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Tectonic models for the Late Cretaceous/Tertiary evolution of the West Antarctic Rift System range from hundreds of kilometres of extension to negligible strike-slip displacement and are based on a variety of observations, as well as kinematic and geodynamic models. Most data constraining these models originate from the Ross Sea/Adare Trough area and the Transantarctic Mountains. We use a new Antarctic continental crustal-thinning grid, combined with a revised plate-kinematic model based on East Antarctic – Australia – Pacific – West Antarctic plate circuit closure, to trace the geometry and extensional style of the Eocene – Oligocene West Antarctic Rift from the Ross Sea to the South Shetland Trench. The combined data suggest that from chron 21 (48 Ma) to chron 8 (26 Ma), the West Antarctic Rift System was characterised by extension in the west to dextral strike-slip in the east, where it was connected to the Pacific – Phoenix – East Antarctic triple junction via the Byrd Subglacial Basin and the Bentley Subglacial Trench, interpreted as pullapart basins. Seismic-reflection profiles crossing the De Gerlache Gravity Anomaly, a tectonic scar from a former spreading ridge jump in the Bellingshausen Sea, suggest Late Tertiary reactivation in a dextral strike-slip mode. This is supported by seismic-reflection profiles crossing the De Gerlache Gravity Anomaly in the Bellingshausen Sea, which show incised narrow sediment troughs and vertical faults indicating strike-slip movement along a north – south direction. Using pre-48 Ma plate circuit closure, we test the hypothesis that the Lord Howe Rise was attached to the Pacific Plate during the opening of the Tasman Sea. We show that this plate geometry may be plausible at least between 74 and 48 Ma, but further work especially on Australian – Antarctic relative plate motions is required to test this hypothesis.

KEY WORDS: Antarctica, crustal stretching, crustal thickness, plate kinematics, rift system.

INTRODUCTION

Understanding the Cenozoic tectonic history of Antarctica is crucial for global plate circuit closure during this time. In turn, the closure of the plate circuit between the Pacific Plate and the plates surrounding the Atlantic and Indian Oceans is required to construct correct global relative and absolute plate motion models. Based on a mantle convection model constrained by a plate-kinematic model, Steinberger *et al.* (2004) recently proposed that the bend in the Hawaiian – Emperor chain can be modelled best if the Pacific Plate is fixed to the Lord Howe Rise before about 43 Ma and back to 83 Ma. This model is intriguing in the context that arc magmatism is unknown in the period after the cessation of subduction along the eastern Gondwanaland margin at around 100 Ma [111 – 108 Ma in Fiordland, New Zealand (Scott & Copper 2006)] and before 50 Ma (Finn *et al.* 2005). This suggests an absence of subduction during this time period, but the kinematics of the area north of New Zealand have alternatively been modelled as characterised by ongoing subduction before 50 Ma (Sdrolias *et al.* 2003; Schellart *et al.* 2006), mainly based on plate circuit closure arguments. In Steinberger *et al.*'s (2004) scenario, the Tasman Sea would have opened simply reflecting Pacific – Australian plate divergence during that time, without any plate boundary between the Lord Howe Rise and the Pacific Plate. However, the rotations used by Steinberger *et al.* (2004) imply substantial displacement (namely compression) between East and West Antarctica for the time period between 83 and 52 Ma, while the Tasman Sea was opening, putting this model into question. Here we investigate the viability of this model via plate circuit closure, testing alternative rotations for Australia – Antarctica separation during the Late Cretaceous/Early Tertiary.

The primary evidence for Tertiary extension between East and West Antarctica is found in the Adare Trough, located 100 km northeast of Cape Adare. It represents the extinct third arm of a Tertiary spreading ridge system near a triple junction that separated East and West Antarctica between 43 Ma and 28–26 Ma (Cande *et al.* 2000). Recently, Cande & Stock (2005) extended this period of extension back to 61 Ma (Chron 27), based on additional magnetic and bathymetric data from the area northeast of the Adare Trough, resulting in a total of about 200 km separation between East and West Antarctica in the northern Ross Sea region in the Cenozoic. This model is generally supported by the stratigraphy and fault orientations of drillcores from the western Ross Sea suggesting Oligocene to mid-Miocene extension in the Ross Sea (Cape Roberts Science Team 1998, 1999, 2000). However, the idea of any substantial Cenozoic extension between East and West Antarctica is not universally accepted. Siddoway *et al.* (2004) and Walcott (1998) argued that the lack of geological evidence for large Cenozoic faults does not support large-magnitude, regional extension in much of the region. According to Rocchi *et al.* (2003) and Wilson (1995), the Transantarctic Mountains front, as well as offshore faults and fractures, identify a stress regime compatible with regional Late Cenozoic, but not Early Cenozoic, dextral transtension. There is no published geological or geophysical evidence that deformation between East and West Antarctica may have occurred before 61 Ma, other than the model implications of Steinberger *et al.* (2004).

Our objective is to test these competing models first by using a new crustal thickness and a published sediment-thickness grid for Antarctica to compute rough estimates of crustal stretching factors and to outline the most likely geometry and rift axis of the West Antarctic Rift System from the Ross Sea to the Bellingshausen Sea to the De Gerlache Gravity Anomaly (Figures 1a, 2). We use published plate-kinematic models (Cande *et al.* 1995, 2000; Royer & Rollet 1997; Gaina *et al.* 1998; Larter *et al.* 2002; Keller 2004; Cande & Stock 2005) to compute the predicted relative motion along the axis of the East–West Antarctic plate boundary back to chron 34 (83 Ma), testing the hypothesis that the Pacific Plate was fixed to the Lord Howe Rise before 43 Ma (Steinberger *et al.* 2004) and taking into account two alternative (Royer & Rollet 1997; Tikku & Cande 1999) rotation models for the pre-chron 24 separation between Australia and Antarctica. We utilise seismic-reflection profiles across the inferred East–West Antarctic plate boundary location in the Bellingshausen Sea to test the implications of competing kinematic models for this area.

ANTARCTIC CRUSTAL AND SEDIMENT THICKNESS

Early estimates of crustal thickness in Antarctica were obtained from surface-wave-dispersion studies (Evison *et al.* 1959; Kovach & Press 1961), as well as an analysis that combined the dispersion data with West Antarctic gravity data (Bentley & Ostenso 1962). Regional crustal thickness variations have also been obtained by deep seismic-refraction profiles (Kogan 1972; Ito & Ikami 1986; Trey *et al.* 1999; Leitchenkov & Kudryavtzev 2000; Bannister *et al.* 2003). Segawa *et al.* (1986) analysed the gradients of the power spectrum of Bouguer gravity anomalies that were determined from mean free-air anomaly estimates, whereas Groushinsky & Sazhina (1982) used a linear relation between Moho depths and mean Bouguer gravity anomalies. Von Frese *et al.* (1999) investigated the use of enhanced spectral correlation theory for modelling the crustal features of the Antarctic from regional observations of gravity and terrain, whereas Ritzwoller *et al.* (2001) produced a new model of the crust and upper mantle beneath Antarctica by using a large, new dataset of fundamental mode surface-wave dispersion measurements.

