

Weddell triple junction: The principal focus of Ferrar and Karoo magmatism during initial breakup of Gondwana

D.H. Elliot
T.H. Fleming } Department of Geological Sciences and Byrd Polar Research Center, Ohio State University, Columbus, Ohio 43210, USA

ABSTRACT

Middle Jurassic Ferrar tholeiites of Antarctica were emplaced during a short time interval (<1 m.y.) into an active rift system initiated in the Early Jurassic. Ferrar magmas were dispersed into the Antarctic sector of Gondwana from a source in the Weddell Sea region, within the thermal anomaly that also gave rise to the Karoo basaltic rocks of southern Africa. The Golden Gate lavas, part of the Karoo central area low-Ti tholeiites, show geochemical similarities to Ferrar rocks. Tectonic and geochemical relationships of the Ferrar and Karoo low-Ti magmas, which constitute a major part of the Jurassic Gondwana large igneous province, suggest that they were derived from a single source associated with a triple junction in the proto-Weddell Sea region.

Keywords: Ferrar, Karoo, Weddell, geochemistry, tectonics.

INTRODUCTION

Asthenospheric plumes are important in the generation of large igneous provinces, which are commonly associated with supercontinent breakup (Morgan, 1981). Opinions differ on whether plumes are the active driving mechanism for breakup or play a more passive role (e.g., Duncan and Richards, 1991; White and McKenzie, 1989). In the Gondwana context, the Cretaceous-Tertiary Deccan flood basalts can be traced to the Réunion hotspot, and Early Cretaceous magmatism associated with South Atlantic opening can be linked to the Tristan hotspot (Richards et al., 1989). Middle Jurassic breakup and Karoo magmatism have been related (White and McKenzie, 1989) to a plume centered on the South Africa–East Antarctica conjunction (Fig. 1). Storey and Kyle (1997) proposed several plumes in close proximity to account for breakup magmatism, but convincing hotspot traces linking independent plumes to Jurassic magmatism are lacking (Hawkesworth et al., 1999).

A plume has been specifically linked to a triple junction at Nuanetsi where the Lebombo belt, Botswana dike swarm, and Sabi River belt intersect (see Ernst and Buchan, 1997); however, the plume center is often depicted farther south along the Lebombo monocline (e.g., Storey, 1995). Extension of the rift toward the Gondwana plate margin has remained uncertain because of subsequent fragmentation of the margin (Dalziel and Elliot, 1982). Ferrar magmas of Antarctica, which were contemporaneous with tholeiitic magmas of Karoo, Queen Maud Land, and the Falkland Islands, provide further constraints on the initial stages of rifting. Geochemical and tectonic relationships suggest that a major magmatic source associated with a triple junction existed in the proto-Weddell Sea region in the Middle Jurassic.

FERRAR LARGE IGNEOUS PROVINCE

The Ferrar tholeiites, extending 3500 km from the Theron Mountains to southeast Australasia (Fig. 1), consist principally of the Dufek intrusion (0.6×10^5 km²) and Ferrar Dolerite sills ($1.1\text{--}1.7 \times 10^5$ km³), plus the Tasmanian Dolerites and extrusive rocks in Antarctica. Ferrar tholeiites are characterized by enriched initial Sr and Nd isotope ratios and low high field strength element (HFSE) concentrations with crust-like ratios, even in the most mafic rocks with ~9% MgO (Fleming et al., 1997, and references therein).

The outcrop pattern of the Ferrar rocks (Fig. 1) led Cox (1988) to propose a linear source beneath the Transantarctic Mountains. Ferrar geochemistry has been attributed to source enrichment by subduction along the Gondwana plate margin (Hergt et al., 1991; De Wit and Ransome, 1992), or to a linear zone of lithospherically derived magmatism controlled by plate

margin forces (Hawkesworth et al., 1999). Alternatively, Ferrar magmas had a narrowly focused origin in the proto-Weddell Sea region (Elliot et al., 1999, and references therein). Dispersal from this source region entailed long-distance transport of magmas, which was controlled by an extensional tectonic regime initiated in the Early Jurassic (see Elliot et al., 1999). The Dufek intrusion was considered by Ford and Kistler (1980) to be close to a triple junction and the Ferrar rocks to be located along an associated rift; Storey and Kyle (1997) regarded the Dufek intrusion as the source from which Ferrar magmas were dispersed.

