What can potential field data really tell us about Continent-Ocean transitions?

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SUMMARY

We investigate the ability of gravity and magnetic data to define the distribution of crustal types at continental margins, with specific focus on the conjugate Australia-Antarctica margins. Previous studies have used features in gravity maps as a proxy for the pre-rift location of plate boundaries. Instead, we discuss the use of potential field data to define the boundaries of stretched continental crust on a regional scale, and demonstrate this process for the conjugate margins of South Australia and Antarctica. In a companion paper (Whittaker et al, 2010) we show how these boundaries are used along with estimates of crustal thickness to determine the location of the plate boundaries prior to rifting, and ultimately to derive full-fit plate tectonic reconstructions.

Key words: Gravity, Magnetic, Continent, Ocean, Restoration

INTRODUCTION

Defining the extent of continental and oceanic crust at passive rifted margins is of great importance for hydrocarbon exploration – and is also notoriously difficult. Our focus is on defining crustal boundaries for the purpose of deriving full-fit plate tectonic reconstructions. To properly account for the deformation along the continental margins during rifting, we must first identify the crust within which this deformation occurred. We then need to define the crustal thinning along the continental margins in a way that is simple and practical to apply on regional and global scales, which incorporates knowledge from seismic data where available but does not rely on seismic data for margins where such data are sparse.

We investigate the ability of gravity and magnetic derivative maps to define the distribution of crustal types at the conjugate Australia-Antarctica continental margins. Studying these maps where they are to some extent 'ground-truthed' by seismic data, allows us to develop a better understanding of gravity signatures due to crustal thinning and density variations within the crust. We can then evaluate different approaches to the interpretation of Continent-Ocean transitions (COT) from potential field data, and determine the level of uncertainty in COT's interpreted from these data where seismic data are sparse.

In a companion presentation, Whittaker et al (2010) present new estimates of the pre-rift plate boundary locations for the conjugate Australian-Antarctic margins. These reconstructions are truly palinspastic, incorporating estimates of crustal thickness along these margins, derived for example by gravity inversion. The restored plate boundary is derived by integrating the crustal thickness across the stretched continental crust within the continental margin. This integration relies on defining the present-day extent of stretched continental crust within the margin, which is the subject of this paper.

PREVIOUS STUDIES

A number of methods have been used to estimate continent-ocean boundary (COB) positions on a regional scale, including; using isobaths; gravity anomalies and gradient maps; gravity inversion; magnetic anomalies and spreading rates, and continental stretching factors. Bullard et al (1965) presented an early attempt to derive quantitative full-fit reconstructions of the conjugate Atlantic margins, testing different bathymetric contours and finding the 500 fm contour to yield the best fit. Many subsequent plate tectonic studies have used potential field data to constrain the extent of continental margins, but the details and limitations of the methods used are rarely well described. Lawver et al (1999) used the major free-air gravity anomalies as a proxy for the pre-breakup ocean-continent boundary, while Schettino and Scotese (2005) used the 'horizontal gradient of gravity anomalies' to identify unstretched pre-rift plate boundaries. Although these authors claim to be mapping 'palinspastically restored' continent-ocean boundaries, no justification is provided as to why this should be the case. Such approaches also ignore differences between the gravity signatures over volcanic and non-volcanic margins, and the complex nature of continent-ocean transition zones (e.g. Direen et al, 2007).

MAGNETIC ANOMALIES

Linear magnetic anomalies generated by seafloor spreading help to define the extent of oceanic crust towards the continental margins. Margin-parallel magnetic anomalies are often observed within the continent-ocean transition. At volcanic margins, broad and laterally extensive magnetic anomalies have been used to define the extent of seaward dipping reflector packages (e.g. Gaina et al, 2009). By contrast, data from non-volcanic margins indicate linear anomalies apparently originating in exhumed, serpentinized mantle lying in the continent-ocean transition between the definite continental and oceanic crust. The origin of these anomalies is controversial (Whittaker et al, 2007b; Tikku and Direen, 2008; Whittaker et al, 2008). While the exhumed mantle is not generated by classical seafloor spreading, recent studies have shown that conjugate linear magnetic anomalies within the exhumed mantle are generated by reversals in the Earth's magnetic field in a similar way to those observed in oceanic crust, and so can be used to constrain the temporal evolution of this crust (Sibuet et al, 2007; Sauter et al, 2008).