For this study, we compute the Antarctic continental crustal thickness by using an empirical dependence between crustal thickness and topography of solid cover (Demenitskaya 1975):

$$H = 33 \times th\,(0.38 \times Dh - 0.18) + 38$$

where Dh is surface elevation in kilometres (positive on land, negative offshore), and th is hyperbolic tangent.

To estimate bedrock topography for our purposes, we used the BEDMAP grids (at 5 km intervals) (<http://www.nerc-bas.ac.uk/public/aedc/bedmap/>) with information about the bedrock topography and ice thickness (Lythe *et al.* 2000). Total errors of about 1–5% (radar data) and 3% (seismic data) on the related ice thickness determinations suggest that the results in Figure 1 may involve uncertainties of roughly 0.04 km for typical thickness values to possibly as much as 0.12–0.15 km for the thickest ice estimates. The result of this application provides a unique view of the Antarctic crust that is consistent with our current understanding of the region's terrain and that can be tested against the results of other crustal investigations.

We utilise the calculation of 'effective topography' to account for the effect of ice cover in Antarctica. One-third of the ice thickness (the density of ice is $\sim 1/3$ of standard upper continental crust density of 2.67 g/cm^3) is added to bedrock topography resulting in an estimate of 'effective topography'. That value is then used as Dh in the formula of Demenitskaya (1975) at each calculation point to derive a new crustal thickness grid (Figure 1b). Comparison of these results with post-1975 seismic estimates of crustal thickness in Antarctica shows that the accuracy of crustal thickness estimates derived by this method is within ± 5 km. We are aware of Zoback & Mooney's (2003) global analysis of topography and crustal thickness, suggesting that a wide range of crustal thicknesses between 25 and 55 km can be associated with topography at or close to sea-level. Our simple approach for estimating crustal thickness is therefore mainly useful for delineating rifted continental crust < 25 km thick, representing our main objective. A comparison of our crustal thickness estimates for Marie Byrd Land with those by Winberry & Anandakrishnan (2004) demonstrates that our model results compare well with crustal thickness estimates from broadband seismic experiments in West Antarctica.
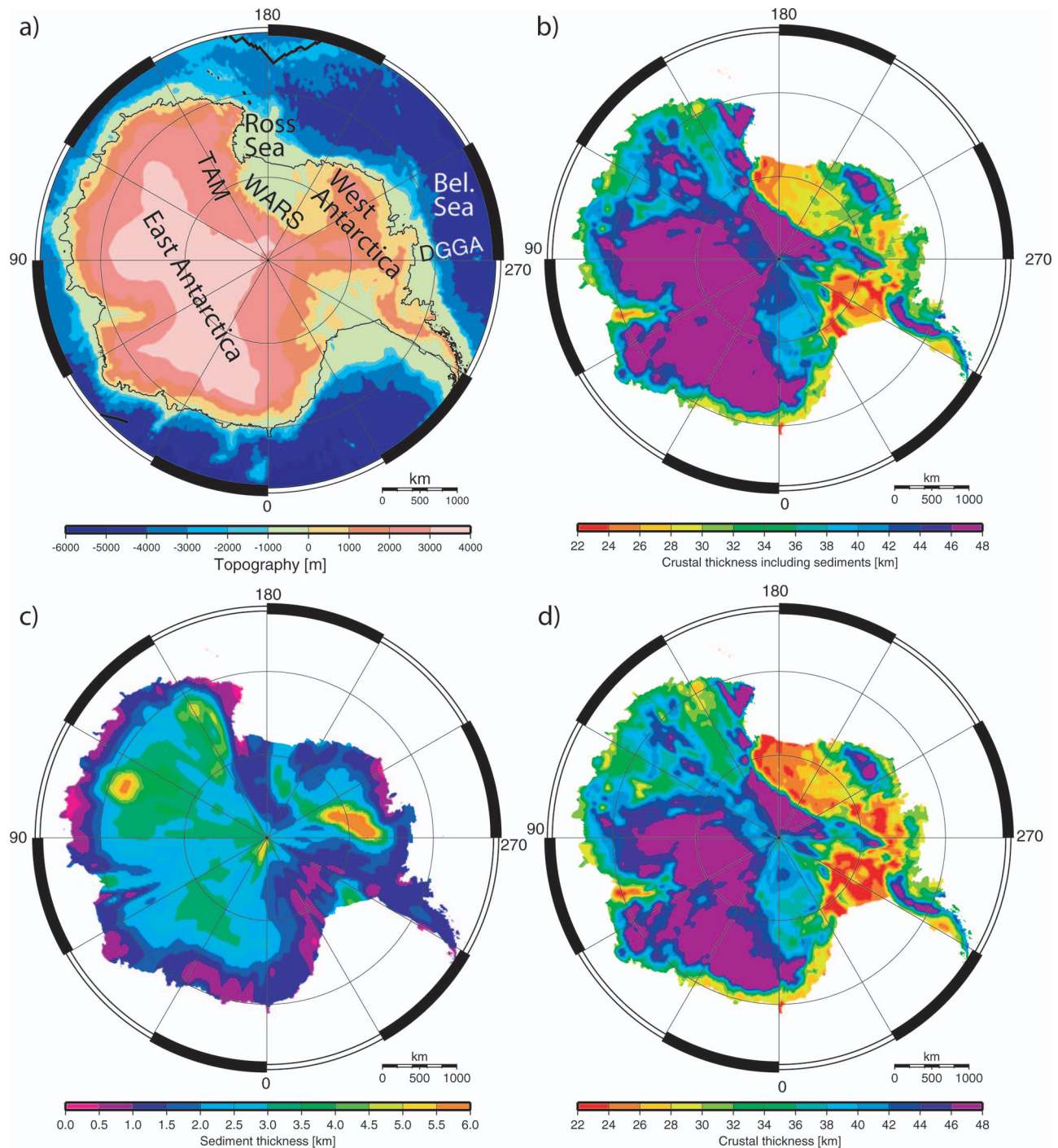
Figure 1 (a) Circum Antarctic bathymetry/topography (WARS, West Antarctic Rift System; DGGA, De Gerlache Gravity Anomaly; TAM, Transantarctic Mountains). (b) Crustal thickness, including sediment thickness. (c) Sediment thickness from CRUST5.2 model. (d) Crustal thickness without sediments derived by subtracting grid (c) from grid (b).

