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Key Points:

- Onset of seafloor spreading is temporally coincident with rupture of the adjacent continental crust
- Rifted continental crust has a very sharp continental-oceanic crustal boundary
- Continuity of seafloor spreading anomalies across the morphological continental shelf edge

Supporting Information:

- Supporting Information S1

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Synchronous oceanic spreading and continental rifting in West Antarctica

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Abstract Magnetic anomalies associated with new ocean crust formation in the Adare Basin off north-western Ross Sea (43–26 Ma) can be traced directly into the Northern Basin that underlies the adjacent morphological continental shelf, implying a continuity in the emplacement of oceanic crust. Steep gravity gradients along the margins of the Northern Basin, particularly in the east, suggest that little extension and thinning of continental crust occurred before it ruptured and the new oceanic crust formed, unlike most other continental rifts and the Victoria Land Basin further south. A preexisting weak crust and localization of strain by strike-slip faulting are proposed as the factors allowing the rapid rupture of continental crust.

1. Introduction

The transition from seafloor spreading (new oceanic crust formation) to continental rifting is usually considered to coincide with major strike-slip/transcurrent fault or accommodation zones (e.g., Gakkel Ridge and Laptev Sea [*Mazur et al.*, 2015]) with seafloor spreading propagating across the accommodation zone after a degree of continental extension has occurred [*Van Wijk and Blackman*, 2005]. This leads to a propagating spreading center, e.g., Woodlark Basin [*Taylor et al.*, 1999] and Gulf of Aden [*Manighetti et al.*, 1997], with extensional segments separated by transfer zones. At the north-west part of the West Antarctic Rift, our study suggests that the onset of seafloor spreading in oceanic crust and rupture of adjacent continental crust has apparently occurred at the same time with no intermediate transcurrent discontinuity and associated continental crustal thinning.

The West Antarctic Rift system (Figure 1) was formed by rifting during the breakup of Gondwana, starting some 180 Myr ago [*Behrendt et al.*, 1993], that led to extension and thinning of West Antarctica. In the Ross Sea region at the northwestern end of the West Antarctic Rift, extension occurred in two main episodes, a regional thinning associated with the breakup of New Zealand and Australia from Antarctica in the Cretaceous, and more focused extensional episodes during the Cenozoic [*Cooper et al.*, 1987] with the locus of extension moving sequentially from east (Eastern Basin) to the west (Victoria Land Basin and Northern Basin) toward the Transantarctic Mountains [*Wilson and Luyendyk*, 2009]. The Transantarctic Mountains traverse Antarctica, separating East from West Antarctica, along a major lithospheric boundary between the cold East Antarctica craton and warm mobile West Antarctica [*Ritzwoller et al.*, 2001; *An et al.*, 2015]. They form the western rift margin within the Ross Sea region and were primarily uplifted about 55–50 Ma, with the main uplift in the first 10 Myr [*Fitzgerald*, 2005]. Seafloor magnetic anomalies between Antarctica, Australia, and New Zealand [*Cande et al.*, 2000] define an episode of seafloor spreading between East and West Antarctica from about 43 Ma to 26 Ma that has resulted in the rifting of continental lithosphere along the western margin of the Ross Sea [*Davey et al.*, 2006]. This rifting has occurred within a zone of already extended continental lithosphere and produced basins varying from continental to oceanic along strike. It is an analogous situation to the actively rifting Gulf of California relative to the extended Basin and Range region [*Bennett and Oskin*, 2014; *Umhoefer*, 2011], although with a lower degree of oblique extension.

Marine seismic data delineate four major sedimentary basins up to 14 km deep underlying the Ross Sea at water depths <1500 m (Figure 1) [*Brancolini et al.*, 1995]. Limited drill hole data, igneous geology, and marine geophysical data indicate that the last episode of extension, largely from about 43 Ma to 26 Ma but with minor movements since [*Cande et al.*, 2000; *Granot et al.*, 2010], formed the Victoria Land Basin (VLB) in the south-west, the Northern Basin (NB, offset from the VLB) in north-western Ross Sea, and the Adare Basin in

