Extension in the western Ross Sea region-links between Adare Basin and Victoria Land Basin

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[1] Spreading in the Adare Basin off north-western Ross Sea (43–26 Ma) and extension in the Victoria Land Basin (VLB, > 36 Ma) are used to constrain the pole of rotation for the Adare Basin, providing a rifting model for the region for the past 45 Ma. The offset from Northern Basin to VLB at about 74°S coincides with the linear Polar-3 magnetic anomaly, inferred to be caused by a major 48 - 34 Ma igneous intrusion. The style of extension apparently changed at about 34 Ma, with the end of intrusion at the Polar-3 anomaly, a change from highly asymmetric extension in Adare Basin, and the onset of major subsidence on the flanks of VLB. Ductile lower crustal and lithospheric flow is proposed as the cause of the inferred thick crust underlying southern Adare Basin, and a result of the constraining of extension to the adjacent contiguous Northern Basin. **Citation:** Davey, F. J., S. C. Cande, and J. M. Stock (2006), Extension in the western Ross Sea region-links between Adare Basin and Victoria Land Basin, *Geophys. Res. Lett.*, *33*, L20315, doi:10.1029/2006GL027383.

1. Introduction

[2] The western margin of the Ross Sea is formed by the Transantarctic Mountains, a rift mountain range considered to have formed in the Cretaceous and marking the margin between the East Antarctic craton and the extended, thinned continental lithosphere of the Ross Sea. Subsequent Cenozoic lithospheric extension along the rift margin in the western Ross Sea region (Figure 1) has formed the Northern Basin [*Brancolini et al.*, 1995] in the north and the Victoria Land Basin (VLB) to the south [*Cooper and Davey*, 1987]. A major east-west trending magnetic anomaly, the Polar-3 anomaly [*Bosum et al.*, 1989], coincides with an offset of the VLB from the Northern Basin. Off north-western Ross Sea, marine magnetic anomalies have defined an episode of seafloor spreading from about 43 - 26 Ma that formed the Adare Basin [*Cande et al.*, 2000; *Cande and Stock*, 2005]. About 170 km of ENE-WSW extension occurred. The linear relationship and the close temporal association of these features suggest that they may have a common cause that has extended across the continent - ocean boundary. A simple rift model is proposed linking these extensional features, and inconsistencies with this model are discussed to help understand the propagation of rifting across ocean-continent boundaries.

2. Adare Basin and Northern Basin

[3] The Adare basin is defined by a NNW - SSE trending set of oceanic magnetic anomalies (9 through 19: 26 Ma to 43 Ma) that extend from a triple junction in the north, at about 69°S, 170°E, to the western Ross Sea continental slope in the south [*Cande and Stock*, 2005]. The extinct spreading center was subsequently obscured by a major morphological rift graben, the Adare Trough [*Cande et al.*, 2000] with bounding faults that caused approximately 5 km of extension up to 5 million years after Adare Basin spreading ceased [*Mueller et al.*, 2005]. Opening was asymmetric, particularly in the south, until about anomaly 13 time (34 Ma) and the anomalies are not well defined in the south of the western plate where those older than anomaly 13 apparently trend into a single large anomaly [*Cande and Stock*, 2005]. The pole of rotation for the opening of the Adare Basin is poorly controlled, particularly for the earlier stages of spreading [*Cande et al.*, 2000]. The southern part of the basin is distinctive as the Adare Trough does not extend into it as a major morphological feature, the depth of the oceanic seafloor shoals markedly southwards and is shallow for its age, and the basin is contained between the continental shelf near Cape Adare in the west and the inferred continental sliver of Hallett Ridge in the east (Figure 2). Immediately south, the Northern Basin contains up to 5 km of sediments inferred to be of late Eocene/Oligocene age and younger, and forming a prograding wedge on the continental margin [*Brancolini et al.*, 1995]. The nature of the boundary between Adare Basin and the Ross Sea shelf is controversial. Previous interpretations [e.g., *Weissel et al.*, 1977; *Stock and Molnar*, 1987; *Salvini et al.*, 1997] place a transcurrent fault along the Ross Sea continental edge, along which the oceanic extension to the north was accommodated, and very little extension is inferred in the Ross Sea region during the Cenozoic [e.g., *Lawver et al.*, 1994]. *Cande and Stock* [2005] however, propose that there has been no transcurrent motion between the Ross Sea continental shelf and the Adare basin during or since its (basin) formation as: (i) the easternmost anomalies of the Adare basin (anomalies 16–18) continue unbroken into a linear magnetic anomaly - the Northern Basin Magnetic Anomaly, Figure 2 - that runs approximately north-south along the eastern side of the Northern Basin, (ii) there is a continuous positive Bouguer anomaly across the Adare basin and the Northern Basin, and (iii) existing seismic data across the western Ross Sea -

