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West Antarctic Rift System in the Antarctic Peninsula

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[1] Decades after the recognition of the West Antarctic Rift System, and in spite of its global importance, the location and nature of the plate boundary it formed at are unknown east of the Byrd Subglacial Basin. Alternative constructions of the circuit of South Pacific plate boundaries suggest the presence of either a transcurrent plate boundary or a continuation of the extensional rift system. We identify George VI Sound, a curved depression separating Alexander Island from Palmer Land, as the easternmost basin of a rift system that terminated at a triple junction with the Antarctic Peninsula subduction zone. The history of the triple junction's third, transform, arm suggests extension started around 33.5–30 Ma. A more speculatively identified basin further west may have formed earlier during the same episode of rifting, starting around 43 Ma. Proposals of earlier Cenozoic relative motion between East and West Antarctica cannot be verified from this region.

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1. Introduction

[2] The West Antarctic Rift System formed at a plate boundary that separated East and West Antarctica (Figure 1). Observation-based quantifications of the mobility of thermal plumes in the mantle depend on accurate knowledge of this boundary's development, and disagree prior to mid Eocene times [*Steinberger et al.*, 2004; *Tarduno et al.*, 2009]. The base of the West Antarctic Ice Sheet lies well below sea level in the rift system's basins, and its consequent instability makes it a key factor in past and future sea level change [*Vaughan*, 2008; *Bamber et al.*, 2009]. Understanding the rift system's development through time is therefore important, and plate kinematic models are crucial to this understanding.

[3] Direct knowledge of the rift system comes from geological and geophysical surveying and drilling in the Ross Sea region. Late Cretaceous rifting of southern New Zealand from Marie Byrd Land is recorded in rocks exposed at the margins of the Eastern Basin [e.g., *Luyendyk et al.*, 2001]. On the other side of the Ross Sea, fission track analyses betray later unroofing of the Transantarctic Mountains in Victoria Land starting at 55–45 Ma [*Fitzgerald and Baldwin*, 1997], and magnetic anomalies in the Adare Trough record seafloor spreading in the period 43–26 Ma [*Cande et al.*, 2000]. Strata seen on seismic data from the Central, Northern, and Victoria Land basins are interpreted as dating from this period [*Cande and Stock*, 2004a, 2006], and coring to the base of the Victoria Land Basin returned sediments with a maximum age of 34 Ma [*Wilson et al.*, 1998; *Hannah et al.*, 2001]. Sub-ice topography maps show that the rift system continues eastwards between the Transantarctic Mountains and Marie Byrd Land as far as the Byrd Subglacial Basin [*Lythe et al.*, 2001]. Beyond this, although the Transantarctic Mountains continue to the northeast, it is not clear from surveying within Antarctica where the plate boundary lies and what form it takes.

2. Plate Kinematic Models for the West Antarctic Rift System

[4] Despite being very short, the spreading anomalies in the Adare Trough are confidently dated because they form parts of prominent magnetic bights in seafloor around the triple junction of the Australian, East and West Antarctic plates [*Cande and Stock*, 2006]. *Cande et al.* [2000] used data from the bights to close the circuit of those plates, giving Euler parameters that describe the orientation and separation of the Adare Trough anomalies. *Müller et al.* [2007] used a longer circuit involving the Australia–Pacific plate boundary in the Macquarie and Emerald basins south of New Zealand [*Keller*, 2004], and also reproduced the Adare Trough record. Although the resulting stage pole falls within the 95% confidence ellipse of *Cande et al.*'s [2000] stage pole (Figure 1), the two are separated by over 5000 km, and yield very different models of the eastern end of the East-West Antarctic plate boundary. *Müller et al.*'s [2007] stage pole predicts a transcurrent boundary, whereas *Cande et al.*'s [2000] predicts further extensional basins.

[5] Unlike the southern offshore reaches of the East African Rift, where it hosts its own instantaneous motion pole [*Chu and Gordon*, 1999], both stage poles require the eastern parts of the East-West Antarctic plate boundary to have accommodated significant relative motion (Figure 1). Because of this, it is most likely to have terminated at a triple junction with another active plate boundary. The nearest of these was at the western margin of the Antarctic Peninsula where the oceanic Phoenix plate was subducting [*Larter and Barker*, 1991]. Various Cenozoic basins are known from this margin. In the following, we show how the formation of one of them, George VI Sound (GVIS), might be related to extension in the West Antarctic Rift System.