U/Pb dates (183–184 Ma) for Ferrar sills and the New Amalfi sheet, South Africa (see Fig. 1) (Encarnación et al., 1996), and for the Dufek intrusion (Minor and Mukasa, 1997), demonstrate contemporaneity of Ferrar and at least part of the Karoo magmatism at a resolution of ~1 m.y. The ⁴⁰Ar/³⁹Ar dates for Ferrar, Karoo, and Queen Maud Land rocks (Fleming et al., 1997, and references therein; Duncan et al., 1997) also establish contemporaneity when recalculated to a common standard. Although the Falkland Islands dikes are apparently older by about 6–10 m.y. (Mussett and Taylor, 1994), the saddle-shaped spectra suggest that the dates reflect excess argon and are therefore too old.

KAROO PROVINCE

Geochemically, Karoo rocks are divided into high-Ti and low-Ti compositions (Cox, 1988). The former has Sr and Nd isotope ratios that overlap

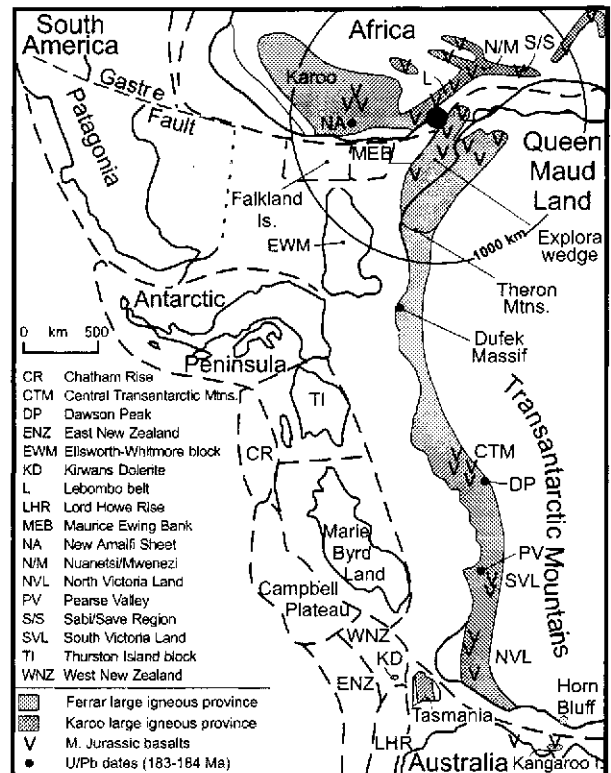


Figure 1. Gondwana reconstruction illustrating distribution of Middle Jurassic basaltic rocks in Antarctica and southern Africa. Plume center and head are from White and McKenzie (1989).

oceanic basalts (although extending to lower initial $^{143}\text{Nd}/^{144}\text{Nd}$ isotope ratios) and high concentrations of HFSEs, whereas the latter has enriched isotope compositions and low concentrations of HFSEs with crust-like ratios. The high-Ti rocks, centered on Nuanetsi (Fig. 2), interfinger southward with the low-Ti rocks. The low-Ti rocks, which consist mainly of low-MgO tholeiites, include the south Lebombo and Karoo central area, almost all basaltic rocks in Queen Maud Land, and dikes in the Falkland Islands (references in Fig. 3 caption). The Explora wedge dipping reflector sequences (Jokat et al., 1996) were formerly juxtaposed with the Lebombo belt and its extension, and therefore a large part probably consists of low-Ti rocks.

On the basis of trace element ratios and isotopic characteristics, several geochemical types have been distinguished among the low-Ti basalts in the Karoo central area (Marsh et al., 1997). The Golden Gate flows, a magma type in the Barkly East Formation which is the lower of the two basalt formations in the Karoo central area, show similarities in trace element and Sr isotope ratios to Ferrar rocks (Fig. 3A and 3B), although Nd isotope ratios are more scattered. Nevertheless, the Golden Gate lavas, and others in the Karoo central area, may represent magmas derived from the same source as the Ferrar. On the Nd-Sr isotope diagram (Fig. 3B), Karoo central area and Ferrar rocks form an array that is quite distinct from the low-Ti rocks of the Lebombo monocline, Queen Maud Land, and the Falkland Islands, despite one set of Falkland Islands dikes having been likened to the Ferrar tholeiites (Mitchell et al., 1999). The tight array formed by the Ferrar-Karoo central area rocks suggests a similar origin; other low-Ti magmas (low-Ti Sabie River, Queen Maud Land, Falkland Islands) indicate different evolutionary trends.

