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Review
Age of pre-break-up Gondwana magmatism

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Abstract: Extensive outpourings of basalt, and to a lesser extent rhyolite, are closely associated with continental break-up and plume–lithosphere interactions. The Gondwana supercontinent began to fragment during Early–Middle Jurassic times and was associated with the eruption of over three million km^3 of dominantly basaltic magma. This intense magmatic episode is recorded in volcanic rocks of the Karoo (Africa), Ferrar (Antarctica) and Chon Aike (South America). K–Ar and Rb–Sr whole rock geochronology has consistently failed to produce reliable ages for these volcanic rocks, but in the last four years, the wider application of single grain $^{40}Ar/^{39}Ar$ and/or U–Pb geochronology has produced more robust and precise dating of the magmatism. This paper reviews the recent advances in high precision geochronology and provides a full recalibrated $^{40}Ar/^{39}Ar$ dataset. Application of these methods across the majority of the volcanic provinces indicates that approximately 80% of the volcanic rocks were erupted within a short, 3–4 Myr period at *c.* 182 Ma. This burst of magmatism occurred in the Karoo province at *c.* 183 Ma and in the Ferrar provinces at *c.* 180 Ma, and was dominated by mafic volcanism. This peak in volcanism is coincident with a second order mass extinction event at the end of the Pliensbachian when *c.* 5% of marine families were wiped out coinciding with widespread oceanic anoxia in the early Toarcian. A prolonged period of silicic volcanism occurred along the proto-Pacific margin, prior to, and during the main phase of break-up. Silicic volcanism was initially coincident with the plume related Karoo–Ferrar provinces, but continued over *c.* 40 Myr, associated with lithospheric extension and subduction along the proto-Pacific continental margin.

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Key words: $^{40}Ar/^{39}Ar$, geochronology, Gondwana, large igneous province, U–Pb

Introduction

Jurassic magmatism in Gondwana formed the most voluminous outpouring of continental volcanic rocks on Earth during the Phanerozoic. During the Early–Middle Jurassic, over three million km^3 of dominantly basalt and to a lesser extent rhyolite, were erupted onto a continent during the initial stages of break-up (Cox 1992, Pankhurst *et al.* 2000). The eruption rate is even more significant when it is considered that approximately 80% of the volcanic rocks were emplaced during a short, 3–4 million year (Myr) period.

Evidence of a magmatic mega-province in pre-break-up reconstructions of Gondwana (Fig. 1) is recorded in the volcanic rocks of southern Africa (Marsh *et al.* 1997), South America (Pankhurst *et al.* 1998), south-east Australia (Hergt *et al.* 1991), New Zealand (Mortimer *et al.* 1995), Tasmania (Hergt *et al.* 1989), and Antarctica (Brewer *et al.* 1996, Riley & Leat 1999). The Karoo igneous province of southern Africa and its continuation into east Antarctica (Harris *et al.* 1990) is the largest of the Gondwana magmatic provinces, consisting of thick sequences of volcanic and subvolcanic rocks. Tholeiitic basalts dominate, but in the Lebombo–Mwenezi area, rhyolitic ignimbrites are the principal rock type. The Dronning Maud Land magmatic province of east Antarctica consists of mafic dykes, sills, and lava flows and alkaline intrusions (Harris *et al.* 1990). The Ferrar province of the Transantarctic Mountains is represented by the mafic layered intrusion of the Dufek Massif (Ford & Himmelberg 1991, Ferris *et al.* 1998), the Ferrar dolerite sills (Elliot *et al.* 1999), and the comagmatic Kirkpatrick basalts (Kyle 1980). Mafic rocks of 'Ferrar' composition also occur in south-east Australia (Hergt *et al.* 1991), Tasmania (Hergt *et al.* 1989), and New Zealand (Mortimer *et al.* 1995). The origin of these provinces has been linked to intracontinental lithospheric extension related to early stages of continental break-up, and plume–lithosphere interaction (White & McKenzie 1989, Storey & Kyle 1997). The major silicic portion of pre-break-up Gondwana magmatism is exposed in the Patagonian region of South America. The dominant Patagonia formations are collectively called the Chon Aike province (Pankhurst *et al.* 1998). These volcanic rocks are predominantly pyroclastic, dominated by ignimbrites of rhyolitic composition (Pankhurst *et al.* 1998). Volcanic rocks exposed along the Antarctic Peninsula are also dominated by rhyolitic ignimbrites, and are believed to form an extension of the Chon Aike province (Riley & Leat 1999).

The initiation of magmatism is linked to a major mantle plume beneath southern Africa at *c.* 182 Ma, and a second

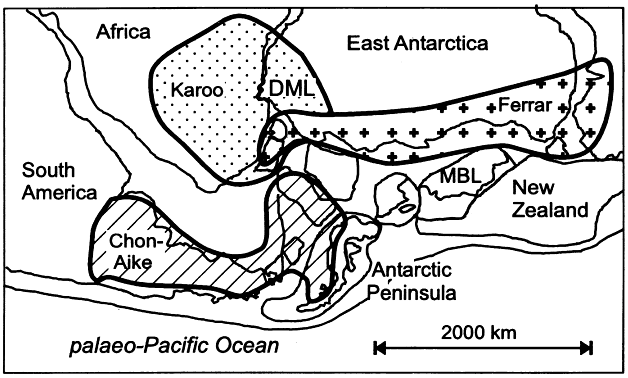

Fig. 1. Reconstruction of pre-break-up western Gondwana showing the major magmatic provinces associated with the early stages of break-up (*c.* 182 Ma). Key: MBL = Marie Byrd Land, DML = Dronning Maud Land. Stippled fill = mafic rocks of the Karoo–DML province, hashed fill = silicic rocks of the Chon Aike province, crosses = mafic rocks of the Ferrar province.

contemporaneous mantle plume beneath the Dufek intrusion (Storey *et al.* in press). In South America and the Antarctic Peninsula, a prolonged episode of silicic volcanism began just prior to Karoo–Ferrar magmatism and migrated westward to the continental margin, at about the same time as the initiation of sea-floor spreading between Antarctica and Africa.

Links between magmatism, continental break-up, mantle plume activity, and active subduction associated with Gondwana break-up have been extensively explored (e.g. Storey & Kyle 1997), but poorly constrained geochronology has, until recently, prevented authors from completing a detailed picture. Recently published dates from these magmatic provinces using $^{40}Ar/^{39}Ar$ and/or U–Pb geochronology now enable a clear temporal picture of pre-break-up Gondwana magmatism.