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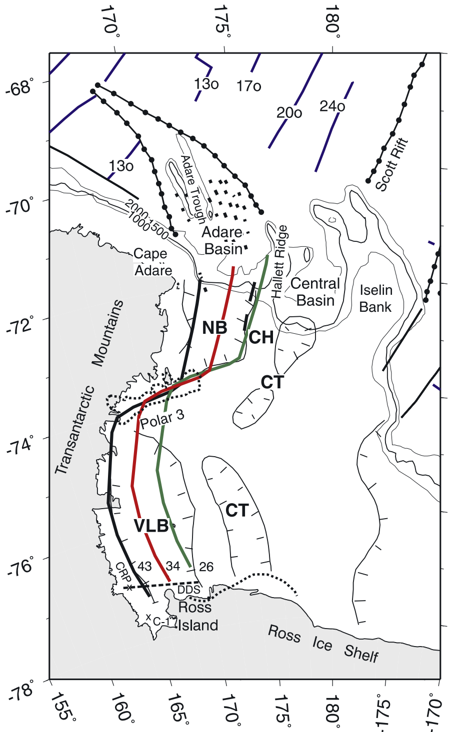

Figure 1. Western Ross Sea. NB, CH CT, VLB mark the Northern Basin, Coulman High, Central Trough and Victoria Land Basin. Bathymetry contours are at 1000m, 1500m, and 2000m. Dashed line - DDS - is profile for the extension modeling [*Davey and De Santis*, 2005]. Cape Roberts drill sites (CRP) and CIROS-1 drill site (C-1) - crosses. The dotted line along the Ross Ice Shelf marks the northern limit of large magnetic anomalies (see text). Rift model - black, red and green thick lines mark the east rift margin prior to rifting and at 34 Ma and 26 Ma (after rotation about the pole of rotation, Figure 4), respectively.

Adare basin boundary do not show any major features that could be interpreted as transcurrent faults.

3. Victoria Land Basin

[4] The VLB is a major rift basin that lies along the central and southern margin of western Ross Sea, along the Transantarctic Mountains front [*Davey et al.*, 1983; *Cooper and Davey*, 1987]. It contains up to 14 km of sedimentary rocks, in two main packages, thought to be of Mesozoic and mid-late Cenozoic age [*Cooper and Davey*, 1987]. Sediments with ages greater than 36 Ma have been recovered from CIROS drill site in southern McMurdo Sound [*Hannah et al.*, 1997] with possibly 1500 m of sediments beneath [*Brancolini et al.*, 1995]. However, drilling near Cape Roberts on the western flank of the VLB [*Cape Roberts Science Team*, 2000; *Davey et al.*, 2001] recovered 1500 m of core, at the base of which terrestrial conglomeratic rocks overly Mesozoic Beacon Supergroup metasediments. The overlying 1400 m sedimentary section, of latest Eocene age (34 Ma), became more marine and finer up hole, and was interpreted to record the initial rifting of the VLB and its subsequent subsidence. The youngest sediments recovered (under a thin Quaternary cover sequence) were 17 Ma. Four major unconformities were recorded in the sedimentary section and can be traced into the VLB, using seismic data, where a more complete sedimentary section, including post-17 Ma sediments, is imaged. *Davey and De Santis* [2005] interpret the unconformities, dated at the drill holes, as indicating four episodes of extension, and use a flexural cantilever model to reproduce the main features (shape, size, timing and broad stratigraphy) of the VLB by movements along five major faults that were active at the times of the major unconformities. Part of the extension may have been older, pre 34 Ma, as *De Santis et al.* [2001] interpret a pre 34 Ma sedimentary sequence over Beacon Supergroup basement on seismic data, and/or younger (post 17 Ma), but as these sediments were not sampled, the basin was modeled solely on extensional episodes (unconformities) between 34 and 24 Ma with only thermal subsidence after 17 Ma. Their results indicate a total extension of 95 km to form the 145 km wide and 14 km deep basin, of which about 35 km of extension occurred during the initial rift episode.