In order to outline the geometry of the West Antarctic Rift System, an estimate of crustal stretching is useful. For this purpose, we need to remove the sediment thickness from the grid shown in Figure 1b. The best available Antarctic sediment-thickness grid is that as part of the CRUST5.2 dataset (Figure 1c), superseding CRUST5.1 (Mooney *et al.* 1998). Figure 1c illustrates that this dataset includes some artefacts such as a questionable general thinning of the sedi-

mentary cover from Antarctica's interior towards its coast. However, despite its shortcomings, we prefer to use this dataset to compute crustal thickness without sediments in order to obtain a crustal stretching factor estimate, as the only alternative would be to use crustal thickness including all sediments (Figure 1b) for this purpose. The latter method would without doubt result in a substantially more inaccurate estimate for crustal stretching.
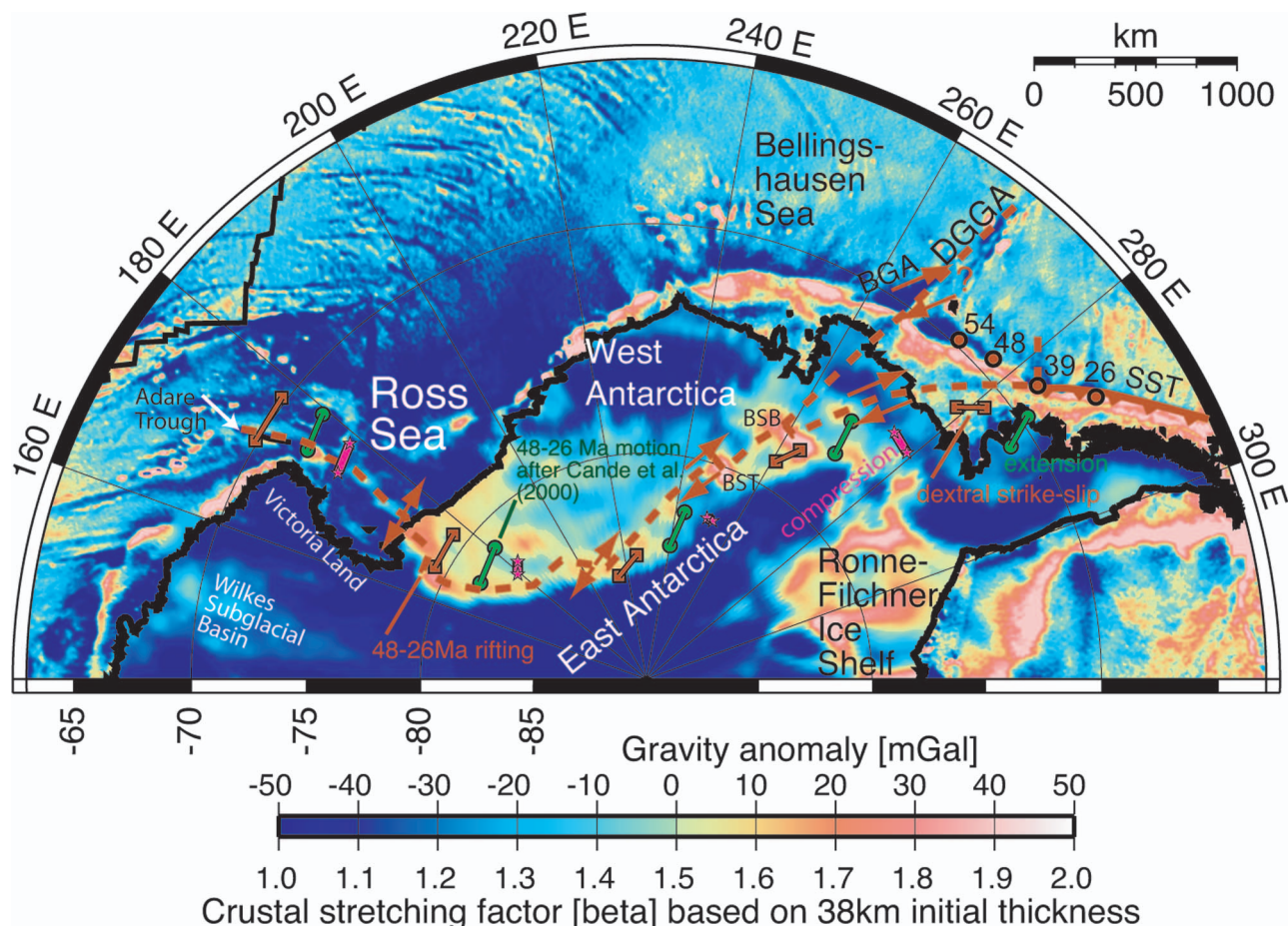
Figure 2 Crustal stretching factor (beta) of Antarctic continental crust assuming initial crustal thickness of 38 km (global average crustal thickness for unthinned plateau-type crust) landward of coastline, based on crustal thickness grid from Figure 1d, combined with marine free-air gravity from satellite altimetry seaward of coastline (McAdoo & Laxon 1997). The combined grid highlights the continuity of tectonic features from onshore Antarctica to offshore areas. Red dashed line corresponds to interpreted West Antarctic Rift System axis, based on locations of crustal stretching maxima and our plate-kinematic model. Predicted relative plate-motion vectors between East and West Antarctica between chron 21 (48 Ma) and chron 8 (26 Ma) are shown based on rotations in Table 1: red lines with diamonds correspond to the model suggested in this paper (pole at 71.1°S, 22.8°W), whereas green lines with circles correspond to stage pole by Cande *et al.* (2000) and magenta lines with stars correspond to stage pole by Davey *et al.* (2006) (see Table 1). BGA, Bellingshausen Gravity Anomaly; BSB, Byrd Subglacial Basin; BST, Bentley Subglacial Trench; DGGA, De Gerlache Gravity Anomaly; SST, South Shetland Trench; TU, Thurston Island. Note that all three models predict extension in the Ross Sea area, but the model from Cande *et al.* (2000) (green) predicts extension for the entire rift system, whereas Davey *et al.*'s (2006) model (magenta) predicts compression southeast of the DGGA, and our model (red) predicts right lateral strike-slip along the eastern branch of the rift system. Plate-motion arrows with arrowheads are symbolic for illustrating direction of motion based on our preferred rotation model (red). The red circles with black outlines and associated numbers indicate the times (in Ma) and locations of a triple junction between Phoenix Plate, Pacific Plate and West Antarctica which migrated from west to east as a result of the ridge–trench collision along the Bellingshausen Sea margin of the Antarctic Peninsula (Eagles *et al.* 2004).

