Gondwana breakup and plate kinematics: Business as usual

Graeme Eagles[1] and Alan P. M. Vaughan[2]

Received 30 January 2009; revised 23 April 2009; accepted 24 April 2009; published 23 May 2009.

[1] A tectonic model of the Weddell Sea is built by composing a simple circuit with optimized rotations describing the growth of the South Atlantic and SW Indian oceans. The model independently and accurately reproduces the consensus elements of the Weddell Sea's spreading record and continental margins, and offers solutions to remaining controversies there. At their present resolutions, plate kinematic data from the South Atlantic and SW Indian oceans and Weddell Sea rule against the proposed, but controversial, independent movements of small plates during Gondwana breakup that have been attributed to the presence or impact of a mantle plume. Hence, although supercontinent breakup here was accompanied by extraordinary excess volcanism, there is no indication from plate kinematics that the causes of that volcanism provided a unique driving mechanism for it. **Citation:** Eagles, G., and A. P. M. Vaughan (2009), Gondwana breakup and plate kinematics: Business as usual, *Geophys. Res. Lett.*, *36*, L10302, doi:10.1029/2009GL037552.

1. Introduction

[2] As it opened, the Weddell Sea was situated near the heart of Gondwana and the concurrence of several large igneous provinces, leading to its plate kinematic and volcanic history being used in generating and testing ideas about the dynamics of supercontinent breakup [*Storey*, 1995]. Kinematic schemes for the region featuring numerous small plates and vast areas of non-rigid continental deformation [*Dalziel and Lawver*, 2001] are consistent with models of fragmentation over mantle plume-related uplifts [*Gurnis*, 1988]. Such arrangements imply something super about supercontinents: a deformational style during breakup that significantly diverges from that implied by plate tectonics. Here we examine this issue using a new plate kinematic model for the region.

2. Rotating Fold Belts and the Weddell Sea

[3] *Adie* [1952] and *Schopf* [1969] suggested that Permo-Triassic fold belts in the Falkland Islands and Ellsworth-Whitmore Mountains dispersed from between Africa and East Antarctica's Cape and Pensacola Mountains fold belts (Figure 1). Although such placement leaves little space in Gondwana for the Precambrian Maurice Ewing Bank, the Mesozoic apparent polar wander paths of rocks from Ellsworth Land and the Falkland Islands can be interpreted as if they experienced, as parts of small plates that moved rapidly and independently of major plate motion, 90°–100° of vertical-axis rotation and hundreds of kilometres of translation along the margins of the Weddell Sea and Falkland Plateau [*Grunow et al.*, 1987; *Taylor and Shaw*, 1989]. These motions imply that Falkland Plateau and Weddell Sea Embayment basins form a space like that swept out by the doors of a wild-west saloon bar [*Martin*, 2007]. However, there is little evidence at the basin margins for the complicated variation in plate boundary processes that would have accompanied this [*Richards et al.*, 1996; *Hübscher et al.*, 1996; *Studinger and Miller*, 1999; *Ferris et al.*, 2002; *von Gosen and Loske*, 2004].

[4] A proposed resolution to this quandary invokes widespread non-rigid crustal growth in the basins, promoted by the heat of regional Karoo–Ferrar excess magmatism [*Dalziel and Lawver*, 2001]. The Afar Triangle is suggested as a modern analogue. There are problems with this idea. Firstly, the Falklands rotation post-dates the 183 Ma magmatic peak (178–121 Ma [*Stone et al.*, 2008]), as do 400 km of translation and 15° rotation of the Ellsworth block, suggested to have occurred as part of a 'Weddellia' plate [*Grunow et al.*, 1987; *Dalziel and Lawver*, 2001]. Secondly, at the plate scale, geological and geophysical data from the Afar Triangle are quite explicable in terms of rigid plate motions [e.g., *Chu and Gordon*, 1998; *Eagles et al.*, 2002].

