hikurangi Plateau after the collision of the Hikurangi Plateau with the Chatham Rise, in response to the slowing of spreading at the Osbourn Trough while spreading continued unabated east of the East Wishbone Ridge, from ca. 105 Ma. Reorientation of spreading at the Osbourn Trough at this time resulted in short-lived, oblique subduction beneath the southern extent of the WWR. Motion along the WWR likely ceased with the cessation of Osbourn Trough spreading. Using our seismic reflection data and gravity modeling across those same profiles, we locate, for the first time, the eastern boundary of the Hikurangi Plateau between 42–43°S. We also find anomalously thick oceanic crust (~12 km thick) north of the Hikurangi Plateau. Matching tectonic fabric and fracture zone links between the East Wishbone Ridge and the De Gerlache Gravity Anomaly near Ellsworth Land on the West Antarctic margin indicates that these features were linked or parallel during the Late Cretaceous, and fed strike-slip motion southward into the Gondwana interior, contributing to the onset of Gondwana rifting ca. 85 Ma.

1. Introduction

The Wishbone Ridge is an intra-oceanic feature that extends southward from the eastern edge of the Osbourn Trough and forks into two at ~32°S (Figure 1). The eastern of the two forks (the East Wishbone Ridge, EWR) has previously been interpreted as a Cretaceous fracture zone (Downey et al., 2007; Sutherland & Hollis, 2001; Worthington et al., 2006). The nature of the western fork (the West Wishbone Ridge, WWR), however, remains disputed, and several theories have been postulated for what motion was fed along it and the timing of that motion (Table 1). Much of the oceanic crust in the western Pacific was emplaced during the Cretaceous Normal Superchron (Cande & Kent, 1995). This leads to significant uncertainties in determining the timing of events in this region, no less for the crust on either side of the WWR. This uncertainty in the crustal age has proved a problem for determining the nature, and timing, of any motion along the WWR.

Based on similarities of the gravity signature of the WWR with stalled spreading ridges west of the Antarctic Peninsula and in the west Scotia Sea, Luyendyk (1995) suggested that the WWR marks the rift valley of such a spreading ridge that stalled outboard of the trench. However, the identification of the Osbourn Trough as an extinct spreading ridge (Billen & Stock, 2000; Downey et al., 2007; Worthington et al., 2006) indicated that this stalled-rift model for the WWR was unlikely.

A second possibility is that the WWR was predominantly a dextral strike-slip fault (Davy et al., 2008; Larter et al., 2002; Sutherland & Hollis, 2001). This theory is consistent with bathymetric fabric evident in multibeam bathymetric data (Sutherland & Hollis, 2001). Based on satellite gravity data, Sutherland and Hollis (2001) interpreted the WWR as a dextral strike-slip fault and suggested that it can be extended westward through the Chatham Islands and along the northern Gondwana margin. However, it is also possible that it (a) extends southwestward onto Campbell Plateau; (b) extends along the eastern margin of the Campbell Plateau (Davy et al., 2008); (c) is subdivided into some combination of these; or (d) ceases at the Chatham

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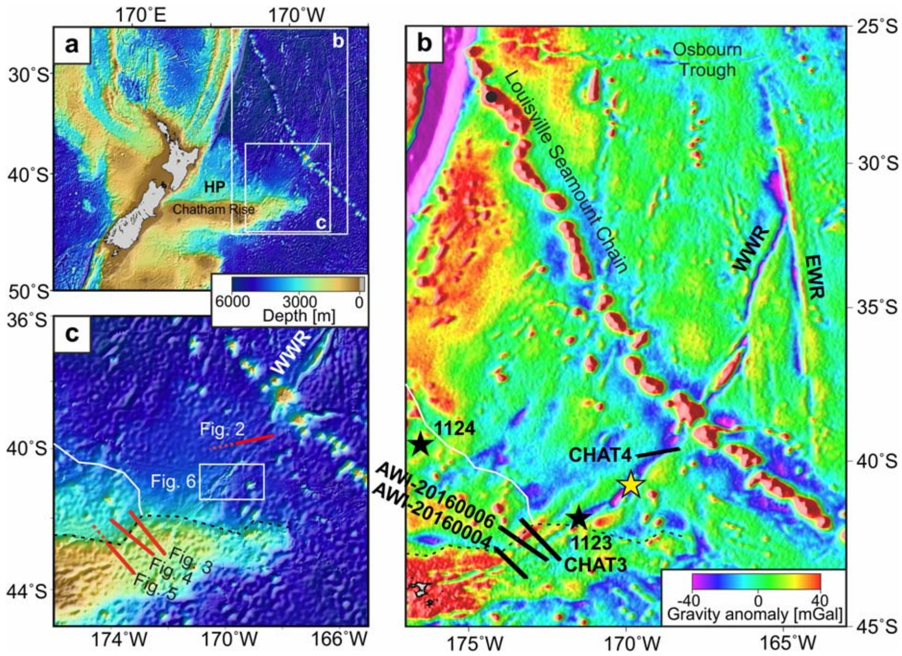

Figure 1. (a) Regional overview map of the New Zealand region with bathymetry from the GEBCO (General Bathymetric Chart of the Oceans; http://www.gebco.net/) 2014 grid. The box overlays show the location of Figures 1b and 1c. (b) Sun-illuminated satellite gravity map (Sandwell et al., 2014) showing the locations of discussed seismic reflection profiles that cross the West Wishbone Ridge (WWR) near to its intersection with the Chatham Rise. (c) Zoomed bathymetric map highlighting the intersection of the WWR with the Chatham Rise with the location of later figures overlain. Dotted red line: westward extension of the gravity model along profiles CHAT-4 and AWI-20160004. Black stars: ODP sites 1123 and 1124, whose results are important for identification of regional seismic stratigraphy. Yellow star: 115 Ma Wishbone dredge (Mortimer et al., 2006). Black point: Louisville Guyot. EWR: East Wishbone Ridge. Black dotted line: northern margin of the Chatham Rise. Solid white line: northern margin of the Hikurangi Plateau (HP).

Rise margin. If the WWR continues through the Chatham Rise convergent margin into the Gondwana interior, then motion along it may have contributed to the Late Cretaceous onset of rifting of the New Zealand sector of the Gondwana super-continent (Davy et al., 2008).

A third suggestion for motion along the WWR was based on the isotopic analysis of two lavas and a volcaniclastic sandstone recovered from the WWR at 40.5°S (Figure 1), which have an average age of 115 ± 1 Ma (Mortimer et al., 2006). Analysis of these samples revealed low concentrations of High Field Strength Elements and high concentrations of Large Ion Lithophile Elements: characteristics indicative of slab dewatering and subduction. This led Mortimer et al. (2006) to postulate a composite model, whereby the WWR was an intra-oceanic fracture zone prior to 115 Ma, a subduction arc at 115 Ma, and a rift system after this time.

Table 1
Summary of Previous Theories for Cretaceous Motion Along the West Wishbone Ridge

Reference	Suggested motion along the WWR	Suggested timing of WWR motion	Model based on
Luyendyk (1995)	Rifting	Pre-83 Ma	Similarity of the WWR gravity anomaly with that of stalled spreading ridges elsewhere
Sutherland and Hollis (2001) Larter et al. (2002) Davy et al. (2008)	Strike-slip	Late Cretaceous	Multibeam and satellite gravity data
Mortimer et al. (2006)	Strike-slip Subduction Rifting	Pre-115 Ma 115 Ma Post-115 Ma	Age and subduction-related characteristics of dredge samples from the WWR scarp at ~40.5°S

The nature of the WWR, and the timing of any motion along it, has an important bearing on our understanding of the Cretaceous plate dynamics in the southwest Pacific region, particularly because motion along the WWR has been suggested to have played a role in the break-up of the New Zealand-sector of Gondwana (Davy et al., 2008; Mortimer et al., 2006; Sutherland & Hollis, 2001). Using recently acquired seismic reflection data from the SO246 cruise of R/V *Sonne*, as well as previously collected but unpublished seismic reflection data, we aim to better constrain the structure and southward extent of the WWR, as well as the timing of motion and the role (if any) of the WWR in the break-up of Gondwana.

2. Tectonic Setting

At its southern end, the WWR is apparently co-incident with the eastern margin of the Hikurangi Plateau, a Large Igneous Province (LIP) which lies east of, and beneath, New Zealand, and underlies the Chatham Rise (Figure 1; Mortimer & Parkinson, 1996). LIPs are predominantly mafic in composition and, while a number of theories have been suggested, are commonly thought to result from ascending mantle plumes (Coffin & Eldholm, 1994). Geochemical and age distribution data indicate that the Hikurangi Plateau is comparable in both age and composition to the Manihiki and Ontong-Java Plateaus (Billen & Stock, 2000; Mahoney et al., 1993; Zhang & Li, 2016), which lie to the north and northwest of Hikurangi Plateau respectively. These similarities led Taylor (2006) to suggest a super-LIP, combining the Ontong-Java, Manihiki and Hikurangi Plateaus ("Ontong-Java Nui"). The first stage of Ontong-Java Nui volcanism began ca. 125 Ma (Timm et al., 2011). It is estimated that this super-LIP covered 1.1% of Earth's surface at the time of formation (Hochmuth et al., 2015).