The Ferrar and Karoo-Queen Maud Land tholeiites have been considered geochemically distinct and geographically separated, with overlap confined to the Theron Mountains where only intrusive rocks are present.

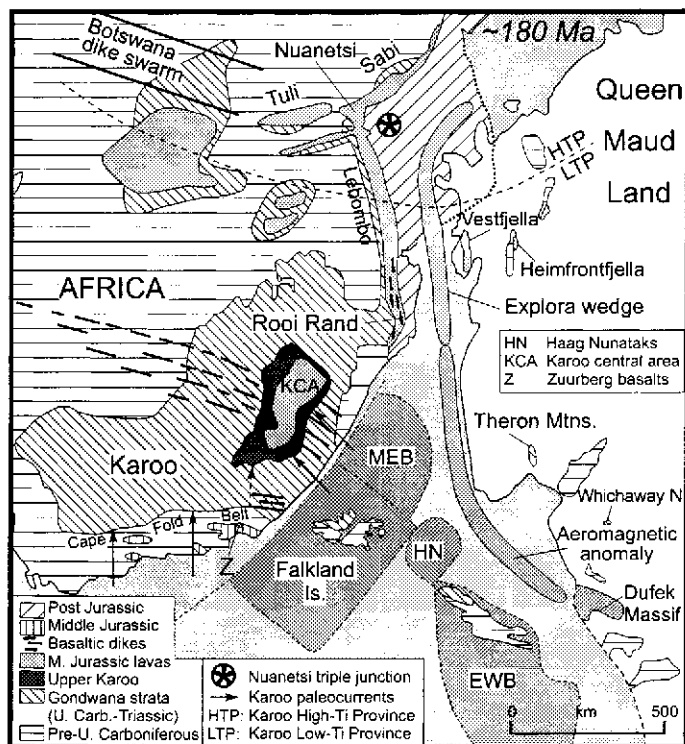


Figure 2. Reconstruction of southern Africa and Queen Maud Land, Antarctica, showing distribution of Gondwana strata and overlying Middle Jurassic basaltic rocks. Karoo and Ferrar dolerites are coextensive with Gondwana strata. Aeromagnetic anomaly interpreted as basaltic rocks—Hunter et al. (1996). Agulhas Plateau is omitted because it is primarily oceanic in origin (Uenzelmann-Neben et al., 1999). Other place names are given in Figure 1.

The geochemical similarity between Ferrar rocks and Golden Gate lavas suggest additional overlap and interfingering of the tholeiites.

WEDDELL TRIPLE JUNCTION

The Ferrar and Karoo central area rocks represent a substantial volume ($>2 \times 10^6 \text{ km}^3$) of rapidly emplaced magma. Indirect evidence of associated tectonism comes from the upper Karoo strata (Molteno and Clarens Formations) in South Africa (Turner, 1999). The Molteno basal sandstones (Middle Triassic, ca. 230 Ma) mark a significant change in paleocurrent patterns and provenance that persisted through Late Triassic to Early Jurassic time. Whereas grain provenance for lower Karoo strata was to the south, for the upper Karoo it was mainly to the southeast in the region of breakup between Africa and Queen Maud Land (Fig. 2). Furthermore, the provenance, located along strike of the principal Karoo depocenter, included basement rocks, which implies significant unroofing. Turner (1999) proposed that the upper Karoo stratigraphic record reflects thermal doming caused by plume-initiated uplift ca. 230 Ma. Although upper Karoo rocks reportedly contain a sparse record of early mafic volcanism, unequivocal evidence is found only in basaltic deposits either interbedded with the upper part of the Lower to Middle Jurassic Clarens Formation or forming crosscutting bodies. On the conjugate Queen Maud Land margin, the Gondwana sequence consists of 0–160 m of Permian strata overlain by 420 m of flood basalts (Harris et al., 1990). Locally lavas overlie basement, indicating erosion of Gondwana strata in Triassic to Middle Jurassic time and doming in the Nuanetsi region, as postulated by Cox (1989) to control modern drainage patterns in southern Africa.