[5] Because of this, it is reasonable to expect to find identifiable traces of independent post-183 Ma plate motions in the Weddell Sea and at its margins, and so to be able to model those motions using geophysical and geological data. Unfortunately, subduction has obscured the conjugate to the Weddell Sea, leaving only a remote, ice covered and heavily sedimented half spreading system (Figure 2). Consequently, basement geophysical signals are fragmentary, weak, and of limited value as kinematic markers south of 70°S. For example, some models that satisfy these data show Jurassic—Cretaceous convergence, instead of the expected divergence, between Ellsworth Land and Coats Land [*Dalziel and Lawver*, 2001; *Ghidella et al.*, 2002] whereas others reject any such motion in favour of various Patagonian and Falkland plates [e.g., *König and Jokat*, 2006].

3. Plate Circuit Model

[6] One way of assisting interpretation of the Weddell Sea data is to derive a kinematic model for the encircling South American and Antarctic plates by closing the plate circuit they formed with Africa in opening the South Atlantic and SW Indian oceans. Large disagreements between such a model and real kinematic markers can be attributed to independent motions of small plates in the region. To do this confidently, inaccuracy in the kinematic model must be minimized. Inaccuracy in a model is not the same as the statistical uncertainty in its constituents that can

[1]Department of Earth Sciences, Royal Holloway University of London, Egham, UK.

[2]British Antarctic Survey, Cambridge, UK.

0094-8276/09/2009GL037552

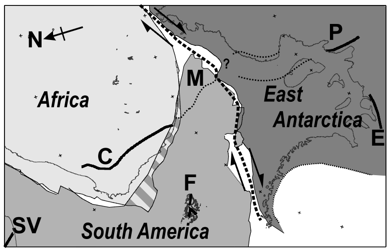

Figure 1. Three-plate reconstruction [*Eagles*, 2007; *Eagles and König*, 2008] with Permo-Triassic fold belts (thick black lines, C, Cape; E, Ellsworth-Whitmore Mountains; F, Falkland Islands; P, Pensacola Mountains; SV, Sierra de la Ventana). Hatched pattern: overlap. Dotted lines: possible links in the fold belt through Berkner Island, Coats Land, and Maurice Ewing Bank (M). Dashed line: plate boundary immediately after 183 Ma.

be derived using covariance matrices for rotation parameters and populations of minimised misfits of data sets with estimated precisions [e.g., *Kirkwood et al.*, 1999]. Statistical uncertainty cannot be calculated here because of *Eagles'* [2007] use of a visual fitting technique, but would be relatively meaningless because of the lack of any formal requirement for the summed rotations to satisfy the Weddell

Table 1. Finite Rotations for Motion of South America With Respect to East Antarctica[a]

Latitude	Longitude	Angle	Chron	Age	Notes
77.59	64.42	29.16	C34y	83.5	Circuit
74.92	57.18	30.76	Intra-C34 #1	unknown	Interpolated for visual fit
73.98	78.08	42.88	Intra-C34 #2	unknown	Interpolated for visual fit
72.70	82.86	45.24	C34o	124.61	Circuit
71.14	87.46	48.28	M5n	130.80	Circuit
66.31	90.59	53.71	M22	150.21	Circuit
64.62	92.65	54.64	M24	154.37	Circuit
60.17	98.51	59.74	FIT	183	Circuit

[a]Neogene extension of Africa has been taken account of using the rotation of *Royer et al.* [2006].