Rifting of Ontong-Java Nui initiated soon after the initial volcanism stage of the super-LIP ca. 120 Ma (Taylor, 2006; Worthington et al., 2006). Plate motion data and rotated block basement structure along the northeastern Hikurangi Plateau indicate that rifting of the Hikurangi and Manihiki plateaus occurred at the Osbourn Trough (Billen & Stock, 2000; Downey et al., 2007; Hochmuth et al., 2015), with the Hikurangi Plateau initially migrating toward the SSW (Davy, 2014). When the Hikurangi Plateau reached the Gondwana margin, it began to subduct beneath its northern margin: the present-day Chatham Rise (Wood & Davy, 1994). The timing of this impact on the Chatham Rise has been suggested to be between 110 and 105 Ma (Davy, 2014; Reyners et al., 2017), corresponding with a regional change in tectonic regime from convergent to extensional (Bradshaw, 1989; Laird & Bradshaw, 2004). Following the onset of subduction of the Hikurangi Plateau beneath the Chatham Rise, or perhaps as a result of this impact, subduction onshore began to stall and ceased at ca. 105 Ma (Bradshaw, 1989). Following this onshore stalling of subduction, between ca. 105 and 100 Ma, subduction slowed offshore of eastern New Zealand (most significantly in the west and more gradually in the east), resulting in an anticlockwise rotation (to the present-day east-west orientation) of sectors of the convergent margin offshore before subduction ceased altogether (Davy, 2014). This rotation was accommodated by margin offset and offshore extension zones which formed between, and within, rotated crustal blocks (Davy, 2014) that are evident in both gravity and seismic reflection profiles across the Chatham Rise.

Seafloor spreading fabric in the vicinity of the Osbourn Trough indicates that the spreading ridge began to rotate in an anti-clockwise direction (to its present-day east-west orientation) at a similar time to the onshore jamming of Hikurangi Plateau subduction, after which the spreading rate began to slow (Downey et al., 2007). It should be noted, however, that the timing of cessation of spreading at the Osbourn Trough is poorly constrained as a result of the emplacement of crust during the Cretaceous Normal Superchron, and has been variously estimated to have occurred between 105 and 71 Ma (Billen & Stock, 2000; Davy et al., 2008; Downey et al., 2007; Larson et al., 2002; Worthington et al., 2006; Zhang & Li, 2016).

3. Data Acquisition, Processing and Modeling Methodology

3.1. Seismic Reflection Data

Seismic reflection profiles AWI-20160006 and AWI-20160004 were collected during the voyage SO246 of RV Sonne in 2016 in order to investigate the structure of the WWR near its intersection with the northern margin of the Chatham Rise. The source used for acquisition of these reflection profiles consisted of 6 G-Guns (total volume of 51 l) towed at a depth of 6 m and fired at 20 s intervals ($\sim$ 50 m). Data were recorded with a 3 km long digital solid streamer with 240 channels at intervals of 12.5 m and at an initial sampling rate of

1 ms (Gohl et al., 2016). Processing of these data involved resampling to 4 ms, applying regularized geometry (50 m shot spacing), amplitude recovery, trace edits, removal of swell noise, band-pass filtering, and sorting by CDP with bin spacings manually set to 25 m (resulting in a nominal fold of 120). Detailed velocity analysis was undertaken every 2.5 km along profile and was used to correct the data for normal moveout (NMO) before applying parabolic radon transform and f-k filtering. The NMO correction was removed before a secondary velocity analysis at the same CDP interval. This revised velocity field was used to correct for NMO before the data were stacked, post-stack finite difference time migrated, and scaled using a full trace balance.

Magnetic data were also collected during the acquisition of profiles AWI-20160006 and AWI-20160004, and were subtracted from the international geomagnetic reference field (Gohl et al., 2016).

Seismic reflection profiles CHAT-3 and CHAT-4 were collected by MV Geco Resolution, for GNS Science, between profiles collected for the delineation of New Zealand's extended continental shelf UNCLOS project. CHAT-3 and CHAT-4 were collected using an airgun array with a total volume of 134.4 l, towed at a depth of 7 m and fired at 50 m intervals. Data were recorded using a 6 km long streamer with 480 channels, and at a sampling rate of 2 ms. These data were processed by Robertson Research (Perth, Australia) in 2002. Processing involved preliminary steps of gain recovery, resampling to a rate of 4 ms, static correction, filtering,

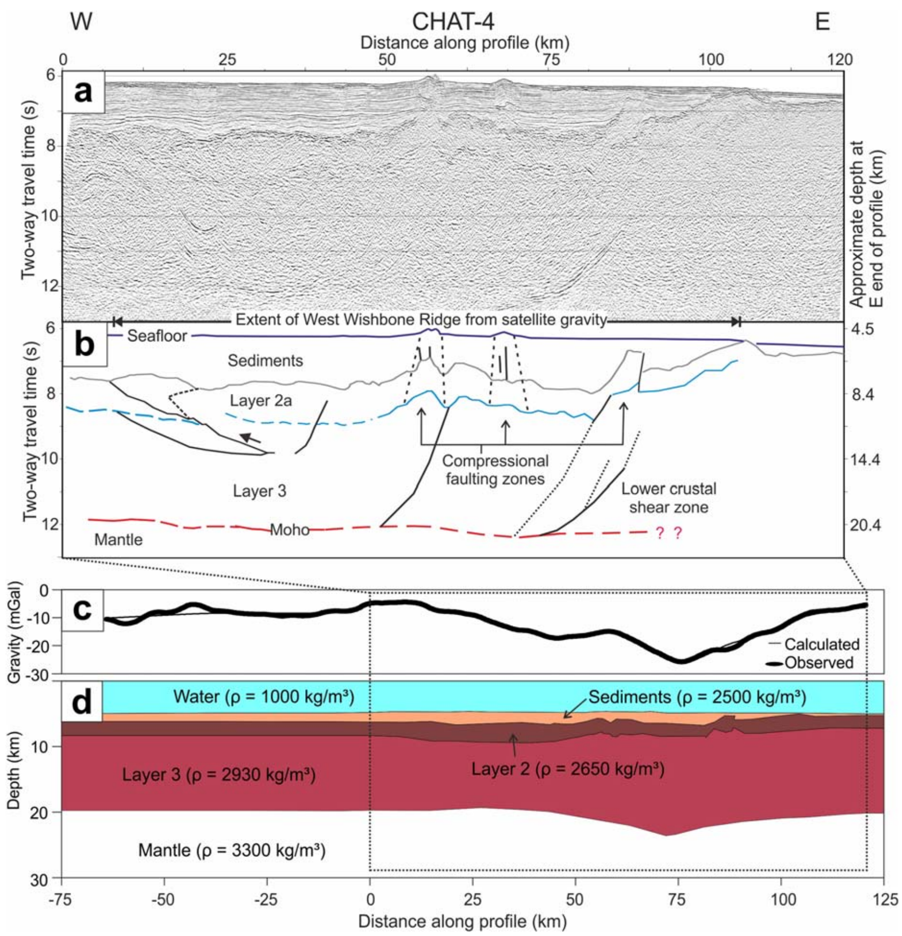

Figure 2. (a) Time migrated seismic reflection profile CHAT-4. (b) Interpreted horizons across profile CHAT-4 are indicated with colored lines as marked and faults are shown with black lines. Dashed lines indicate interpolated horizons/faults. Dotted black lines indicate the boundaries of the regions of compressional faulting. The black arrow shows the direction of motion along the fault plane. The ages of the units imaged on this profile are poorly constrained due to their emplacement during the Cretaceous Normal Superchron. (c) Observed gravity anomaly across profile CHAT-4 and the calculated gravity anomaly for the model in Figure 2d.

