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Robin Bell
Columbia University

Carol A Finn
United States Geological Survey

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M. STUDINGER

R. E. BELL

Lamont-Doherty Earth Observatory of Columbia University
P.O. Box 1000
Palisades, NY 10964, USA
email: mstuding@ldeo.columbia.edu

C. A. FINN

U.S. Geological Survey
MS 964, Box 25046
Denver Federal Center
Denver, CO 80225, USA

D. D. BLANKENSHIP

Institute for Geophysics
The University of Texas at Austin
4412 Spicewood Springs Rd
Austin, TX 78759, USA

Abstract The West Antarctic Rift System dominates the lithospheric structure of the Ross Sea sector of West Antarctica. A suite of aerogeophysical data has been used to compile a complete Bouguer anomaly map and to reveal the crustal architecture of a major portion of the rift system between Marie Byrd Land and the Whitmore Mountains. Three major crustal segments are proposed. The Whitmore Mountains crustal block, a segment of transitional crust between the Whitmore Mountains and the Bentley Subglacial Trench, and a unit of stretched crust towards the rift centre. The crustal thickness has been estimated from power spectral analysis and forward modelling of the gravity data. Beneath the Whitmore Mountains, a crustal thickness of 34 km has been estimated, which thins to 26 km beneath the Bentley Subglacial Trench. The distinct changes in Bouguer gravity from the transitional crust, the Bentley Subglacial Trench, and the stretched crust possibly represent the differential crustal extension during the Mesozoic. The lower boundary for the amount of extension has been estimated as $\beta = 1.3$. The influence of rifting for the crustal evolution seems to be weaker in the region between Marie Byrd Land and the Whitmore Mountains than in the Ross Sea. Similarities in the signature of the gravity anomalies and models between the Ross Sea and our study area suggest a possible early rift origin for the Bentley Subglacial Trench. The narrow basins along the rift shoulder close to the Whitmore Mountains block might have been reactivated during regional Cenozoic right-lateral strike-slip movements as well as a proposed en echelon sedimentary basin near Siple Dome.

Keywords airborne geophysics; West Antarctic Rift System; crustal extension

INTRODUCTION

The West Antarctic Rift System dominates the lithospheric structure of the Ross Sea sector of West Antarctica. Detailed geophysical and geological studies during the past decades focused mainly on the Ross Sea Embayment and Marie Byrd Land (Fig. 1). In contrast, models of the Mesozoic and Cenozoic evolution of the region between the eastern rift shoulder in Marie Byrd Land and the Transantarctic Mountains discuss only the basic tectonic features, since geophysical data coverage has been sparse and geological mapping of the area is restricted to only a few nunatak outcrops in Marie Byrd Land and the Whitmore Mountains.

Although the origin and nature of the West Antarctic Rift System are not fully understood, it is well established that its complex crustal structure has been mainly influenced by two distinct phases of episodic tectonic activity. During the Jurassic, the progressive fragmentation of Gondwana caused extensional and translational plate movements between the West Antarctic microplates. Regional stretching, subsidence, and the development of subglacial basins principally formed the current rift system (e.g., Dalziel & Elliot 1982; Tessensohn & Wörner 1991; Behrendt et al. 1991; Cooper et al. 1991; Wilson 1992, 1995). During the Cenozoic, a second phase of episodic activity continued the evolution of the West Antarctic Rift System. The extrusion of bimodal alkalic volcanic rocks from the late Cenozoic to the present may be associated with a mantle plume beneath Marie Byrd Land (LeMasurier 1990; Behrendt et al. 1992). The present-day state of the rift is a matter of debate. Two end-member models include a hot, active extensional regime suggested from volcanic studies (e.g., Blankenship et al. 1993; Hole & Masurier 1994; Hart et al. 1997), versus a dormant rift with normal mantle temperatures implied by magnetotelluric and refraction seismic profiling (Wannamaker et al. 1996; Clarke et al. 1997).

Our paper focuses on the Mesozoic and Cenozoic extensional structures of the region between Marie Byrd Land and the Transantarctic Mountains rift shoulder. The anticipated tectonic features associated with an extensional regime include fault-bounded, sediment-filled grabens (basins), and major geological faults along the rift shoulder. The structural alignment and extent of these features can be detected by regional mapping of gravity and magnetic anomalies. In ice-covered regions, aerogeophysical imaging is the optimum approach to survey large areas and to resolve the geological structures beneath the ice.

