Synchronous emplacement of Ferrar and Karoo dolerites and the early breakup of Gondwana

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ABSTRACT

Constraints on the timing of Karoo and Ferrar continental flood-basalt magmatism in Africa and Antarctica, respectively, are critical to understanding the relationship of the Karoo and Ferrar to mantle plumes, subduction, and the initial breakup of Gondwana. Although recent work has shown that Ferrar magmas were emplaced over a short interval (<1 m.y.), the timing of magmatism within the Karoo and its relationship to the Ferrar have been problematic. New zircon and baddeleyite U-Pb ages on Ferrar (183.6 ± 1.0 Ma) and southern Karoo (183.7 ± 0.6 Ma) dolerites demonstrate that part of Karoo magmatism occurred during the rapid emplacement of Ferrar magmas. A mantle plume is thought to have been important in the genesis of the Karoo province, whereas lithospheric extension, perhaps related to subduction, has been invoked for Ferrar magmatism. The new ages now suggest that Ferrar and southern Karoo magmatism were related to a single mantle thermal anomaly and rifting event. This event may have produced local rift basins and caused rotation of microblocks in west Antarctica several million years before the breakup of east and west Gondwana.

INTRODUCTION

The Ferrar and Karoo continental flood-basalt provinces form a contiguous Jurassic igneous province in Gondwana reconstructions (Fig. 1). They are the oldest and largest of a series of flood-basalt provinces that punctuated the protracted breakup of Gondwana. The possible presence of a plume in the Karoo area (e.g., White and McKenzie, 1989), the presence of subduction and extension along the proto–Pacific margin of Gondwana (e.g., Cox, 1978), and the potential for insulative heating and uplift beneath the supercontinent (Anderson et al., 1992) make it difficult to identify a definite cause for flood-basalt magmatism and initial breakup. Whereas several lines of evidence support a plume origin for the Karoo province (White and McKenzie, 1989; Richards et al., 1989; Cox, 1989), the geochemistry and regional setting of Ferrar magmas have suggested a dominantly lithospheric source for the Ferrar and an association with subduction, lithospheric extension, and a "hot line" (e.g., Elliot, 1974; Cox, 1978, 1988; Hergt et al., 1991). These differences, along with uncertainties in the relative timing of Karoo and Ferrar magmatism, have precluded relating these two provinces in any precise way other than their broad association with early breakup events. New U-Pb ages presented here demonstrate synchroneity of magmatism in large parts of these two provinces. The results indicate a common heat source and suggest a sequence of events leading to the breakup of Gondwana.

SAMPLES AND GEOLOGIC SETTING

Dolerite sills and gently dipping sheets, the most prominent and widespread rocks of the Ferrar Group (Kyle et al., 1981), are exposed for >3000 km along the Transantarctic Mountains (Fig. 1). Isolated volcanic equivalents of the dolerites (Kirkpatrick Basalt) may have once formed extensive lava plateaus. The minimum volume of the Ferrar Group is ~0.5×10^6 km^3, of which ~80% is represented by the mafic Dufek layered intrusion in the Pensacola Mountains (Kyle et al., 1981). Zircon and baddeleyite were separated from granophyric pods within two Ferrar sills. Sample 90-76-12 is from an ~300-m-thick sill that was intruded into Cambrian-Ordovician granite on the south side of Pearse Valley in the Taylor Glacier area, south Victoria Land. Sample 90-63-9 comes from an

