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Linking active margin dynamics to overriding plate deformation: Synthesizing geophysical images with geological data from the Norfolk Basin

Lydia DiCaprio and R. Dietmar Müller
School of Geosciences, University of Sydney, Sydney, New South Wales 2006, Australia (lydia@gps.caltech.edu)

Michael Gurnis
Seismological Laboratory, California Institute of Technology, Pasadena, California 91125, USA

Alexey Goncharov
Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia

[1] The Tonga-Kermadec subduction system in the southwest Pacific preserves a series of crustal elements and sediments which have recorded subduction initiation, rift, and back-arc basin formation. The Norfolk Basin is the farthest landward of all back-arc basins formed in the Tonga-Kermadec region and may preserve the earliest record of subduction initiation regionally. For the Norfolk Basin, we use a set of multibeam bathymetry, magnetic, and seismic reflection and refraction data to constrain basin structure and the mode and timing of formation. A structural interpretation reveals a two-stage tectonic evolution: (1) a convergent tectonic regime until 38–34 Ma, alternatively related to island arc collision or subduction initiation, and (2) lithospheric extension after 34 Ma. These observations may help to constrain mechanical models that predict rapid extension following convergence of the overriding plate during subduction initiation or arc reversals.

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1. Introduction

[2] The Norfolk Basin is located west of the Tonga-Kermadec trench in the southwest Pacific on the Australian plate. It is bounded by two north-south oriented ridges, the Three Kings Ridge on the east and the Norfolk Ridge on the west (Figure 1). Currently, the southwest Pacific is an area of westward dipping subduction and back-arc basin extension. The Norfolk Basin is thought to have formed by back arc extension during the Miocene either behind the active proto Tonga trench or

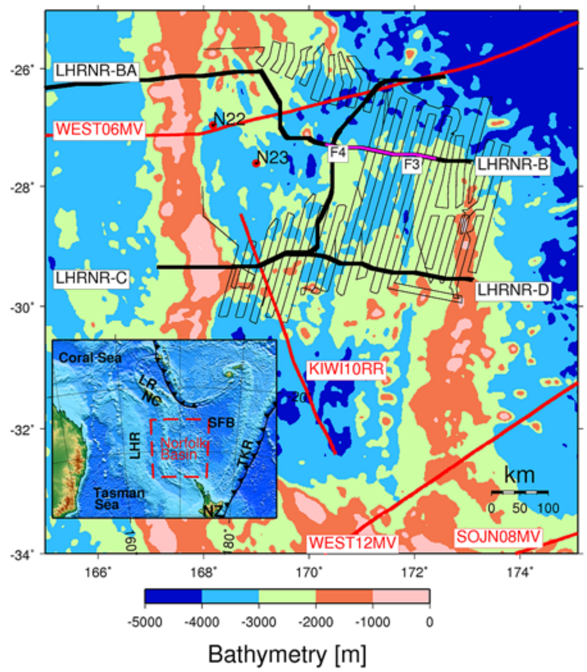

Figure 1. The Norfolk Basin located within the southwest Pacific west of the TKR (Tonga Kermadec Trench). LHR (Lord Howe Rise), NC (New Caledonia), LR (Loyalty Ridge), SFB (South Fiji Basin). (inset) Data coverage from the Norfolk Basin on bathymetry from ETOPO2. The deep reflection seismic lines are plotted as thick black tracks and labeled LHRNR-BA, B, C, or D. The location of seismic sections which are referred to in the text are highlighted in magenta and labeled with a figure number. Ship tracks for the FAUST-2 multibeam and seismic reflection coverage is plotted as thin black tracks. In addition, multibeam bathymetry from GEODAS is shown in red. Location of seismic refraction sites N22 and N23 are also shown.

behind an additional (but now extinct) trench whose remnant arc may be preserved on the Three Kings and Norfolk ridges [*Herzer et al.*, 1997; *Mortimer et al.*, 1998; *Sdrolias et al.*, 2004].

[3] There are various hypotheses for the driving mechanism of back arc basin extension. These include slab rollback (slab pull and/or trench suction) [*Dvorkin et al.*, 1993; *Elsasser*, 1971; *Malinverno and Ryan*, 1986; *Molnar and Atwater*, 1978; *Schellart et al.*, 2007], induced mantle wedge flow (corner flow) [*Sleep and Toksöz*, 1971] and relative motion of the overriding plate with respect to the subduction trench [*Dewey*, 1980; *Heuret and Lallemand*, 2005; *Jarrard*, 1986; *Volti et al.*, 2006]. Back-arc extension preferentially occurs in young subduction zones and most extension occurs within the first 50 million years following subduction initiation [*Gurnis et al.*, 2004].

[4] Despite multiple cruises to the Norfolk Basin and the collection of geophysical and geological data we still cannot answer the fundamental question about the basin. How and when was the Norfolk Basin formed? The answer to this question undoubtedly lies in the nature and age of the crust. Most authors believe the main phase of extension in the Norfolk Basin was during the Miocene [*Herzer et al.*, 2000; *King*, 2000; *Mortimer et al.*, 1998; *Schellart et al.*, 2006; *Sdrolias et al.*, 2004]. This postdates major spreading within the South Fiji Basin which opened as a back arc basin to the Tonga Kermadec subduction system between 36 Ma [*Malahoff et al.*, 1982] and 25–22 Ma [*Crawford et al.*, 2003; *Mortimer et al.*, 2007; *Sdrolias et al.*, 2003]. If the Miocene age is correct, then the Norfolk Basin opened to the west of the South Fiji Basin up to 1000 km west of the Tonga-Kermadec trench.

[5] This large distance makes it difficult to attribute the opening of the Norfolk Basin during the Miocene to the Tonga Kermadec subduction system. In some cases backarc basin formation may occur at distances up to 1500 km behind a subduction system [*Schellart et al.*, 2003; *Schellart and Lister*, 2005]. However, if the Norfolk Basin formed as a back arc behind the Tonga Kermadec, what is potentially more perplexing is the age progression of the back arc basins behind the Tonga Kermadec Trench. In general, when multiple back arc basins form behind a single trench the age of the basins decrease toward the trench [*Müller et al.*, 2008]. The formation of the Norfolk Basin during the Miocene requires first spreading within the South Fiji Basin and then for the spreading center to jump westward into the Norfolk Basin.