Sea data. Inaccuracy is more damaging to confidence and arises from erroneous interpretations or assumptions, or data absence, in kinematic models. It is this that has recently been reduced in models of the South Atlantic and SW Indian oceans [*Eagles*, 2007; *Eagles and König*, 2008]. Closing the circuit with these yields a model of Weddell Sea motions (Table 1) in which we can have high qualitative confidence; artefacts arising from the propagation of inaccuracies are minimized. As we will see, despite the lack of

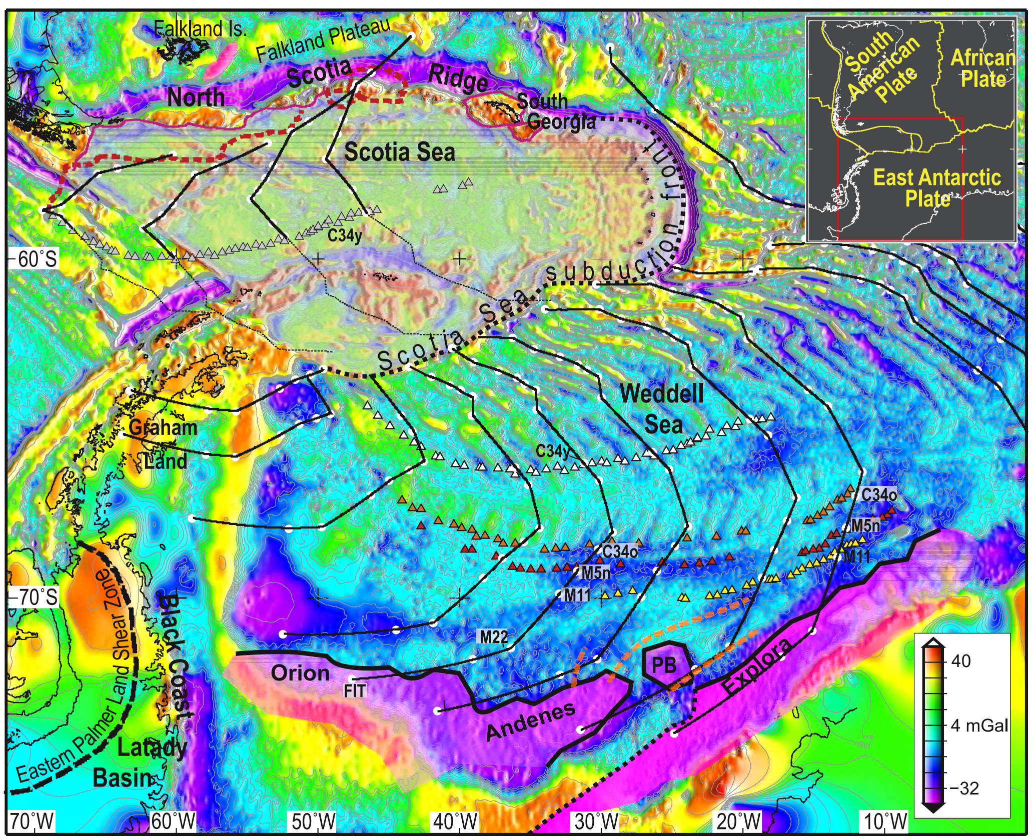

Figure 2. Synthetic Weddell Sea spreading system (black lines with white discs at constrained points) plotted over gravity anomalies [*Sandwell and Smith*, 1997; *McAdoo and Laxon*, 1997]. Violet: magnetic anomalies. Red dashed lines: pre-Neogene positions of North Scotia Ridge and South Georgia. Triangles denote magnetic anomalies from *König and Jokat* [2006]: C34y (white and grey, rotated to South America), C34o (orange), M5n (red) and M11 (yellow). Orange dashed lines: channel-levee systems. PB, Polarstern Bank. Inset: Major plates and boundaries at the present day.

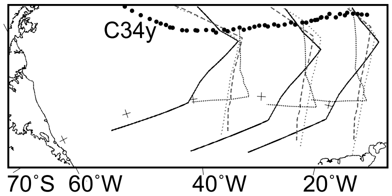

Figure 3. Comparison of synthetic flowlines from this study (continuous lines) with those from *Ghidella et al* [2002] (grey, dotted, post-165 Ma), *König and Jokat* [2006] (grey, dashed, post-150 Ma) and *Dalziel and Lawver* [2001] (black, dashed, post-165 Ma).

such any requirement to do so, our rotations satisfy the Weddell Sea data quite well.