We subtract the CRUST5.2 sediment-thickness grid (Figure 1c) from the crustal-thickness grid shown in Figure 1b to derive a crustal-thickness grid without sediments (Figure 1d). This grid clearly outlines the thinned crust associated with the West Antarctic Rift System, as well as crustal-thickness lows associated with several known subglacial basins (Figures 2, 3). Assuming an initial crustal thickness of 38 km, corresponding to the global average crustal thickness for unthinned plateau-type crust from Mooney *et al.* (1998), we compute a grid for the Antarctic crustal stretching factor (beta), combined with marine free-air gravity from satellite altimetry seaward of coastline to high-light the continuity of tectonic features from onshore Antarctica to offshore areas (Figure 2). The assumption of an initial thickness of 38 km introduces another uncertainty into the computed beta stretching factors, as the initial crustal thickness of the West Antarctic Rift System is unknown. It may well have been <38 km. For this reason, as well as other uncertainties in deriving the crustal thickness grid described above, we do not consider our beta factor grid to be of sufficient fidelity to test different kinematic models quantitatively in terms of their predictions for the amount of stretching along the West Antarctic Rift System.
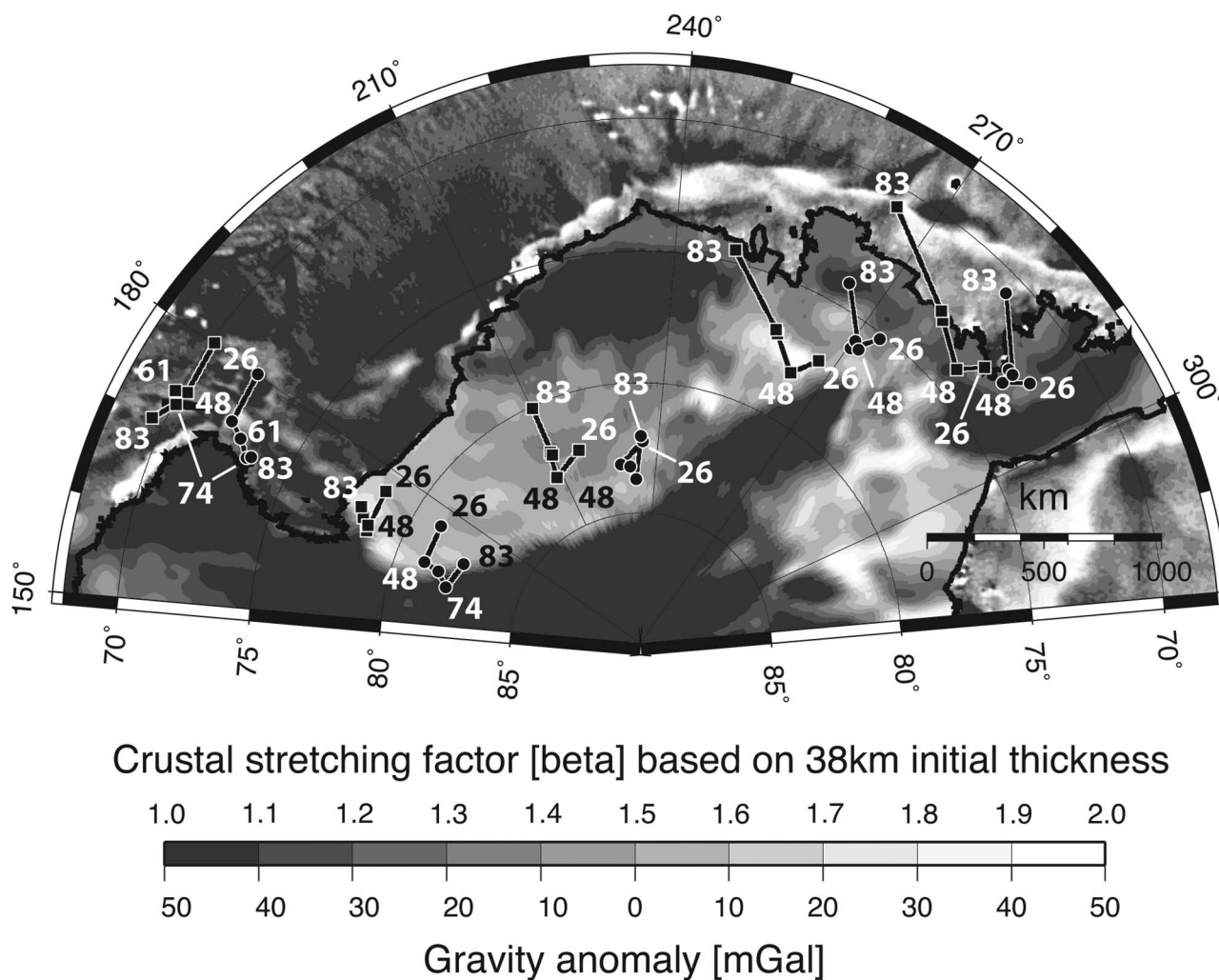
Figure 3 Predicted relative plate motions of West Antarctica relative to East Antarctica within the West Antarctic Rift System from 83 to 26 Ma, based on keeping the Pacific Plate fixed to the Lord Howe Rise between 83 and 52 Ma, as suggested by Steinberger *et al*. (2004), and using two alternative models for relative motion between Australia and Antarctica. Squares and circles for plate motion paths are always plotted for times 83, 74, 51, 48 and 26 Ma. Model 1 (squares) is based on rotations from Cande *et al*. (1995, 2000), Gaina *et al*. (1998), Tikku & Cande (2000), Larter *et al*. (2002), and Keller (2004) (see Table 1), whereas model 2 (circles) is based on the same rotations as model 1 with the exception of the rotations between Australia and Antarctica from chron 27 (61.1 Ma) to chron 34 (83.5 Ma) which are taken from Royer & Rollet (1997). Plate-motion vectors are overlain over combined crustal stretching and gravity anomaly grid as in Figure 2. See text for discussion.

We locate the axis of the West Antarctic Rift System by following crustal stretching maxima, starting with the known location of extension in the Adare Trough at the well-mapped northwestern extension of the rift system (Figure 2). To the southeast, the rift axis follows the edge of the Transantarctic Mountains (Figure 2) until it is offset by a transform fault connecting it to the Bentley Subglacial Trough (Figure 2), which we interpret as part of the rift centre. A second transform fault connects the extinct rift system to the Byrd Subglacial Basin (Figure 2). In this model, both the Bentley Subglacial Trough and the Byrd Subglacial Basin are predicted to have formed as pullapart basins at right-lateral offsets of the plate boundary, which continues east towards the Antarctic Peninsula where it connects with the South Shetland Trench (Figure 2).

MODELLED KINEMATICS BETWEEN EAST AND WEST ANTARCTICA

After outlining the likely location and geometry of the West Antarctic Rift System, we compute the predicted relative motion through time between East and West Antarctica, based on keeping the Pacific Plate fixed to the Lord Howe Rise between 83 and 52 Ma, as suggested by Steinberger *et al*. (2004), and using two alternative models for relative motion between Australia and Antarctica (2005) (Figure 3). Pacific–West Antarctic rotations are well established based on Cande *et al*. (1995) and Larter *et al*. (2002), as well as Lord Howe Rise–Australia rotations (Gaina *et al*. 1998). Recently, Keller (2004) computed Australia–Pacific rotations for the time period between chrons 21 and 8 (*ca* 48–26 Ma). Here we use a plate circuit closure approach, including

Keller's (2004) rotations, to estimate a revised rotation between East and West Antarctica for *ca* 48–26 Ma (Table 1). This preliminary rotation (71.1°S, 22.80°W, rotation angle 3.43°) slightly overestimates the amount of extension in the Adare Trough area, as compared with the magnetic lineations mapped by Cande *et al.* (2000), but results in a more geologically reasonable tectonic regime for the West Antarctic Rift System, indicating strike-slip instead of extension along the eastern portion of the rift system, where little crustal thinning is suggested by our crustal extension map (Figure 2).