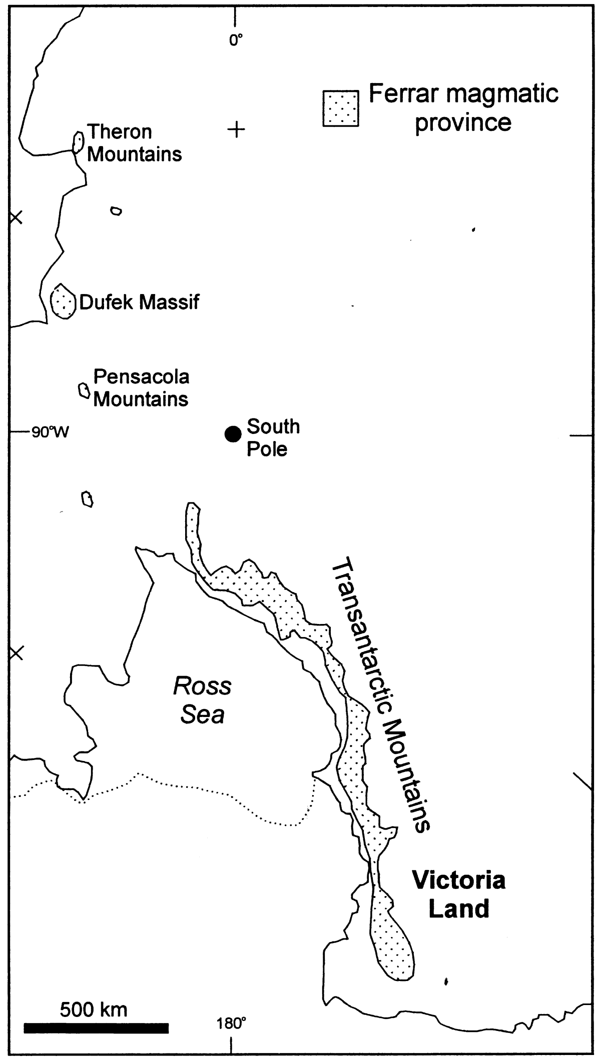

Fig. 2. Map of central Antarctica showing the distribution of the Ferrar magmatic province (from Fleming *et al.* 1997).

Age recalculations and methodology

The application of K–Ar and Rb–Sr whole rock geochronology has consistently failed to produce reliable ages for the volcanic rocks of the Karoo, Ferrar, and Chon Aike provinces. However, the last four years have seen the wider application of $^{40}Ar/^{39}Ar$ and/or U–Pb geochronology on mineral separates, leading to more robust and precise dating of the volcanic events. This paper provides a review of recent 'high precision' dating, and includes recalculation of all referenced $^{40}Ar/^{39}Ar$ dates to a common standard. Given that much of the older K–Ar and Rb–Sr whole rock data is largely redundant, this will not be reviewed in detail.

Until recently, the precision from $^{40}Ar/^{39}Ar$ dating had not reached the point where the error in the standard surpassed the error from the actual date. With improved analytical precision, many of the older standards that exhibit grain inhomogeneity are no longer suitable if high precision, comparable data are required (Renne *et al.* 1998). Individual laboratories favour their own laboratory neutron fluence monitors (Table I), which provide internal consistency. Inter-laboratory calibrations are often carried out against the McClure Mountain hornblende monitor (MMhb-1; Alexander *et al.* 1978). Problems with this monitor such as grain inhomogeneity have now become apparent (Baksi *et al.* 1996, Renne *et al.* 1998) and increasingly $^{40}Ar/^{39}Ar$ ages are tied to GA-1550 biotite (McDougall & Roksandic 1974) either directly or via FCT sanidine through the intercalibration of Renne *et al.* (1998). Given the widespread use of MMhb-1 in $^{40}Ar/^{39}Ar$ geochronology in the past and the availability of cross calibration data, we use this standard (calibrated to GA-1550 at 98.79 Ma) for the calibrations in this paper.

There is still disagreement over the age of MMhb-1, varying from 513.5 to 523.5 Ma (Renne *et al.* 1994) and the application of different ages for MMhb-1 can lead to significant differences

Table I. $^{40}Ar/^{39}Ar$ data for Gondwana magmatic province recalculated to a common monitor age (MMhb-1 at 523.1 Ma).

Original paper	Province	Sample number	Formation/ location	Neutron fluence monitor, age (Ma), author	MMhb-1 assigned age	Analysis	Reported age	Adjusted age	Reported 1σ error	Adjusted 1σ error	Notes
Foland *et al.* (1993)	FP	81-7-2 A	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[3]	176.8	180.4	0.8	1.2	plateau age
Foland *et al.* (1993)	FP	90-75-2	Carapace Nunatak Pillow Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	glass	176.6	180.2	0.5	0.7	plateau age
Heimann *et al.* (1994)	FP	85-76-63	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.8	180.4	0.5	0.7	total gas age
Heimann *et al.* (1994)	FP	85-76-61	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.2	180.8	0.5	0.7	total gas age
Heimann *et al.* (1994)	FP	85-76-18	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.5	180.1	0.4	0.6	total gas age
Heimann *et al.* (1994)	FP	85-11-4	TAM breccia clast	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.4	180.0	0.4	0.6	total gas age
Heimann *et al.* (1994)	FP	90-75-20	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.4	180.0	0.5	0.7	plateau age
Heimann *et al.* (1994)	FP	90-75-2	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.4	180.0	0.4	0.6	total gas age
Heimann *et al.* (1994)	FP	81-7-2A	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.8	180.4	0.8	1.2	plateau age
Heimann *et al.* (1994)	FP	81-13-3	Kirkpatrick Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.4	180.0	0.9	1.3	plateau age
Brewer *et al.* (1996)	KIP	Z.350.1	Semberget Lava	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	172.4	172.0	2.1	3.0	correlation age
Brewer *et al.* (1996)	KIP	Z.353.6	Schivestolen Sill	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	182.4	182.0	1.9	2.7	"adopted age"
Brewer *et al.* (1996)	KIP	Z.487.1	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	175.7	175.3	1.0	1.4	correlation age
Brewer *et al.* (1996)	FP	Z.489.4	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	173.4	173.0	1.7	2.4	plateau age
Brewer *et al.* (1996)	KIP	Z.483.8	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	181.9	181.5	2.5	3.5	plateau age
Brewer *et al.* (1996)	KIP	Z.485.1	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	177.5	177.1	1.7	2.4	plateau age
Brewer *et al.* (1996)	FP	Z.481.1	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	172.5	172.1	1.7	2.4	"adopted age"
Brewer *et al.* (1996)	KIP	Z.500.1	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	179.5	179.1	1.8	2.5	plateau age
Brewer *et al.* (1996)	FP	Z.463.3	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	176.4	176.0	1.7	2.4	plateau age
Brewer *et al.* (1996)	FP	Z.475.1	Theron Mt Dolerite	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	177.4	177.0	1.1	1.6	total gas age
Brewer *et al.* (1996)	FP	R.4724.4	Dufek Gabbro	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	182.9	182.5	2.5	3.5	correlation age
Brewer *et al.* (1996)	FP	R.4727.11	Dufek Gabbro	HB3gr, 1072 ± 5.4, Turner *et al.* (1973)	524.2	plagioclase[1]	182.1	181.7	2.4	3.4	correlation age
Duncan *et al.* (1997)	KIP	OXB-01	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	186.5	186.3	1.9	1.9	plateau age
Duncan *et al.* (1997)	KIP	MLP-172	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	179.5	179.3	2.1	2.1	plateau age
Duncan *et al.* (1997)	KIP	BUS-18	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	182.4	182.2	1.7	1.7	plateau age
Duncan *et al.* (1997)	KIP	ROM-01B	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	184.4	184.2	1.0	1.0	plateau age
Duncan *et al.* (1997)	KIP	BMC-04	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	184.3	184.1	1.7	1.7	plateau age
Duncan *et al.* (1997)	KIP	NN-01	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	182.9	182.7	2.1	2.1	plateau age
Duncan *et al.* (1997)	KIP	KF-10 OmegA	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	183.9	183.7	1.0	1.0	plateau age
Duncan *et al.* (1997)	KIP	KF-10 OmegB	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	183.9	183.7	0.7	0.7	plateau age
Duncan *et al.* (1997)	KIP	KRB-7 Moshesh	Lesotho andesite	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	181.0	180.8	1.7	1.7	plateau age
Duncan *et al.* (1997)	KIP	KR-29 Moshesh	Lesotho basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	186.5	186.3	1.1	1.1	plateau age
Duncan *et al.* (1997)	KIP	KVU-5 Jozini	Lebombo rhyolite	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	179.7	179.5	0.7	0.7	plateau age
Duncan *et al.* (1997)	KIP	KSA-12 Jozini	Lebombo rhyolite	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	178.1	178.0	0.6	0.6	plateau age
Duncan *et al.* (1997)	KIP	RSS-82 Sabie	Lebombo basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	181.2	181.0	1.0	1.0	plateau age
Duncan *et al.* (1997)	KIP	KOL-2 Sabie	Lebombo basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	183.2	183.0	1.3	1.3	plateau age
Duncan *et al.* (1997)	KIP	RSV-35 SabieA	Lebombo basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	184.2	184.0	1.0	1.0	plateau age
Duncan *et al.* (1997)	KIP	RSV-35 SabieB	Lebombo basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	184.2	184.0	0.6	0.6	plateau age
Duncan *et al.* (1997)	KIP	KP-121 Letaba	Lebombo picrite	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	182.7	182.5	0.8	0.8	plateau age
Duncan *et al.* (1997)	KIP	KP-92 Mashikiri	Lebombo nephelinite	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	182.1	181.9	1.6	1.6	plateau age