[6] However, the Norfolk Basin may not be uniquely composed of Miocene aged crust. Previously published geological and geophysical data is insufficient to completely explain the crustal composition (continental or oceanic) and age of the Norfolk Basin. The crust within the Norfolk Basin cannot be exclusively of Miocene aged oceanic crust since there are no identifiable magnetic reversals and few magnetic anomalies are observed [*Sdrolias et al.*, 2004]. This has led to the hypothesis that the Norfolk Basin is largely comprised of oceanic crust formed during the Cretaceous Normal Superchron (CNS) [*Eade*, 1988; *Launay et al.*, 1982; *Sdrolias et al.*, 2003]. In addition, some parts of the South Norfolk Basin are more than 4000 m deep and have been interpreted to be remnants of a Late Cretaceous basin [*Bernardel et al.*, 2002]. On

average, a Late Cretaceous age is inconsistent with the depth of the Norfolk Basin which is more consistent with a maximum age of 27 Ma [*Sdrolias et al.*, 2004]. However, such discrepancies may suggest that the Norfolk Basin has experienced multiple phases of opening preserving both Cretaceous and Tertiary crustal fragments.

[7] There is regional evidence for significant compression to the west of the Tonga Kermadec since the Eocene which may have affected the Norfolk Basin. The Norfolk Basin lies between New Caledonia and Northland, New Zealand, which have been dominated by convergence and obduction since the Eocene. Northeastward dipping subduction to the east of New Caledonia [*Cluzel et al.*, 1994, 1997; *Eissen et al.*, 1998] (Figure 1) may have been initiated as early at 55 Ma [*Cluzel et al.*, 2001, 2006; *Crawford et al.*, 2003; *Eissen et al.*, 1998; *Schellart et al.*, 2006; *Whattam et al.*, 2008] and consumed Cretaceous oceanic crust within the South Loyalty Basin forming the Loyalty Ridge oceanic arc [*Aitchison et al.*, 1995, 1998; *Cluzel et al.*, 2001; *Collot et al.*, 1988; *Lagabrielle et al.*, 2005]. The collision of the arc and continued convergence resulted in overthrusting and ophiolite emplacement by 34 Ma [*Cluzel et al.*, 2001]. In Northland, New Zealand obduction of the northland ophiolite occurred between 24 and 21 Ma [*Ballance and Sporli*, 1979; *Herzer*, 1995; *Isaac et al.*, 1994; *Mortimer et al.*, 2003; *Whattam et al.*, 2005]. However, since the relics of Early Miocene arc-type volcanism are now located on both sides of Northland [*Hayward et al.*, 2001; *Herzer and Mascle*, 1996] the vergence of putative subduction is less clear and has been variously attributed to westward [*King*, 2000; *Mortimer et al.*, 1998], southwestward [*Hayward et al.*, 2001], northwestward dipping [*Brothers*, 1984; *Kamp*, 1984], or northeastward dipping subduction [*Crawford et al.*, 2003; *Schellart*, 2007; *Schellart et al.*, 2006].

[8] The mid-Cenozoic obduction events in New Caledonia and Northland, New Zealand support the presence of NE-dipping subduction located west of the proto Tonga-Kermadec subduction zone during the Tertiary [*Nicholson et al.*, 2000]. In tectonic models of the South West Pacific, the Norfolk Basin is located along the southern continuation of the New Caledonia convergence. It is thought that eastward (or alternatively westward) dipping subduction within the Norfolk Basin formed the Three Kings Ridge volcanic arc [*Herzer et al.*, 2000; *Herzer and Mascle*, 1996; *Mortimer et al.*, 1998]. Subduction at the proto-Tonga-Kermadec initiated as early as 46 Ma [*Bloomer et al.*, 1995; *Duncan et al.*, 1985; *Ewart et al.*, 1977; *Tappin and Ballance*, 1994]. Therefore, the subduction at the Loyalty arc and within the Norfolk Basin between the Eocene and the Miocene may have been coeval with the westward dipping subduction of the proto-Tonga Kermadec [*Bernardel et al.*, 2002; *Herzer and Mascle*, 1996; *Kroenke and Dupont*, 1982; *Kroenke and Eade*, 1982b; *Mortimer et al.*, 1998; *Schellart et al.*, 2006].

[9] Thus an outstanding question is how crustal structure that records the convergent and extensional tectonic history of the Norfolk Basin is related to regional tectonic events. Here we use available seismic reflection profiles in combination with a synthesis of all published constraints from the Norfolk Basin to investigate the structural elements of the Norfolk basin crust. Notably, we propose that convergence continued southward from New Caledonia and into the Norfolk Basin.

2. Data

[10] Bathymetric data sets were merged from several sources. High-resolution multibeam data covering an area of 186,000 km^2 were collected in 1999 during the French-Australian Seismic Transect (FAUST-2) survey by IFREMER and Geoscience Australia by the N.O. L'Atalante (Figure 1). ETOPO2 satellite derived bathymetry [*NOAA*, 2006] was overlain by all available GEODAS multibeam bathymetry data and the FAUST-02 multibeam bathymetry data (Figure 2).

[11] The principal seismic reflection data were collected in the Norfolk Basin during two cruises. Deep seismic reflection data were collected in 1997 on AGSO's (Australian Geoscience Survey Organisation, now Geoscience Australia) Rig Seismic survey 177. These lines provide seismic images with up to 11 s two-way travel time (twt) [*Bernardel et al.*, 2002] (Figure 1). Higher resolution seismic reflection data were acquired in 1999 on AGSO Survey 221. These lines provide seismic images with up to 2 s (twt) [*Bernardel et al.*, 2002]. Seismic refraction data from the 1967 Nova cruise [*Shor et al.*, 1971] were collected using a two ship seismic refraction method. There are two refraction data points located within the Norfolk Basin corresponding to the two vessels used (Figure 1) (N22 and N23).

