Cooper, A. K., P. J. Barrett, H. Stagg, B. Storey, E. Stump, W. Wise, and the 10th ISAES editorial team, eds. (2008). *Antarctica: A Keystone in a Changing World.* Proceedings of the 10th International Symposium on Antarctic Earth Sciences. Washington, DC: The National Academies Press.
doi:10.3133/of2007-1047.kp10

The Significance of Antarctica for Studies of Global Geodynamics

R. Sutherland[1]

ABSTRACT

Antarctica has geometric significance for global plate kinematic studies, because it links seafloor spreading systems of the African hemisphere (Indian and Atlantic Oceans) with those of the Pacific. Inferences of plate motions back to 44 Ma, around the onset of rapid spreading south of Australia and formation of a new boundary through New Zealand, are consistent with Antarctic rifting and formation of the Adare Basin during 44-26 Ma (i.e., no additional plate motions are required in the South Pacific). The time period 52-44 Ma represents a profound global and South Pacific tectonic change, and significant details remain unresolved. For 74 Ma a significant nonclosure of the South Pacific plate-motion circuit is identified if Antarctic motion is not included. Alternate inferences of motion through Antarctica during the interval 74-44 Ma imply significantly different subduction volumes and directions around the Pacific, and imply different relative motions between hotspots.

INTRODUCTION

The surface of Earth can be divided into hemispheres with distinct tectonic character. The African hemisphere contains spreading ridges in the Indian and Atlantic Oceans that allow relative plate motions to be determined, and the motions are shown by studies of seamount chains to be well approximated by a single hotspot (absolute) reference frame (Muller et al., 1993). The Pacific hemisphere is surrounded by subduction zones with highly uncertain relative motions between subducting and overriding plates (Figures 1 and 2). A full understanding of geodynamics requires global determinations of past relative plate motions and boundary locations, and motions of plates relative to hotspots (e.g., Lithgow-Bertelloni and Richards, 1998).

Most previous calculations of global plate motions assume that hotspots in the Pacific hemisphere, specifically Hawaii and Louisville, have been fixed relative to each other and to African-hemisphere hotspots during Cretaceous-Cenozoic time (Engebretson et al., 1985; Gordon and Jurdy, 1986). However, paleomagnetic data from the Emperor seamount chain in the North Pacific are inconsistent with this assumption, and mantle flow calculations predict significant advection of the rising mantle plume responsible for the Hawaii hotspot (Tarduno et al., 2003; Steinberger et al., 2004). The only way to determine global relative plate motions and, hence, test predictive hotspot models based on mantle flow calculations is to piece together the kinematic evidence that was formed at plate boundaries; this includes seafloor fracture zones and magnetic anomalies, and the records that are preserved within continents and their margins.

Antarctica is significant in the global relative plate-motion circuit because it geometrically connects the African and Pacific hemispheres along a path that can be directly reconstructed at past times from seafloor and continental records (Figures 1 and 2). Therefore, quantification of internal deformation of Antarctica is an essential part of any global relative-plate-motion model. Further, because internal deformation of plates is commonly characterized by local rotation poles (Gordon, 1998), small local displacements may be described by relatively large rotation angles, which propagate (when incorporated into a plate-motion chain) into

[1]GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand (r.sutherland@gns.cri.nz).

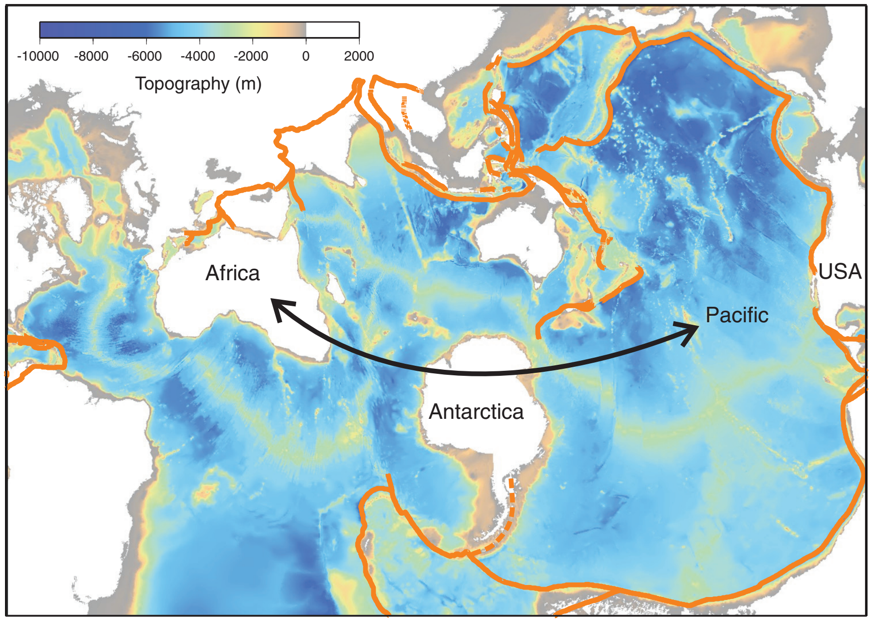

FIGURE 1 Global bathymetry (from Smith and Sandwell, 1997). Convergent plate boundaries shown in orange. Arrow indicates the pathway of kinematic connection between the African and Pacific hemispheres that did not contain destructive boundaries during the Cenozoic era. Oblique Mercator projection.

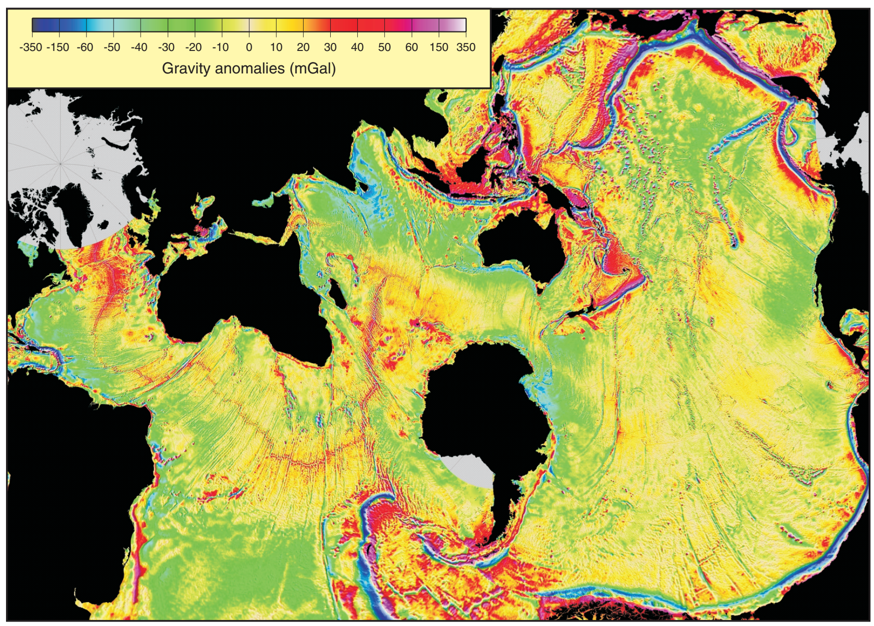

FIGURE 2 Gravity anomalies (from Sandwell and Smith, 1997).

