Cretaceous and Tertiary extension throughout the Ross Sea, Antarctica

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Abstract Marine geophysical data from the deep sea adjacent to the Ross Sea, Antarctica suggest that 170 km of extension occurred between East and West Antarctica from 46 to 21 Ma. The Northern and Victoria Land Basins in the western Ross Sea adjacent to the Transantarctic Mountains accommodated 95 km of this extension. Several kilometers of Oligocene sediments are found in the Central Trough and Eastern Basin in the eastern Ross Sea. Subsidence modeling accounts for these accumulations with about 40 km of extension in each basin centered on 35 Ma; therefore Ross Sea-wide Tertiary extension was comparable to extension in the deep-sea system. The early Tertiary geometry was of one oceanic rift that branched into at least three rifts in the continental lithosphere. This pattern is likely due to the contrast of physical properties and thermal state between the two different lithospheres at the continent-ocean boundary.

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Introduction

The Ross Sea overlies the extended lithosphere of the West Antarctic Rift System between East and West Antarctica. Extension in the rift is believed to have occurred in two main episodes; in the Cretaceous and in the Cenozoic (Davey and Brancolini, 1995). Cenozoic extension can be related to sea floor spreading on the Adare spreading system located northwest of the Ross Sea. Here 170-175 km of extension are thought to have occurred between 46 and 21 Ma (Davey et al., 2006; Mueller et al., 2005). Extension was transferred across the continent-ocean boundary into the western Ross Sea to form or deepen basins in the margin. Cenozoic extension in the westernmost basin, the Victoria Land Basin, can be reconstructed to be about 95 km, leaving a deficit of 75 km that must have occurred elsewhere (Davey et al., 2006). Others have suggested that extension was transferred eastward in the Ross Sea by right lateral shear (Salvini et al., 1997). The details of where the missing extension occurred and how this happened bear on rifting process at the continent-ocean transition. One possibility that we explore here is that other basins to the east of the Victoria Land basin also were extended during the Cenozoic.

The Ross Sea margin has four major basins, Northern Basin (NB), Victoria Land Basin (VLB), Central Trough (CT), and Eastern Basin (EB) (Fig. 1). Filling the basins are the Ross Sea seismic stratigraphic sequences RSS-1 (putative Cretaceous) through RSS-8 (Pleistocene) separated by unconformities RSU6 (~30 Ma) through RSU1 (Pleistocene) (ANTOSTRAT, 1995). We observe great thicknesses of Oligocene and younger strata in all basins and hypothesize that Cenozoic (Early Tertiary) extension and subsidence associated with Adare Basin spreading affected the VLB, and also the CT and EB, creating the necessary accommodation space needed for deposition. An alternative hypothesis limits Tertiary extension to only the VLB, suggesting the CT and EB were only affected by Cretaceous extension (Karner et al., 2005). To test these hypotheses we use the backstripping method to determine the observed tectonic subsidence in the CT and EB and compare that to predicted tectonic subsidence curves using

