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The timing and duration of the Karoo igneous event, southern Gondwana

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Abstract. A volcanic event of immense scale occurred within a relatively short period in early Jurassic time over large regions of the contiguous Gondwana supercontinent. In southern Africa, associated remnants of thick volcanic successions of lava flows and extensive dike and sill complexes of similar composition have been grouped together as the Karoo Igneous Province. Correlative volcanic and plutonic rocks occur in Antarctica and Australia as the Ferrar Province. Thirty-two new ^{40}Ar-^{39}Ar incremental heating experiments on feldspars and whole rocks from Namibia, South Africa and East Antarctica produce highly resolved ages with a vast majority at 183 ± 1 Ma and a total range of 184 to 179 Ma. These are indistinguishable from recent, high-resolution ^{40}Ar-^{39}Ar and U-Pb age determinations reported from the Antarctic portion of the province. Initial Karoo volcanism (Lesotho-type compositions) occurred across the entire South African craton. The ubiquitous distribution of a plexus of generally nonoriented feeder dikes and sills intruding Precambrian crystalline rocks and Phanerozoic sediments indicates that these magmas penetrated the craton over a broad region. Lithosphere thinning of the continent followed the main pulse of igneous activity, with volcanism focused in the Lebombo-Nuanetsi region, near the eventual split between Africa and Antarctica. Seafloor spreading and dispersion of east and west Gondwana followed some 10-20 m.y. afterward. The volume of the combined Karoo-Ferrar province (~2.5 x 10^6 km^3) makes it one of the largest continental flood basalt events. The timing of this event correlates with a moderate mass extinction (Toarcian-Aalenian), affecting largely marine invertebrates. This extinction event was not as severe as those recorded at the Permian-Triassic or Cretaceous-Tertiary boundaries associated with the Siberian and Deccan flood basalts events, respectively. The difference may be due to the high southerly latitude and somewhat lower eruption rates of the Karoo event.

Introduction

Plate tectonics is central to our current picture of Earth dynamics. Ocean basins open and close, and continents disperse and coalesce in a perpetual dance paced by upper mantle convection. The two major classes of volcanic activity are understandable in terms of steady state processes of crustal accretion at spreading ridges and plate recycling at subduction zones. However, a third class of volcanic activity, that associated with mantle plumes, is unrelated to plate tectonics but spans plate boundaries and interiors of all ages. This latter type is volumetrically minor but is significant in sampling portions of the deeper mantle not routinely participating in plate tectonics.

Recently, much attention has focused on examining the proposal that mantle plumes begin with extremely rapid, large volume eruptions of basaltic magmas that form the continental flood basalt provinces on land and oceanic plateaus in the ocean basins [*Richards et al.*, 1989; *Griffiths and Campbell*, 1990; *Duncan and Richards*, 1991]. These rare, catastrophic events may be spawned by gravitational instabilities in a thermal boundary layer deep in the mantle (e.g., the core-mantle boundary), and evidence is mounting that their occurrence correlates with profound changes in the surface environment, including mass biotic extinctions [*Larson*, 1991; *Renne et al.*, 1995]. Additional significance is attached to the coincidence of many continental flood basalt provinces with continental rifting [*Morgan*, 1981; *White and McKenzie*, 1989; *Storey*, 1995]. Critical information needed to assess these proposed correlations is the timing and duration of igneous activity relative to other geologic events, such as tectonism and environmental crises.

The Karoo Igneous Province (KIP) (Figure 1) is one of the largest and best exposed of the classic Mesozoic Gondwana continental flood basalt provinces [*Erlank*, 1984; *Cox*, 1988]. It comprises thick sequences of volcanic rocks preserved in erosional remnants and a well-developed subvolcanic plexus of dikes and sills scattered throughout southern Africa. Its formation is broadly correlated with the breakup of Gondwana, although details of the temporal relationship remain unclear. Karoo igneous rocks have also been emplaced in different tectonic settings across the province, and there are considerable differences in the lithostratigraphic sequences in these different settings. For example, the thick volcanic remnants of Lesotho, south and central Botswana, and central Namibia, including the huge volume of intrusives in the cratonic interior of southern Africa (the central area of *Marsh and Eales* [1984]), are remarkably homogeneous tholeiitic basalts. In contrast, a diverse suite of nephelinites, picrites, low- and high-Ti basalts, and rhyolites have built the

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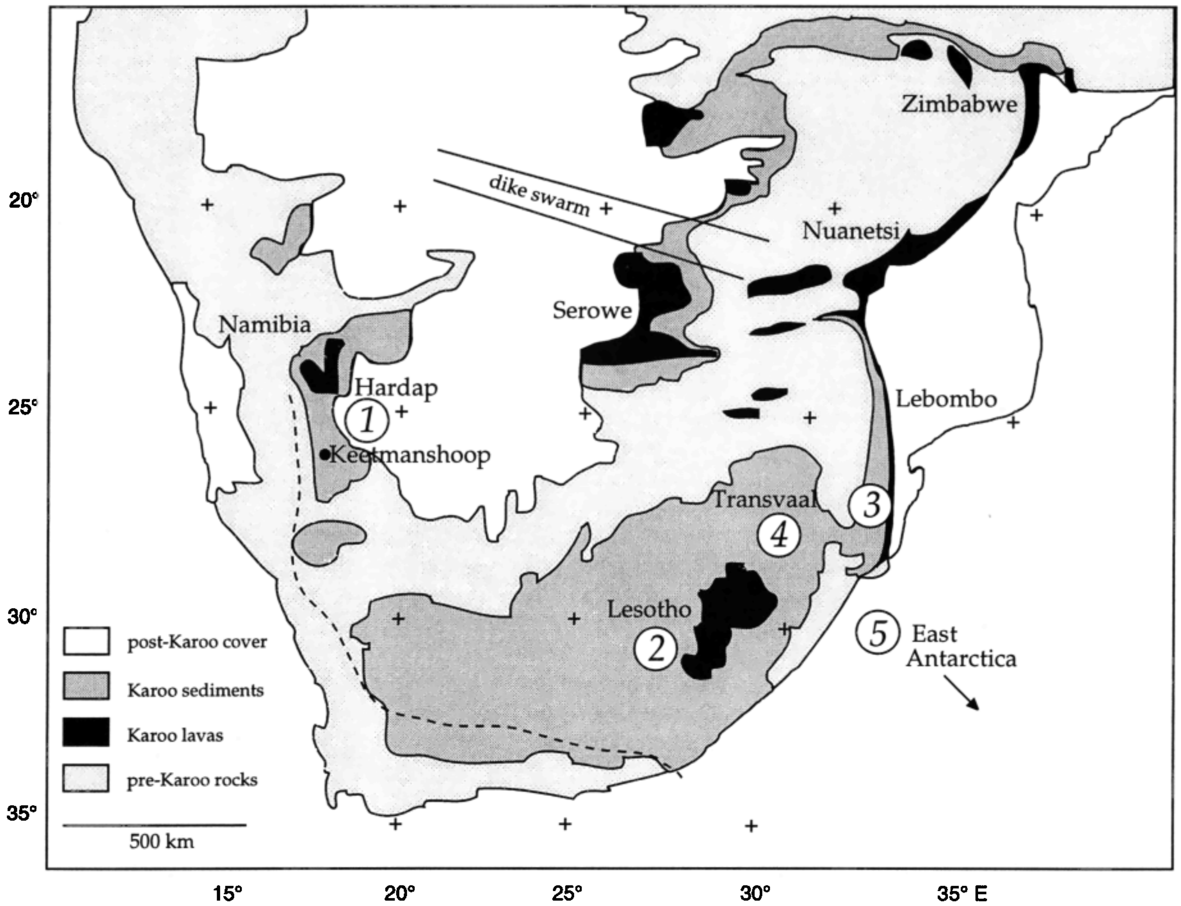


Figure 1. Schematic geological map of South Africa, showing the distribution of erosional remnants of the Karoo Igneous Province [after *Eales et al.*, 1984]. Major lava sections are named, and five major sampling localities are indicated by circled numbers. The East Antarctica (Kirwan Mountains) location is shown in its predrift position. The dashed line indicates the southern and western limit of dolerites and sills, intrusive into Permo-Triassic age Karoo sediments and Precambrian cratonic rocks. Dikes are both oriented, as in the WNW-ESE trending swarm from Zimbabwe to Namibia, and nonoriented.