DIFFERENT TYPES OF GRAVITY ANOMALY

A broad philosophy of gravity processing is to compute corrections that strip away the gravity signals of parts of the Earth that we understand, so that we can study the residual signals due to parts of the Earth we don't understand. Maps of the free-air gravity anomaly are the most commonly used for analysis of ocean areas. The free-air anomaly is strongly influenced by bathymetry, which is not an issue in much of the deep ocean basins but becomes far more significant around the continental margins.

Various corrections and transformations can be applied to the free-air gravity to better study density variations within the Earth (e.g. Blakely, 1995). The Bouguer correction attempts to remove the influence of bathymetry from the gravity data. Bouguer Gravity maps are dominated by variations in crustal thickness, with thin crust corresponding to high Bouguer gravity values due to the dense mantle material at shallow levels. The isostatic correction attempts to remove the influence of crustal thickness variations by making an assumption of the Moho depth based on Airy isostasy. This approach is limited by the assumption that the crust is of constant density, particularly is areas of thick sedimentary cover as is often the case at continental margins.

A limitation of the derivative maps discussed so far is that they are influenced by large variations in sediment thickness. Sediment thickness data can be used to isolate the gravity signal due to the underlying basement rocks - the gravity effect of the sediments can be estimated using forward-modelling methods described by Parker (1972) and Blakely (1995). Rabinowitz and Labreque (1977) used estimates of sediment thickness from seismic reflection profiles to calculate isostatic corrections for gravity profiles across continental margins. More quantitative methods to interpret gravity data also incorporate sediment thickness data – these include combined backstripping and gravity modelling (e.g. Watts and Fairhead, 1999) and gravity inversion (Chappel and Kusznir, 2008). Such methods use gravity data to provide useful estimates of the crustal thinning across continental margins, but do have some limitations. For example these methods inherently assume no lateral density variations within the crust across the entire continent ocean transition. Gravity inversion requires the use of low-pass filters that may smooth out detailed features observed in the gravity data, and produces a range of crustal thickness estimates depending on the initial parameters used to define the margin type, pre-rift crustal thickness.

THE AUSTRALIAN AND ANTARCTIC MARGINS

There is broad consensus on many aspects of the crustal structure of the conjugate Australian and Antarctic margins. On both margins, linear seafloor spreading magnetic anomalies have been identified back to at least chron 33o. Similarly, on both margins continental crust is generally interpreted to extend at least as far oceanwards as the location of prominent peridotite ridges. These ridges have been identified on seismic profiles across both margins, and on both margins correspond to prominent, laterally continuous magnetic anomalies concordant with the magnetic lineations in the 'certain' oceanic crust further outboard (figures 1a and 2a). The corridors of uncertainty lie between the peridotite ridges and magnetic chrons 33o. Some authors have interpreted these zones to be underlain by stretched continental crust (Sayers et al, 2001; Espurt et al, 2009), while an alternative hypothesis suggests that a zone of exhumed, serpentinized mantle extends from the peridotite ridge to the oceanic crust marked by chron 33o (Whittaker et al, 2007a).

The gravity anomalies derived from satellite altimetry (Sandwell and Smith, 1997) over the conjugate southern Australian and Antarctic margins are shown in figures 1 and 2. The free-air anomaly exhibits a strong 'edge-effect' in the region of the bathymetric shelf break. The Bouguer gravity anomaly shows the more regional transition from low values over the continents to high values over the oceans, reflecting lateral changes in crustal thickness and density. In order to better understand discrete, regionally pervasive changes in crustal thickness and/or density we applied an upward continuation to the Bouguer gravity data then derived the total horizontal gradient of the smoothed Bouguer data. To estimate the gravity effect of the sediments, we computed a regional high-resolution sediment thickness grid for the Australian Southern Ocean using sonobuoy-derived sediment thicknesses for the Great Australian Bight and Wilkes Land margins (generated by Geoscience Australia and described by Kusznir, 2009), merged with sediment thickness data from Geli et al. (2007) and the NGDC global sediment thickness grid (Divins, 2004).