FP = Ferrar province, KIP = Karoo igneous province, CAP = Chon Aike province.
Analysis [1] = bulk, [2] = single crystal, [3] = separate. *misprint per J. Marsh (personal communication), n r = not reported, n a = no adjustment
All errors are noted at 1 standard deviation. Decay constant uncertainties are not included.

Original paper	Province	Sample number	Formation/ location	Neutron fluence monitor, age (Ma), author	MMhb-1 assigned age	Analysis	Reported age	Adjusted age	Reported 1σ error	Adjusted 1σ error	Notes
Duncan *et al.* (1997)	KIP	TRA-76	Transvaal intrusive	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	181.4	181.2	1.1	1.1	plateau age
Duncan *et al.* (1997)	KIP	TRA-84	Transvaal intrusive	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	182.8	182.6	1.6	1.6	plateau age
Duncan *et al.* (1997)	KIP	TRA-95	Transvaal intrusive	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	180.3	180.1	1.8	1.8	plateau age
Duncan *et al.* (1997)	KIP	HAR-02B	Hardap basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	183.0	182.8	0.6	0.6	plateau age
Duncan *et al.* (1997)	KIP	HAR-08	Hardap basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	184.2	184.0	1.0	1.0	plateau age
Duncan *et al.* (1997)	KIP	HAR-13	Hardap basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	186.0	185.8	0.8	0.8	plateau age
Duncan *et al.* (1997)	KIP	KEE-03	Keetmanshoop basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	184.7	184.5	0.5	0.5	plateau age*
Duncan *et al.* (1997)	KIP	KEE-05	Keetmanshoop basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	181.5	181.3	0.8	0.8	plateau age
Duncan *et al.* (1997)	KIP	KEE-10A	Keetmanshoop basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	whole rock	184.7	184.5	0.7	0.7	plateau age
Duncan *et al.* (1997)	KIP	KEE-10B	Keetmanshoop basalt	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	180.5	180.3	0.7	0.7	plateau age
Duncan *et al.* (1997)	KIP	LAD-7	Kirwan Mts	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	180.6	180.4	0.6	0.6	plateau age
Duncan *et al.* (1997)	KIP	LAG-22	Kirwan Mts	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	182.7	182.5	0.6	0.6	plateau age
Duncan *et al.* (1997)	KIP	LAG-31	Kirwan Mts	FCT-3, 28.03 ± 0.18, Renne *et al.* (1994)	523.5	plagioclase[1]	182.8	182.6	0.6	0.6	plateau age
Fleming *et al.* (1997)	FP	HB-1	Halfmoon Bluff Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.2	180.8	0.5	0.7	plateau age
Fleming *et al.* (1997)	FP	85-72-11	Dawson Peak Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	feldspar[1]	175.8	179.4	0.5	0.7	total gas age
Fleming *et al.* (1997)	FP	90-63-9	Dawson Peak Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.4	181.0	0.5	0.7	total gas age
Fleming *et al.* (1997)	FP	96-10	Rougier Hill Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	biotite [1]	176.4	180.0	0.7	1.0	total gas age
Fleming *et al.* (1997)	FP	96-12	Rougier Hill Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	biotite [1]	176.9	180.5	1.1	1.6	total gas age
Fleming *et al.* (1997)	FP	90-76-12	Pearse Valley Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.2	179.8	0.7	1.0	plateau age
Fleming *et al.* (1997)	FP	82-10-5	Exposure Hill Dolerite Sill	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.7	180.3	0.5	0.7	plateau age
Hargraves *et al.* (1997)	KIP	85-01	Karoo basalt	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	193.3	194.4	6.5	9.2	laser spot fusion age
Hargraves *et al.* (1997)	KIP	85-16	Karoo basalt	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	178.3	179.3	1.6	2.3	laser spot fusion age
Hargraves *et al.* (1997)	KIP	85-19	Karoo basalt	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	182.1	183.1	4.2	6.0	laser spot fusion age
Hargraves *et al.* (1997)	KIP	87-04	Karoo basalt	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	181.9	182.9	5.2	7.4	laser spot fusion age
Hargraves *et al.* (1997)	KIP	87-06	Karoo basalt	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	191.1	192.2	8.0	11.4	laser spot fusion age
Hargraves *et al.* (1997)	KIP	87-24	Rooirand dyke	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	200.8	201.9	4.5	6.4	laser spot fusion age
Hargraves *et al.* (1997)	KIP	87-9	Bumbeni sanidine	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	feldspar[3]	145.8	146.6	1.3	1.8	laser spot fusion age
Minor& Mukasa (1997)	FP	93D-76A	Lexington Granophyre	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	hornblende[1]	174.1	175.1	0.8	1.1	plateau age
Minor& Mukasa (1997)	FP	93D-76B	Lexington Granophyre	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	hornblende[1]	175.6	176.6	0.8	1.1	plateau age
Minor& Mukasa (1997)	FP	93D-86C	Dufek Felsic Dyke	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	hornblende[1]	180.0	181.0	0.8	1.1	plateau age
Minor& Mukasa (1997)	FP	93D-86D	Dufek Felsic Dyke	MMhb-1, 520.4 ± 1.7, Samson & Alexander (1987)	520.4	hornblende[1]	178.1	179.1	1.1	1.6	plateau age
Antonini *et al.* (1998)	FP	SPCT 2140	Brimstone Peak Andesite	FC, 28.02 ± 0.28, Renne *et al.* (1998)	523.1	plagioclase[3]	175.1	175.1	1.0	n a	plateau age
Elliot *et al.* (1999)	FP	78209	Griffin Nunatak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.1	180.7	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	97-51-53 A	Brimstone Peak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	174.9	178.5	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	97-51-53 B	Brimstone Peak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	175.4	179.0	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	97-55-1 A	Brimstone Peak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.4	181.0	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	97-55-1 B	Brimstone Peak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.2	180.8	n r		single fusion age
Elliot *et al.* (1999)	FP	97-55-1 C	Brimstone Peak Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	176.9	180.5	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	96-52-1 A	Mt Bumsted Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.2	180.8	0.5	0.7	plateau age
Elliot *et al.* (1999)	FP	96-52-1 B	Mt Bumsted Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.1	180.7	n r		single fusion age
Elliot *et al.* (1999)	FP	96-52-1 C	Mt. Bumsted Basalt	MON-4, 121.7 ± 1.2, Foland *et al.* (1986)	513.5	plagioclase[1]	177.2	180.8	0.5	0.7	plateau age
Feraud *et al.* (1999)	CAP	PAT49 A	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	185.3	184.9	0.3	0.4	plateau e

FP = Ferrar province, KIP = Karoo igneous province, CAP = Chon Aike province.
Analysis [1] = bulk, [2] = single crystal, [3] = separate. *misprint per J. Marsh (personal communication), n r = not reported, n a = no adjustment
All errors are noted at 1 standard deviation. Decay constant uncertainties are not included.

