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Development of the Australian-Antarctic depth anomaly

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[1] The oceanic Australian-Antarctic Discordance (AAD) contains two unusual features: (1) N–S trending anomalously deep bathymetries and (2) rough basement morphologies in young (<~20 Ma) crust between 120°E and 128°E. Models generally attribute AAD formation to underlying cold and/or depleted upper mantle, but no model adequately accounts for all the anomalous attributes. We quantify anomalous basement roughness and basement depths utilizing new seismic reflection data, in combination with all available geophysical and geological observations. We find that the interaction of negative dynamic topography and crustal thickness variations results in the observed complex patterns of residual basement depths. Downwelling, caused by a sinking Mesozoic slab, is the most likely cause of the broad N–S trending residual depth anomalies, while overprinting by westward flowing, buoyant Pacific mantle resulted in the distinctive V-shaped eastern boundary of the AAD. The particularly large residual depths proximal to the Australian and Antarctic margins may be due to negative dynamic topography combined with thinned oceanic crust caused by ultraslow (<10 mm/yr) half-spreading rates and sampling of depleted subduction wedge contaminated mantle. Only oceanic basement aged <20 Ma is anomalously rough, a result of sampling of cool/depleted upper mantle material. Although oceanic crust older than 43 Ma may have sampled depleted mantle, the resulting oceanic basement is not anomalously rough likely because a melt volume controlled threshold of accretion-related roughness had already been reached due to ultraslow spreading rates. Our analysis reveals that the enigmatic roughness of the Diamantina Zone is mainly related to >45° spreading obliquities.

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1. Introduction

[2] The Southern Ocean between Australia and Antarctica encompasses a large swath of anomalously deep oceanic basement, which defines the extent of the AAD. The best way to view the extent of this unusual bathymetry is through maps of residual depth anomaly where normal ocean-lithospheric subsidence and sediment loading are removed from observed bathymetry [e.g., *Crough*, 1983]. In the

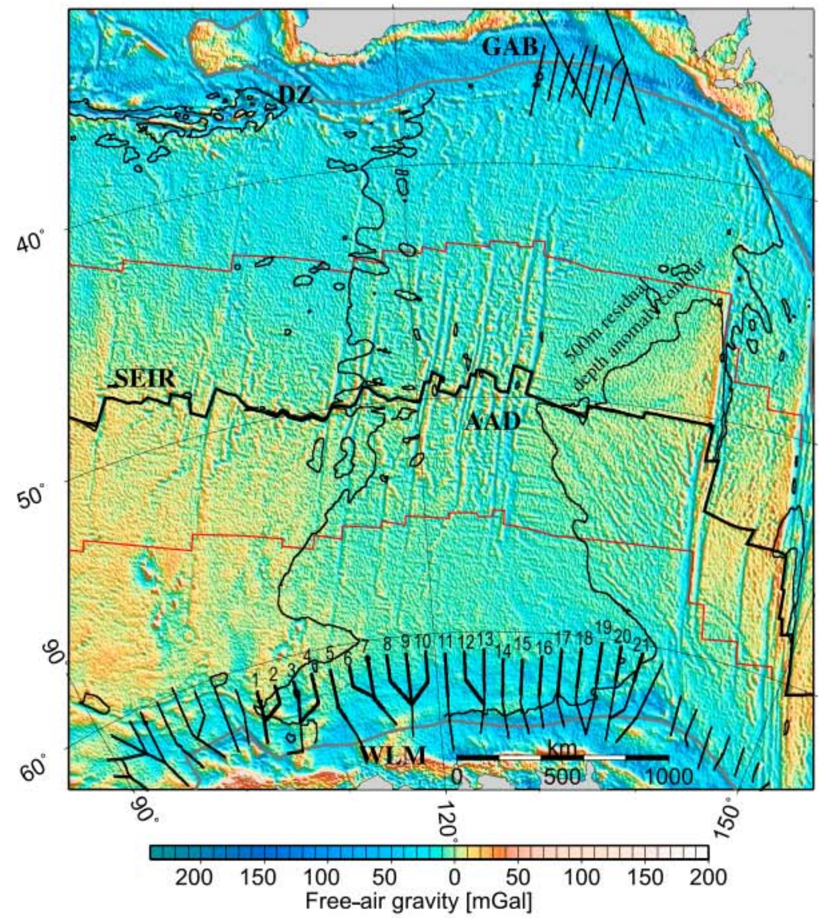

Figure 1. Regional 1 min marine gravity anomaly map [*Sandwell and Smith*, 2005] illustrating the main structural elements of the southeast Indian Ocean using an illumination azimuth of 45°. Overlain are deep seismic profile locations (black lines) along the Australian and Antarctic margins, the location of the Southeast Indian Ridge, and a revised estimate of the location of the 500 m RDA contour. Also shown is the rough basement morphology of the Australian-Antarctic Discordance (AAD), Great Australian Bight (GAB), Southeast Indian Ridge (SEIR), Diamantina Zone (DZ), and Wilkes Land Margin (WLM). The projection is a Lambert equal area projection, with a center at 125°E and 50°S. Red lines are the 20 Ma isochron on each flank of the Southeast Indian Ridge. Thin black lines show locations of ship tracks, and bold sections represent the locations of profiles shown in Figure 7.

Southern Ocean, the resulting depth anomaly encompasses a broad N–S trending band of oceanic crust (Figure 1). *Hayes and Conolly* [1972] first mapped the anomalous depths of the Southeast Indian Ridge between the longitudes of 120°E and 128°E. Using maps of residual depth, *Marks et al.* [1990] found the depth anomaly extended north and south from the Southeast Indian Ridge in an arcuate, symmetrical pattern. *Gurnis and Müller* [2003] used the same technique to show that the residual depth anomaly extends from the Southeast Indian Ridge to the Australian and Antarctic margins with an hourglass geometry where the depth anomaly becomes wider and deeper toward the passive margins. There is also evidence that the anomalous depths may continue onshore Australia and Antarctica [*Veevers*, 1982]. This feature, defined by tracing the relative highs running roughly from north to south at its flanks, has been linked to Australian and Antarctica topographic features as old as the Carboniferous [*Veevers*, 1982] and the Cretaceous marine inundation of Australia which was out of phase with global sea level variations [*Gurnis et al.*, 1998].