[12] Magnetic data were compiled from both NGDC data and include Faust-02 magnetic anomaly data. These data sets were used to create a

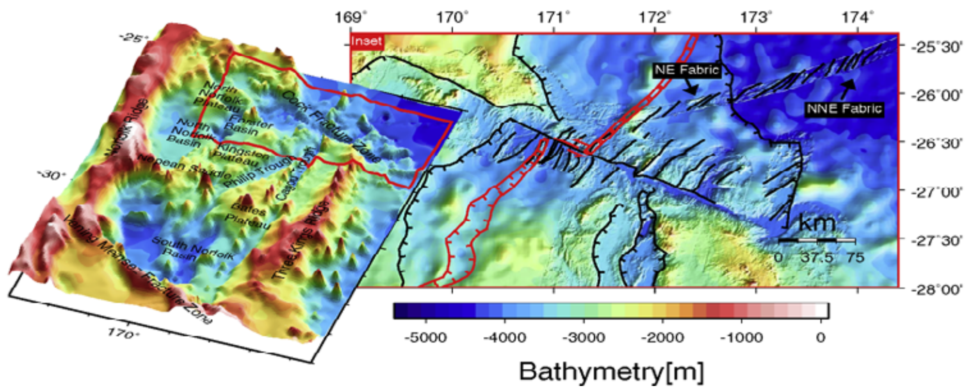

Figure 2. (left) Bathymetry of the Norfolk Basin from merged satellite [*Smith and Sandwell*, 1997] and multibeam bathymetry. The North Norfolk, South Norfolk, and Forster basins are labeled in red; the ridges, plateaus, and fracture zones are in black; and the Philip and Cagou troughs are in white. (right) Interpreted bathymetry of the Cook Fracture Zone and Northern Forster Basin. Abyssal hill-type fabric is interpreted perpendicular to the Cook Fracture Zone. An extinct spreading ridge is also interpreted on a ridge within the Forster Basin and the northern South Fiji Basin. Merged satellite bathymetry is upsampled using a linear interpolant to the resolution of the FAUST-2 multibeam data (0.18 min longitude, 0.15 min latitude, 300 m resolution).

regional grid of magnetic anomalies. More details can be found in the work of *Sdrolias et al.* [2004].

3. Results

3.1. Bathymetry

[13] The Norfolk Basin is a rhomb-shaped, 500 km wide by 720 km long basin between the Three Kings Ridge and the Norfolk Ridge. The Three Kings Ridge appears to have been pulled away from the Norfolk Ridge and is left laterally offset from the Norfolk and Loyalty Ridge along the Cook Fracture Zone [*Bernardel et al.*, 2002]. The Norfolk Basin is characterized by regions of elevated plateaus which range in depth from 2000 m to 3100 m [*Sdrolias et al.*, 2004] (Bates Plateau, Kingston Plateau, North Norfolk Plateau) separated by basins, which range in depth between 3100 and 4300 m (North and South Norfolk Basin, Cagou Trough, Philip Trough, and Forster Basin) (Figure 2).

[14] These basins have been interpreted as Miocene aged oceanic crust considering the occurrence of Miocene rocks dredged throughout the basin [*Sdrolias et al.*, 2004], a back-arc basin type basalt recovered from the Cook Fracture Zone [*Bernardel et al.*, 2002], and a back-arc basin type basalt recovered from the South Norfolk Basin abyssal plain [*Mortimer et al.*, 1998]. The rugged bathymetry of the Forster Basin is interpreted as abyssal hill fabric [*Bernardel et al.*, 2002]. The Cook Fracture Zone has been similarly interpreted [*Sdrolias et al.*, 2004]. The combined FAUST-2 and GEODAS multibeam bathymetry data reveal that a similar bathymetric roughness is observed on either side of Cook Fracture zone which separates the Norfolk Basin from the South Fiji Basin (Figure 2).

[15] The formation of abyssal hill fabric within the Norfolk Basin requires a spreading center. We identify a ridge on each side of the Cook Fracture Zone, which is perpendicular to the Cook Fracture Zone and right-laterally offset by the Cook Fracture Zone (Figure 2). It has a graben at the ridge apex and we interpret this NE trending ridge as the extinct spreading ridge in the Forster and South Fiji Basin. The seafloor within the northern part of the Norfolk Basin and the northern South Fiji Basin on either side of the Cook Fracture Zone is similar in depth, supporting the interpretation of a similar age of formation.

[16] The abyssal hill fabric on either side of the Cook Fracture Zones is generally oriented in a northeast direction. However, along the swath WEST06MV (swath location shown in Figure 1) the fabric changes from a northeastern orientation at 172.60 E to an east-northeast orientation further eastward in the South Fiji Basin. This change in orientation of the fabric into the deeper northeastern South Fiji Basin indicates the northeastern and northwestern South Fiji Basin underwent two separate opening events. The abyssal hill fabric of the northwestern section of the South Fiji Basin directly north of the Norfolk Basin, is similar to that observed in the Norfolk Basin. Therefore we

