# Australian-Antarctic rifting

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## Introduction

Rifting between Australia and Antarctic began as early as 140 MM years ago. However, the timing of continental breakup and the manner in which rifting proceeded have remained controversial. A major reason for the ambiguity surrounding the Australian-Antarctic breakup and early spreading history is the lack of a clear boundary between continental and oceanic crust. Instead of a sharp boundary there is a zone of transitional crust, up to 120 km in width, along the entire conjugate southern Australian and east Antarctic margins (Sayers et al. 2001). The presence of wide zones of so-called transitional crustal on conjugate rifted Australian-Antarctic margins have resulted in considerable scientific debate regarding the nature of the transitional crust. Here we assess the ability of available data to discriminate between different hypotheses regarding the nature of the crust of the Australian-Antarctic conjugate transition zones. We also assess the suitability of applying depth-dependent rifting models recently developed for the well-studied Iberian-Newfoundland conjugate margins to the Australian-Antarctic context in order to resolve the nature of the transitional crust and the manner in which it formed.

The nature of the crust in the continent-ocean transition zone is ambiguous as it exhibits both a tilted-block basement morphology, generally suggestive of continental crust, but also linear magnetic anomalies (chrons 33 and 34) that are normally associated with oceanic crust, as summarised by Gohl (2008). Here, we define the inboard boundary of the continent-ocean transition zone (COTZ) using a distinctive gravity high that corresponds to basement ridges identified in seismic profiles from both the central southern Australian and Wilkes Land margins (Fig. 1 – red line), and the oceanward boundary of the COTZ as the isochron delineated by identifications of magnetic anomaly 33 (79 Ma) (Fig. 1 – blue line). The presence of symmetric magnetic lineations in apparent extended continental crust means there is no consensus as to the crustal nature of the COTZ. Three main hypotheses have been proposed to explain the crustal nature of the COTZ. Hypothesis 1 suggests that conjugate magnetic lineations are sourced from magmatic segments embedded in highly extended and faulted continental crust, Antarctica (e.g. Colwell et al. 2006). Hypothesis 2 suggests that the crust is mainly oceanic in nature, and represents an end-member of slow, relatively amagmatic spreading (e.g. Tikku & Cande 1999). Hypothesis 3 suggests that the COTZ is composed of exhumed continental mantle (e.g. Beslier et al. 2004).

A variety of geological and geophysical data has been published by various authors to support these three hypotheses regarding the composition of the COTZ. Sayers et al. (2001) and Colwell et al. (2006) used seismic reflection and refraction data to observe that the COTZ is characterised by thin post-breakup sediments overlying a tilted basement block morphology, which generally indicates thinned continental crust. The COTZ is bounded landward by a basement ridge complex, interpreted by Sayers et al. (2001) and Colwell et al. (2006) to be composed of serpentinised peridotites. In this hypothesis, the COTZ is interpreted as formed from highly stretched continental crust containing mafic intrusions that produce the observed linear magnetic anomalies ─ sea floor spreading may have ranged from commencing in association with magnetic chron 33 in the Central Australian Bight region to chron 20 farther to the west (Sayers et al. 2001; Colwell et al. 2006).

Alternatively, magnetic and dredge data have led other researchers to propose that at least some of the COTZ is deformed oceanic or exhumed mantle in nature (e.g. Beslier et al. 2004; Mutter and Cande 1983; Royer and Sandwell 1989; Munschy et al. 1992; Munschy 1998). It is possible that ultra-slow and/or episodic spreading, from ~83 Ma to 50 Ma, led to the observed rough basement topography. Basement morphology is strongly correlated with spreading rate, with slower spreading rates correlating to rougher basement topographies (e.g. Small & Sandwell 1989). Intermittent crustal addition (Shillington et al. 2006), oblique sea floor spreading and the temperature and fertility of the underlying mantle (Whittaker and Müller 2008) are also known to influence basement morphology. Backstripping curves of Totterdell et al. (2000) show that subsidence rates in the Central Australian Bight region diminish from ~85–83 Ma onwards, a pattern typical of thermally-driven subsidence, which is indicative of a transition from continental rifting to sea floor spreading. Further support that the COTZ is composed of oceanic or mantle material comes from the interpretation by Totterdell and Bradshaw (2004) of a break-up unconformity at ~83 Ma in the Central Australian Bight region. In all cases, linear magnetic anomalies may be produced by mantle serpentinisation and/or syn-extensional intrusions.