4. Polar-3 Anomaly and Igneous Intrusions

[5] The Polar-3 anomaly [*Bosum et al.*, 1989] is a major west-east trending magnetic anomaly that extends eastwards for about 170 km from the Victoria Land coast at 74°S. It reaches a maximum amplitude of over 1000 nT on the aeromagnetic data (610 m altitude *Bosum et al.*, 1989]). It is inferred by *Behrendt et al.* [1991] to be caused by igneous intrusions related to a possible transfer fault. *Damaske et al.* [1994] infer a similar cause for the large magnetic anomalies along the Ross Ice Shelf edge east from Southern Victoria Land (Figure 1). Conversion to pseudogravity anomalies [*Damaske et al.*, 1994] indicates a 100 mgal anomaly and a causative body about 12 km thick, assuming

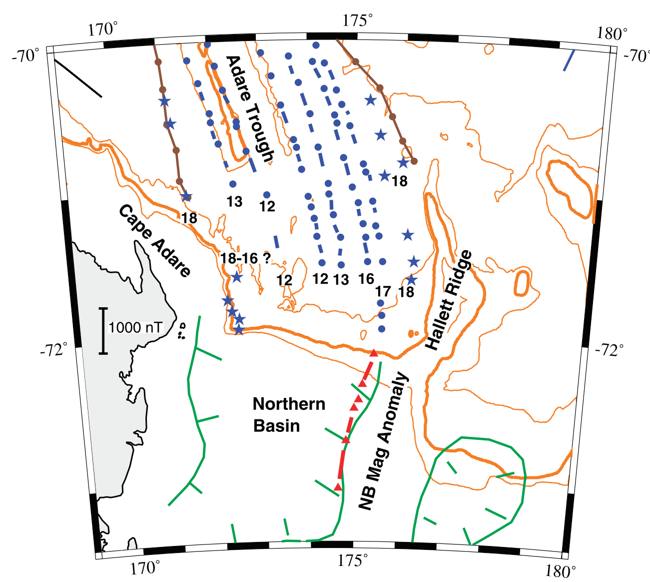

Figure 2. The southern Adare Basin and Northern Basin. The extent of the Adare Basin (brown line) and identified magnetic anomalies within it (blue dash-dot lines) are after *Cande at al.* [2000] and *Cande and Stock* [2005]. The Northern Basin magnetic anomaly is marked by red dash-dot line. Anomaly 18o picks used in the calculation of the pole of rotation - blue stars.