The Gondwana paleo-Pacific plate margin was also significant in the tectonic history. Early Jurassic rifting in the Transantarctic Mountains (Fig. 4A) is associated with a disconformity-bounded sequence of silicic pyroclastic rocks that separates Triassic siliciclastic strata from basaltic extrusive rocks. This rift system, which later controlled Ferrar magma dispersal (Elliot et al., 1999), terminated in the Weddell Sea region, where the Ellsworth-Whitmore block and the Triassic-Jurassic ($203 \pm 8 \text{ Ma}$) Mt. Seelig granite (Pankhurst et al., 1991) were located. They record the approximate geographic extent of Early Jurassic silicic magmatism in an extended backarc region of the Gondwana plate margin. In this region, extension translated into contemporaneous strike-slip movement along the Gastre fault (Storey et al., 1999, and references therein), which projects along the margin of Africa in Gondwana reconstructions. Subduction-related Lower Jurassic granitoids occur in the Antarctic Peninsula (Leat et al., 1995) and Patagonia

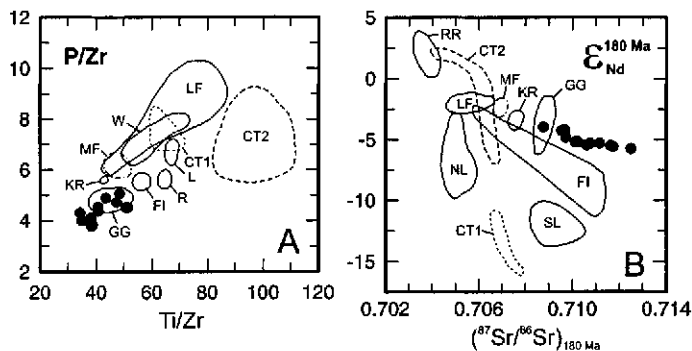


Figure 3. Geochemical characteristics of Ferrar and selected Karoo, Queen Maud Land, and Falkland Islands tholeiites. A: High field strength element ratios (P/Zr vs. Ti/Zr). B: $\epsilon_{\text{Nd}}^{180\text{Ma}}$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_{180\text{Ma}}$ diagram. Solid dots—Ferrar; GG—Golden Gate, KR—Kraai River, L—Letele, MF—Moshesh's Ford, R—Roma, W—Wonderkop (all belong to Barkly East Formation); LF—Lesotho Formation; SL—south Lebombo, NL—north Lebombo, RR—Rooi Rand; CT1 and CT2—Queen Maud Land; FI—Falkland Islands. Data sources: Ferrar—Fleming et al. (1995, 1997); Queen Maud Land—Luttinen et al. (1998); Karoo—Marsh et al. (1997), Hawkesworth et al. (1984); Falkland Islands—Mitchell et al. (1999).