Different rifting models that account for the formation of symmetric linear magnetic anomalies in a block-faulted basement, will require, or be compatible, with varying geological and geophysical characteristics. These parameters are testable and will likely enable resolution regarding the nature of the crust in the Australian-Antarctic COTZ.

The formation of symmetric linear magnetic anomalies in an ultra-slow to slow sea floor spreading system is unproblematic. Consequently, various authors have proposed ultra-slow to slow sea floor spreading models to explain the COTZ (Tikku & Cande 1999; Whitmarsh & Sawyer 1996; Cannat 1993). However, the formation of pairs of symmetric magnetic lineations on conjugate margins over 1000 km long, akin to normal sea floor spreading anomalies, within stretched continental crust or exhumed continental mantle is more difficult to explain. A number of models have been proposed for a transition zone composed of extended continental crustal or mantle material, including thinned continental crust underplated with gabbroic material (Whitmarsh & Miles 1995; Whitmarsh & Sawyer 1996), large-scale detachment

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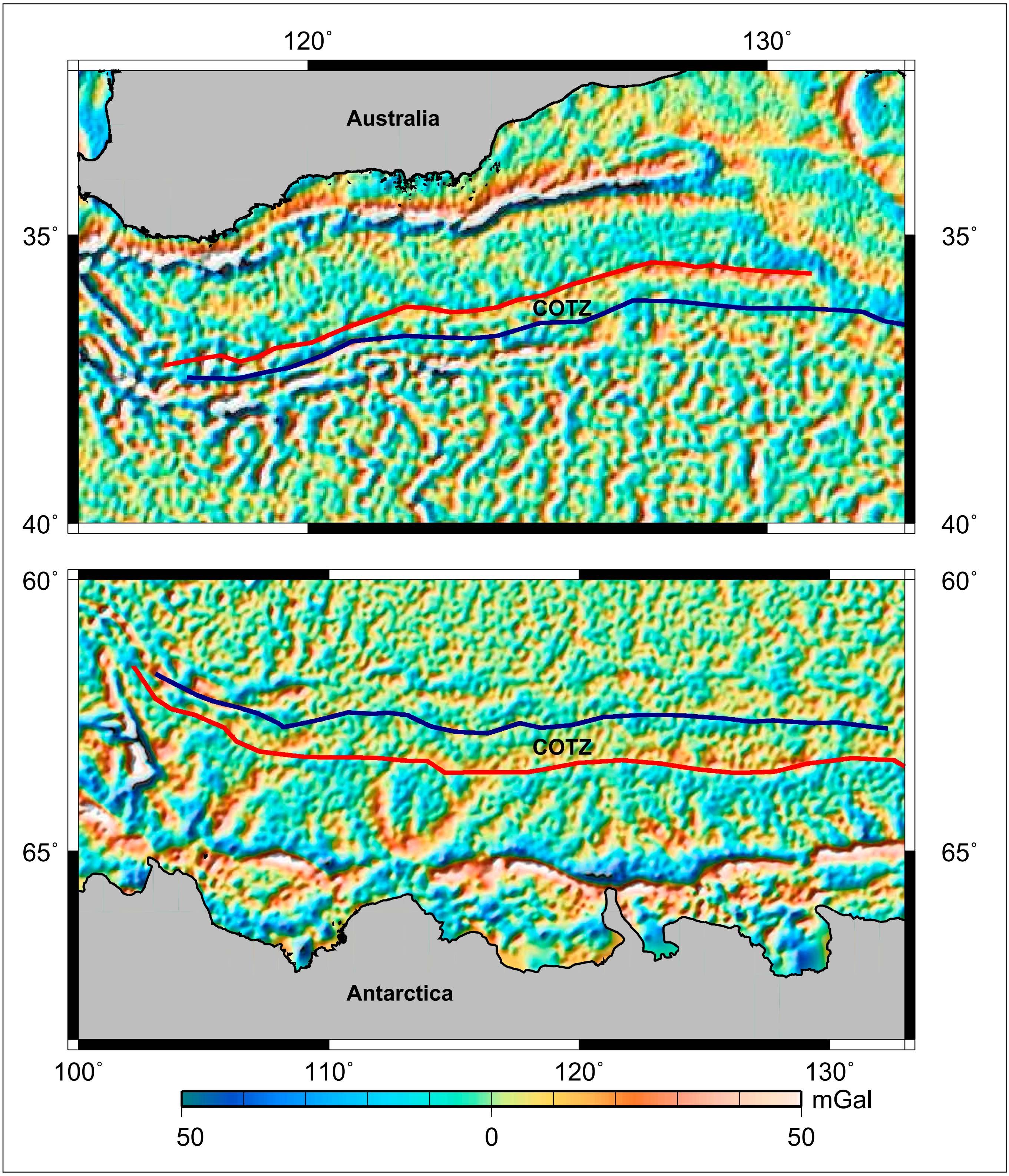