AIRBORNE GEOPHYSICAL DATA

We use a set of integrated airborne geophysical data collected onboard a ski-equipped DeHavilland Twin Otter. The surveys were flown on a 5.3 km grid during five Antarctic field seasons (1991–93, and 1995–97) by the United States Support Office for Aerogeophysical Research (SOAR). In

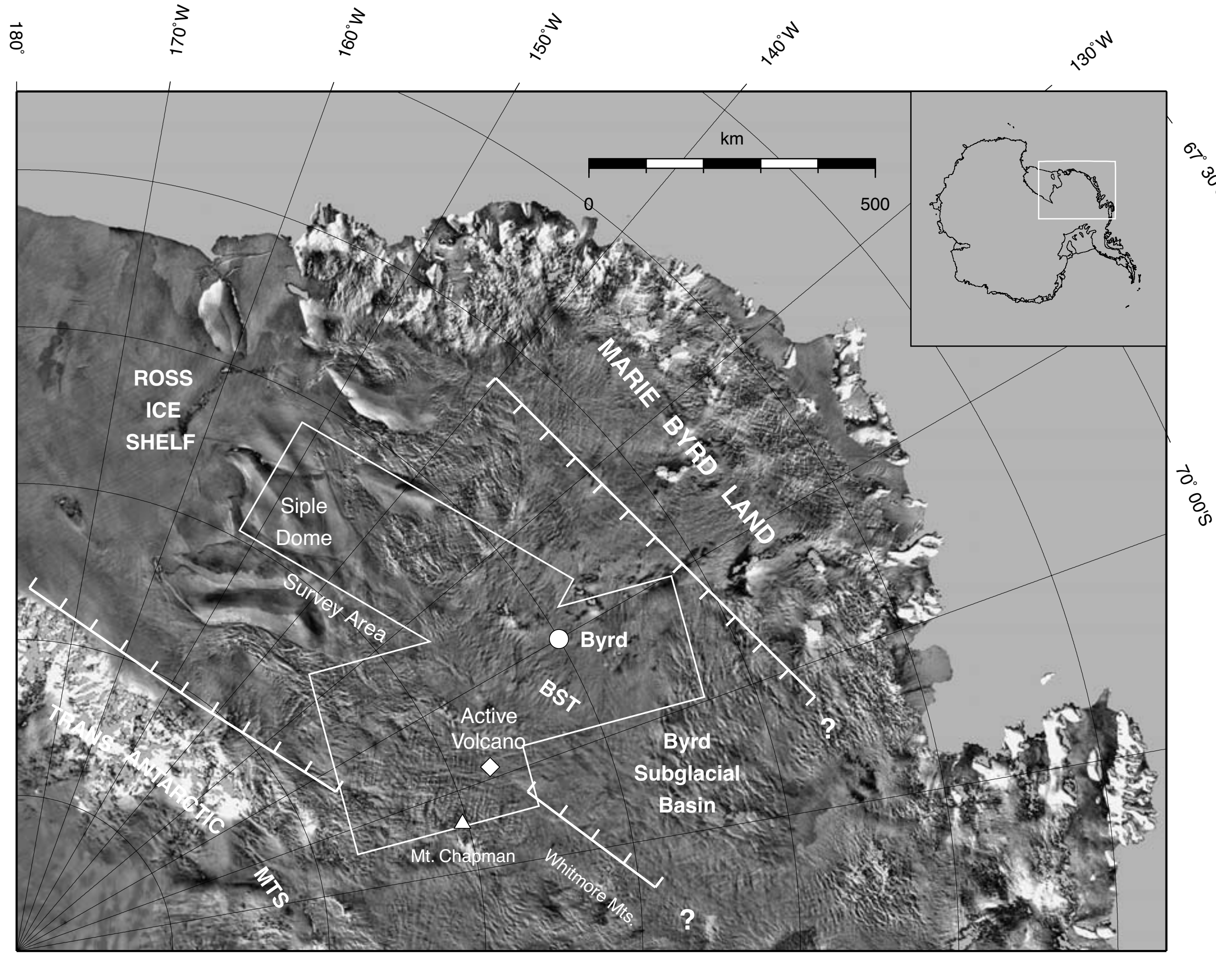

Fig. 1 Location map of the West Antarctic Ice Sheet. Basemap is a portion of the AVHRR (advanced very high resolution radiometer) composite map from Ferrigno et al. (1996). Solid white box outlines the survey. Hatched line marks the location of the inferred rift shoulder of the West Antarctic Rift System. BST, Bentley Subglacial Trench. Map projections throughout this paper are polar stereographic.

total, more than 150 000 line-km of gravity, magnetic, ice-thickness and topography data were acquired, covering 300 000 km^2 over West Antarctica (Fig. 1).