3. Extension and Transtension in George VI Sound

[6] The 800 m deep north-striking arm of GVIS separates the largely sedimentary Fossil Bluff Group of Alexander Island from the intruded metamorphic basement of Palmer Land and probably originated as a terrane boundary in Cretaceous times [*Ferraccioli et al.*, 2006; *Vaughan and Storey*,

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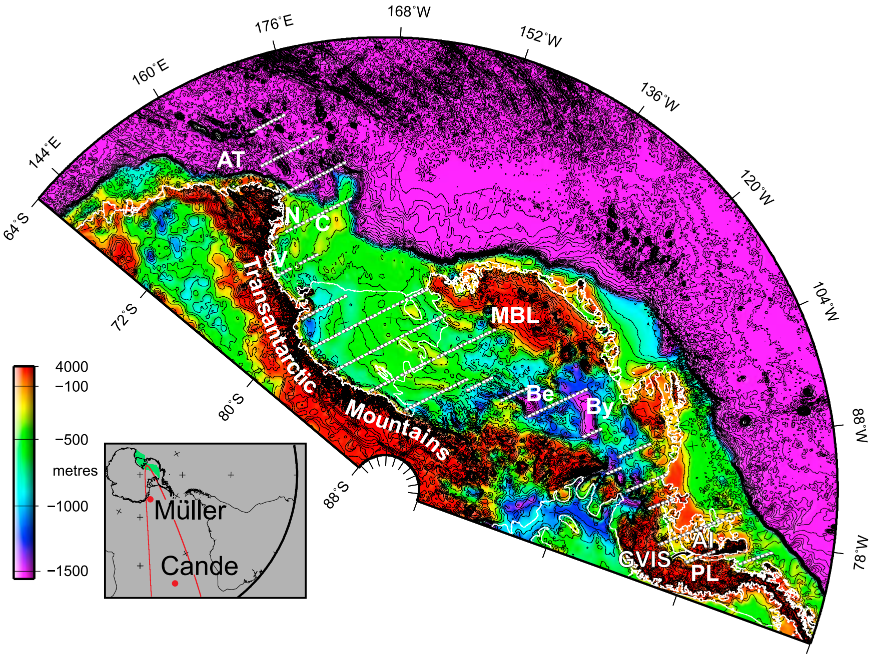

Figure 1. Sub ice topography [*Lythe et al.*, 2001] of the West Antarctic Rift System. AI: Alexander Island, AT: Adare Trough, Be: Bentley Subglacial Trench, By: Byrd Subglacial Basin, C: Central Basin, GVIS: George VI Sound, MBL: Marie Byrd Land, N: Northern Basin, PL: Palmer Land, V: Victoria Land Basin. White lines: segments of small circles about *Cande et al.*'s [2000] rotation pole. Inset: red dots: two alternative stage poles for East−West Antarctic relative motion during 48−26 Ma from *Cande et al.* [2000] (with red line part of its 95% confidence ellipse) and *Müller et al.* [2007].

2000]. Structural studies show that this boundary ultimately evolved into a basin that opened in dextral transtension [*Storey and Nell*, 1988], which may have started around 40−35 Ma as interpreted from fission track data from Alexander Island [*Storey et al.*, 1996]. Gravity modeling implies a stretching factor of ∼1.3 [*Maslanyj*, 1988]. A free-air (Figure 2) and Bouguer gravity low suggests the basin continues north across the shelf north of Alexander Island where it is named George VI trough [*Johnson*, 1997; *McAdoo and Laxon*, 1997]. The trough merges opposite the Tula Fracture Zone, via a discrete step in Bouguer gravity, with a margin-parallel sedimentary basin on the continental shelf [*Larter et al.*, 1997; *Johnson*, 1997]. The east-striking southern arm is wider and deeper; here a simple gravity model implies a stretching factor of ∼1.5, consistent with formation by lower-obliquity extension than in the northern arm [*Maslanyj*, 1987, 1988]. Volcanic activity resulting from this much stretching may explain the large positive magnetic anomalies observed along the southern arm [*Golynsky et al.*, 2001].