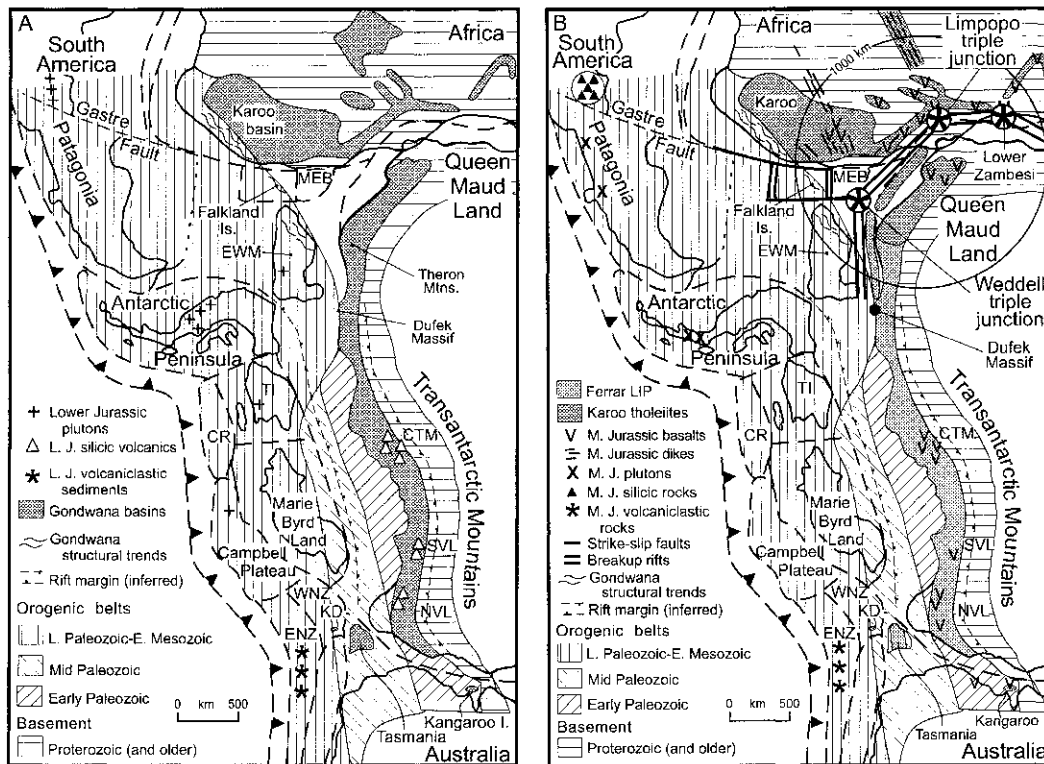


Figure 4. Gondwana reconstructions. Abbreviations as in Figure 1. **A:** Early Jurassic illustrating distribution of silicic magmatic rocks and associated extensional regime along and adjacent to Gondwana plate margin, and distribution of Gondwana strata. MS—Mount Seelig. **B:** Middle Jurassic illustrating Weddell triple junction and associated rifts, continental flood basalts, and silicic Marifil Group of Patagonia. Rotations and displacements of continental blocks followed large igneous province emplacement; ca. 175 Ma Ellsworth-Whitmore block had rotated 90° anticlockwise (Grunow et al., 1986).

(Pankhurst et al., 1998), although Vaughan and Storey (1997) noted that in the Antarctic Peninsula the Late Triassic through Late Jurassic was a period of extension that was possibly related to trench rollback.

Other evidence for Jurassic magmatism in the proto-Weddell Sea region comes from the Cape Fold Belt (Fig. 2), where Karoo (Zuurberg) basalts occur in one of the Mesozoic grabens. The basalts are interbedded in coarse conglomeratic strata that interfinger with Middle Jurassic beds (Dingle et al., 1983), indicating rifting prior to basalt eruption. The orientation of these grabens was controlled by the preexisting Cape Fold Belt tectonic fabric.

Evidence for uplift and tectonism in the proto-Weddell Sea region is complemented by evidence for a magmatic source region. Dike arrays (Fig. 2) trending west, west-northwest, and north converge off the southeast coast of Africa (Hunter and Reid, 1987) in the inferred source region of the Ferrar and Karoo central area magmas. It is therefore proposed that this major magmatic source, responsible for both the Ferrar and Karoo low-Ti magmas and the pre-Middle Jurassic doming inferred from upper Karoo stratigraphic data, was associated with the Weddell triple junction (Fig. 4B).

The Dufek intrusion has been advocated as the upper crustal magma chamber from which Ferrar magmas migrated (Storey and Kyle, 1997). However, Ferrar Dolerite sills within basement rocks preclude supracrustal transport as the only mode of magma dispersal. Rather, the Dufek intrusion is regarded as one of several possible foci where Ferrar magmas migrated into supracrustal rocks or to the surface. The principal structures controlling dispersal of Ferrar magmas were most likely in what is now West Antarctica, rather than directly beneath the Transantarctic Mountains or the East Antarctic Ice Sheet, and formed one arm of the Weddell triple junction. Another arm was the Lebombo volcanic belt and its conjugate margin rocks, the Explora wedge and Queen Maud Land basalts. The third arm was the extension of the Gastre fault. The contemporaneous Marifil Group silicic rocks in Patagonia (Pankhurst et al., 1998), the oldest part of the diachronous Chon Aike province, are north of and adjacent to the Gastre fault and were interpreted as anatectic melts formed by basalt underplating. Speculatively, Marifil Group rocks may reflect channeling of basaltic magmas along a zone of weakness, expressed at the surface by the Gastre fault, to a site of magma ponding where anatectic melting occurred. Both the Gastre fault zone and the Juras-

sic rift in Antarctica predated flood-basalt magmatism. Most of the granites in the Ellsworth-Whitmore Mountains block (dated as 175 ± 8; Storey et al., 1988; Pankhurst et al., 1991), located in the breakup region in Gondwana, were emplaced after the principal episode of flood-basalt magmatism and rotation of the block (Grunow et al., 1986). The granites may record late magma generation at or near the Weddell triple junction.