Gravity data

A Bell Aerospace BGM-3 gravity meter and a LaCoste & Romberg "S" gravity meter modified by ZLS Corporation have been used for measuring relative changes in the Earth's gravity field (Brozena et al. 1993; Bell et al. 1999). These measurements have been tied to the International Gravity Standardization Network (IGSN-71) station at McMurdo. The data reduction process includes corrections for the aircraft's vertical acceleration, a compensation for measuring gravity from a moving platform on a rotating Earth (Eötvös correction for airborne measurements), a free-air correction, and the subtraction of the predicted gravity for the latitude at the ellipsoid. A combination of all these corrections yields the free-air gravity anomaly. Bell et al. (1998, 1999) estimated the accuray of the gravity measurements from an evaluation of crossover errors (2.98 mGal) and repeat measurements (1.39 mGal). The spatial resolution of the airborne gravity data along-profile is 5 km.

The free-air gravity data from Bell et al. (1999) and the ice surface and subglacial topography from Blankenship et al. (2001) have been used to compile a complete Bouguer anomaly map. We calculated the gravitational effect of the density contrast between the ice surface and air and at the bed of the ice sheet using Parker's (1972) frequency domain approach (Studinger et al. in press). Bulk densities of 910 and 2670 kg/m^3 have been assumed for ice and bedrock, respectively. The mean flight elevation was assumed as 2500 m above sea level.

Complete Bouguer gravity map

The Bouguer gravity field beneath the Whitmore Mountains is dominated by a large negative (–60 to –140 mGal) anomaly, which roughly coincides with the subglacial morphologic boundary of the Whitmore Mountains (Fig. 2). This crustal unit is bounded by c. 40 km wide lineated gravity lows. The edge of the Whitmore Mountains is offset c. 75 km by a deep trench, which we interpret as a major geological fault (Fig. 2).

Between the rift shoulder and the Bentley Subglacial Trench, the Bouguer gravity shows a smooth anomaly