Lebombo-Mwenezi-Save monoclinal remnant along the northeastern margin of the province, where the magmatism was associated with lithospheric thinning and continental rifting.

Such differences have hampered lithological correlation between the widely spaced erosional remnants of Karoo magmatism and so limited our understanding of the temporal and spatial evolution of the province as a whole. Solutions to these problems have been frustrated by the wide range of reported radiometric ages for Karoo igneous rocks. For example, the temporal correlation between the important Lesotho and Lebombo remnants still remains unresolved. The total duration of Karoo magmatism is unknown, and a 85 m.y. span of periodic activity suggested by *Fitch and Miller* [1984] stands in contrast to the short duration of activity reported from modern dating of other flood basalt provinces [*Duncan and Pyle*, 1988; *Courtillot et al.*, 1988; *Baksi and Farrar*, 1991; *Renne and Basu*, 1991; *Renne et al.*, 1991, 1992; *Sinton et al.*, 1997]. Of wider importance are indications from a limited amount of new age data that the Karoo province may be temporally related to the large Ferrar Province in Antarctica-Australia [*Encarnacion et al.*, 1996], data which support continental reconstructions that place Africa and Antarctica adjacent in the early Jurassic prior to the breakup of Gondwana.

We report high-resolution age determinations from ^{40}Ar-^{39}Ar incremental heating experiments on whole basalts, nephelinites, picrites, and rhyolites and feldspar separates from basalts and diabases from the complete stratigraphic range at widely separated locations in the KIP and from the Kirwan Mountains, East Antarctica. The experimental procedure is able to identify excess-Ar and Ar-loss problems that have plagued previous radiometric studies based on K-Ar methods. The overwhelming majority of the igneous activity occurred within a narrow time frame, at 183 ± 1 Ma, which matches the most recent results of dating of the Antarctic Ferrar Province, indicating that this igneous province was rapidly erupted over a vast, asymmetric region of Gondwana, prior to continental rifting.

Sample Locations and Descriptions

Samples were collected during two field seasons from outcrops of lava flow sequences and laterally extensive sills and dikes across a large area of southern Africa, from southern and central Namibia to Lesotho and eastern South Africa (Figure 1). An additional set of samples from basalt flows from the Kirwan Mountains, East Antarctica, was provided by C. J. Harris. Samples can be conveniently divided into five coherent groups according to location (Figure 1): (1) basaltic flows and sills of southern and central Namibia, (2) basaltic flows of northeastern Cape Province and Lesotho, (3) basaltic, picritic, nephelinitic, and rhyolitic flows of the Lebombo monocline, (4) doleritic dikes and sills of Transvaal and Natal, and (5) basaltic flows of the Kirwan Mountains, Dronning Maud Land, western Antarctica. Stratigraphic position within each group of lavas is clear from field relations, while between-group correlations were made from considerations of composition [*Marsh et al.*, 1997], magnetic stratigraphy [*Hargraves et al.*, 1997] and age determinations reported here (Figure 2).

Basalts, rhyolite sheets, and central intrusive complexes in northwestern Namibia (the Etendeka Province) were previously included in the Karoo Igneous Province but are now known to be of early Cretaceous age [*O'Connor and le Roex*, 1992; *Renne et al.*, 1992] and coeval with volcanic activity of the Parana flood basalt province of central eastern South America, occurring slightly before, or contemporaneously with, continental rifting in the South Atlantic [*Renne et al.*, 1992]. Basaltic flows and doleritic sills of southern Namibia, in the Hardap and Keetmanshoop region, are compositionally correlated with the main Lesotho magma type [*Hooper et al.*, 1993; *Marsh et al.*, 1997] and previous radiometric dating [*Siedner and Miller*, 1976; *Gidskehaug et al.*, 1975] showed them to be middle Jurassic in age. The basalt formation in the Hardap area varies between 100 and 300 m thick and comprises three thick, compound lava flows separated by two thin sedimentary layers composed of siliciclastics and evaporites [*Gerschutz et al.*, 1995]. Each of the flows is built of a sequence of internal flow units, which grade from compact at the base to increasingly vesicular basalt at the top. The base of each flow contains pipe vesicles curved in the direction of flow. Such structures elsewhere have been proposed to indicate relatively low effusion rates from a nearby eruptive center [*Walker*, 1970].

Doleritic sills and dikes occur in great abundance across the whole of southern Africa, intruding the Karoo sedimentary strata [*Walker and Poldevaart*, 1949; *Marsh et al.*, 1997]. Dikes are typically from 1 m to a few meters thick and are generally fine-grained, sparsely plagioclase-phyric rocks. Gabbroic sills may be over 100 m thick, the grain size decreasing and alteration increasing toward the chilled margins. These are typically columnar-jointed with reddish-brown weathered surfaces.

Samples of Karoo lavas from NE Cape Province and Lesotho are described by *Marsh et al.* [1997], whereas those from the Lebombo section are described by *Cox and Bristow* [1984], *Sweeney* [1988], and *Sweeney et al.* [1994]. Detailed descriptions of typical Karoo lavas and intrusive rocks abound in the literature [e.g., *Walker and Poldevaart*, 1949; *Erlank*, 1984, and references within] and apply to the samples analyzed in this study. Briefly, the basalts are of virtually indistinguishable tholeiitic compositions on the basis of major and trace elements [*Marsh et al.*, 1997] but vary texturally as a function of cooling rate. Single thick flows vary from doleritic interiors to aphanitic margins, commonly with amygdaloidal tops and bases and compact centers. Petrographically, rocks vary from fine grained, aphyric to