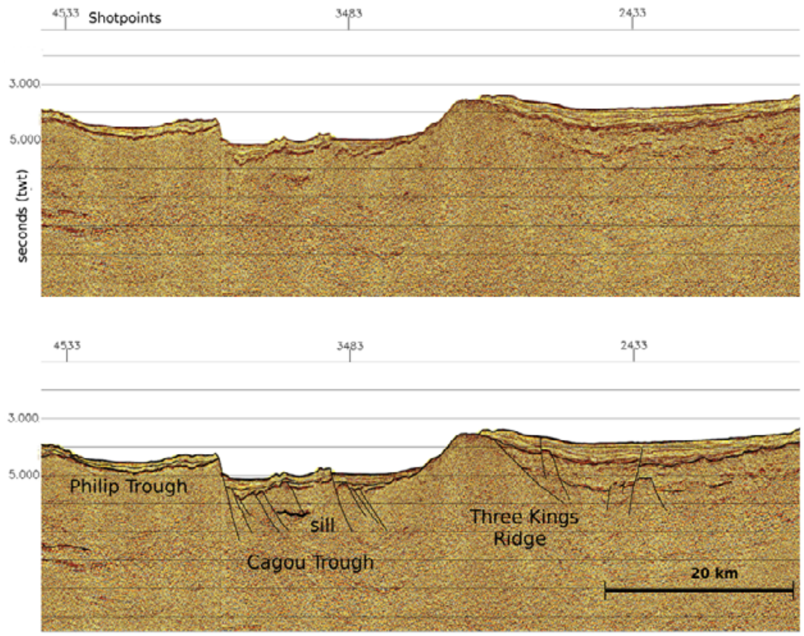

Figure 3. The Cagou Trough seismic section on LHRNR-B in the North Norfolk Basin. (see Figure 1 for profile location). The eastern portion of the profile is a portion of the Three Kings Ridge and the Philip Trough bounds the profile to the west. Strong high-amplitude reflections interpreted as sills are underneath the acoustic basement of the Cagou Trough and may be a relict magma chamber or cumulate layer.

propose the crust within the Norfolk Basin and the northwestern South Fiji Basin were formed contemporaneously, in agreement with previous interpretations [*Bernardel et al.*, 2002; *Crawford et al.*, 2003; *Schellart et al.*, 2006].

3.2. Interpretation of Seismic Reflection Profiles in the Norfolk Basin

3.2.1. Cagou Trough

[17] The Cagou Trough is a dominant north-south oriented feature that is bound on its western flank by a normal fault clearly visible on seismic reflection profile LHRNRC (Figure 3). The western flank is steep and a normal fault clearly crosscuts the Phillip Trough and terminates the northeastern extent of the Philip Trough. The eastern flank of the Cagou Trough has subdued relief.

[18] The top of crystalline basement is identified throughout the Norfolk Basin by a high amplitude reflector. The basement surface and sediment of the Cagou Trough is more rugged than the adjacent Philip Trough and the top of the basement is rough and crosscut by faults. Within the basement numerous discontinuous reflectors can be seen. At a depth of 6.3 s (twt) below sea level (bsl) (1.3 s twt) below the seafloor corresponding to a depth of about 1.75 km within the igneous crustal basement) a bright and undulating reflector is seen. Such shallow and bright reflections within the igneous crustal basement may indicate the top of a relict magma chamber [*Maldonado et al.*, 2000] or a cumulate layer. High-amplitude magnetic anomalies and a thin or dense crust indicated by its Bouguer gravity signature suggest that the Cagou Trough may contain oceanic crust [*Sdrolias et al.*, 2004] or highly thinned continental crust. We propose that these bright reflections are sills that were formed by the crystallization of melts below the upper crust associated with an axial magma chamber or a cumulate layer. These discontinuous internal reflections are also observed on profiles from the Cagou Trough on the line FAUST-034 (Figure S1 in the auxiliary material[1]).

3.2.2. Kingston Plateau

[19] The Kingston Plateau is crosscut by normal faults. Some tilted basement blocks are elevated well above the sedimentary cover and upper crustal reflections appear to be connected to deeper intra-basement reflections (Figure 4). The latter are located at 7.3 s (twt) (between SP 4358 and 6000) and gently dip toward the east. These reflections are distinct from possible seafloor multiples and are pervasive across the 75 km width of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GC002222.

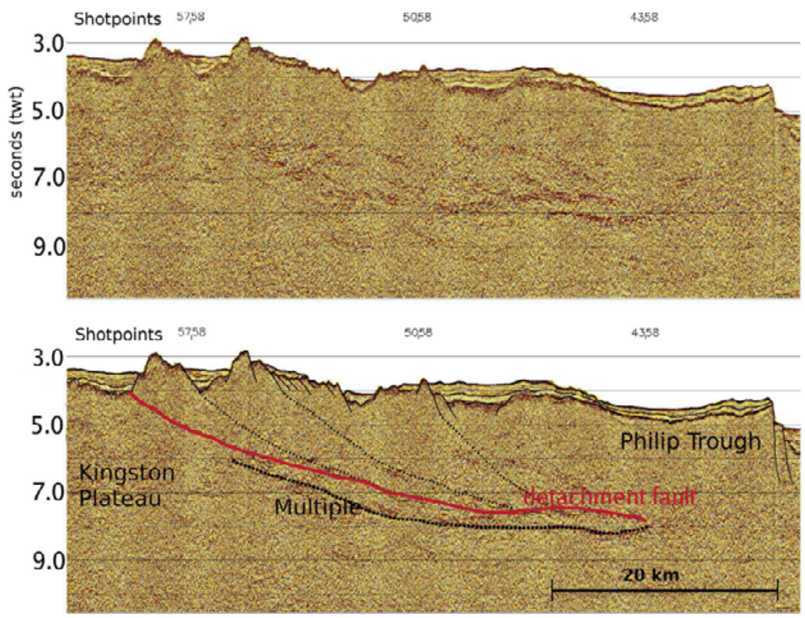

Figure 4. The Kingston Plateau on LHRNR-B showing intracrustal reflections above the depth expected for multiples. They are interpreted as listric normal faults, connected to a detachment fault at about a depth of 8 s twt. This likely represents a thrust fault reactivated during extension.

the Kingston Plateau on LHRNR-B. The intrabasement reflections are not observed within the crystalline basement of the Philip Trough or Forster Basin. Similar reflections are however observed within the crystalline basement of the Bates Plateau (line LHRNR-D) and gently dip toward the Three Kings Ridge. Less continuous intrabasement reflections are also observed on LHRNR-C beneath the Kingston Plateau. We interpret these low-angle intrabasement reflections as faults.