The gravity derivative maps provide a qualitative understanding of crustal thickness variations. The total horizontal gradient of the Bouguer gravity (figure 1e) shows a ~100km wide zone of high gradient that extends along the south Australian margin. When a correction for the gravity effect of the sediments is incorporated, the resulting gradient map (figure 1f) is broadly similar with the exception of the areas around the thick sediment accumulations in the Ceduna sub-basin, where the strong gravity gradient lies significantly further landward of the high gradient zone across the same part of the margin in figure 1e. Grids of crustal thickness derived from gravity inversion (e.g. figure 1g) show that the majority of crustal thinning takes place within the same >100km wide zone of high gravity gradient (as we would expect since the inversion result is based on the same gravity data). The two approached are complementary – the gravity inversion provides quantitative estimates of crustal thickness while the derivative maps are simpler to derive, require fewer assumptions, and preserve more detail since low-pass filtering is not required. On this basis, we define the landward limit of stretched crust to lie at the landward margin of the regional gravity gradient shown in figure 1e.

The total horizontal gradient maps show a distinct linear trend along the location of the peridotite ridge. Oceanward of this, there is little evidence for major, laterally continuous changes in crustal type and/or thickness. Hence we define our oceanward limit of the 'certain' stretched continental crust to follow the gravity and magnetic trends delineating the peridotite ridge.

The analysis of the conjugate Antarctic margin is less certain then for the Australian margin. The difficulty in acquiring geophysical data close to the Antarctic coast means that the datasets needed to constrain the Bouguer and sediment thickness corrections are less complete for this margin. For this reason, our landward limit of stretched continental crust for this margin is based largely on that presented by O'Brien and Stagg (2007). In common with the Australian margin, the total horizontal gradient of Bouguer gravity maps show a linear trend following the peridotite ridge (figures 2d-e). We use this trend to define the oceanward boundary of 'certain' stretched continental crust for out plate reconstruction calculations, although other authors have interpreted some continental crust oceanward of the ridge (Colwell et al, 2006).

Estimates of the pre-rift plate boundary locations for the conjugate Australia and Antarctic margins (Whittaker et al, 2010) are shown in figures 1g and 2g. On the Australian margin our palinspastically restored plate boundaries lie consistently oceanward of the free-air gravity anomaly used by Lawver et al (1999) as a proxy for the pre-rift COB. On the Antarctic margin, the two approaches yield similar boundaries at some points but significant divergence in others.

CONCLUSIONS

We have used potential field data to estimate the extent of stretched continental crust along the conjugate continental margins of South Australia and Antarctica. The interpreted crustal boundaries, together with estimates of crustal thickness from gravity inversion (Kusznir, 2009), form the basis to calculate the pre-rift boundaries of these margins and so generate more robust full-fit reconstructions of Australia and Antarctica presented in Whittaker et al (2010).

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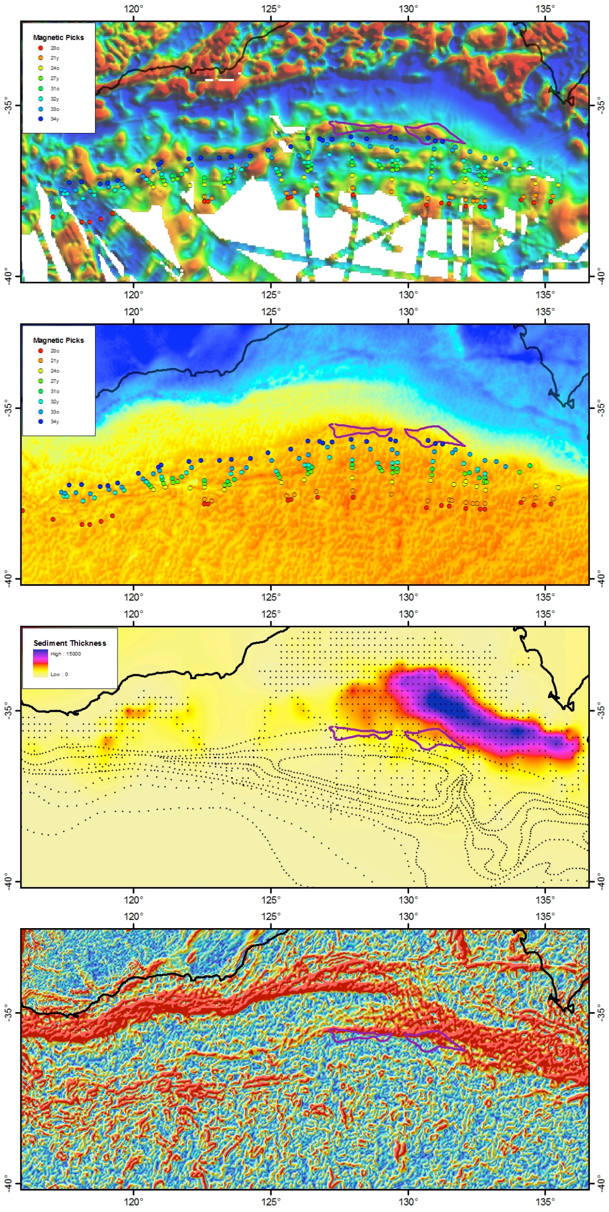