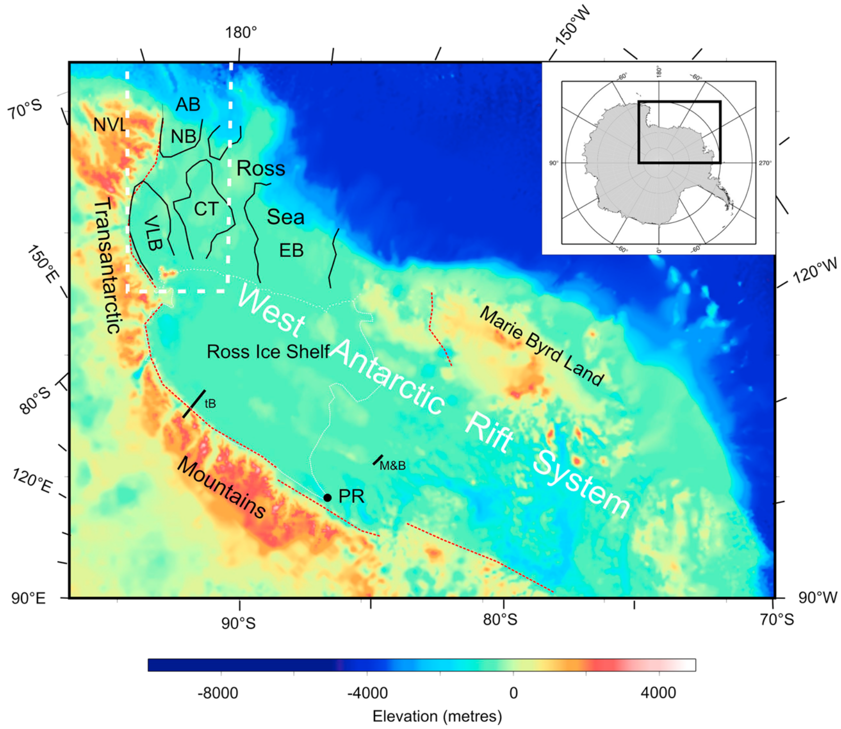

Figure 1. The West Antarctic Rift System and location of the study area. Inset, location within Antarctica. The Ross Sea basins (outlined by black lines): AB, Adare Basin; NB, Northern Basin; VLB, Victoria Land Basin; CT, Central Trough; EB, Eastern Basin. The black dot (pole of rotation (PR)) indicates the pole of rotation for East-West Antarctica for 43–26 Ma [*Granot et al.*, 2013]. "tB" and "M&B" seismic profiles [*ten Brink et al.*, 1993; *Munson and Bentley*, 1992]. The location of Figure 2 is shown by the thick white dashed line.

the deep ocean to the north [*Davey et al.*, 2006]. Although these basins formed at the same time, aeromagnetic data over western Ross Sea [*Ferraccioli et al.*, 2009; *Granot et al.*, 2013] show different characteristics for each of the basins (Figure 2), suggesting that different processes controlled extension within them. A sequence of linear magnetic anomalies can be traced through the oceanic Adare Basin in the north and into the Northern Basin [*Granot et al.*, 2013]. In contrast, highly subdued magnetic anomalies coincide with the VLB. ENE trending major magnetic anomaly belts mark the boundary linking the Northern Basin and VLB (Polar3 anomaly [*Bosum et al.*, 1989]) and the southern boundary of VLB (Ross magnetic zone) and are inferred to mark transfer faults or accommodation zones [*Damaske et al.*, 1994; *Davey et al.*, 2006] or a strike-slip fault for the Ross magnetic zone [*Behrendt et al.*, 1996]. The Polar3 anomaly coincides in part with mafic igneous intrusions of 43–35 Ma [*Rocchi et al.*, 2002]. Bouguer anomaly gravity data [*Reitmayr*, 1997; *Cande and Stock*, 2006] show high values associated with the oceanic Adare Basin that cross the continental shelf edge and into Northern Basin, consistent with oceanic crust under the Northern Basin. East of Northern Basin and Victoria Land Basin are the older (60 Ma) rifts of Central Trough and Central Basin (Figure 4) [*Wilson and Luyendyk*, 2009]. The deep water and limited Bouguer gravity anomaly data [*Reitmayr*, 1997; *Cande and Stock*, 2006] for the Central Basin indicate that thin, possibly oceanic, crust may exist there and extend almost as far south as the southern end of Northern Basin.