very large predicted plate displacements at greater distances (e.g., at equatorial latitudes). The validity of Antarctic reconstructions must be consistent with other motions in the South Pacific, because Antarctica is part of a closed plate-motion circuit that includes Australia and New Zealand.

This paper presents a model for the block motion of Marie Byrd Land relative to the East Antarctic craton since 74 Ma. The model is simplistic by design, because the primary purpose of this paper is to propose a new and quantitative hypothesis for motion on an intra-Antarctic plate boundary during the interval 74-50 Ma. It is accepted that refinement to this model will be necessary, to fit observations of crustal strain and the timing of deformation in detail. The hypothesis is presented and then tested against crustal geology of the Antarctic continent, the geometry of seafloor in the South Pacific plate-motion circuit, and the global motions of plates relative to hotspots. A plausible tectonic explanation for why such a model makes physical sense is briefly discussed. Finally, global implications of the hypothesis are explored with regard to subduction budgets since the late

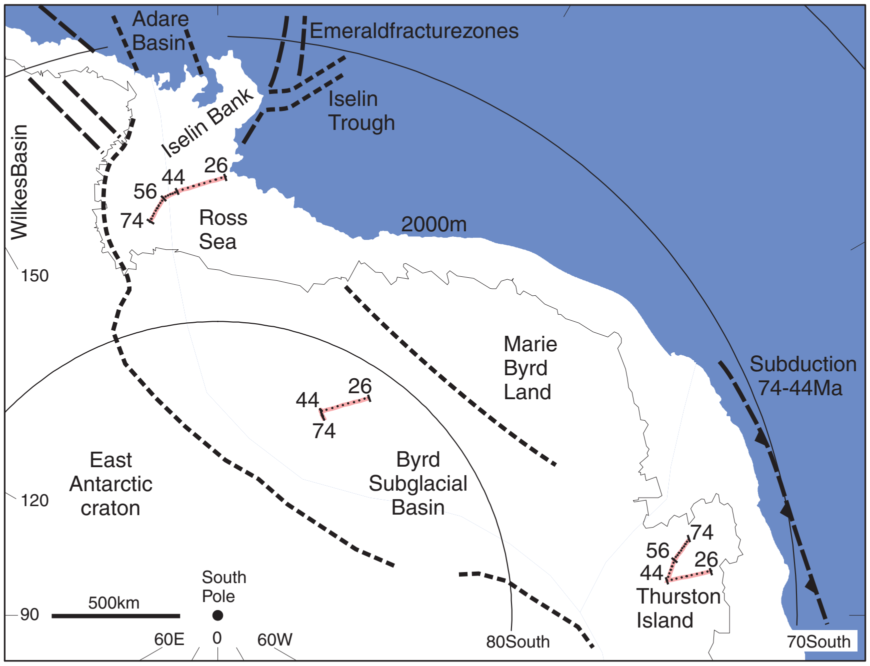

FIGURE 3 Map of the hypothesized intra-Antarctic plate boundary that stretches between the Ross Sea through the Byrd Subglacial Basin to inboard of Thurston Island. Significant tectonic regions are labeled and their margins are shown bold dashed. Arbitrary points within the plate boundary zone show the motion of the Marie Byrd Land plate relocated (pink dotted) relative to the East Antarctic plate using the proposed kinematic model (Table 1).

Cretaceous, because this is of broad international interest for both geodynamics and continental margin geology.

MOTION OF MARIE BYRD LAND RELATIVE TO EAST ANTARCTICA

The plate-motion model (Figure 3) is divided into four phases: (1) 74-56 Ma is a time of slow dextral extension in the Ross Sea and dextral transpression near Thurston Island; (2) 56-44 Ma is a time of accelerated rifting in the Ross Sea and highly oblique dextral transpression near Thurston Island; (3) 44-26 Ma is the time of Adare Basin formation (Cande et al., 2000) and includes rifting inboard of Thurston Island; and (4) there has been no significant motion since 26 Ma (Table 1). The oldest finite rotation corresponds to chron 33y (Cande and Kent, 1995), which is the time of the oldest magnetic anomaly that is widely preserved and recognized in the South Pacific.

Test 1: Antarctic Geology and Geophysical Data

Ross Sea Rift

It has been known for several decades that the Ross Sea has thinned crust, rifted sedimentary basins, and a rift flank uplift called the Transantarctic Mountains, and that Cretaceous-Cenozoic extensional tectonics were implicated (Davey et al., 1982; Behrendt et al., 1991; ten Brink et al., 1993; Fitzgerald, 1994; Cooper et al., 1995). Crustal thickness estimates imply 350-400 km of total extension, which could be revised to >400-450 km if crustal addition were accounted for (Behrendt et al., 1991).

TABLE 1 Finite Rotations Describing Marie Byrd Land Relative to East Antarctica

Age (Ma)	Latitude (°N)	Longitude (°E)	Angle (°)
26.6	–18.2	–17.9	0.0
33.6	–18.2	–17.9	0.7
43.8	–18.2	–17.9	1.7
56.0	–70.0	–30.0	4.0
73.6	–80.0	–70.0	8.5

The total motion in the Ross Sea that is implied by the model proposed in this paper is ca. 300 km since 74 Ma (Figure 3). Therefore, ca. 70 percent of the total thinning is implied to have occurred after 74 Ma. This estimate could be revised downward if some extension were distributed over a broader region.

The oldest strata in the Ross Sea that have been drilled are late Eocene and Oligocene in age (Hayes et al., 1975; Barrett, 1989; Barrett et al., 1995), and these postdate normal-faulted strata everywhere except the Victoria Land Basin in the western Ross Sea, where faulting continued through Oligocene time (34-24 Ma) (Cooper et al., 1987; Henrys et al., 1998; Hamilton et al., 2001). Hence, a large component of the extension is constrained to be Eocene or older. Models of apatite fission track data from a basement rock sample collected at DSDP site 270, which is sited on a rifted horst in the central Ross Sea, suggest exhumation was completed at some time during the interval 90-50 Ma (Fitzgerald and Baldwin, 1997).