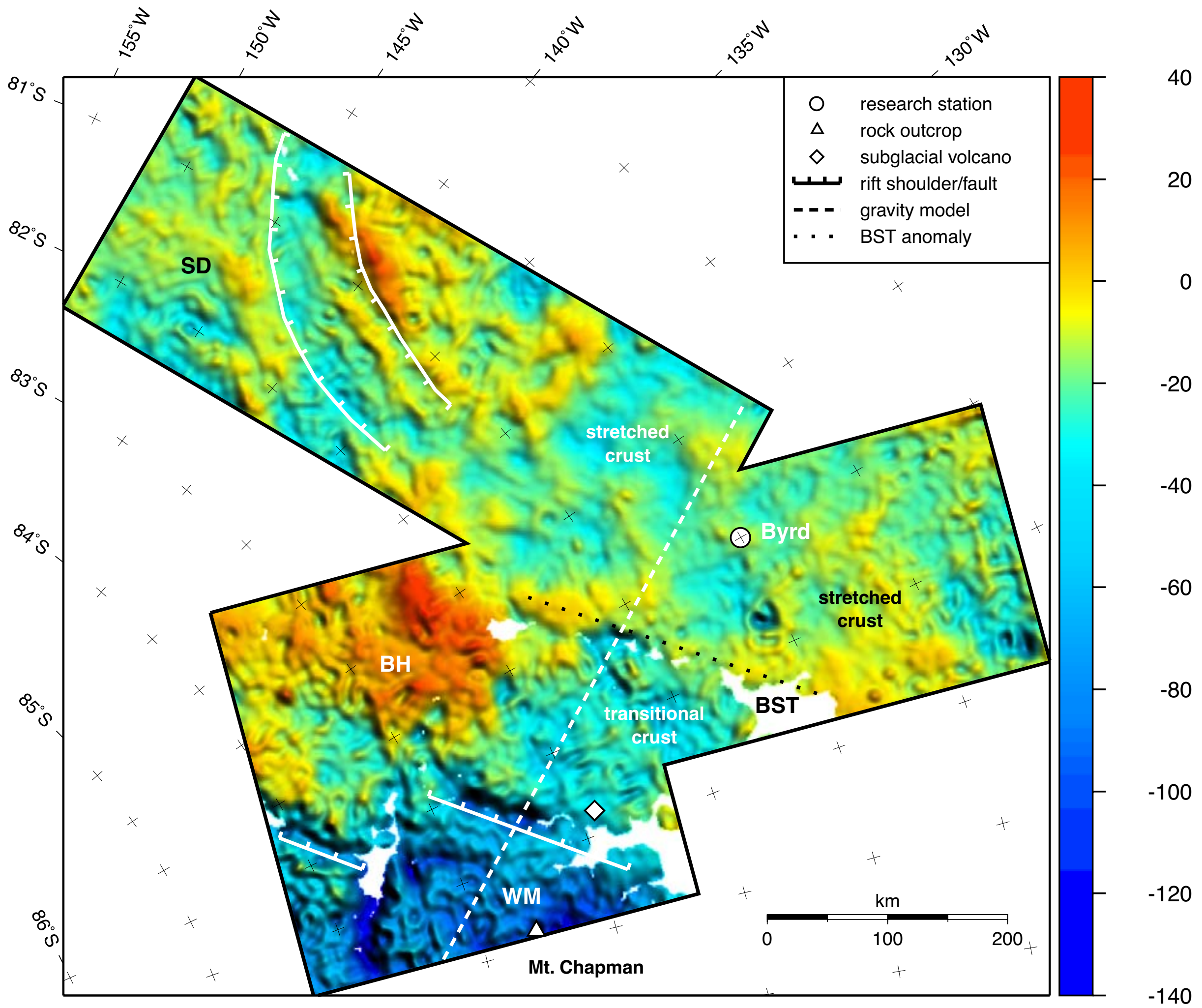

Fig. 2 Complete Bouguer anomaly map. The map is illuminated to reveal smaller relief features. BH, Bouguer high; BST, Bentley Subglacial Trench; SD, Siple Dome; WM, Whitmore Mountains.

pattern with only small variations between –20 and –40 mGal. The pronounced change from the Whitmore Mountains Bouguer gravity low to this adjacent plateau suggests that the plateau has undergone some crustal extension and may represent a transitional crustal segment between the Whitmore Mountains and the Bentley Subglacial Trench (Fig. 2).

A weak, elongated positive anomaly (+10 mGal) associated with the Bentley Subglacial Trench marks the northern boundary of the transitional crust between the Whitmore Mountains block and the Bentley Subglacial Trench (dotted line, Fig. 2). North of the Bentley Subglacial Trench, the Bouguer anomaly is characterised by a slight increase. This crustal unit shows a few prominent positive anomalies (c. 15 mGal) in the Bouguer gravity. The slight increase in Bouguer gravity compared to the transitional crust possibly indicates a higher amount of stretching for this crustal segment (stretched crust, Fig. 2). The distinct changes in Bouguer gravity from the transitional crust, the Bentley Subglacial Trench, and the stretched crust possibly represent the differential crustal extension during the Mesozoic. In the southwestern corner of the survey area, a pronounced Bouguer gravity high (c. 40 mGal) dominates the gravity field (BH, Fig. 2).

The gravity low near Siple Dome (SD, Fig. 2) coincides with a magnetic low and a quiet zone in the magnetic anomaly (Finn et al. unpubl.; Sweeney et al. 1999) (Fig. 2). This coincident low in gravity and magnetics is interpreted as a fault-bounded sedimentary basin. Following Salvini et al. (1997, 1998), we tentatively interpret this basin as an en echelon structure. This interpretation of extensional tectonics is based on the assumption that the crust between Marie Byrd Land and the Whitmore Mountains has been influenced by tectonic stresses similar to the Ross Sea Embayment and Marie Byrd Land. During the Cenozoic, regional right-lateral strike-slip tectonics along major fault zones dominated the stress pattern in the Ross Sea Embayment (Salvini et al. 1997, 1998). If we assume that the regional strike-slip faulting occurred along a direction parallel to the rift shoulder, the orientation of this sedimentary basin suggests an en echelon origin for the extension (Salvini et al. 1997, 1998).

