# Constraints on the Timing of Extension in the Northern Basin, Ross Sea

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**Abstract.** Recent kinematic constraints for the region north of the western Ross Sea suggest that there was approximately 150 km of seafloor spreading in the Adare Basin, northeast of Cape Adare, between Chrons 20 and 8 (43 to 26 Ma). This kinematic history has important implications since the 150 km of extension in the Adare Basin occurred immediately north along strike from the Northern Basin of the Ross Sea, whose extensional history is not well known. This paper examines the transition from the structures in the Adare Basin to the structures of the Northern Basin and speculates on the manner in which the extension was accommodated in the Ross Sea. Magnetic anomaly data in the Adare Basin document a sequence of anomalies 18 to 12 formed during a period of very slow spreading. The easternmost part of this sequence, anomalies 16 to 18, coalesces into a single positive anomaly near 72° S, forming a distinct anomaly that can be traced southward from the Adare Basin across the continental margin and down the east side of the Northern Basin to a latitude of roughly 73° S. This observation has important implications for the tectonic history of the Ross Sea since it suggests that most of the extension in the Adare Basin continued into the Northern Basin. This, in turn, suggests that the Northern Basin was formed by a combination of crustal thinning and massive, narrowly focused intrusions.

## Introduction

The Cenozoic tectonic evolution of the West Antarctic Rift System has been a major focus of geological research in Antarctica (e.g., Behrendt et al. 1991; Behrendt et al. 1993) including several MCS seismic reflection programs (see in Cooper et al. 1995) and a recent drilling program near Cape Roberts (Barrett et al. 2000). Cenozoic extension between East and West Antarctica produced the deep sedimentary basins in the Ross Sea (Cooper et al. 1987) and the uplift of the Transantarctic Mountains (Fitzgerald 1992). The rift system has clearly experienced several distinct episodes of extension with changing stress directions and strain rates (Salvini et al. 1997). However, because of the complexity of the plate motion history, the connection between the geological structures imaged in the Rift System and the plate motions responsible for them has been poorly known.

The West Antarctic Rift System is the result of the complex interaction of the Pacific, Australia, Lord Howe Rise (prior to 53 Ma), West Antarctic and East Antarctic Plates. Although the major aspects of these plate motions have been known for 30 years (e.g., Molnar et al. 1975), important new details have been revealed by recent work. In particular, Cande et al. (2000a) used magnetic lineations to constrain at least one and perhaps two episodes of major East-West Antarctic separation in Cenozoic time. The younger episode of separation, between Chrons 20 and 8 (43 to 26 Ma), involved about 150 km seafloor spreading in the Adare Basin (Fig. 6.5-1), between Cape Adare and the Hallett Ridge, north of the Ross Sea embayment (Cande et al. 2000a). The older episode is more poorly constrained, but it may have involved up to 100 km of E-W directed extension in the Central Basin,

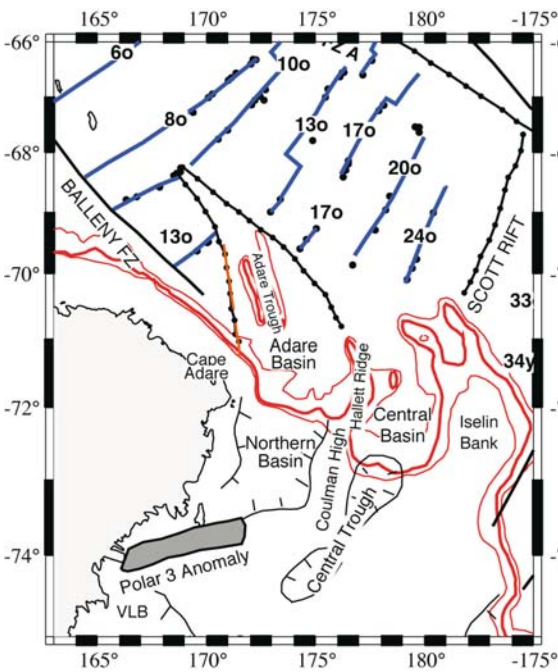


**Fig. 6.5-1.** Location of basins and structural highs in the western Ross Sea referred to in the text. Boundaries of sedimentary basins are from Davey and Brancolini (1995). The 1 000, 1 500 (*heavy*) and 2 000 m bathymetric contours (*red lines*) are shown. *Blue lines* show magnetic isochrons associated with spreading on the Southeast Indian Ridge. These anomalies constrain the amount and timing of extension in the northern Ross Sea. The Polar 3 Anomaly (*shaded region*) is a prominent magnetic anomaly between the Victoria Land Basin (*VLB*) and the Northern Basin

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between the Hallett Ridge and Iselin Bank, between roughly Chrons 27 and 24 (61 to 53 Ma; Cande et al. 2000b). These results have fundamental implications for the timing and amount of Cenozoic extension in the Ross Sea region but they remain to be reconciled with existing geological and geophysical data from the Ross Embayment and the West Antarctic Rift System.