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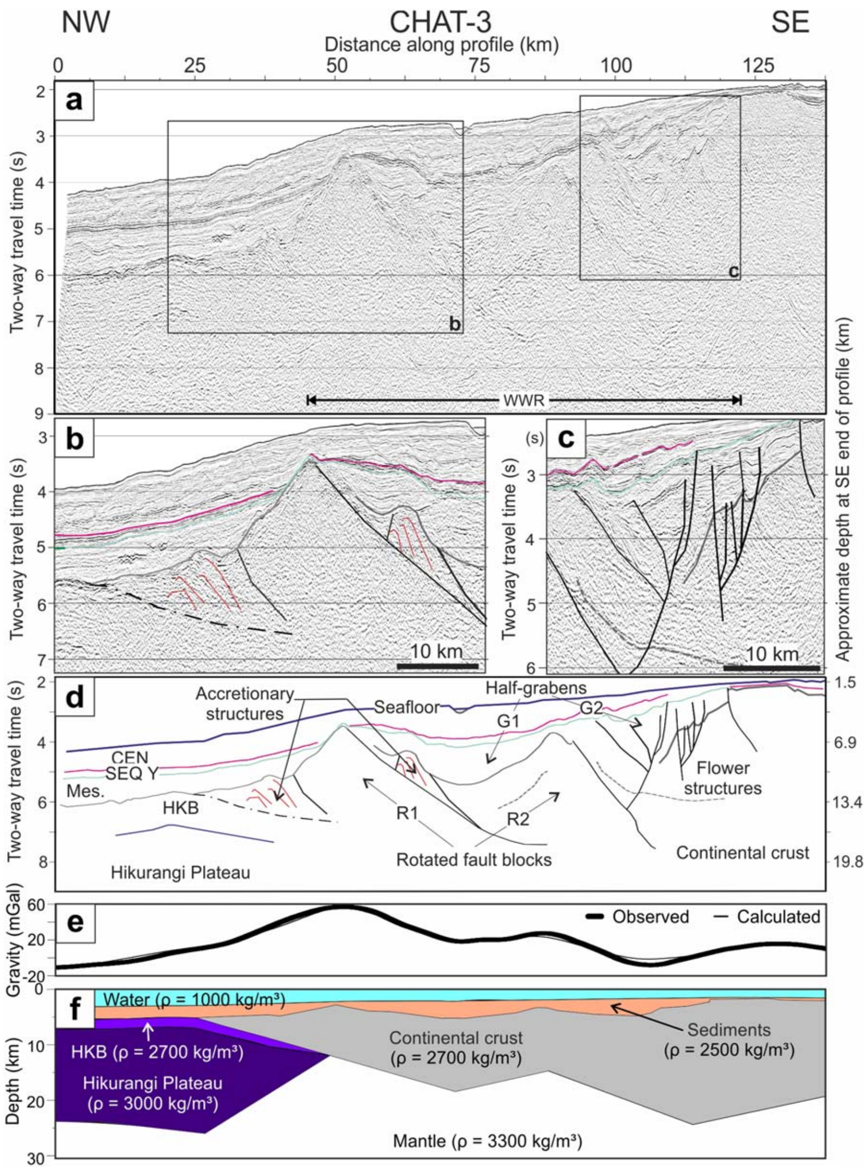

Figure 3. (a) Time migrated seismic reflection profile CHAT-3. (b) Accretionary prism structures (with fabric highlighted in red) are present both northwest and southeast of an uplifted, rotated basement block. (c) Flower structures, indicative of transform motion, are associated with the WWR on this profile. (d) Interpretation of the seismic reflection data. (e) Gravity anomaly across profile CHAT-3: observed and that calculated for the model shown in Figure 3f. HKB: volcaniclastic, limestone and chert sediments that overlie the igneous crust of the Hikurangi Plateau.

receiver array simulation, signature deconvolution, and sorting by CDP with bin spacings of 12.5 m (resulting in a nominal fold of 60). Geometry was then applied and an initial velocity analysis at intervals of 4 km was undertaken. Two radon demultiple stages were applied – the first using a velocity of 1,500 m/s and the second using the velocities from the initial velocity analysis. Following the radon demultiple, predictive deconvolution was applied to the data before an NMO correction and muting. The data were then scaled and stacked before gun and cable corrections and a zero phase conversion were applied. Finalization involved post-stack finite difference time migration, filtering, and scaling.

Pervasive deep water multiples proved a significant problem for studying the deeper crustal structure along these profiles. The longer streamer and larger source used during acquisition of CHAT-4 and CHAT-3 (Figures 2 and 3) enabled the long period multiples on those profiles to be removed with a greater level of success than for profiles AWI-20160006 and AWI-20160004 (Figures 4 and 5).

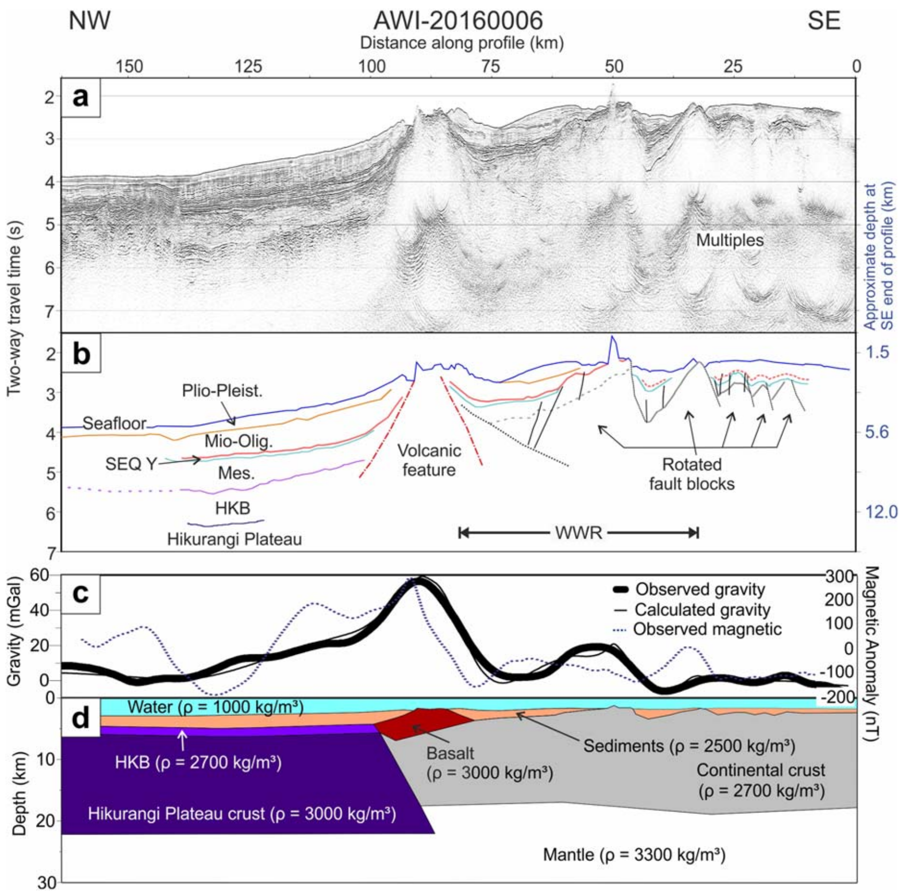

Figure 4. (a) Time-migrated seismic reflection profile AWI-20160006 and (b) interpreted horizons (colored lines as marked) and faults (black lines). Dotted lines indicate interpolated horizons/faults. (c) Observed gravity and magnetic anomalies along the profile, as well as the gravity anomaly calculated for the model in Figure 4d, which uses the seismic reflection profile as a starting constraint.

3.2. Seismo-Stratigraphic Model

Few cores have been collected in the immediate vicinity of the WWR so an interpretation of the seismic stratigraphy along the profiles considered in this study is primarily based on the results of Ocean Drilling Program (ODP) Leg 181 – Sites 1123 and 1124 (Figure 1), which extend down to Paleogene and Late Cretaceous sediments, respectively (Carter et al., 1999a, 1999b). For the seismic profiles that cross the interface between the eastern margin of the Hikurangi Plateau and the Chatham Rise (AWI-20160004, AWI-20160006 and CHAT-3), the sedimentary horizons are correlated to those on seismic profiles from further west along the Chatham Rise; in particular, profiles HKDC-1 (Davy et al., 2008) and SAHKE-1 (Bland et al., 2015), which bear strong similarities in character. The regionally-widespread Eocene-Oligocene limestone (Davy et al., 2008; Wood & Davy, 1994; here referred to as SEQ-Y following the unit-naming conventions of those publications) is clearly identified on the southern three reflection profiles that are described in this study on the basis of its strong reflectivity. This horizon acts as an important constraint on the ages of sediment above and below.

3.3. Modeling of Satellite Gravity Data

The resolution at depth of the seismic profiles AWI-20160006 and AWI-20160004 is limited as a result of deep bathymetry and a streamer length of 3km. This makes it difficult to answer questions about the nature of the interface between the continental crust of the Chatham Rise and the Hikurangi Plateau at its eastern margin, as well as about the eastern extent of the Hikurangi Plateau, based on the seismic data alone. In order to address these questions, we construct two-dimensional gravity models along the southern three profiles considered in this study using satellite-altimetry derived gravity data from Sandwell et al. (2014).