Original paper	Province	Sample Number	Formation/ location	Neutron fluence monitor, age, author	MMhb-1 assigned age	Analysis	Reported age	Adjusted age	Reported 1σ error	Adjusted 1σ error	Notes
Feraud *et al.* (1999)	CAP	PAT49 B	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	186.3	185.9	0.3	0.4	weighted mean age
Feraud *et al.* (1999)	CAP	PAT50	Rhyolite (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	187.2	186.8	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	M2 A	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	186.2	185.8	1.5	2.1	plateau age
Feraud *et al.* (1999)	CAP	M2 B	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	187.4	187.0	0.6	0.8	one step plateau
Feraud *et al.* (1999)	CAP	PAT34 A	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	181.6	181.2	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT34 B	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	181.7	181.3	0.4	0.6	plateau age
Feraud *et al.* (1999)	CAP	PAT55	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	182.7	182.3	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT53	Trachyte (dyke)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	amphibole[2]	178.5	178.1	0.9	1.3	plateau age
Feraud *et al.* (1999)	CAP	PAT31	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	biotite[2]	178.5	178.1	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT4	Trachy-basalt (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	biotite[2]	177.0	176.6	0.8	1.1	plateau age
Feraud *et al.* (1999)	CAP	PAT39 A	Trachyte (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	175.1	174.7	0.5	0.7	plateau age
Feraud *et al.* (1999)	CAP	PAT39 B	Trachyte (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[1]	176.2	175.8	0.3	0.4	weighted mean
Feraud *et al.* (1999)	CAP	PAT118	Basaltic andesite (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	whole rock	164.1	163.7	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT144	Basaltic andesite (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	whole rock	160.5	160.1	0.5	0.7	weighted mean age
Feraud *et al.* (1999)	CAP	GEO8	Andesite (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	plagioclase[1]	152.7	152.3	1.2	1.7	plateau age
Feraud *et al.* (1999)	CAP	GEO2	Andesite (lava)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	plagioclase[1]	152.8	152.4	2.6	3.7	plateau age
Feraud *et al.* (1999)	CAP	PAT126	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	168.6	168.2	0.4	0.6	plateau age
Feraud *et al.* (1999)	CAP	PAT111	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	153.4	153.0	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT42	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	177.7	177.3	0.4	0.6	weighted mean age
Feraud *et al.* (1999)	CAP	PAT43	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[1]	177.8	177.4	0.4	0.6	plateau age
Feraud *et al.* (1999)	CAP	PAT48	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[1]	154.6	154.2	0.5	0.7	plateau age
Feraud *et al.* (1999)	CAP	PAT47	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	151.5	151.1	0.5	0.7	plateau age
Feraud *et al.* (1999)	CAP	PAT89	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	158.4	158.0	0.3	0.4	plateau age
Feraud *et al.* (1999)	CAP	PAT90	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	157.9	157.5	0.5	0.7	plateau age
Feraud *et al.* (1999)	CAP	PAT104	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	sanidine[2]	144.2	143.9	0.4	0.6	plateau age
Feraud *et al.* (1999)	CAP	PAT106	Rhyolite (ignimbrite)	Hb3gr, 1072 ± 5.4, Turner *et al.* (1971)	524.2	biotite[2]	147.1	146.8	0.5	0.7	plateau age
Leat *et al.* (2000)	FP	R.4735.1	lamprophyre dyke	GA1550, 98.8 ± 1.0, Renne *et al.* (1998)	523.1	whole rock	183.2	183.2	2.2	n a	plateau age
Pankhurst *et al.* (2000)	CAP	PAT.19.5	Cabo Dañoso Ignimbrite	GA1550, 98.8 ± 1.0, Renne *et al.* (1998)	523.1	feldspar[3]	177.8	177.8	0.8	n a	plateau age
Pankhurst *et al.* (2000)	CAP	PAT.16.1	Puerto Deseado Ignimbrite	GA1550, 98.8 ± 1.0, Renne *et al.* (1998)	523.1	feldspar[3]	169.1	169.1	1.6	n a	plateau age
Pankhurst *et al.* (2000)	CAP	PAT.24.1	Bajo Pobre Andesite	GA1550, 98.8 ± 1.0, Renne *et al.* (1998)	523.1	biotite[3]	150.6	150.6	2.0	n a	isochron fit

FP = Ferrar province, KIP = Karoo igneous province, CAP = Chon Aike province.
Analysis [1] = bulk, [2] = single crystal, [3] = separate. *misprint per J. Marsh (personal communication), n r = not reported, n a = no adjustment
All errors are noted at 1 standard deviation. Decay constant uncertainties are not included.

in the calculated $^{40}Ar/^{39}Ar$ age. We have used an age of 523.1 ± 2.6 Ma (Renne *et al.* 1998) for MMhb-1 in order to recalculate ages determined using different laboratory monitors and/or assigned monitor ages (Table I). Normalization calculations use a ^{40}K lambda value of 5.543×10^{-11} (Steiger & Jäger 1977). Uncertainties in the ^{40}K decay constant are ± 2% at the 2σ level (Min *et al.* 2000, Renne 2000), and are not accounted for. Additional uncertainty due to the recalibration of sample ages based on the monitor MMhb-1 is also recalculated using authors reported error (1σ). Various authors have included or excluded different parameters when reporting data uncertainties. We have not attempted to unravel other author's error calculations, mainly because adequate information permitting this is usually not published, and we have added no further corrections.

All $^{40}Ar/^{39}Ar$ ages quoted in the text are recalculated to a MMhb-1 monitor age of 523.1 ± 2.6 Ma. Original and recalculated $^{40}Ar/^{39}Ar$ ages appear in Table I, although ages considered unreliable by their authors are excluded. A variance of up to 2% in the decay constant for ^{40}K (versus the much more accurately determined U decay constants) should also be considered (Min *et al.* 2000) when comparing $^{40}Ar/^{39}Ar$ data with U–Pb data. Caution should be exercised when considering multigrain U–Pb analyses of zircon. If multigrain analyses are used, phenomena such as Pb-loss and inheritance may be averaged in and impossible to recognize (Mundil *et al.* 1999). In many cases the resulting bias can be in excess of the quoted error. Where Rb–Sr ages are mentioned it should be noted that recent studies have shown the ^{87}Rb decay constant to be *c.* 2% less than the conventional value (Minster *et al.* 1982, Begemann et al. 2000).