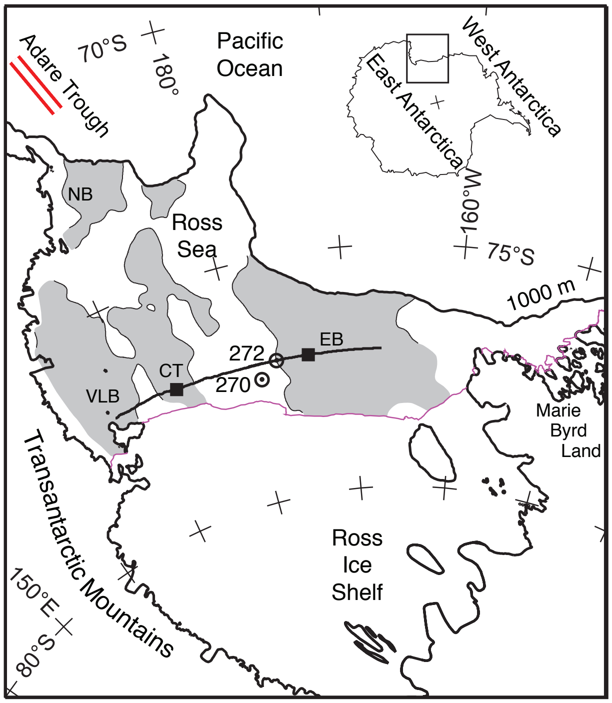

Figure 1. Location map for the Ross Sea area. Shading highlights sedimentary basins in Ross Sea, based on depth to basement deeper than 2.5 km [ANTOSTRAT, 1995]; NB, Northern Basin; VLB, Victoria Land Basin; CT, Central Trough; EB, Eastern Basin. Bold line shows coincident seismic profiles BGR-02 [ANTOSTRAT, 1995] and ACRUP2 [Trey et al., 1999]. Double circles show DSDP Sites 270 and 272 [Hayes et al., 1975]. Squares show locations analyzed for backstripping and 1-D subsidence.

different combinations of lithosphere stretching factors. We find that for reasonable stretching, 80 km of total extension can be proposed for the CT and EB.

Methods

Backstripping analysis (Steckler and Watts, 1978) was done to convert observed basin stratigraphic thicknesses to basement subsidence history. A one dimensional (1-D) Airy isostatic subsidence history was produced for the CT and EB at two points along German seismic profile BGR-02 (ANTOSTRAT, 1995). The VLB was not included in our analysis due to uncertainties in basement depth, unit thicknesses, and the unknown influence of Cenozoic volcanism. Corrections that were applied to the present stratigraphic thickness include decompaction (following Sclater and Christie (1980) using data from Hayes, Frakes et al. (1975); details in Decesari (2006)) of the sedimentary infill, isostatic compensation after decompaction, and paleobathymetric and eustatic sea level corrections. The result is the tectonic subsidence as a function of time. Global eustasy is accounted for using the curves of Miller et al. (2005). Due to limited available data, paleobathymetry was assumed as described later.

We predicted thermal subsidence using a model generalized from the instantaneous, pure-shear extension model of McKenzie (1978). Rather than his original Fourier-series solution for a single extension event, we used a finite-difference solution for temperature as a function of depth, which allows multiple extension events at different times. Following McKenzie, we used an initial lithosphere thickness of 125 km, thermal expansion coefficient of 3.28×10^{-5} $^{\circ}C^{-1}$, mantle temperature of 1330 ˚C, and mantle density of 3.33 g cm^{-3}. Subsidence for a single Cretaceous extension event and dual Cretaceous and Tertiary events were predicted for comparison against observations.

Stratigraphic analysis

Stratigraphic depths published for BGR-02 were based on stacking velocities (ANTOSTRAT, 1995). However, we consider depths computed from interval velocities to be more accurate. An interval velocity model for BGR-02 was computed from velocities for seismic profiles obtained on *RVIB Nathaniel B. Palmer* cruises NBP96-01 and NBP03-01 that cross this line.

We reinterpreted unconformities RSU6-RSU3 in the CT and EB from the revised BGR-02 depth section. These unconformities separate the RSS-1 through RSS-6 seismic sequences (ANTOSTRAT, 1995) and are interpreted to have formed at or close to sea level (DeSantis et al., 1999). Thicknesses of RSS-2 (early Oligocene-early Miocene) through RSS-6, 7 & 8 (late Miocene-Pliocene grouped as one unit) were calculated at the deepest locations of the basins (BGR-02 shot points 10450 in the CT and 4200 in the EB), ensuring analysis for the most extended crust. Acoustic basement depths in the basins could not be resolved from reflection seismic data and were obtained from gravity and seismic refraction modeling (Trey et al., 1999). Thickness of RSS-1 is then the difference between depths of the basement and RSU6. We assign an original depth of 100 ± 50 m for RSU6 and 200 ± 200 m for the younger unconformities.