[3] The oceanic crust between Australia and Antarctica also exhibits other unusual morphologic characteristics. Within the AAD is a region of young (<~20 Ma) oceanic crust characterized by distinctive basement morphologies, with closely spaced fracture zones and irregular basement blocks characterized by high-amplitude topographic relief of 600–1000 m, at ~15 km wavelength [*Weissel and Hayes*, 1971] and a lack of axis-parallel fab-

rics typical of abyssal plains [*Christie et al.*, 1998]. This distinctive oceanic basement occurs between ~120°E and ~128°E, straddling the deepest (4–5 km) section of the global mid-ocean ridge system (Figure 1). The AAD is one of the most highly segmented sections of the Southeast Indian Ridge with a complex pattern of short, deep axial valleys that are offset by left and right stepping fracture zones [e.g., *Christie et al.*, 2004; *Marks et al.*, 1999; *Small et al.*, 1999].

[4] In addition to uncommonly deep bathymetries and distinctive basement morphologies, a number of other unusual geological characteristics occur in the AAD. Wide-angle seismic refraction reveals that crust proximal to the ridge within the AAD is only 3.6–4.2 km thick, considerably thinner than 7–7.5 km thick oceanic crust found to the east, and 7.2 km thick crust to the west [*Holmes et al.*, 2010].

[5] Geochemical analyses of dredged basalts reveal that the boundary between Pacific MORB source mantle (Pacific mantle) and Indian MORB source mantle (Indian mantle) lies close to the eastern boundary of the AAD [*Christie et al.*, 1998; *Pyle et al.*, 1995]. The close association between the residual depth anomaly and the Indian-Pacific mantle boundary has existed since ~28 Ma [*Christie et al.*, 2004; *Marks et al.*, 1990].

[6] A clear understanding of the anomalous features within the AAD is crucial to unraveling the mechanism(s) responsible for forming these features. A long-standing problem concerns a poor understanding of the spatial extent of the distinctive AAD basement morphologies. *Christie et al.* [1998] argued that "chaotic" basement extended to crust formed at least 30 Ma based on swath bathymetry, while *Marks et al.* [1999] found that the onset of the unusual basement morphologies was at approximately 20 Ma.

[7] Almost all models [e.g., *Forsyth et al.*, 1987; *Hayes*, 1988; *Klein et al.*, 1988; *Kuo*, 1993; *Kuo et al.*, 1996; *West et al.*, 1997] have assumed that the rough basement morphologies and residual depth anomaly of the AAD are spatially correlated and formed by the same process(es). However, recently, the eastern boundaries of the rough basement and residual depth anomaly have been found to be geographically distinct, having come into alignment only since ~12 Ma [*Christie et al.*, 2004]. *Gurnis and Müller* [2003] also noted the independent nature of these features, observing that rough basement morphologies are restricted to oceanic basement <~20–30 Ma, while the residual depth anomaly extended to the continental margins and also, possibly onshore.

[8] Most early models focused on the young (<20–30 Ma) portion of the AAD and sought mechanisms that explained the formation of both the rough ocean basement and the residual depth anomaly. One group of models invoked downwelling mantle material beneath the Southeast Indian Ridge as the main mechanism responsible for forming the AAD [e.g., *Hayes*, 1988; *Klein et al.*, 1988]. However, this proposal implies the paradoxical presence of downwelling mantle within a mid-ocean ridge system that is normally associated with upwelling. Later models attempted to avoid this geodynamic problem by proposing that the anomalous depths and basement morphologies were related to inhibited mantle upwelling [*Kuo*, 1993; *Kuo et al.*, 1996] or that downwelling was related to passive westward mantle flow along the axis of the Southeast Indian Ridge from the Pacific toward cold upper mantle located beneath the AAD [*Forsyth et al.*, 1987; *West et al.*, 1997]. The presence of cool mantle material beneath the AAD has long been proposed. *Weissel and Hayes* [1974] and *Hayes* [1976] proposed a stable, suspended mantle cold spot that migrated with the Southeast Indian Ridge, although how the cold spot remained beneath the Southeast Indian Ridge is geodynamically problematic. *Lin et al.* [2002] suggested that ascending cold material beneath the mid-ocean ridge can only be sustained for ~20–40 Ma following continental rifting.

[9] Recently, *Buck et al.* [2009] proposed a variant mantle flow model for the formation of the AAD. In this hypothesis the deep roots of Australia and Antarctica inhibited upper mantle replenishment as they separated, eventually leading to the development of thin and depleted asthenosphere beneath the AAD portion of the Southeast Indian Ridge [*Buck et al.*, 2009]. Similarly to many earlier hypotheses this model assumes that the depth anomaly and the anomalous basement were formed by the same mechanism and does not attempt to account for the changing basement morphologies perpendicular to the ridge. Also, the AAD is a globally unique feature and deep continental roots that separate following continental breakup are not, making it unclear as to why AAD-type features are not found in more ocean basins formed during the breakup of Pangaea.

[10] A third, alternative model for the formation of the AAD utilizes a westward dipping Mesozoic subducted slab [*Gurnis et al.*, 1998, 2000]. This hypothesis has two components. First, down-

welling ancient slab material trending roughly N–S at depth is responsible for the depth anomaly. Second, cool/depleted slab material has been progressively drawn up beneath the mid-ocean ridge following continental breakup and was first sampled at the mid-ocean ridge at 20 Ma, some 25 million years after the onset of fast spreading between Australia and Antarctica at ~45 Ma. A fast seismic velocity structure imaged in the upper mantle beneath the AAD support a subducted slab origin [*Ritzwoller et al.*, 2003]. The upper mantle anomaly is tomographically imaged as striking NW–SE [*Ritzwoller et al.*, 2003], but geodynamically modeled as N–S trending [*Gurnis et al.*, 1998]. This discrepancy is most likely due to the poorly constrained Mesozoic subduction zone geometry, uncertainties in mantle tomographic images, or a combination of both.

[11] While the formation of the rough <20 Myr old crust of the AAD has been addressed extensively, only one model [*Gurnis and Müller*, 2003] has attempted to explain the formation of anomalous crust across the entire Australian Southern Ocean. Two crucial observations need to be accounted for: (1) the depth anomaly is most prominent (broadest and deepest) proximal to the Australian and Antarctic continental margins and (2) the ocean basement morphology changes across the AAD. *Gurnis and Müller* [2003] expanded on their previous model and proposed that, following cessation of Mesozoic subduction, ancient mantle wedge material remained in the upper mantle. Following the onset of seafloor spreading at ~83 Ma this anomalous mantle was immediately sampled by the Southeast Indian Ridge leading to the formation of the large depth anomalies observed close to both margins.