Apatite fission-track and (U-Th)/He thermochronology results from the Transantarctic Mountains record cooling and hence inferred exhumation during the time interval 80-40 Ma (Fitzgerald, 1992, 1994; Stump and Fitzgerald, 1992; Lisker, 2002; Fitzgerald et al., 2006). Age-elevation correlations have been used to suggest an episodic uplift model with an initial phase starting before 80 Ma and a second phase of more rapid exhumation starting at 55-45 Ma (Stump and Fitzgerald, 1992). This model has appeal, because the first phase corresponds to Gondwana breakup (local separation of New Zealand) and the second phase is a time of profound global and South Pacific tectonic change (below). However, close inspection of the data does not provide compelling evidence for a discrete regional (rather than local) event before 80 Ma. Instead, the ages are broadly distributed across the time interval 80-45 Ma (or even older) and thermal model inversions produce results that are consistent with exhumation histories during that interval. The regional increase in cooling rate within the Transantarctic Mountains at ca. 55-45 Ma is compelling, and hence an increase in exhumation rate is inferred.

Byrd Subglacial Basin

South of the Ross Sea the Byrd Subglacial Basin is a region of bedrock elevations below sea level, with some regions being deeper than 1000 m below sea level (Lythe et al., 2001). The basin is interpreted to be of rift origin and has only a thin (<1 km) sedimentary record imaged beneath the ice, but gravity interpretations suggest localized narrow basins with up to 5 km of sediment (Behrendt et al., 1991; Anandakrishnan et al., 1998; Studinger et al., 2001). Fission track data from the southern Transantarctic Mountains (Scott Glacier) yield ages in the range 120-60 Ma (Stump and Fitzgerald, 1992). The Byrd Subglacial Basin has a similar width to the Ross Sea (ca. 800 km) and is entirely ice-covered.

Thurston Island Region

The region of Antarctica from Thurston Island to the Antarctic Peninsula has undergone a complex tectonic history since Jurassic time (Dalziel and Elliot, 1982). Pre-Gondwanaland breakup reconstructions must account for extensional basins, such as the Byrd Subglacial Basin; dextral transpression along the paleosubduction continental margin; and continuity of geological characteristics (Storey and Nell, 1988; Storey, 1991; McCarron and Larter, 1998; Larter et al., 2002). The relative magnitudes, timing, and spatial distribution of dextral transpression and extension remain constrained by only a small number of field observations due to extreme remoteness and ice cover.

Summary of Test 1

The kinematic hypothesis predicts that 70 percent of extension in the Ross Sea occurred after 74 Ma, and that dextral-oblique compression followed by extension occurred in the Thurston Island region. I contend that both predictions are consistent with local observations, but are not necessarily the favored models of local workers. The initial phase is most controversial, because there is so little geological evidence for activity during this time. However, the syn-rift strata have not been sampled and if a heating model were proposed to explain the rift flank uplift (ten Brink et al., 1993), burial rather than exhumation could be expected during the early stages of rifting, which could explain the apatite fission track results.

Test 2: South Pacific Plate Motions

43-0 Ma

Rifted boundaries in the southeast Indian Ocean (East Antarctica-Australia) and south of New Zealand (ENZ-WNZ) formed at about chron 20 (43 Ma) (Sutherland, 1995; Tikku and Cande, 2000), after cessation of spreading in the Tasman Sea (Australia-WNZ) (Gaina et al., 1998). Pacific-Marie Byrd Land spreading is constrained by numerous magnetic anomaly and fracture zone picks (Cande et al., 1995; Cande and Stock, 2004). The “missing link” in this plate-motion circuit (Figure 4) is rifting within Antarctica and formation of seafloor in the Adare Basin (Cande et al., 2000). However, the location of the pole of rotation that describes Antarctic rifting is imprecisely constrained by this analysis, and a rotation pole nearer to Antarctica has been suggested (Davey et al., 2006). This paper uses a magnetic anomaly 13 plate-motion circuit inversion and extrapolation to anomaly 20 (Cande et al., 2000); the model (Table 1; Figure 5) produces rifting of only slightly decreased magnitude toward the east (Figure 3).

56-43 Ma

This was a time of profound change throughout the Pacific and Indian Oceans, and uncertainty surrounds the exact nature and timing of these changes. One of the least affected boundaries was that between East New Zealand and Marie Byrd Land, where seafloor spreading continued with only minor changes in direction and rate (Cande et al., 1995). The Tasman Sea stopped opening at chron 24 (52 Ma) (Gaina et al., 1998), but rapid divergence south of New Zealand (WNZ-ENZ) and Australia did not start until ca. 43 Ma (Sutherland, 1995; Wood et al., 1996; Tikku and Cande, 2000). Analysis of plate closure (Figure 5) during this interval is hampered by the relatively short time interval; the possibility of intraplate deformation within New Zealand, which was very close to the instantaneous pole of ENZ-WNZ rotation after 43 Ma;