2. The Northern Basin

Geophysical data in the Northern Basin illustrate its unusual characteristics within the rift system. As noted above, the continuity of identified marine magnetic anomalies from the Adare Basin onto the morphological continental shelf of the Northern Basin (Figure 2; see the supporting information for more detailed magnetic data) indicates that the latter basin is underlain by oceanic crust, and this is consistent with Bouguer gravity anomalies (based on satellite gravity data and corrected for water depth and sediment thickness [*Cande and Stock*, 2006]) (Figure 3a) that remain high across the continental shelf edge and into Northern Basin. Both

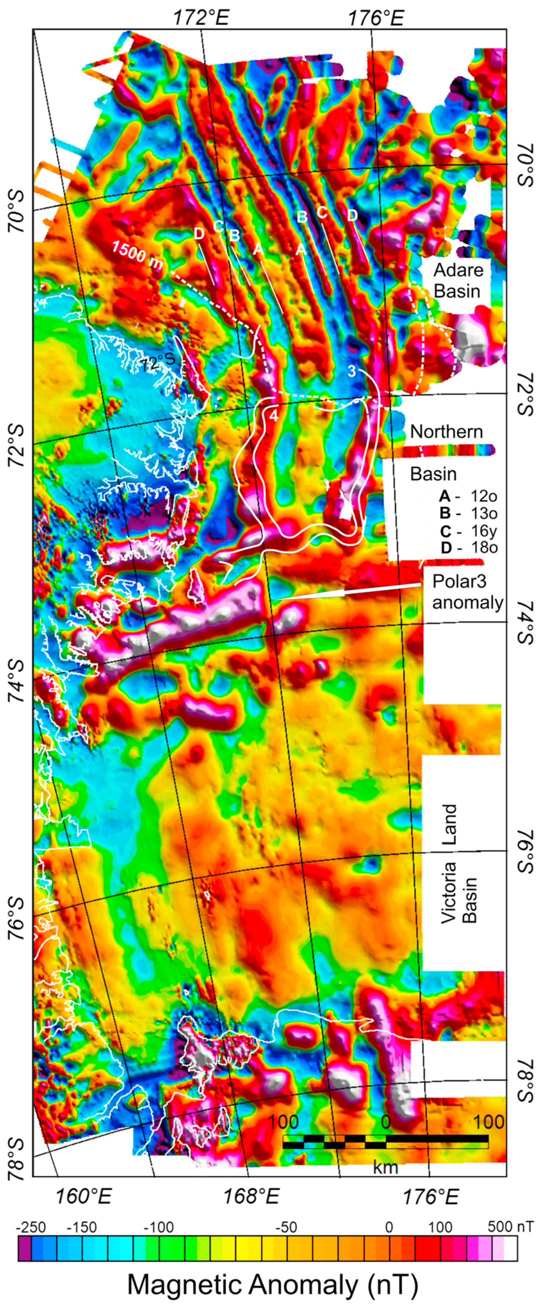

Figure 2. Aeromagnetic anomaly map for western Ross Sea and Victoria Land, compiled from *Granot et al.* [2013] and *Ferraccioli et al.* [2009]; note that the magnetic anomaly scale is expanded for smaller values of magnetic field. Adare Basin, Northern Basin, and Victoria Land Basin are marked alongside the basins. The white line indicates the coastline and ice edge, the thick white line labeled "3" and "4" marks the 3 and 4 km sediment isopachs for Northern Basin, and the dashed white line indicates the 1500 m depth contour. The white arrow points to the Polar3 anomaly. Anomalies 12o, 13o, 16y, and 18o are located by the white lines labeled A, B, C, and D respectively.