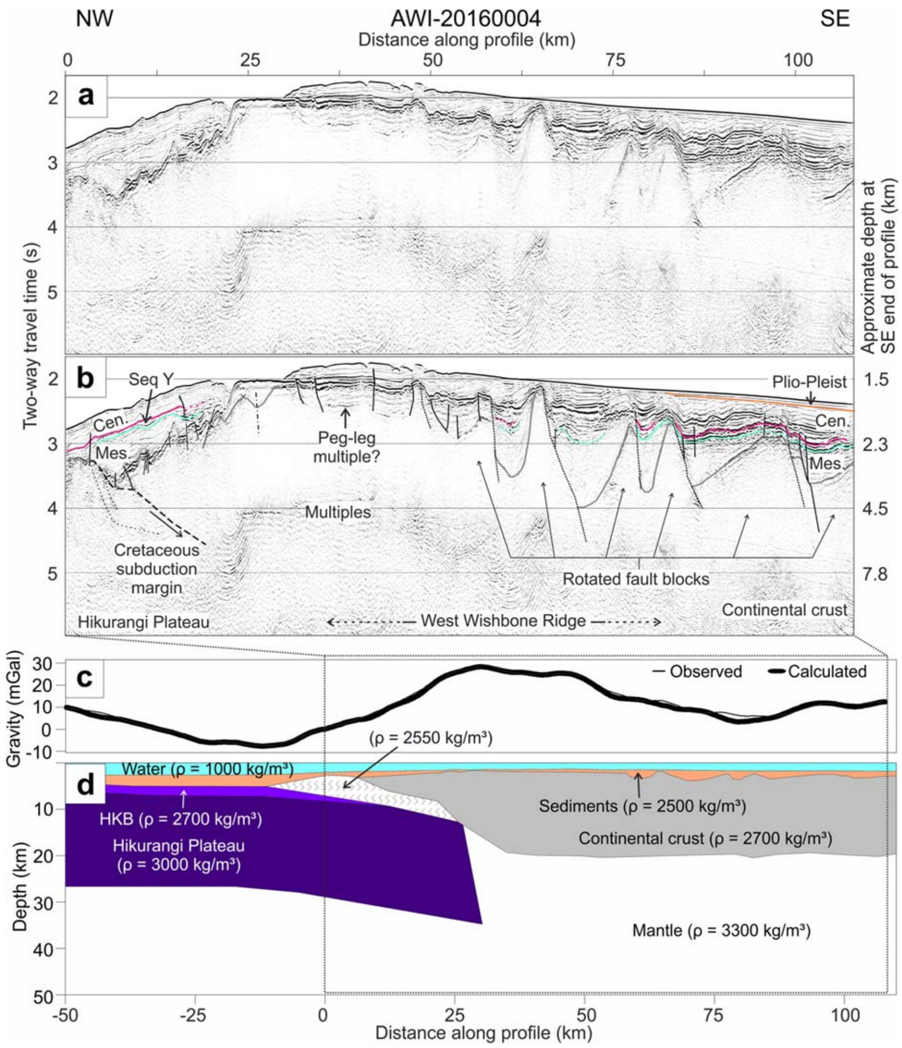

Figure 5. (a) Time-migrated seismic reflection profile AWI-20160004. (b) shows the same reflection profile overlain with interpreted horizons and faults. (c) Observed gravity anomaly along the profile, and the gravity anomaly calculated for the model in Figure 5d, which uses horizons identified in the seismic reflection data as starting constraints.

Table 2
Geophysical Parameters for the Profiles Considered in This Study

	Unit	Velocity used for conversion to depth in this study (m/s)	Density used for gravity modeling in this study (kg/m^3)
Continental (used for AWI-20160004, AWI-20160006 and CHAT-3)	Marine Sediments	2,400	2,500
	Continental crust (Torlesse)	6,450	2,700
	HKB (volcaniclastic, limestone and chert sediments that overlie the Hikurangi Plateau	3,200	2,700
	Crust of the Hikurangi Plateau	6,000	3,000
Oceanic (used for CHAT-4)	Oceanic Layer 2a	4,600	2,650
	Oceanic Layer 3	6,700	2,930
	Mantle (to 50 km depth)	8,040	3,300

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Horizons identified in the seismic reflection profiles were converted from two-way travel time to depth in meters using velocities within a typical range for each layer (Table 2). These horizons were then input as initial constraints for gravity modeling along those profiles and their depths were not subsequently altered during modeling. The sedimentary cover (incorporating Late Cretaceous to Recent sediments) is modeled as having a single, averaged density. As our gravity models are intended to yield information about deeper crustal features (long-wavelength gravity anomaly features) rather than the shallow sub-surface (associated with short-wavelength gravity anomalies), we consider this a reasonable approximation. As there are no constraints on internal variations in the density or velocity structure of the crust and mantle, these layers are also modeled as having constant density (Table 2). This assumption of constant density and lateral homogeneity within the upper mantle is at odds with interpretations of regional asthenospheric upwelling as a result of slab and mantle lid detachment beneath the Chatham Rise (Hoernle et al., 2006; Ball et al., 2016). Such variations could have significant implications on the density structure of the upper mantle; however, as there are no constraints on that density structure, the approximation of constant mantle density is necessary.

The crustal thickness of both the Chatham Rise and the Hikurangi Plateau is poorly constrained by previous studies; however, seismic refraction/wide-angle reflection profiles acquired during SO246 indicate a crustal thickness of 12–18 km on the southern Chatham Rise east of the WWR, as well as seismic velocities consistent with continental crust (Riefstahl et al., 2018). Consequently, we modeled the continental crust at the southeastern end of the profiles that cross onto the Chatham Rise (CHAT-3, AWI-20160006 and AWI-20160004; Figures 3–5) to be within this thickness range. We then performed an isostatic mass balance calculation to determine the corresponding thickness of the Hikurangi Plateau at the northwestern end of each profile, using an isostatic compensation depth of 50 km and horizon constraints from the seismic data. The thickness of the crust on the western side of the gravity model across profile CHAT-4 (Figure 2) is constrained by the seismic reflection data. An isostatic mass balance calculation (also employing an isostatic compensation depth of 50 km) is performed to constrain the thickness of the crust on the eastern side of the profile.

It is important to note that although gravity modeling is helpful for constraining the crustal structure, it is an inherently non-unique geophysical method involving a trade-off between density-distribution and depth. However, the consistency of our gravity models with each other and with what would be expected from the literature provides support to both the modeled crustal structure and the gravity model.

4. Results

4.1. Seismic Reflection Profile CHAT-4

Seismic reflection profile CHAT-4 (Figure 2) is located approximately 300 km north of the Hikurangi Plateau, and crosses the WWR at an oblique angle (Figure 1). The sedimentary cover on the western 85 km of seismic profile CHAT-4 is horizontally stratified and has a relatively uniform thickness of ~2 km (1.6 s two-way travel time, hereafter referred to as twt). Between 85 and 100 km along the profile, there is an abrupt vertical step in the boundary between the upper crust and the sedimentary cover. East of this step in the crustal/sedimentary boundary, the sedimentary cover thins to ~300 m (0.25 s twt). The vertical step in the crustal/sedimentary boundary is also accompanied by crustal deformation: west of the step, the crust has a 2.2 km (~1 s twt) thick upper layer that has a seismically reflective character and interval velocity of 3.6 km/s near the top of the layer; however, this layer is not evident east of ~105 km along the profile in the seismic data (Figure 2). Beneath the vertical crustal step, extending from 10.5 to 12.5 s twt, we identify a series of parallel, strongly reflective, westward-dipping reflectors that flatten out at depth. These reflectors have an apparent dip of approximately 30° when converted to depth, assuming a crustal velocity of 6 km/s (Figure 2). If this feature is related to the WWR, then a calculation compensating for the oblique angle of the WWR to the profile indicates a true dip of 45° (Dobrin, 1976).

On CHAT-4, there are three fault-bound regions where the upper crustal layer has been uplifted and the overlying sedimentary cover is faulted and folded. This combination of uplift, steep faulting and folding is indicative of compression. An additional feature of interest on this profile is a strong reflection 25–40 km along the profile, at a depth of ~12.2 s twt.

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4.2. Seismic Reflection Profiles That Cross onto the Eastern Chatham Rise

Seismic reflection profiles CHAT-3, AWI-20160006 and AWI-20160004 (Figures 3–5, respectively) are parallel to each other and are roughly perpendicular to the WWR (Figure 1). Together, they image the transition from the Hikurangi Plateau (at the northwestern end of the profiles) to the Chatham Rise (at the southeastern end; Figure 1). This crustal transition is marked by a change in the seafloor elevation: on CHAT-3 (Figure 3), water depth changes from ~3.2 to 1.5 km from northwest to southeast along the profile, and the other profiles show bathymetric variations of a similar magnitude. The crust on these southern three profiles differs markedly from that on CHAT-4 (Figure 2) and is significantly deformed with uplifted and rotated basement blocks dominating the Chatham Rise portion of each profile (Figures 3–5). The sedimentary cover infills basement topography and, consequently, has highly variable thickness. A strongly reflective series of reflectors (120–240 m/0.1–0.2 s twt thick) is imaged mid-way through the sedimentary cover on all of these profiles. On the basis of its highly reflective and condensed character, this is recognized as the regionally-widespread Early Oligocene to Late Cretaceous Sequence Y (Carter et al., 1999a, 1999b; Davy et al., 2008; Wood & Davy, 1994), which serves as a key constraint on the ages of sediment above and below this unit.

4.2.1. Seismic Reflection Profile CHAT-3

On the northwestern end of profile CHAT-3 (Figure 3), a series of strongly reflective, parallel reflections are imaged beneath the sedimentary cover, between approximately 6 and 7 s twt. The dip direction of this 1.6 −2 km thick series of reflections changes at ~20 km from the northwestern end of the profile. From this point of inflection until ~40 km along the profile, the series of reflections is overlain by a significantly deformed sedimentary wedge. Southeast of this sedimentary wedge an uplifted basement block ('R1', centered at 50 km along the profile) and a second, similarly-deformed sedimentary wedge are imaged in the seismic reflection data. The uplifted basement block 'R1' on CHAT-3 is then abutted, both on the northwest and southeast, by sedimentary wedges whose internal architecture is faulted and folded (Figure 3). The sedimentary fill southeast of the uplifted basement feature 'R2' on profile CHAT-3 is heavily faulted, with normal and reverse faults seeming to splay off a common, central fault.