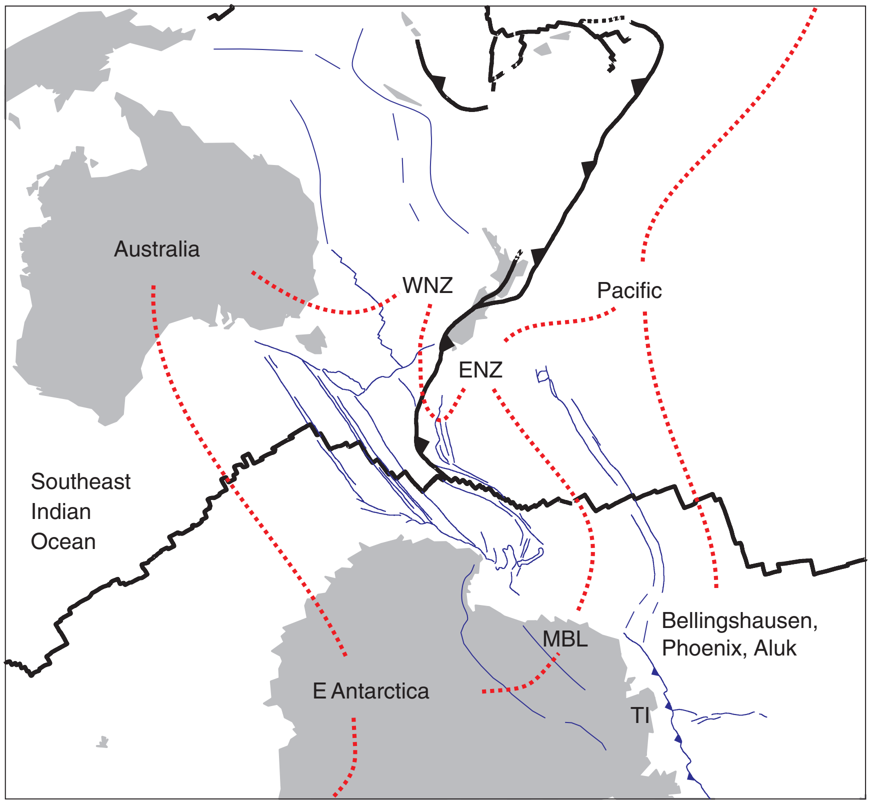

FIGURE 4 The South Pacific plate-motion circuit is the closed loop Australia-East Antarctica-Marie Byrd Land (MBL)-East New Zealand (ENZ)-West New Zealand (WNZ)-Australia. Bold lines show active plate boundaries. Fine blue lines show locations of significant boundaries during the interval 74-0 Ma. TI = Thurston Island.

and the difficulty of interpretation of crust in the southeast Indian Ocean.

74-56 Ma

This was a time of tectonic quiescence within New Zealand, with the only records of tectonic activity coming from the Taranaki Basin of central New Zealand, where very small amounts of rifting are implied (King and Thrasher, 1996). Therefore, the total motion through New Zealand is very similar at 56 Ma and 74 Ma, and is well approximated by fitting rift boundaries (ENZ-WNZ) (Figure 4) south of New Zealand (Sutherland, 1995). Tasman Sea spreading (Australia-WNZ) is quantified by magnetic anomalies (Gaina et al., 1998), as is ENZ-MBL spreading (Cande et al., 1995). It is not clear that magnetic lineations in the southeast Indian Ocean are isochrons, but detailed analyses and published reconstructions exist (Tikku and Cande, 1999, 2000; Muller et al., 2000). It is notable that substantial overlaps between Tasmania and Wilkes Land region have been predicted by some regional analyses (Tikku and Cande, 2000) and are inconsistent with local restoration of seafloor (Royer and Rollet, 1997; Tikku and Cande, 2000); this suggests some internal deformation (extension) of either the Australian or Antarctic plates, or the regional data are open to alternate interpretation (Whittaker et al., 2007). Reconstructions of seafloor older than 74 Ma in the southeast Indian Ocean, and Australia-Antarctic continental geology, are achieved with only a slightly larger plate movement and the Australia-Antarctica boundary is relatively long, so the implications for global plate motions are relatively small. During this time, oblique convergence occurred adjacent to Thurston Island and a subducting microplate, the Bellingshausen plate, moved independently to Marie Byrd Land until ca. 60 Ma (Stock and Molnar, 1987; Heinemann et al., 1999; Larter et al., 2002). The tectonic model (Table 1; Figure 5) results in acceptable plate closure for this time interval.

Test 3: Global Plate Motions Relative to Hotspots

With a model for intra-Antarctic motion (Table 1), it is possible to compute the relative motion of the Pacific plate relative to those in the African hemisphere by following a path Africa-East Antarctica-Marie Byrd Land-East New Zealand-Pacific (Cande et al., 1995; Nankivell, 1997; Cande and Stock, 2004), assuming the motions of Table 1 and that East New Zealand was fixed to the Pacific during this time. Therefore, it is possible to rotate the African hotspot reference frame to Hawaii and account for predicted movement of the Hawaii hotspot caused by mantle flow (Steinberger et al., 2004). The results (Figure 6) reveal that inclusion of the Antarctic deformation model (Table 1) produces a good fit between observations and predictions.

DISCUSSION OF THE ANTARCTIC PLATE-MOTION MODEL

The kinematic model (Table 1) results in a much improved fit to global observations of hotspots and it adequately closes the South Pacific plate-motion circuit. I believe the model to lie within the constraints of local observations from Antarctica, but I accept that fine-tuning will be required as the hypothesis is tested in detail. Specifically, it is likely that the number of continental fragments will be increased and the precise locations of the poles of the relative rotations that describe their movements will be revised.

South Pacific reconstructions (Figure 5) place moderately strong constraints on predicted movements between

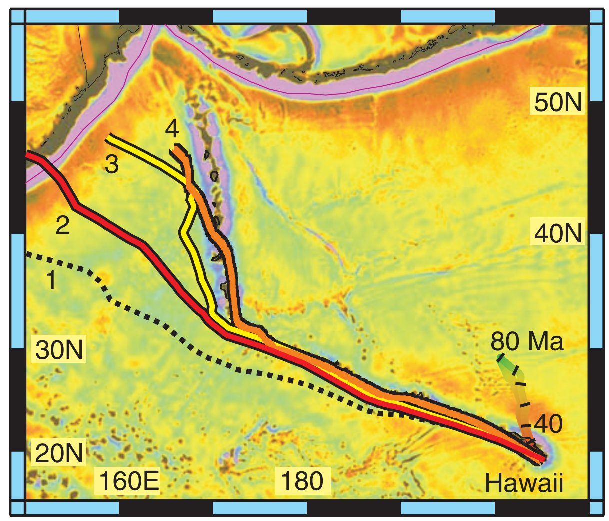

FIGURE 6 Model positions of Emperor-Hawaii seamounts for the time 0-74 Ma, based upon rotation of the African hotspot reference frame (Muller et al., 1993) and predicted movements of the Hawaii hotspot (movement of the hotspot is shown in the Pacific plate frame of reference; it is color-coded green-orange and tick marks are shown at 10 Myr increments; and the two movement lines were computed for models 2 and 3 below) (Steinberger et al., 2004). From east to west the model assumptions are: (1) (dotted), no relative hotspot motion and no intra-Antarctic motion; (2) (red), Adare Basin motion 43-26 Ma (Cande et al., 2000) and hotspot motion; (3) (yellow), hotspot motion and the intra-Antarctic issue avoided by following a path through Australia before 50 Ma; (4) (orange), hotspot motion and the Antarctic deformation model of this paper (Table 1).