POWER SPECTRAL ANALYSIS

Power spectral analysis can be used to estimate the crustal thickness from gravity data (e.g., Spector & Grant 1970; Karner & Watts 1983). The mathematical expectation of the power spectrum of an essentially horizontal density contrast is proportional to and dominated by the term e^{-2hk_r}, where h is the depth to the top of the density contrast and k_r is the radially averaged wavenumber. By plotting the natural logarithm of the radially averaged power spectrum versus wavenumber, and fitting straight lines to the linear segments of the resulting curve, we can estimate mean depths of the density contrasts from the slopes of the best fitting lines.

The area selected for the 2D power spectral analysis should contain uniform crustal structure and should be large enough to resolve anomalies of long wavelengths and thus to characterise deep sources. The estimated power spectrum of an area covering 475 × 475 km shows a pronounced change in slope at a wavenumber of 0.089/km, which marks the endpoint for the linear regression of the long wavelength band (Fig. 3). The slope of this segment corresponds to a depth estimate of 27.5 ± 5.1 km. Following Studinger et al. (1997) and Studinger & Miller (1999), we use the standard error from the linear regression of each slope segment as the error bound for the depth estimate. The necessarily subjective choice of endpoints for the regression, however, may have introduced significant uncertainties into the depth estimation. We estimated additional source depths by increasing and decreasing the length of the wavenumber band towards the neighbouring samples around the choosen endpoint (i.e., k_r = 0.11/km and k_r = 0.077/km, respectively). Both depth estimations are well within our confidence limit; however, these estimates have a considerable greater standard error, indicating a digression from the linear relationhip between k_r and the power spectral density. Thus, the choice of the wavenumber band for depth estimation appears appropriate.

The deepest density contrast d_1 at 27.5 ± 5.1 km depth is interpreted to reflect the transition from the crust to the mantle. Our estimation of crustal thickness is in good agreement with depth estimations from seismic refraction measurements. According to Clarke et al. (1997, 1998), the crustal thickness in the survey area is thinning from 30 to 26 km (see inset in Fig. 3 for location of profile), which is within the confidence limits of our power spectral analysis. Our estimation of the crustal thickness represents an average value for the area outlined in Fig. 3.

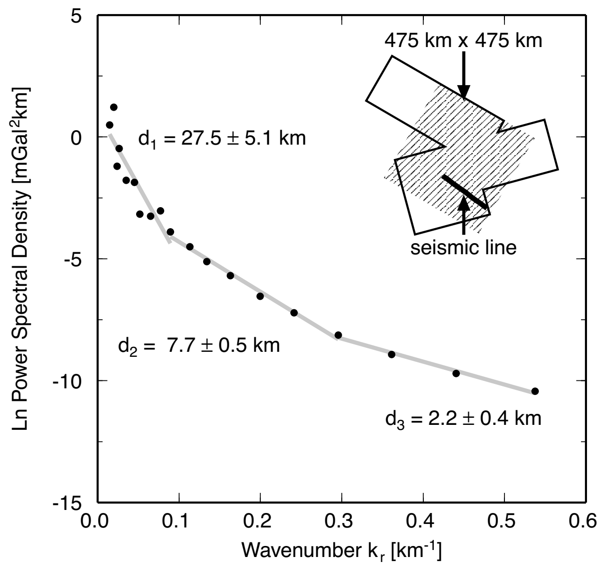

Fig. 3 Power spectral analysis of gravity data. Natural logarithm of the radially averaged power spectrum of the Bouguer gravity (power spectral density) versus radial wavenumber k_r. The radially averaged power spectrum of an area covering 475 × 475 km was calculated by means of a fast Fourier transform (FFT). The dataset (96 × 96 grid cells) was mirrored about its eastern and southern edge to create an array four times the size of the input array. Twenty-five radial bands in the wavenumber plane were used to calculate the radially averaged spectral power. Mean depth to crustal interfaces estimated from the slope of the corresponding segments are shown. Depth estimations were corrected for the mean flight elevation and are thus relative to sea level. Inset map shows area of 2D power spectrum and refraction seismic line.

GRAVITY MODELLING

Forward modelling of the free-air gravity data has been used to constrain the crustal structure along profile (dashed line, Fig. 2). The simple 2D gravity model is constrained by ice-surface and subglacial topography. We chose the density of ice as 910 kg/m^3. Crustal thickness and densities are controlled by the refraction seismic model of Clarke et al. (1997), crossing at kilometre 200, and regression parameters from Christensen & Mooney (1995) to convert the velocity model into a density model (Fig. 4).