Geochronology

Ferrar Province

Previous dates for the Ferrar province of East Antarctica (Fig. 2) covered a broad range (90–308 Ma; Elliot *et al.* 1985) although a 'preferred' age of 180 ± 5 Ma has been advocated as the best estimate (Elliot *et al.* 1985). Recent, high precision ages for the Ferrar province rocks demonstrate a short-lived episode of magmatism. The Kirkpatrick basalts have been dated using $^{40}Ar/^{39}Ar$ geochronology (Heimann *et al.* 1994), who determined ages between 180.0 ± 0.6 to 180.8 ± 0.7 Ma from different stratigraphical levels within the Kirkpatrick basalts. Similar ages were produced by Elliot *et al.* (1999), who determined a range of 178.5 ± 0.7 to 181.0 ± 0.7 Ma from several localities along the Transantarctic Mountains. A preliminary study (abstract) reports a significantly younger $^{40}Ar/^{39}Ar$ age of 175.1 ± 1.0 Ma for a high Fe andesite (Antonini *et al.* 1998) which may indicate the presence of later stage Ferrar volcanism.

Encarnación *et al.* (1996) used multigrain U–Pb analyses on zircon and baddeleyite to determine the age of dolerite sills from the central Transantarctic Mountains and Victoria Land, which yielded ages of 183.4 ± 1.4 and 183.8 ± 1.6 Ma (Table II), respectively. $^{40}Ar/^{39}Ar$ geochronology by Fleming *et al.* (1997) on feldspar and biotite separates from five individual dolerite sills yielded a range of plateau and total gas ages from 179.4 ± 0.7 to 181.0 ± 0.7 Ma. There is still discrepancy between the recalibrated $^{40}Ar/^{39}Ar$ ages and the U–Pb ages, with the $^{40}Ar/^{39}Ar$ ages typically being a few million years younger than the U–Pb data. This discrepancy may be attributed to a depletion of radiogenic ^{40}Ar in the

Table II. Published U–Pb ages for the Gondwana break-up magmatic provinces.

Paper	Province	Sample Number	Formation/Location	U-Pb age	Reported 1σ error
Encarnación *et al.* (1996)	FP	90-63-9	Ferrar dolerite sill	183.4	1.4
Encarnación *et al.* (1996)	FP	90-76-12	Ferrar dolerite sill	183.8	1.6
Encarnación *et al.* (1996)	KIP	I-247	New Amalfi granophyre	183.7	0.6
Minor & Mukasa (1997)	FP	93D-86	Dufek felsic dyke	182.7	0.4
Minor & Mukasa (1997)	FP	93D-76	Lexington granophyre (Dufek)	183.9	0.4
Fanning & Laudon (1999)	CAP	Mount Peterson	Mount Poster Formation	188*	3
Fanning & Laudon (1999)	CAP	Sweeney Mts	Mount Poster Formation	189*	3
Pankhurst *et al.* (2000)	CAP	R.4182.10	Brennecke Formation	184.2*	2.1
Pankhurst *et al.* (2000)	CAP	R.4197.2	Brennecke Formation	183.9*	1.7
Pankhurst *et al.* (2000)	CAP	PAT.70.8	Tobífera Formation	178.4*	1.4
Pankhurst *et al.* (2000)	CAP	MV99.40	Tobífera Formation	171.8*	1.2
Pankhurst *et al.* (2000)	CAP	PAT.19.2	Chon Aike Formation	168.4*	1.6
Pankhurst *et al.* (2000)	CAP	PAT.65.2	Chon Aike Formation	162.7*	1.1
Pankhurst *et al.* (2000)	CAP	R.6632.10	Mapple Formation	168.3*	2.2
Pankhurst *et al.* (2000)	CAP	R.6619.4	Mapple Formation	172.6*	1.8
Pankhurst *et al.* (2000)	CAP	R.6914.6	Mapple Formation	171.0*	1.1
Pankhurst *et al.* (2000)	CAP	R.6908.7	Mapple Formation	170.0*	1.4
Pankhurst *et al.* (2000)	CAP	R.601.9	Mapple Formation	162.2*	1.1
Pankhurst *et al.* (2000)	CAP	R.631.1	Mapple Formation	166.9*	1.6
Pankhurst *et al.* (2000)	CAP	PAT.62.2	El Quemado Formation	154.5*	1.4
Pankhurst *et al.* (2000)	CAP	PAT.34.1	El Quemado Formation	154.1*	1.5

FP = Ferrar province, KIP = Karoo igneous province, CAP = Chon Aike province. *Analyses by U–Pb SHRIMP (Sensitive high resolution ion microprobe).

analysed mineral (feldspar–biotite) which would yield apparently younger ages. Additionally, the smaller discrepancies may just reflect differences in decay constant uncertainties (Min *et al.* 2000).

The age of emplacement of the Dufek Intrusion has also been determined using multigrain U–Pb techniques on zircon separates (Minor & Mukasa 1997) which produced crystallization ages of 182.7 ± 0.4 and 183.9 ± 0.4 Ma for a silicic dyke from the Dufek Massif and a capping granophyre intrusion respectively (Table II). Minor & Mukasa (1997) also used $^{40}Ar/^{39}Ar$ geochronology on hornblende separates from the granophyre and a different silicic dyke, which yielded ages of 175.1 ± 1.1 to 176.6 ± 1.1 Ma (granophyre) and 179.1 ± 1.6 to 181.0 ± 1.6 Ma (silicic dyke). The contrast between $^{40}Ar/^{39}Ar$ and U–Pb ages in the granophyre was attributed to hydrothermal alteration preventing closure of the Ar–Ar geochronometer. The $^{40}Ar/^{39}Ar$ age of the silicic dyke was interpreted as representing a cooling age, with the U–Pb age representing a crystallization age. The dyke therefore yielded a cooling rate of 100°C Ma^{-1}. Brewer *et al.* (1996) dated two gabbros from the Dufek massif using the $^{40}Ar/^{39}Ar$ method and obtained correlation ages of 181.7 ± 3.4 and 182.5 ± 3.5 Ma, in surprisingly close agreement with the U–Pb ages of Encarnación *et al.* (1996).

Recent work by Leat *et al.* (2000) on an ultramafic lamprophyre dyke from the Pensacola Mountains, interpreted as forming part of the Ferrar magmatic province, yielded an $^{40}Ar/^{39}Ar$ age of 183.2 ± 2.2 Ma. This age is in close agreement with the age of the Dufek intrusion and slightly older than (but within error of) the age of the Ferrar tholeiitic rocks.

The extension of the Ferrar mafic rocks into south-east Australia (Hergt *et al.* 1991), Tasmania (Hergt *et al.* 1989) and New Zealand (Mortimer *et al.* 1995) has been substantiated on largely geochemical grounds. Available age data are restricted to K–Ar whole rock ages, which provide an age range of 170–190 Ma (Hergt *et al.* 1991), supporting contemporaneity with the rest of the Ferrar province.