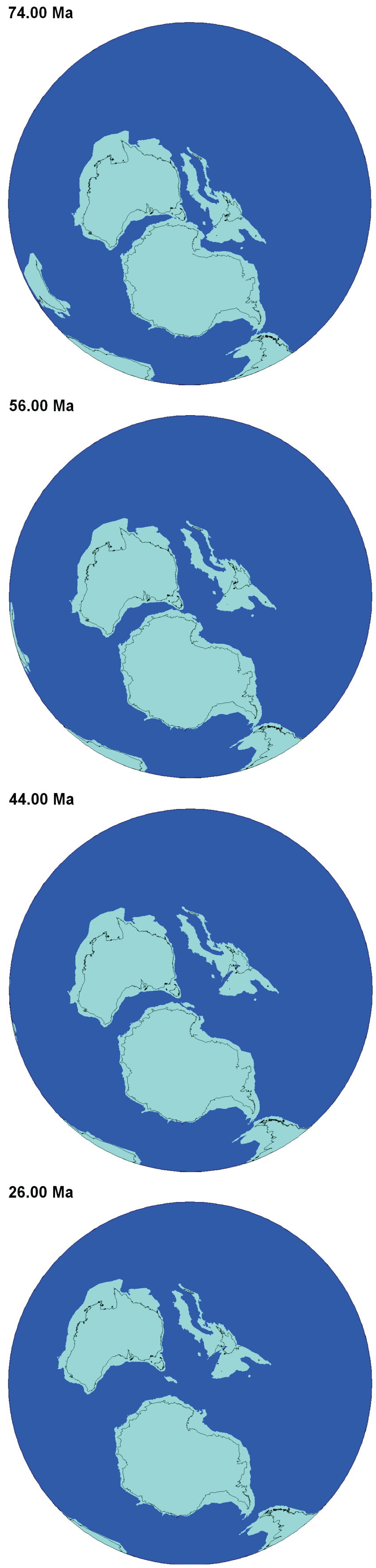

FIGURE 5 South Pacific tectonic reconstructions. See discussion in text and animated version at http://www.gns.cri.nz/research/tectonics.

East Antarctica and Marie Byrd Land in the Ross Sea, and to a lesser extent on the angle of rotation between East Antarctica and Marie Byrd Land. Hotspot observations (ages and positions of seamounts) place a moderately strong constraint on the angle of rotation between East Antarctica and Marie Byrd Land, because most hotspot chains are at middle or low latitudes and the likely pole of intra-Antarctic rotation is at high latitude.

Intra-Antarctic motion during the interval 74-56 Ma, which is the most controversial part of the model, is plausible because it connects a complex zone of rifting near the Ross Sea (Figure 3) with a subduction boundary adjacent to Thurston Island and the Antarctic Peninsula. Antarctica was not an isolated continent surrounded by spreading ridges at that time. It is possible that features such as the Iselin Trough and Wilkes Basin also formed during this time interval (Figure 3).

IMPLICATIONS FOR GLOBAL SUBDUCTION BUDGETS

The relative motions of oceanic plates in the Pacific hemisphere can be determined from magnetic anomalies within the Pacific, based upon the assumption of symmetric spreading because conjugate crust has mostly been subducted (Engebretson et al., 1985). The motion of the Pacific plate relative to Africa can be computed from Table 1 and magnetic anomalies in the southwest Indian Ocean (Nankivell, 1997) and South Pacific (Cande et al., 1995; Larter et al., 2002; Cande and Stock, 2004). Hence it is possible to compute the relative positions of Pacific hemisphere oceanic plates with overriding plates that border the African hemisphere: South America (Muller et al., 1993); India (Muller et al., 1993); North America (Klitgord and Schouten, 1986; Muller et al., 1990); and Eurasia (Lawver et al., 1990; Srivastava and Roest, 1996; Rosenbaum et al., 2002). Hence, it is possible to compute subduction histories.

Since the time of the Emperor-Hawaii bend at ca. 50 Ma (Sharp and Clague, 2006), there is fairly good agreement within the published literature with estimates of relative and absolute plate motions (Steinberger et al., 2004). However, there is substantial disagreement before that (Raymond et al., 2000; Tarduno et al., 2003; Steinberger et al., 2004). Consequently, I focus here on the time interval 74-50 Ma. Specifically, the plate pairs examined are Pacific-Eurasia, Kula-North America, Farallon-North America, and Farallon-South America (Figure 7). Two Antarctic models are used (Figure 8): the preferred model is given in Table 1; the second is the same, but assumes no intra-Antarctic motion during the interval 74-44 Ma.

It is clear from Figure 8 that the model of Antarctic motion is significant for the computation of global subduction rates and directions for the interval 74-50 Ma. The preferred model (yellow, Table 1) predicts a hinge point, where Pacific plate subduction rates were very low in southeast Asia; this may have geodynamic significance, because it is close to the southern limit of the plate boundary and may represent a propagating system (perhaps similar to the tectonic setting of the Scotia Sea today). Alternatively, it is

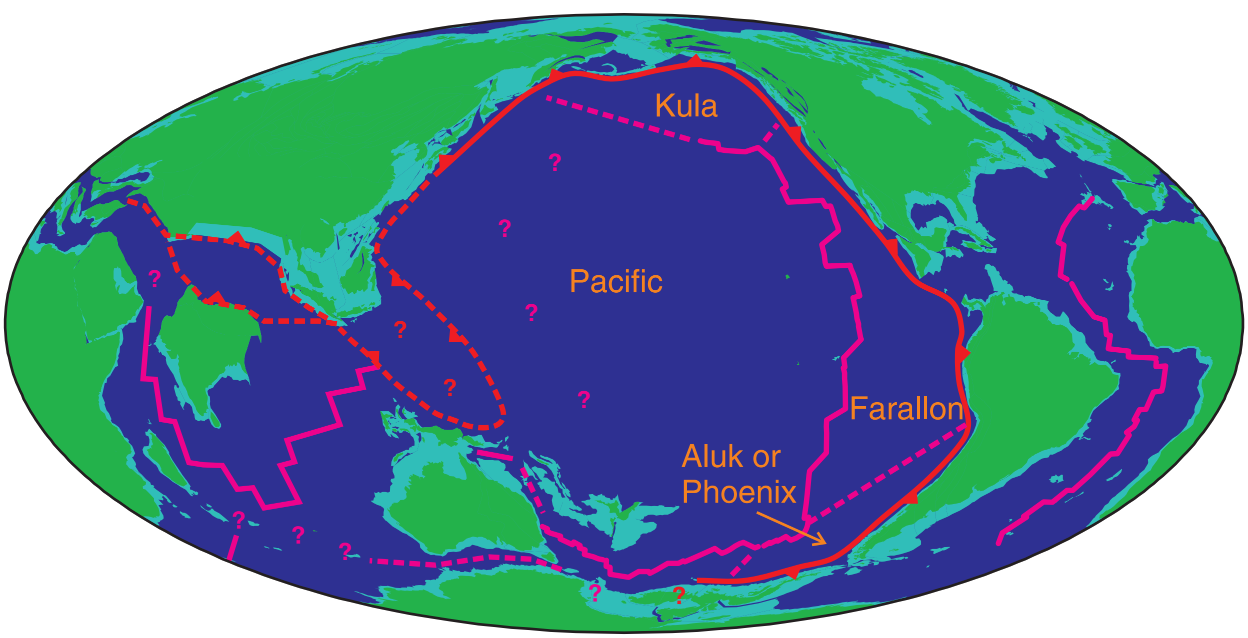

FIGURE 7 Simplified global plate tectonic reconstruction for 55 Ma.