4.2.2. Seismic Reflection Profile AWI-20160006

The 1.6-2 km thick series of strongly reflective, parallel reflections imaged beneath the sedimentary cover on the northwestern end of profile CHAT-3 (Figure 3) is also identified in seismic reflection data along AWI-20160006 (Figure 4). This reflective series can be traced for ~70 km until it abruptly ends at the edge of the Chatham Rise, which on AWI-20160006 is indicated by a conically-shaped feature that is devoid of internal reflections. This location of this conical feature correlates with strongly positive magnetic and gravity anomalies (Figure 4c).

4.2.3. Seismic Reflection Profile AWI-20160004

On the northwestern side of profile AWI-20160004 (Figure 5), a southeastward-dipping reflector can be traced from the base of the sedimentary cover to ~4.6 s twt. The boundary between sediment and basement that overlies this reflector is heavily faulted, and the overlying Mesozoic sediments are also deformed. On the southeastern end of this profile, a series of narrower rotated basement blocks than those imaged on AWI-20160006 (Figure 4) and CHAT-3 (Figure 3) are identified.

5. Discussion

5.1. Over-Thickened Oceanic Crust North of the Hikurangi Plateau

The reflective nature and layered structure of the crust on the western side of profile CHAT-4 (Figure 2) is indicative of oceanic crust, and the interval velocity of the upper crustal unit (~3.6 km/s near the top of the layer) is consistent with that layer being oceanic Layer 2a (Carlson & Herrick, 1990). Gravity modeling across this profile, using densities typical of oceanic crustal layers (Table 2) also supports this interpretation, which is consistent with the crust having been formed at the Osbourn Trough (Billen & Stock, 2000). The total thickness of oceanic crust is typically 5–8.5 km (White et al., 1992). On the basis of the change in reflectivity across the reflector at a depth of ~12.2 s twt between 25 and 40 km along profile CHAT-4 (Figure 2), and its stratigraphic position, we interpret that reflector to be the Moho. This interpretation is problematic, however, because it implies a crustal thickness of ~12 km – substantially thicker than is typical for oceanic crust. While continental crust can be thinned to ~12 km in regions of continental rifting such as the Taupo Volcanic Zone of New Zealand (Stern & Benson, 2011), features characteristic of rifting, such as rotated fault blocks and half-grabens, are not observed on this profile. Consequently, we disregard the possibility of this being continental crust and consider it as over-thickened oceanic crust.

Similar over-thickening of oceanic crust has been identified adjacent to other Large Igneous Provinces. White et al. (1992) suggested that observed over-thickened oceanic crust adjacent to the Ontong Java Plateau is a consequence of the interaction of a spreading center with the hotter-than-normal mantle adjacent to the mantle plume responsible for the formation of the Ontong-Java LIP. Gohl et al. (2011) interpreted that the over-thickened oceanic crust at the Transkei Ridge, located between the Mozambique Ridge and the Agulhas Plateau, is indicative of sustained (for ~20 Myr) LIP magmatism at a lower intensity than during the main LIP-forming event. It is plausible that both, or either, of these mechanisms may have contributed to the over-thickened crust we observe on profile CHAT-4, north of the Hikurangi Plateau (Figure 2).

Alternatively, the over-thickened oceanic crust is a localized effect: a result of the proximity of this profile to the younger Louisville Seamount Chain (Figure 1) and the possibility of associated magmatic addition to the crust, or of compression across the profile. Several regions of uplift of the upper crust and sedimentary cover, accompanied by faulting and folding, and indicative of compressional faulting are evident in the seismic reflection data along CHAT-4 (Figure 2). However, the magnitude of uplift associated with these regions indicates that it is unlikely that compression is the main factor responsible for the thickening of oceanic crust that we observe here:1.5–2 times that of 'normal' oceanic crust.

If magmatic addition to the crust as a consequence of proximity to the Louisville hotspot was responsible for the observed over-thickening, we would expect to find over-thickened oceanic crust along the full extent of the Louisville Seamount Chain. However, a seismic refraction/wide-angle reflection profile that crosses the Louisville Guyot (located at the northwestern end of the Louisville Seamount Chain; Figure 1) shows that the oceanic crust proximal to that guyot is of normal thickness (Contreras-Reyes et al., 2010). At that site, they also found high lower crustal and upper mantle velocities, indicating that ultramafic rocks were intruded rather than underplated beneath the crust. Additionally, extending the gravity model along CHAT-4 beyond the western end of the seismic reflection profile shows that the over-thickened oceanic crust continues at least 75 km further west of CHAT-4 (Figure 2). The widespread extent of this over-thickening is further evidence for it being a consequence of proximity to the Hikurangi Plateau and its associated mantle plume.

Identification of the nature of the crust in the easternmost ~90 km along CHAT-4 is more challenging, as the stratifications typically associated with oceanic crust are not obvious in the seismic reflection data. However, gravity modeling across this profile (Figure 2d) indicates that a layered density structure typical of oceanic crust is required across the whole profile in order to match the observed gravity anomaly.

5.2. The Eastern Margin of the Hikurangi Plateau

Based on their reflectivity and location beneath the sedimentary cover, the ~2 km thick series of parallel, dipping reflections imaged on CHAT-3 and AWI-20160006 (Figures 3 and 4) are interpreted to be the HKB volcaniclastic, limestone and chert sediments that overlie the igneous crust of the Hikurangi Plateau elsewhere along the margin (Davy et al., 2008). This unit is not imaged in the seismic reflection data along profile AWI-20160004 (Figure 5), whose northwestern end coincides with the northern margin of the Chatham Rise. However, the fit of the modeled gravity anomaly to the observed anomaly was improved by adding this unit (with a thickness based on that imaged on in the seismic reflection data across profiles CHAT-3 and AWI-20160006) on the northwestern end of the profile. Our model also includes a 2,550 kg/m^3 unit overlying unit HKB and abutting the Chatham Rise crust. This is interpreted to be sediments that have accreted onto the front of the Chatham Rise and is consistent with the previous interpretation of Cretaceous subduction of the Hikurangi Plateau beneath the Chatham Rise extending to this point (Davy, 2014; Wood & Davy, 1994).

Gravity modeling across the interface between the Hikurangi Plateau and the continental crust of the Chatham Rise (along the southern three profiles considered in this study: Figures 3–5), indicates that the eastern edge of the Plateau is likely abrupt and steeply dipping, rather than gradually tapering. Hochmuth and Gohl (2017) proposed that the Ontong-Java Nui super-LIP may have extended further east than the present eastern limits of the Manihiki and Hikurangi Plateaus, and identified a possible rifted fragment in the Bellingshausen Sea sector of the West Antarctic margin and another west of the northern South American

Andes. These postulated fragments were interpreted to have rifted from the Hikurangi and Manihiki plateaus during the initial rifting phase of Ontong-Java Nui ca. 120 Ma (Hochmuth & Gohl, 2017; Hochmuth et al., 2015; Pietsch & Uenzelmann-Neben, 2015). If these fragments were indeed once an extension of the Ontong-Java Nui super-LIP, then their rifting, and that of similar fragments from the eastern edge of the Hikurangi Plateau, could explain the abrupt nature of the eastern edge of the Hikurangi Plateau identified here.

The gravity models across CHAT-3, AWI-20160006 and AWI-20160004 (Figures 3–5) all show the eastern margin of the Hikurangi Plateau as steeply dipping; however, the nature of the interface between LIP and continental crust varies along the different profiles. This is discussed in the following paragraphs.

On AWI-20160006 (Figure 4), the modeled interface between LIP and continental crust is overlain by a high-density feature that we interpret to be a basaltic volcanic feature based on its conical shape, correlation with strongly positive gravity and magnetic anomalies, and the results of gravity and magnetic modeling. The modeled crustal interface on this profile (AWI-20160006) is near-vertical, with LIP and continental Chatham Rise crust juxtaposed adjacent to each other in a manner indicative of strike-slip faulting. Attempts to model subduction along the interface resulted in a poor fit to the observed satellite gravity data.