[12] In essence, the *Gurnis and Müller* [2003] model proposes a link between the deep mantle and the upper mantle in order to explain both the residual depth anomaly and the changing morphologies of the oceanic crust across the Southern Ocean. This model proposed a downwelling slab (cool mantle) at depth to explain the residual depth anomaly combined with three stages of oceanic crustal accretion. Ocean crust proximal to the Australian and Antarctic continental margins formed as the Southeast Indian Ridge sampled depleted upper mantle derived from an ancient wedge. The young (<25 Ma), rough ocean basement of the AAD formed from cool and/or depleted upper mantle derived from the ancient downwelling slab. Oceanic crust formed in between these two end-members can be assumed to have sampled "normal" upper mantle material. Cool/depleted mantle material is believed to result in the accretion of oceanic basement exhibiting rougher oceanic basement morphologies [*Meyzen et al.*, 2003]. An implication of the *Gurnis and Müller* [2003] model is that both the youngest AAD oceanic basement and the oldest, margin proximal oceanic basement should exhibit basement morphologies that are much rougher than average oceanic basement. An additional issue is that the distinctive V shape of the eastern boundary of the residual depth anomaly is not adequately explained.

2. Methods

[13] We employ recent, high-resolution global satellite-derived gravity, and sediment thickness estimates derived from recently acquired seismic reflection data, to compute the shape, extent and magnitude of the depth anomalies and the anomalous basement roughness of the AAD.

2.1. Basement Roughness

[14] In order to analyze the oceanic basement of the Southern Ocean we apply the methodology of *Whittaker et al.* [2008] to compute a roughness grid. Oceanic basement roughness varies globally and relationships between roughness, sediment thickness, seafloor spreading rates, and spreading obliquities have been quantified. For four regions, Broken Ridge-Kerguelen Plateau (BRKP), West AAD, AAD, and East AAD (see Figure 2), we compute expected basement roughness given spreading rate (Figure 3b) and sediment thickness (Figure 4b). In order to determine areas of oceanic crust that exhibit anomalously rough or smooth ocean basement we compare our observed roughness against computed roughness for each area in 5 Ma bins of ocean crust (Figure 5). Computation of residual roughness removes roughness variations attributed to spreading rate, sediment thickness and spreading obliquity. Remaining patterns of residual roughness are likely attributable to variations in mantle temperature and magmatic fertility [*Whittaker et al.*, 2008], or possibly to other unknown parameters.

[15] Our analysis of roughness includes roughness attributable to both fracture zones and abyssal plains. It should be noted that where we use the term "chaotic" in reference to basement morphologies, we use in the context of *Christie et al.* [1998] to refer only to the fabric of the oceanic crust between fracture zones, but excluding the fracture zones themselves.

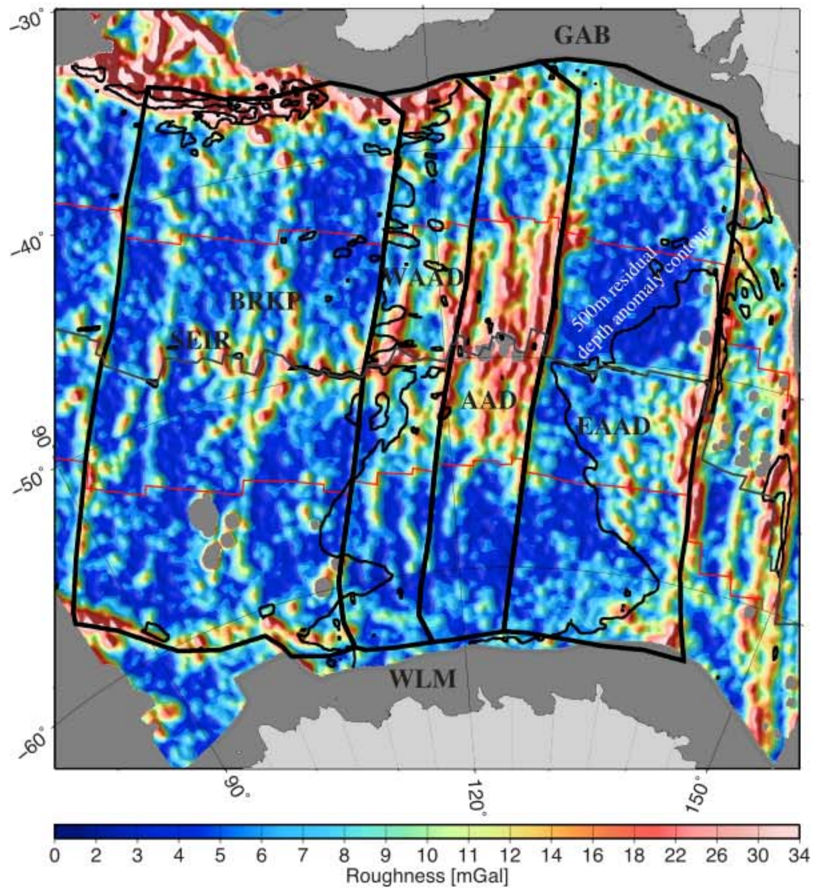

Figure 2. Downward continued gravity RMS roughness calculated using a Gaussian filter with a half-width of 50 km. Four analysis regions are outlined in thick black lines: Broken Ridge Kerguelen Plateau (BRKP), West AAD (WAAD), AAD, and East AAD (EAAD). Red lines are the 20 Ma isochron on each flank of the Southeast Indian Ridge.

[16] The longitudinal boundaries of the four regions in our analysis follow tectonic flowlines seeded at the Southeast Indian Ridge at 120°E and 128°E, for the eastern and western boundaries of the AAD. The western boundary of WAAD was seeded at the fracture zone at ~115E, marking the western extent of rough basement evident in satellite gravity (Figure 1). Further west, the BRKP region does not exhibit either rough basement morphologies or a residual depth anomaly, and so provides a good comparison for the AAD with oceanic crust resulting from typical Indian-type mantle.

2.2. Residual Depth Anomaly

[17] Previously, computation of the AAD residual depth anomaly, has revealed the anomaly becomes wider and deeper toward both the passive continental margins, e.g., hourglass in shape [*Gurnis and Müller*, 2003]. However, previously the sediment thickness maps used were poorly constrained, even though the sediment correction on the Antarctic margin was large.