**Figure 1** Location of the Continent-Ocean Transition Zone (COTZ) on the southern Australia (top) and east Antarctic (bottom) margins. This study defines (1) the inboard boundary of the COTZ (red line) using a distinctive gravity high that corresponds to basement ridges identified in seismic profiles from both the central southern Australian and Wilkes Land margins and (2) the oceanward boundary of the COTZ (blue line) as the isochron delineated by identifications of magnetic anomaly 33 (79 Ma) from Tikku and Cande (1999) and Whittaker et al. (Sayers et al. 2001).

faulting resulting in progressive unroofing of the deep lithosphere (Krawczyk et al. 1996), and depth-dependent stretching of brittle upper and ductile lower layers (Sayers et al. 2001).

## Iberian-Newfoundland conjugate margins

The Iberian-Newfoundland rift system has many similarities with the Australian-Antarctic conjugate margins, including a wide transition zone between continental and oceanic crust that juxtaposes a block-faulted basement with magnetic anomalies. Extensive research has found that the Iberian-Newfoundland transition zones are composed of exhumed continental mantle rather than extended continental or oceanic material (Whitmarsh et al 2001). In order to account for the presence of exhumed continental mantle, models for the Iberia-Newfoundland rift system have moved away from uniform stretching models to depth-dependent stretching models. Extension in the Iberian-Newfoundland system occurs in two main phases separated by approximately 15 MM years (Péron-Pinvidic et al. 2007). A polyphase evolution model of margin development has been developed for the Iberian-Newfoundland system with three major modes of extension; a stretching mode, a thinning mode and an exhumation mode (Whitmarsh et al. 2001). When continental rifting and rift basin formation occurred, the continental lithosphere remained intact. A prolonged extensional phase (~15 MM years) subsequently unroofed this continental mantle until rifting of the continental lithosphere finally occurred (e.g. Tucholke & Whitmarsh 2007; Kusznir & Karner 2007). Normal sea floor spreading commenced at the time of continental lithospheric rifting. For the Iberian-Newfoundland margin, the interpreted ‘breakup’ unconformity separating synrift sediments from postrift sediments coincides with the mechanical decoupling of the lithosphere rather than the first occurrence of ‘oceanic crust’ (Péron-Pinvidic et al. 2007).