[7] Given the timing of these processes and their position between the Byrd Subglacial Basin and formerly active Antarctic Peninsula margin (Figure 1), it is conceivable that GVIS formed a segment of the West Antarctic Rift System. If so, the distinctive transtensional and extensional tectonics should obey the constraints of a rotation pole for relative motions between East and West Antarctica. This is indeed the case with *Cande et al.*'s [2000] pole, which prescribes a NNW translation of Alexander Island away from Palmer Land (Figure 2). With the margins of the stretched region taken to be beneath ice covered scarps in Palmer Land, and along the LeMay Range Fault in Alexander Island [*Crabtree et al.*, 1985], stretching factors like those *Maslanyj* [1988] modeled require a rotation of ∼0.7° about this pole. Assuming stretching occurred on the extensional arm of a ridge-trench-fault triple junction, its onset can be dated to a ridge-crest−trench collision SW of the Tula Fracture Zone at 30.1 ± 3 Ma [*Larter et al.*, 1997]. *Cande et al.*'s [2000] West

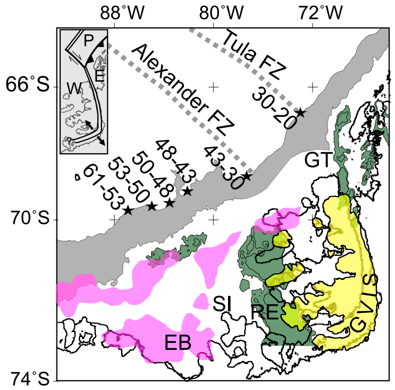

Figure 2. Reconstruction of a closed GVIS. EB: Eltanin Bay; GT: George VI trough; RE: Ronne Entrance; SI: Smyley Island. Light gray: positive free-air gravity anomaly related to modern continental shelf edge, green: negative anomalies (<−20 mgal) on the continental shelf [*McAdoo and Laxon*, 1997]. Stars: positions of possible past triple junctions at the West Antarctic margin, age ranges (in Ma) of their residence [*Larter et al.*, 1997]. Yellow: Alexander Island rotated by 0.7° about *Cande et al.*'s [2000] stage pole. Magenta: positive magnetic anomalies >100 nT [*Golynsky et al.*, 2001]. Inset: triple junction near Alexander Island at ∼27 Ma. E: East Antarctic Plate, P: Phoenix Plate, W: West Antarctic plate.

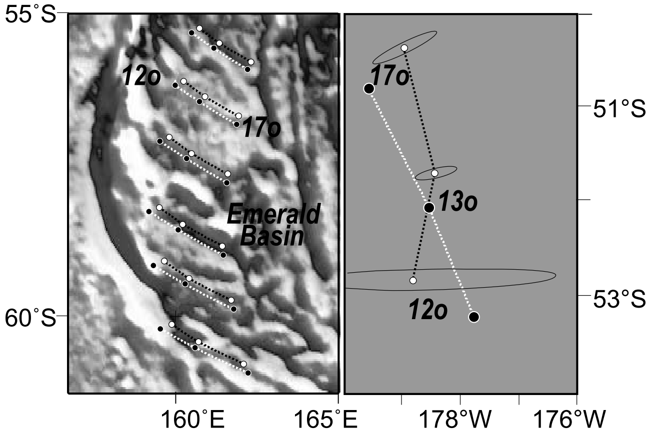

Figure 3. Results of interrogating the South Pacific circuit for Pacific–Australia motions. (left) New synthetic flowlines (white lines with black age points) compared to those of *Keller* [2004] (black lines with white age points); both sets of lines originate from the same seed points, and are overlain on satellite gravity showing fracture zones. (right) Finite rotation poles from circuit (black dots) compared to those of *Keller* [2004] (white dots), with 95% confidence ellipses. Comparisons not possible before chron 17o and after chron 12o as no suitable rotations are available.

Antarctica–East Antarctica rotation for chron C13 (33.5 Ma) also uses an angle of 0.7°, and so we adopt 33.5–30 Ma as a reasonable estimated time range for the onset of GVIS extension.

[8] In contrast, *Müller et al.* [2007] interpret a dominantly transcurrent East Antarctica–West Antarctica boundary in and offshore of the Antarctic Peninsula. The interpretation is based on a grid of crustal stretching factors calculated using sub ice topography and sediment thickness data [*Lythe et al.*, 2001; *Laske and Masters*, 1997]. Examination of the sub ice topography data set reveals that depths in GVIS are erroneously depicted some 600–800 m shallower than have been measured seismically [*Maslanyj*, 1987; *Bell and King*, 1998]. Using more appropriate depths of 800–1000 m, *Müller et al.*'s [2007] method of calculating crustal stretching factors returns values of 1.50–1.64, similar to the results of gravity modelling, consistent with an extensional eastern West Antarctic Rift System.