[18] To improve the accuracy of the residual depth anomaly we incorporate new sediment thickness information obtained from seismic reflection data from the Australian and Antarctic margins (Figures 6 and 7). During the Antarctic summers of 2000/01 and 2001/02, Geoscience Australia acquired a major deep water geophysical data set off the East Antarctica margin (~36°E–152°E), which included high-quality deeply penetrating multichannel seismic data with coincident gravity, magnetic and bathymetry [*Stagg and Colwell*, 2003]. Interpretation of sediment thickness and depth to igneous basement along profiles off the Wilkes Land margin (Figures 6 and 7) provide observations that we have used to improve the residual depth anomaly map on Cretaceous aged crust. The regional high-resolution sediment

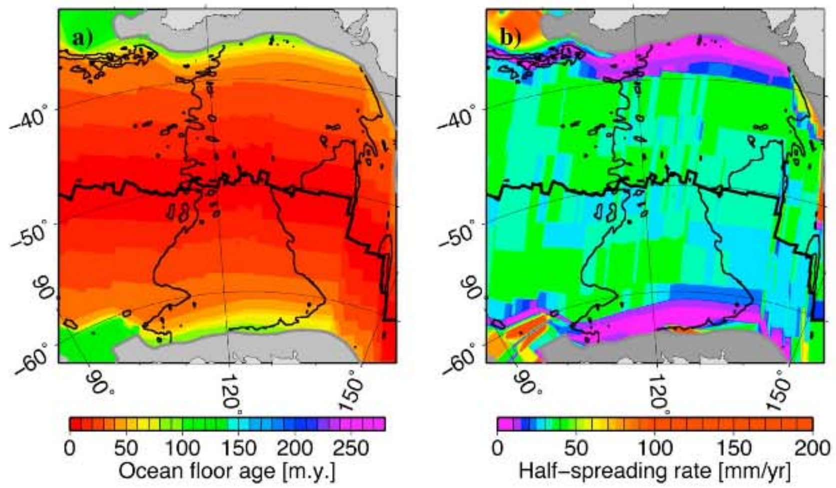

Figure 3. (a) Regional map showing color-coded oceanic age using the following isochrons, using the *Cande and Kent* [1995] and *Gradstein et al.* [1994] time scales from young to old: C5 (10.9 Ma), C6 (20.1 Ma), C13 (33.1 Ma), C18 (40.1 Ma), C21 (47.9 Ma), C25 (55.9 Ma), C31 (67.7 Ma) C34 (83.5 Ma), 100 Ma, M0 (120.4 Ma), and M4 (131.9 Ma). (b) Regional map showing spreading half rates The 500 m depth anomaly is plotted as a thin black line, and the bold black line shows the current location of the Southeast Indian Ridge. Regions of continental crust are shaded in gray.

thickness grid for the Wilkes Land was merged with sediment thickness data from *Géli et al.* [2007] and the NGDC global sediment thickness grid [*Divins*, 2004] to create a sediment thickness grid for the Australian Southern Ocean with substantially improved sediment thicknesses for the margins as well the AAD region (Figure 4b).

[19] To calculate the residual depth anomaly grid (RDA) (Figures 4d and 8), where the effects of sediment loading and crustal age have been removed, we start with a predicted bathymetry grid (ETOPO2v2). To compute unloaded igneous basement (IB_U) depth (Figure 4c) we correct for sediment loading using predicted bathymetry [*Smith and Sandwell*, 1997], sediment thicknesses (Figure 4b) and the procedure outlined by *Sykes* [1996]. The residual depth anomaly grid, *RDA*, is then created by removing the unloaded basement grid (IB_U) (Figure 4c) from the grid of predicted depth to igneous basement (IB_P) (Figure 4a), which estimates the average depth of comparably aged oceanic crust. The predicted depth to igneous basement (IB_P) is calculated using the seafloor age grid from *Müller et al.* [2008] and the *Pribac* [1991] thermal boundary layer model that describes the relationship between the depth of the seafloor and its age. The *Pribac* [1991] age-depth was selected because it accounts for conductive cooling of the oceanic lithosphere between a deeper than normal ridge crest and its flanks (ridge crest depth = 2600 m, subsidence constant = $220\ \mathrm{m/m.y.}^{1/2}$).

$$IB_P = -\left(2600 + 220\sqrt{t}\right);\ \text{where t is time in million years:} \qquad (1)$$

$$RDA = IB_P - IB_U \qquad (2)$$

[20] Residual depth anomalies in oceanic crust are caused by two main mechanisms, crustal thickness variations and dynamic topography. In order to investigate whether crustal thickness anomalies alone are sufficient to explain the residual depth patterns in the AAD we compute an oceanic crustal thickness grid (Figure 10). We estimate oceanic crustal thickness based on the assumption that the entire depth anomaly is due to crustal thickness variations, following the method of *Louden et al.* [2004] assuming the average oceanic crustal density of 2.95 Mg/m3, water density of 1.03 Mg/m3, mantle density of 3.3 Mg/m3 and average oceanic crustal thickness of 7 km [*White et al.*, 1992].

3. Results

[21] The free-air gravity (Figure 1) and RMS roughness (Figure 2) show that basement morphologies are highly variable in the Australian Southern Ocean. Within the AAD and WAAD, rough basement extends across both flanks of the Southeast