The main uncertainty in closing this plate circuit, besides uncertainties in relative motion between the Pacific Plate and the Lord Howe Rise, and in East–West Antarctic motion, is the relative motion history between Australia and Antarctica before 52 Ma. Tikku & Cande (1999) raised and discussed the question whether or not the oldest magnetic anomalies between the two plates actually represent isochrons, and the early opening history between this plate pair is substantially different comparing the rotations from Tikku & Cande (1999) with those of Royer & Rollet (1997). Following Steinberger *et al.*'s (2004) hypothesis, in terms of fixing the Pacific Plate to the Lord Howe Rise between 83 and 52 Ma, we compute the resulting relative motion between East and West Antarctica based on Tikku & Cande's (1999) and alternatively on Royer & Rollet's (1997) rotations. Uncertainties of all combined rotations are currently impossible to compute, because the magnetic anomalies in the ocean basins involved have not been identified based on the same chrons, prohibiting the quantitative addition of coeval rotations for plate circuit closure.

Nevertheless, both models result in a plausible relative motion history dominated by extension/transtension in the Ross Sea, but model 1, based on Tikku & Cande's (1999) model, results in severe compression between East and West Antarctica before 48 Ma along the Transantarctic Mountains, increasing eastwards, for which there is no geological evidence (Figure 3). In contrast, model 2, using Royer & Rollet's (1997) rotations, results in negligible relative motion between 74 and 48 Ma along the eastern portion of the rift system. Reconstructions between 74 and 83 Ma are ill-constrained for nearly all plates involved in plate circuit closure, resulting in unreasonable compression for all plate pairs, but model 2 minimises relative motion in this area. Both models also result in compression increasing eastwards to 300–400 km between 83 and 74 Ma in the Antarctic peninsula, for which there is clearly no evidence. Model 1 (squares) gives smaller 74–48 Ma relative motion along the Transantarctic Mountains, whereas model 2 predicts extension from 74 to 48 Ma along the Transantarctic Mountains (Figure 3).

An alternative rotation between East and West Antarctica for the time period between about 45 and 26 Ma has recently been proposed by Davey *et al.* (2006), based on using the constraint of the amount of extension in the Victoria Land Basin in addition to marine magnetic anomalies and fracture zones. The combined constraints result in a best-fit rotation pole at 84.85°S, 139.37°W and a rotation angle of 4.82° (Table 1). This pole is located close to the geographic south pole, within the large 95% error ellipse of the earlier rotation computed by Cande *et al.* (2000). Even though this rotation satisfies the constraints of the Adare Trough magnetic lineations and the assumed Victoria Land extension [modelled to be 95 km based on gravity modelling (Davey & De Santis 2005), although the exact age and amount of this extension are subject to some uncertainty], it results in compression within a substantial portion of Antarctica east of this rotation pole, irrespective of exactly where the plate boundary would have been located. Evidence for such compression does not exist, but depending on the uncertainties assigned to the Victoria Land Basin extension, a 95% error ellipse for this rotation can be obtained that allows for a pole location close to the southernmost South Atlantic, potentially removing the need for compression within Antarctica during this time period in the model of Davey *et al.* (2006). However, the further this rotation pole is moved into the South Atlantic, the larger the amount of extension required for the Victoria Land Basin (as the colatitude between the rotation pole and the basin increases).

EVIDENCE FOR TECTONIC ACTIVITY ACROSS THE DE GERLACHE GRAVITY ANOMALY

As the geometries of the eastern West Antarctic Rift System seem to be aligned with prominent gravity anomalies in the Bellingshausen Sea (Figure 2), we search for structural connections between West Antarctic Rift System and the tectonics of this area. This system of gravity anomaly lineations is aligned in direct northward prolongation of the eastern West Antarctic Rift System axis through the Bentley Subglacial Trough and the Byrd Subglacial Basin (Figure 2). Geophysical data and detailed plate-kinematic reconstructions have shown that these lineations are primarily associated with the eastern boundary of the former Bellingshausen Plate and tectonic events resulting from a plate reorganisation in the South Pacific around chron C27o (61 Ma) (Larter *et al.* 2002; Eagles 2004). The Bellingshausen Plate existed from about 80 to 61 Ma with a strike-slip and transpressional eastern plate boundary at the location of the Bellingshausen Gravity Anomaly (Figures 2, 4). Gravity and seismic data show that the Bellingshausen Gravity Anomaly extends across the continental slope and shelf northeast of Thurston Island. Analyses of these data also provide evidence for crustal convergence across this boundary (Gohl *et al.* 1997; Cunningham *et al.* 2002), and plate-kinematic modelling suggests up to 200 km of crustal shortening between 80 and 61 Ma (Eagles 2004).

The De Gerlache Gravity Anomaly system stretches from Peter I Island northward across the De Gerlache Seamounts (Figure 4) and fades away north of 62°S. A possible low-amplitude continuation may be correlated along longitude 270°E from 55° to 59°S. Seismic data have shown that the De Gerlache Gravity Anomaly south of 62°S is caused by a north–south-trending system of single and subparallel basement ridges (Hagen *et al.* 1998; Cunningham *et al.* 2002) (Figure 5). A clear crustal

Table 1 Finite rotations used to compute Marie Byrd Land—East Antarctica stage rotation (bold) from plate circuit closure based on references 1–8. Published alternative stage rotations for Marie Byrd Land relative to East Antarctica (italics) from references 4 and 9.

Moving plate	Fixed plate	Age (Ma)	Chron	Latitude (°)	Longitude (°)	Angle (°)	Reference
AUS	ANT	26.55	8o	13.80	33.56	−15.92	1
AUS	ANT	47.9	21o	14.00	33.34	−24.70	1
AUS	ANT	61.1	27o	9.95	36.52	−25.55	1
AUS	ANT	73.6	33y	8.10	37.90	−26.25	Interpolated from 1
AUS	ANT	83.5	34	2.05	40.79	−27.12	1
AUS	ANT	61.1	27o	12.10	32.90	−25.75	Interpolated from 5
AUS	ANT	73.6	33y	11.27	33.08	−26.59	5
AUS	ANT	83.5	34	10.67	33.22	−27.22	5
MBL	PAC	26.0	20o	74.60	−67.30	−21.11	2
MBL	PAC	43.8	20o	74.90	−51.31	−34.54	2
MBL	PAC	47.9	21o	74.52	−50.19	−37.64	2
MBL	PAC	61.1	27o	71.38	−55.57	−44.90	2
MBL	PAC	73.6	33y	66.72	−55.04	−53.74	6
MBL	PAC	83.5	34	65.58	−52.38	−63.07	6
LHR	AUS	61.1	27o	−4.70	131.50	4.43	7
LHR	AUS	73.6	33y	−9.50	137.20	12.94	7
LHR	AUS	83.5	34	−2.70	136.40	14.60	8
PAC	LHR	26.0	8o	55.05	3.13	29.23	3
PAC	LHR	Unknown (see text)	20o–24o	−49.66	177.95	−47.86	3
MBL	ANT	61.1	27o	45.40	144.40	3.28	LHR-PAC fixed and based on rotations from 1 for Australia and Antarctica
MBL	ANT	73.6	33y	50.40	133.20	4.29	LHR-PAC fixed and based on rotations from 1 for Australia and Antarctica
MBL	ANT	83.5	34	77.60	84.50	9.48	LHR-PAC fixed and based on rotations from 1 for Australia and Antarctica
MBL	ANT	61.1	27o	57.00	145.60	3.18	LHR-PAC fixed and based on rotations from 5 for Australia and Antarctica
MBL	ANT	73.6	33y	68.00	127.80	4.65	LHR-PAC fixed and based on rotations from 5 for Australia and Antarctica
MBL	ANT	83.5	34	83.70	27.10	13.13	LHR-PAC fixed and based on rotations from 5 for Australia and Antarctica
MBL	**ANT**	**26.55–47.9**	**21o**	**−71.10**	**−22.80**	**3.43**	Stage rotation based on rotations from 1, 2, 3 (this paper)
MBL	*ANT*	*26.0–47.9*	*21o*	*−18.15*	*−17.85*	*1.70*	Stage rotation from 4
MBL	*ANT*	*26.0–47.9*	*21o*	*−84.85*	*−139.37*	*4.82*	Stage rotation from 9