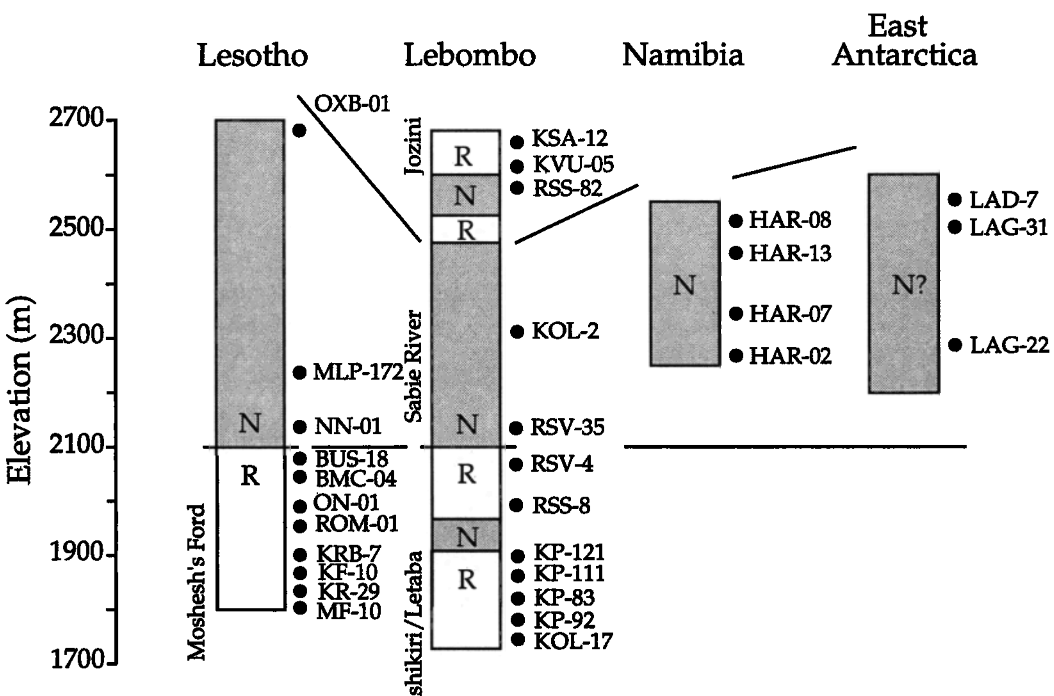


Figure 2. Sample locations within volcanic stratigraphic sections from the Karoo Igneous Province and the Kirwan Mountains, East Antarctica [*Cox and Bristow*, 1984; *Sweeney*, 1988; *Harris et al.*, 1990; *Marsh et al.*, 1997]. Lava formations, referred to in the text, are shown in approximate positions along the sections. Correlations between sections are based on compositional, magnetostratigraphic [*Hargraves et al.*, 1997] and age determinations reported here. The single reversal in the Lesotho section is the main tie-point. All Namibian lavas are of normal polarity and correlate chemically with the main Lesotho section. The magnetization of the East Antarctic lavas is unknown, but their compositions are most similar to the Sabie River basalts in the Lebombo section.

sparsely phyric to porphyritic, containing phenocrysts of plagioclase feldspar and augite. The common matrix is composed of feldspar, augite and pigeonite, Fe-Ti oxides, and glass. Rhyolites in the Lebombo area have a microporphyritic texture, with zoned plagioclase, clinopyroxene, and Fe-Ti oxides in a matrix of alkali feldspar, quartz, and oxides.

We made extensive collections of dikes and sills in the Transvaal between the main Lesotho and Lebombo lava sections for geochemical correlation to lava stratigraphy [*Marsh et al.*, 1997] and paleomagnetic studies [*Hargraves et al.*, 1997]. These have an appearance similar to that of the Namibian intrusive rocks, but they are more deeply dissected, in places observed to be intruding the Archean craton. There is a strong compositional and mineralogical unity among the basalt flow sequences and doleritic sills and dikes, although the latter are petrographically and geochemically more varied than the basalts, by virtue of low-pressure differentiation processes operating during emplacement. The order of crystallization for intrusive rocks was Cr-spinel, olivine, plagioclase, augite and pigeonite, and Fe-Ti oxides. Augites generally grew around plagioclase and olivine/spinel. Interstitial glass is common in finer-grained dikes.

Finally, basaltic samples from the Kirwan Mountains, East Antarctica, are plagioclase-phyric tholeiites which, on the basis of major and trace element compositions, have been correlated with the Sabie River basalts of the Lebombo region [*Harris et al.*, 1990]. Phenocrysts are Ca-plagioclase, often in clusters, and augite, while interstitial patches of altered glass are common. Alteration of primary igneous phases in both lavas and intrusive rocks occurred during deuteric, low-temperature regional burial, and surface weathering processes. Olivine, where present, is usually replaced by iddingsite and clays; phenocrysts of plagioclase and augite are mostly fresh but are partially replaced by clays and sericite; matrix feldspar, pyroxene, and glass are variably replaced by clay, sericite, carbonate, and zeolite.

Previous Results and Geochronological Methods

Radiometric determination of the crystallization ages of Mesozoic fine-grained volcanic rocks of basaltic composition is best accomplished with K-Ar methods because of the ubiquitous distribution of K in bulk rocks and Ar-retentive minerals (primarily feldspar), the suitability of the decay constant for ^{40}K in this time frame, and the precision with which mass spectrometric measurements can be made. Conventional, total fusion K-Ar analyses, however, are plagued by several effects that can produce inaccurate results.

The first of these is loss of ^{40}Ar during and following low-temperature burial metamorphism (zeolite facies) and surface weathering. The secondary mineral phases, such as clays and zeolites, that replace primary igneous phases do not quantitatively retain ^{40}Ar, so measured ages are typically significantly less than crystallization ages. The second important disruption is the incorporation of a nonatmospheric source of Ar ("excess") at the time of crystallization. This is mantle-derived and is borne in minerals that begin to crystallize at depth, under higher than atmospheric pressures. Hence, the rocks do not start out with an atmospheric composition of Ar, and ages calculated under this assumption are older than the time of crystallization. The net result of these geological effects is to produce a range of K-Ar ages that greatly exaggerates the true duration of magmatism, and whose mean may not accurately reveal the peak time of activity.

Figure 3 illustrates in histogram form the K-Ar ages summarized by *Fitch and Miller* [1984], showing a range of about 85 m.y. and several "peaks" of activity (~160, 170-180, 190 Ma). *Fitch and Miller* [1984] attempted to address alteration effects by preparing whole rock samples in a variety of size fractions and acid leachings. Multiple age determinations for the same samples range over 50 m.y.; mean ages are not useful because of unknown bias in alteration and excess Ar effects. *Fitch and Miller* [1984] plotted their results in ^{40}Ar/^{36}Ar versus ^{40}K/^{36}Ar isotope correlation diagrams and argued that scatter confirmed a high level of age discrepancy but that some colinear points produced linear correlations with age significance. From this heavily filtered data set they concluded that intense periods of volcanic activity occurred at about 193 Ma in the Lesotho area and at 178 Ma in the Lebombo area. However, there are no objective criteria for selecting data, and given the petrographic and experimental evidence for both alteration and excess Ar effects, all regressions must be considered errorchrons. *Fitch and Miller* [1984] also conducted ^{40}Ar-^{39}Ar incremental heating experiments to distinguish alteration and excess Ar effects from crystallization ages (see below). Analytical details were not given, but none of these experiments confirmed the 193 Ma age, although a few results supported the 178 Ma age.

More recently, *Hargraves et al.* [1997] report six age determinations for Karoo dikes, using ^{40}Ar-^{39}Ar laser spot fusion on small populations of plagioclase crystals in thick sections cut from paleomagnetic cores. Gas compositions for all crystals fused from a given sample were plotted in isotope correlation diagrams and ages were calculated from the slope of colinear points, ranging from 181 to 204 (relative to Mmhb-1 monitor age of 523.5 Ma [*Renne et al.*, 1994]). However, this technique does not clearly separate ^{40}Ar-loss and excess-^{40}Ar effects from radiogenic accumulation; only one of these sample sets (181 Ma) produced a ^{40}Ar/^{36}Ar intercept of atmospheric composition.

Other radiometric systems, mostly the Rb-Sr isochron method, have been applied to Karoo igneous rocks. *Richardson* [1984] reported an age of 182 ± 2 Ma (internal isochron) for the Tandjiesberg sill, southern Namibia, while *Allsopp et al.* [1984b] produced ages of 175 ± 5 to 191 ± 9 Ma (external isochrons) for basalts and rhyolites from the Lebombo-Nuanetsi region. The poor precision in these latter results could be due to both variable initial whole rock ^{87}Sr/^{86}Sr and open system behavior. More recently, U-Pb ages on both zircon and baddeleyite from the New Amalfi sill, at the eastern edge of the Lesotho region, produced a mean of 183.7 ± 0.6 Ma [*Encarnacion et al.*, 1996].