Here we discuss magnetic and gravity data that constrain a small but critical aspect of the tectonic development of the sedimentary basins in the northern Ross Sea (Northern Basin, Central Trough, Fig. 6.5-1). The conventional wisdom is that these basins formed by stretching and thinning of continental crust. However, the striking alignment of shelf and deepwater structures in the northern Ross Sea (e.g., the Coulman High aligns with the Hallett Ridge), combined with the constraints of our kinematic model, suggests that the Northern Basin may have formed by extensive crustal thinning and very focused, massive intrusions synchronous with, and kinematically linked to, seafloor spreading in the Adare Basin. This has important implications for the tectonics of other sedimentary basins in the Ross Sea.

## Constraints on Cenozoic Extension in the West Antarctic Rift System

The tectonic history of the Ross Sea region has been difficult to unravel in large part because of the lack of a well-constrained plate kinematic framework. There has clearly been a considerable amount of extension in the Ross Sea region as evidenced by the anomalously thin crust (~20 km) and shallow Moho across the embayment (e.g., Cooper et al. 1987; Davey and Cooper 1987); the total amount of extension has been estimated to be on the order of 400 km (Behrendt et al. 1991). Paleomagnetic studies (DiVenere et al. 1994; Luyendyk et al. 1996) independently indicate between 440 and 1 820 km of relative motion between East and West Antarctica in the last 100 Ma. The timing of the extension, however, has been poorly constrained. Fission track dates on basement rocks from DSDP site 270 in the Ross Sea indicate at least two periods of extension, one in the Jurassic and a second in the late Cretaceous (Fitzgerald and Baldwin 1997). The Late Cretaceous extension, documented in West Antarctica and Marie Byrd Land, on the eastern side of the Ross Sea, is coeval with the separation of the surrounding fragments of Gondwana (New Zealand and West Antarctica) (e.g., Siddoway et al. 2004). Based on regional plate reconstructions, Lawver and Gahagan (1994) argued that the bulk of the extension within the Ross Sea must have taken place in Late Cretaceous time.

Cande et al. (2000a) showed that, contrary to earlier indications, there has probably been a considerable amount of extension between East and West Antarctica in the western Ross Sea region in mid-Cenozoic time. The critical constraint on this motion is the misfit of magnetic anomalies 10 and older on the Antarctic Plate northeast of the Adare Basin (blue lines in Fig. 6.5-1) when rotated back to their conjugate location on the Australian Plate using rotation parameters for Australia-East Antarctica. Specifically, there is a progressively larger misfit for increasingly older anomalies, starting with a 10 km misfit for anomaly 10 and increasing to a roughly 170 km misfit for anomaly 20. Cande et al. (2000a) showed that the systematic misfit of these Southeast Indian Ridge (SEIR) anomalies indicated that there was an extensional boundary between East and West Antarctica that ran south from the SEIR and into the western Ross Sea starting around Chron 20 (43 Ma) and ending around Chron 8 (26 Ma).

Further evidence for the timing and the amount of extension in the region of the northern Ross Sea comes from the presence of linear magnetic anomalies straddling the Adare Trough, a large NNW-trending graben located along the west side of the Adare Basin (Fig. 6.5-2). Cande et al. (2000a) showed that these anomalies were consistent with a period of slow seafloor spreading (12 mm $yr^{-1}$ full rate) between Chrons 20 and 8 (43 to 26 Ma) (see projected profiles and model in Fig. 6.5-3; see Fig. 6.5-2 for location of profiles). The anomaly pattern indicates that the spreading rate was asymmetrical, with the west flank (5.5 mm $yr^{-1}$) slower than the east flank (7 mm $yr^{-1}$). Although the anomalies are difficult to recognize because of the slow spreading rate, their identification is consistent with the motion required by the systematic misfit in SEIR anomalies 10 and older from northeast of the Adare Basin. Cande et al. (2000a) concluded that the Adare Basin anomalies were caused by roughly 150 km of seafloor spreading between East and West Antarctica north of the Ross Sea, and that the pole of rotation for this motion was sufficiently far away that there should have been a similar amount of extension further south in the northern Ross Sea.