4. Seafloor Spreading and the Margins of the Weddell Sea

[7] Figure 2 compares geophysical data to a synthetic Weddell Sea spreading system defined from Table 1, anchored at anomaly C34y. Using a similar approach to this, *Nankivell* [1996] proved a two plate system in the Weddell Sea at C34y, a result that we independently duplicate. Predictions of anomalies C34o, M5n and M11 (by linear interpolation) also match, to <15 km, published anomaly identifications [*König and Jokat*, 2006], qualitatively confirming the existence of just two plates back to at least 136 Ma. Despite the demonstrable closure of the circuit at each end of the Cretaceous superchron, C34, the two interpolated rotations within it do not explicitly close the circuit as no similarly-dated rotations exist for the South Atlantic and SW Indian oceans. In older seafloor, *Livermore and Hunter* [1996], *LaBrecque and Ghidella* [1997], and *Kovacs et al.* [2002] interpreted FZs under NE-striking gravity and magnetic anomalies (e.g., west of 33°W, 69°S) and, further south, very low amplitude ENE-trending gravity anomalies (e.g., north of Polarstern Bank). These latter anomalies parallel contourite channel-levee systems [*Michels et al.*, 2002], but variations in basement topography suggest a tectonic component [*Rogenhagen et al.*, 2004]. Despite alternative interpretations, these FZ trends are reproduced in the synthetic flowlines, and are thus consistent with a two-plate Weddell Sea since the onset of seafloor spreading. Figure 3 shows that the use of independent plates, as in alternative reconstructions, produces flowlines that fail to reproduce the published FZ trends and so suggests that such plates are unnecessary.

[8] The Weddell Sea's margins support a two-plate interpretation. Off the Black Coast, the oldest (~183 Ma) segments of the synthetic flowlines terminate at a N-trending continent-ocean boundary [*Ferris et al.*, 2002]. The magnetically quiet shelf here displays a deep gravity low over a sedimentary basin whose fill is exposed onshore as the post-185 Ma Latady Formation [*Willan and Hunter*, 2005]. This suggests that the basin formed at the East Gondwana margin and has not since moved with respect to it. To the east, continental-slope related gravity anomalies lie landward of a set of prominent magnetic anomalies (dubbed Explora, Andenes, and Orion). The oldest parts of the synthetic flowlines parallel these anomalies, faithfully reproduce their 45° variation in strike, and subsequently bend away from them with the onset of South Atlantic relative motions. These relationships suggest how a transform-dominated plate boundary evolved to an extended margin, as from *Kristoffersen and Haugland*'s [1986] interpretation of seaward dipping basalt flows overlying steep basement scarps. A pronounced negative magnetic anomaly crosses the Weddell Sea Embayment to ~76°S [*Johnson et al.*, 1992] and is related to *Kristoffersen and Haugland*'s [1986] transtensional rift. This may be interpreted as an early East-West Gondwana boundary that was abandoned in favour of an Orion-Andenes branch. The thinned crust of the embayment [*Hübscher et al.*, 1996; *Studinger and Miller*, 1999] may record this abandonment, as the transtensional boundary stepped northwards.

[9] The northern conjugate margin, the North Scotia Ridge, is today a chain of bathymetric highs whose western parts converged with the Falkland Plateau whilst the remainder moved eastwards away from them during Miocene seafloor spreading in the west Scotia Sea [*Eagles et al.*, 2005]. With these movements reconstructed (Figure 2), the ridge lies adjacent and subparallel to the oldest parts of the synthetic flowlines, as would be expected of a conjugate to the southern Weddell Sea transform margin. Southern parts of the Falkland Plateau Basin, just to the north, might be related to pull-apart movements on this margin and to the later phase of margin-normal stretching. Trace element geochemistry of ~150 Myr old basalts and paleocurrent measurements from South Georgia confirm the existence of a narrow, transform-dominated, oceanic basin [*Alabaster and Storey*, 1990].