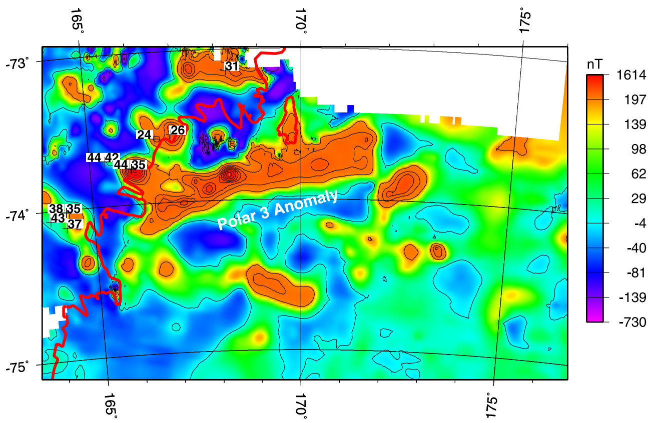

Figure 3. Polar Three magnetic anomaly (contours in nT, after *Bosum et al.* [1989]). Igneous intrusions and dikes with ages (m.y.) [after *Rocchi et al.*, 2002].

a density contrast of 0.2 Mg/m^3 (2.9 - 2.7). The western end of the Polar-3 anomaly overlies the Meander Intrusive Group [*Muller et al.*, 1991; *Tonarini et al.*, 1997], a group of intrusives with ocean island basalt affinities [*Rocchi et al.*, 2002] (Figure 3). *Rocchi et al.* [2002] classify the Cenozoic igneous activity in the northern Victoria Land region into two regions. In the Aviator Glacier-Campbell Glacier region, corresponding to the western end of the Polar Three anomaly, plutons and dikes, striking N-S and WNW - ESE, with ages of 48 Ma to 34 Ma occur, followed by a gap in activity until volcanic activity starts at about 15 Ma. To the north, between Aviator and Borchgrevink Glaciers, plutonic activity does not start until 32 Ma and extends to 22 Ma, no significant dike activity is reported, and no volcanic activity occurred until about 15 Ma. Further north and south, only volcanic deposits are reported, mostly less than 15 Ma with the oldest 24 Ma (in a core off Cape Roberts, [*Cape Roberts Science Team*, 1999]).

5. An Euler Rotation for the Western Ross Sea for Anomaly 18o

[6] The alignment, common extensional style of deformation, and the common or overlapping time frame of the deformation in the Adare Basin, Northern Basin, Polar-3 anomaly, and the Victoria Land basin suggest a single extensional system operated from about 48 Ma - present. In order to calculate an Euler rotation for East– West Antarctica motion that accounts for the mid-Cenozoic motion that took place in the Adare Basin, we determined an Euler rotation for anomaly 18o, which is the oldest isochron observed in the Adare Basin (Figure 2). We followed a very similar data setup to the one used by *Cande et al.* [2000] to determine an East– West Antarctic rotation for anomaly 13o. *Cande et al.* [2000] noted that the anomalies in the Adare Basin represent the third limb of the triple junction between Australia, East Antarctic and West Antarctica. Anomalies and fracture zone trends on the Southeast Indian Ridge (SEIR) between roughly 80° East and the Balleny Fracture Zone at 150° East constrain Australia - East Antarctica motion, magnetic anomalies and fracture zones from the SEIR east of the Balleny FZ constrain Australia - West Antarctica motion, and anomalies in the Adare Basin constrain motion between East and West Antarctica. This “3 plate ” configuration was solved using the statistical methods of *Royer and Chang* [1991]. Although this approach gave a solution for anomaly 13o, the confidence ellipse was very large because the region over which the East– West Antarctica motion was constrained, limited to the anomaly 13o picks in the Adare Basin, was very short. Figure 4 shows the data setup that we used to solve for an anomaly 18o rotation. Although similar to the data setup used by *Cande et al.* [2000] for anomaly 13o, we use the additional constraint of the total amount of extension in the VLB (95 km) to lengthen the region over which we have constraints on East– West Antarctica motion, assuming that the computed extension for VLB corresponds to the total extension for the post 48 Ma time period. The additional constraint from the VLB reduces the uncertainty ellipse for the pole of rotation (red ellipse in Figure 4). The best fit estimate for the East-West Antarctic rotation for anomaly 18o is 84.84° S, 139.53° W, 4.83°. We then computed the flow lines and boundaries, based on an initial rift along the present western margin of the VLB and Northern Basin, for the extension from Adare basin to VLB (Figure 1).