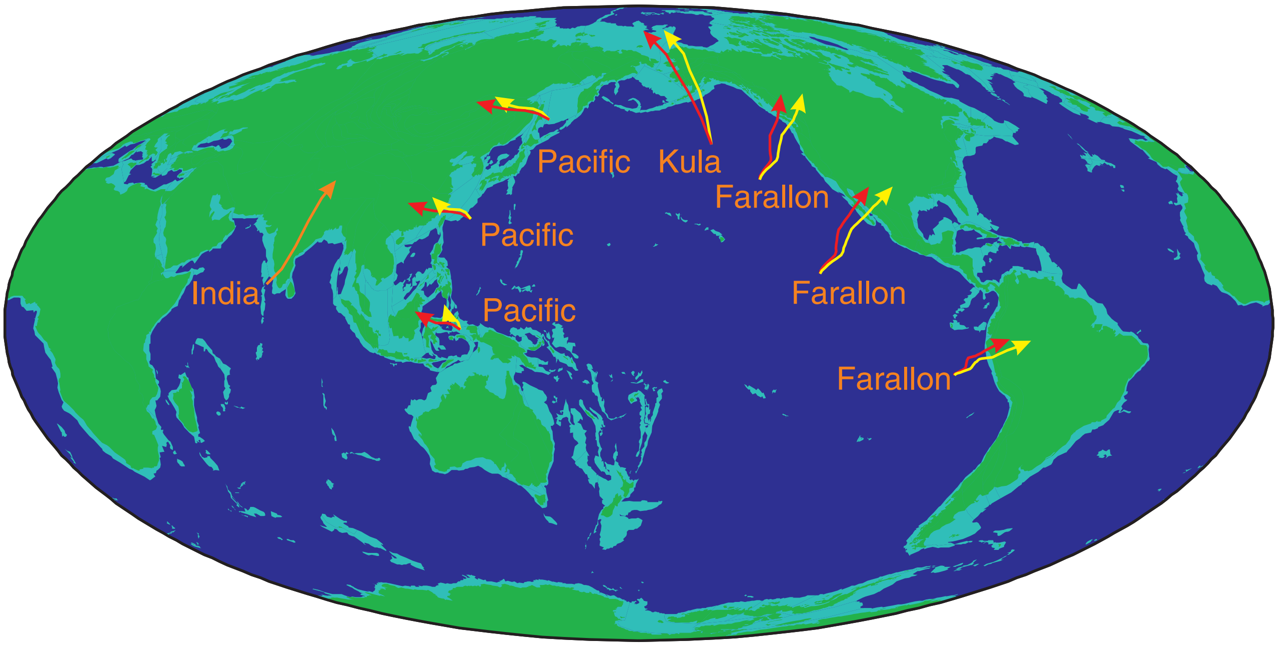

FIGURE 8 Model subduction directions, relative to the overriding major plate, and magnitudes during the interval 74-50 Ma. Red arrows assume no intra-Antarctic deformation before 44 Ma and predict a more westward motion of oceanic plates than a model (yellow) with Antarctic motion during 74-44 Ma (Table 1).

possible that a ridge has since been subducted and that a remanent of the Izanagi plate, rather than Pacific plate, was being subducted beneath Eurasia at that time (Whittaker et al., 2007). Kula and Farallon subduction for the period 74-50 Ma beneath North and South America, when computed using the preferred Antarctic model, is rotated clockwise by 10-15° to an orientation more closely orthogonal to the margin, and has a rate that is ca. 15 percent higher at equatorial latitudes. The increase in rate at equatorial latitudes results from the additional intra-Antarctic rotation about a pole at high latitude.

CONCLUSIONS

An hypothesis for the motion of Marie Byrd Land relative to East Antarctica is presented. The model is shown to be consistent with South Pacific plate motions and it provides an improved global reconciliation of relative versus hotspot-derived plate motions. While the proposed model is broadly consistent with available observations from Antarctica, it is inevitable that a more complex and precise model will emerge as the hypothesis is tested in the future. However, I conclude that South Pacific and global data constrain the motion of Marie Byrd Land relative to East Antarctica to be described by a rotation pole with high latitude and rotation angles similar to those proposed. Such a model is plausible because the proposed intracontinental plate boundary connected active tectonic zones of rifting near the Ross Sea (Figure 3) with a subduction boundary adjacent to Thurston Island and the Antarctic Peninsula.

The key geographic connection that Antarctica provides between subducting oceanic plates of the Pacific with diverging plates of the African hemisphere means that an understanding of Antarctic deformation has significance for both global geodynamics and for subduction-related geology of the entire circum-Pacific.

ACKNOWLEDGMENTS

I thank Bryan Storey, Alan Cooper, and the ISAES 2007 organizing committee for their editorial and facilitation roles, and Carol Finn and Joann Stock for their very helpful reviews. I used GMT software (Wessel and Smith, 1995) and Atlas software of Cambridge Paleomap Services. This research was funded by the New Zealand Foundation for Research, Science and Technology.

REFERENCES

Anandakrishnan, S., D. D. Blankenship, R. B. Alley, and P. L. Stoffa. 1998. Influence of subglacial geology on the position of a West Antarctic ice stream from seismic observations. *Nature* 394:62-65.

Barrett, P. J. E. 1989. Antarctic Cenozoic history from CIROS-1 drillhole, McMurdo Sound. *DSIR Bulletin* 245:1-254.

Barrett, P. J., S. A. Henrys, L. R. Bartek, G. Brancolini, M. Busetti, F. J. Davey, M. J. Hannah, and A. R. Pyne. 1995. Geology of the margin of the Victoria Land Basin off Cape Roberts, southwest Ross Sea. In *Geology and Seismic Stratigraphy of the Antarctic Margin,* eds. A. K. Cooper, P. F. Barker, and G. Brancolini, *Antarctic Research Series* 68:183-207. Washington, D.C.: American Geophysical Union.