Our proposed identification of the Adare Basin anomalies is supported by magnetic anomaly data collected on R/VIB Nathaniel Palmer in February 2005 (NBP0501). These data, shown in red in Fig. 6.5-2, demonstrate the existence of a classic magnetic bight between the NNW-SSE striking Adare Basin anomalies and the NE-SW striking SEIR anomalies between 69° S and 70° S. In particular, anomalies 17 and 18 clearly wrap around in a bight between 174° W and 175° W near 70° S. The continuity of the negative anomaly between anomalies 17 and 18 as it wraps around the bight is marked by the dashed white line in Fig. 6.5-2.

The implications of these kinematic constraints for the tectonic evolution of the western Ross Sea basins since the late Eocene have not been developed. Ideally, they would provide a check on a tectonic history independently constrained by drilling and seismic stratigraphy. However, because the sedimentary sequences drilled at Cape Rob-

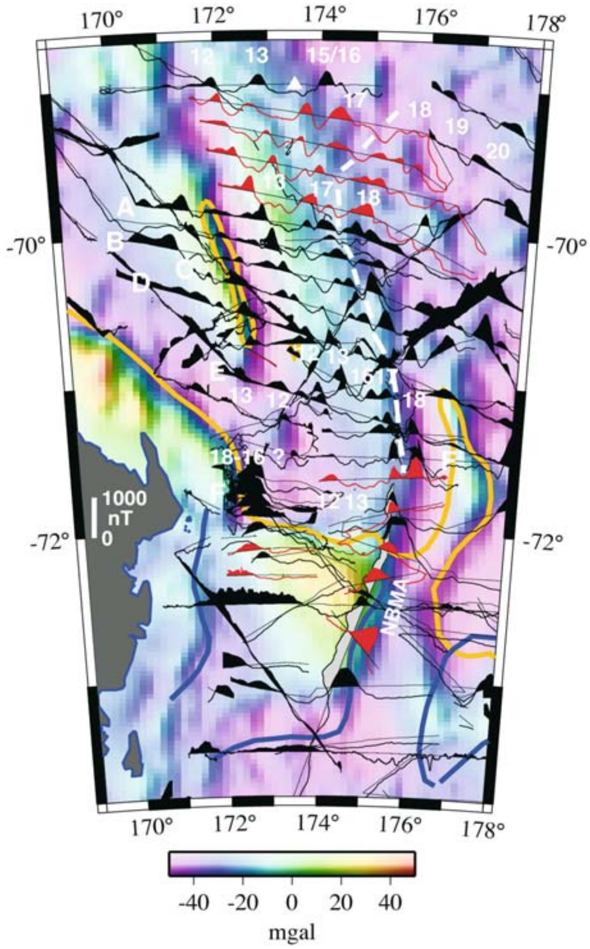


**Fig. 6.5-2.** Magnetic anomaly data in the region of the Adare Trough shown superimposed on the satellite-derived free-air gravity field of McAdoo and Laxon (1997). Note the apparent continuity of anomalies 16–18 on the east flank of the Adare Basin with the Northern Basin Magnetic Anomaly (*NBMA*). The continuity of this anomaly across the margin suggests that most of the spreading in the Adare Basin was accommodated by extension in the Northern Basin. The *dashed white line* follows the negative anomaly between anomalies 17 and 18 as it wraps around the magnetic bight between the NNW-SSE striking Adare Basin anomalies and the NE-SW striking SEIR anomalies. Positive anomalies are *shaded black* except for the north-south profile near 175° E which is *shaded in gray*. Magnetic data collected on the R/VIB "Nathanial Palmer" in February 2005 are *shaded red*. The 1 500 m bathymetric contour is shown by the *heavy gold line*. The boundaries of the sedimentary basins are shown by the *heavy blue line*. *White triangle* shows location of DSDP site 274. The labels *A* through *F* refer to profiles shown in Fig. 6.5-3

erts proved to be younger than anticipated (Barrett et al. 2000), the previous interpretations of the stratigraphic constraints on the early Cenozoic tectonic evolution of the Ross Sea basins are now in question. At the latitude of Cape Roberts (77° S) there was a major basin-forming event in Eocene-Oligocene time, synchronous with the seafloor spreading in the Adare Basin (Hamilton et al. 2001); however the net amount of extension during this time interval, and how it connects to structures farther north in the Ross Sea, is still not understood. Thus the kinematic constraints of the Adare Basin seafloor spreading anomalies take on added importance. To understand their significance requires tracing the Adare Basin structures southward.

