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From flood basalts to the inception of oceanization: Example from the $^{40}\text{Ar}/^{39}\text{Ar}$ high-resolution picture of the Karoo large igneous province

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[1] The Jurassic Karoo large igneous province consists of vast quantities of basaltic lava flows, giant dike swarms, and poorly dated silicic magmatism. The Karoo magmatism occurred over more than 3×10^6 km² and was associated with the opening of the Indian Ocean. We present new $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data concerning the easternmost part (i.e., the Mwenezi and Lebombo areas) of the Karoo province, close to the future rifted margin. These data allow documenting the final history of the province and the time elapsed between the end of the Karoo magmatism and the inception of oceanization. This important type of information is poorly constrained for most of the large igneous provinces. Eighteen plagioclase separates yielded 14 plateau and “mini-plateau” ages obtained on 3 basaltic dikes (178.1 ± 1.1 to 177.2 ± 2.4 Ma; 2σ), 3 gabbroic (178.2 ± 1.7 to 176.8 ± 0.7 Ma) and 2 silicic (175.8 ± 0.7 to 174.4 ± 0.7 Ma) plutons, and 1 rhyolitic lava flow (177.8 ± 0.7 Ma). We also obtained three concordant plateau and mini-plateau ages ranging from 173.9 ± 0.7 Ma to 172.1 ± 2.3 Ma on the atypical E-MORB-like N–S striking Rooi Rand dikes. One dike from the Save-Limpopo N70°-oriented giant dike swarm provides a mini-plateau age of 177.7 ± 0.8 Ma in agreement with the dates previously determined on this branch and possibly assessing the same age and short duration (≤ 1 – 2 Myr) as for the 179 Ma giant Okavango dike swarm. New and previous selected age data obtained on the Karoo province show that the magmatism was active over ~ 10 Myr from 184 to 174 Ma. The main basaltic phase occurred mostly over the first ~ 5 Myr and was progressively followed by a more differentiated and less voluminous magmatism over the last 4 Myr. The easternmost Lebombo-Mwenezi long-lasting magmatism is interpreted as being triggered by the progressive lithospheric extension preceding the continental disruption. The transition from rifting to oceanization is probably illustrated by the E-MORB-like Rooi Rand dikes which are likely to be emplaced during or shortly after the final stage of the Karoo magmatism. A geodynamic evolution of the province is proposed. These data indicate that the Karoo magmatism represents an atypical province (admitting that other large igneous provinces are sufficiently known) with a long-lasting and relatively low-emission rate magmatic activity. It appears from a reevaluation of major Phanerozoic Continental Flood Basalts (CFBs) that for most of them, including the Karoo, the onset of oceanization shortly follows (or is coeval to) the latest CFB-related activity more closely than previously thought.

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1. Introduction

[2] The Phanerozoic continental flood basalts (CFBs) are considered as key events in the earth evolution because of their huge extension and their possible relationship with continental breakup and mass extinctions [Courtilot and Renne, 2003]. Over last decades, CFBs have been increasingly precisely dated as analytical techniques were improved. Most of the geochronology studies (although far to represent achieved databases) mainly focus on basaltic volcanic sequences whereas silicic volcanism and other late intrusive formations are often neglected despite their potential to bring important geodynamic constraints [e.g., Bryan et al., 2002]. Moreover, the timing between the CFB emplacement and the subsequent oceanization process is generally not enough constrained despite its crucial implication for the Pangaea breakup reconstruction. On the latter aspect, models are mostly based on approximate ages of the oldest sea floor magnetic anomalies because of the difficulty to obtain (and thus date) magmatic rocks directly from the oldest sea floor. Only a few studies [Renne et al., 1997] have attempted to characterize the onset or the first inception of oceanization using reported on-land CFB-related rocks having MORB affinity. Finally, a recent model focusing on the development of CFBs suggests a prolonged duration of the magmatism over 5–10 Myr comprising onset, brief basaltic acme (1–5 Myr) and subsequent waning (silicic-rich) phases [Jerram and Widdowson, 2005], but it still lacks sufficient high-quality geochronology data to be fully tested.

[3] The Karoo CFB consists of more than 3×10^6 km² outpouring of dominantly basaltic lava flows and intrusions of giant dike swarms. Along with the Ferrar CFB, it is related to the early breakup of southern Gondwana and the opening of the Indian Ocean. Recent dating on basaltic lava

flows and sills (Figure 1) [Encarnacion et al., 1996; Duncan et al., 1997; Jones et al., 2001; Jourdan et al., 2005a] and the giant dike swarms [Le Gall et al., 2002; Jourdan et al., 2004, 2005a] suggest that Karoo is an atypical CFB characterized by a sustained high volume outputs emplaced over a longer time span (~ 4 –5 Myr) compared to other provinces (~ 1 –2 Myr). However, this longer duration may also be the result of a better knowledge of this province, when compared to most of the other ones. Previous dating illustrates that the basalts were emplaced over a relatively long period between 185 and 177 Ma and that the magmatism possibly migrated from south to north [Jourdan et al., 2005a]. Few reliable dates are available concerning two of the three major Karoo dike swarms (Save-Limpopo and Lebombo dike swarms [Le Gall et al., 2002; Jourdan et al., 2005a, 2006a]), the silicic volcanism [Riley et al., 2004] and the Save-Mutandawhe plutons [Landoll et al., 1989]. Moreover, no reliable age data have been provided on the E-MORB Rooi Rand dike swarm (southern Lebombo) which was suggested to represent the very first initiation of the oceanization process [Armstrong et al., 1984; Duncan et al., 1990].