In Africa, except for the main Karoo basin, Gondwana sequences and breakup basalts are located in rifts that reactivated structures dating from at least late Neoproterozoic–early Paleozoic time (De Wit and Ransome, 1992; Daly et al., 1991). The pattern of structural features in Africa and Antarctica, which extended far beyond the limits of any plume head, indicates that preexisting crustal weaknesses determined the locus of fragmentation; the plume further weakened the lithosphere and caused enhanced melt production required for flood-basalt magmatism. Regions already weakened by extension facilitated local upwelling of the plume and it is proposed that melt production was concentrated at the Weddell triple junction, yielding the Ferrar and Karoo low-Ti rocks, and at the Limpopo (Nuanetsi) triple junction, producing the Karoo high-Ti tholeiites. Another possible center is in the lower Zambesi region (Ernst and Buchan, 1997). The Karoo high-Ti rocks and basalts of the Zambesi region appear to form minor parts of the Gondwana large igneous province. Similar to the widely dispersed magmatism linked to a plume in the Afar region of Africa (Ebinger and Sleep, 1998), the Jurassic Gondwana province is attributed to a single large plume head with two, if not three, distinct magmatic foci, the locations of which were tectonically controlled.

CONCLUSIONS

1. The geochemistry of the Golden Gate lavas of the Karoo central area indicates that they may be closely related to the Antarctic Ferrar magmas.
2. The Ferrar and Karoo low-Ti tholeiites constitute the major part of the Jurassic Gondwana large igneous province and are related to magmatic upwelling at a triple junction in the proto-Weddell Sea region.
3. The Weddell triple junction formed the principal focus of magmatism within the envelope of a plume-related thermal anomaly associated with Gondwana breakup.

ACKNOWLEDGMENTS

We thank J.S. Marsh for permission to use unpublished Sr and Nd isotope data for the Golden Gate lavas. We also thank M.J. De Wit and R.A. Duncan for critical reviews. Research on Ferrar tholeiites has been supported by the Office of Polar Programs, National Science Foundation, most recently by grant OPP-9420498. Byrd Polar Research Center contribution number C-1172.