The Iberian-Newfoundland transition zone is characterised by magnetic anomalies and a pronounced basement topography, characteristics it is known to share with the Australian-Antarctic margin. To explain the presence of linear magnetic anomalies, dredged mantle rocks and a block faulted basement, Sibuet et al. (2007) propose a mechanism by which linear magnetic anomalies are formed over a large lateral area by mantle exhumation and serpentinisation (leading to magnetisation) in thinned continental crust. The Iberian-Newfoundland margin is also characterised by a particular seismic velocity profile with strong gradients and no clear Moho reflection.

## Results from the Australian-Antarctic conjugate margins

Recently acquired seismic velocity data derived from a synthesis of seismic refraction and sonobuoy information have allowed us to map the lithospheric structure of the Australian-Antarctic margins in a revised plate reconstruction context. This dataset will enable comparison of lithospheric margin structures predicted by different models of Australian-Antarctic margin formation with observed structures reconstructed to an initial rift context.

In order to create the palaeo-velocity depth slices, velocity data points from the Australian and Antarctic margins are restored to their palaeo-locations at 50 Ma, 65 Ma and 83 Ma. Velocity data situated on ocean crust younger than the reconstructed age are excluded from the reconstruction. The data points are rotated back through time using finite poles of rotation (Whittaker et al. 2007) that describe northwest–southeast relative motion between Australian and Antarctica prior to 50 MM years, and north–south relative motion from 50 MM years to the present. After reconstruction of the velocity data points to their palaeo-locations, velocity grids are created at 1 km depth intervals from 5 km to 15 km depth. Gridding of the velocity data after reconstruction allows interpolation between points that were adjacent at 50 Ma, 65 Ma or 83 Ma, but are currently separated by 1000s of kilometers, leading to more accurate calculations of Australian-Antarctic margin crustal architecture as rifting and sea floor spreading progressed. The same data point reconstruction technique has also been used to reconstruct crustal and pre-rift sediment thickness.

Our novel approach to reconstructing seismic velocity and other associated data, including crustal and sediment thickness, provides crucial new information about the structure of the Australian-Antarctic margin. When used in combination with seismic reflection and refraction, magnetic, and gravity data, this will enable resolution of the crustal composition and formation mechanism of the COTZ.

Understanding the compositional nature of the COTZ is crucial not only to understanding the mechanism and timing of Australian-Antarctic breakup and rifting, but also to accurately reconstruct the Cenozoic and Late Cretaceous relative plate motions of Australia and Antarctica. Plate tectonic reconstructions are predominantly based on marine magnetic and fracture zone data. It is therefore imperative to know the compositional nature of crust that exhibits magnetic lineations interpreted to be chron 33 and 34 on the Australian–Antarctic margins in order to know whether these anomalies can be utilised for reconstruction purposes. If magnetic anomalies 33 and 34, both located within the COTZ, are due to the presence of serpentinised ridges lying within continental crust, then they cannot be used as constraints for the derivation of finite reconstructions. Conversely, if the crust of the COTZ is composed of ‘normal’ but highly deformed oceanic material, then magnetic anomalies 33 and 34 can be used to understand the relative motions that have occurred between Australia and Antarctica. Presently there are two main reconstructions for the Australian-Antarctic breakup and early rift history. The essential difference between these models is the relative direction of motion, either north–south or northwest–southeast, between Australia and Antarctica from ~53 Ma until full closure is achieved at either chron 32 or chron 34, depending on the interpretation of the nature of the crust of the COTZ. Knowing the crustal nature of the COTZ, and the inclusion or exclusion of magnetic chrons 33 and 34, would likely lead to resolution regarding the early relative plate tectonic history of Australia and Antarctica.