3.2.3. Nepean Saddle

[20] The Nepean Saddle is an elevated region straddling the North and South Norfolk Basin. Numerous magmatic intrusions and volcanic seamounts are apparent from seismic reflection profiles. Seismic profiles show that both seamounts and magmatic intrusions on the Nepean Saddle are largely aligned in an east-west direction. The distribution of intrusions and seamounts on the Nepean Saddle is interpreted to be fault controlled. The high-amplitude magnetic anomalies from the Nepean Saddle are coincident with both interpreted magmatic intrusions and seamounts accounting for the overall high magnetic amplitude signature of the Nepean Saddle compared to the rest of the basin. The Nepean Saddle is adjacent to Norfolk and Philip Islands which are sites of recent ($\sim$3 Ma) basaltic intraplate (OIB) volcanism [*Dupont et al.*, 1975; *Jones and McDougall*, 1973]. This recent volcanism on the Norfolk and Philip Island may have also overprinted and intruded the much older extensional faulting on the Nepean Saddle. Therefore the observed volcanism within the Norfolk Basin which is particularly concentrated on the Nepean Saddle, may not be synchronous with extension and may not be the driving force for extension of the Norfolk Basin which was previously suggested by *Sdrolias et al.* [2004].

3.3. Magnetically Quiet Portions of the Norfolk Basin

[21] When compared to adjacent basins, the Norfolk Basin is predominantly an area of relatively contiguous low-amplitude magnetic anomalies (Figure 5b). Magnetic anomalies within the adjacent New Caledonia, South Fiji and the South Loyalty Basins mostly fluctuate between $\pm$ 200 nT (Figure 5c), in contrast to the majority of the Norfolk Basin which displays magnetic anomalies fluctuating between -100 and 100 nT. These magnetically quiet areas within the Norfolk Basin include the South and North Norfolk Basin and the Kingston and Bates Plateau. The observed sediment thickness in the Norfolk Basin is generally less than 1 s (twt) thick [*Bernardel et al.*, 2002; *Herzer and Mascle*, 1996; *Shor et al.*, 1971] and too thin to attenuate the crustal magnetic anomalies significantly. Both the elevated plateaus and deeper

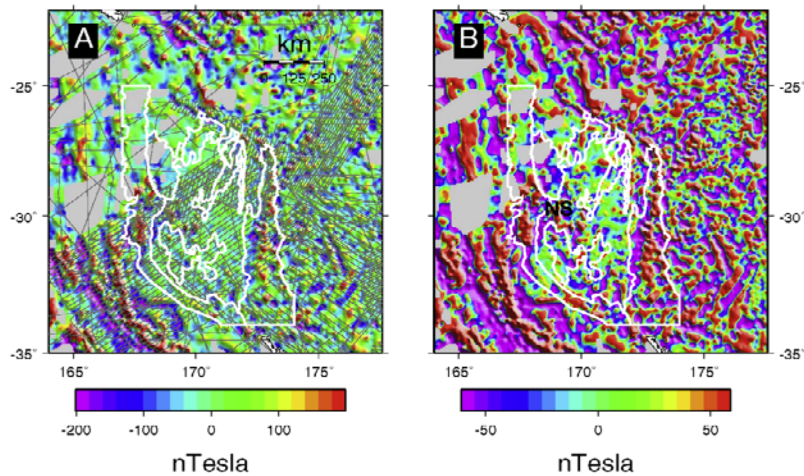

Figure 5. Magnetic anomalies from the South West Pacific region covering the Norfolk Basin. Along-track anomalies are gridded using a natural cubic spline. Areas without data coverage are shown in gray. (a) Magnetic anomaly grid and profile coverage in the Norfolk Basin and (b) the same grid with a color scale restricted to +− 60nTesla. This color scale highlights that the Norfolk Basin is magnetically much quieter than the adjacent basins. NS is the Nepean Saddle.

basinal features have a similarly muted magnetic signature.

[22] The Nepean Saddle, the Cook Fracture Zone, the Three Kings Ridge, and the adjacent Cagou Trough produce the highest amplitude magnetic anomalies in the Norfolk Basin fluctuating between −210 to 370 nT. On the Nepean Saddle, Cook Fracture Zone, and Three Kings Ridge, these high-amplitude anomalies are correlated to magmatic intrusions and seamounts observed in the seismic reflection profiles. On the Nepean Saddle this east-west oriented volcanism may be related to recent (∼3 Ma) volcanism observed on Norfolk Island and Philip Island. Within the Cagou Trough and on the Three Kings Ridge, seamounts are aligned north-south. Seamounts on the Three Kings Ridge have been dredged and contain Miocene shoshonitic rocks implying arc related volcanism [*Mortimer et al.*, 1998].

3.4. Refraction Measurements From the Norfolk Basin

[23] Two 1-D seismic profiles from refraction studies are located in the Norfolk Basin (sites N23 and N22). These sites both show velocities consistent with oceanic crust in the North Norfolk Basin but are thicker than normal oceanic crust (Figure 6). Typical oceanic crust is between 6 and 8 km thick [*White et al.*, 1992]. Velocities recorded in oceanic crust increase with depth and are expected to reach gabbro-type velocity (7–7.7 km/s) in the lower crust [*Sobolev and Babeyko*, 1994]. In contrast, continental crust is generally thick (>10 km) with velocity ranging consistently from 6 to 7 km/s [*Christensen and Mooney*, 1995]. Site N23 has 12 km thick crust compared to N22 with an 8 km thick crust. This may indicate that the crust thickens eastward away from the Norfolk Ridge in this area.