Behrendt, J. C., W. E. LeMasurier, A. K. Cooper, F. Tessensohn, A. Trefu, and D. Damaske. 1991. Geophysical studies of the west Antarctic rift arm. *Tectonics* 10:1257-1273.

Cande, S. C., and D. V. Kent. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research, B, Solid Earth and Planets* 100(4):6093-6095.

Cande, S. C., and J. M. Stock. 2004. Pacific-Antarctic-Australia motion and the formation of the Macquarie Plate. *Geophysical Journal International* 157:399-414.Cande, S. C., C. A. Raymond, J. Stock, and W. F. Haxby. 1995. Geophysics of the Pitman Fracture Zone. *Science* 270:947-953.

Cande, S. C., J. M. Stock, R. D. Mueller, and T. Ishihara. 2000. Cenozoic motion between East and West Antarctica. *Nature* 404(6774):145-150.

Cooper, A. K., F. J. Davey, and J. C. Behrendt. 1987. *Seismic Stratigraphy and Structure of the Victoria Land Basin, Western Ross Sea, Antarctica.* Houston, TX: Circum-Pacific Council for Energy and Mineral Resources.

Cooper, A. K., P. F. Barker, and G. Brancolini. 1995. *Geology and Seismic Stratigraphy of the Antarctic Margin*. Antarctic Research Series 68, Washington, D.C.: American Geophysical Union.

Dalziel, I. W. D., and D. H. Elliot. 1982. West Antarctica: Problem child of Gondwanaland. *Tectonics* 1:3-19.

Davey, F. J., D. J. Bennett, and R. E. Houtz. 1982. Sedimentary basins of the Ross Sea, Antarctica. *New Zealand Journal of Geology and Geophysics* 25(2):245-255.

Davey, F. J., S. C. Cande, and J. M. Stock. 2006. Extension in the western Ross Sea region—Links between Adare Basin and Victoria Land Basin. *Geophysical Research Letters* 33.

Engebretson, D. C., A. Cox, and R. G. Gordon. 1985. Relative motions between oceanic and continental plates in the Pacific basin. *Geological Society of America Special Paper* 206:1-59.

Fitzgerald, P. G. 1992. The Transantarctic Mountains in southern Victoria Land: The application of apatite fission track analysis to a rift-shoulder uplift. *Tectonics* 11:634-662.

Fitzgerald, P. G. 1994. Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica. *Tectonics* 13:818-836.

Fitzgerald, P., and S. Baldwin. 1997. Detachment fault model for the evolution of the Ross Embayment, the Antarctic region, geological evolution and processes. In *Proceedings of the VII International Symposium on Antarctic Earth Sciences,* ed. C. A. Ricci, pp. 555-564. Siena: *Terra Antartica* Publication.

Fitzgerald, P. G., S. L. Baldwin, L. E. Webb, and P. B. O'Sullivan. 2006. Interpretation of (U-Th)/He single grain ages from slowly cooled crustal terranes: A case study from the Transantarctic Mountains of southern Victoria Land. *Chemical Geology* 225:91-120.

Gaina, C., D. R. Mueller, J.-Y. Royer, J. Stock, J. L. Hardebeck, and P. Symonds. 1998. The tectonic history of the Tasman Sea: a puzzle with 13 pieces. *Journal of Geophysical Research* 103(6):12413-12433.

Gordon, R. G. 1998. The plate tectonic approximation: Plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. *Annual Review of Earth and Planetary Sciences* 26:615-642.

Gordon, R. G., and D. M. Jurdy. 1986. Cenozoic global plate motions*.* *Journal of Geophysical Research* 91:12389-12406.

Hamilton, R. J., B. P. Luyendyk, and C. C. Sorlien. 2001. Cenozoic tectonics of the Cape Roberts rift basin and Transantarctic Mountains front, southwestern Ross Sea, Antarctica. *Tectonics* 20:325-342.

Hayes, D. E., L. A. Frakes, P. J. Barrett, D. A. Burns, P.-H. Chen, A. B. Ford, A. G. Kaneps, E. M. Kemp, D. W. McCollum, D. J. W. Piper, R. E. Wall, and P. N. Webb. 1975. Sites 270, 271, 272. *Initial Reports of the Deep Sea Drilling Project* 28, eds. D. E Hayes, I. A. Frakes et al., pp. 211-334. Washington, D.C.: U.S. Government Printing Office.

Heinemann, J., J. Stock, R. Clayton, K. Hafner, S. Cande, and C. Raymond. 1999. Constraints on the proposed Marie Byrd Land-Bellingshausen plate boundary from seismic reflection data. *Journal of Geophysical Research, B, Solid Earth and Planets* 104(11):25321-25330.

Henrys, S. A., L. R. Bartek, G. Brancolini, B. P. Luyendyk, R. J. Hamilton, C. C. Sorlien, and F. J. Davey. 1998. Seismic stratigraphy of the pre-Quaternary strata off Cape Roberts and their correlation with strata cored in the CIROS-1 drillhole, McMurdo Sound. *Terra Antartica* 5:273-279.

King, P. R., and G. P. Thrasher. 1996. Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. Lower Hutt, N.Z.: Institute of Geological and Nuclear Sciences.

Klitgord, K. D., and H. Schouten. 1986. Plate kinematics of the central Atlantic. In *The Geology of North America,* vol. M, *The Western and North Atlantic Region,* eds. P. R. Vogt and B. E. Tucholke, pp. 351- 378. Boulder, CO: Geological Society of America.

Larter, R. D., A. P. Cunningham, and P. F. Barker. 2002. Tectonic evolution of the Pacific margin of Antarctica. 1. Late Cretaceous reconstructions. *Journal of Geophysical Research* 107:2345.

Lawver, L. A., R. D. Muller, S. P. Srivastava, and E. R. Roest. 1990. The opening of the Arctic Ocean. In *Geological History of the Polar Oceans: Arctic Versus Antarctic,* eds. U. Bleil and J. Thiede, pp. 29-62. Dordrecht: Kluwer Academic.

Lisker, F. 2002. Review of fission track studies in northern Victoria Land, Antarctica-passive margin evolution versus uplift of the Transantarctic Mountains. *Tectonophysics* 349:57-73.

Lithgow-Bertelloni, C., and M. A. Richards. 1998. The dynamics of Cenozoic and Mesozoic plate motions. *Reviews of Geophysics* 36(1):27-78.