The crustal thickness changes from 34 km at the southeastern end of the profile to 26 km beneath the Bentley Subglacial Trench, marking the transition from the Whitmore Mountains crustal block to the stretched crust in the centre of the rift. Around kilometre 130, a low-density body (2300 kg/m^3), interpreted as sedimentary basin, is necessary to match the modelled and observed gravity. The thickness in the centre of the basin is not well constrained, due to a gap in ice-thickness measurements. Adjacent to this basin, a body of higher density (2750 kg/m^3) improved the fit between observed and modelled gravity. The transition from the thicker crust to the transitional crust (at kilometre 120) coincides with a change in magnetic anomaly pattern from a relative quiet zone to short wavelength (<25 km) anomalies, and marks the boundary of the Whitmore Mountains crustal block (Fig. 4).

Our model assumes no lateral changes in the basement density structure between the Whitmore Mountains crustal block and the region northwest of it. A possible lateral change in average basement density would result in different values for the crustal thickness. We cannot rule out the possibility of an isostatically compensated sediment infill in the Bentley Subglacial Trench, which would also change our crustal thickness estimate.

DISCUSSION OF EXTENSIONAL STRUCTURES

Crustal thickness

The crustal thickness estimated from power spectral analysis and gravity modelling indicates significant crustal stretching.

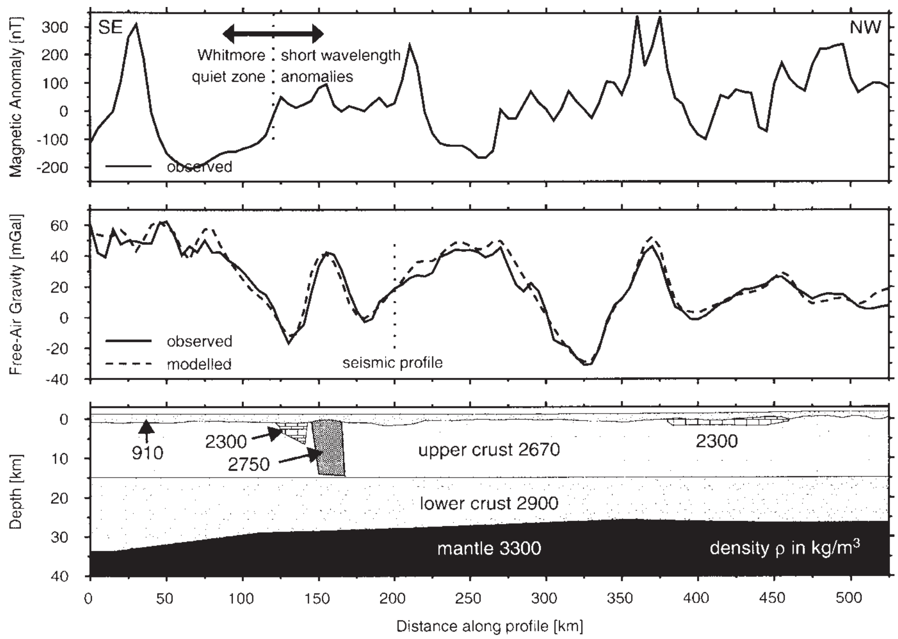

Fig. 4 Free-air gravity model. The upper panel shows the total field magnetic anomaly (not used for modelling), middle panel shows modelled and observed free-air gravity, and lower section shows the preferred density distribution.

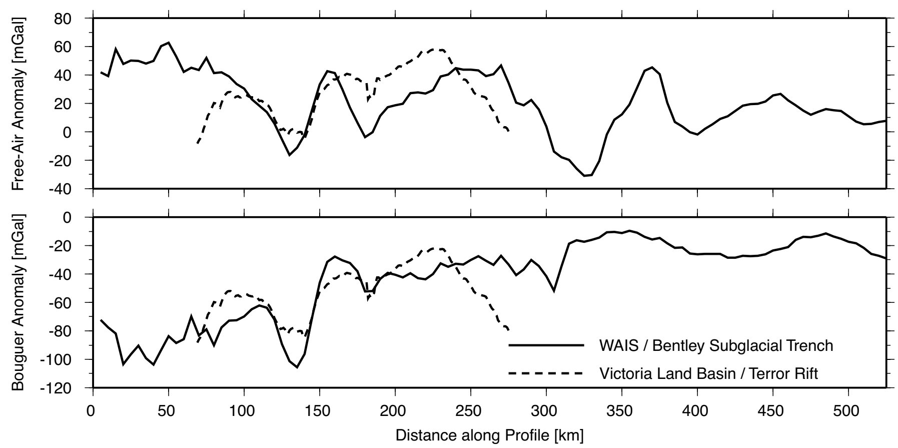

Fig. 5 Comparison of gravity data along the model with data from the Victoria Land Basin/Terror Rift (Davey & Cooper 1987).