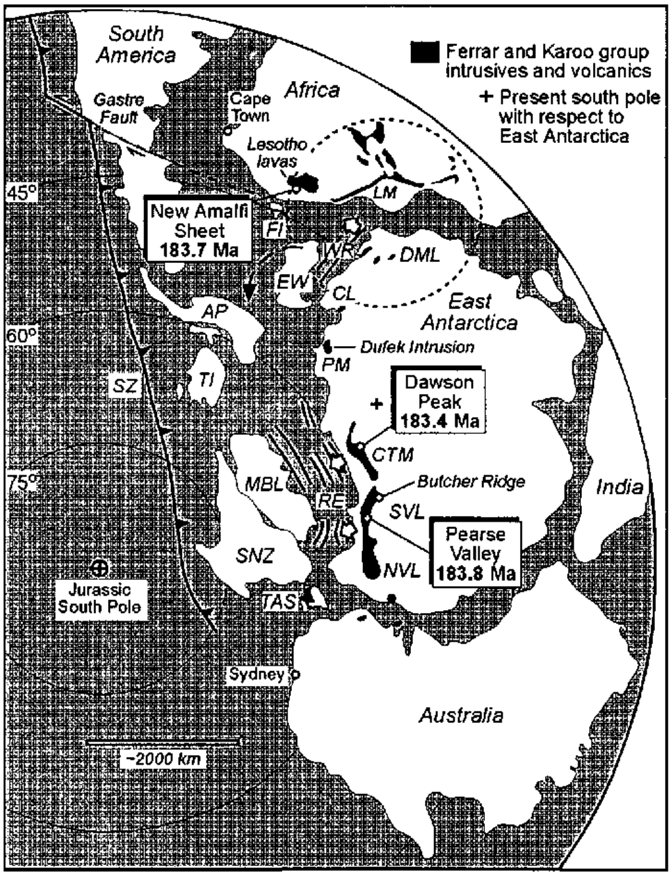

Figure 1. Karoo and Ferrar continental flood-basalt provinces in schematic early Middle Jurassic (~183 Ma) reconstruction of Gondwana. Sample sites and ages are indicated in boxes. Dashed circle marks location of ~2000-km-diameter thermal anomaly proposed to have been caused by a mantle plume (White and McKenzie, 1989). Movement of paleo-Pacific margin blocks of Gondwana (AP—Antarctic Peninsula, MBL—Marie Byrd Land, SNZ—southern New Zealand, TI—Thurston Island) away from east Antarctica is suggested to have been associated with rifts along Transantarctic Mountains, Weddell Rift (WR) (Kristoffersen and Hinz, 1991), and early rifts in Ross Embayment (RE) (bold lines). Rotation of Ellsworth-Whitmore Mountains block (EW), indicated by dashed arrow, may have occurred during rifting. Pre- and syn-Ferrar principal extension directions in Transantarctic Mountains and Dronning Maud Land (DML) are shown as open arrows (Wilson, 1992). Reconstruction is modified from Grunow et al. (1991) and Rapela and Pankhurst (1992). CL—Coats Land, CTM—Central Transantarctic Mountains, FI—Falkland Islands, LM—Lebombo monocline, NVL—north Victoria Land, PM—Pensacola Mountains, SVL—south Victoria Land, SZ—subduction zone, TAS—Tasmania.

~170-m-thick sill intruded into the Permian Buckley Formation at Dawson Peak in the upper Lennox–King Glacier area of the central Transantarctic Mountains.

Tholeiitic dikes, sills, and sheetlike bodies in southern Africa are the intrusive equivalents of the Karoo lavas, most prominently exposed in Lesotho (Fig. 1) (Eales et al., 1984). The minimum volume of the Karoo intrusive and volcanic rocks is ~2×10^6 km^3 (Cox, 1988). Our Karoo sample is granophyre from the New Amalfi sheet, near Matatiele, South Africa. The New Amalfi sheet is a bowl-shaped intrusion, ~15 km in diameter, which was fed by the Elephant's Head dike. The latter extends ~30 km westward from the New Amalfi sheet and cuts the lowermost lavas of the Lesotho basalt plateau. The Elephant's Head dike is subparallel to several west-northwest–trending dolerite dikes that were probably feeders for the Lesotho lavas (Walker and Poldervaart, 1949).