indicate a continuity of lithospheric structure across the continental shelf edge. Limited crustal seismic reflection data [*Brancolini et al.*, 1995] define the Northern Basin as a 6 km deep basin, about 100 km long, trending NNE to the continental shelf break. The oldest major magnetic anomalies on either side of the Adare Basin (anomalies 18o and 16y) continue into the Northern Basin where they coincide with the margins of the basin, as defined by seismic reflection data (3 km isopach [*Brancolini et al.*, 1995]) (Figure 2). These basin flanking anomalies are large, particularly in Northern Basin, where they appear to merge, but the central anomalies (anomalies 12o and younger), although continuous, are reduced in Northern Basin (see the supporting information). The subdued nature of the younger anomalies may be caused by hydrothermal alteration [*Levi and Riddihough*, 1986] resulting from blanketing by syn-accretion sedimentation that occur there or a result of the 3 km thick sedimentary cover that has infilled from the south and may have subdued the magnetic signature. The anomalies terminate at the southern margin of the basin that is aligned normal to the rift margin. A 30° change in azimuth of the anomalies occurs in the Adare Basin about 20–60 km north of the continental shelf edge, in the east close to the northern end of Hallett Ridge (Figure 4).

We use the geophysical constraints to derive a preliminary gravity model of the lithospheric structure of the Northern Basin. Seismic reflection data [*Brancolini et al.*, 1995] show that the depth to basement is constant at about 6 km across the continental shelf edge from Adare Basin into Northern Basin. Deeper crustal seismic data in the Northern Basin are limited, with only two sonobuoy data sets detecting velocities above 5 km/s (BGR7 [*Davey et al.*, 1983] and L14S1 [*Selvans et al.*, 2014]) (Figure 3a). The two sonobuoys detected seismic velocities typical of ocean crust layer 3 (6.7 to 7.5 km/s) at depths of about 7.5 km (Figure 3a). The horizontal layer model of *Selvans et al.* [2014] for sonobuoy L14S1 has been corrected for an updipping seafloor that gives a seismic velocity of 7.5 km/s for the deepest layer.