We feel that the Australian-Antarctic conjugate margins share enough similar geological and geophysical characteristics with the Iberia-Newfoundland rift system to justify applying depth-dependent rifting models developed for the Iberia-Newfoundland margin in an Australian-Antarctic rift system context. Close examination of all available geological and geophysical data will lead to a greater understanding regarding the nature of the crust in the controversial COTZ and the history of the Australian-Antarctic rift system from continental breakup through to the onset of ‘normal’ sea floor spreading. Development of an accurate model describing the breakup of Australia and Antarctica will allow a better understanding of the temporal tectonic and thermal regimes influencing the basins of the southern Australian margin from 140 Ma to 50 Ma. Accurate delineation of the boundaries between continental, transitional and oceanic crust are also important for reconstructing paleo-bathymetries, as the nature of the crust on the Australian-Antarctic margins may produce considerable differences in the width and depths of gateways for paleo-ocean currents (Gohl 2008).

# References

BESLIER, M. O., ROYER, J. Y., GIRARDEAU, J., HILL, P. J., BOEUF, E., BUCHANAN, C., CHATIN, F., JACOVETTI, G., MOREAU, A., MUNSCHY, M., PARTOUCHE, C., ROBERT, U. and THOMAS, S., 2004. A wide ocean-continent transition along the south-west Australian margin: first results of the MARGAU/MD110 cruise. Bulletin De La Societe Geologique

De France, v. 175, 629–641.

CANNAT, M., 1993. Emplacement of mantle rocks in the sea floor at mid-ocean ridges. Journal of Geophysical Research, v. 98, 4163–4172.

COLWELL, J. B., STAGG, H. M. J., DIREEN, N. G., BERNARDEL, G. and BORISSOVA, I., 2006. The structure of the continental margin off Wilkes Land and Terre Adélie, East Antarctica. IN FÜTTERER, D. K., DAMASKE, D., KLEINSCHMIDT, G., MILLER, H. and TESSENSOHN, F. (Eds), Antarctica: Contributions to Global Earth Sciences, Berlin, Springer Verlag.

GOHL, K., 2008. Antarctica's Continent-Ocean Transitions: Consequences for Tectonic Reconstructions. IN COOPER, A. K., BARRETT, P. J., STAGG, H., STOREY, B., STUMP, E., WISE, W. and TEAM, A. T. T. I. E. (Eds), Antarctica: Keystone in a Changing World, Proceedings of the 10th International Symposium on Antarctic Earth Sciences, Washington, DC, The National Academies Press.

KRAWCZYK, C. M., RESTON, T. J., BESLIER, M. O. and BOILLOT, G. (1996), Evidence for detachment tectonics on the Iberia Abyssal Plain rifted margin. Proc. ODP, Sci. Results, v. 149, 603–615.

KUSZNIR, N. and KARNER, G., 2007. Continental lithospheric thinning and breakup in response to upwelling divergent mantle flow: application to the Woodlark, Newfoundland and Iberia margins. *In*: KARNER, G., MANATSCHAL, G. & PINHEIRO, L. (Eds), Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup, London, Geological Society.

MUNSCHY, M., 1998. La zone de Diamantine, temoin de la separation de l'Australie et de l'Antarctique: arguments geophysiques. Comptes Rendus de l'Academie des Sciences - Series IIA - Earth and Planetary Science, v. 327, 533–540.

MUNSCHY, M., DYMENT, J., BOULANGER, M. O., BOULANGER, D., TISSOT, J. D., SCHLICH, R., ROTSTEIN, Y. and COFFIN, M. F., 1992. Break-up and sea floor spreading between the Kerguelen Plateau-Labuan Basin and Broken Ridge-Diamantina Zone. *In*: WISE, S. W. J., SCHLICH, R. & AL., E. (Eds), Proceedings of the Ocean Drilling Program, Scientific Results, College Station, Texas, ODP.

MUTTER, J. C. and CANDE, S. C., 1983. The early opening between Broken Ridge and Kerguelen Plateau. Earth and Planetary Science Letters, v. 65, 369–376.

PÉRON-PINVIDIC, G., MANATSCHAL, G., MINSHULL, T. A. and SAWYER, D. S., 2007. Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: Evidence for a complex breakup history. Tectonics, v. 26, doi:10.1029/2006TC001970.