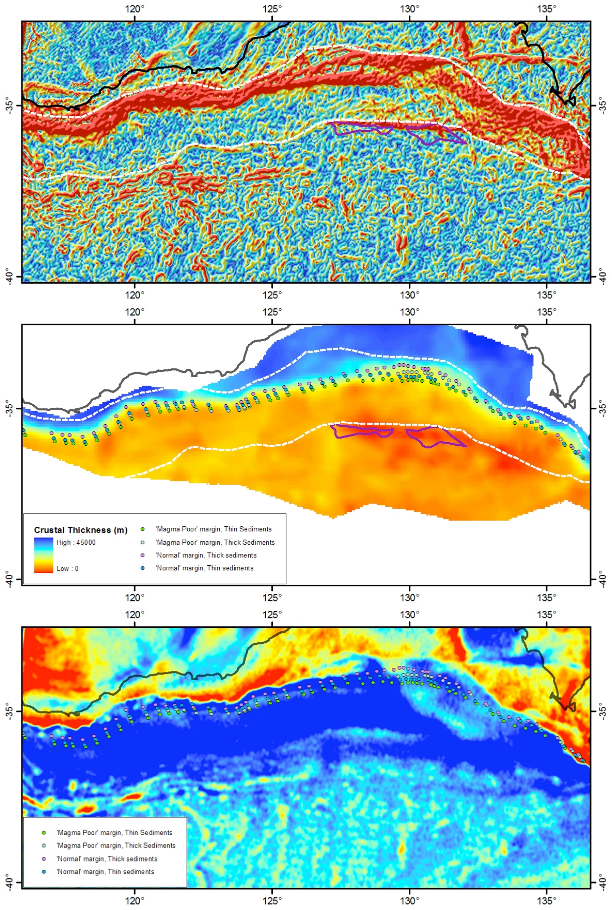
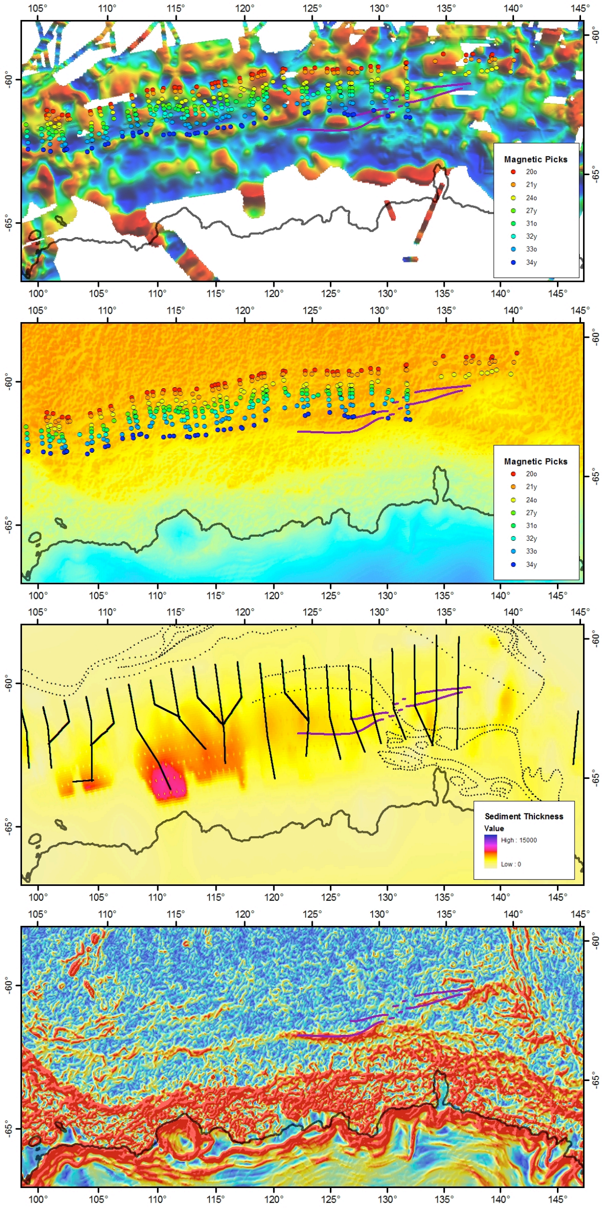