[4] Here we provide 18 new $^{40}\text{Ar}/^{39}\text{Ar}$ data including 14 plateau and “mini-plateau” ages on (1) the Mwenzezi (formerly named Nuanetsi)-Mutandawhe intrusive system; (2) MORB-like Rooi Rand dikes; (3) the Lebombo rhyolite; and (4) the Lebombo and Save-Limpopo dike swarms. This contribution investigates in detail the transition from basaltic to silicic magmatism and from the Karoo magmatism to the first inception of oceanization. This paper is also an attempt to provide a possible scenario for the emplacement of the Karoo large igneous province (LIP) in relation to the disruption of Gondwana. Finally, we investigate the timing and the relationship between rifting, flood basalt eruption

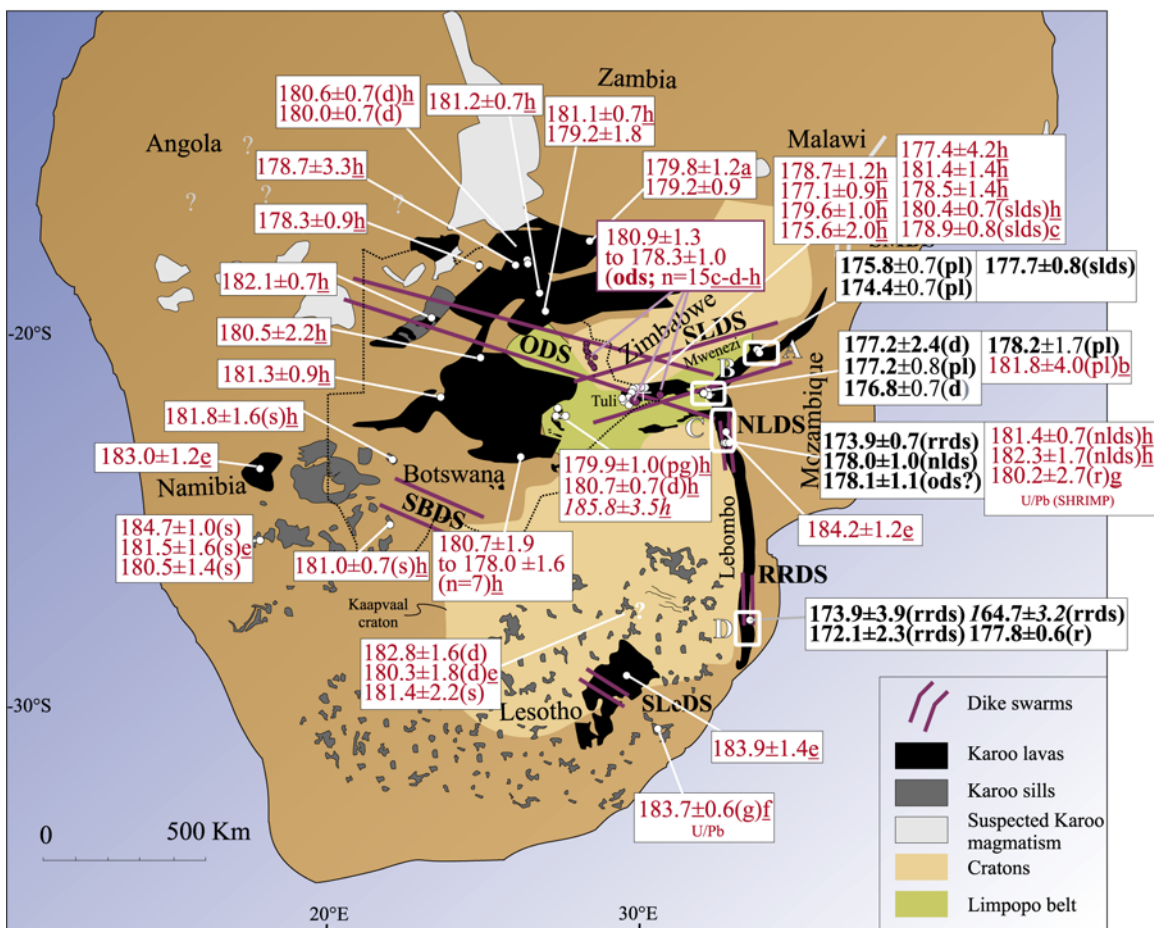


Figure 1. Sketch map of the remnants of African Karoo flood basalts, sills, and related dike swarms (modified after Jourdan *et al.* [2004, 2005a]). ODS, Okavango dike swarm; SLDS, Save Limpopo dike swarm; LDS, Lebombo dike swarm; RRDS, Rooi Rand dike swarm; SLeDS, south Lesotho dike swarm; SBDS, south Botswana dike swarm. Previous (on minerals separates only) and new $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages and U/Pb ages are indicated ($\pm 2\sigma$). Ages alone represent lava flows; otherwise, quotations in brackets beside the ages are ODS, SLDS, and LDS (corresponding dike swarm), d (dike with not well-constrained direction), s (sill), pl (pluton), r (rhyolite), g (granophyre), and pg (plug). When too numerous data are reported from the same locality, only bracketing ages are mentioned for clarity, with n being the number of plateau ages. Previous ages are reported in red with underlined letter as follows: a [Jones *et al.*, 2001], b [Landoll *et al.*, 1989], c [Le Gall *et al.*, 2002], d [Jourdan *et al.*, 2004], e [Duncan *et al.*, 1997], f [Encarnacion *et al.*, 1996], g [Riley *et al.*, 2004], and h [Jourdan *et al.*, 2005a]. The rectangles represent A, B, C, and D areas (not at scale for clarity) represented in Figure 2.

and onset of oceanization of various CFBs related to Gondwana breakup.

2. Geological Background and Previous Age Data

[5] This study concerns the easternmost part of the Karoo province including both early- and late-stage magmatism [Watkeys, 2002]. The eastern magmatism mainly occurred as a ~ 1100 km long structure which can be subdivided into the N70° oriented Save-Limpopo and the N–S Lebombo “branches” (Figure 1).