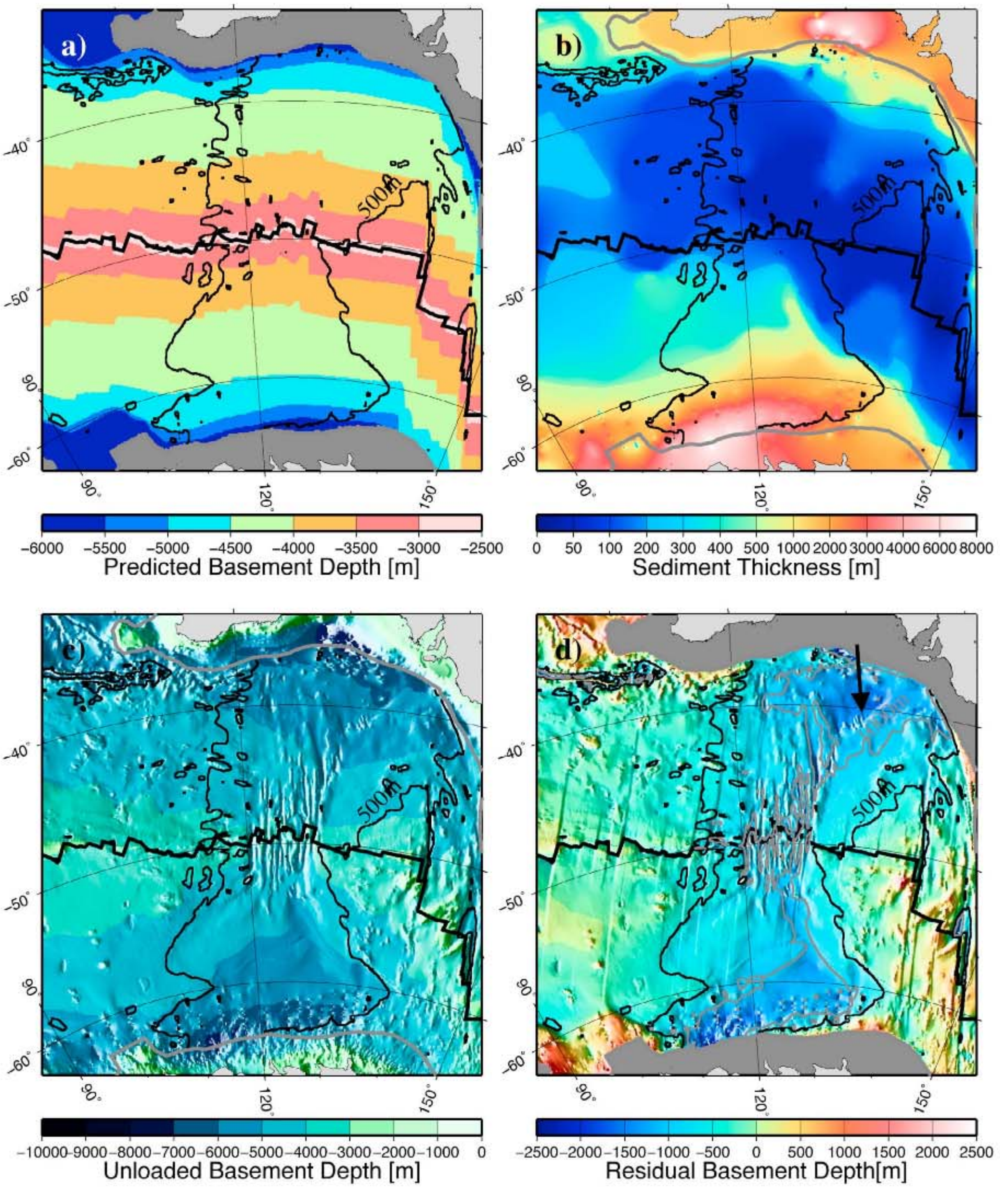

Figure 4. Regional maps showing (a) a predicted basement depth grid based on the thermal boundary layer depth-age relationship from *Pribac* [1991] ($2600 + 315\text{Age}^{1/2}$); (b) sediment thickness from *Géli et al.* [2007] combined with gridded sediment thickness interpreted from the seismic profiles in the Great Australian Bight and off Wilkes land shown in Figure 1 and the NGDC sediment thickness grid [*Divins*, 2004]; (c) unloaded basement depth from combining etopo2 bathymetry [*National Geophysical Data Center*, 2006] with sediment thickness from Figure 4b, using an isostatic correction after *Sykes* [1996]; and (d) residual depth anomaly between Australia and Antarctica, based on our unloaded basement depth grid (Figure 4c) and a predicted depth grid based on the thermal boundary layer depth-age relationship (Figure 4a). Residual depth anomaly contours at 500 m (black) and 1000 m (gray). Black arrow shows location of sharp gradient in the residual depth anomaly grid.

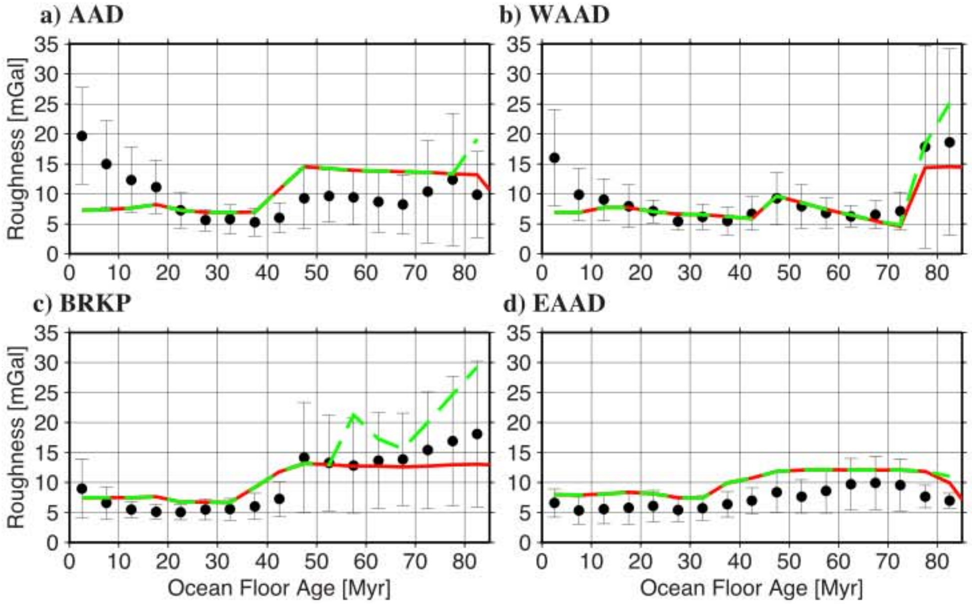

Figure 5. Gravity roughness as a function of seafloor age for four regions: (a) AAD, (b) WAAD, (c) BRKP, and (d) EAAD. Black dots and error bars show observed median roughness and its median absolute deviation in 5 Ma bins. The red line shows the roughness for each bin predicted based on the relationship between half-spreading rate and roughness and sediment thickness and roughness from *Whittaker et al.* [2008], and green lines shows roughness predicted based on sediment thickness, spreading rate, and spreading obliquity. Note the misfit between observed and predicted roughness for ocean crust formed <20 Ma in the AAD and WAAD.

Indian Ridge to approximately chron 6o (20.1 Ma) [*Müller et al.*, 2008]. Basement morphologies in adjacent, older crust are less rough and have more typical "abyssal plain" morphologies, similar to the majority of basement in the BRKP and EAAD regions. Oceanic crust proximal to the Australian southern margin is also rougher than adjacent younger basement (Figure 2). The purpose of our analysis is to remove roughness attributable to variations in spreading rate, sediment cover, and spreading obliquity in order to reveal oceanic basement that is anomalously rough. The presence of anomalously rough basement indicates the influence of anomalous mantle temperature and/or mantle fertility [*Whittaker et al.*, 2008].