4. Accuracy in the South Pacific Plate Circuit

[9] This interpretation of GVIS is persuasive in its simplicity. Accepting it, however, draws attention back to the fact that the South Pacific plate circuit yields very different East Antarctica–West Antarctica rotations when constructed with the Pacific–Australia rotations of *Keller* [2004]. Figure 3 illustrates that the differences are artifacts of those rotations by using *Cande et al.*'s [2000] East Antarctica–West Antarctica rotation along with Australia–East Antarctica and Pacific–West Antarctica rotations [*Cande and Stock*, 2004b; *Croon et al.*, 2008] to predict Pacific–Australia motion independently of *Keller*'s [2004] data. The resulting rotations cannot be compared quantitatively to *Keller*'s [2004] as *Cande et al.* [2000] did not provide formal error estimates that would enable us to calculate a set of confidence ellipses. Nonetheless, the circuit-derived finite poles produce synthetic flowline orientations that are qualitatively almost identical both to *Keller*'s [2004] and to fracture zone traces in free-air gravity data.

[10] The artifacts arise from the magnification of small inaccuracies in the Pacific–Australia parameters through their large rotation angles. Despite being small, these inaccuracies are evidently larger than might be expected from *Keller*'s [2004] error analysis (Figure 3), and so must be attributed to factors he did not consider for it. Amongst these factors, we note that some of *Keller*'s [2004] data occupy a broad zone of post-Pliocene deformation attributed to incipient subduction south of New Zealand [*Cande and Stock*, 2004b; *Hayes et al.*, 2009]. These data are not likely to describe relative motions between the Pacific and Australian plates as completely as they would have done if they had not experienced this deformation.

5. Cenozoic Motion Between East and West Antarctica

[11] Sixty percent of *Cande et al.*'s [2000] modeled post-43 Ma West Antarctica–East Antarctica motion would have been expressed prior to and away from the extension in GVIS. By analogy, one can hypothesise a rift basin connecting the precursor to the 'Tula' triple junction, which existed since 43 Ma at the SE end of the Alexander Fracture Zone (Figure 2) [*Larter et al.*, 1997; *Scheuer et al.*, 2006]. Although the fission track evidence from Alexander Island [*Storey et al.*, 1996] is consistent with this timing, evidence for the presence of the basin itself is not overwhelmingly strong. Satellite altimetry data show a broad free-air gravity anomaly crossing the shelf towards the fracture zone. Despite a smooth sedimented seafloor, reverberations in seismic data mask any indication of how deep beneath the anomaly the sediments continue, except near the east coast of Smyley Island [*Nitsche*, 1998]. A positive magnetic anomaly at ~79°W might be interpreted in terms of an uplifted rift flank (Figure 2). High smectite concentrations in sediments from the Ronne Entrance suggest the presence of volcanic or volcaniclastic rocks, perhaps related to rifting, at the seabed [*Hillenbrand et al.*, 2009].

[12] Before 43 Ma, reconstruction misfits between Lord Howe Rise and Campbell Plateau suggest even earlier motion between East and West Antarctica [*Cande and Stock*, 2004a; *Steinberger et al.*, 2004]. Although it has been suggested that this motion created some of the basins of the Ross Sea, there is no firmly-established record of it there in the form of cored or sampled Paleocene or older Eocene sediments. Added to this, there is no evidence for basins connecting to pre-43 Ma triple junctions off Eltanin Bay, where they might be expected (Figure 2). While this absence of evidence is no basis on which to dismiss the idea of Paleocene relative motions between West and East Antarctic plates, it should be taken as a reminder that that idea, while intuitively attractive, remains only indirectly proved and should be applied with caution.

6. Conclusion

[13] The geology of the GVIS region can be interpreted in terms of the eastern reaches of an extensional West Antarctic Rift System. The interpretation reinforces the already strong

evidence for intra-Antarctic extension since 34–30 Ma, and to a lesser degree since 43 Ma, but there is as yet no evidence here for earlier extension. This interpretation further implies that the Antarctic Peninsula has been part of a stable East Antarctic plate since mid Eocene times, and that additional rift basins exist in Ellsworth Land, linking GVIS and the Byrd Subglacial Basin, where elevated heat flow is likely to have influenced ice sheet development and stability.

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