[6] The Lebombo is an eastward dipping, N–S oriented and 700 km long “monocline” sequence and rests (1) at the eastern edge of the Achaean Kaapvaal craton and (2) on the Proterozoic Limpopo and the Proterozoic Namaqua-Natal belts on its northern and southern extremities, respectively [Watkeys and Sokoutis, 1998; Watkeys, 2002] (Figure 1). The Save-Limpopo “monocline” occurs from Mwenezi trough and follows the NE–SW-striking edge of the Zimbabwe Craton over ~ 400 km. It partially covers the gneisses of the Limpopo-belt [Cox, 1988].

[7] Both sequences include a succession of Permian–Jurassic sedimentary rocks filling sedimentary basins overlain by the thick (possibly up to 10 km [Eales *et al.*, 1984; Watkeys, 2002]) Karoo volcanic sequence. The latter includes from the base to the top: the Mashikiri nephelinitic and the Letaba picritic formations (restricted to the northern Lebombo and Save monocline), the Sabie River basaltic and the Jozini rhyolitic lava flows (cropping out along the entire monocline structure) and the Mbuluzi rhyolite formation (restricted to the southern Lebombo) [e.g., Eales *et al.*, 1984; Cox, 1988]. The Lebombo/Sabie-River basalts were previously dated on plagioclase separates (whole rock/groundmass data are more difficult to interpret because of alteration and potential recoil effects and will not be considered in this study) by $^{40}\text{Ar}/^{39}\text{Ar}$ at 184.2 ± 1.2 Ma [Duncan *et al.*, 1997] (all uncertainties in this paper are given at the 2σ level), but the slight saddle shaped age spectrum may indicate some slight amount of excess argon. The Lebombo rhyolites interbedded with the top of the basaltic sequence provided one regression zircon U/Pb (SHRIMP) age of 180.2 ± 2.7 Ma [Riley *et al.*, 2004] (other given $^{206}\text{Pb}/^{238}\text{U}$ mean ages are derived from more discordant and scattered data that are more difficult to interpret). Other ages have been obtained on the Lebombo rhyolites but they are based on whole rocks analysis [e.g., Duncan *et al.*, 1997] and as explained above, will not be included in our discussion. The Lebombo sequence is intruded by numerous (~ 630 as given by Chavez Gomez [2001]), mainly N–S oriented dikes. These dikes comprise the Lebombo dikes (s.s.) with a composition similar to the main high-Ti basaltic sequence and the Rooi Rand dikes that are supposed to be restricted to the southern Lebombo. The latter shows an E-MORB affinity [Armstrong *et al.*, 1984; Duncan *et al.*, 1990]. Two Lebombo dikes were previously dated by Jourdan *et al.* [2005a], with $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 182.3 ± 1.7 and 181.4 ± 0.7 Ma, partly concordant with the previously mentioned 184.2 Ma plateau age obtained by Duncan *et al.* [1997].