[22] Estimates of oceanic basement roughness, based on spreading rate and sediment thickness, closely match predicted basement roughness for the regions analyzed here (red lines, Figure 5). One surprising result is that crust aged 50–83 Myr, proximal to both the Australian and Antarctica margins, exhibits high roughness amplitudes (Figure 2), but is not anomalously rough (Figure 5). The high roughness values are accounted for by the slow and oblique spreading prior to ~43 Ma (<10 mm/yr half-spreading rate). Slow and ultraslow spreading rates are known to result in rough oceanic basement which has been attributed to decreasing melt availability at slower spreading rates [*Chen and Phipps-Morgan*, 1996] and enhancement of the episodic magmatism and tectonic processes at mid-ocean ridges [*Malinverno and Pockalny*, 1990].

[23] Basement older than 75 Ma in the BRKP and the WAAD is rougher than predicted based on spreading rates and sediment thicknesses (red lines in Figures 5b and 5c). However, the roughness of these regions is more than accounted for when spreading obliquity is included (green dashed lines, Figure 5). Spreading obliquities >45° are related to increased roughness of oceanic basement, most likely due to an increase in brittle fracturing [*Whittaker et al.*, 2008]. Early opening between Australia and Antarctica has been modeled as highly oblique [*Whittaker et al.*, 2007]. Moreover, spreading prior to ~50 Ma was more oblique in the west compared to the east. This phenomenon likely explains the presence of the extremely rough Diamantina Zone (see Figure 1 for location) offshore southwest Australia, and why the elevated roughness decreases to the east. Close examination of Antarctic basement profiles, interpreted from multichannel seismic profiles (Figures 6 and 7), reveals the change in basement character from west to east caused by the slower and more oblique

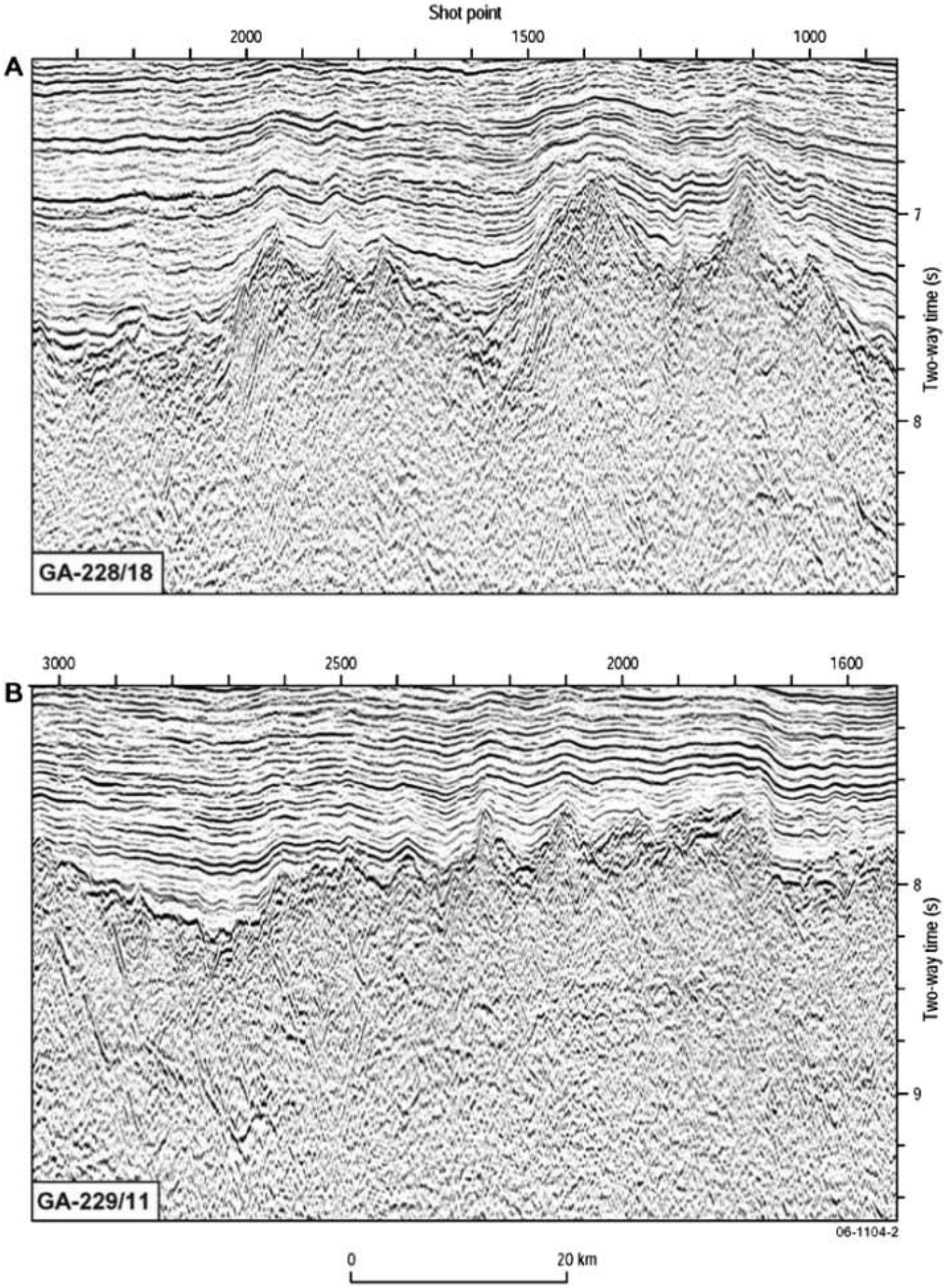

Figure 6. Selected seismic profiles illustrating characteristics of oceanic crust along strike of the Antarctic margin. (a) Line GA-228/18, west Wilkes Land (corresponds to central part of profile 5 in Figures 1 and 7). (b) Line GA-229/11, central Wilkes Land (corresponds to central part of profile 10 in Figures 1 and 7). (c) Line GA-228/23, central Wilkes Land (corresponds to central part of profile 14 in Figures 1 and 7). (d) Line GA-228/28, east Wilkes Land (corresponds to central part of profile 19 in Figures 1 and 7).

spreading. To the west, basement inboard of chron 20o shows higher-amplitude, longer-wavelength morphologies which decrease toward the east into lower-amplitude, shorter-wavelength basement morphologies.