Lythe, M. B., D. G. Vaughan, A. Lambrecht, H. Miller, U. Nixdorf, H. Oerter, D. Steinhage, I. F. Allison, M. Craven, I. D. Goodwin, J. Jacka, V. Morgan, A. Ruddell, N. Young, P. Wellman, A. P. R. Cooper, H. F. J. Corr, C. S. M. Doake, R. C. A. Hindmarsh, A. Jenkins, M. R. Johnson, P. Jones, E. C. King, A. M. Smith, J. W. Thomson, M. R. Thorley, K. Jezek, B. Li, H. Liu, M. Hideo, V. Damm, F. Nishio, S. Fujita, P. Skvarca, F. Remy, L. Testut, J. Sievers, A. Kapitsa, Y. Macheret, T. Scambos, I. Filina, V. Masolov, S. Popov, G. Johnstone, B. Jacobel, P. Holmlund, J. Naslund, S. Anandakrishnan, J. L. Bamber, R. Bassford, H. Decleir, P. Huybrechts, A. Rivera, N. Grace, G. Casassa, I. Tabacco, D. Blankenship, D. Morse, H. Conway, T. Gades, N. Nereson, C. R. Bentley, N. Lord, M. Lange, and H. Sanhaeger. 2001. BEDMAP; a new ice thickness and subglacial topographic model of Antarctica. *Journal of Geophysical Research* 106:11335-11351.

McCarron, J. J., and R. D. Larter. 1998. Late Cretaceous to early Tertiary subduction history of the Antarctic Peninsula. *Journal of the Geological Society of London* 155:255-268.

Muller, R. D., D. T. Sandwell, B. E. Tucholke, J. G. Sclater, and P. R. Shaw. 1990. Depth to basement and geoid expression in the Kane Fracture Zone: A comparison. *Marine Geophysical Researches* 13:105-129.

Muller, R. D., J.-Y. Royer, and L. A. Lawver. 1993. Revised plate motions relative to the hotspots from combined Atlantic and Indian Ocean hotspot tracks. *Geology* 21(3):275-278.

Muller, R. D., C. Gaina, A. Tikku, D. Mihut, S. C. Cande, and J. M. Stock. 2000. Mesozoic/Cenozoic tectonic events around Australia. *Geophysical Monograph* 121:161-188.

Nankivell, A. P. 1997. *Tectonic Evolution of the Southern Ocean between Antarctica, South America and Africa over the Past 84 Ma.* Oxford: University of Oxford.

Raymond, C. A., J. M. Stock, and S. C. Cande. 2000. Fast Paleogene motion of the Pacific hotspots from revised global plate circuit constraints. *Geophysical Monograph* 121:359-376.

Rosenbaum, G., G. S. Lister, and C. Duboz. 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics* 359:117-129.

Royer, J. Y., and N. Rollet. 1997. Plate-tectonic setting of the Tasmanian region. *Australian Journal of Earth Sciences* 44(5):543-560.

Sandwell, D. T., and W. H. F. Smith. 1997. Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research* 102:10039-10054.

Sharp, W. D., and D. A. Clague. 2006. 50-Ma initiation of Hawaiian-Emperor bend records major change in Pacific Plate motion. *Science* 313:1281-1284.

Smith, W. H. F., and D. T. Sandwell. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277:956-1962.

Srivastava, S. P., and W. R. Roest. 1996. Porcupine plate hypothesis: Comment. *Marine Geophysical Researches* 18:89-595.

Steinberger, B., R. Sutherland, and R. J. O'Connell. 2004. Prediction of Emperor-Hawaii seamount locations from a revised model of global plate motion and mantle flow. *Nature* 430:67-173.

Stock, J. M., and P. Molnar. 1987. Revised history of early Tertiary plate motion in the South-west Pacific. *Nature* 325(6104):495-499.

Storey, B. C. 1991. The crustal blocks of West Antarctica within Gondwana: Reconstruction and breakup model. In *Geological Evolution of Antarctica,* eds. M. R. A. Thompson, J. A. Crame, and J. W. Thompson, pp. 587-592. Cambridge: Cambridge University Press.

Storey, B. C., and P. A. R. Nell. 1988. Role of strike-slip faulting in the tectonic evolution of the Antarctic Peninsula. *Journal of the Geological Society of London* 145(2):333-337.

Studinger, M., R. E. Bell, D. D. Blankenship, C. A. Finn, R. A. Arko, D. L. Morse, and I. Joughin. 2001. Subglacial Sediments: A regional geological template for ice flow in West Antarctica. *Geophysical Research Letters* 28:3493-3496.

Stump, E., and P. G. Fitzgerald. 1992. Episodic uplift of the Transantarctic Mountains; with supplemental data 92-08. *Geology* 20(2):161-164.

Sutherland, R. 1995. The Australia-Pacific boundary and Cenozoic plate motions in the SW Pacific; some constraints from Geosat data. *Tectonics* 14(4):819-831.

Tarduno, J. A., R. A. Duncan, D. W. Scholl, R. D. Cottrell, B. Steinberger, T. Thordarson, B. C. Kerr, C. R. Neal, F. A. Frey, M. Torii, and C. Carvallo. 2003. The Emperor Seamounts: Southward motion of the Hawaiian Hotspot plume in Earth's mantle. *Science* 301(5636):1064-1069.

ten Brink, U. S., S. Bannister, B. C. Beaudoin, and T. A. Stern. 1993. Geophysical investigations of the tectonic boundary between east and west Antarctica. *Science* 261:45-50.

Tikku, A. A., and S. C. Cande. 1999. The oldest magnetic anomalies in the Australian-Antarctic Basin; are they isochrons? *Journal of Geophysical Research* 104(1):661-677.

Tikku, A. A., and S. C. Cande. 2000. On the fit of Broken Ridge and Kerguelen Plateau. *Earth and Planetary Science Letters* 180:117-132.

Wessel, P., and W. H. F. Smith. 1995. New version of the generic mapping tools released. *Eos, Transactions of the American Geophysical Union* 76:329.

Whittaker, J. M., R. D. Muller, G. Leitchenkov, H. Stagg, M. Sdrolias, C. Gaina, and A. Goncharov. 2007. Major Australian-Antarctic plate reorganisation at Hawaiian-Emperor bend time. *Science* 318:83-86.

Wood, R. A., G. Lamarche, R. H. Herzer, J. Delteil, and B. Davy. 1996. Paleogene seafloor spreading in the southeast Tasman Sea. *Tectonics* 15:966-975.