6. Discussion

[7] A number of issues arise from this model. The age of the oldest sediments sampled in VLB is late-Eocene

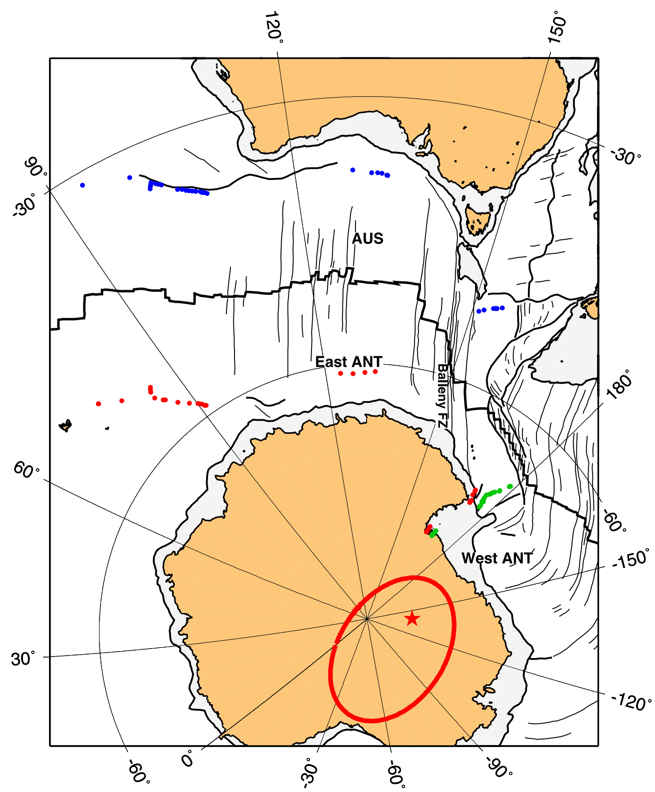

Figure 4. Plate reconstruction for the Pacific, Australian and Antarctic Plates showing the conjugate anomaly positions for anomaly 18 for the Australian - Antarctic plates (red and blue) and the Adare Basin (green and blue), and the pole of rotation for the Adare basin-VLB (red star, with uncertainty - red ellipse).

[*Hannah et al.*, 1997] and older sediments lie beneath, possibly of similar age to the Adare Trough and the inferred age of the Polar-3 intrusion. However, the inferred initial rifting of VLB at the Cape Roberts drill sites is about 10 m.y. younger. The Cape Roberts drill sites are high on the western flank of the VLB. The adjacent Transantarctic Mountains underwent rapid exhumation and inferred uplift from 55 Ma to at least 45 Ma [*Fitzgerald*, 1992] and may be recording the precursory and initial rifting processes during which the CRP sites were either above sea-level or were subsequently uplifted above sea-level and eroded prior to the observed subsidence at about 34 Ma. We therefore prefer the presence of an older (early Adare spreading) rift event and associated sediments. This would not change the modeled total extension for the basin (used to constrain the pole of rotation), only the number of episodes and their extension and age.

[8] The initial rifting at CRP (34 Ma) corresponds to a time when the magnetic anomalies in the Adare Basin became distinctive and spreading became less asymmetric, and when intrusion and dike activity at the Polar-3 intrusive apparently ceased. The Polar-3 anomaly extends east-west about half way across the width of the southern margin of the Northern Basin, equivalent to spreading up to about 34 Ma ago (Figure 1). A possible explanation is that only minor extension occurred in VLB prior to 34 Ma, with major rifting only to the north with the Polar-3 anomaly marking its southern limit. The strain differential across this boundary formed an accommodation zone into which the large amount of intrusion occurred. At 34 Ma, the major rift break in the VLB occurred and allowed extension to continue through the rift system relatively easily with symmetric spreading in the Adare Basin and simple transfer faulting at the Polar-3 anomaly offset. The large amount of extension modeled by *Davey and De Santis* [2005] for their initial rifting episode in VLB (35 km) is approximately the same as that expected to have occurred prior to 34 Ma (45 km). The intervals between the major unconformities at the Cape Roberts drill holes, and inferred extensional episodes are of the order of 1.5– 5 Ma [*Davey and De Santis*, 2005]. Although a higher stress (and longer time interval) for the initial break than for subsequent ones seems reasonable, the large amount of differential stress (stored extension) across the Polar-3 anomaly region for up to 10 m.y. seems excessive and we prefer some pre 34 Ma rifting that has not been recorded at the CRP drill sites as noted earlier. Intrusive activity at Polar-3 anomaly, Adare Basin/Trough faulting and VLB documented extension all ceased at about the same time (22 Ma, 22 Ma and 24 Ma respectively), although the VLB extensional episodes could have continued later but no adequate age data are presently available.