[24] It is possible that the oceanic crust proximal to the margins appears less rough than it should due to attenuation of satellite-derived gravity roughness for areas of deep bathymetry. However, we have attempted to minimize this effect by downward

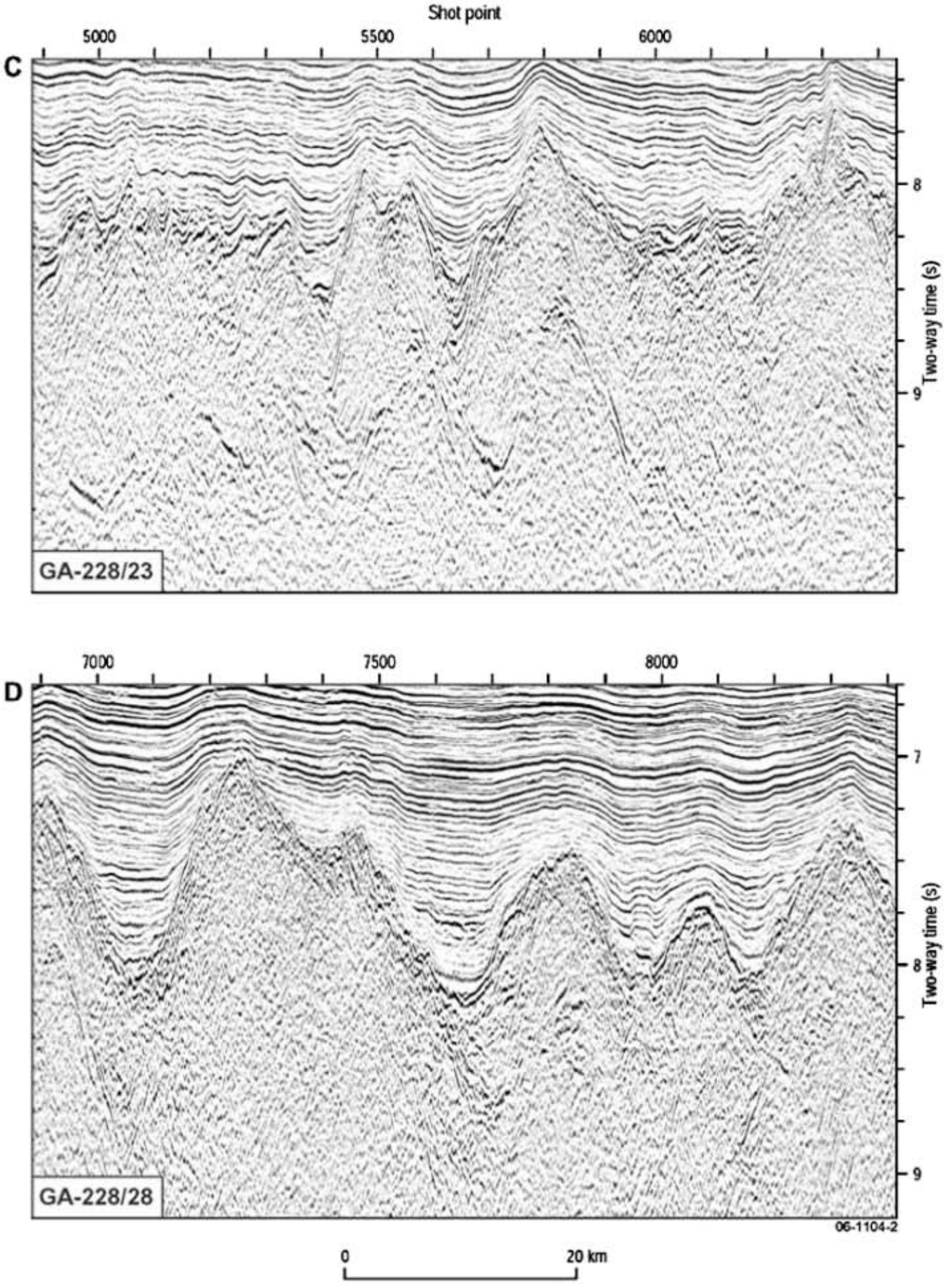

Figure 6. (continued)

continuing the satellite gravity to the seafloor. A global analysis of the relationship between RMS roughness and bathymetry (Figure S1 in the auxiliary material) indicates that there is only a very mild relationship between increasing depth and smoother basement, ~4 mGal of smoothing for an increase of ~3000 m of water depth.[1]

[25] Oceanic basement roughness values throughout the EAAD region are smoother than expected based on spreading rates and sediment thickness (Figure 5d). This result is consistent with results from the North and South Pacific which exhibit oceanic crust that is smoother than the global average [*Whittaker et al.*, 2008]. The EAAD portion of the Southeast Indian Ridge currently overlies Pacific-type mantle [*Christie et al.*, 2004; *Kempton*

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GC003276.