Results

Both the CT and EB have 3 kilometers of Oligocene and younger sediments (post RSU6) that need to be explained by a subsidence history. The subsidence history prior to 30 Ma (putative age of RSU6) is poorly constrained due to the absence of dated unconformities older than early Oligocene. Since 95 Ma (mid-point age we assume for Cretaceous rifting), more than 5.5 km of sediment accumulation has occurred in the Central Trough (Fig. 2a) and more than 7.5 km in the Eastern Basin (Fig. 2b).

Predicted thermal subsidence curves were fitted to tectonic subsidence curves for the CT and EB to determine the amount of Ross Sea lithosphere stretching (β). A single Cretaceous extension event was considered first. Predicted tectonic subsidence curves for $\beta=2$, $\beta=4$, and $\beta=5$ were plotted against the observed tectonic subsidence (Fig. 2c). None of the observed subsidence curves fit the predicted Cretaceous-only extension model. This indicates that no amount of Cretaceous extension can account for the tectonic subsidence of the basement since 30 Ma, assuming that unconformity RSU6 formed at or near sea level.

Predicted two-stage Cretaceous (centered at 95 Ma) and Tertiary (centered at 35 Ma) extension can explain observed tectonic subsidence for the CT and EB. The observed tectonic subsidence of the CT and EB are bracketed by predicted subsidence curves using Cretaceous $\beta=2$, Tertiary $\beta=1.5$ and Cretaceous $\beta=2$, Tertiary $\beta=3$ (Fig. 2d). Further refinement reveals that predicted subsidence resulting from Cretaceous $\beta=2$, Tertiary $\beta=2$ closely fits the EB observed total tectonic subsidence (Fig. 2d). The observed subsidence of the CT does not exactly fit a Cretaceous $\beta=2$, Tertiary $\beta=2$ curve, but does within the error limits. Both the CT and EB observed subsidence can also be explained by Cretaceous $\beta=1.5$, Tertiary $\beta=2.25$ and Cretaceous $\beta=1.5$, Tertiary $\beta=2.5$ (Fig. 2d). It is possible the CT may have a lower Cretaceous β combined with a higher Tertiary β that would produce similar results as the EB with Cretaceous and Tertiary $\beta=2$. Regardless, these results indicate that a period of significant Tertiary extension is needed to account for the observed subsidence of the CT and EB and the large thickness of Oligocene and younger sediments in them, if the unconformities formed at shallow depths.

Discussion

An alternative model for Ross Sea basin formation includes Cretaceous extension for NB, VLB, CT, and EB formation but limits Tertiary extension to the VLB and NB (Karner et al., 2005). The Cretaceous-only model for CT and EB necessitates that most thermal subsidence throughout the Ross Sea predates Oligocene sedimentation and requires that Cretaceous extension created deep paleo-basins that persisted until Oligocene time (Karner et al., 2005).

For a single Cretaceous extension event to explain the subsidence history, Tertiary Ross Sea unconformities