[8] The Save-Limpopo “monocline” is characterized by numerous late-stage gabbroic to granitic plutons, sills and ring-dike complexes of several tens kilometers wide [Eales *et al.*, 1984]. $^{40}\text{Ar}/^{39}\text{Ar}$ dating was previously performed exclusively on the Marangudzi (gabbro to quartz and nepheline syenite) complex [Landoll *et al.*, 1989] and yielded a relatively imprecise mean age. This age has been recalculated relatively to FCs monitor (28.02 Ma [Renne *et al.*, 1998]) at 181.8 ± 4.0 Ma but we note

that it represents the average calculated from the ages obtained from various parts of the complex. These ages were obtained using an internal “Marangudzi” standard (A-2) which reproducibility is unknown and that has been calibrated with the heterogeneous MMhb-1 standard [e.g., Villa *et al.*, 1996; Renne *et al.*, 1998]. Though this “internal” procedure is fine to estimate the emplacement duration of the Marangudzi complex [Landoll *et al.*, 1989], it strongly neglects the heterogeneity of the A-2 standard and the propagation of the associated errors in the final age. Because of the large quantitative and qualitative uncertainties associated with this age, we will not refer to it during this study. Finally, the 600 km-long N70°/N65° oriented Save-Limpopo dike swarm, intruding both the Save-Limpopo volcanic sequence and the basement [Chavez Gomez, 2001], yielded two plateau ages of 178.9 ± 0.8 and 180.4 ± 0.7 Ma [Le Gall *et al.*, 2002; Jourdan *et al.*, 2005a].

3. Sample Descriptions

[9] We mainly focused on intrusives cross-cutting the Lebombo group of the Karoo supergroup (i.e., Lebombo and Save-Limpopo “monoclines”) which may represent the later stage of the Karoo magmatism (Figure 2). In the northern Lebombo, we analyzed one N–S (SA27) and one N125° (SA30) dikes intruding the Sabie River basalts between the Letaba and Olifants Rivers ($\sim 24^\circ\text{S}$; Figure 2c). These dikes show petrographic features similar to Okavango and Save-Limpopo doleritic dikes with variable amounts of plagioclase, augite and Fe-Ti oxides (see description by Le Gall *et al.* [2002] and Jourdan *et al.* [2004]). Three N–S oriented Rooi Rand dikes (SA5, 7 and 8) intruding the Karoo sedimentary sequence were collected in the southern Lebombo, on the bank of the Pongola River ($\sim 27^\circ 20'\text{S}$; Figure 2d, Table 1). Field relationships show that the SA7 dike crosscuts both the SA5 and SA8 dikes. One N–S oriented dike (SA41) sampled close to the northern extremity of the Lebombo was also investigated (Figure 2c). Although its location is far to the north compared to the (classically recognized) southern main Rooi Rand dikes, its incompatible trace and rare earth element chemical signature strongly suggests a cognate origin with the main swarm (Figure 3). SA41 and Rooi Rand dikes are distinct from other high-Ti Karoo rocks, including the N–S Lebombo dikes (Figure 3, Table 2). Regardless of their relatively chemically depleted characteristics [Duncan *et al.*, 1990], all these mafic dikes are