The focus of this paper is the transition from the structures in the Adare Basin to the structures of the northern Ross Sea basins. The Adare Basin structures are best defined in their gravity and magnetic signatures. Although the topographic signature of the Adare Trough disappears around 71° S, a seismic profile at 71°30' S (TH91 Line 28; although not the part of Line 28 shown in Fig. 6.5-4) indicates that a graben is still present in the subsurface at that latitude. This is consistent with the continuity of the gravity low associated with the axis of the trough, which can be traced in the ERS-1 derived free-air gravity field (McAdoo and Laxon 1997) to nearly 72° S, essentially disappearing into the continental slope adjacent to the Northern Basin (Fig. 6.5-2). Magnetic data show that lineations from anomaly 12 to 18 can be clearly traced on the east flank of the trough, just west of the Hallett Ridge, from 70° S to 71°30' S (Fig. 6.5-2). This observation suggests that the Hallett Ridge (and the rest of West Antarctica) was rifted from Cape Adare around Chron 20 (43 Ma) when spreading initiated in the Adare Basin.

The magnetic anomaly pattern on the west side of the Adare Basin, in the conjugate position to anomalies 16–18 in the eastern Adare Basin, is more complicated. First, we note that the anomalies on the west side of the Adare Basin cannot be clearly traced between 71°00' and 71°30' S (Fig. 6.5-2). This might reflect later deformation or strike slip faulting in the region. However, there is a conjugate anomaly to the anomaly 16–18 sequence in the eastern Adare Basin. R/VIB "Nathaniel Palmer" cruise 0209 recorded a prominent linear N-trending positive magnetic anomaly east of the north-south trending margin of Cape Adare. This anomaly is labeled "18–16 ?" in Fig. 6.5-2 and is also shown on the left side of profile F in Fig. 6.5-3. (Note that profile F–F' in Fig. 6.5-3 is a composite profile; no single magnetic profile crosses the Adare Basin at this latitude.) Although this anomaly may be related, in part, to structures associated with the development of the continental margin, it is also consistent with the shape of a coalesced (due to slow spreading) sequence of anomalies 16 to 18, which could have formed by seafloor spreading as the conjugate to the faster spreading (and more easily identified) anomalies 16 to 18 in the eastern Adare Basin. Thus, even at this latitude, there is evidence for a linear pair of conjugate magnetic anomaly sequences generated by seafloor spreading about the axis of the Adare Trough.

The most important new observation is that the southern end of the oldest anomaly sequence on the east side of the Adare Basin, anomalies 16–18, appears to coalesce into a single positive anomaly around 175°30' E, 71°40' S.