4. Discussion

[24] There are two possible explanations for the magnetically quiet nature of the Norfolk Basin crust. The crust may be oceanic, formed during the Cretaceous Normal Superchron (CNS) (i.e., before 83.5 Ma), or alternatively the crust may be continental. Evidence for the age and composition of the oceanic crust within the South Loyalty Basin is inferred from the Poya Terrane rocks in New Caledonia. These rocks contain Late Cretaceous to Early Tertiary (∼83–55 Ma) microfossils [*Aitchison et al.*, 1995; *Cluzel et al.*, 2001] and basalts with back-arc geochemical affinities [*Cluzel et al.*, 2001]. The inferred Cretaceous crust within the South Loyalty Basin may have extended southward into the Norfolk Basin [*Sdrolias et al.*, 2003]. In addition to Cretaceous oceanic crust, the recovery of paleoproterozoic zircons in dredged sandstone from the Bates Plateau (P69238) [*Meffre et al.*, 2006] (Figure 7) indicates that the Norfolk Basin contains fragments that were rifted from the Norfolk Ridge [*Meffre et al.*, 2006]. The Norfolk Ridge comprises Mesozoic continental crustal basement extending between present-day New

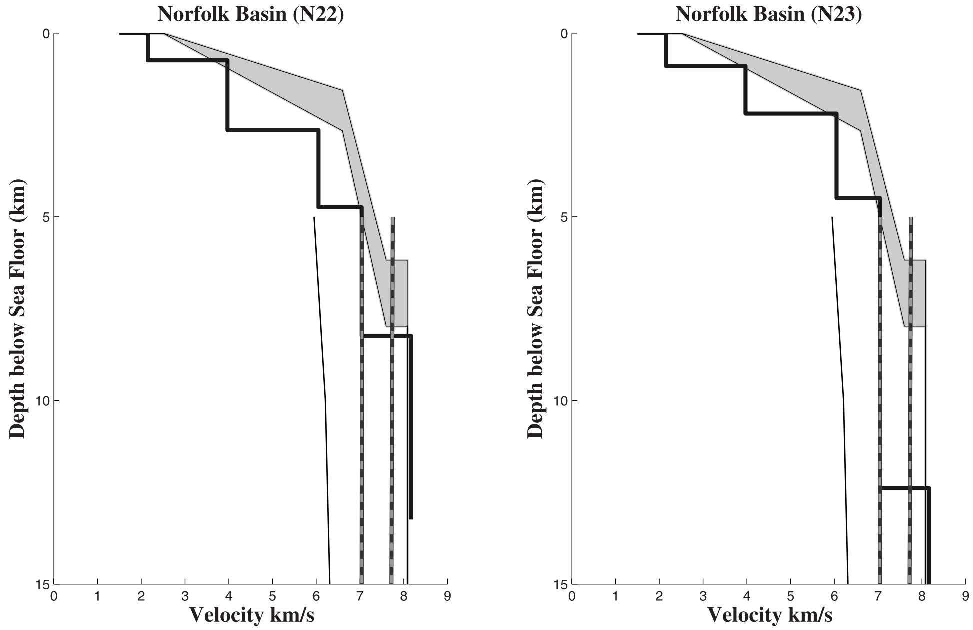

Figure 6. Crustal velocities at two sites (N22 and N23, see Figure 1 for location) from the refraction survey of *Shor et al.* [1971] (thick black line). Typical oceanic crustal velocities are shaded gray [*White et al.*, 1992], gabbroic velocity ranges are shown as dashed lines [*Sobolev and Babeyko*, 1994], and typical continental velocity ranges as thin black lines [*Christensen and Mooney*, 1995]. N23 has very thick crust and is located farther away from the Norfolk Ridge. Both sites show velocities consistent with oceanic crust.

Caledonia to Northland, New Zealand and was detached from the eastern margin of Australia during the Cretaceous opening of the Tasman Ocean [*Gaina et al.*, 1998].

[25] Refraction measurements from the North Norfolk Basin do not allow us to conclusively determine if the crust is continental or oceanic. Sites N22 and N23 show crustal velocities that are consistent with normal oceanic crust. However, the crust is anomalously thick for oceanic crust. The lower crust at site N23 is thicker than at N22, indicating that the crust may thicken with distance away from the Norfolk Ridge. The thickening of the lower crust at site N23 and the proximal location of the these sites to a large seamount within the Forster Basin (Figure 2) may indicate that there is oceanic crustal underplating from the ponding of mantle melts at the base of the crust during episodes of volcanism at this seamount. At present there is no data constraining the age of the crust surrounding the Forster seamount. Since the refraction measurements from the Norfolk Basin are not conclusive in determining the continental or oceanic character we cannot rule out the possibility that the North Norfolk Basin is comprised of thickened CNS oceanic crust, continental fragments or both.

[26] The Kingston and Bates Plateaus are elevated features within the northern Norfolk Basin. They are composed of the same magnetically quiet crust as the majority of the Norfolk Basin including the North Norfolk Plateau and the South Norfolk Basin. Given their magnetically quiet nature and their elevation (since continental crust is generally thicker and more buoyant than oceanic crust) the plateaus within the Norfolk Basin are likely continental fragments, an interpretation supported by recent dredge samples [*Meffre et al.*, 2006] (Figure 7).

[27] Extensional faults are interpreted on seismic reflection profiles across the Kingston Plateau (section 2B). These extensional faults connect to a deep low angle fault. Convergence within the Norfolk Basin during the Eocene is consistent with regional observations of convergence which may have been active as late as 34 Ma when the forearc of the South Loyalty Basin was obducted onto New Caledonia [*Cluzel et al.*, 2001, 2005]. Convergence within the Norfolk Basin during the Eocene is consistent with many Southwest Pacific plate models which suggest that NE-dipping subduction started in the South Loyalty Basin continued southward into the Norfolk Basin at this time. Therefore we propose that the deep low angle fault interpreted within the seismic reflection profiles