NEW U-Pb AGES

The sill from Dawson Peak, Antarctica, yielded concordant zircon analyses with a mean ^{206}Pb/^{238}U age of 183.4 ± 1.4 Ma. The two zircon fractions analyzed were subjected to different degrees of abrasion and differ markedly in final U content (Table 1). That the two analyses are concordant with respect to each other suggests that the zircons have not been affected by significant Pb loss nor by inheritance of xenocrystic zircon. The age of the Dawson Peak sample is indistinguishable from the age of the sill in Pearse Valley (183.8 ± 1.6 Ma, Table 1). The zircon analysis of the latter sample is slightly discordant (Fig. 2) and might be interpreted as indicating the presence of a small amount of xenocrystic zircon. However, given the small degree of discordance and the current uncertainties in the decay constants of U (Mattinson, 1987), this analysis may in fact be concordant. Since baddeleyite is more robust to Pb loss, and the presence of xenocrystic baddeleyite in gabbroic rocks is unlikely, the baddeleyite analysis indicates that this sample is the same age as the Dawson Peak sill. The four ^{206}Pb/^{238}U ages from the two Antarctic sills overlap within analytical uncertainty with a mean of 183.6 ± 1.0 Ma (2σ internal error; see Table 1). This age is indistinguishable from zircon U-Pb ages (determined in the same laboratory as those in this study) obtained for capping granophyre (183.9 ± 0.3 Ma) and a late granitic dike (182.7 ± 0.4 Ma) of the Dufek intrusion (Minor and Mukasa, 1995; 1996, personal commun.) (Fig. 1).

The zircon and baddeleyite analyses from the New Amalfi sheet in southern Africa are all concordant and have a mean ^{206}Pb/^{238}U age of 183.7 ± 0.6 Ma (2σ internal error), which is indistinguishable from the U-Pb age on the Antarctic sills. A recent study of the New Amalfi sheet yielded a whole-rock Rb-Sr isochron age of 178 ± 6 Ma (Williams, 1995), agreeing within error with the zircon and baddeleyite U-Pb ages.

Previous dates (summarized in Heimann et al., 1994, and Fleming, 1995) on Ferrar Group rocks, determined largely by whole-rock K-Ar, Rb-Sr, and ^{40}Ar/^{39}Ar techniques, ranged from 90 to 310 Ma. In contrast, ^{40}Ar/^{39}Ar analyses on feldspar from both the Kirkpatrick Basalt and Ferrar Dolerite sills (Foland et al., 1993; Heimann et al., 1994; Fleming, 1995), including the sills analyzed here, demonstrated a short interval of <1 m.y. for magmatism at 176.7 Ma. The accuracy of ^{40}Ar/^{39}Ar ages depends on the age assigned to the standard used to monitor the neutron flux during irradiation of samples. Recalculating the ^{40}Ar/^{39}Ar date by using a recently proposed age of 523.5 ± 2.9 Ma (Renne et al., 1994), rather than 513.5 Ma, for the standard Mmhb-1 yields 180.4 ± 1.5 Ma (2σ, combined analytical error and uncertainty in the monitor age, as

TABLE 1. ZIRCON AND BADDELEYITE U-Pb ANALYTICAL DATA FROM FERRAR AND KAROO DOLERITES

Sample type[*]	Mass[†] (μg)	U (ppm)	Pb (ppm)	Pb[§] (pg)	^{206}Pb/^{204}Pb[#]	^{206}Pb/^{238}U[**] (2σ)	^{207}Pb/^{235}U[**] (2σ)	^{207}Pb/^{206}Pb[**] (2σ)	Ages (2σ) Ma[††]	
									^{206}Pb/^{238}U	^{207}Pb/^{235}U
New Amalfi sheet, Matatiele, South Africa (I-247)										
(a) Z	76	395	13.4	26	2178	0.02893 (0.42)	0.1984 (0.45)	0.04976 (0.14)	183.8 (0.9)	183.8 (0.9)
(b) Z	45	438	16.7	98	392	0.02894 (0.45)	0.1978 (1.06)	0.04957 (0.87)	183.9 (1.0)	183.6 (2.1)
(c) B	126	96	2.84	32	725	0.02887 (0.44)	0.1979 (0.59)	0.04970 (0.34)	183.5 (0.9)	183.4 (1.1)
Weighted mean ^{206}Pb/^{238}U age = 183.7 (±0.6 Ma 2σ internal error; ±1.9 Ma external error)[§§]										
Sill, Dawson Peak, Central Transantarctic Mts., Antarctica (90-63-9)										
(d) Z	55	638	24.7	18	3668	0.02892 (0.44)	0.1985 (0.45)	0.04978 (0.11)	183.8 (0.9)	183.8 (0.9)
(e) Z	11	2370	93	95	528	0.02880 (0.43)	0.1978 (0.60)	0.04981 (0.39)	183.0 (0.9)	183.2 (1.2)
Mean ^{206}Pb/^{238}U age = 183.4 ± 1.4 Ma (range of uncertainty covered by both analyses)										
Sill, Pearse Valley, South Victoria Land, Antarctica (90-76-12)										
(f) Z	138	1271	53.0	26	12539	0.02904 (0.43)	0.1997 (0.44)	0.04988 (0.08)	184.5 (0.9)	184.9 (0.9)
(g) B	215	204	5.46	31	2643	0.02884 (0.42)	0.1981 (0.44)	0.04982 (0.12)	183.2 (0.9)	183.5 (0.9)
Mean ^{206}Pb/^{238}U age = 183.8 ± 1.6 Ma (range of uncertainty covered by both analyses)										
Weighted mean ^{206}Pb/^{238}U age from both Antarctic sills = 183.6 (±1.0 Ma 2σ internal error; ±2.1 Ma external error)[§§]										