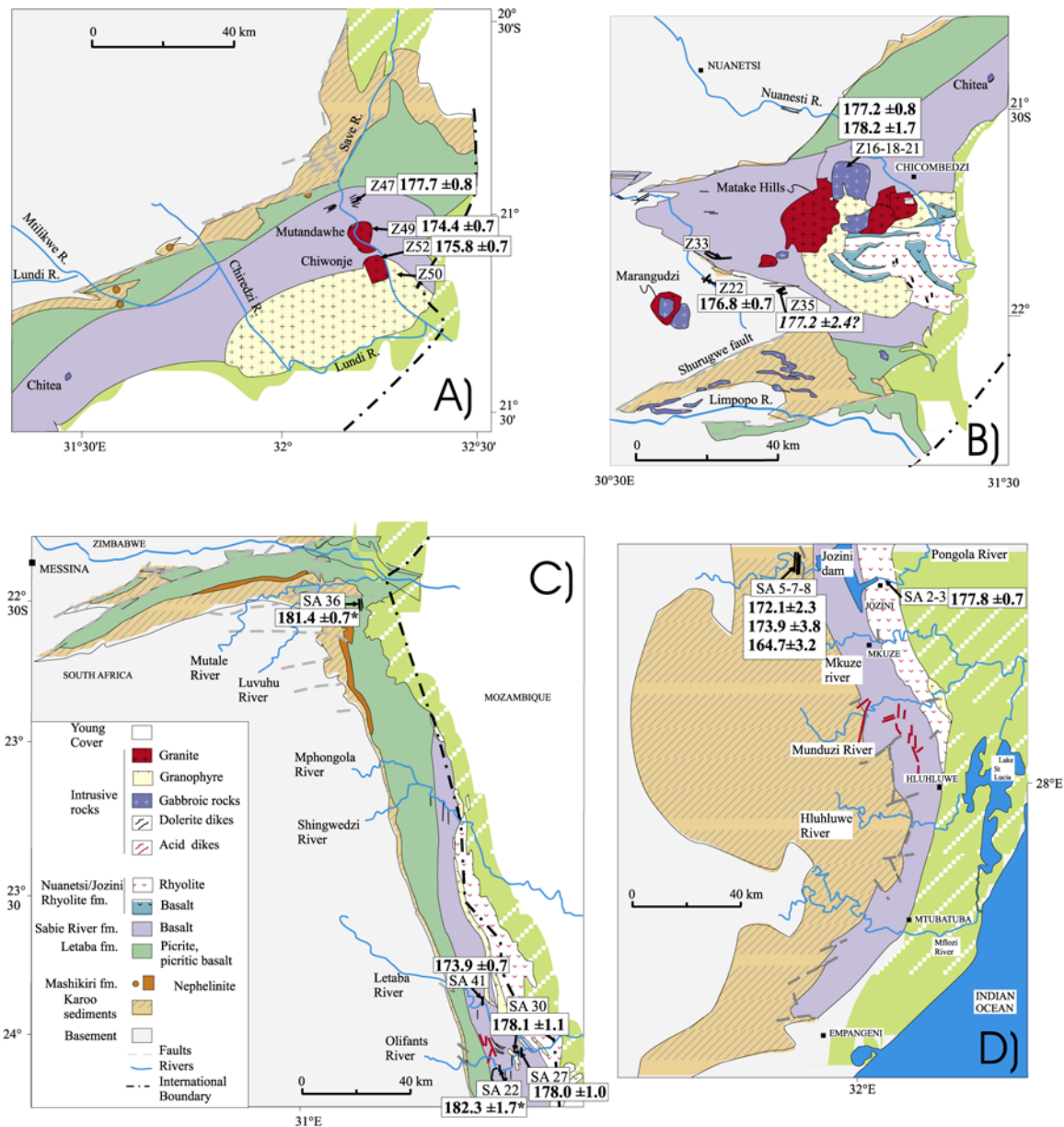


Figure 2. Detailed location and geological maps of the Save-Limpopo and Lebombo monocline modified after *Eales et al.* [1984]. Location of the samples and their plateau and mini-plateau ages are indicated (2σ errors). (a) Mutandawhe region. (b) Mwenezi region. (c) Northern Lebombo. Asterisks indicate two ages from *Jourdan et al.* [2005a]. (d) Southernmost Lebombo. (A, B, C, D areas are located in Figure 1.)

petrographically indistinguishable from other Karoo doleritic dikes. One rhyolite (SA2) from the Jozini formation was collected close to the Jozini dam (Figure 2d). It mainly includes plagioclase, K-feldspar with some minor pyroxene in a glassy-oxidized groundmass. In the same area, we also sampled a basaltic flow (SA3) intruded by aphyric Rooi Rand dikes with a mineralogical composition indistinguishable from doleritic dikes.

[10] In the Mwenezi area (Figure 2b), we analyzed the following samples. (1) Three rocks (Z16, Z18, and Z21) from the gabbroic Northern Ring Complex, close to the Mataka hills granite. These rocks have the same modal composition as the doleritic dikes. (2) One NE–SW striking doleritic dike (Z22) from the Buby River Turf intrusive complex (Figure 2b) consisting of plagioclase and biotite phenocrysts included in a biotite, plagioclase and pyroxene groundmass. (3) One N100–110°-oriented doleritic/picritic dike (Z33) made of

Table 1. Geographic Position, Trend, and $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of 4 Lebombo, 4 Rooi Rand, 10 Mwenezi, and 1 Rhyolite Karoo Magmatic Rocks^a