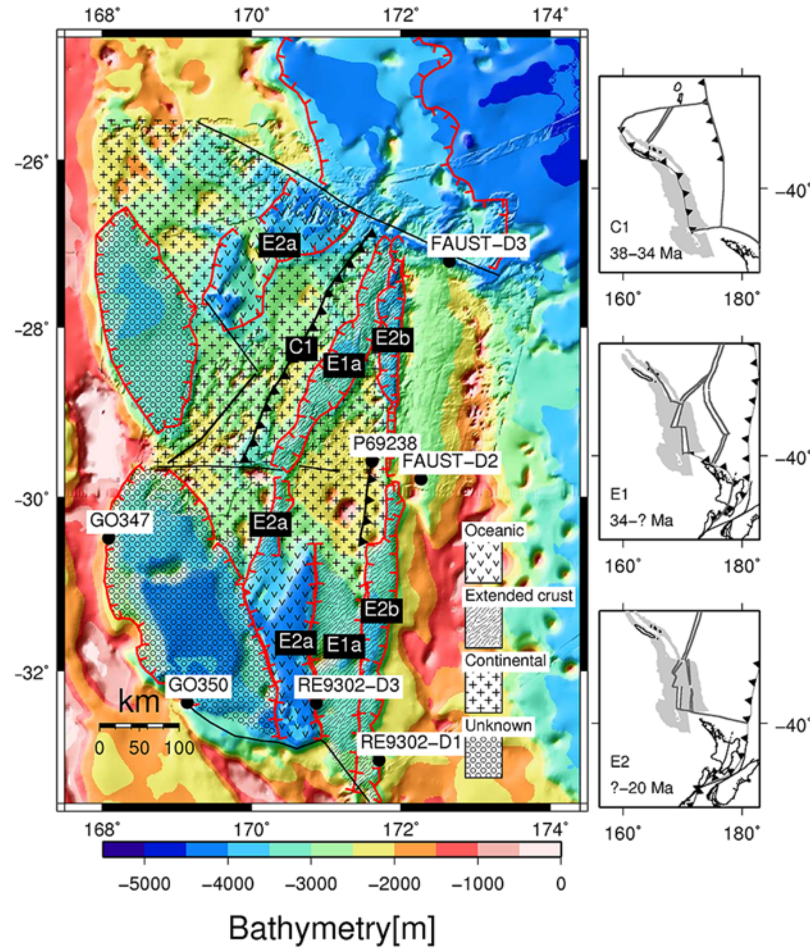

Figure 7. Structural interpretation of the Norfolk Basin crust and regional reconstructions including the locations of key dredges referred to in the text. C1 refers to compression which was likely related to east dipping subduction resulting in the obduction of the New Caledonian ophiolitic nappe. E1 is the first extensional event following convergence C1. E1 extension stretched the crust within the Norfolk Basin forming the Philip Trough and extending crust within the South Norfolk Basin. E2 refers to ongoing or later extension which resulted in new oceanic crust being formed in the Forster Basin, South Norfolk Basin (and perhaps the Cagou Trough) and continuing extension in the northwestern South Fiji Basin.

across the Kingston Plateau is a reactivated thrust fault and is the location of Eocene to Oligocene convergence within the Norfolk Basin.

[28] Several dredges from the Norfolk Basin provide evidence of an episode of convergence or subduction initiation. The oldest volcanic rocks reported from the Norfolk Basin occur to the west of the Three Kings Ridge. A 37.5 Ma old boninite (±0.8 plagioclase Ar/Ar) (FAUST2-D2) was interpreted to be the forearc of an oceanic arc [*Bernardel et al.*, 2002] (Figure 7). In addition, a garnet-bearing high grade amphibolite containing Late Eocene metamorphic minerals was dredged from the Bates Plateau (IGNS: P69238) [*Meffre et al.*, 2006] (Figure 7) suggest collision and exhumation in the Eocene in this area. These samples suggest subduction related volcanism or subduction initiation since at least the late Eocene. In the South Norfolk basin, 20 Ma basalts, andesites and shoshonites were recovered from the Three Kings Ridge and Norfolk Basin [*Mortimer et al.*, 1998]. *Whattam et al.* [2008] linked this volcanism and the inception of the volcanic activity on the Northland Plateau, the Northland arc and the Colville-Kermadec arc to the collision of the Hikurangi Plateau with the southeastern margin of the Australian-Pacific Plate boundary.

[29] Oceanic crust is observed within the Norfolk Basin. Abyssal hill fabric with a similar depth is observed on either side of the Cook Fracture Zone (Figure 2). This suggests that seafloor spreading within the Norfolk Basin was offset by the Cook

Fracture Zone and continued into the northwestern South Fiji Basin. The rugged basement character and intrabasement reflections are suggestive of a relict axial magma chamber or a cumulate layer within the Cagou Trough, indicating that it too may be composed of oceanic crust. However, the Cagou Trough may be too narrow to have developed seafloor spreading and there are no dredge data to confirm the nature of the crust. Dredges provide an age for some of the oceanic crust within the Norfolk Basin. A 23 Ma old BABB-MORB recovered from the Cook Fracture Zone (FAUST-D3: Figure 7) indicates seafloor spreading along a transform fault with backarc basin affinities during the Miocene. Similarly, a BABB-MORB dated at ~20 Ma was recovered from the eastern South Norfolk Basin [*Mortimer et al.*, 1998] (RE9302-D3: Figure 7) and may sample the southern continuation of spreading within either the Forster Basin or Cagou Trough. These observations indicate a Miocene episode of seafloor spreading within the Norfolk Basin.

[30] Dredged rock samples provide a further constraint on the timing of extension and seafloor spreading within the Norfolk Basin. Brecciated rocks recovered from the Vening Meinesz Fracture Zone indicate strike-slip motion along the fracture zone occurred after 45 Ma (GO350: Figure 7) [*Herzer and Mascle*, 1996]. Subsidence, possibly due to extension within the basin, is recorded by the bathyal infillings of Early and Middle Miocene photic zone (deposited above 200m water depth) rocks on the Norfolk Ridge (GO347: Figure 7) [*Herzer and Mascle*, 1996], the lower Three Kings Ridge (RE9302-D1: Figure 7) [*Herzer and Mascle*, 1996] and Bates Plateau (P69238: Figure 7) [*Meffre et al.*, 2006].

[31] A Miocene episode of extension is consistent with regional observations of extension from New Caledonia. The final obduction of the ophiolitic nappe at 34 Ma [*Cluzel et al.*, 2001] in New Caledonia was followed by aggradation and intense erosion in the Late Oligocene expressed as a lateritic surface indicative of uplift and severe weathering [*Chardon and Chevillotte*, 2006; *Dubois et al.*, 1974; *Lagabrielle et al.*, 2005]. Normal faulting during the Neogene tilted the New Caledonian horst blocks toward the southwest [*Chardon and Chevillotte*, 2006]. These episodes of extension may be related to an episode of Miocene extension and seafloor spreading that occurred south of New Caledonia, in the Norfolk Basin.