Note: Chemical procedures and mass spectrometric analyses performed at the University of Michigan.

[*] Z, zircon; B, baddeleyite. (a) Abraded grains; original surfaces removed; 45-100 μm in grain size. (b) Same as (a). (c) Flat, brown, striated, partly broken grains; 50-100 μm. (d) Same as (a), but with narrow brown glass (?)-filled cores; 45-100 μm. (e) Four ~100 μm partly abraded grains. (f) Well-abraded; 45-100 μm. (g) Brown twin-striated grains; ~50 μm blades to stubby ~100 μm grains.

[†] Uncertainty in mass is ±2 μg.

[§] Total common Pb from sample and laboratory procedures.

[#] Measured ratio corrected for spike and Pb fractionation (0.11 ± 0.05% amu^{-1}).

[**] Ratios (with 2σ errors in %) corrected for spike, fractionation (0.13 ± 0.4% amu^{-1} for U; 0.11 ± 0.05% amu^{-1} for Pb), initial Pb (^{206}Pb/^{204}Pb = 17.60 ±0.60, ^{207}Pb/^{204}Pb = 15.65 ±0.20, ^{208}Pb/^{204}Pb = 39.0 ± 1.0 for (a) to (c) (Betton et al., 1984), and ^{206}Pb/^{204}Pb = 18.8 ± 0.2, ^{207}Pb/^{204}Pb = 15.66 ± 0.07, ^{208}Pb/^{204}Pb = 38.6 ±0.3 for (c) to (g) (Kyle et al., 1987; Molzahn et al., 1994); uncertainties cover the range of values reported), blank (20 ±12 pg Pb and 10 pg U; fraction (d) is corrected for 13 pg Pb blank; mean isotopic composition and absolute 2σ of Pb blank is: ^{206}Pb/^{204}Pb = 19. 4 ± 1.2, ^{207}Pb/^{204}Pb = 15.79 ± 0.12, ^{208}Pb/^{204}Pb = 39.0 ± 0.8, and error correlation for blank ^{206}Pb/^{204}Pb-^{207}Pb/^{204}Pb = 0.5).

[††] Ages and absolute 2σ calculated with method of Ludwig (1980) incorporating all uncertainties quoted above and uncertainties in the ^{206}Pb/^{204}Pb and ^{207}Pb/^{206}Pb ratios (±0.5% and ±0.06%, respectively) unrelated to within-run statistics or mass fractionation (variations in collector gain); λ^{238}U = 1.5513×10^{-10}, λ^{235}U = 9.8485×10^{-10}, present ^{238}U/^{235}U = 137.88.

[§§] Weighted by $1/\sigma^2$. External errors incorporate a systematic error of ±1.8 m.y. arising from uncertainty in the ^{238}U decay constant and U-Pb spike calibration. They should be used when comparing with ages determined by other techniques (e.g., ^{40}Ar/^{39}Ar). Internal errors exclude these sources of systematic error.