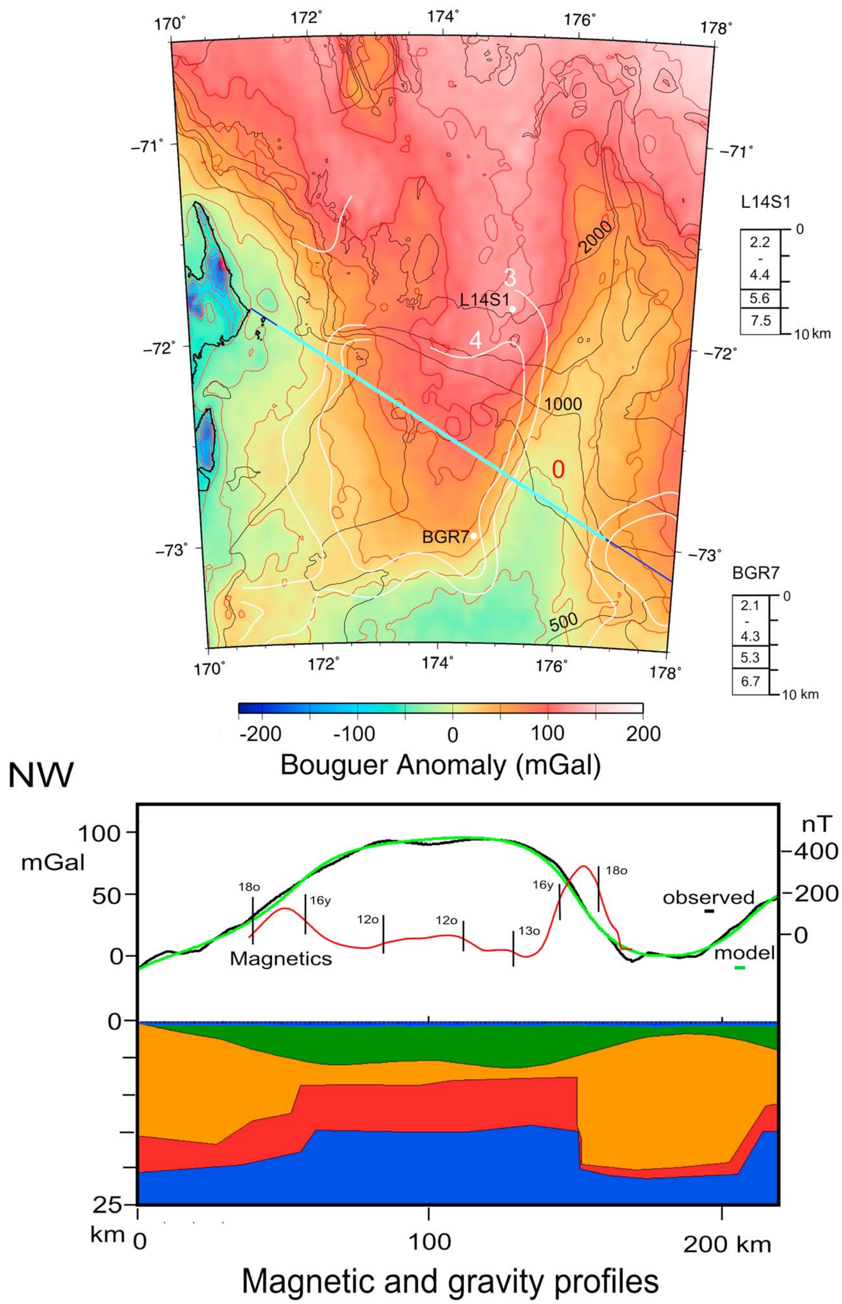

Figure 3. (a) Bouguer anomaly map (modified after *Cande and Stock* [2006]) of Northern Basin and southern Adare Basin showing the continuous high Bouguer anomaly across the continental shelf edge. Bouguer anomaly contours—thin red lines, zero contour labeled red "0," bathymetry contours at 500 m intervals—the black lines annotated at 1000 m and 2000 m; the white lines indicate the sediment isopachs annotated for 3 and 4 km, and the blue line indicates the location of profiles in Figure 3b. Sonobuoy stations (annotated)—white dots—with corresponding velocity (km/s)-depth (km) columns on the right of the map. (b) Gravity model and gravity and magnetic profiles across Northern Basin (blue line in Figure 3a). Observed Bouguer anomaly—black line, model gravity anomaly—green line, and observed magnetic profile—red line—with magnetic anomalies after *Granot et al.* [2013]. Model densities: blue (water, uppermost layer)—1.03 Mg/m^3, green (sediments)—2.5 Mg/m^3, orange (continental crust or oceanic layers 1 and 2)—2.75 Mg/m^3, red (lower crust or oceanic layer 3)—3.0 Mg/m^3, and blue (mantle, lowermost layer)—3.3 Mg/m^3.

Marine gravity data across the Northern Basin, recorded during NB Palmer cruise NBP0701, were used for modeling as they are closest to the structures being investigated. Bouguer anomalies were derived, correcting for water depth and sediment thickness [after *Brancolini et al.*, 1995], and show a very steep gradient over the eastern margin of the Northern Basin. The amplitude and gradient of the gravity anomalies across the basin provide limits to the depth, density contrast, and thickness of the dense body underlying the basin, assuming reasonable densities and thicknesses for continental crust and mantle. Bouguer gravity modeling (using ModelVision ™) was based on a marine gravity profile collected across the basin (profile B, Figures 3a and 3b). The thickness of the sedimentary section along the profile was taken from previously interpreted seismic data [*Brancolini et al.*, 1995] and is incorporated in the Bouguer correction. A constant density for the basin sediments is support by the simple seismic velocity models across the basin derived from sonobuoy measurements by *Selvans et al.* [2014]. The crustal thickness prior to this phase of extension was assumed to be about 20 km, based on seismic refraction data 300 km south [*Trehu et al.*, 1993; *Cooper et al.*, 1987] (Figure 4). We note, however, that the continental crust had already undergone considerable extension and thinning at an earlier time. The maximum gravity gradient and amplitude along the profile require a high-density lower crustal body at shallow depth. The sonobuoy seismic data (above) indicate a depth to the top of the body of 7.5 km. The anomalous body for gravity modeling has two parts, the lower crust slab and a mantle rock body resulting from crustal thinning. Typical crustal and upper mantle densities used were mean continental crust of 2.75 Mg/m^3 and mantle of 3.3 Mg/m^3. A reasonable range of densities (2.75 to 3.0 Mg/m^3) for the lower crust were tried in the modeling. A 2.5-D model was derived (Figure 3b), with a strike length of 110 km approximating the length of the Northern Basin. The maximum measured gradient at the eastern end of the profile (basin) is 4.7 mGal/km and amplitude of the gravity anomaly is 100 mGal. If the lower crustal layer is assumed to be thin or nonexistent, the computed anomaly is too large. If it is too thick or of lower density, then the gravity gradient cannot be fitted. The maximum modeled gradient was 4.0 mGal/km for a density of 3.0 Mg/m^3, indicating a high density, near vertical sided, lower crustal body at shallow depth (Figure 3b). Furthermore, the mantle-continental crust boundary beneath the edge of the high-density crustal body must also be near vertical. Reducing its dip to, for example, 45° significantly reduces the fit of the model to the observed gravity anomaly. The western margin of the body is less steep or stepped. The anomalous body (a density of 3.0 Mg/m^3, 8 km thick) is consistent with an oceanic lower crustal layer with near vertical boundaries underlying Northern Basin, albeit slightly thicker (8 km) than normal but consistent with crustal thicknesses of up to 10 km for the adjacent Adare Basin [*Mueller et al.*, 2005]. It is contiguous (same depth and along strike) with Adare Basin oceanic crust to the north, with its margins corresponding closely to, but within, the outer margins of the large flanking magnetic anomalies (Figure 3 b). The continuity of the identified magnetic anomalies from the Adare Basin into and along the margins of the Northern Basin [*Granot et al.*, 2013] supports the inference that the lower crustal layer of Northern Basin with seismic velocities of 6.7–7.5 km/s is oceanic crust.