The ^{40}Ar-^{39}Ar incremental heating method provides the capability of separating the contributions of primary igneous and secondary alteration phases to the total sample Ar composition and identifying any initial, nonatmospheric Ar, if present. This is accomplished, after neutron irradiation to produce ^{39}Ar from ^{39}K, by heating the sample in ever-increasing temperature steps and analyzing the composition of Ar released at each step [e.g., *Dalrymple et al.*, 1981; *McDougall and Harrison*, 1988]. Crystallization ages are then interpreted from convergence of step ages toward a mid- to high-temperature "plateau" age and independently from the

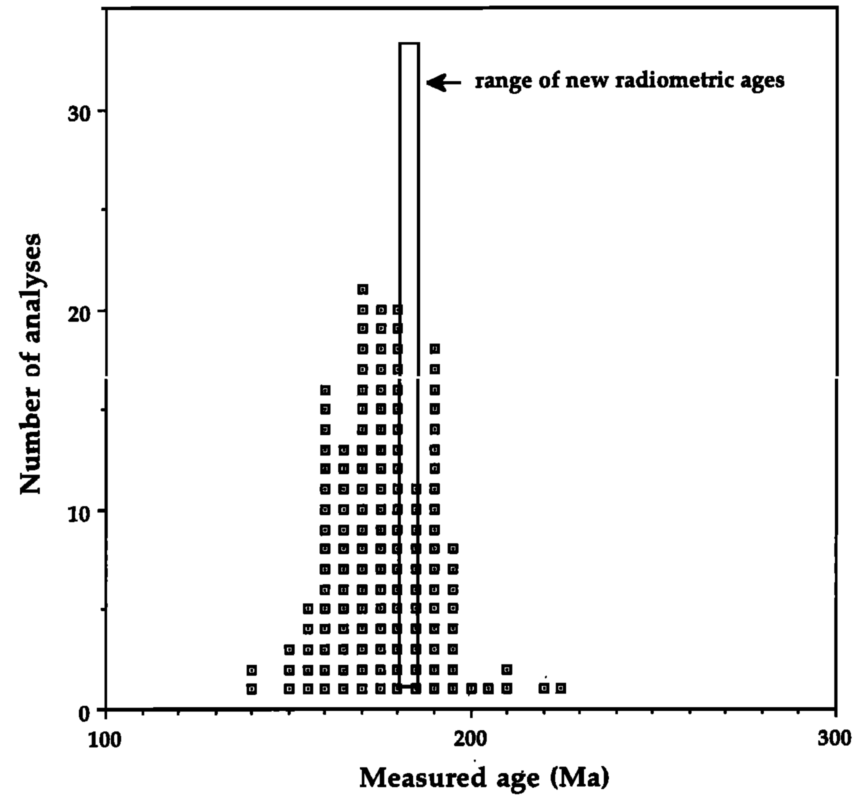


Figure 3. Histogram of previously reported K-Ar age determinations for Karoo rocks, summarized by *Fitch and Miller* [1984]. Also shown is the range of new age determinations from ^{40}Ar-^{39}Ar incremental heating experiments reported here. The larger scatter in K-Ar ages is due to combined effects of ^{40}Ar loss and excess ^{40}Ar.

slope of colinear step compositions in Ar isotope ratio plots, i.e., an isochron age. Irradiation-induced Ar recoil and Ar loss can be significant and must be evaluated for each sample.

Experiments were run for both whole rock basalts and plagioclase feldspar separated from basalts and diabases. Karoo lavas are predominantly aphyric basalts, but plagioclase-phyric flows, dikes, and sills are relatively common. Samples were selected for dating on the basis of macroscopic and microscopic examination, compositional data [*Marsh et al.*, 1997] and stratigraphic position [*Hargraves et al.*, 1997]. Whole rocks were prepared in two ways: a 0.5-1 mm size fraction of chips from fresh slabbed pieces or minicores cut from fresh interiors of large pieces. Plagioclase separates were cleaned in nitric acid, then briefly in 6% HF, followed by ultrasonic washing, and finally handpicked. Chips and plagioclase samples were wrapped in Cu-foil, labeled, and loaded in quartz vials, along with the whole rock minicores. Samples were interspaced with 10-mg aliquots of biotite monitor FCT-3 (28.03 ± 0.18 Ma, calibrated against Mmhb-1 hornblende at 523.5 Ma [*Renne et al.*, 1994]). Quartz vials were evacuated, sealed in standard Al tubes and irradiated for 6-10 hours at 1 MW power in the center ring of the TRIGA reactor at Oregon State Unversity, Corvallis.

FCT-3 biotite was measured at multiple vertical positions along the 80 mm center vial, producing neutron flux (J) values that varied smoothly with a ~10% range. Horizontal gradients in J are known from previous experience to be <1%. J values for the sample positions (Table 1) were extrapolated from a second-order polynomial fit to the monitors. Errors in sample J values accumulate from the individual monitor measurements and gradient fitting and are about 0.5%.

Ar isotopic compositions of samples were measured in one of two mass spectrometer systems: an MAP-215/50 instrument connected to an ultra-high vacuum resistance furnace and Zr-Al getters (for small, ~100 mg whole rock discs and all plagioclase separates), and an AEI-MS10 instrument with dual glass extraction lines heated by RF induction, with Ti-TiO_2 getters (for larger, ~700 mg whole rock chips and cores). Both systems are operated in the peak-hopping mode (for m/z = 35, 36, 37, 38, 39, 40) by microcomputers. Peak decay is typically <10% for the MAP system and <1% for the MS10 system, and regressed peak heights against time follow linear fits. Mass discrimination on the MAP system was measured using zero-age basalt disks run in the same way as the samples and was constant at 1.005 (2 amu). Measurements for the MS10 system were made from a reservoir of atmospheric Ar and varied smoothly from 1.028 to 1.036 (2 amu) over the period of analysis. Additional experimental details are given by *Duncan and Hogan* [1994] and *Mahoney et al.* [1993].

New Results

Mass spectrometric data are summarized in Table 1 and presented graphically in Figures 4a-4f. Fitted Ar isotopic ratios from step measurements are used in two ways. Assuming that initial sample Ar compositions were atmospheric (initial $^{40}Ar/^{36}Ar$ = 295.5), step ages are plotted against cumulative percent ^{39}Ar released, as age spectrum or

Table 1. The ^{40}Ar-^{39}Ar Radiometric Ages for the Karoo Igneous Province in South Africa and Namibia and Correlative Rocks in East Antarctica