1, Tikku and Cande (2000); 2, Cande *et al.* (1995); 3, Keller (2004); 4, Cande *et al.* (1995); 5, Royer and Rollet (1997); 6, Larter *et al.* (2002); 7, Gaina *et al.* (1998); 8, this paper; 9, Davey *et al.* (2006). ANT, East Antarctica; AUS, Australian Plate; LHR, Lord Howe Rise; MBL, Marie Byrd Land (West Antarctica); PAC, Pacific Plate. Positive rotation angles indicate counterclockwise motion.
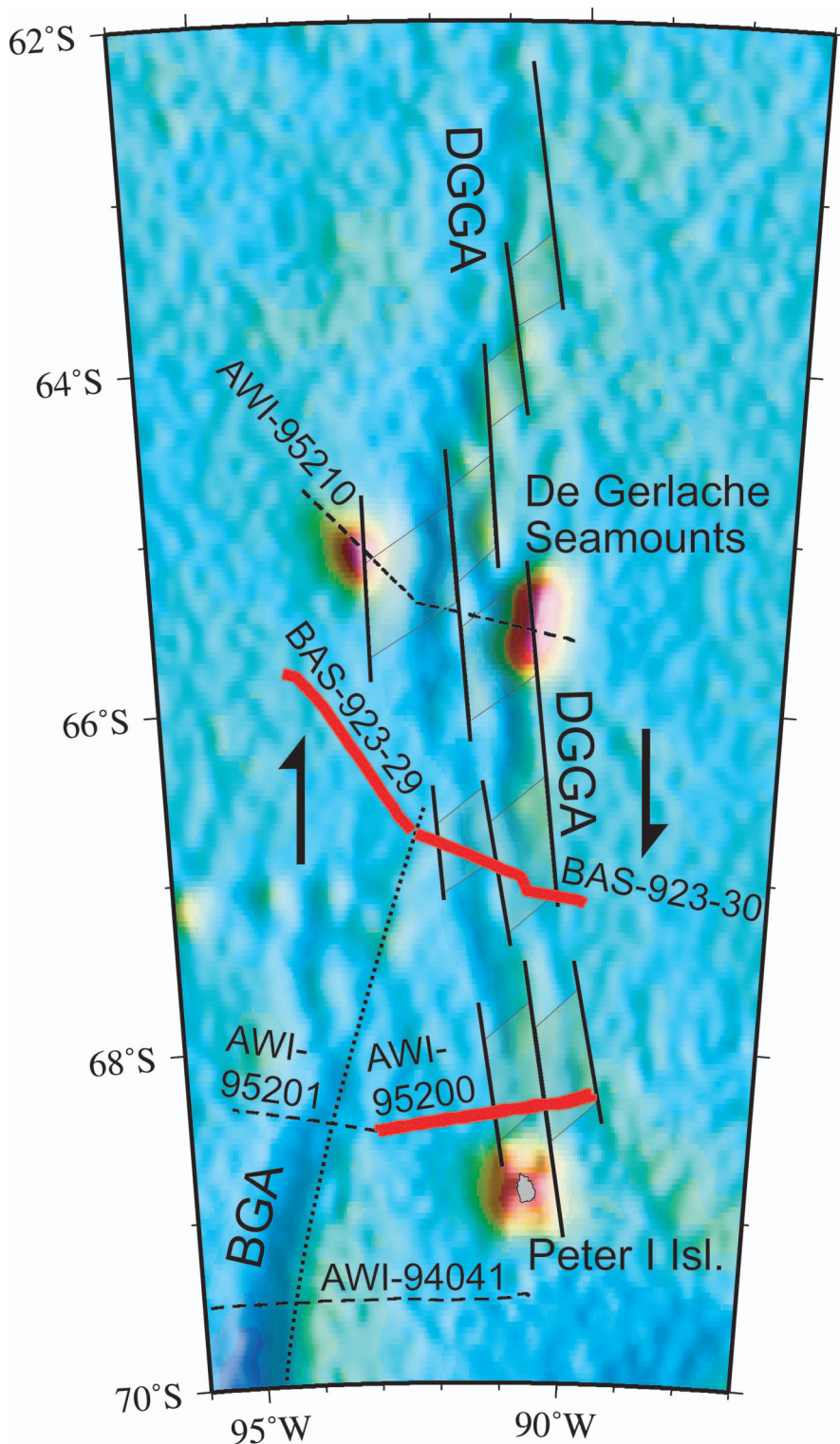
Figure 4 Satellite-derived gravity anomaly map (McAdoo & Laxon 1997) of the Bellingshausen Gravity Anomaly (BGA) and De Gerlache Gravity Anomaly (DGGA) systems of the western Bellingshausen Sea with tracks of seismic profiles (bold solid lines) used in this study and related profiles published in Gohl *et al.* (1997) and Hagen *et al.* (1998) (dashed lines). Thin solid lines and hatched areas illustrate our schematic setting of a Tertiary regime of strike-slip plate motion with near-vertical faults connected with pullapart basins along the DGGA. The dotted line marks an older lineament along the BGA from the time when this acted as the eastern oblique-convergent boundary of the Bellingshausen Plate (Eagles *et al.* 2004).

age difference across the De Gerlache Gravity Anomaly is observed from seafloor-spreading magnetic anomalies C32–34 west of it and C26–24 east of it, indicating that the gravity lineation represents the scar of a ridge jump of the Phoenix–Pacific Ridge at chron C27 (61 Ma) (Larter *et al.* 2002; Eagles 2004). Sampled volcanics along the De Gerlache Gravity Anomaly are of much younger age than the structure of the ridge jump scar. Extrusions of alkaline volcanics of the 23–20 Ma De Gerlache

Seamounts (Hagen *et al.* 1998) and the 13–0.1 Ma Peter I Island (Prestvik *et al.* 1990) suggest that the De Gerlache Gravity Anomaly has acted as a preserved zone of lithospheric weakness after the West Antarctic Rift system became extinct. Miocene to present-day mantle plume activities of the West Antarctic Rift System may have acted as the magmatic source for the volcanics.