3. Discussion

In contrast to the Northern Basin, the Victoria Land Basin to the south shows an extensional thinning of the continental crust. Seismic reflection and gravity data indicate a 14 km deep, 150 km wide sedimentary basin [*Cooper et al.*, 1987, *Brancolini et al.*, 1995] with a thinned lower crust to about 5 km thick [*Davey and Cooper*, 1987; *McGuiness et al.*, 1985], formed by about 95 km of extension [*Davey and De Santis*, 2006]. South of the Victoria Land Basin and Ross Island, no major sedimentary/rift basin has been detected but data are sparse. Although subice rift basins have been postulated on the basis of positive gravity anomalies [*Decesari et al.*, 2007], the limited seismic data available show only small basins associated with negative gravity anomalies [*ten Brink et al.*, 1993; *Munson and Bentley*, 1992]. The three major western Ross Sea basins, thus, show a gradational change from seafloor spreading in the north, continental rupture and oceanic crust emplacement under the northern continental shelf, and continental extension and thinning in the south, with possibly distributed extension further south.

The pole of rotation for the extension between East and West Antarctica from 43 to 26 Ma lies about 1500 km southeast of Ross Sea (latitude = 85.87°, longitude = 220.49°; $\omega = -4.48°$ [*Granot et al.*, 2013]) (Figure 1). It is used to derive an extensional model (Figure 4) based on an assumed rift axis (black line) along the western margin of the basins originally located at or close to the Transantarctic Mountains front. The rate of extension is slow and changes from 10 mm/yr for Adare Basin, 6.5 mm/yr for Northern Basin, to 5.7 mm/yr for southern Victoria Land Basin. The orientation of the original rift axis along the margin changes along strike relative to the extension direction computed from the pole of rotation. This change results in varying proportion of strike-slip motion relative to extension direction during rifting (Figure 4): with obliquity(α) changing from $\alpha = 24°$ for Northern Basin to $\alpha = 6$–$16°$ for Victoria Land Basin. The southern termination of the magnetic

