



## Gondwana breakup and plate kinematics: Business as usual

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[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].

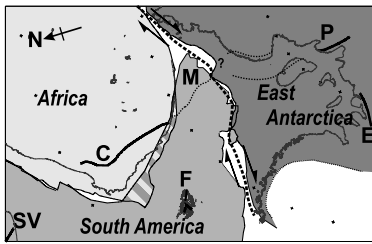
[5] Because of this, it is reasonable to expect to find identifiable traces of independent post-183 Ma plate motions in the Weddell Sea and at its margins, and so to be able to model those motions using geophysical and geological data. Unfortunately, subduction has obscured the conjugate to the Weddell 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

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**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.

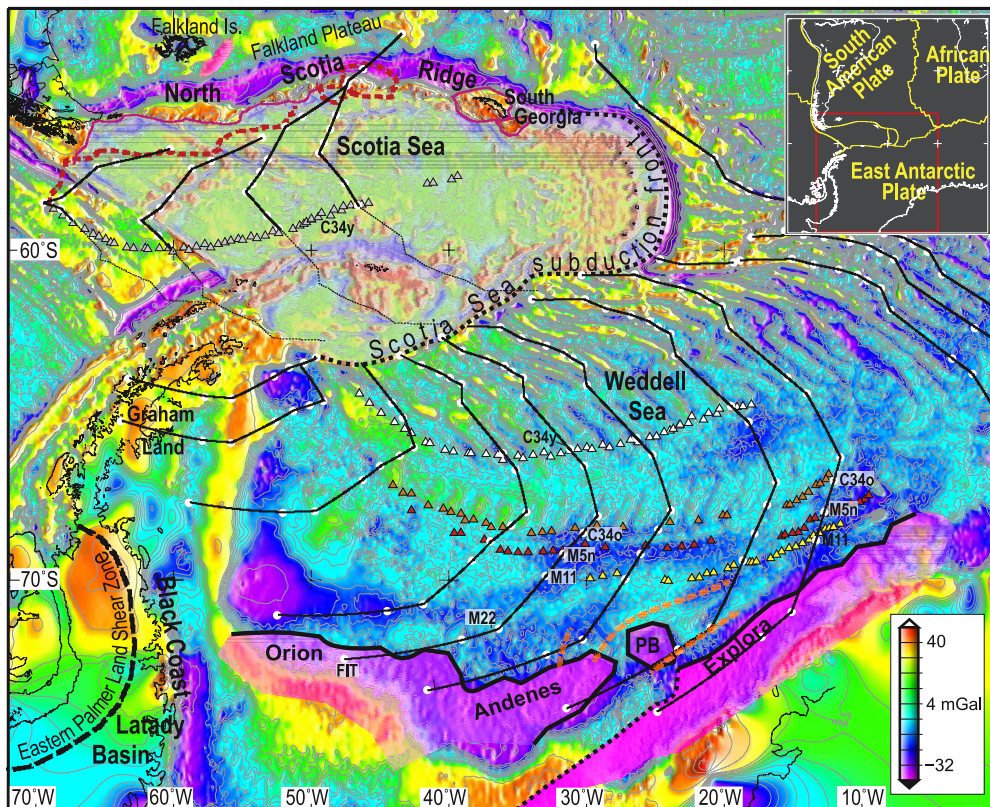
be derived using covariance matrices for rotation parameters and populations of minimised misfits of data sets with estimated precisions [e.g., Kirkwood *et al.*, 1999]. Statistical uncertainty cannot be calculated here because of Eagles' [2007] use of a visual fitting technique, but would be relatively 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<sup>a</sup>

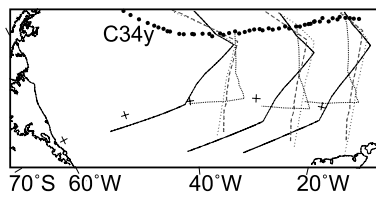
| Latitude | Longitude | Angle | Chron        | Age     | Notes                       |
|----------|-----------|-------|--------------|---------|-----------------------------|
| 77.59    | 64.42     | 29.16 | C34y         | 83.5    | Circuit                     |
| 74.92    | 57.18     | 30.76 | Intra-C34 #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                     |

<sup>a</sup>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; *Stüding 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.

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