[32] The formation of new seafloor may have been limited to the Forster Basin and the South Norfolk Basin (and perhaps the Cagou Trough) where there is clear evidence for oceanic crust. Seafloor spreading was preceded by stretching of the continental and or Cretaceous oceanic crust that already existed within the Norfolk Basin. The Philip Trough may contain oceanic crust. However, although the Philip Trough is deeper than the other plateaus it is magnetically quiet like the plateaus and so may also be a stretched continental fragment. In reflection seismic profiles and bathymetry, the northeastern terminus of the Philip Trough is clearly truncated by the steep normal fault on the western edge of the North South trending Cagou trough. This clearly indicates that extension was located within the Philip trough before extension within the Cagou Trough.

[33] We propose the following sequence for the formation of the crustal elements within the Norfolk Basin.

[34] 1. Between the Late Eocene (at least 38 Ma) and 34 Ma eastward oriented convergence was active to the East of the Norfolk Ridge (C1: Figure 7). This eastward dipping convergence may have represented a southern continuation of subduction along the Loyalty Ridge and may have resulted in subduction of Cretaceous oceanic slab within the basin resulting in arc volcanism along the Three Kings Ridge. The compressive regime likely ended at the same time as the jamming of the subduction zone and the obduction of the New Caledonian ophiolites ~34 Ma [*Cluzel et al.*, 2001].

[35] 2. The compressive regime gave way to extension associated with Tonga-Kermadec subduction and trench rollback. Initially, extension resulted in faulting of the Cretaceous oceanic crust or continental fragments in the South and North Norfolk Basins and within the NE trending Philip Trough (E1a: Figure 7). However, by 20 Ma the extension of preexisting crustal elements was replaced by seafloor spreading or extension within the Cagou Trough and seafloor spreading within the Forster Basin and the South Norfolk Basin (E2a and E2b: Figure 7). Extension continued north into the northwestern South Fiji Basin consistent with a change in bathymetry and fabric of the northwestern South Fiji Basin compared to the northern South Fiji Basin.

[36] Previous models have proposed that dual subduction zones were active along the proto Tonga Kermadec Ridge and the Three Kings Ridge

[*Herzer et al.*, 1997, 2000; *Herzer and Mascle*, 1996; *Mortimer et al.*, 1998] during the Miocene. However, we find that eastward dipping thrusting and possible obduction and/or subduction within the Norfolk Basin likely occurred before 34 Ma. The Tonga arc system was initiated by 46 Ma [*Bloomer et al.*, 1995; *Duncan et al.*, 1985; *Ewart et al.*, 1977; *Tappin and Ballance*, 1994] and continuous arc activity on the Tonga arc is recorded by Oligocene lava flows (33–31 Ma) and Miocene dikes (19–17 Ma) [*Duncan et al.*, 1985]. The proto Tonga-Kermadec subduction hinge is thought to have rolled eastward causing the initiation of spreading within the south Fiji Basin in the late Oligocene [*Malahoff et al.*, 1982; *Sdrolias et al.*, 2003; *Watts et al.*, 1977] suggesting the proto Tonga Kermadec had westward dipping convergence since subduction initiation. Since northeastward and eastward dipping convergence was likely active within the South Loyalty and Norfolk Basins, we infer that subuction systems with opposite polarities coexisted within the South West Pacific between the Eocene and until at least the Oligocene, as shown in the reconstructions of *Schellart et al.* [2006]. Active arc activity on the Colville-Kermadec by 25 Ma [*Ballance et al.*, 1999] is coincident with the collision of the Hikurangi Plateau, and the inception of the Northland volcanic belt 22–23 Ma [*Herzer*, 1995].

[37] Our findings also suggest that seafloor spreading within the Norfolk Basin was concurrent with seafloor spreading in the northwestern South Fiji Basin. This is consistent with previous models for the opening of the Norfolk Basin in which the Tonga Kermadec subduction system opened in a windshield wiper fashion allowing seafloor spreading to propagate from the northern South Fiji Basin concurrently into the Norfolk and southern South Fiji Basins [*Crawford et al.*, 2003; *Herzer et al.*, 2000; *Mortimer et al.*, 2007; *Schellart et al.*, 2006].

5. Conclusions

[38] The Norfolk Basin likely contains both continental fragments and oceanic crust of Cretaceous and Miocene age. These fragments record a history of convergence and multi directional phases of extension. We propose that the proto-Norfolk Basin crust experienced compression at the southern continuation of Eocene eastward dipping subduction along the Loyalty Ridge. Based on dredge results [*Meffre et al.*, 2006; *Mortimer et al.*, 1998], convergence along this "New Caledonia Subduction Zone" likely occurred between the Late Eocene until ~34 Ma with the final obduction of the New Caledonian Ophiolitic Nappe recording the closure of the northern part of the associated small ocean basin as proposed by *Schellart et al.* [2006]. We interpret a thrust fault beneath the Kingston Plateau as recording Eocene compression within the Norfolk Basin.

[39] We observe abyssal hill fabric of a similar depth on both sides of the Cook Fracture Zone indicating seafloor spreading within the Norfolk Basin was offset at the Cook Fracture Zone but continued into the northwestern South Fiji Basin. Extension within the plateaus probably occurred first which was then crosscut by north-south oriented extension within the Cagou Trough. Extension is consistent with observed Oligocene-Miocene extension in New Caledonia.

[40] During the Miocene the Norfolk Basin may have been located as much as 1000 km behind the Tonga Kermadec Trench. Regional extension during the Miocene located within the Norfolk Basin, northwestern South Fiji Basin and in New Caledonia raises an interesting question: what drove this regional phase of extension within this area of the Southwest Pacific? Further investigation of the crust in the Norfolk Basin and particularly in the under sampled South Norfolk Basin is required in order to fully understand the driving force for Miocene extension within the Norfolk Basin and the relationship of convergent events to the evolution of the Tonga-Kermadec subduction system.

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