REFERENCES CITED

- Cox, K.G., 1988, The Karoo Province, in Macdougall, J.D., ed., Continental flood basalts: Boston, Kluwer, p. 239–271.
- Cox, K.G., 1989, The role of mantle plumes in the development of continental drainage patterns: *Nature*, v. 342, p. 873–877.
- Daly, M.C., Lawrence, S.R., Kimuna, D., and Binga, M., 1991, Late Paleozoic deformation in central Africa: Result of distant collision?: *Nature*, v. 350, p. 605–607.
- Dalziel, I.W.D., and Elliot, D.H., 1982, West Antarctica: Problem child of Gondwanaland: *Tectonics*, v. 1, p. 3–19.
- De Wit, M.J., and Ransome, I.G.D., 1992, Regional inversion tectonics along the southern margin of Gondwana, in De Wit, M.J., and Ransome, I.G.D., eds., Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of southern Africa: Rotterdam, Balkema, p. 15–21.
- Dingle, R.V., Siesser, W.G., and Newton, A.R., 1983, Mesozoic and Tertiary geology of southern Africa: Rotterdam, Balkema, 375 p.
- Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts and true polar wander: *Reviews of Geophysics*, v. 29, p. 31–50.
- Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., and Duncan, A.R., 1997, The timing and duration of the Karoo igneous event, southern Gondwana: *Journal of Geophysical Research*, v. 102, p. 18,127–18,138.
- Ebinger, C.J., and Sleep, N.H., 1998, Cenozoic magmatism throughout east Africa resulting from impact of a single plume: *Nature*, v. 395, p. 788–791.
- Elliot, D.H., Fleming, T.H., Kyle, P.R., and Foland, K.A., 1999, Long distance transport of magmas in the Jurassic large igneous province: *Earth and Planetary Science Letters*, v. 167, p. 89–104.
- Encarnación, J., Fleming, T.H., Elliot, D.H., and Eales, H.V., 1996, Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana: *Geology*, v. 24, p. 535–538.
- Ernst, R.E., and Buchan, K.L., 1997, Giant radiating dike swarms: Their use in identifying pre-Mesozoic large igneous provinces and mantle plumes, in Mahoney, J., and Coffin, M., eds., Large igneous provinces: Continental, oceanic, and planetary flood volcanism: American Geophysical Union Geophysical Monograph 100, p. 297–333.
- Fleming, T.H., Foland, K.A., and Elliot, D.H., 1995, Isotopic and chemical constraints on the crustal evolution and source signature of Ferrar magmas, North Victoria Land, Antarctica: *Contributions to Mineralogy and Petrology*, v. 121, p. 217–236.
- Fleming, T.H., Elliot, D.H., Heimann, A., and Foland, K.A., 1997, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of Ferrar Dolerite sills from the Transantarctic Mountains, Antarctica: Implications for the age and origin of the Ferrar magmatic province: *Geological Society of America Bulletin*, v. 109, p. 533–546.
- Ford, A.B., and Kistler, R.W., 1980, K-Ar age, composition and origin of Mesozoic mafic rocks related to Ferrar Group, Pensacola Mountains, Antarctica: *New Zealand Journal of Geology and Geophysics*, v. 23, p. 371–390.
- Grunow, A.M., Dalziel, I.W.D., and Kent, D.V., 1986, Ellsworth-Whitmore Mountains crustal block, western Antarctica: New paleomagnetic results and their tectonic significance, in McKenzie, G.D., ed., Gondwana Six: Structure, tectonics and geophysics: American Geophysical Union Geophysical Monograph 40, p. 161–171.
- Harris, C., Marsh, J.S., Duncan, A.R., and Erlank, A.J., 1990, Petrogenesis of the Kirwan Basalts of Dronning Maud Land, Antarctica: *Journal of Petrology*, v. 31, p. 341–369.
- Hawkesworth, C.J., Marsh, J.S., Duncan, A.R., Erlank, A.J., and Norry, M.J., 1984, The role of continental lithosphere in the generation of Karoo volcanic rocks: Evidence from combined Nd- and Sr-isotope studies, in Erlank, A.J., ed., Petrogenesis of the volcanic rocks of the Karoo Province: Geological Society of South Africa Special Publication 13, p. 341–354.
- Hawkesworth, C., Kelley, S., Turner, S., Le Roex, A., and Storey, B.C., 1999, Mantle processes during Gondwana break-up and dispersal: *Journal of African Earth Sciences*, v. 28, p. 239–261.
- Heigt, J.M., Peate, D.W., and Hawkesworth, C.J., 1991, The petrogenesis of Mesozoic Gondwana low-Ti flood basalts: *Earth and Planetary Science Letters*, v. 105, p. 134–148.
- Hunter, D.R., and Reid, D.L., 1987, Mafic dike swarms in southern Africa, in Halls, H.C., and Fahrig, W.F., eds., Mafic dike swarms: Geological Association of Canada Special Paper 34, p. 445–456.