Karoo Province (southern Africa–Antarctica)

Previous geochronology on mafic lavas and sills from the Karoo Province largely relied upon whole-rock K–Ar and Rb–Sr methods (e.g. Allsopp *et al.* 1984a, 1984b, Fitch & Miller 1984). The K–Ar, whole-rock method is now known to produce widely inaccurate results for volcanic rocks that have undergone low grade metamorphism (Walker & McDougall 1982). Replacement minerals (e.g. clays and zeolites) may significantly postdate igneous crystallization and/or do not quantitatively retain ^{40}Ar; therefore measured ages are typically lower than crystallization ages. A further problem is the incorporation of excess Ar at the time of crystallization and during post extrusion hydrothermal crystallization, which can lead to apparently older ages. Fitch & Miller (1984) dated volcanic rocks from the Karoo using both K–Ar and $^{40}Ar/^{39}Ar$ methods, obtaining an age range of

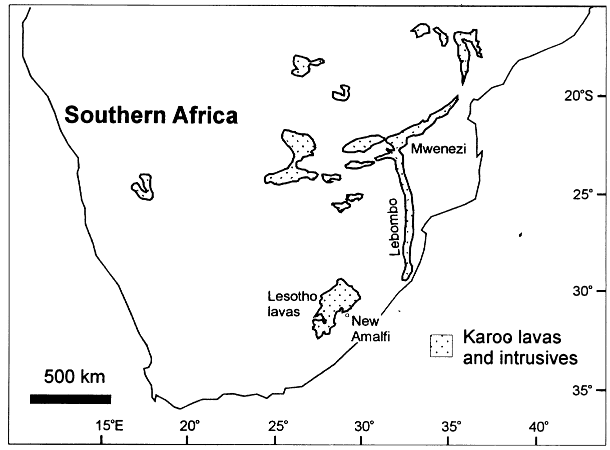

Fig. 3. Map of southern Africa showing the distribution of the Karoo igneous province (from Marsh *et al.* 1997).

c. 85 Myr, with several peaks of activity at *c.* 160, 170–180 and 190 Ma. Several workers have also applied the Rb–Sr isochron method to Karoo igneous rocks. Richardson (1984) reported a whole-rock age of 182 ± 2 Ma for the Tandjiesberg sill (southern Namibia), whereas Allsopp *et al.* (1984a, 1984b) determined Rb–Sr whole rock dates of 175 ± 5 to 191 ± 9 Ma for mafic and silicic rocks from the Lebombo–Mwenezi region.

More recent $^{40}Ar/^{39}Ar$ geochronology has been carried out on whole rock samples as well as feldspar separates, reducing some of the problems outlined earlier. Hargraves *et al.* (1997) used $^{40}Ar/^{39}Ar$ laser spot fusion on plagioclase separates taken from palaeomagnetic cores of Karoo dykes. This study yielded ages of 147 to 202 Ma, though the authors cite problems with Ar leakage as well as the presence of excess Ar. Duncan *et al.* (1997) carried out a detailed $^{40}Ar/^{39}Ar$ incremental heating study of thirty-two mafic and silicic volcanic rocks (plagioclase and whole rock) from South Africa, Namibia and Antarctica. After removing results that they demonstrated were inaccurate because of either geological or experimental effects, the remaining crystallization ages produced a very tight grouping. A 2 km lava succession in Lesotho yielded a close grouping of ages, such that the entire section was adjudged to have been erupted within *c.* 0.5 Myr at 183 ± 1 Ma. Basaltic and rhyolitic volcanism from the Lebombo–Mwenezi region revealed a slightly broader age range, with two rhyolites yielding ages of 178.0 ± 0.6 and 179.5 ± 0.7 Ma and several mafic rocks giving ages between 181.0 ± 1.0 and 184.0 ± 0.6 Ma. Mafic sills, lavas, and dykes were also analysed from the Karoo of Namibia, Transvaal, and Natal (Fig. 3), all of which yielded ages indistinguishable from the main period of Lesotho and Lebombo volcanism, *c.* 183 ± 1 Ma. It is important to note a discrepancy in calculated age between whole rock and plagioclase separate geochronology in the study of Duncan *et al.* (1997). Sample KEEE-10 (Table I) yielded a whole rock $^{40}Ar/^{39}Ar$ age of 184.5 ± 0.7, but a significantly younger age (180.3 ± 0.7 Ma) for the plagioclase separate. It would be anticipated that the plagioclase separate would yield a more reliable age, since whole rock ages involve measuring an average Ar closure age for several phases and can be more prone to problems such as excess Ar. In general, whole rock ages and those determined from plagioclase separates (with average ages of 182.8 Ma and 182.4 Ma, respectively) are virtually identical in this study.

A further geochronological investigation on the Karoo Province has been carried out by Encarnación *et al.* (1996) who selected a granophyre from the New Amalfi sheet (Lesotho lavas) for U–Pb (zircon and baddeleyite) dating. The sheet is fed by a dyke, which crosscuts the lowermost lavas of the Lesotho basalt plateau. They confirmed a weighted mean age for the Karoo granophyre of 183.7 ± 0.6 Ma (Table II), in close agreement with the $^{40}Ar/^{39}Ar$ ages of Duncan *et al.* (1997).

The Dronning Maud Land magmatic province of Antarctica is considered to form an extension of the Karoo Province of southern Africa (e.g. Brewer *et al.* 1996, Luttinen *et al.* 1998). $^{40}Ar/^{39}Ar$ geochronology (plagioclase separates) by Brewer *et al.* (1996) indicated two episodes of mafic magmatism at 182.0 ± 2.7 Ma (dolerite sill) and a younger episode at 172.0 ± 3.0 Ma (basalt lava). The older episode of magmatism has been confirmed by Duncan *et al.* (1997) who carried out an $^{40}Ar/^{39}Ar$ study on basalts from Kirwanveggen (Dronning Maud Land) which yielded plateau ages between 180.4 ± 0.6 and 182.6 ± 0.6 Ma, coincident with the main Karoo volcanism of southern Africa. Preliminary $^{40}Ar/^{39}Ar$ geochronology by Grantham *et al.* (1998) on alkaline intrusions and mafic dykes from western Dronning Maud Land indicate a much broader range in magmatism, from *c.* 170 to 200 Ma, but again with an obvious peak at *c.* 182 Ma.

Silicic volcanism of South America–Antarctic Peninsula (Chon Aike Province)

The silicic volcanic outcrops of Patagonia and the Antarctic Peninsula are shown in Fig. 4. In both regions the rocks have been subdivided into localized formations (Pankhurst *et al.* 1998, Riley & Leat 1999). The first attempts to date the silicic rocks relied largely upon the K–Ar whole-rock method, with highly variable results. A detailed review by Cortés (1981) revealed a considerable age range in Patagonia (240–125 Ma), with a peak in the interval 165–155 Ma. Early geochronology of silicic volcanic rocks from the northern Antarctic Peninsula