On CHAT-3 (Figure 3), steeply dipping reflections with overturned leading edges are identified within the sedimentary wedge that overlies unit HKB on the northwestern end of the profile, and also within the sedimentary wedge on the southeast side of uplifted basement block 'R1'. Such a reflection pattern is characteristic of thrust faulting in an accretionary prism, which, when considered in conjunction with the observation of unit HKB in the seismic reflection data as well as our gravity model along the profile, indicates a small amount of under-thrusting/paleo-subduction of the Hikurangi Plateau along this profile. We consider that this set of observations can only be explained by the following:

1. The initial impact of the 10–15 Myr old Hikurangi Plateau, which was denser, thicker and more buoyant than the leading oceanic crust due to being a LIP, resulted in the compression of the leading convergent margin fabric onto and beneath the Chatham Rise, as well as the margin offset of the Chatham Rise at the eastern margin of the Hikurangi Plateau (present-day $\sim$174°W; Figure 1), by ca. 105 Ma. This is further supported by the orientation of the offset of the Chatham Rise margin at $\sim$174°W, which is semi-parallel to the NNE-striking oceanic fabric that dominates between the Hikurangi Plateau and Osbourn Trough.
2. Following the initial impact of the Hikurangi Plateau with the Chatham Rise and the onset of its subduction, subduction of the Hikurangi Plateau jammed near its southernmost extent beneath the South Island (Davy et al., 2008). This resulted in the slowing of subduction at the Chatham Rise and was accompanied by an anti-clockwise rotation of the Osbourn Trough so that the spreading direction changed from SSW- to south-orientated (Downey et al., 2007). The reorientation of the spreading direction resulted in minor, oblique subduction of the Hikurangi Plateau beneath the $\sim$174°W offset of the Chatham Rise margin.

5.3. The Nature of the West Wishbone Ridge

Three suggestions have previously been raised for the Cretaceous nature of the WWR: (1) that it was a strike-slip fault (2) that it was a rift system; and (3) that it was a subduction margin. On seismic reflection sections, strike-slip faults can be identified by the presence of "flower structures" (where normal and reverse faults splay off a common, central fault), a change in the character or thickness of the seismic unit across a fault, and/or by abrupt changes in the dip or vertical offset of horizons across faults (D'Onfro & Glagola, 1983). Strike-slip faults that extend throughout the crust are also commonly associated with ductile shear zones at the base of the crust (e.g., the San Andreas Fault; Thatcher & England, 1998).

On CHAT-4, the zone of deformation associated with the WWR, as delineated by the satellite gravity anomaly data (Figure 1) extends across $\sim$100 km (Figure 2). The eastern margin of this deformation zone corresponds with the $\sim$2km vertical step in the sediment/basement boundary, the lateral change in the reflectivity of the upper crust, and the dipping series of strong lower-crustal reflections (a shear zone) that intersects the Moho (Figure 2). This combination of features is indicative of strike-slip motion along the WWR, and cannot be explained either by the process of subduction, or that of rifting.

The WWR can be traced southward onto the Chatham Rise margin (Figure 1) where the gravity anomaly associated with the WWR corresponds with a pair of parallel, northeast-striking rotated fault blocks and their associated half-grabens that are imaged on profiles CHAT-3 and AWI-20160006 (Figures 3 and 4). Distinguishing which tectonic features are primarily related to WWR deformation, and which are primarily features of the Chatham Rise fabric can be problematic. However, the northward extension of the pair of half-grabens and uplifted, rotated basement blocks associated with the WWR-region of deformation on CHAT-3 and AWI-20160006 to ~40.5°S, well north of the present-day Chatham Rise margin, leads us to interpret that they are a result of motion along the WWR.

Normal and reverse faults splaying off a common, central fault (i.e., a flower structure; indicative of strike-slip motion) are identified within the half-graben 'G2' on profile CHAT-3 (Figure 3). This half-graben is within the extent of the WWR as identified from the satellite gravity anomaly, and is bound on its southeastern edge by a vertical step in the basement topography. The identification of a flower structure within the WWR-related zone of deformation on CHAT-3 is further evidence for strike-slip motion along the WWR.

5.3.1. Sense of Motion Along the West Wishbone Ridge

The next question is whether strike-slip motion along the WWR was dextral or sinistral. The WWR can be separated into different segments according to variations in the strike direction (Figure 6). Some of these segments may correlate with pre-existing faults in the oceanic crust they propagate through, and are linked by other segments. When a strike-slip fault steps laterally across strike, compressional or extensional regimes will dominate in the region of this step (e.g., Cunningham & Mann, 2007). Which of these regimes dominates depends on whether the fault is sinistral or dextral, and whether it steps left or right of the direction of propagation (Figure 6).

Between 39°S, where the WWR is overlain by the Louisville Seamount Chain, and 40.2°S the southward-propagating WWR steps to the left (eastward); a step that coincides with the region of compressional faulting observed on CHAT-4 (Figure 6). This combination of a leftward step in strike in the direction of propagation and compressional faulting is indicative of dextral motion, a finding that supports previous interpretations of Cretaceous dextral motion along the WWR (Davy et al., 2008; Larter et al., 2002; Sutherland & Hollis, 2001).

5.3.2. Southern Extent of the West Wishbone Ridge

At the northern margin of the Chatham Rise, the deformation zone associated with the WWR is adjacent to the eastern margin of the Hikurangi Plateau (Figures 3–5), indicating that the location of the WWR south of the intersection with the Chatham Rise is controlled by the location of the eastern margin of the Hikurangi Plateau. This boundary was likely a weak point in the accretionary margin as a result of faulted uplift of the margin where the buoyant plateau was subducted. Based on satellite gravity data, Sutherland and Hollis (2001) suggested that the WWR extends westward through the Chatham Islands and along the northern Gondwana margin, while Davy et al. (2008) and Davy (2014) suggested that the WWR may have extended south of the Chatham Rise, into the Gondwana interior and along the present-day eastern margin of the Campbell Plateau. The seismic reflection data presented here allow us to better define the southern extent of the WWR. The flower structures associated with the WWR on CHAT-3 (Figure 3) provide strong evidence for the WWR extension onto the northernmost Chatham Rise and the rotated basement blocks and half-grabens associated with the WWR on CHAT-3 can be traced southward to AWI-20160004 in the satellite gravity data (Figure 1). However, the region of deformation associated with the WWR on profiles AWI-20160006 and AWI-20160004 (Figures 4 and 5) is narrower than on CHAT-3, and there is no evidence for strike-slip faulting on these profiles. This reduction in the observed WWR-related deformation could be due to the dispersal of motion within the continental crust, which would be consistent with well-documented global findings (Molnar, 1988).

5.3.3. Subduction Beneath the Southern Extent of the West Wishbone Ridge

Based on the seismic reflection data and gravity modeling across profile CHAT-3 (Figure 3), we have suggested that the eastern margin of the Hikurangi Plateau subducted obliquely beneath the margin offset of the Chatham Rise at ~174°W, from ca. 105 Ma. The relation between the WWR and the eastern margin of the Hikurangi Plateau implies oblique subduction beneath the southernmost part of WWR. The seismic reflection data across CHAT-4 (Figure 2) indicates that subduction beneath the WWR did not extend as far north as that profile (Figure 1).

The Wishbone dredge of Mortimer et al. (2006; Figure 1) has geochemical characteristics indicative of subduction; however the 115 Ma age of that sample requires an explanation. We have suggested that the impact of the Hikurangi Plateau with the northern Gondwana margin west of the WWR resulted in major

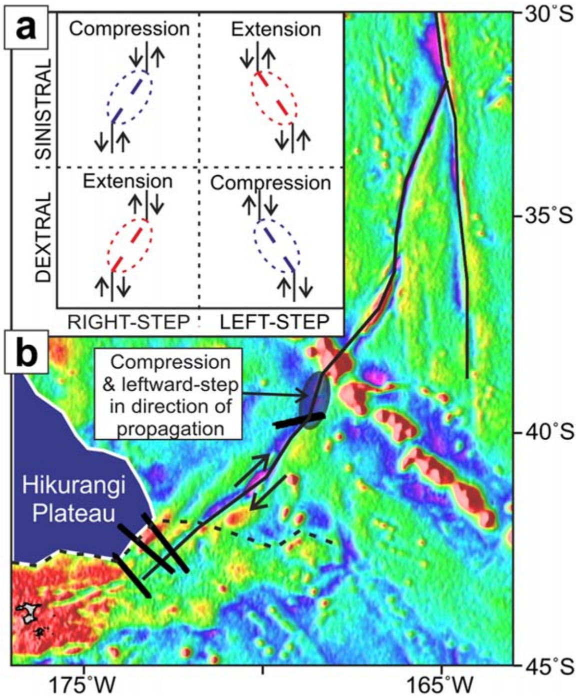

Figure 6. (a) Schematic showing the extensional and compressional regimes which arise from a right- or leftward step in strike of a transform fault in the direction of propagation. (b) Along the WWR, a step in strike to the left in the direction of propagation (southward) corresponds with a region of compressional faulting identified on the seismic profile CHAT-4, indicating a dextral sense of motion along the WWR. Black dashed line: northern margin of the Chatham Rise.

compressional offset of that margin. Such compressive offset may have resulted in residual fragments of the Chatham Rise remaining north of the Chatham Rise and adjacent to the WWR. Multibeam data across this region (Figure 7) reveal apparent residual basement fragments whose presence supports this interpretation. The Wishbone dredge site of Mortimer et al. (2006; Figure 1) might have sampled one such crustal fragment; its 115 Ma age indicative of subduction of oceanic crust beneath the Chatham Rise prior to the collision of the Hikurangi Plateau with the northern Gondwana margin. Alternatively, the dredge sample is sourced from the zone where the WWR branches into sub-parallel rotated fault blocks (Figure 1), and may be an uplifted fragment of ocean crust related to this process.