Sample	Material	Total Fusion Age, Ma	Plateau Age Ma	^{39}Ar of Total %	Isochron Age, Ma	*N*	$^{40}Ar/^{36}Ar$ Intercept ± 1σ	*J*
				South Africa: Lesotho				
OXB-01	basalt	187.5	186.5 ± 1.9	81	189.6 ± 3.2	5	235.1 ±21.6	0.001686
MLP-172	basalt	180.3	179.5 ± 2.1	79	181.7 ± 2.2	3	280.9 ± 9.6	0.001680
BUS-18	basalt	184.8	182.4 ± 1.7	94	186.4 ± 2.6	5	283.5 ±28.3	0.001690
ROM-01	basalt	180.4	180.0 ± 2.1	88	180.6 ± 4.3	4	253.5 ±39.7	0.001695
		186.8	184.4 ± 1.0	69	181.9 ± 2.3	3	298.2 ± 5.6	0.001593
BMC-04	basalt	184.3	184.3 ± 1.7	95	183.5 ± 1.9	5	292.2 ± 6.4	0.001686
NN-01	basalt	190.4	182.9 ± 2.1	60	184.1 ± 2.5	3	287.2 ±10.9	0.001688
ON-01[a]	basalt	166.7						0.001695
KF-10 Omeg[a]	basalt	173.7	183.9 ± 1.0	77	183.5 ± 1.7	5	302.7 ± 9.1	0.001653
	plagioclase	187.9	183.9 ± 0.7	93	183.8 ± 2.4	6	294.7 ± 2.7	0.001496
MF-09 Moshesh[b]	basalt	185.9						0.001358
KRB-7 Moshesh	andesite	183.2	181.0 ± 1.7	82	182.0 ± 3.2	4	295.8 ±27.9	0.001628
KR-29 Moshesh	basalt	190.5	186.5 ± 1.1	72	184.5 ± 3.2	3	308.9 ±70.6	0.001324
				South Africa: Lebombo				
KVU-5 Jozini	rhyolite	180.3	179.7 ± 0.7	98	180.0 ± 1.8	4	315.3 ±91.7	0.001469
KSA-12 Jozini	rhyolite	177.7	178.1 ± 0.6	91	177.6 ± 1.9	6	308.7 ±38.2	0.001430
RSS-82 Sabie	basalt	179.0	181.2 ± 1.0	79	182.6 ± 2.1	4	296.0 ±13.9	0.001398
KOL-2 Sabie	basalt	186.2	183.2 ± 1.3	83	181.4 ± 3.7	4	306.0 ± 9.5	0.001680
RSV-4 Sabie[c]	basalt	180.8						0.001503
RSV-35 Sabie	basalt	188.4	184.2 ± 1.0	81	182.8 ± 4.9	3	305.6 ±51.7	0.001525
	plagioclase	190.4	184.2 ± 0.6	76	182.9 ± 2.5	6	295.1 ± 3.4	0.001574
RSS-8 Sabie[b]	basalt	186.7						0.001621
KP-121 Letaba	picrite	184.5	182.7 ± 0.8	90	182.2 ± 2.5	4	356.6 ±31.6	0.001675
KP-111 Letaba	picrite	129.5	141.9 ± 1.5	62	139.8 ± 2.5	3	267.0 ±14.1	0.001385
KP-83 Mashikiri[d]	nephelinite	219.4						0.001382
KP-92 Mashikiri	nephelinite	194.2	182.1 ± 1.6	54	181.7 ± 3.9	2	313.1 ±29.0	0.001436
KOL-17 Mashikiri[b]	nephelinite	206.3						0.001599
				South Africa: Transvaal Dikes and Sills				
TRA-71[c]	plagioclase	177.2						0.001378
TRA-76	plagioclase	180.6	181.4 ± 1.1	95	183.5 ± 1.6	7	257.2 ±35.5	0.001391
TRA-84	plagioclase	189.4	182.8 ± 1.6	68	182.4 ± 2.8	4	309.0 ±25.0	0.001470
TRA-95	plagioclase	207.6	180.3 ± 1.8	65	184.1 ± 2.2	4	294.8 ±16.0	0.001353
				Namibia: Hardap				
HAR-02[b]	basalt	188.4						0.001265
	plagioclase	183.4	183.0 ± 0.6	100	184.4 ± 1.8	6	294.6 ± 2.6	0.001448
HAR-07[b]	basalt	182.7						0.001746
HAR-08	basalt	177.4	184.2 ± 1.0	50	185.4 ± 1.9	4	290.2 ± 3.7	0.001275
HAR-13	basalt	185.4	186.0 ± 0.8	92	187.4 ± 2.0	5	291.0 ± 2.1	0.001605

Table 1. (continued)

				Namibia: Keetmanshoop				
KEE-02[c]	basalt	179.8				0.001305		
KEE-03	plagioclase	183.4	184.7 ± 0.5	95	183.8 ± 1.7	8	268.1 ±37.6	0.001548
KEE-05	plagioclase	176.0	181.5 ± 0.8	50	182.9 ± 2.8	3	295.2 ± 8.5	0.001641
KEE-07[b]	basalt	185.0						0.001774
KEE-10	basalt	184.1	184.7 ± 0.7	100	185.8 ± 2.0	6	292.5 ± 3.8	0.001710
	plagioclase	189.0	180.5 ± 0.7	90	181.8 ± 2.3	4	294.7 ± 4.1	0.001591
KEE-11[a]	basalt	181.7						0.001255
				Antarctica: Kirwan Mountains				
LAD-7	plagioclase	183.9	180.6 ± 0.6	89	182.0 ± 3.2	5	294.9 ± 3.1	0.001650
LAG-22	plagioclase	182.1	182.7 ± 0.6	97	180.9 ± 2.0	6	294.9 ± 0.9	0.001630
LAG-31	plagioclase	183.4	182.8 ± 0.6	98	181.5 ± 1.5	7	293.2 ± 4.3	0.001640

Ages are reported relative to biotite monitor FCT-3 (28.03 ± 0.18 Ma), which is calibrated against hornblende Mmhb-1 (523.5 Ma, [*Renne et al.*, 1994]. Plateau ages are the mean of concordant step ages (*N* , number of steps), weighted by the inverse of their variances. Calculations use the following decay and reactor interference constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}, $\lambda_\beta = 4.963 \times 10^{-10}$ yr^{-1}; $(^{36}Ar/^{37}Ar)_{Ca} = 0.000264$, $(^{39}Ar/^{37}Ar)_{Ca} = 0.000673$, $(^{40}Ar/^{39}Ar)_{Ca} = 0.01$. J is the neutron fluence factor, determined from measured monitor $^{40}Ar/^{39}Ar$.

[a]none developed (Ar-loss and recoil pattern).
[b]none developed (recoil pattern).
[c]none developed (Ar-loss and excess-Ar pattern).
[d]none developed (recoil and excess-Ar pattern).

plateau diagrams. In addition, isotope correlation diagrams, i.e., $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$, are examined for colinear step compositions whose slope is equivalent to age since closure and whose $^{36}Ar/^{40}Ar$ intercept reveals the initial Ar composition of the system (rock or mineral). We accept an apparent age as an accurate estimate of the sample crystallization age if several statistically testable conditions are met [*Dalrymple et al.*, 1981; *Pringle*, 1993], namely, (1) a well-defined, mid- to high-temperature plateau is formed by at least three concordant, contiguous steps representing $\geq$50% of the ^{39}Ar released; (2) a well-defined isochron exists for the plateau step Ar compositions; (3) the plateau and isochron ages are concordant; and (4) the isochron $^{40}Ar/^{36}Ar$ intercept is atmospheric. Most whole rock and all plagioclase samples presented in Table 1 meet the criteria listed above. Plateau ages (1σ uncertainties) are the mean of three to eight step ages, representing $\geq$50% of the total sample ^{39}Ar, weighted by the inverse of variance. Corresponding isochron ages are concordant, although generally have significantly larger uncertainties (± 1s) because of the small dispersion of very radiogenic step compositions. The $^{40}Ar/^{36}Ar$ intercepts are, with a few exceptions, within 1σ uncertainty of the atmospheric value, and these departures are again due to fitting small numbers of closely grouped points in isotope correlation space. A small but expected subset failed to provide acceptable age information, owing to combined effects of Ar loss, excess Ar, and Ar recoil, as noted. Total fusion ages are calculated by recombining all steps from each sample and are roughly equivalent to conventional K-Ar ages. We next examine examples that illustrate various screening criteria.