[9] The major issue, as *Cande and Stock* [2005] note, is the accommodation of 170 km of extension of the Adare Basin across the continental shelf edge into the Northern Basin region. They dismiss a model of continental extension distributed across the Northern Basin and the Central Trough because of the continuity of geophysical markers across the shelf edge as noted earlier, and prefer massive localised intrusion into the continental crust of Northern Basin. The proposed massive intrusions (almost 100% of the crust) are unlikely to be mafic in composition because there are no magnetic and gravity anomalies across the region that might be expected for mafic intrusive crustal rocks. Two factors may be of importance: i) the asymmetry of spreading in the Adare Basin that is much less for the western plate than for the eastern plate, with the anomalies at the southern end of the western Adare Basin so close that they coalesce into a single large anomaly (and strong seafloor volcanism), and ii) shoaling and inferred thickening of oceanic crust of the Adare Basin towards the continental shelf. The rifting of the continental sliver of Hallett Ridge appears to have resulted in a transitional crust between the simple oceanic spreading and continental rifting. The smooth continuity of the Bouguer gravity anomaly from the Adare Basin into the Northern Basin, the thickened oceanic crust of the southern Adare basin and the substantive crustal thickness of the Northern Basin may be explained by some form of partitioning of the lithospheric extension, for example between brittle upper continental crust and ductile lithospheric mantle, and by ductile flow of the lower crust and mantle lithosphere into this extensional region.

[10] A final observation about the deformation of the region is the continuous extension in Adare Basin but episodic extension in VLB. This is probably a result of the difference in response to stress build-up of continental and oceanic lithosphere involving different crustal strength, strain weakening, and thermal history.

7. Conclusions

[11] Marine magnetic data off north-western Ross Sea and estimates of extension for the VLB in south-western Ross Sea have been used to constrain an extensional model for the region for the past 48 Ma. Continuous extension occurred in the oceanic area north of the Ross Sea for the period of 43– 26 Ma with minor extension to about 22 Ma, and episodic extension from before 36 Ma to possibly the present for the continental region to the south. The apparent onset of the extension at 34 Ma recorded high on the rift margin probably records a later, possibly major, rifting phase in a region either uplifted and eroded or unaffected by earlier subsidence. However, a change in style of extension occurred at 34 Ma. An offset in rifting at about 74° S results in a transtensional stress regime that coincides closely with the existence of a major igneous crustal intrusion associated with the Polar-3 magnetic anomaly. The southern limit of the extension, south of Ross Island, is poorly constrained, but may be accommodated by distributed deformation that is reflected in the magnetic anomalies detected over the northern margin of the Ross Ice Shelf. The observed amount of spreading at the southern end of the Adare Basin based on magnetic anomaly identification is about twice the extension of the adjacent contiguous Northern Basin inferred from gravity modeling of crustal thinning [*Davey and Brancolini*, 1995]. A strong linear magnetic anomaly along the east side of the junction of the two regions indicates there is no distributed extension east of the Northern Basin. Partitioning of extension between brittle continental crust and underlying more ductile lithosphere, and ductile lower lithospheric flow into the extensional region of southern Adare Basin and Northern Basin are proposed.

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