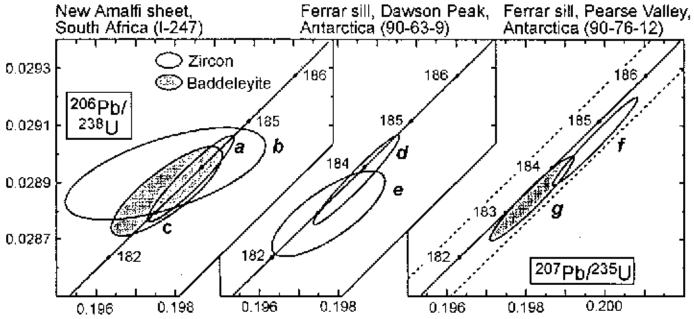

Figure 2. Conventional concordia diagrams showing U-Pb data for zircon and baddeleyite from Ferrar and Karoo dolerites. Error ellipses represent ±2σ internal errors and are labeled with lowercase letters keyed to Table 1. Dashed lines in third panel show range in uncertainty in position of concordia resulting from uncertainties in decay constants of U (Mattinson, 1987). Numbers labeling concordia are in millions of years.

quoted). This age is within uncertainty of the mean U-Pb age for the Antarctic sills of 183.6 ± 2.1 Ma (2σ external error) (Table 1).

Previous whole-rock K-Ar dates on Karoo magmatic rocks are also diverse—from 135 to 225 Ma, with apparent peaks at 193 and 178 Ma (Fitch and Miller, 1984). Many of these dates may be compromised by excess or loss of Ar, and accepting them leads to several geologic problems that are discussed elsewhere (Cox, 1988). The lack of weathering horizons within the Lesotho basalt section suggests that the southern Karoo lavas were emplaced over a relatively short interval (Walker and Poldervaart, 1949). Recent $^{40}Ar/^{39}Ar$ whole-rock analyses (Hooper et al., 1993) on the upper and lower Lesotho basalts, recalculated with Mmhb-1 at 523.5 Ma (Renne et al., 1994), fall in the range 184 ± 2 Ma, which is indistinguishable from the U-Pb ages on the New Amalfi sheet. The available geochronologic and field data therefore suggest that the basalts and dolerites in the Lesotho area were emplaced during a short interval that was synchronous with the rapid emplacement of Ferrar magmas.

RELATIONSHIP BETWEEN FERRAR AND KAROO MAGMATISM

The present outcrop pattern of Ferrar rocks in Antarctica is a long narrow belt. This pattern may reflect their original distribution or may be an artifact of exposure. The magmas may have been generated from a restricted mantle source and then transported long distances through the crust, or they may have been generated from several separate source regions. These issues bear on the problem of the location and shape of the mantle thermal anomaly associated with Ferrar magmatism. The lack of any significant exposure of dike swarms, and the general absence of dikes cutting basement units, suggests extensive lateral transport of magmas as sills (Fleming, 1995). Local sources that may have fed magmas into the supracrustal sequences include the Butcher Ridge Complex (Behrendt and McCafferty, 1995) and the Dufek intrusion (Minor and Mukasa, 1995). These potential feeders may be independently rooted in the mantle or connected at depth by a dike system running beneath the Transantarctic Mountains. On the basis of their geochemical uniformity and rapid emplacement, it has been suggested that Ferrar magmas were derived from a restricted source, perhaps in the vicinity of the Dufek intrusion, rather than from several mantle source regions along the Transantarctic Mountains (Fleming, 1995). Ferrar magmas, from the Dufek intrusion to Tasmania, carry a strong lithospheric geochemical signature (Hergt et al., 1991; Fleming et al., 1995). Hence, the geochemistry of the thermally anomalous asthenospheric mantle underneath is equivocal.

In the Karoo region and Dronning Maud Land, several lines of evidence appear to support the former presence of a plume head. Among these are the volume of Karoo magmatic rocks (White and McKenzie, 1989), preservation of drainage controlled by regional doming (Cox, 1989), abundance of picrites in the northern Karoo (Cox, 1992), and the presence of a hot-spot trail following separation of Africa and Antarctica (Richards et al., 1989). If Ferrar magmas were derived near the region of the Dufek intrusion, then the thermal anomaly that has been suggested for Karoo and Dronning Maud Land magmatism (White and McKenzie, 1989) could also account for Ferrar magmatism. The anomaly in Figure 1 may have been centered, or may have extended, slightly south.