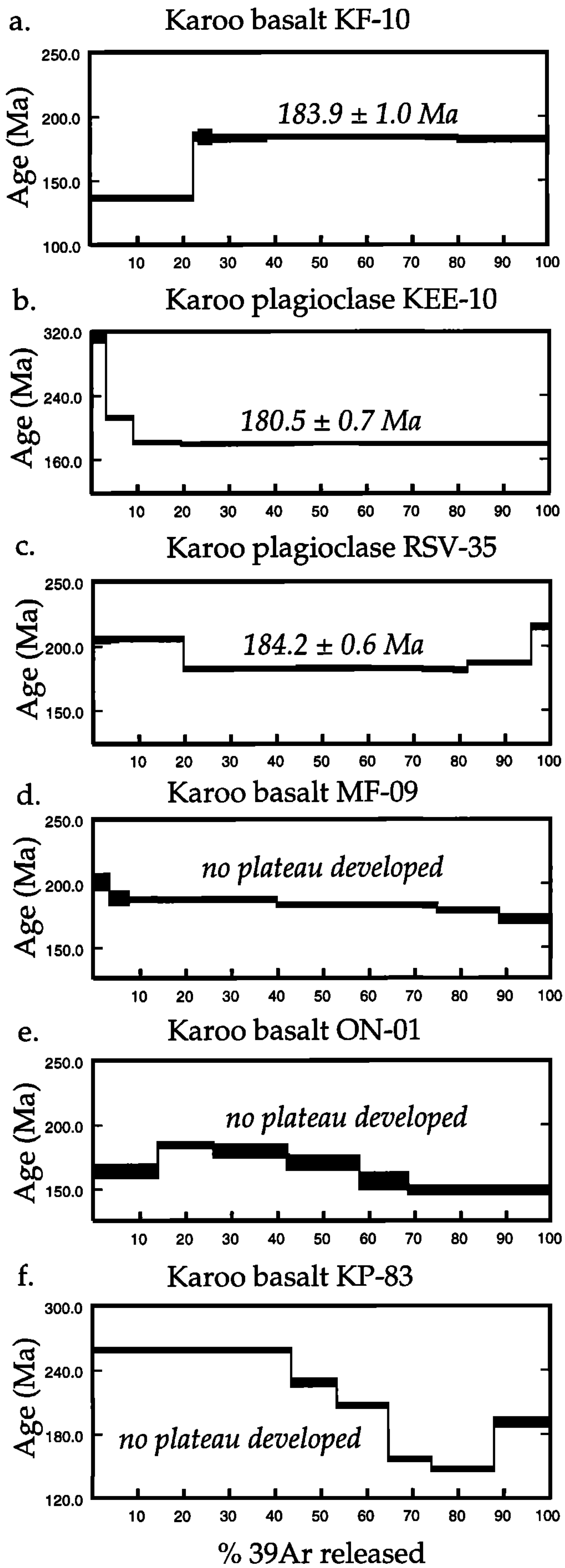
Ar-Loss Spectra

Ar loss is suspected where total fusion ages are significantly younger than plateau ages (Table 1). An example is KF-10, a coarse-grained Omega basalt flow from the Kraai River pass lying between the Moshesh's Ford basalts and the Kraai River basalts [*Marsh and Eales*, 1984]. The first step (lowest temperature) gave an apparent age of 140 Ma, while five subsequent steps up to fusion gave concordant ages around 183 Ma (Figure 4a). Reference to $^{39}Ar/^{37}Ar$ compositions from these steps confirms that the Ar released during the first step came from phases significantly higher in K/Ca, such as smectites, compared with higher-temperature compositions dominated by values associated with plagioclase [*Walker and McDougall*, 1982].

Excess-Ar Spectra

Inheritance of a nonatmospheric (excess) initial Ar composition is suspected when the total fusion age is significantly older than the plateau age, as is the case in several samples found in Table 1. A common pattern is that seen in the plagioclase separate from Namibian basalt KEE-10 (Figure 4b) for which the total fusion age is 189 Ma, compared with a well-defined plateau age of 181 Ma. The first two steps produced apparent ages of 316 and 217 Ma, followed by a seven-step plateau comprising 90% of the total ^{39}Ar released. The isochron age for the plateau-forming steps is 182 Ma, and the $^{40}Ar/^{36}Ar$ intercept is atmospheric, confirming that the excess-Ar component had been removed at low temperature.

A slightly different pattern is seen in the experiment on plagioclase from Lebombo basalt RSV-35 (Figure 4c) in



which >200 Ma apparent ages were calculated for the lowest- and highest-temperature steps, while the six intervening steps produced a well-defined plateau age of 184 Ma. Such "saddle-shaped" patterns are commonly seen in feldspars crystallized under high lithostatic pressures [*Lanphere and Dalrymple*, 1976; *McDougall and Harrison*, 1988] and have been interpreted to reflect excess Ar and radiogenic Ar release from different structural sites within the feldspar crystals. Both patterns are reported from plagioclases in other flood basalt provinces [*Renne et al.*, 1992; *Sinton and Duncan*, 1997]. In the North Atlantic Igneous Province, associated with the earliest activity of the Iceland plume, pronounced saddle-shaped age spectra were produced from plagioclase separated from the earliest, continentally-hosted basalt flows [*Sinton and Duncan*, 1997]. In these cases, plateau ages were significantly older than isochron ages, and $^{40}Ar/^{36}Ar$ intercepts were greater than atmospheric, indicating incomplete separation of excess and radiogenic Ar. These plagioclase phenocrysts are characterized by dense trails of melt inclusions, compared with clear groundmass plagioclase that yield relatively flat release patterns. It appears likely that the larger crystals began to form at considerable depth, where they trapped nonatmospheric Ar from the surrounding melt. We infer a similar history for Karoo magmas erupted through the thick South African craton.

The ^{39}Ar and ^{37}Ar Recoil

The production of ^{39}Ar and ^{37}Ar from ^{39}K and ^{40}Ca, respectively, by fast neutron capture, involves energetic reactions that cause recoil of the target atom. In fine-grained, multiphase systems, such as basalts, recoil can move ^{39}Ar and ^{37}Ar atoms from relatively K, Ca-rich to K, Ca-poor phases. This transfer of ^{39}Ar and ^{37}Ar from relatively radiogenic to unradiogenic sites leads to apparent ages that are too old for low- temperature steps and too young for high- temperature steps. This is because K-rich phases (mesostasis) outgas at lower temperatures than Ca-rich phases (pyroxene, feldspar). The resulting age spectra from such samples show decreasing step ages with %^{39}Ar released, the so-called "inverse staircase" pattern (Lesotho basalt MF-09, Figure 4d). This is an experimental artifact due to the texture of whole rocks (grain size and K distribution), and the best estimate of the time of crystallization from these experiments is the total fusion age. However, there is no way to adequately assess Ar-loss or excess-Ar effects in these cases. Single-phase samples

Figure 4. (opposite) Examples of experimental data, plotted as age spectrum (plateau) diagrams, in which step ages, shown as horizontal rectangles whose height is ± 1s analytical (external) uncertainty, are plotted against proportion of total gas released. (a) Typical middle-high temperature plateau with ^{40}Ar-loss from alteration phases evident at low temperature. (b) Typical plateau (>90% of gas released) with excess ^{40}Ar seen at the two lowest temperature steps. (c) Excess ^{40}Ar seen at low and high temperatures, but a five-step plateau developed in the middle portion of the spectrum. (d) Recoil pattern due to irradiation-induced redistribution of ^{37}Ar, ^{39}Ar from Ca-rich and K-rich phases to Ca-poor and K-poor phases. (e) An example of recoil combined with ^{40}Ar-loss problems. (f) An example of recoil combined with excess-^{40}Ar problems.

(i.e., plagioclase) will not produce a recoil effect except if there is a small amount of alteration (e.g., sericite), which through ^{39}Ar loss may yield old ages at the lowest temperature. Not surprisingly, some samples analyzed showed evidence of combinations of the above effects, such as recoil and Ar loss (Lesotho sample ON-01, Figure 4e) or recoil and excess Ar (Lebombo nephelinite KP-83, Figure 4f).

Interpretations

Having removed results that we can demonstrate are inaccurate because of either geologic or experimental effects, we are left with a set of crystallization ages (Table 1) that is remarkably tightly grouped, especially compared with previously reported ages. Although plateau and isochron ages are concordant, the latter have generally larger analytical errors because tight clustering of step compositions in isotope correlation space leads to relatively imprecise regressions. For the same reason, $^{40}Ar/^{36}Ar$ intercepts sometimes have large uncertainties and are occasionally different from the atmospheric value, and resulting ages are either slightly older or younger than the plateau age. Hence we use the plateau ages for estimating the timing and duration of igneous activity at each of the locations sampled.