ROYER, J.-Y. and SANDWELL, D. T., 1989. Evolution of the Eastern Indian Ocean since the Late Cretaceous: Constraints from Geosat altimetry. Journal of Geophysical Research, v. 94, 13755–13782.

SAYERS, J., SYMONDS, P. A., DIREEN, N. G. and BERNADEL, G., 2001. Nature of the continent-ocean transition on the non-volcanic rifted margin in the central Great Australian Bight. *In*: WILSON, R. C. L., WHITMARSH, R. B., TAYLOR, B. and FROITZHEIM, N. (Eds), Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geological Society of London.

SHILLINGTON, D. J., HOLBROOK, W. S., VAN AVENDONK, H. J. A., TUCHOLKE, B. E., HOPPER, J. R., LOUDEN, K. E., LARSEN, H. C. and NUNES, G. T., 2006. Evidence for asymmetric nonvolcanic rifting and slow incipient oceanic accretion from seismic reflection data on the Newfoundland margin. Journal of Geophysical Research, 111, doi:10.1029/2005JB003981.

SIBUET, J.-C., SRIVASTAVA, S. and MANATSCHAL, G., 2007. Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies. Journal of Geophysical Research, 112.

SMALL, C. and SANDWELL, D. T., 1989. An abrupt change in ridge-axis gravity with spreading rate. Journal of Geophysical Research, v. 94, 17383–17392.

TIKKU, A. A., 1999. Late Cretaceous to Early Tertiary tectonics of the Southeast Indian Ocean. Scripps Institute of Oceanography. San Diego, University of California.

TIKKU, A. A. and CANDE, S. C., 1999. The oldest magnetic anomalies in the Australian-Antarctic Basin: Are they isochrons? Journal of Geophysical Research, v. 104, 661–677.

TOTTERDELL, J. M., BLEVIN, J. E., STRUCKMEYER, H. I. M., BRADSHAW, B. E., COLWELL, J. B. and KENNARD, J. M., 2000. A new sequence framework for the great Australian Bight: starting with a clean slate. APPEA Journal, v. 40, 95–117..

TOTTERDELL, J. M. and BRADSHAW, B. E., 2004. The structural framework and tectonic evolution of the Bight Basin. Eastern Australasian Basins Symposium II, *In:* Boult, P.J., Johns, D.R. and Lang, S.C. (Eds), PESA Special Publication, 41–61..

TUCHOLKE, B. E. and WHITMARSH, R. B., 2007. The Newfoundland-Iberia Conjugate Rifted Margins. *In*: BALLY, A. W. & ROBERTS, D. G. (Eds), Principles of Phanerozoic Regional Geogolgy.

WHITMARSH, R. B., MANATSCHAL, G. and MINSHULL, T. A., 2001. Evolution of magma-poor continental margins from rifting to sea floor spreading. Nature, v. 413, 150–154.

WHITMARSH, R. B. and MILES, P. R., 1995. Models of the Development of the West Iberia Rifted Continental Margin at 40°30'N deduced from Surface and Deep-Tow Magnetic Anomalies. Journal of Geophysical Research, v. 100, 3789–3806.

WHITMARSH, R. B. and SAWYER, D. S., 1996. The ocean/continent transition beneath the Iberia Abyssal Plain and continental-rifting to sea floor-spreading processes. Proc. ODP, Sci. Results, v. 149, 713–733.

WHITTAKER, J. and MÜLLER, R. D., 2008. The origin of sea floor roughness. EGU General Assembly, Vienna, Austria.

WHITTAKER, J. M., MÜLLER, R. D., LEITCHENKOV, G., STAGG, H., SDROLIAS, M., GAINA, C. and GONCHAROV, A., 2007. Major Australian-Antarctic plate reorganisation at Hawaiian-Emperor bend time. Science, v. 138, 83–86.