We investigate tectonic activity along the De Gerlache Gravity Anomaly using multi-channel seismic
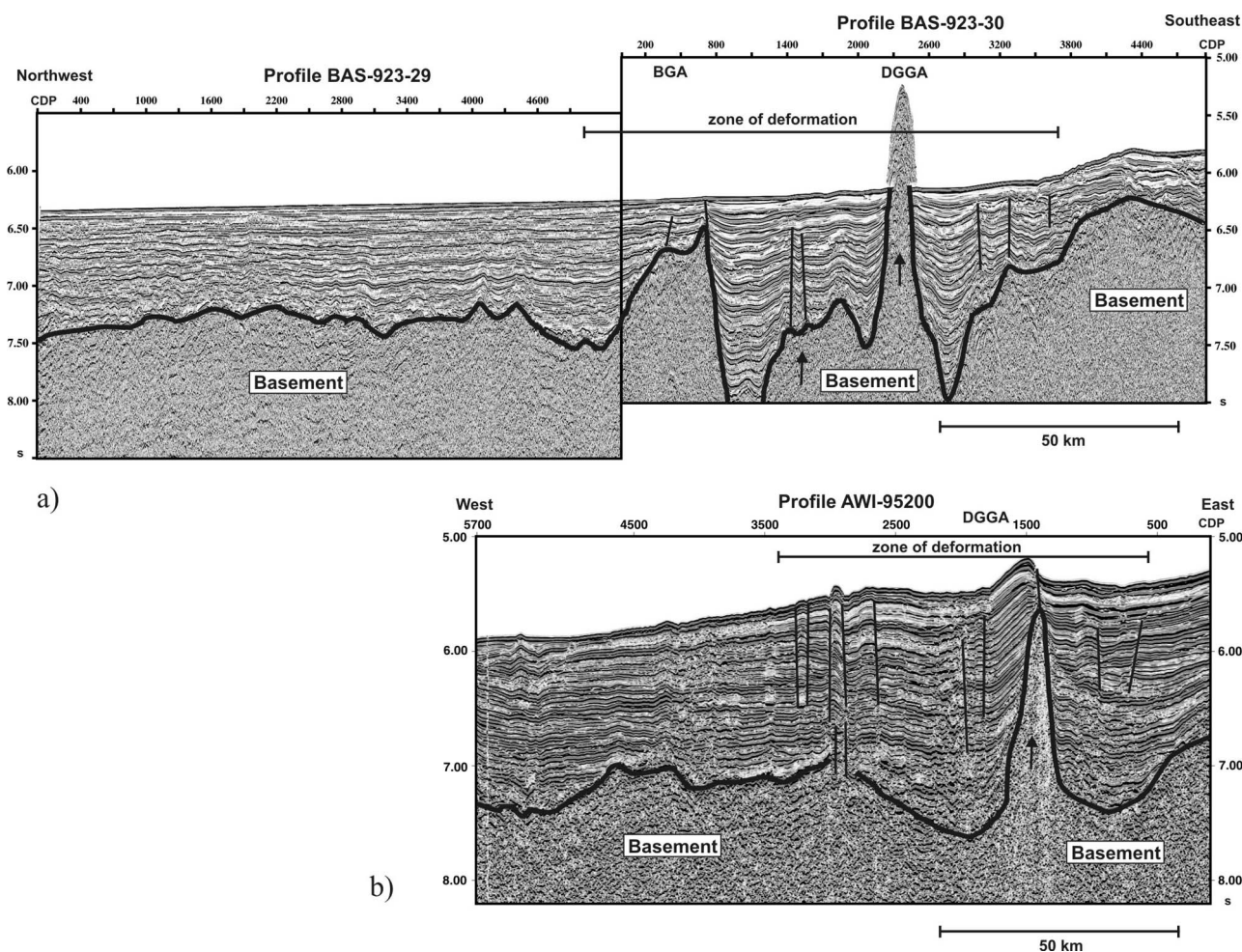
Figure 5 (a) Seismic profile BAS-923-29/30 across the tectonic lineaments under the De Gerlache Gravity Anomaly (DGGA) and the northern part of the Bellinghausen Gravity Anomaly. (b) Seismic profile AWI-95200 crosses the DGGA north of Peter I Island. Top of basement is marked with bold solid lines. Both profiles reveal a zone in which sediments are deformed by basement tectonics and the rise of volcanic cones. Vertical faults (thin solid lines) and overdeepened sediment troughs indicate transtensional deformation. See Figure 4 for locations.

profiles that cross the De Gerlache Gravity Anomaly at two locations between Peter I Island and the De Gerlache Seamounts. Profiles BAS-923-29/30 and AWI-95200 (Figure 5a, b) reveal a zone in which a strongly undulating basement is characterised by intrusions of volcanic cones or ridges under the Bellingshausen Gravity Anomaly (BAS-923-30) and De Gerlache Gravity Anomaly (both profiles). Such a north–south-oriented ridge has been imaged with multibeam data (Figure 6) and seismic profile BAS-923-30 north of Peter I Island. Although we do not have direct evidence for its origin, we can infer its volcanic origin from the observation that it is the only edifice rising above the sediments between volcanic Peter I Island and the De Gerlache Seamounts, which both display north–south-trending flanks. The multibeam image shows that the north-trending axis of this ridge has a lateral offset close to its peak. Any later lateral tectonic deformation of an elongated ridge would result in fracturing which is not observed in this case. We therefore suggest that this ridge is a result of volcanic eruption along a pre-existing orthogonal fault system in the basement.