[10] The synthetic system fits into the Weddell Sea with two modest exceptions. First is an underlap between the flowlines and the continent-ocean boundary south of the Andenes Anomaly. The conjugate flowlines overlap with the reconstructed South Georgia, suggesting that seafloor was transferred from west to east Gondwana by a plate boundary jump towards South Georgia. Second, pre-Albian parts of the synthetic flowlines overlap the eastern margin of Graham Land. Graham Land's tectonic affinities are not fully understood, but it seems only to have occupied its present position in the Antarctic Peninsula since Albian times [*Vaughan and Livermore*, 2005]. The overlap is fully consistent with an Albian-aged Weddell Sea passive margin to Graham Land, and says nothing about the pre-Albian nature of that margin.

5. Anomalous Rotations, Gondwana Breakup, and Plate Kinematics

[11] The paleomagnetic enigmas of the Falkland Islands and Ellsworth Land undoubtedly relate to post-breakup processes [*Grunow et al.*, 1987; *Stone et al.*, 2008]. The strong resemblance of the Weddell Sea to the predictions of a two-plate model shows that these processes either did not act at the plate scale or, if they did so, it was outside the Gondwana plate circuit. Given Ellsworth Land's present position, vertical-axis rotations of upper crustal blocks at Gondwana's active margin might be invoked to explain its long-term anomalous apparent polar wander. Analogous rotations may have accompanied basin formation around

the Falkland Islands [*Hyam et al.*, 2000] as plate boundaries reorganised at the onset of South Atlantic opening.

[12] The difficulty of independently and unequivocally interpreting geophysical data in the Weddell Sea makes it impossible to assert that published alternative plate kinematic models are untenable when viewed in isolation. But those models are now challenged to justify the complexity they imply in the Gondwana plate circuit. The data available to us from the Weddell Sea to the West Somali Basin show that Gondwana broke up into just two plates by continental deformation in broad plate boundary zones and, afterwards, seafloor spreading in narrow ones. In these ways, plate kinematics during supercontinent breakup appears not to differ significantly from that during post-breakup times. Hence, although excess volcanism undoubtedly accompanied breakup, there is no evidence from plate kinematics that the causes of that volcanism had any unique dynamic influence on it.

[13] **Acknowledgments.** GE acknowledges support from Royal Holloway University of London. Figures were generated using GMT.

References

Adie, R. J. (1952), The position of the Falkland Islands in a construction of Gondwanaland, *Geol. Mag.*, *89*, 401–410.

Alabaster, T., and B. C. Storey (1990), Modified Gulf of California model for south Georgia, North Scotia Ridge, and implications for the Rocas Verdes back-arc basin, southern Andes, *Geology*, *18*, 497–500.

Chu, D., and R. G. Gordon (1998), Current plate motions across the Red Sea, *Geophys. J. Int.*, *135*, 313–328.

Dalziel, I. W. D., and L. A. Lawver (2001), The lithospheric setting of the West Antarctic Ice Sheet, in *The West Antartic Ice Sheet: Behavior and Environment*, *Antarct. Res. Ser.*, vol. 77, edited by R. B. Alley and R. A. Bindschadler, pp. 29–44, AGU, Washington, D. C.

Eagles, G. (2007), New angles on South Atlantic opening, *Geophys. J. Int.*, *168*, 353–361, doi:10.1111/j.1365-246X. 2006.03206.x.

Eagles, G., and M. König (2008), A model of plate kinematics in Gondwana breakup, *Geophys. J. Int.*, *173*, 703–717, doi:10.1111/j.1365-246X. 2008.03753.x.

Eagles, G., R. Gloaguen, and C. J. Ebinger (2002), Kinematics of the Danakil microplate, *Earth Planet. Sci. Lett.*, *203*, 607–620.