- Hunter, R.J., Johnson, A.C., and Aleshkova, N.D., 1996, Aeromagnetic data from the southern Weddell Sea embayment and adjacent areas: Synthesis and interpretation, in Storey, B.C., et al., eds., Weddell Sea tectonics and Gondwana breakup: Geological Society [London] Special Publication 108, p. 143–154.
- Jokat, W., Hübscher, C., Meyer, U., Oszko, L., Schöne, T., Versteeg, W., and Miller, H., 1996, The continental margin off East Antarctica between 10°W and 30°W, in Storey, B.C., et al., eds., Weddell Sea tectonics and Gondwana breakup: Geological Society [London] Special Publication 108, p. 129–141.
- Leat, P.T., Scarrow, J.H., and Millar, I.L., 1995, On the Antarctic Peninsula Batholith: *Geological Magazine*, v. 132, p. 399–412.
- Luttinen, A.V., Ramo, O.T., and Huhma, H., 1998, Neodymium and strontium isotopic and trace element composition of a Mesozoic CFB suite from Dronning Maud Land, Antarctica: Implications for lithospheric and asthenospheric contributions to Karoo magmatism: *Geochimica et Cosmochimica Acta*, v. 62, p. 2701–2714.
- Marsh, J.S., Hooper, P.R., Rehacek, J., Duncan, R.A., and Duncan, A.R., 1997, Stratigraphy and age of Karoo Basalts of Lesotho and implications for correlations within the Karoo Igneous Province, in Mahoney, J.J., and Coffin, M.F., eds., Large igneous provinces: Continental, oceanic, and planetary flood volcanism: American Geophysical Union Geophysical Monograph 100, p. 247–272.
- Minor, D., and Mukasa, S., 1997, Zircon U-Pb and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the Dufek layered mafic intrusion, Antarctica: Implications for the age of the Ferrar large igneous province: *Geochimica et Cosmochimica Acta*, v. 61, p. 2497–2504.
- Mitchell, C., Ellam, R.M., and Cox, K.G., 1999, Mesozoic dolerite dikes of the Falkland Islands: Petrology, petrogenesis and implications for geochemical provinciality in Gondwanaland low-Ti basaltic rocks: *Geological Society [London] Journal*, v. 156, p. 901–916.
- Morgan, W.J., 1981, Hotspot tracks and the opening of the Atlantic and Indian Oceans, in Emiliani, C., ed., The sea, Volume 7: New York, Wiley Interscience, p. 443–487.
- Mussett, A.E., and Taylor G.K., 1994, $^{40}\text{Ar}/^{39}\text{Ar}$ ages for dikes from the Falkland Islands with implications for the break-up of southern Gondwanaland: *Geological Society [London] Journal*, v. 151, p. 79–81.
- Pankhurst, R.J., Storey, B.C., and Millar, I.L., 1991, Magmatism related to the break-up of Gondwana, in Thomson, M.R.A., et al., eds., Geological evolution of Antarctica: Cambridge, UK, Cambridge University Press, p. 573–579.
- Pankhurst, R.J., Leat, P.T., Sruga, P., Rapela, C.W., Mäquez, M., Storey, B.C., and Rile, T.R., 1998, The Chon Aike province of Patagonia and related rocks in West Antarctica: A silicic large igneous province: *Journal of Volcanology and Geothermal Research*, v. 81, p. 113–136.
- Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hotspot tracks: Plume heads and tails: *Science*, v. 246, p. 103–107.
- Storey, B.C., 1995, The role of mantle plumes in continental breakup: Case histories from Gondwanaland: *Nature*, v. 377, p. 301–308.
- Storey, B.C., and Kyle, P.R., 1997, An active mantle mechanism for Gondwana breakup: *South African Journal of Geology*, v. 100, p. 283–290.
- Storey, B.C., Hole, M.J., Pankhurst, R.J., Millar, I.L., and Vennum, W.R., 1988, Middle Jurassic within-plate granites in West Antarctica and their bearing on the break-up of Gondwanaland: *Geological Society [London] Journal*, v. 145, p. 999–1007.
- Storey, B.C., Curtis, M.L., Ferris, J.K., Hunter, M.A., and Livermore, R.A., 1999, Reconstruction and break-out model for the Falkland Islands within Gondwana: *Journal of African Earth Sciences*, v. 29, p. 153–163.
- Turner, B.R., 1999, Tectono-stratigraphic development of the Upper Karoo foreland basin: Orogenic unloading versus thermally-induced Gondwana rifting: *Journal of African Earth Sciences*, v. 28, p. 215–238.
- Uenzelmann-Neben, G., Gohl, K., and Ehrhardt, A., 1999, Agulhas Plateau, SW Indian Ocean: New evidence for excessive volcanism: *Geophysical Research Letters*, v. 26, p. 1911–1944.
- Vaughan, A.P.M., and Storey, B.C., 1997, Mesozoic geodynamic evolution of the Antarctic Peninsula, in Ricci, C.A., ed., The Antarctic region: Geological evolution and processes: Siena, Terra Antarctica Publication, p. 373–382.
- White, R.S., and McKenzie, D., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: *Journal of Geophysical Research*, v. 94, p. 7685–7729.

Manuscript received November 15, 1999

Revised manuscript received March 20, 2000

Manuscript accepted March 28, 2000