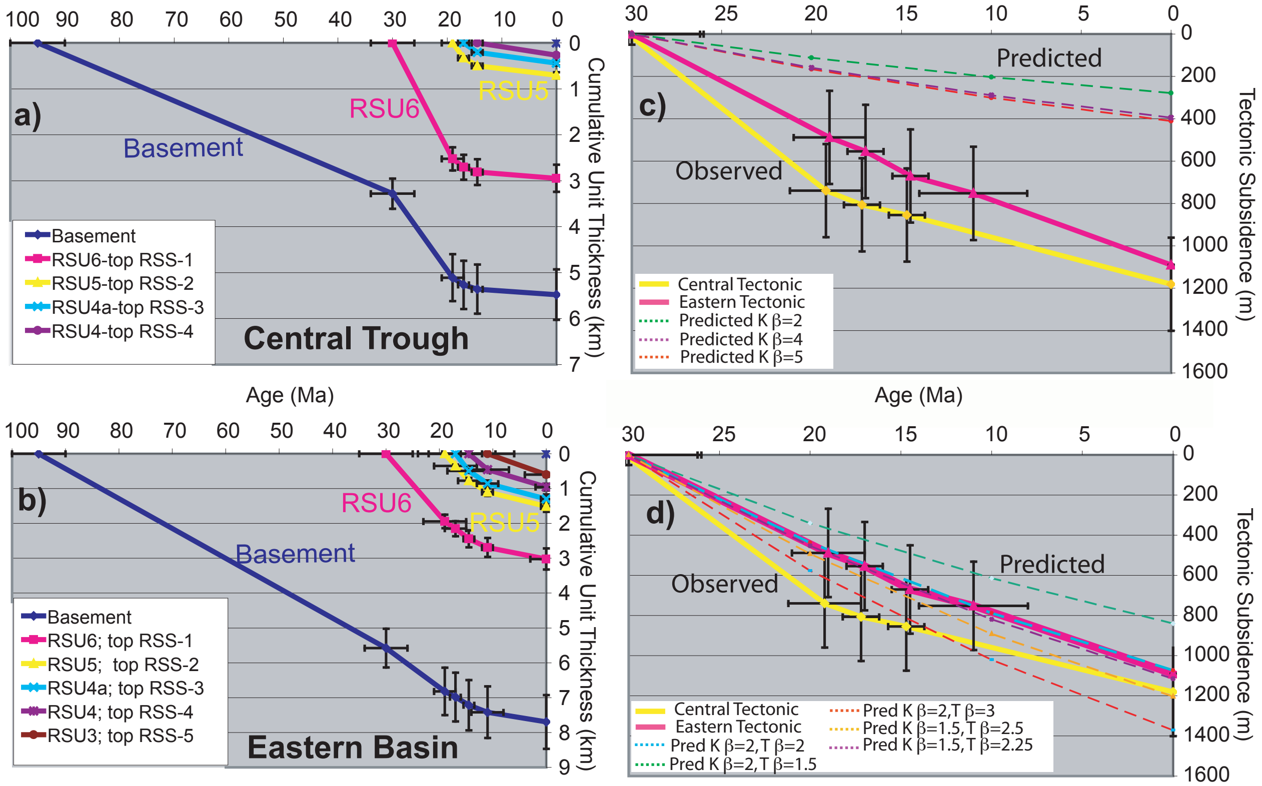

Figure 2. Decompacted sediment thickness histories and subsidence models. Left panels show thickness history corrected for compaction for Central Trough (a) and Eastern Basin (b) sites, with observed thickness at zero age. Right panels show observed tectonic subsidence for both sites (computed from thickness history, Airy load model, and estimated paleobathymetry), compared with subsidence predictions for models with extension at 95 Ma (K) only (c) and at both 95 Ma and 35 Ma (T) (d). For Cretaceous-only extension, even high stretching factors of β = 4-5 do not predict the computed subsidence (c). For the two-stage model, moderate stretching factors around 2 for both K and T events are consistent with the computed subsidence (d).

would have to have formed at depths of many hundreds of meters. The total tectonic subsidence of the EB was fitted to a Cretaceous β=4 predicted subsidence curve by increasing the paleo-water depth at each unconformity (Decesari, 2006). The results show that unconformity RSU6 would have to have formed at 900-m depth to fit this model.

How would the results for Cretaceous-only extension be different had flexural compensation been assumed as opposed to local Airy compensation? A local sediment load produces a broader area subsidence response in a flexural process than an Airy process. In a flexural response, the subsidence for a given sediment load is less than a local isostatic response. The backstripping analyses accounts for the observed sediment thickness by combining effects including tectonic subsidence, isostatic response and paleobathymetry. Therefore, less isostatic response at a basin center in a flexural compensation model requires deeper bathymetry to account for the observed thicknesses than a local compensation model. The paleobathymetry for RSU6 in flexural compensation with Cretaceous-only extension would be significantly deeper than 900 m found for the 1-D model. Alternatively, forming RSU6 at shallow depth in a flexural-compensation model would require more Tertiary extension than we have modeled. Properly accounting for flexural compensation may well be important for the Central Trough, which is fairly narrow and has a large positive gravity anomaly (e.g. Trey et al., 1999), but probably not for the wider Eastern Basin, where the low-amplitude gravity anomaly suggests that local compensation is a good approximation.