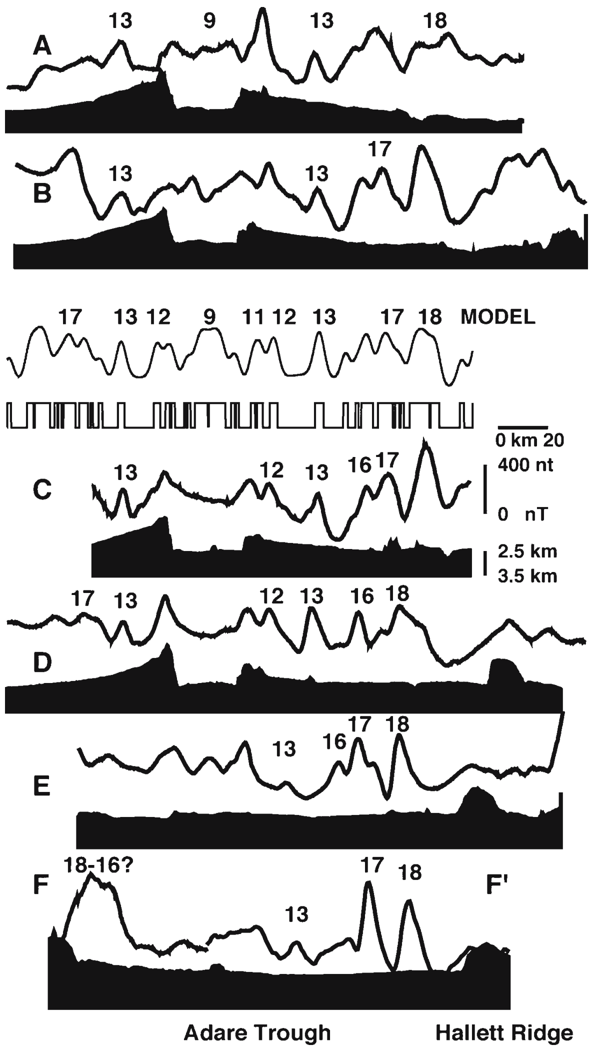


**Fig. 6.5-3.** Magnetic and topographic profiles across the Adare Trough. Profile *F–F'* is a composite of two profiles (NBP0209 on the left and TH91 on the right) crossing the southern Adare Basin. A magnetic model is shown between profiles *B* and *C* (see Fig. 6.5-2 for locations). Polarity widths based on timescale of Cande and Kent (1995)

From there it can be traced onto the shelf and along the east side of the Northern Basin south to about 73° S (Fig. 6.5-2). The continuity of this anomaly, which we call the Northern Basin Magnetic Anomaly, was first noted in archival magnetics data (shaded black in Fig. 6.5-2), including a line which fortuitously ran along the axis of the anomaly (shaded gray in Fig. 6.5-2), and was confirmed by several additional crossings which were made by the R/VIB "Nathaniel Palmer" in February 2005 (shaded red in Fig. 6.5-2). The Northern Basin Magnetic Anomaly (NBMA), which is continuous from 71°40' to 73°00' S, is very significant since it strongly suggests that there is no offset between the structures of the Adare Basin and the Northern Basin. This, in turn, suggests that the Coulman High was rifted as part of a continuous feature with the Hallett Ridge from the Cape Adare margin at Chron 20. Although there are fewer data on the west side of the basin, the existing lines suggest that the positive anomaly corresponding to anomalies 18–16? on the west flank of the Adare Basin (abutting the Cape Adare margin) might also continue southward into the Northern Basin.

The seismic data in the southern Adare Basin supports the continuity of structures between the Adare Basin and the Northern Basin. TH91 Line 28 (middle line, Fig. 6.5-4) shows that the basement beneath anomalies 16–18 on the east side of the Adare Basin, just west of the Hallett Ridge, is relatively shallow, in fact shallower than basement beneath the younger, central part of the basin. The average depth to the top of the basement, corrected for the sediment cover, is only about 2 300 m, which is about 1 500 m shallower than the expected basement depth for 40 Ma oceanic crust (Müller et al. in press). A north-south crossing seismic line (TH91 Line 17; top line, Fig. 6.5-4) shows that the basement beneath anomalies 16–18 shallows gradually but continuously to the south as the Adare Basin merges into the Northern Basin, without any evidence of offsetting structures. The gradually shallowing basement implies a gradual thickening of the oceanic crust as the Northern Basin is approached. Unfortunately, basement cannot be imaged beneath the multiple in the Northern Basin on this line. Basement on IT88 Line 6 (bottom line, Fig. 6.5-4) beneath magnetic anomaly 16–18 ? on the western side of the Adare Basin, has a similar character to basement on the two TH91 lines in the eastern Adare Basin, which we interpret as supporting the oceanic character of the basement in this region. Unfortunately, basement on this line cannot be followed southward into the Northern Basin.

Where the sedimentary packages can be seen above the basement on these three lines, there are also general similarities in the lower part of the section, as would be expected if the seafloor in these two regions were formerly adjacent. On the TH91 Line 28, a seismically transparent package of sediment directly overlies acoustic basement in the vicinity of magnetic anomaly 16–18 (eastern side). On IT88 Line 6, which is interpreted to run right along the 16–18? anomaly on the (conjugate) western side, the lowest sedimentary package, immediately overlying the deepest basement, is similarly quite transparent. This package lies beneath the early Miocene RSU4a unconformity as defined by Brancolini et al. (1995).