Eagles, G., R. A. Livermore, J. D. Fairhead, and P. Morris (2005), Tectonic evolution of the west Scotia Sea, *J. Geophys. Res.*, *110*, B02401, doi:10.1029/2004JB003154.

Ferris, J. K., A. P. M. Vaughan, and E. C. King (2002), A window on West Antarctic crustal boundaries: The junction between the Antarctic Peninsula, the Filchner Block, and Weddell Sea oceanic lithosphere, *Tectonophysics*, *347*, 13–23.

Ghidella, M. E., G. Yáñez, and J. L. LaBrecque (2002), Revised tectonic implications for the magnetic anomalies of the western Weddell Sea, *Tectonophysics*, *347*, 65–86.

Grunow, A. M., D. V. Kent, and I. W. D. Dalziel (1987), Ellsworth-Whitmore Mountains crustal block, western Antarctica: New paleomagnetic results and their tectonic significance, in *Gondwana Six: Structure, Tectonics and Geophysics*, *Geophys. Monogr. Ser.*, vol. 40, edited by G. D. McKenzie, pp. 161–172, AGU, Washington, D. C.

Gurnis, M. (1988), Large-scale mantle convection and the aggregation and dispersal of supercontinents, *Nature*, *332*, 695–699.

Hübscher, C., W. Jokat, and H. Miller (1996), Structure and origin of the southern Weddell Sea crust: Results and implications, in *Weddell Sea Tectonics and Gondwana Break-up*, edited by B. Storey, E. King, and R. Livermore, *Geol. Soc. Spec. Publ.*, vol. 108, pp. 201–211.

Hyam, D. M., J. E. A. Marshall, J. M. Bull, and D. J. Sanderson (2000), The structural boundary between East and West Falkland: New evidence for movement history and lateral extent, *Mar. Pet. Geol.*, *17*, 13–26.

Johnson, A. C., N. D. Aleshkova, P. F. Barker, A. V. Golynsky, V. N. Masolov, and A. M. Smith (1992), A preliminary aeromagnetic anomaly compilation map for the Weddell province of Antarctica, in *Recent Progress in Antarctic Earth Science*, edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 545–553, Terra Sci., Tokyo.

Kirkwood, B. H., J.-Y. Royer, T. C. Chang, and R. G. Gordon (1999), Statistical tools for estimating and combining finite rotations and their uncertainties, *Geophys. J. Int.*, *137*, 408–428.

Kovacs, L. C., P. Morris, J. Brozena, and A. Tikku (2002), Seafloor spreading in the Weddell Sea from magnetic and gravity data, *Tectonophysics*, *347*, 43–64.

König, M., and W. Jokat (2006), The Mesozoic breakup of the Weddell Sea, *J. Geophys. Res.*, *111*, B12102, doi:10.1029/2005JB004035.

Kristoffersen, Y., and K. Haugland (1986), Geophysical evidence for the East Antarctic plate boundary in the Weddell Sea, *Nature*, *322*, 538–541.

LaBrecque, J. L., and M. E. Ghidella (1997), Bathymetry, depth to magnetic basement, and sediment thickness estimates from aerogeophysical data over the western Weddell Basin, *J. Geophys. Res.*, *102*, 7929–7945.

Livermore, R., and R. Hunter (1996), Mesozoic seafloor spreading in the southern Weddell Sea, in *Weddell Sea Tectonics and Gondwana Break-up*, edited by B. Storey, E. King, and R. Livermore, *Geol. Soc. Spec. Publ.*, vol. 108, pp. 227–241.

Martin, A. K. (2007), Gondwana breakup via double-saloon-door rifting and seafloor spreading in a backarc basin during subduction rollback, *Tectonophysics*, *445*, 245–272.

McAdoo, D., and S. Laxon (1997), Antarctic tectonics: Constraints from a new ERS-1 satellite marine gravity field, *Science*, *276*, 556–561.