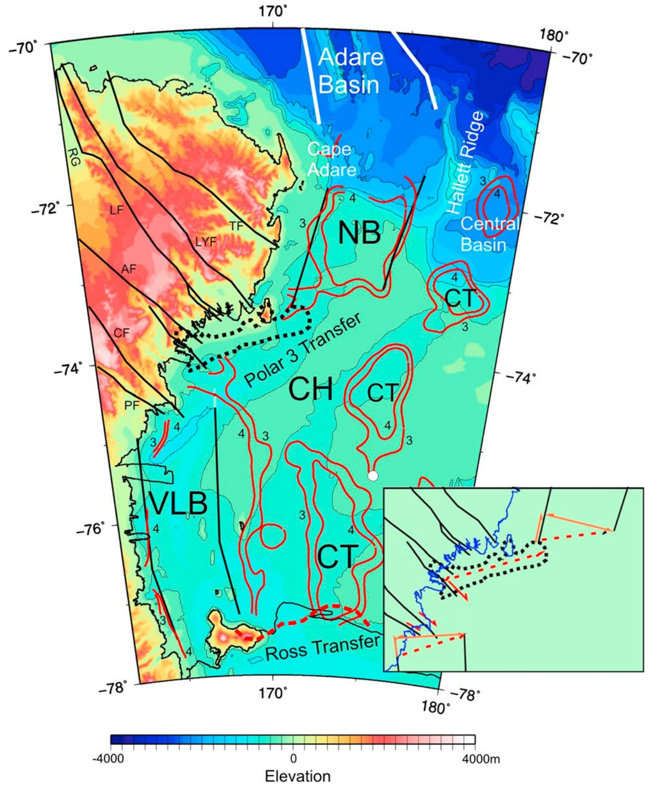

Figure 4. Rifting model for western Ross Sea. Bathymetry base map color coded. NB, Northern Basin; VLB, Victoria Land Basin; CT, Central Trough; CH, Central High. Onshore major faults: TF, Tucker fault; LYF, Leap Year fault; LF, Lanterman fault; AF, Aviator fault; CF, Campbell fault; PF, Priestley fault. Crustal seismic station [*Trehu et al.*, 1993]—white dot. The thick black lines mark the proposed original rift axis at 43 Ma and the present west rift margin, and the east rift margin at 26 Ma after rotating around the pole of rotation (PR; Figure 1). The red lines mark the 3 and 4 km isopachs (annotated) for the basins. Note that the east rift margin for the Victoria Land Basin is west of the isopachs as the original rift was estimated to be about 45 km wide [*Davey and De Santis*, 2006]. The Polar3 anomaly delineated by the thick dashed black lines. The north margin of the Ross transfer zone south of the Victoria Land Basin—red dashed line. Inset—Polar3 transfer zone—outline of Polar3 anomaly, faults and rift margins as for main figure. The red dashed lines indicate the vector for plate rotation for Northern Basin, Polar3 transfer, and Victoria Land Basin, separated into with rift normal extension and rift parallel displacements shown by the orange arrows. The red arrows indicate the proposed distributed motion across the southern Northern Victoria Land faults.

anomalies and the orientation of the southern end of the Northern Basin are both normal to the rift axis. We infer that extension (relative plate motion vector) has been partitioned into rift normal extension, resulting in the rifting of Northern Basin, and rift parallel displacement of the western margin of the rift to the north (Figure 4 inset, yellow arrow). This rift parallel displacement and the change in orientation and offset of the rift axes from Northern Basin to Victoria Land Basin results in transtensional motion along the transfer zone between the two basins that we suggest comprises transcurrent motion along the line of the Polar3 anomaly and extension that allows the intrusion of the Polar3 igneous body. This transtension extends from the eastern margin of Northern Basin to the thicker crust of the Transantarctic Mountains, where we suggest that it is transferred to the Victoria Land Basin through reactivation (Figure 4, inset—red arrows) of the some of the Northern Victoria Land right-lateral strike-slip faults noted by *Salvini et al.* [1997]. However, there appears to be little evidence for other significant post 43 Ma NNW trending, right-lateral strike-slip offset east of the western margins of the Northern Basin, Victoria Land Basin, and Polar3 anomaly. No volcanism is known for the period of rifting, the oldest Cenozoic volcanism in the region being 25 Ma [*Rocchi et al.*, 2002].