The samples from the Lesotho region cover the entire ~2 km-thick composite section described by *Marsh et al.* [1997] and are arranged in stratigraphic order (Figure 2) in Table 1. Three samples from the base of the section (Moshesh's Ford and Omega units) are slightly discrepant, producing ages between 179 and 184 Ma. Sample KF-10 overlies Moshesh's Ford basalt KR-29 and the Pronksberg dacites and produced concordant whole rock and plagioclase ages of 183.9 ± 1.0 Ma, which is our best age for the base of the main section of lava flows. Samples NN-01 and BMC-04 are from the base of the basalt sequence near the southeast corner of Lesotho. Their plateau ages overlap (at the 1σ level), giving a mean of 182.8 ± 1.3 Ma. Sample ROM-01 is a basal flow from the center of Lesotho, which was run a second time because the first result was slightly discrepant relative to the stratigraphy. Both age spectra show slight recoil patterns; the first analysis showed some Ar loss as well, producing a lower total fusion age and slightly younger plateau. Because of this, we prefer the second analysis, which also gave a tighter plateau age of 184.4 ± 1.0 Ma.

Sample MLP-172 comes from the middle of the section in north Lesotho (179.5 ± 2.1 Ma), while OXB-01 (186.5 ± 1.9 Ma) comes from the uppermost flow in the section. Isochron ages for these two samples were barely concordant with age plateaus, and intercepts were nonatmospheric. The age of the top of the section is thus not especially well constrained but is not significantly younger than the base of the section. This conclusion is supported by magnetostratigraphic data [*Rehacek*, 1995; *Hargraves et al.*, 1997], which reveal a single polarity reversal within the section. Reference to the middle Jurassic magnetic reversal timescale [*Gradstein et al.*, 1994] indicates that this was a time of rapid field reversals (~ 0.5 m.y.), so this entire section was erupted within about 0.5 m.y. at 183 ± 1 Ma.

Volcanic activity in the Lebombo region (Figure 2) appears to have been somewhat longer lived. A single Mashikiri nephelinite (KP-92), one Letaba picrite (KP-121), and two Sabie River basalts (RSV-35, KOL-2) produced indistinguishable plateau ages within 183 ± 1 Ma. Sabie River basalt RSV-35 gave especially tight whole rock and plagioclase ages at 184.2 ± 1.0 Ma. RSS-82, from just below the Sabie River basalt/Jozini rhyolite contact, is significantly younger at 181.2 ± 1.0 Ma. Two rhyolites produced still younger ages with a mean of 178.9 ± 0.5 Ma. On the basis of magnetostratigraphic mapping, *Henthorn* [1981], *Rehacek* [1995] and *Hargraves et al.*, [1997] have correlated the single reverse to normal (R-N) magnetic reversal in the Lesotho section with a R-N reversal within the Sabie River basalts. The new age determinations appear to confirm this correlation and indicate that most of the lower two thirds of the Lebombo section were erupted in about 0.5 m.y. (*Hargraves et al.* [1997], however, report the presence of a short, N polarity section of Mashikiri nephelinites, representing a slightly earlier onset of volcanism than has been found in the Lesotho section.) An additional three or more reversals in the upper basalt-rhyolite section indicate a longer total period of activity in the Lebombo region, culminating in the eruption of rhyolites. We note, however, that the extremely rapid reversal frequency during this early Jurassic period (Figure 5) is still compatible with a total duration of volcanic activity of a few million years.

A conspicuous anomaly is the apparently robust crystallization age of 141.9 ± 1.5 Ma for Letaba picrite KP-111. The sample produced an Ar-loss pattern for the three low-temperature steps but a four-step high-temperature plateau comprising 62% of the total ^{39}Ar. This early Cretaceous age is contemporaneous with intrusive centers in the Lebombo region (e.g., the Bumbeni syenite at 143 ± 2 Ma, ^{40}Ar-^{39}Ar incremental heating [*Fitch and Miller,* 1984]; 133 ± 4 Ma [*Allsopp et al.*, 1984b]; 146 ± 1 Ma [*Hargraves et al.*, 1997] and Kuleni rhyolites (145 ± 3 Ma [*Allsopp et al.*, 1984b]) and age resetting of Karoo lavas by contact metamorphism with younger dikes is a possibility that must be fully evaluated.

Basalt and plagioclase ages from lavas, sills, and dikes from Namibia; dikes and sills from Transvaal and Natal provinces, South Africa, and lavas from the Kirwan Mountains, Antarctica, are, with a few exceptions, indistinguishable and fall in the age range for the main period of Lesotho and Lebombo volcanism, 183 ± 1 Ma. All rocks from Namibia are N-magnetized [*Hargraves et al.*, 1997] and are compositionally correlated with the main sequence Lesotho magma type [*Marsh et al.*, 1997]. The South African sills and dikes are of mixed polarities but can all be correlated with Lesotho magma types [*Marsh et al.*, 1997]. There is strong evidence for excess Ar in plagioclase from two of these samples (TRA-84, 95), but concordant, high-temperature plateaus developed. The Antarctic basalts are compositionally similar to the southern (low-Ti) Sabie River basalts [*Harris et al.*, 1990]; plagioclase separated from these samples produced excellent, concordant plateau and isochron ages in the 181-183 Ma range.

Conclusions

The overwhelming majority of rocks in the Karoo Igneous Province, and correlative mafic rocks in Antarctica, were crystallized within a very short period, at 183 ± 1 Ma. This includes all of the Namibia, Lesotho, East Antarctic, and South Africa sills and lower two thirds of the Lebombo exposures. A volumetrically subordinate, principally felsic phase of volcanic activity continued in the Lebombo area

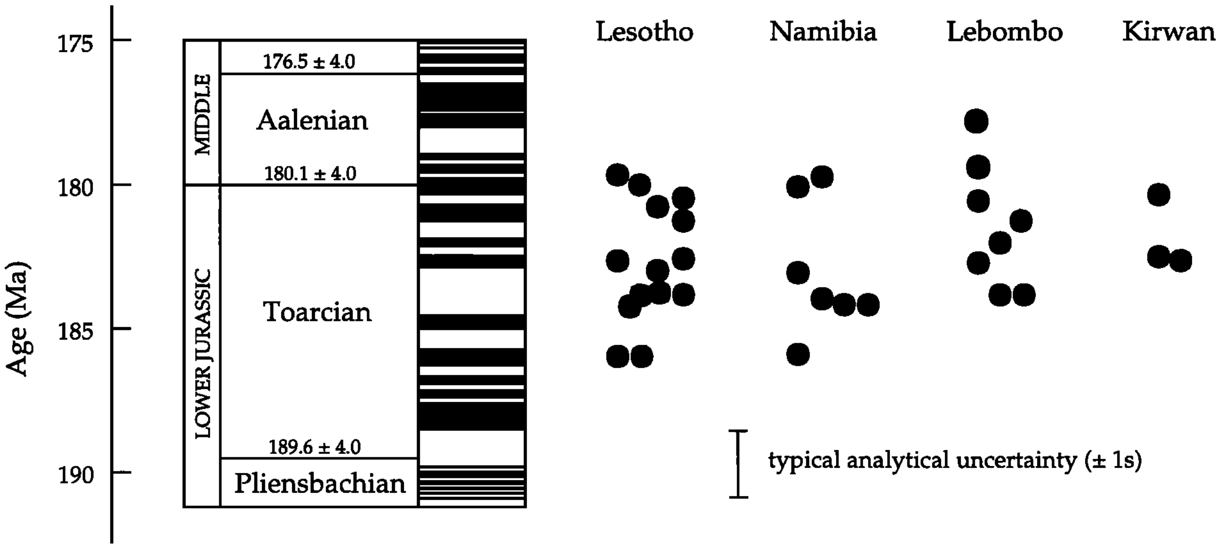


Figure 5. Comparison between acceptable plateau ages determined here, grouped by lava section, and the latest Mesozoic magnetostratigraphic timescale [*Gradstein et al.*, 1994]. Stage boundary ages are estimated to be accurate to ± 4 m.y., so direct correlation to the timing of Karoo magmatism cannot be made definitively, although the lower-middle Jurassic boundary (Toarcian-Aalenian stages) appears to be approximately coeval with the KIP. It is important to note, as well, that the magnetic field reversed rather frequently at this time, so that the lack of reversals observed in most sections (except Lebombo) indicates a shorter duration than that indicated by the range of age determinations.