The Bouguer gravity anomaly (Fig. 6.5-5) also supports the continuity of structures from the Adare Basin southward into the Northern Basin. The Bouguer anomaly was calculated for the free-air gravity field of McAdoo and Laxon (1997) and includes corrections for both the sediment water interface, based on a revised topographic map of the Ross Sea (Davey 2004) and the sediment basement interface based on the depth to basement map from the Antostrat volume (Brancolini et al. 1995). The Bouguer anomaly shows that the large free air gravity high at the

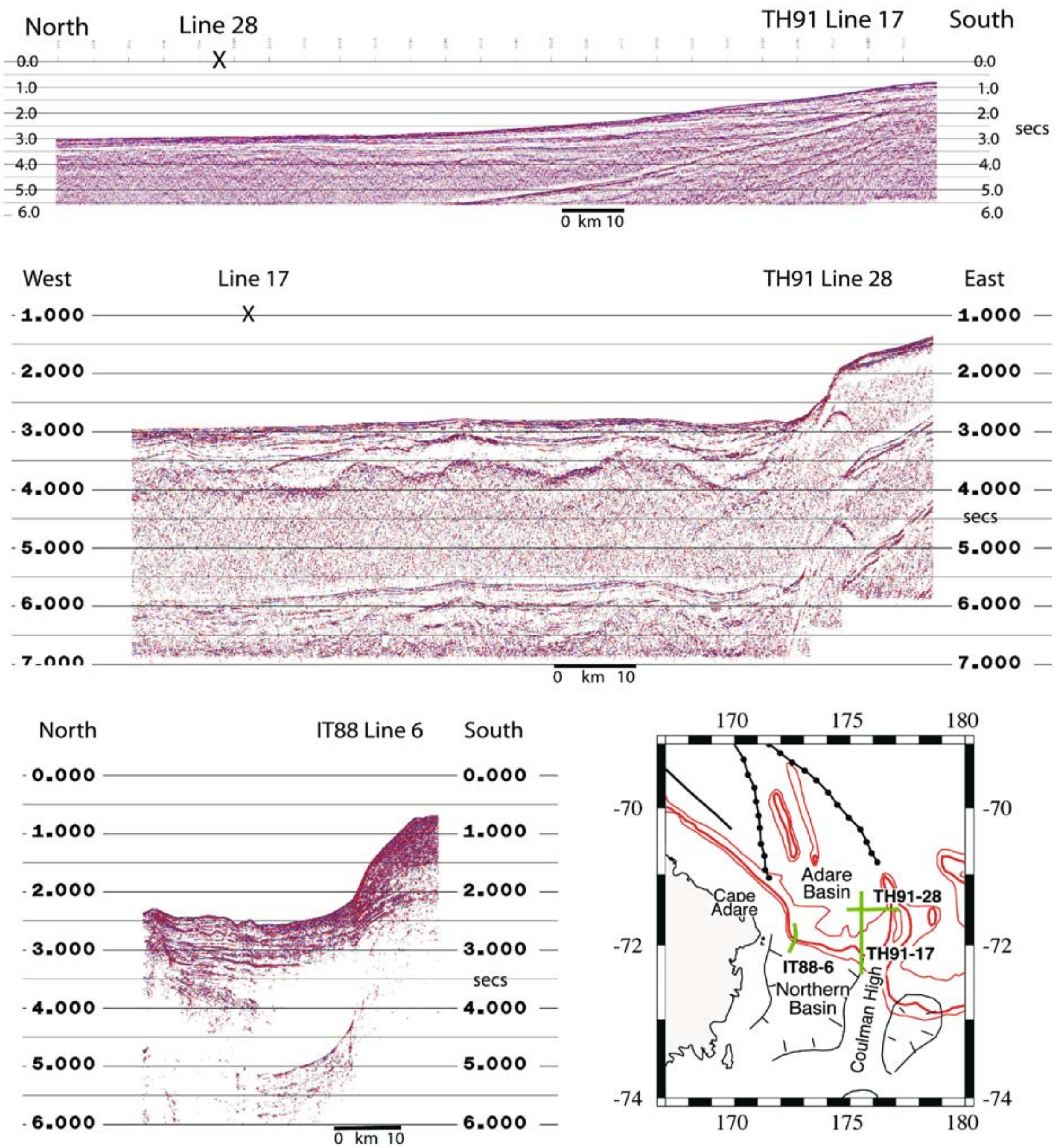


**Fig. 6.5-4.** Seismic reflection data supporting the continuity of structures between the Adare Basin and Northern Basin. *TH91 Line 28* (*middle profile*) shows that the acoustic basement (which we hypothesize to be oceanic crust) on the east side of the Adare Basin is relatively shallow for its age (40 Ma). *TH91 Line 17* (*top*) shows that this basement shallows gradually but continuously to the south without evidence of any off-setting structures beneath the lower continental slope. *IT88 Line 6* (*bottom*) shows that the basement reflector on the west side of the Adare Basin has a similar character to the basement on the east side of the basin. In the *center* of the *middle frame*, and in the *bottom frame*, which are from approximately conjugate locations on the margins of the Adare Basin rift system, a similarly transparent character of the lowest sediments above basement is apparent. The location of the profiles is shown in the *insert* on the *lower right* and in Fig. 6.5-5. Note difference in scale among the profiles. Seismic lines are available from the SCAR Seismic Data Library System

shelf edge is primarily due to the changing water depth and is not a reflection of a structural feature near the shelf edge. More importantly, Fig. 6.5-5 shows that the Bouguer gravity high over the eastern Adare Basin continues southward into the Northern Basin without an offset at the continental slope. This is contrary to what would be expected if there was a major fault along this margin transforming motion into the Central Basin.