Michels, K. H., G. Kuhn, C.-D. Hillenbrand, B. Diekmann, D. K. Fütterer, H. Grobe, and G. Uenzelmann-Neben (2002), The southern Weddell Sea: Combined contourite-turbidite sedimentation at the southeastern margin of the Weddell Gyre, in *Deep- Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics*, edited by D. A. Stow et al., *Geol. Soc. Mem.*, vol. 22, pp. 305–323.

Nankivell, A. P. (1996), Tectonic evolution of the Southern Ocean, Ph.D. thesis, Oxford Univ., Oxford, U. K.

Richards, P. C., R. W. Gatliff, M. F. Quinn, J. P. Williamson, and N. G. T. Fannin (1996), The geological evolution of the Falkland Islands continental shelf, in *Weddell Sea Tectonics and Gondwana Break-up*, edited by B. Storey, E. King, and R. Livermore, *Geol. Soc. Spec. Publ.*, vol. 108, pp. 105–128.

Rogenhagen, J., W. Jokat, K. Hinz, and W. Kristoffersen (2004), Improved seismic stratigraphy of the Mesozoic Weddell Sea, *Mar. Geophys. Res.*, *25*, 265–282, doi:10.1007/s11001-005-1335-y.

Royer, J.-Y., R. G. Gordon, and B. C. Horner-Johnson (2006), Motion of Nubia relative to Antarctica since 11 Ma: Implications for Nubia-Somalia, Pacific-North America, and India-Eurasia motion, *Geology*, *34*, 501–504.

Sandwell, D. T., and W. H. F. Smith (1997), Marine gravity anomaly from Geosat and ERS 1 satellite altimetry, *J. Geophys. Res.*, *102*, 10,039–10,054.

Schopf, J. M. (1969), Ellsworth Mountains: Position in West Antarctica due to seafloor spreading, *Science*, *164*, 63–66.

Stone, P., P. C. Richards, G. S. Kimbell, R. P. Esser, and D. Reeves (2008), Cretaceous dykes discovered in the Falkland Islands: Implications for regional tectonics in the South Atlantic, *J. Geol. Soc. London*, *165*, 1–4.

Storey, B. C. (1995), The role of mantle plumes in continental breakup: Case histories from Gondwanaland, *Nature*, *377*, 301–308.

Studinger, M., and H. Miller (1999), Crustal structure of the Filchner-Ronne shelf and Coats Land, Antarctica, from gravity and magnetic data: Implications for the breakup of Gondwana, *J. Geophys. Res.*, *104*, 20,379–20,394.

Taylor, G. K., and J. Shaw (1989), The Falkland Islands: New paleomagnetic data and their origin as a displaced terrane from southern Africa, in *Deep Structure and Past Kinematics of Displaced Terranes*, *Geophys. Monogr. Ser.*, vol. 50, edited by J. W. Hillhouse, pp. 59–72, AGU, Washington, D. C.

Vaughan, A. P. M., and R. A. Livermore (2005), Episodicity of Mesozoic terrane accretion along the Pacific margin of Gondwana: Implications for superplume-plate interactions, in *Terrane Processes at the Margins of Gondwana*, edited by A. P. M. Vaughan, P. T. Leat, and R. J. Pankhurst, *Geol. Soc. Spec. Publ.*, vol. 246, pp. 143–178.

von Gosen, W., and W. Loske (2004), Tectonic history of the Calcatapul Formation, Chubut Province, Argentina, and the "Gastre Fault System", *J. S. Am. Earth Sci.*, *18*, 73–88.

Willan, R. C. R., and M. A. Hunter (2005), Basin evolution during the transition from continental rifting to subduction: Evidence from the lithofacies and modal petrology of the Jurassic Latady Group, Antarctic Peninsula, *J. S. Am. Earth Sci.*, *20*, 171–191.

G. Eagles, Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK. (g.eagles@es.rhul.ac.uk)

A. P. M. Vaughan, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. (alan.vaughan@bas.ac.uk)