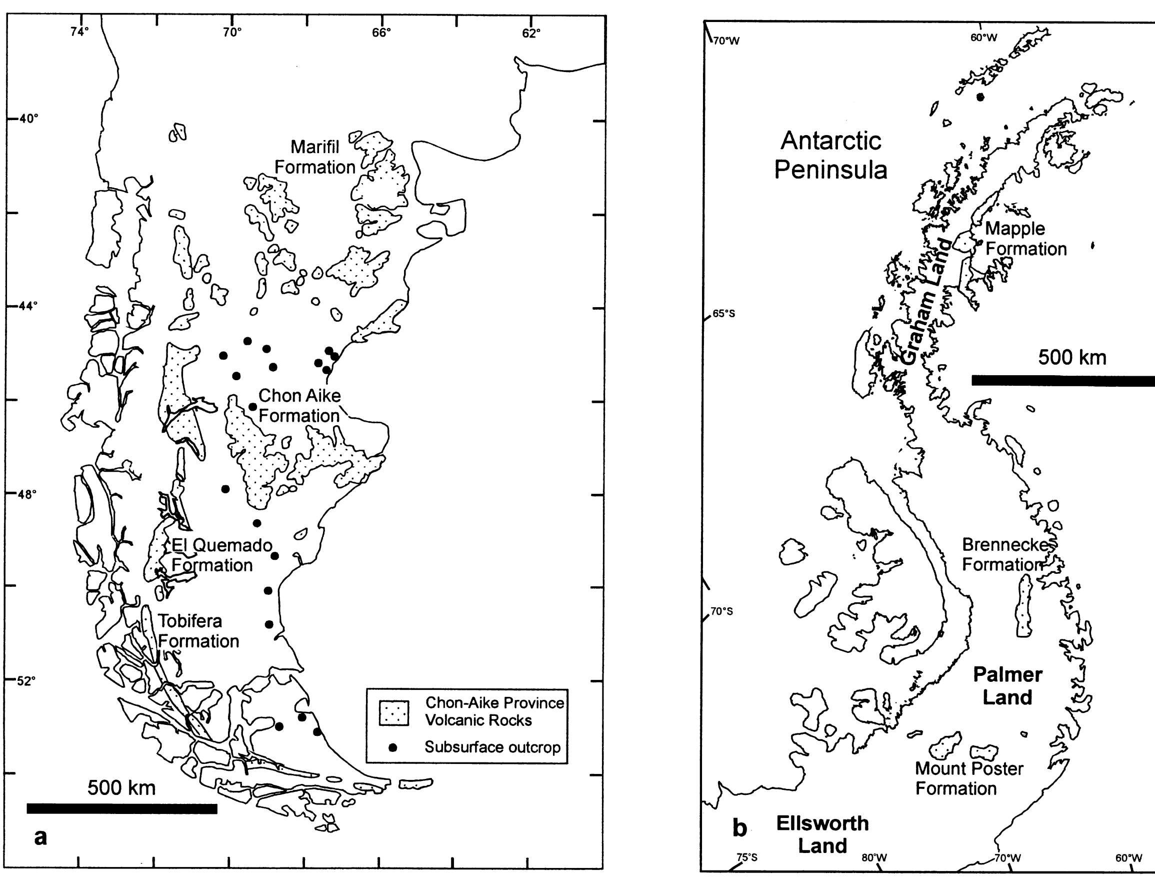

Fig. 4. Outcrop pattern of silicic volcanic rocks of the Chon Aike province (South America–Antarctic Peninsula), from Pankhurst *et al.* (2000).

(Graham Land) also failed to produce a reliable age. Rex (1976) determined three K–Ar ages of 190, 160 and 88 Ma, whereas Pankhurst (1982) produced a single Rb–Sr isochron of 174 ± 2 Ma and Millar *et al.* (1990) determined a Sm–Nd isochron of 156 ± 6 Ma from a garnet-bearing sill.

The first systematic dating in the Chon Aike province was by the Rb–Sr whole-rock method (Rapela & Pankhurst 1992) for the Marifil Formation (Fig. 4), a strongly welded rhyolitic ignimbrite sequence in north-eastern Patagonia. Rb–Sr isochrons from four localities yielded a tight range of ages (182.6 ± 1.5 to 178.4 ± 1.3 Ma), although later Rb–Sr geochronology from the remainder of the Marifil Formation (Pankhurst & Rapela 1995) slightly increased this range with a further isochron of 187.7 ± 1.3 Ma. The Chon Aike Formation, to the south of the Gastre Fault zone, has also been dated by the Rb–Sr whole-rock method (Pankhurst *et al.* 1993), yielding an age of 168.0 ± 1.9 Ma. Alric *et al.* (1996) presented $^{40}Ar/^{39}Ar$ data for the rhyolitic rocks of Patagonia, including ages of 178.7 ± 0.4 to 187.4 ± 0.6 Ma for the Marifil Formation and an age of 177.6 ± 0.7 Ma for the Chon Aike Formation (N.B. $^{40}Ar/^{39}Ar$ ages not recalculated as full analytical data have not been published).

The uncertainty regarding the age of the silicic rocks of Patagonia and the Antarctic Peninsula led Féraud *et al.* (1999) and Pankhurst *et al.* (2000) to carry out a systematic dating programme of individual formations. Féraud *et al.* (1999) used $^{40}Ar/^{39}Ar$ geochronology (mineral separates and whole rock) to date samples of andesite to rhyolite composition. Pankhurst *et al.* (2000) used high-precision U–Pb SHRIMP (sensitive high resolution ion microprobe) dating on zircon separates (Table II), $^{40}Ar/^{39}Ar$ geochronology (feldspar separates) and Rb–Sr geochronology (mineral and whole-rock) on silicic volcanic units from across the province.

Féraud *et al.* (1999) reports twenty-seven $^{40}Ar/^{39}Ar$ ages considered as valid, which included twenty plateau ages and indicated a period of volcanism from 187.0 ± 0.8 to 143.9 ± 0.6 Ma, migrating 650 km from east-north-east to west-south-west. Féraud *et al.* (1999) recorded a continuous spread of ages from *c.* 187 to 176 Ma and a second group from 160 to 151 Ma. Additionally, they include two ages of 168.2 ± 0.6 and 163.7 ± 0.4 Ma from the central part of the province and two Lower Jurassic ages (146.8 ± 0.7 and 143.9 ± 0.6 Ma) from the western margins of the province.

Pankhurst *et al.* (2000) identified a very similar period of silicic volcanism, extending from 187.7 ± 1.3 to 153.0 ± 1.0 Ma, which they grouped into three separate volcanic episodes (V_1: 188–178 Ma, V_2: 172–162 Ma, V_3: 157–153 Ma), presenting parallels to the work of Féraud *et al.* (1999), but extending the Middle Jurassic age range. The work of Pankhurst *et al.* (2000) also includes a detailed geochronology of the once contiguous Antarctic Peninsula. The first episode, V_1 includes the Marifil Formation of Patagonia (Fig. 4) and rhyolites of the southern Antarctic Peninsula (Brennecke and Mount Poster formations, Fig. 4). The rhyolites of the Marifil Formation have an age range of 188–178 Ma, with a peak at 184 ± 2 Ma. Although this range is produced from Rb–Sr geochronology, a very similar age range is provided by $^{40}Ar/^{39}Ar$ geochronology (Féraud *et al.* 1999). The Brennecke Formation of southern Antarctic Peninsula has yielded a U–Pb age of 184.2 ± 2.5 Ma (Pankhurst *et al.* 2000) indicating a contemporaneous event to the Marifil Formation. This event may also extend to the Mount Poster Formation, which has yielded U–Pb ages of 188 ± 3 and 189 ± 3 Ma in the main part of the formation and 167 ± 3 Ma at the periphery (Fanning & Laudon 1999). The identification of *c.* 185 Ma inherited zircons in younger granitoids of the Antarctic Peninsula (Pankhurst *et al.* 2000) suggests that V_1 volcanic rocks may be more widespread at depth than indicated by the present outcrop.

A second episode, V_2, which occurred in the interval 172–162 Ma (weighted mean 169 ± 3 Ma; Pankhurst *et al.* 2000) is represented in the central part of the province (Chon Aike Formation), the Andean margin (Tobífera Formation) and the northern Antarctic Peninsula (Mapple Formation). Féraud *et al.* (1999) analysed only one sample (168.2 ± 0.6 Ma) from the Chon Aike Formation, and this fell within the V_2 episode of Pankhurst *et al.* (2000), although their study did not include rocks from the Tobífera Formation or the Antarctic Peninsula.

A third event, V_3, occurred in the interval 157–153 Ma, with a weighted mean age of 156 ± 2 Ma (U–Pb SHRIMP data), consists of the eastern Andean outcrops of ignimbrite and associated granitoid intrusions. This event includes the El Quemado Formation and correlative Ibañez Formation on the Chilean side of the Andes. The work of Féraud *et al.* (1999) increased the known range of the younger episode, with $^{40}Ar/^{39}Ar$ ages of 146.8 ± 0.7 and 143.9 ± 0.6 Ma from close to the Chile–Argentina border.