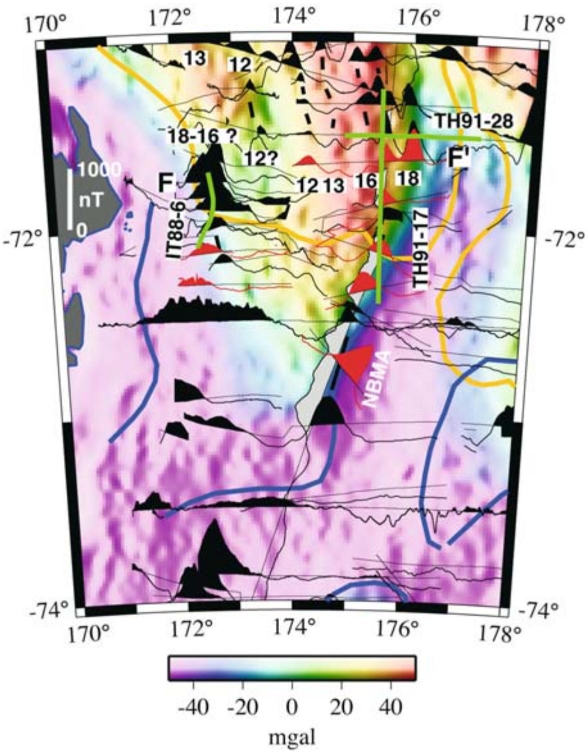


**Fig. 6.5-5.** The Bouguer gravity anomaly over the southern Adare Basin and Northern Basin. Note that the Bouguer gravity high over the eastern Adare Basin continues into the Northern Basin without any obvious offset near the continental slope (corresponding roughly to the region near the 1 500 m isobath). The Bouguer anomaly includes corrections for water depth and the sediment basement interface. Magnetic anomaly data and other symbols are plotted as in Fig. 6.5-2. The *heavy green lines* show the location of the seismic profiles in Fig. 6.5-4

## Implications

The Adare Basin kinematic history places tight constraints on the development of the Northern Basin. The kinematic constraints require that the Hallett Ridge, at least that part adjacent to where we can positively identify anomaly 18 (i.e. north of 71°30' S), was abutting Cape Adare prior to Chron 20. This in turn implies that there was an equivalent amount of extension, about 170 km, across the northern Ross Sea sedimentary basins between Chrons 20 and 8. There are two alternative models by which this extension could have been accommodated.

### Model 1

In the first model, the extension is taken up primarily by continental stretching and thinning. If this is the case, it must have been taken up by stretching and thinning over both the Northern Basin and Central Trough since the crustal thickness (~12 km) and inferred $\beta$ (thinning) factor in the Northern Basin (Davey and Brancolini 1995) preclude it from taking up more than about 50% of the extension. This, in turn, requires that there was a major transform boundary between the Adare Basin and the Northern Basin. Salvini et al. (1997) analyzed all the existing seismic data and concluded that a NW-SE striking fracture zone, which they called the Adare Fracture Zone, separates the shallow water and deep water basins. They asserted that this fracture zone has been active in the last 30 Ma. We have examined the existing seismic data to look for evidence of such a fracture zone and conclude that the data are too sparse to draw this conclusion. Indeed, the apparent continuity of magnetic anomalies 16–18 along the east side of the Adare Basin with the Northern Basin Magnetic Anomaly suggests that the offset across any such fault must be small. Alternatively, the alignment of these magnetic and gravity anomalies is a coincidence.