The markedly different response of adjacent continental rift segments forming the Northern Basin and Victoria Land Basin to the same extension episode [*Davey et al.*, 2006] provides constraints on the processes causing rifting. Both segments occur in regions of high mantle temperature [*Ritzwoller et al.*, 2001; *An et al.*, 2015], with low magmatic activity (Cenozoic volcanism is all younger than 25 Ma [*Rocchi et al.*, 2002]) and significant syn-rift sedimentation ($>$1.5 km thick for Northern Basin [*Brancolini et al.*, 1995]) with post rifting sedimentation infilling largely from the south to form the prograding continental shelf edge for the Northern Basin. The rate of extension is relatively small (6–10.5 mm/yr) and similar for both basins and to other continental rifts [*Ebinger et al.*, 2013; (*GeoPRISMS*, 2015, http://geoprisms.org/initiatives-sites/rie/)]. The thinning of continental crust to 5 km in Victoria Land Basin by 95 km of extension over 17 Myr is consistent with numerical and analogue modeling [*Brune*, 2014; *Autin et al.*, 2010] and other rifts globally. However, the Northern Basin, where a larger degree of strike-slip motion occurs, is unusual, as crustal rupture and the emplacement of oceanic crust started when this episode of East and West Antarctica extension commenced. The spatial coincidence of the margins of the Northern Basin (3 km contour; Figures 2 and 3a) and the oceanic crust inferred from magnetic and gravity data;

the common age of extension from marine magnetic anomalies and the steep ocean-continent boundaries from gravity model all indicate that little, if any, continental extension and thinning of this age occurred prior to rifting, suggesting a preexisting zone of major crustal weakness along which continental rupture took place. The model also indicates that the continental-ocean boundary is narrow (<5 km), similar to that found elsewhere [e.g., *Taylor et al.*, 1999]. Although extensional rates are low and only moderately oblique within this part of the continent, the very sharp rift boundaries imply that strike-slip faulting of probable lithospheric extent and a preexisting crustal weakness are the important parameters focusing continental rifting and the emplacement of oceanic crust in an already extended continental lithosphere. Although the existence of oceanic lithosphere in Central Basin to the east is conjectural, a narrow strip of continental lithosphere east of the Northern Basin (Figure 4) may be weak enhancing rapid crustal rupture.

4. Conclusions

Gravity and magnetic data are presented that show that unlike other ocean-continental rifts, the northern part of this continental rift (Northern Basin) ruptured rapidly at the onset of extension, and its oceanic crust is continuous with the well-defined seafloor spreading Adare Basin formed in oceanic crust immediately north. Little continental thinning occurred, and minor subsidence of the continental rift margins is attributed to postrift cooling and sediment loading. In contrast, farther south, away from the continental margin, rifting along the same plate boundary (Victoria Land Basin) is consistent with the conventional mechanism of continental lithosphere extension and thinning as supported by modeling results. South of Victoria Land Basin, no focused rifting is apparent as extension rates are low. This study suggests that in already extended continental lithosphere, continental rupture and concomitant emplacement of oceanic crust can occur when subsequent extension commences, without an initial phase of crustal extension and thinning; this may be driven by the oblique extension that appears to be an important factor in focusing rupturing of continental lithosphere. A sharp continent-ocean boundary (<5 km) is derived for the margins of the Northern Basin model. The accommodation of extension from oceanic lithosphere across a continental margin at high angle can range from continuous rift, as with the Adare Basin and Northern Basin, to a more distributed continental extension across a continental margin transcurrent fault system as noted in Woodlark Basin [*Taylor et al.*, 1999] and with the Gakkel Ridge and Laptev Sea [*Mazur et al.*, 2015].

Acknowledgments
The aeromagnetic map in Figure 2 is available from F.F. and will be submitted to the NERC/BAS Polar Data Centre. Magnetic anomaly picks have been submitted to The Global Seafloor Fabric and Magnetic Lineation Data Base Project, link: http://www.soest.hawaii.edu/PT/GSFML/ML/index.html. The marine gravity data are available from GeoMap App, cruise NBP0701. The seismic data of *Brancolini et al.*, 1989 are also available from the SCAR seismic Data Library System—http://sdls.ogs.trieste.it/. Sonobuoy data from NBP0701 are available from http://web.gps.caltech.edu/~clay/Adare_Sonobuoy/Adare_Sonobuoy.html). Adare Basin Sonobuoy data (2007), Sonobuoy Data from the Adare Basin, Antarctica. Caltech. Dataset. doi:10.7909/C37P8W9P. S.C. acknowledges funding from NSF grant OPP04-40959 and F.D. for funding from NZGSF. We acknowledge the critical reviews by John Behrendt and two anonymous reviewers that has greatly improved the paper. F.D. thanks Susan Ellis for advice.

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