Unconformity RSU6 has been suggested to have formed as a 29-Ma deepwater unconformity resulting from strong currents related to the opening of the Drake Passage (Hinz and Block, 1984). Deep water Oligocene unconformities are interpreted in the Indian Ocean and the western Pacific Ocean and may have resulted from erosive Oligocene Antarctic Bottom Water currents (Carter et al., 2004; Davies et al., 1975). Anderson and Bartek (1992) suggest subglacial erosion may have formed RSU6. However, DeSantis, et al. (1999) argue against this based on the improbability that a large-sized ice sheet was grounded on the seafloor at significant depth without leaving any signs of both erosion or deposition.

If unconformity RSU6 was cut at 900 m or more by grounded ice, significant erosion of RSS-1 would be expected. Rather, relatively parallel reflectors are seen above and below RSU6 (Decesari et al., 2004). This is characteristic of gentle sea floor slopes that are typical of shallow shelves. It seems unlikely that unconformity RSU6 formed at depths from glacial erosion. We favor the Ross

Sea Tertiary unconformities originating at shallow water depths, formed from a combination of sea level changes and ice erosion. Therefore, we prefer a two-stage tectonic model starting with Cretaceous extension and followed by an early Tertiary event consistent forming unconformities in shallow water. The large degree of extension that we interpret requires a large initial crustal thickness. Prior to Cretaceous extension, the Ross Sea was probably an elevated region high above sea level (Fig. 3a) with thick continental crust (~50 km). Cretaceous extension, possibly totaling several hundred kilometers, occurred between 105 and 80 Ma (Siddoway et al., 2004). Modeled east-west extension centered on ~95 Ma at β=~2 thinned the crust to ~20-25 km (Fig. 3b). Cretaceous sedimentary unit RSS-1 was deposited and deformed within basement grabens.

Modeled Tertiary extension centered around ~35 Ma correlates to the Adare Trough seafloor spreading event. Magnetic anomaly interpretation indicates about 180 km of E-W seafloor spreading occurred (Cande et al., 2000). However, the VLB is only 130 to 150 km wide, and Davey and De Santis (Davey and De Santis, 2006) interpreted only about 95 km of lithosphere extension in the VLB for Tertiary time. An excess of up to 85 km of Adare Trough extension must have been accommodated elsewhere. Cande and Stock (2006) propose either partitioning extension between the VLB and the Central Trough or the VLB accommodating all of the extension. Tertiary extension of ~2:1 extended the Ross Sea further in localized areas corresponding to the proto-VLB (and NB), CT, and EB (Fig. 3c). We suggest the extension was partitioned over all of the Ross Sea basins, perhaps 100 km in VLB and 40 km each in CT and EB. Tertiary extension resulted in subsidence of RSS-1 and RSU7 below sea level. No later than 30 Ma, unconformity RSU6 was cut near sea level.

Gravity data from the Ross Sea indicate the basins are characterized by positive anomalies, which can be used as a proxy for thinned continental crust (Hayes and Davey, 1975; Luyendyk et al., 2002), confirmed by seismic refraction experiments (Trey et al., 1999). We have complied a new gravity map of the Ross Sea and Ice Shelf from marine, ice surface, and satellite data ((modified after Luyendyk et al., 2002); Fig. 4), which shows a relationship between gravity highs and sedimentary basins. This map can therefore show the extent and location of Tertiary extension. Using the gravity proxy, Adare Trough extension splits into three branches in the Ross Sea continuing south under the ice shelf. The amplitude of the CT anomalies decreases to the south (Fig. 4), possibly indicating extension decreases to the south.