Sample	GPS Coordinates	Type	Direction, °	Method	Plateau/ Mini-Plateau Age ^b (Ma, $\pm 2\sigma$)	Total ^{39}Ar Released, %	Isochron Age (Ma, $\pm 2\sigma$)	Steps (°C)/ Steps n ^o	$^{40}\text{Ar}/^{36}\text{Ar}$ Intercept ($\pm 1\sigma$)	MSWD (Isochron)	Integrated Age (Ma, $\pm 2\sigma$)
SA27	24°00'296S 31°45'105E	Dike (dolerite)	N170	Laser (I)	Lebombo 178.0 \pm 1.0	95.4	177.3 \pm 1.2	3–12	320.8 \pm 12.3	0.7	178.4 \pm 1.0
SA30	24°00'296S 31°45'105E	Dike (dolerite)	N125	Laser (I)	178.1 \pm 1.1	90.2	175.9 \pm 1.7	5–13	405.8 \pm 1.7	0.6	178.3 \pm 1.0
SA2	27°27'795S 32°01'178E	Flow (rhyolite)	-	Laser (I)	177.8 \pm 0.7	89.9	178.7 \pm 1.1	6–22	215.6 \pm 37.5	0.5	178.3 \pm 0.6
SA3	27°25'877S 32°51'881E	Flow (basalt)	-	Laser (I)	-	-	111.3 \pm 22	-	739 \pm 93.3	7.0	150.5 \pm 3.9
SA5	~27°20'S ~31°50'E	Dike (dolerite)	N20	Laser (I)	Rooi Rand 173.9 \pm 3.8^b	53.6	155.0 \pm 14	4–7	391.3 \pm 36.1	0.2	200.2 \pm 2.8
SA7	~27°20'S ~31°50'E	Dike (dolerite)	N20	Laser (I)	172.1 \pm 2.3^b	57.9	172.6 \pm 2.8	4–11	277.7 \pm 27.3	0.9	175.9 \pm 1.7
SA8	~27°20'S ~31°50'E	Dike (dolerite)	N20	Laser (I)	164.7 \pm 3.2^b	60.2	164.8 \pm 5.7	2–6	293.9 \pm 26.4	0.4	170.1 \pm 2.4
SA41	23°50'379S 31°38'238E	Dike (dolerite)	N20	Furnace	173.9 \pm 0.7	90.3	173.2 \pm 1.3	850–1500	315.5 \pm 13.0	0.8	175.0 \pm 0.6
Z16	21°40'913S 31°09'787E	Pluton (gabbro)	-	Furnace	Mwenezi -	-	178.1 \pm 4.4	-	289.1 \pm 5.1	38.9	177.8 \pm 0.8
Z18	21°41'272S 31°09'243E	Pluton (gabbro)	-	Laser (I)	177.2 \pm 0.8	92.2	176.3 \pm 2.4	4–13	318.1 \pm 29.6	0.6	176.8 \pm 1.0
Z21	21°40'953S 31°09'875E	Pluton (gabbro)	-	Laser (I)	178.2 \pm 1.7	78.6	178.4 \pm 3.7	5–10	293.7 \pm 16.0	0.8	177.1 \pm 1.8
Z22	21°56'948S 30°45'622E	Dike in intrusive complex (gabbro + biotite)	-	Laser	176.8 \pm 0.7	94.1	176.3 \pm 0.7	4–12	369.7 \pm 33.7	0.2	176.4 \pm 0.3
Z33	21°53'450S 30°46'667E	Dike (picrite)	N110–100	Laser (I)	-	-	150.0 \pm 9.5	-	721.8 \pm 110.3	37.0	167.3 \pm 0.6
Z35	21°58'718S 30°57'793E	Dike (dolerite)	?	Laser (I)	177.2 \pm 2.4	36.5	165.8 \pm 21	3–6	477.3 \pm 96.0	22.0	198.2 \pm 7.9
Z47	20°57'783S 32°09'683E	Dike (dolerite)	N70	Furnace	177.7 \pm 0.8^b	61.1	177.4 \pm 0.7	875–1200	302.9 \pm 0.6	2.6	188.9 \pm 2.3

Table 1. (continued)

Sample	GPS Coordinates	Type	Direction, °	Method	Plateau/ Mini-Plateau Age ^b (Ma, ±2 σ)	Total ³⁹ Ar Released, %	Isochron Age (Ma, ±2 σ)	Steps (°C)/ Steps n°	⁴⁰ Ar/ ³⁶ Ar Intercept (±1 σ)	MSWD (Isochron)	Integrated Age (Ma, ±2 σ)
Z49	~27°00'S ~32°15'E	Pluton (syenite; amphibole Pluton	-	Laser	174.4 ± 0.7	99.4	172.6 ± 1.4	3–8	311.2 ± 52.4	0.7	174.6 ± 0.6
Z50	21°08'733S 32°18'387E	(granophyre) Pluton (granite; biotite)	-	Laser (I)	-	-	176.0 ± 2.2	-	356.9 ± 25.3	13.8	178.1 ± 0.4
Z52	21°06'997S 32°18'387E	Pluton (granite; biotite)	-	Laser	175.8 ± 0.7	88.9	173.2 ± 1.0	3–9	514.9 ± 64.7	1.4	176.2 ± 0.3

^a Geographic position: GPS spheroid, WGS-84. Inverse isochron (³⁶Ar/⁴⁰Ar versus ³⁹Ar/⁴⁰Ar) ages, initial ⁴⁰Ar/³⁶Ar ratios, and mean square weighted deviation (MSWD) are indicated. Analytical uncertainties on the ages are quoted at 2 sigma (2σ) confidence level. Both laser and furnace dating were undergone. Laser (I) corresponds to laser beam focused by an integrator lens to increase the temperature homogeneity (see text). For dikes, the orientation is given except for Z35 for which field conditions do not allow orientation measurement. Number or temperatures of steps used for calculating age are quoted.
^b Correspond to mini-plateau ages.

olivine, plagioclase microlite, clino- and orthopyroxene and (4) one ~E-W coarse-grained doleritic dike (Z35) with no visible orientation intruding the Limpopo basement. It is not clear whether this dike is related to intrusive bodies or belongs to the Save Limpopo dike swarm.