Figure 1. Potential field data for the southern Australian continental margin. (a) Total magnetic intensity (EMAG3, Maus et al, 2007); (b) Bouguer gravity anomaly; (c) Estimated Sediment thickness, with dots showing locations of data used to derived the regional grid; (d) Total horizontal gradient of the 1km upward continued Bouguer gravity; (e) Same as (d), but calculated for a gravity anomaly with the estimated gravity effect of the sediments removed; (f) Crustal thickness derived by gravity inversion, with estimates of the pre-rift plate boundary location; (g) Free-air gravity, with estimates of the pre-rift plate boundary. Purple lines show locations of peridotite ridges (from Sayers et al, 2001); White dashed lines show landward and oceanward limits of ‘certain’ stretched continental crust used to derive pre-rift plate boundary locations.



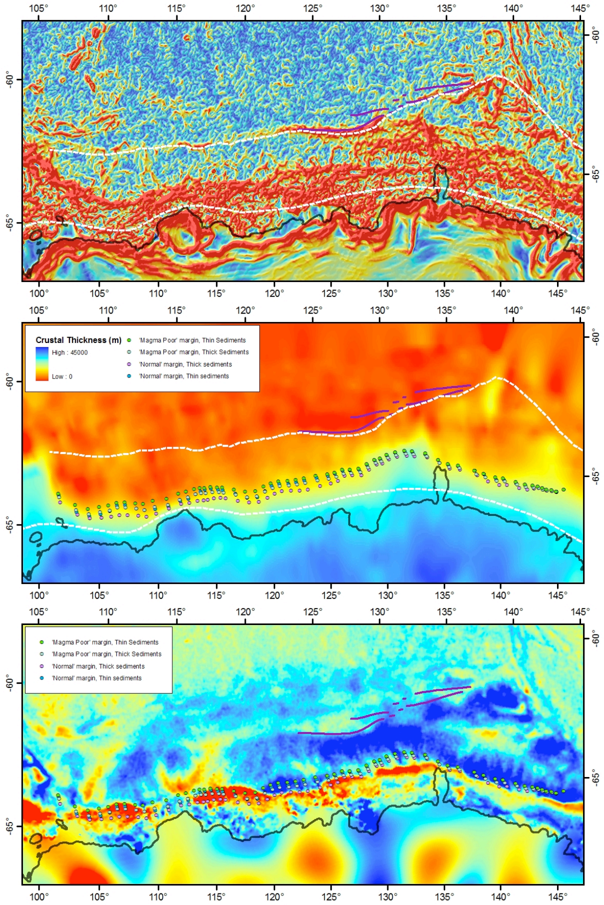


Figure 2. Potential field data for the Wilkes Land continental margin of Antarctica. (a) Total magnetic intensity (EMAG3); (b) Bouguer gravity anomaly; (c) Estimated Sediment thickness, with dots showing locations of data used to derived the regional grid; (d) Total horizontal gradient of the 1km upward continued Bouguer gravity; (e) Same as (d), but calculated for a gravity anomaly with the estimated gravity effect of the sediments removed; (f) Crustal thickness derived by gravity inversion, with estimates of the pre-rift plate boundary location; (g) Free-air gravity, with estimates of the pre-rift plate boundary. Purple lines show locations of peridotite ridges (from O'Brien and Stagg, 2007); White dashed lines as figure 1.