Davey et al. (2006) proposed that 95 km of Tertiary extension was accommodated in the VLB; our interpretation stipulates that an additional ~80 km is distributed between the CT and EB. Therefore, within uncertainties, this amount matches the 170 km proposed for the Adare spreading system. For these amounts of extension to agree, the relative motion pole must have been a moderate distance away from the Ross Sea. Davey et al. (2006) show a rotation pole for anomaly 18 in Marie Byrd Land; Cande et al. (2000) show a pole for anomaly 13 located in the South Atlantic with a large uncertainty extending from the Weddell Sea to the northeast Atlantic. Because our analysis suggests that the Cenozoic extension amount is not discernibly different between the Adare system and the Ross Sea, the relative motion poles must have been farther away rather than closer.

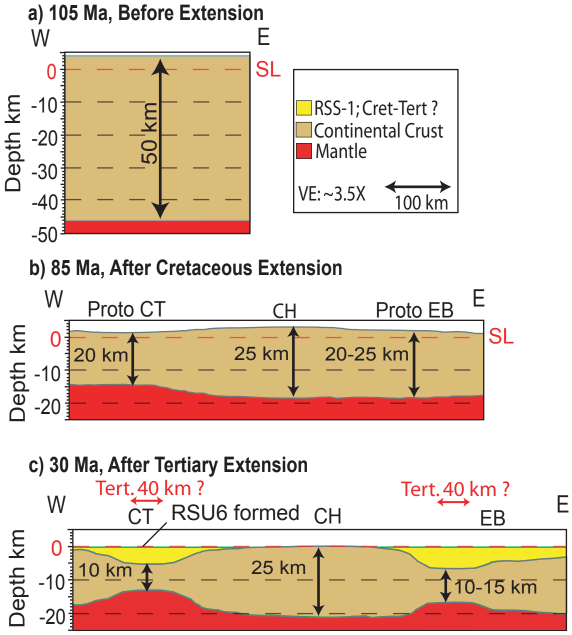

Figure 3. Model of central Ross Sea extension. a) 105 Ma, before Cretaceous extension. The Ross Sea may have been an elevated region with crustal thickness of ~50 km. b) 85 Ma, after Cretaceous extension. Crust thins to 20-25 km, graben formation accommodates a combined >200 km of E-W extension. c) 30 Ma, after Tertiary extension; localized crustal thinning of the proto-basins to ~10 km thick and the formation of present-day Ross Sea basins. The Central High crust does not extend further and remains 25 km thick. The region is largely below sea level except for the Central High. Unconformity RSU6 is interpreted to form near sea level. SL= Sea Level.

Cande and Stock (2006) argue that because there are alignments of gravity and magnetic anomaly trends to the east of NB, all of the Adare extension must be restricted to the NB and the VLB to the south and none occurred to the east. We propose instead that extension in the NB decreases southward accommodated by clockwise rotation or distributed shear of the east flank of the NB (Figure 4b).

Conclusions

The Ross Sea may cover foundered continental crust from the collapse of thick, elevated lithosphere since the Cretaceous (Fig. 3 Luyendyk et al., 2001). The Transantarctic Mountains (TAM) may be the preserved inland edge of the elevated region. Studinger et al. (2004) also interpret that West Antarctic structure and geologic history may be consistent with high plateau collapse. Bialas et al. (2005) propose a model of a thick lithosphere