[11] Farther to the northeast and within the Save-Limpopo “monocline” (Figure 2a), we collected one syenitic rock (Z49) from the Mutandawhe pluton which intrudes the Sabie River basalt formation. This sample contains K-feldspar and

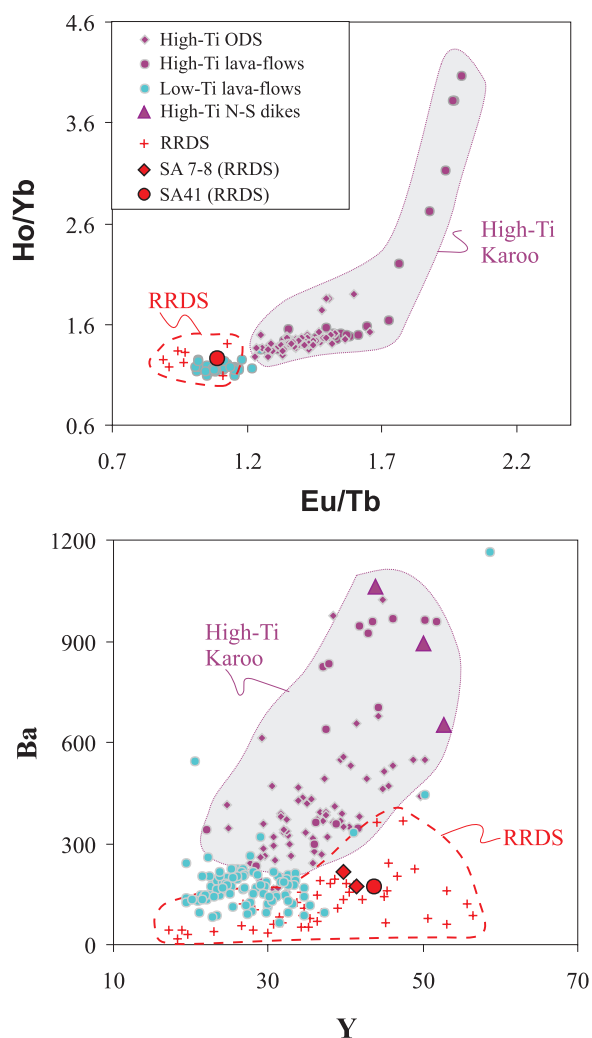


Figure 3. Ba versus Y plot for three N–S dikes from the Lebombo dike swarm, two dikes from the Rooi Rand dike swarm, and SA41 and Ho/Yb versus Eu/Tb plot for SA41 altogether analyzed in this study (concentrations in ppm). Data for Okavango dikes and high- and low-Ti lava flows from Botswana are from Jourdan *et al.* [2005b]. Data for the Rooi Rand dikes are from M. K. Watkeys (unpublished data, 2006). Gray field, high-Ti rocks; red dashed contoured field, RRDS.

Table 2. Major and Trace Element Analyses for 1 Rhyolite and 7 Dikes From the Lebombo and 6 Mwenezi Intrusives^a

Sample	SA2	SA41	SA7	SA8	SA22	SA27	SA30	SA36	Z18	Z21	Z35	Z22	Z49	Z52
Type	Jozini rhyolite	RRDS? ²	RRDS	RRDS	LDS	LDS	LDS	LDS	Pluton (gabbro)	Pluton (gabbro)	Dike	Dike	Pluton (syenite)	Pluton (granite)
Orientation	-	N20°	N20°	N20°	N20°	N170°	N125°	N160°	-	-	N90°	N40°	-	-
Major, wt%														
SiO ₂	70.89	49.51	50.04	49.06	49.87	48.22	49.49	52.85	49.31	49.25	50.17	55.35	62.35	76.74
Al ₂ O ₃	12.25	13.44	13.52	12.87	12.75	12.46	10.38	13.62	14.20	14.35	13.80	18.12	18.85	11.83
Fe ₂ O ₃	5.46	14.65	14.84	16.27	13.76	15.17	17.41	11.64	11.46	8.17	13.29	6.62	2.86	1.40
MgO	0.13	4.71	6.03	5.65	3.29	4.21	4.4	3.60	8.62	10.72	5.77	1.62	0.30	0.05
CaO	0.97	10.13	10.52	10.14	8.20	8.14	7.88	6.58	12.81	14.79	9.57	4.85	1.97	0.61
Na ₂ O	3.32	2.31	2.30	2.38	2.14	2.92	2.08	2.73	1.81	1.32	2.50	4.28	5.37	3.35
K ₂ O	4.93	0.82	0.46	0.53	2.31	1.56	1.64	2.84	0.17	0.08	0.90	4.70	6.82	5.02
TiO ₂	0.40	2.85	2.06	2.70	3.86	3.93	4.26	3.65	0.66	0.19	2.88	1.00	0.36	0.08
P ₂ O ₅	0.09	0.38	0.24	0.29	0.65	0.96	0.69	0.72	0.02	0.01	0.37	0.39	0.07	0.01
MnO	0.05	0.21	0.22	0.23	0.17	0.22	0.24	0.11	0.20	0.17	0.18	0.08	0.08	0.03
LOI	0.60	0.31	0.11	-0.19	2.57	0.81	0.24	0.56	-0.04	0.12	0.86	2.96	0.09	0.47
H ₂ O-	0.36	0.41	0.23	0.16	0.41	0.51	0.42	0.75	0.07	0.07	0.12	0.16	0.07	0.17
Total	99.45	99.73	100.57	100.09	99.98	99.11	99.13	99.65	99.29	99.24	100.41	100.13	99.19	99.76
Trace, ppm														
Sc	9	36	39	39	24	21	35	19	41	42	33	9	1	1
V	6	443	347	443	347	299	417	231	235	131	395	58	9	1
Cr	20	197	170	197	103	14	56	40	84	61	186	7	2	9
Co	5	46	44	46	38	33	44	33	49	50	40	6	1	0
Ni	9	61	63	61	58	8	42	52	74	88	101	7	4	2
Rb	130	19	11	18	44	34	36	59	2	2	19	288	130	270
Sr	125	481	193	203	879	796	238	1006	251	157	462	543	567	24
Ba	1423	174	217	174	651	894	546	1060	128	35	369	1288	1655	66
Zr	971	230	151	175	458	343	501	525	24	13	223	277	101	150
Nb	74	13	8	9	23	32	31	28	1	1	20	120	45	87
Y	163	44	40	41	53	50	73	44	15	7	34	33	11	66