5.4. The De Gerlache and Bellingshausen Gravity Anomalies—A Paleo-Southern Companion to the East and West Wishbone Ridge?

The gravity anomaly profile of the paired De Gerlache and Bellingshausen Gravity Anomalies (DGGA and BGA, respectively), which intersect crustal blocks of Thurston Island/Ellsworth Land on the West Antarctic margin, together bear a striking resemblance to that of the combined East and WWR gravity structures (Figure 8). The two regions are also bracketed, and connected, by the Tharp and Udintsev Fracture Zones, indicating that they were adjacent during the Late Cretaceous. This is supported by the plate reconstruction of Eagles et al. (2004), which shows the formation of these fracture zones from 83 Ma. The co-location and similarity in the structure of the gravity signature leads us to interpret that the De Gerlache feature may have been either a southward extension of the EWR or that of a proximal, semi-parallel ridge prior to the onset of rifting of the New Zealand sector of Gondwana in the Late Cretaceous.

Based on differences in crustal age and in the direction of crustal aging on either side of the DGGA, Larter et al. (2002) and Eagles et al. (2004) interpreted the DGGA as a ridge-jump scar, marking the backward jump of the Phoenix-Pacific spreading center at about 61 Ma (Chron 27). It is possible that this ridge jump occurred to the position of a pre-existing transform fault system – the southward extension of the EWR. If so, we suggest that the BGA was semi-parallel, and equivalent, to the WWR prior to the onset of Gondwana breakup (Figure 9). The existence of such intra-oceanic strike-slip faults, semi-parallel to the EWR, and sub-parallel WWR counterparts, also feeding dextral strike-slip motion into the Cretaceous Gondwana interior, infers major extensional/transtensional motion in the region of the Amundsen Sea Embayment (ASE). This corresponds with the previous interpretation, based on magnetic data across the highly extended continental margin of the ASE, that rift activity preceded breakup in this region (Gohl et al., 2013).

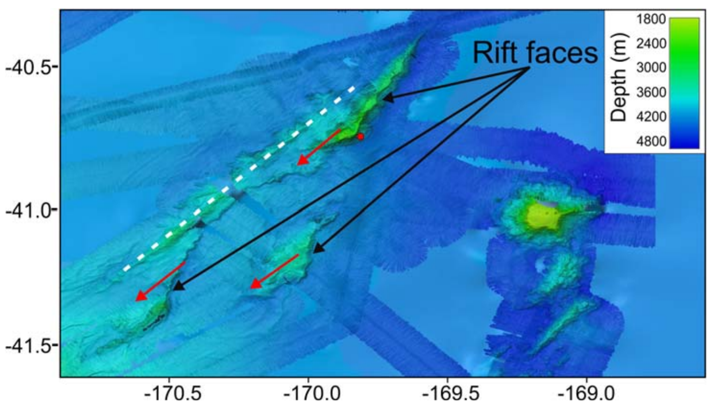

Figure 7. Northwest sun-illuminated image of swath bathymetry in the region of the WWR intersection with the Chatham Rise. The fault pattern on basement blocks imaged on the seafloor suggests these blocks are crustal fragments transposed and extended to the southwest, possibly fragments of the Chatham Rise that were left behind after the collision of the Hikurangi Plateau resulted in southwestward compressive offset of the Chatham Rise west of the WWR. Red dot: Wishbone dredge site of Mortimer et al. (2006). White dashed line: Western margin of the WWR.

The gravity anomaly signature across the BGA is much larger than that across the WWR (Figure 8). Gohl et al. (1997) suggested that eastward subduction occurred at the BGA during the early Tertiary, similar to that we observe on CHAT-3 at the southern end of the WWR, but we suggest subduction initially occurred in the Late Cretaceous (Figure 3). If the subduction beneath the BGA continued for a longer period than that beneath the WWR, then that may account for the accentuated gravity signature across the BGA compared to that across the WWR.

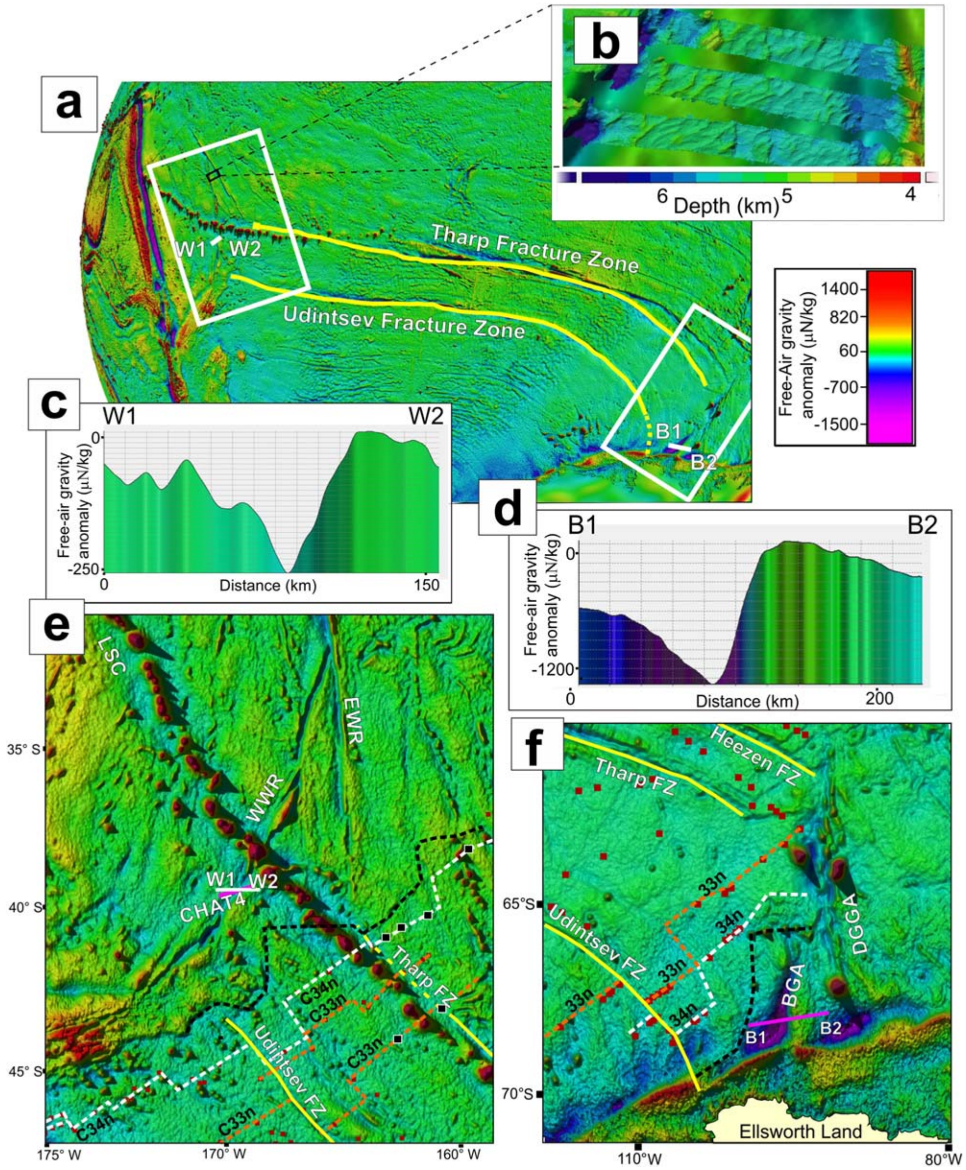

Figure 8. The gravity anomaly of the forked Wishbone Ridge bears a striking similarity to that of the combined De Gerlache and Bellingshausen Gravity Anomalies (DGGA and BGA, respectively), and offset matching across fracture zones (a) leads us to suggest that the DGGA was either a southward continuation of, or a parallel feature to, the East Wishbone Ridge prior to the onset of NZ-Antarctic rifting. The boxed overlays show the locations of Figures 8e and 8f. (b) Multibeam data reveal seafloor spreading fabric between the East and WWR. (c) The gravity anomaly across the WWR is similar in structure to that across the BGA (d). (e) and (f) show the satellite gravity (Sandwell et al., 2014) of the Wishbone and De Gerlache/Bellingshausen features. Dashed black line: breakup line between the Chatham Rise and Ellsworth Land. Dashed white and orange lines: magnetic anomaly picks based on Wobbe et al. (2012; red squares) and Larter et al. (2002; black squares).

5.5. Timing of Motion Along the West Wishbone Ridge

The dextral sense of motion along the WWR is seemingly at odds with the sinistral offset of the Chatham Rise margin at 174°W (Figure 1). We suggest that that this offset formed as a result of the compressive impact of the Hikurangi Plateau with the Chatham Rise ca.105 Ma. Consequently, we suggest that the WWR first developed and propagated through this margin offset as the spreading rate at the Osbourn Trough began to slow and rotate (Downey et al., 2007), post-105 Ma. This occurred as a consequence of differential spreading rates either side of the Wishbone Ridge – spreading slowed on the western side but continued at the same rate as previously to the east (Figure 9).