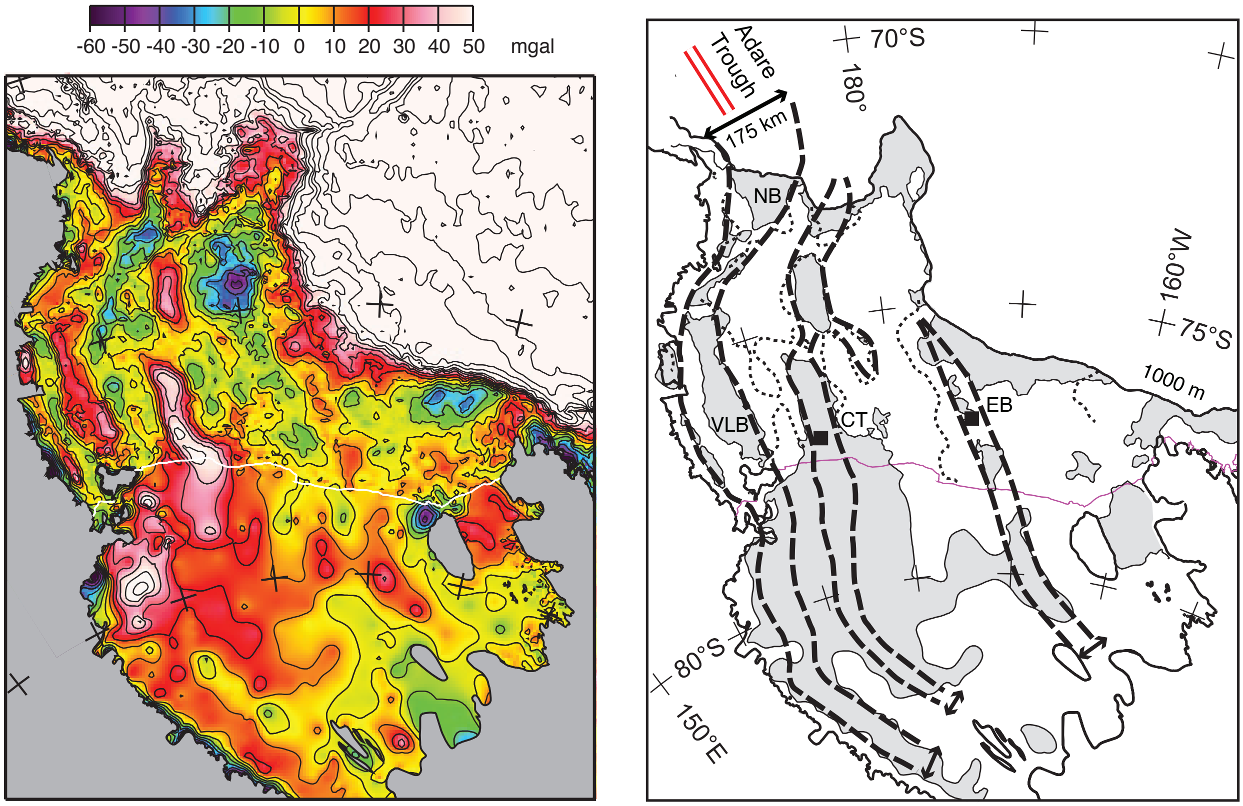

Figure 4. a) Bouguer gravity map of the Ross Sea and Ice Shelf (reduced at bed density 2300 Mg m-3 estimated density of compacted surface sediments). Gravity data include ice shelf surface, [Greischar et al., 1992], satellite [McAdoo and Laxon, 1997], and new marine compilation [updated from Luyendyk et al., 2002]. Contour interval 10 mgal < 60 mgal; 20 mgal > 60 mgal. b) Interpretation with bold dashed lines outlining bands of highly extended crust interpreted from depth to basement and gravity anomalies. Shading shows Bouguer gravity anomaly greater than +10 mgal. Dotted lines in Ross Sea show 2.5-km basement contour (Fig. 1). Positive gravity anomalies are located over the basins, indicating thinned crust. Arrow adjacent to Adare trough shows across-strike width of oceanic crust formed by the latest spreading episode; a similar amount of total extension must also be present to the south.

retaining significant elevation as adjacent lithosphere is extended and subsides.

Our analyses support extension and subsidence of Ross Sea lithosphere in two phases, the last of which occurred in three basins during early Tertiary time synchronous with Adare Trough spreading. A test for our hypotheses would include drilling and sampling Oligocene and older units in the Ross Sea.

We have presented a case where a rift in oceanic lithosphere crosses obliquely into continental lithosphere at the content-ocean boundary and shows a distributed region of strain. One or two oceanic rifts have branched into at least three rifts in the continental lithosphere. This pattern is likely due to the contrast of physical properties and thermal state between the two different lithospheres.

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