Some of the basement peaks within the De Gerlache Gravity Anomaly correlate with near-vertical faults situated above them. These faults continue to the upper level of the widely folded sediments observed in this area. Deep narrow troughs with total sediment thicknesses of 2–3 km ($\sim$2 s TWT) are situated next to the flanks of the major basement uplifts and intrusions on profile BAS-923-29/30. The troughs observed on this profile reach about 1 km deeper than the undisturbed basement surface farther west, while the sediment troughs on profile AWI-95200 are less deep but wider. On the northern profile (Figure 5a), the sediment trough adjacent to the east of the main basement ridge is deeper than that directly adjacent to the western flank. Along the southern profile, the opposite basement geometry is observed. Almost all sedimentary sequences are dragged up along the flanks of the basement highs, except on the wide basement high at the eastern end of profile BAS-923-29/30. Here, only the deepest sediments of the trough appear to be dragged up along the basement flank, while the mid-level and shallower sequences onlap the basement. Three
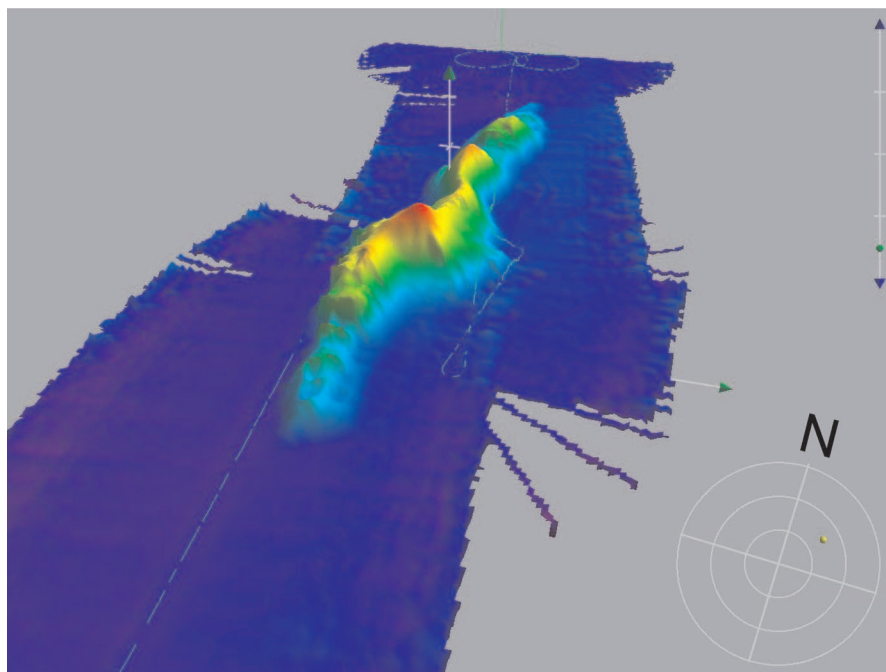
PLATE-KINEMATIC IMPLICATIONS

Plate circuit closure, together with a complete mapping of the axis of the West Antarctic Rift System from the Adare Trough to the Bellingshausen Sea, allows us to evaluate the implications of the hypothesis that the Pacific Plate was attached to the Lord Howe Rise between about 83 and 52 Ma (Steinberger *et al.* 2004), during the opening of the Tasman Sea. Given that the errors in published Pacific–Antarctic, Pacific–Bellingshausen, and Australian–Lord Howe Rise reconstructions are relatively small, we focus on the implication of two alternative Australian–Antarctic reconstructions. The Australian–Antarctic end-member reconstructions considered here represent a set of reconstructions in which the pre-chron 27 (61 Ma) Australian–Antarctic magnetic anomalies are considered as isochrons or some conjugate magnetic anomaly misfits are permitted to avoid unreasonable overlaps between continental margins during the early opening of the Great Australian Bight.

An isochron fit of the pre-chron 27 Australian–Antarctic magnetic anomaly data results in a tight fit between Tasmania and Antarctica with finite rotation poles relatively close to the Kerguelen Plateau, and in negligible motion between the Kerguelen Plateau and the Broken Ridge before chron 20 (43 Ma) (Tikku & Cande 1999, 2000; Cande & Stock 2005), whereas reconstructions which allow for some misfit between pre-chron 27 magnetic anomalies in the Great Australian Bight and offshore Antarctica result in a looser fit between Tasmania and Antarctica (Royer & Rollet 1997). Between 83 and 74 Ma, both models result in substantial compression in the eastern portion of the West Antarctic rift system, if combined with published rotations for the closure of the Tasman Sea and the Southwest Pacific (Table 1; Figure 3). There is no evidence that such an episode of crustal shortening has occurred along the West Antarctic Rift System. From 74 to 48 Ma, model 2 predicts little relative motion at the eastern branch of the rift system, compared with model 1. This implies that, using Royer & Rollet's rotations (1997), a fixed Pacific–Lord Howe Rise is conceivable during the time of Tasman Sea opening, at least after 74 Ma, without requiring an active West Antarctic Rift System.

CONCLUSIONS

Combined mapping of crustal continental extension in Antarctica and a revised plate-kinematic model allow us to estimate the geometry of the Oligocene to Miocene West Antarctic Rift System. However, the exact kinematic history of this extension is still subject to large uncertainties, as indicated by the different pole locations for the main extension period (*ca* 48–26 Ma) suggested here, by Cande *et al.* (2000) and by Davey *et al.* (2006). The model presented here results in strike-slip for the eastern extension of the plate boundary within Marie Byrd Land, instead of extension as implied by Cande *et al.*'s (2000) rotation pole. In our scenario, the eastern strike-slip portion of the West Antarctic Rift System would have connected to the South Shetland Trench via a triple junction between the Pacific,

Phoenix and East Antarctic Plates. In contrast, Davey *et al.*'s (2006) best-fit rotation pole implies compression for the eastern portion of the rift system between 48 and 26 Ma, a scenario we regard as unlikely. Seismic-reflection data suggest that the older tectonic lineaments in the Bellingshausen Sea under the De Gerlache Gravity Anomaly, and possibly the Bellingshausen Gravity Anomaly, may have been reactivated during this time in a right-lateral strike-slip sense. Using Australia–Antarctica rotations from Royer & Rollet (1997), and rotations for the remaining plate circuit as listed in Table 1, we show that it is plausible that no subduction (or other relative motion) existed between the Lord Howe Rise and the Pacific Plate at least between 74 and 48 Ma. Such a model is consistent with the complete lack of arc-volcanics from this time period in the area of the Lord Howe Rise and associated backarc basins, even though a fairly extensive sample base exists for this area (Mortimer *et al.* 1998).

Published relative plate-motion parameters are not consistent with the notion that the Pacific Plate was fixed to the Lord Howe Rise before 74 Ma. The implied episode of shortening between East and West Antarctica is unlikely, meaning either that a plate boundary still existed at that time between the Pacific Plate and the Lord Howe Rise, or that one or several of the published rotations involved for Chron 34 are associated with large errors. This may indicate problems with Tikku & Cande's (1999) Australian–Antarctic fit for chrons 31–34, or it may indicate that a plate boundary still existed before 74 Ma between the Pacific Plate and the Lord Howe Rise, continuing through New Zealand, where some deformation during this time period is suggested by geological data (Sutherland 1999). A more robust method for computing a better-constrained Australia–Antarctic fit for this time would be triple-junction closure, simultaneously fitting data for chrons 31, 33 and 34 between Australia, Antarctic and India. Tikku & Cande's (1999) rotations for this time period, if combined with published rotations for India–Antarctica, result in flow-lines for the Wharton Basin west of Australia which deviate from the fracture zone azimuths in this area, which are well mapped from the marine gravity field derived from satellite altimetry (Sandwell & Smith 1997). Therefore, revised Indian Ocean reconstructions using triple-junction closure, and including uncertainties, will be an essential next step to further test whether a self-consistent plate circuit closure before chron 31 (74 Ma) is possible while fixing the Pacific Plate to the Lord Howe Rise.

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