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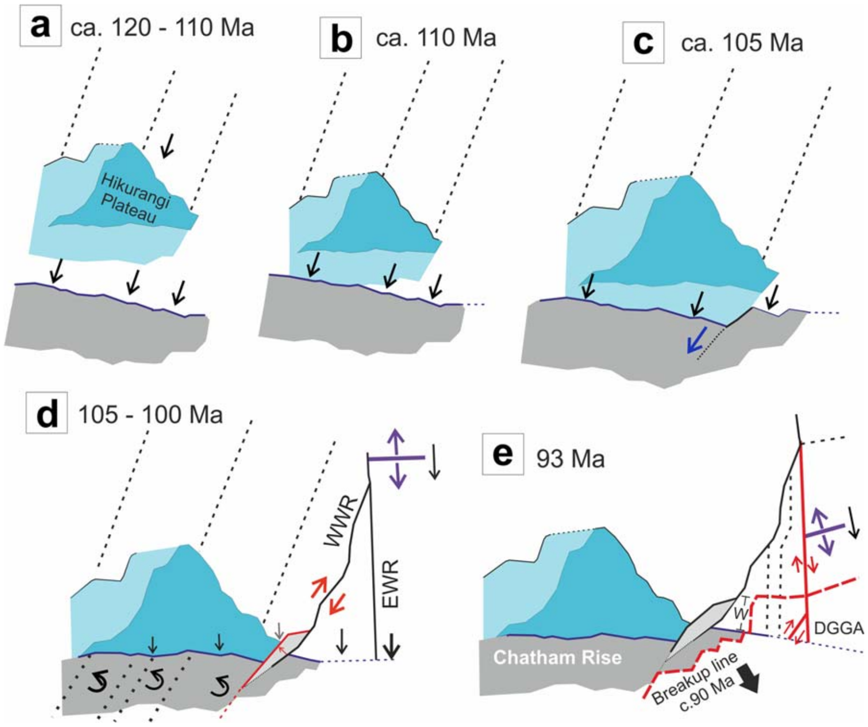

Figure 9. Schematic illustrating the Cretaceous interaction between the Hikurangi Plateau and the northern margin of the New Zealand sector of Gondwana (the modern-day Chatham Rise). The dates for this sequence of events are based on those suggested by Davy (2014). (a) Between ca. 120 and 110 Ma, oceanic crust subducted beneath the northern Gondwana margin. (b) The Hikurangi Plateau began to collide with the Chatham Rise ca. 110 Ma. (c) That collision resulted in margin offset of the Chatham Rise at the eastern boundary of the Hikurangi Plateau by ca. 105 Ma. (d) ca. 105 Ma, subduction of the Hikurangi Plateau jammed onshore beneath the South island, and began to slow offshore. However, seafloor spreading (and subduction of oceanic crust beneath the northern Gondwana margin) continued at the same rate east of the jammed Hikurangi Plateau. In response to this differential motion, the WWR propagated southward along the eastern margin of the Hikurangi Plateau. The direction of spreading at the Osbourn Trough changed to be southward-orientated (Downey et al., 2007) and segments of the Chatham Rise rotated to accommodate the change in motion that resulted from the onshore jamming of subduction and the change in subduction orientation (Davy, 2014). The WWR expanded westward to accommodate the rotation of the Chatham Rise segments, resulting in the uplift and rotation of the basement block R1 (Figure 3). At the same time, the reorientation of the subduction direction resulted in oblique subduction beneath the (present-day) 174°W offset in the Chatham Rise margin (solid red line on Figure 9d) and the southern extent of the WWR. (e) Seafloor spreading continued east of the East Wishbone Ridge and strike-slip motion was fed through that feature into the Gondwana interior. The De Gerlache Gravity Anomaly (DGGA) was a southern extension of, or a parallel feature to, the EWR prior to the onset of rifting (Figure 8). The line marked 'W' highlights the minimum dextral offset along the WWR. The light blue regions of the Hikurangi Plateau have subsequently been subducted; their extent is based on that suggested by Reyners et al. (2011).

We have suggested that the elongated features evident in multibeam data east of the WWR and immediately north of the eastern Chatham Rise (Figure 7), may be remnant crustal fragments of the Chatham Rise that were left behind after collision of the Hikurangi Plateau compressed the Chatham Rise margin southward. Prior to the onset of rifting of Gondwana, the East Wishbone Ridge extended to the northern margin of the super-continent (Figure 9). Consequently, the latitudinal offset between the crustal fragments adjacent to the WWR and the present-day northern limit of the Chatham Rise east of 174°W, ~250 km, represents a minimum estimate of the strike-slip displacement along the WWR (marked as 'W' on Figure 9). This displacement implies an average slip rate of 50 mm/yr over 5 Myr. However, if subduction continued beneath the Gondwana margin in the segment between the East and West Wishbone Ridges, some of the dextral motion could be absorbed by differential subduction rates across the southern extent of the WWR between 105 and 100 Ma.

On CHAT-3, accretionary prism structures are identified both northwest and southeast of uplifted, rotated basement block 'R1', which is associated with the WWR (Figure 3). This juxtaposition of structures indicates

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that the rotation and uplift of basement block R1 occurred after the initiation of oblique subduction beneath the WWR, constraining the timing of uplift of R1 to after the reorientation of the Osbourn Trough. Davy (2014) suggested that segments of the Chatham Rise margin rotated in an anti-clockwise direction in response to the slowing and reorientation of subduction between ca. 105 Ma and 100 Ma. Rotation of the segment of the Chatham Rise margin west of the WWR would have resulted in an effective westward movement of the Chatham Rise 174°W offset fault (Figure 9). We suggest that the WWR expanded westward to follow this offset fault, resulting in the uplift and rotation of the basement block R1 imaged on CHAT-3 (Figure 3).

We see no evidence in the seismic data to suggest that strike-slip motion continued to be fed along the WWR after the Late Cretaceous. Consequently, it would seem that strike-slip motion along the WWR ceased along with the cessation of spreading at the Osbourn Trough. After this, spreading ridges both east and west of the extinct Osbourn Trough continued to migrate south toward the Gondwana margin and dextral strike-slip motion continued to be fed into the Gondwana margin on fault complexes in, and branching southwest from, the zone between the East and West Wishbone Ridges (Figure 9). These suggestions are supported by several N-S orientated gravity lineations evident in this zone (Figure 8e), as well as multibeam bathymetry data (Figure 8b) that reveals WSW-ENE spreading ridge fabric between the N-S-orientated transform faults. Such spreading motion would support the development of strike-slip motion on faults such as the WWR and Bellingshausen Gravity Anomaly, and is also consistent with the seafloor spreading orientation east of the East Wishbone Ridge. Subduction at the Gondwana margin continued east of the WWR, only ceasing when the spreading ridge was near the Eastern Chatham Rise and NW-SE seafloor spreading along the Sub-Antarctic margin became more mechanically favorable, leading to Gondwana breakup.

6. Conclusions

Recently acquired seismic data in the region of the intersection of the WWR with the northern margin of the Chatham Rise show that the WWR was primarily a strike-slip fault during the Cretaceous. Regions of compressional faulting that correspond with a leftward step in strike in the direction of propagation indicate a dextral sense of motion along the WWR. Strike-slip motion along the WWR initiated as a consequence of the slowing of spreading at the Osbourn Trough (west of the WWR) ca. 105 Ma while spreading to the east continued unabated, and ceased with the cessation of spreading at the Osbourn Trough. The slowing of spreading at the Osbourn Trough was accompanied by a reorientation in the direction of spreading, resulting in short-lived, oblique subduction beneath the southern extent of the WWR. The WWR can be traced southward onto the northern Chatham Rise, where its location is controlled by the eastern margin of the Hikurangi Plateau. However, south of 42.5°S, the WWR is not visible in our seismic reflection data. This suggests that motion along the WWR is either dispersed into a series of smaller faults south of profile CHAT-3, or that it does not propagate south of this point.

Similarities in the gravity signature of the Wishbone Ridge with that of the paired De Gerlache and Bellingshausen gravity anomalies near Thurston Island/Ellsworth Land, together with offset matching across fracture zones, indicates that the De Gerlache Gravity Anomaly was a southern extension of, or a parallel feature to, the East Wishbone Ridge prior to sea-floor spreading during the initial stages of Gondwana break-up. The Bellingshausen gravity anomaly would then have been a parallel, and equivalent, feature to the WWR, and fed extension into the Ellsworth Land interior.

Seismic reflection data crossing the $\sim$174°W offset of the northern margin of the Chatham Rise show that this offset has a strike-slip character. This indicates that the initial collision of the Hikurangi Plateau with the Chatham Rise ca. 110-105 Ma resulted in southward compression of the northern Gondwana margin.

Anomalously thick oceanic crust ($\sim$12 km thick) is identified in seismic reflection data north of the Hikurangi Plateau. The over-thickening of this oceanic crust is attributed to its proximity to the Hikurangi Plateau and the associated mantle plume.

Combining our seismic reflection data with gravity models across these profiles allows identification of the eastern margin of the Hikurangi Plateau between 42–43°S.

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