Geologic evidence along the Transantarctic Mountains indicates that lithospheric extension occurred before and during flood-basalt magmatism, an observation consistent with extending lithosphere having caused adiabatic upwelling of anomalously hot mantle (White and McKenzie, 1989; Wilson, 1992; Elliot, 1992). The ~5000 km length of the extensional zone and its orientation subparallel to the paleo–Pacific margin subduction zone (Fig. 1) suggest control by plate forces related to subduction (e.g., Elliot, 1974; Cox, 1978; Storey, 1995). It remains unknown whether arrival of a plume head beneath the Karoo region triggered the rifting of lithosphere that was already under tension (e.g., Storey, 1995), or whether rifting triggered upwelling of an incubating thermal anomaly (e.g., Anderson et al., 1992).

EARLY RIFTING AND GONDWANA BREAKUP

The new data presented here and by Hooper et al. (1993) will require reevaluation of breakup models based partly on previous Karoo dates, which suggested pulses of magmatism at ~193 and ~178 Ma (Fitch and Miller, 1984). Additional ages are needed from the northern Karoo area (Fig. 1) to determine the relative timing of magmatism there and to evaluate breakup models for that area (e.g., Cox, 1992). In the following discussion we focus on breakup events along the paleo–Pacific margin where our samples were obtained.

Along with the rifting event associated with Ferrar and southern Karoo magmatism, one of the earliest manifestations of disintegration of Gondwana was the displacement of microblocks on its paleo–Pacific side such as the Falkland Islands and Ellsworth-Whitmore Mountains blocks (Mitchell et al., 1986; Dalziel and Grunow, 1992) (Fig. 1). The Ellsworth-Whitmore Mountains block rotated ~90° counterclockwise relative to East Antarctica some time between the Early Permian and the Middle Jurassic. Completion of this rotation by Middle Jurassic time is constrained by paleomagnetic poles obtained from granitoids that intrude the Ellsworth-Whitmore Mountains block (Grunow et al., 1991). The most precisely dated granitoid is 173 ± 3 m.y. old, based on a 12-point whole-rock Rb-Sr isochron (mean square of weighted deviates = 1.8) (Millar and Pankhurst, 1987). Because of the broad concordance of this age with some of the previous ages on the Ferrar it has been assumed that rotation occurred before Ferrar magmatism. Rotation during pre-Ferrar time has been problematic because of the lack of an obvious tectonic mechanism to account for the movement (Dalziel and Grunow, 1992).

A possible interpretation is that rotation occurred during and/or soon after Ferrar magmatism at ~184 Ma and before the intrusion of the granitoids into the Ellsworth-Whitmore Mountains block at ~173 Ma. Rotation of the Ellsworth-Whitmore Mountains block may therefore be linked to the rifting event associated with Ferrar and southern Karoo magmatism. Rift basins in the Ross Embayment (Wilson, 1992) and the Weddell rift off Coats Land (Kristoffersen and Hinz, 1991) may have been initiated at this time (Fig. 1). The latter structure is inferred to be a failed rift that predates the breakup of Africa and Antarctica because it is truncated by a transform associated with later sea-floor spreading between the two continents (Lawver et al., 1991).

Rotation and displacement of the Falkland Islands block occurred after intrusion of dikes of Karoo age that yielded paleomagnetic poles strongly discordant with South American and African poles (Mitchell et al., 1986). Rotation and displacement may have begun, along with rotation of the Ellsworth-Whitmore Mountains block, during the early rifting event with additional motion occurring when Antarctica separated from Africa.

We suggest that this early extensional event was associated with rifting of blocks along the paleo–Pacific margin of Gondwana, perhaps including the region of South America south of the Gastre fault (Rapela and Pankhurst, 1992), away from east Antarctica (Fig. 1). Movement of this terrane (or these terranes) may have been accommodated by rollback of the trench along the paleo–Pacific margin. Rifting may have been aborted when the southern section of the trench aligned with the northern section and the intervening transform was consumed.

The proposed early rifting event at ~184 Ma, and associated Ferrar–southern Karoo flood-basalt magmatism, may have occurred >10 m.y. before the separation of east (Antarctica, Australia, and India) and west Gondwana (Africa and South America). That event was marked by the generation of oceanic crust between Africa and Antarctica beginning at 155 Ma and possibly as early as ~170 Ma (Lawver et al., 1991).

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