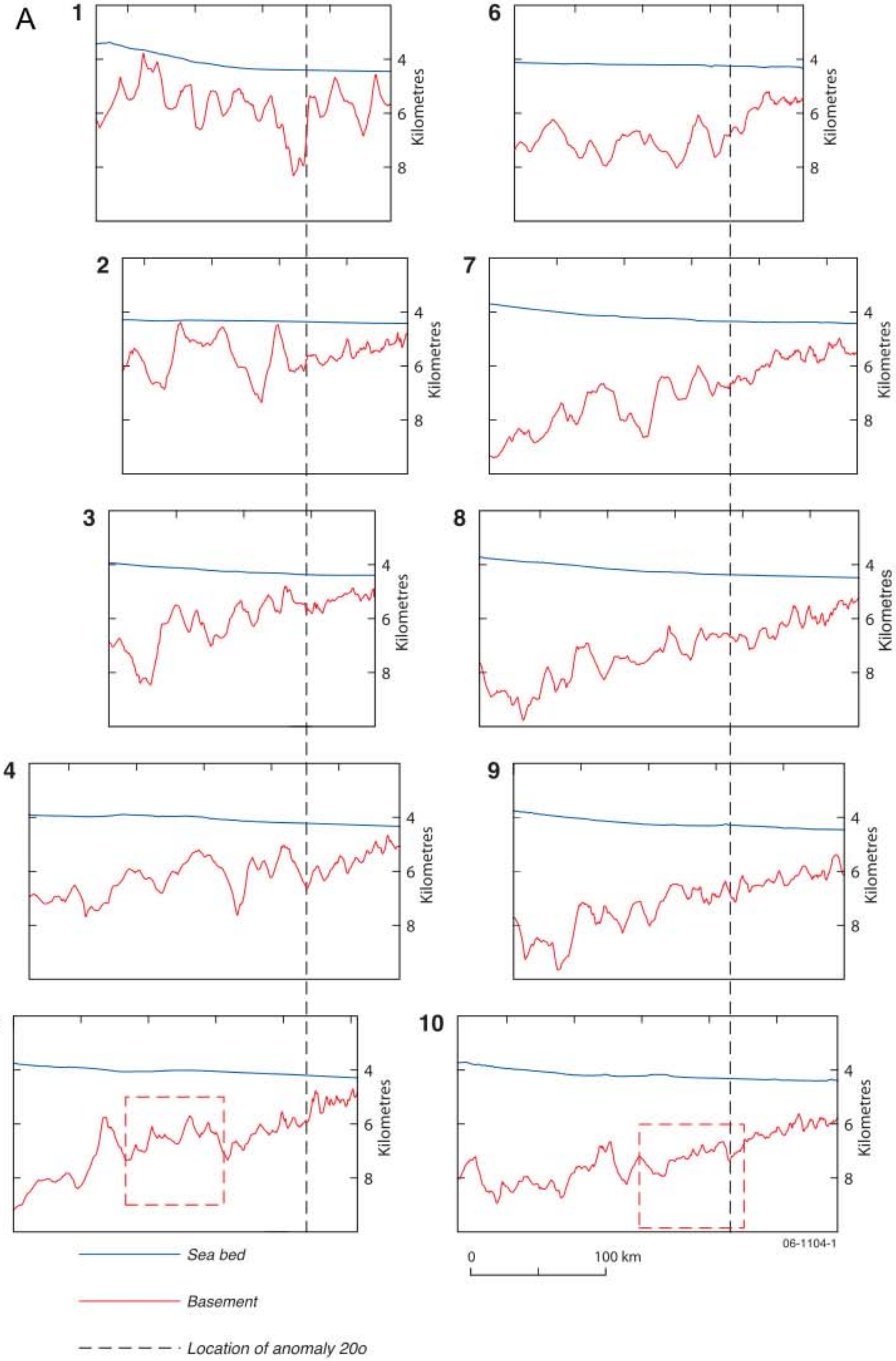

Figure 7. Profiles of water depth and depth to basement of the postrift section (i.e., depth to basement over oceanic crust) for the continental margin of (a) west and central Wilkes Land and (b) central Wilkes Land to Terre Adélie. Profile numbers correspond to numbered profiles on Figure 1. Depth conversion was carried out using smoothed stacking velocities and used the interpretation contained by *Stagg et al.* [2005]. Profiles are aligned on seafloor spreading magnetic anomaly 20o (43.8 Ma [*Cande and Kent*, 1995]). The magnetic anomaly 20o alignment is extrapolated for profiles 1–4 as they do not cross this anomaly.

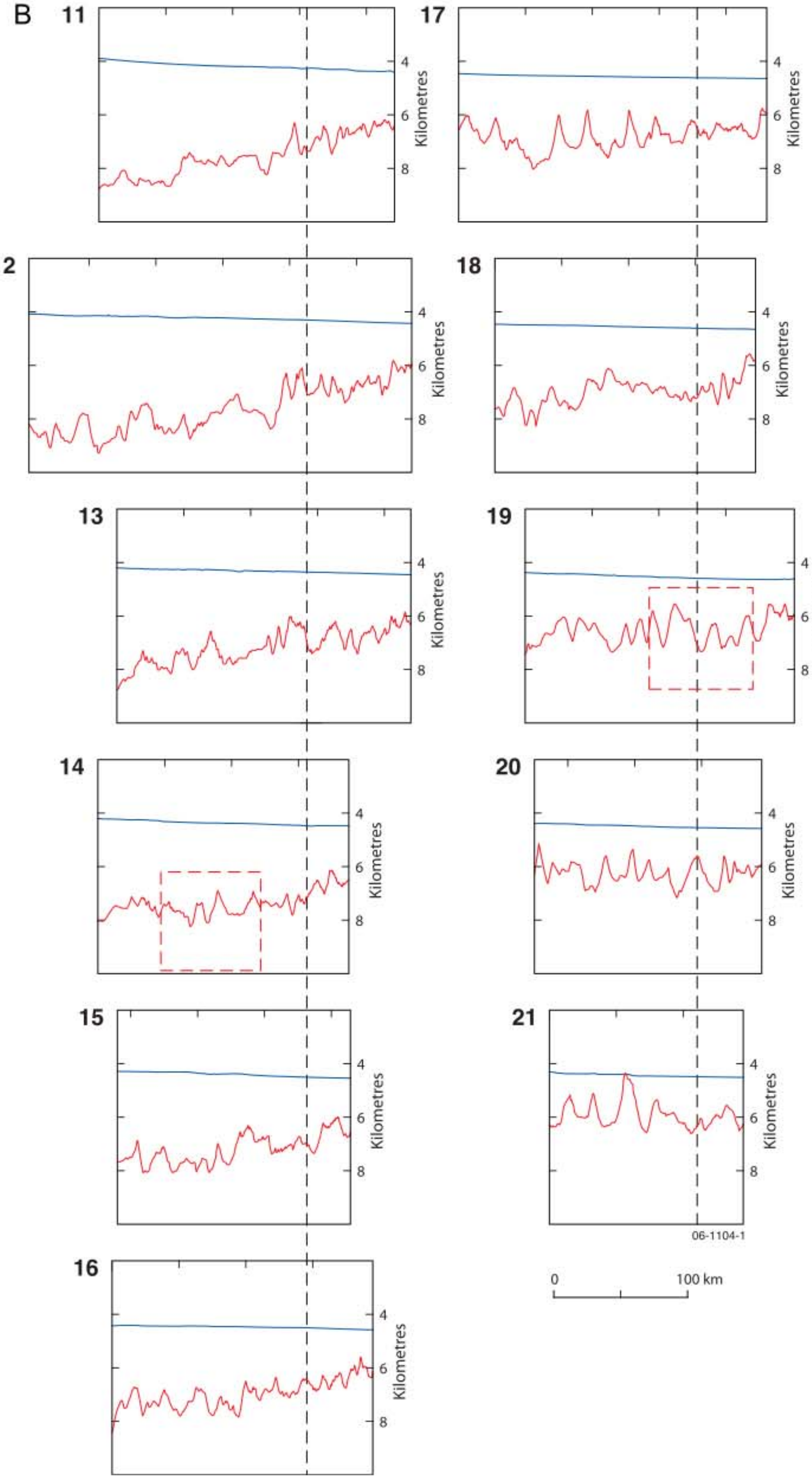

Figure 7. (continued)