### Model 2

The alternative model is that the Northern Basin took up all of the extension by major localized crustal thinning and massive intrusion into the lower continental crust at the same time as the Adare Basin was spreading. Although this mechanism has been invoked in other basins of the Ross Sea (e.g., Cooper et al. 1987), the process by which the Northern Basin alone accommodated the 150 km of extension would have required extreme thinning and considerable addition of new crustal material from elsewhere, since, if the Coulman High is reconstructed to its "pre-breakup" position at Chron 20, there would have been only a small amount of pre-existing continental crust between the Coulman High and the Cape Adare margin available to intrude and extend. If the Northern Basin Magnetic Anomaly is really continuous with anomalies 16–18 in the Adare Basin, it suggests that the intrusions were very narrowly focused at the time of anomalies 16–18. The argument in favor of this alternative is the continuity of structures across the margin and the lack of evidence for a major transform offset between the Adare Basin and the Northern Basin.

Note that if Model 2 is correct, the percentage of extension inferred by Davey and Brancolini (1995) (with a $\beta$ factor of ~3) must be underestimated. Calculations of $\beta$ factor are based on the assumption that continental crust has thinned in place without any lateral flow in the lower crust different from that of the upper crust. These calculations frequently underestimate the amount of extension in continental rift systems with large magnitudes of extension, where lateral flow of the lower or middle crust has occurred to fill in the gap as the two sides of the extensional system move apart (e.g., Block and Royden 1990; Wernicke1992). Other rift systems that are transitional from continental to oceanic have extensive regions of new area that are not fully oceanic crust but instead inferred to be transitional crust (Oskin et al. 2001). If Model 2 is correct, scenarios similar to these will need to be explored for the Northern Basin.

Both of these models also have important implications for the seismic stratigraphic history of the Northern Basin. If there were a major extensional event in the Northern Basin at the same time as spreading in the Adare Trough (40 Ma to 28 Ma), then any stratigraphic packages deposited during this time would be highly faulted and disrupted. The lowest seismic stratigraphic package in the Western Ross Sea that is discussed by Brancolini et al. (1995), RSS-1, is inferred to have an age of early Oligocene and older. RSS-1 appears to be absent in many places, and it is therefore difficult to correlate it across basement highs. However, where it is identified in the Northern Basin, it overlies faulted blocks of acoustic basement and has mostly sub-parallel reflectors (Brancolini et al. 1995). This suggests that it post-dates any major extensional event that would have opened the basin. We therefore suggest that in the Northern Basin, the strata that have been interpreted as RSS-1 are most likely younger than the major extension in the Adare Basin; i.e., no older than latest Oligocene in age. Any units that were deformed or intruded during the major rifting event between 40 and 28 Ma should therefore lie below RSS-1, within what is interpreted as acoustic basement in the seismic sections.

## Summary and Conclusions

Recent studies have led to the development of a detailed kinematic model for the region north of the Western Ross Sea. The aspect of this model that has the most important ramifications for the tectonics of the region is the demonstration that there was an episode of extension between East and West Antarctica in mid-Cenozoic time. This period of extension was constrained both by broad scale regional studies that determined the motion of East and West Antarctica using a plate circuit (i.e. by the summation of finite rotations constraining Australia and East Antarctic motion and Australia and West Antarctica motion) and by the analysis of magnetic anomalies straddling the Adare Trough. These results demonstrate that in the region of the Adare Trough there was roughly 150 km of approximately East-West extension between Chrons 20 and 8.

The important question now is what happened to this motion farther south in the western Ross Sea. In particular, it is important to establish whether *(a)* the motion is taken up over a broad area of the northern Ross Sea, i.e. between both the Northern Basin and Central Trough or *(b)* the motion continued straight south into the Northern Basin. Our analysis of magnetic anomalies and gravity data to the south of the Adare Trough suggest the latter, i.e. that the motion continued directly into the Northern Basin. The observations that support this conclusion are as follows:

Magnetic lineations on the east side of the Adare Basin continue southwards for 50 km after the Adare Trough ends at 71° S.

The sequence of positive magnetic anomalies along the east side of the Adare Basin (anomalies 16–18) coalesces into a single positive magnetic anomaly (the Northern Basin Magnetic Anomaly) around 71°40' S that continues along the eastern side of the Northern Basin to 73° S.

The Bouguer gravity high on the east side of the Adare Basin continues across the continental margin and into the Northern Basin without a major offset.

These observations imply structural continuity between the Adare and Northern Basins and, therefore, suggest that the Northern Basin should have a similar history of extension (~150 km of extension between 43 and 26 Ma) as the Adare Basin. This, in turn, suggests that the Northern Basin formed in Cenozoic time, most likely by a combination of major localized crustal thinning and massive, narrowly focused intrusions into the lower continental crust. The style of extension in the Northern Basin may be analogous to that seen in the Northern Gulf of California.

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