If we assume, that the crust beneath the Whitmore Mountains (34 km) is not stretched, the β factor for the thinned area beneath the Bentley Subglacial Trench (26 km) is $\beta = 1.3$ (β = initial crustal thickness/present crustal thickness without sediment cover). Since our survey area covers only the edge of the Whitmore Mountains block, we cannot rule out the possibility that the crustal thickness increases towards the interior of the Whitmore Mountains; thus, the β estimation represents a lower boundary for the amount of extension. However, this crustal stretching is significantly lower than the crustal stretching in the Ross Sea portion ($1.6 < \beta < 4.0$) of the West Antarctic Rift System (Trey et al. 1999).

Sedimentary basins

The sedimentary basins along the rift shoulder can be compared to extensional structures in the Ross Sea. Along the Transantarctic Mountains, the Victoria Land Basin and the Terror Rift mark the major depocentres close to the rift shoulder (e.g., Cooper et al. 1987). Figure 5 shows a comparison of our gravity profile with data from Davey & Cooper (1987) across the Victoria Land Basin/Terror Rift. The Terror Rift corresponds to the low in free-air and Bouguer gravity between kilometre 120 and 150 (dashed curves, Fig. 5). The Terror Rift gravity structure coincides well with the gravity anomaly observed across the sedimentary basins close to the Whitmore Mountains block (solid lines, Fig. 5). The estimated thickness of the Terror Rift basin from Cooper et al. (1987) and the sedimentary basin close to the Whitmore Mountains are comparable (c. 5 km).

The major early rift basins in the Ross Sea, such as the Victoria Land Basin, generally show positive gravity anomalies despite several kilometres of low-density infill. In contrast, narrow, reactivated Cenozoic structures, such as the Terror Rift, are associated with negative gravity anomalies (e.g., Davey & Cooper 1987). The weak, positive Bouguer gravity anomaly associated with the Bentley Subglacial Trench might represent such an early rift structure (kilometre 330–375 in Fig. 5). If the geological history in our survey region is similar to the Ross Sea, a similar origin for the Bentley Subglacial Trench and a Cenozoic reactivation for the basins close to the Whitmore Mountains is possible. Furthermore the proposed en echelon origin within a Cenozoic right-lateral strike-slip stress pattern for the sedimentary basin near Siple Dome (Fig. 2) and the corresponding gravity low suggest a Cenozoic activation for this basin.

Although the similarity between the Victoria Land Basin/ Terror Rift and the basins close to the Whitmore Mountains in gravity signature is strong, differences include a generally higher crustal thickness beneath the West Antarctic Ice Sheet basins and a missing of significant sedimentary infill in the Bentley Subglacial Trench. We cannot rule out the possibility of a sedimentary infill into the Bentley Subglacial Trench, since the gravity modelling of crustal thinning associated with an overlying sedimentary basin is not well constrained for longer wavelength anomalies.

CONCLUSIONS

Aerogeophysical data have been used to compile a complete Bouguer anomaly map and to reveal the little-known crustal architecture of a major portion of the West Antarctic Rift System. Three major crustal segments are defined. The Whitmore Mountains crustal block, a segment of transitional crust between the Whitmore Mountains and the Bentley Subglacial Trench, and a unit of stretched crust towards the rift centre. The crustal thickness has been estimated from power spectral analysis and forward modelling of the gravity data. Beneath the Whitmore Mountains, a crustal thickness of 34 km has been estimated, which thins to 26 km beneath the Bentley Subglacial Trench. The lower boundary for the amount of extension has been estimated to $\beta = 1.3$. The influence of rifting for the crustal evolution seems to be weaker in the region between Marie Byrd Land and the Whitmore Mountains than in the Ross Sea.

Similarities in the signature of the gravity anomalies and models between the Victoria Land Basin in the Ross Sea and the Bentley Subglacial Trench in our study area, possibly suggest a similar origin. The narrow basins along the rift shoulder close to the Whitmore Mountains block might have been reactivated during regional Cenozoic right-lateral strike-slip movements as well as the proposed en echelon sedimentary basin near Siple Dome.

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