until about 179 Ma. There is no reliable evidence for the punctuated, extended volcanic history proposed by *Fitch and Miller* [1984]. Apparent early (~193 Ma) and late (~163 Ma) peaks in age determinations are evidently due to incompletely resolved excess-^{40}Ar and ^{40}Ar-loss effects. The narrow range of crystallization ages in the present study is considered reliable based on rigorous criteria for individual samples, stratigraphic data for relative ages, and concordant mineral (plagioclase) and whole rock ages for a number of samples. Magnetostratigraphic data support the notion of extremely rapid eruption rates during the main basaltic phase of KIP formation. Additional magnetic studies indicate that paleomagnetic pole positions (VGPs) for all principal Karoo formations are indistinguishable, confirming the rapid and contemporaneous nature of this igneous event [*Hargraves et al.*, 1997].

Radiometric dating of lower-middle Jurassic igneous rocks from East Antarctica (the Ferrar dolerites and Kirkpatrick basalts) has recently defined a similarly narrow timeframe. A dozen high-precision ^{40}Ar-^{39}Ar incremental heating ages for plagioclase and basaltic glass samples from the Kirkpatrick basalts [*Foland et al.*, 1993; *Heimann et al.*, 1994] fall in the range 180.0 ± 1.8 Ma (external error, recalculated to Mmhb-1 monitor age of 523.5 Ma [*Renne et al.*, 1994]. Four U-Pb zircon and baddeleyite ages for associated Ferrar dolerites [*Encarnacion et al.*, 1996] average 183.7 ± 2.1 Ma, while Rb-Sr internal isochrons for the related Dufek intrusion are 183.9 ± 0.3 Ma and 182.7 ± 0.4 Ma [*Minor and Mukasa*, 1995]. Hence there is compelling evidence that Karoo and Ferrar igneous activity were virtually synchronous and that the provinces should be considered as part of a single large igneous event that spanned much of southern Gondwana between 184 and 179 Ma, with a peak in activity in the first 2 m.y. of that period.

The elongate, rather than circular shape of this composite province has been noted [*Cox*, 1978; *Storey*, 1995] and proposed to reflect a relationship to the geometry and melting regime of the subduction zone operating along the Pacific margin of Gondwana, between principally the Phoenix plate and the western Gondwana active continental margin at this time [*Storey et al.*, 1992; *Storey*, 1995]. Indeed, compositional aspects of the province are often more compatible with a subduction rather than a plume source [*Cox*, 1992; *Brewer et al.*, 1992]. The surface expression of magmatism may have been controlled by the temperature and viscosity structure of the upper mantle beneath western Gondwana at 184 Ma. An active subduction zone would have produced a heterogeneous upper mantle and crustal structure in the region, with a warm mantle wedge and thinned continental lithosphere above the downgoing Phoenix plate. This subduction-parallel fabric would have provided an asthenospheric channel for eastward lateral flow of hot material from the plume head surfacing under South Africa, beneath eastern Antarctica to southern Australia, and even as far as New Zealand, reported by *Mortimer et al.* [1995] (Figure 6). Mixing of plume with subduction-influenced mantle prior to decompression melting or contamination of plume melts with lower continental lithosphere would be expected.

As proposed initially by *Rampino and Stothers* [1988], the timing of several well-dated Mesozoic continental flood basalt provinces coincides with major mass extinctions of biota: e.g., the Siberian Traps with the Permian-Triassic boundary [*Renne et al.*, 1995; *Kamo et al.*, 1996] and the Deccan Traps with the Cretaceous-Tertiary boundary [*Courtillot et al.*, 1986, 1988; *Duncan and Pyle*, 1988; *Baksi and Farrar*, 1991]. The Karoo magmatic event (179-184 Ma) may or may not be linked to the faunal changes that occurred at lower-middle Jurassic time (Toarcian-Aalenian stages, Figure 5). Even if this coincidence is confirmed, the extinction event was comparatively minor and confined principally to groups of shallow-dwelling marine invertebrates [*Arkell*, 1956]. Why didn't the KIP have equally

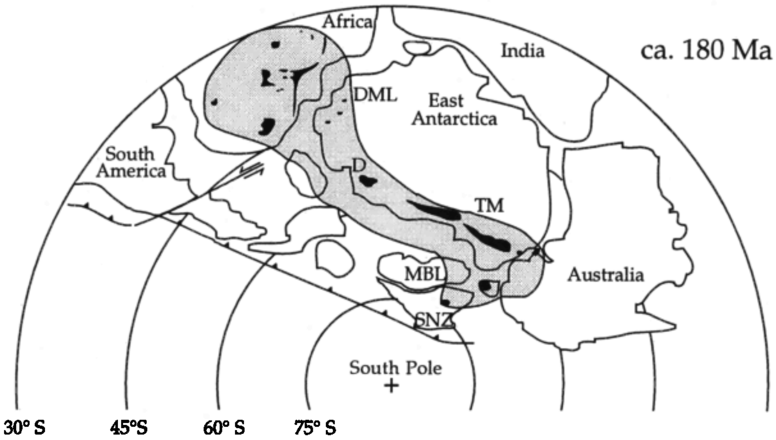


Figure 6. Estimated initial distribution of Karoo-Ferrar lavas and intrusive rocks (gray) and exposures today (black) [after *Encarnacion et al.*, 1996], from an early Middle Jurassic plate reconstruction by *Grunow et al.* [1991]. Contemporary, flood basalt-style magmatism occurred throughout this region within the period 179-184 Ma. The elongate, rather than circular expression possibly reflects the mantle upwelling geometry or lateral flow in the upper mantle guided by low- viscosity regions produced by plate interaction (i.e., subduction along west Gondwana). Abbreviations are Dronning-Maud Land (DML), Dufek intrusion (D), Marie Byrd Land (MBL), Transantarctic Mountains (TM), and South New Zealand (SNZ).

devastating effects on the biosphere as, say, the Siberian Traps? The answer will ultimately rely on study of detailed sedimentary records of this interval but may have to do with both the relatively protracted period of Karoo volcanism and the high southern latitude of the eruptions, which would have limited the dispersion of volcanic gases.

From recent studies of the size, composition, structure, and chronology of both continental and oceanic large igneous provinces [e.g., *Coffin and Eldholm*, 1994], it is apparent that material and energy from Earth's interior move through surface reservoirs in two fundamental modes: the predominant, steady state plate tectonic regime driven by upper mantle convection, and a punctuated, intermittently dominant, mantle overturn regime driven by plume convection [*Larson*, 1991]. This second regime, while ephemeral, is periodically significant in orogenesis [*Stein and Hofmann*, 1994] and continental breakup [*Storey*, 1995] and offers an intriguing mechanism for linkage between convective overturn in the deep interior of the planet, environmental change, and punctuated evolution.

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