Causes of magmatism

The Karoo province of southern Africa and east Antarctica has been reliably dated at *c.* 183 ± 2 Ma (Encarnación *et al.* 1996, Brewer *et al.* 1996, Duncan *et al.* 1997) and produced over two million km^3 of dominantly basaltic magma during an event that lasted less than 4 Myr. Most workers (e.g. Cox 1992) suggest that a mantle plume was responsible for the Karoo volcanic series, in order to account for the large volume of mafic magma erupted within a small time frame.

The near coincidence in age between Ferrar and Karoo magmatism has been taken as evidence of a common heat source (Duncan *et al.* 1997, Pálfy & Smith 2000); supported by close geochemical similarities between the Ferrar dolerites and the low-Ti tholeiites of the Karoo (Elliot & Fleming 2000). However this review indicates that the two provinces were not exactly synchronous (Fig. 5). Storey & Kyle (1997) favoured the idea of a megaplume in the South Atlantic, with smaller plumes feeding off the megaplume, leading to the production of the Karoo and Ferrar provinces, which may correspond to the present day Discovery and Bouvet plumes

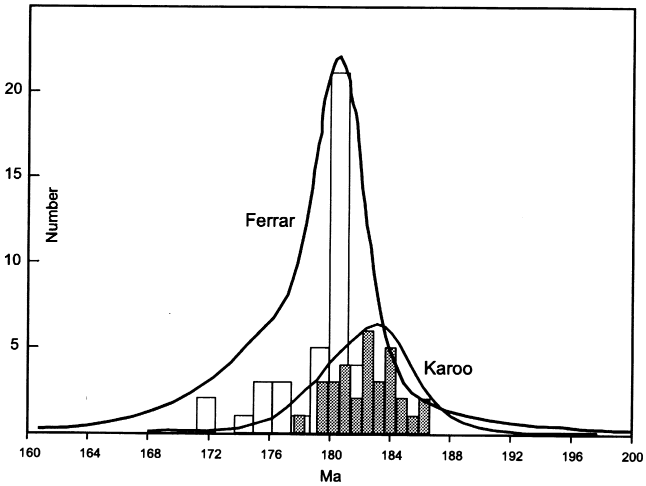

Fig. 5. Histograms and cumulative probability curve for $^{40}Ar/^{39}Ar$ ages of basaltic rocks from the Karoo and Ferrar provinces (Table I). The ages are plotted using Isoplot/Ex (Ludwig 1999). The plot indicates the main peak of Ferrar magmatism is at 180–181 Ma, which is slightly younger than the peak age for the Karoo (183–184 Ma).

respectively (Thompson 1998, Storey *et al.* in press). Evidence for a plume source in the Ferrar Province is given support by the occurrence of rare ultramafic lamprophyre dykes with OIB-like chemistry in the Pensacola Mountains (Leat *et al.* 2000). A plume source for the Ferrar is likely to be centred under the Dufek Massif and dolerite sills and dykes would have undergone lateral transport over great distances from a central source (Elliot *et al.* 1999). This suggestion is supported by the remarkably homogeneous chemistry of the magmas, even at great distances (> 2000 km) from the Dufek Massif. A similar model of lateral injection from a central source situated within the crust is suggested for the Proterozoic Mackenzie Dyke Swarm of Canada (Baragar *et al.* 1996). The Ferrar tholeiites have been related to a major volcano-tectonic rift system (Elliot *et al.* 1999), which may be linked to tectonic processes along the parallel, proto-Pacific margin.

The proto-Pacific margin of Gondwana itself was characterized by extensive silicic-dominated volcanism, prior to, and during supercontinent break-up. Geochronological studies have established a long period of silicic magmatism (*c.* 40 Myr; Féraud *et al.* 1999) marked by three principle magmatic episodes (Pankhurst *et al.* 2000) at *c.* 188–178 Ma (V_1), *c.* 172–162 Ma (V_2) and *c.* 157–153 Ma (V_3). Geochemical arguments (Pankhurst & Rapela 1995, Riley *et al.* in press) have been used to conclude that the rhyolites were generated as a result of lower crustal anatexis in an extensional environment. Although the province developed adjacent to the proto-Pacific continental margin, the silicic rocks of the V_1 and V_2 episodes are not interpreted as having developed in direct response to subduction. Earlier subduction was, however, crucial in the development of hydrous, readily fusible mafic underplate at the base of the continental crust. Partial melting of this mafic underplate led to silicic melt production and may have been initiated in response to the peripheral effects of the megaplume event that led to the eruption of the Karoo and Ferrar provinces. Although accepting the role of hydrous, highly fusible mafic crust in rhyolite generation, Pankhurst & Rapela (1995) concluded that partial melting might occur without substantial heat input into the crust, but in response to lithospheric thinning.

Conclusions

K–Ar and Rb–Sr whole rock geochronology has consistently failed to produce reliable ages for volcanic rocks that have undergone even low grade metamorphism. The last four years have seen an increase in the application of high precision (often single crystal) $^{40}Ar/^{39}Ar$ and /or U–Pb geochronology to the volcanic provinces associated with the break-up of Gondwana (Karoo–Ferrar–Chon Aike). However, many of the published $^{40}Ar/^{39}Ar$ dates have been calibrated to a monitor where there is considerable disagreement over the most 'correct' age, leading to significant discrepancies in the final calculated age. This study has recalculated all published ages to one widely accepted monitor and age (523.1 ± 2.6 Ma; Renne *et al.* 1998) validating comparison between $^{40}Ar/^{39}Ar$ ages produced from different laboratories.

Mineral separate $^{40}Ar/^{39}Ar$ and U–Pb geochronology from the Karoo and Ferrar provinces show a cluster of ages at 182 ± 2 Ma (Tables I & II, Fig. 5), demonstrating a major peak of volcanism prior to Gondwana fragmentation. Silicic volcanism along the proto-Pacific margin of Gondwana was characterized by a prolonged episode of volcanism (*c.* 40 Myr), which began just before Karoo–Ferrar magmatism in the eastern part of the province, and migrated west toward the continental margin through the Jurassic.

The rapid emplacement (3–4 Myr) of the basaltic successions in the Karoo and Ferrar provinces indicates average eruption rates of 0.5–1 km^3a^{-1}. These high levels of eruption are thought to have been responsible for triggering the Early Jurassic (end Pliensbachian) extinction event (Pálfy & Smith 2000), which although not a major event, still led to the extinction of about 5% of marine animal families and genera. The end Pliensbachian event is also associated with a major inflection in the $^{87}Sr/^{86}Sr$ seawater curve. The subsequent rise of the curve in the Toarcian is thought to reflect increased humidity and continental weathering triggered by global warming associated with the increased volcanic emissions (Pálfy & Smith 2000). Evidence for a catastrophic global event is also recorded in the $\delta^{13}C$ signal (Jenkyns 1988).

Given the prolonged (*c.* 40 Myr) and presumably sporadic nature of the silicic volcanism, any associated global impact is much harder to quantify in terms of related events in the geological record. The silicic volcanic rocks indicate that volcanism would have been highly explosive, caldera-forming eruptions, which would lead to vastly increased CO_2, sulphur gases and fine grained particulates in the atmosphere. The effects of such explosive eruptions (e.g. Tambora 1815) can cause significant disturbances to climate, but these typically only last months–few years.

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