^aMajor elements are in wt%; trace elements are in ppm. Mwenezi intrusives are plutons and dikes. Sample coordinates are listed in Table 1 and with SA22 (24°03'752S; 31°40'953E) and SA36 (22°29'902S; 31°12'162E).

amphibole with minor amount of quartz and plagioclase. The Chiwonje granitic ring complex (Z52; quartz, K-feldspar and biotite), intruding the “main granophyre” sill (Z50; quartz, plagioclase, amphibole with chlorite alteration and basalt xenoliths) was also sampled. In the same area, we collected one N80° oriented doleritic dike (Z47) from the Save-Limpopo dike swarm that intrudes the Sabie River basalts.

4. Analytical Methods

[12] We investigated nineteen fresh mineral-separated samples for ⁴⁰Ar/³⁹Ar dating. Plagioclase grains were dated using 20–30 mg or 1–2 mg of fresh transparent grains (fraction 150–300 μm) using a high frequency furnace or a laser heating device, respectively. Samples Z22 and Z52 were measured on a single biotite grain (~800 μm), and sample Z49 on a single amphibole grain (~400 μm). These minerals were separated using a Frantz magnetic separator, and then carefully picked under

a binocular microscope. The selected minerals were subsequently leached for 10 mn using hot diluted nitric acid. The samples were irradiated for 70 hours in the Hamilton McMaster University nuclear reactor (Canada) in position 5C along with the Hb3gr hornblende neutron fluence monitor for which an age of 1072 ± 11 Ma was adopted [Turner *et al.*, 1971; Renne *et al.*, 1998; Jourdan *et al.*, 2006b] and a good in-between-grains reproducibility has been demonstrated [Jourdan *et al.*, 2006b]. The total neutron flux density during irradiation was 8.8 × 10¹⁸ neutron/cm². The biotite and amphibole single grains were step heated using a CO₂ Synrad 48–5 laser beam. A beam-integrator lens was used for laser heating of the 1–2 mg bulk plagioclase samples. Isotopic measurements were performed with a VG3600 mass spectrometer with a Daly-photomultiplier system. The twenty to thirty milligrams plagioclase samples were heated in a double vacuum high frequency furnace allowing a better temperature homogenization within the mineral population compared to the laser-integrator system.

The mass spectrometer is composed of a 120°–12 cm M.A.S.S.E. tube, a Baur GS 98 -Signer source and a Balzers SEV 217 electron multiplier. The criteria to define a plateau age are (1) at least 70% of the ^{39}Ar released; (2) a minimum of three successive steps in the plateau; and (3) the integrated age of the plateau should agree with each apparent age-increment of the plateau within a two sigma confidence level (2σ). Plateau and integrated ages are given at the 2σ level (Table 1). Mini-plateaus are defined by the same criteria as for plateaus but include between 50% and 70% of the ^{39}Ar released. The decay constants are those recommended by Steiger and Jager [1977]. The correction factors for interfering isotopes were $(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 7.30 \times 10^{-4}$ ($\pm 3\%$), $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}} = 2.82 \times 10^{-4}$ ($\pm 1\%$) and $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}} = 2.97 \times 10^{-2}$ ($\pm 3\%$). The uncertainties on the $^{40}\text{Ar}^*/^{39}\text{Ar}$ ratios of the monitors are included in the calculation of the integrated and plateau age uncertainties, but not the errors of the age of the monitor and of the decay constant (internal errors only; see discussion by Min *et al.* [2000] and hereafter). The J and discrimination values range from 0.016093 ± 0.000048 to 0.017050 ± 0.000051 and 1.00492 ± 0.00002 to 1.00912 ± 0.00005 , respectively (Auxiliary Material¹ Table S1). Fourteen samples were crushed and powdered in an agate mill and analyzed for major and trace elements on a Philips PW 1404 XRF spectrometer at the University of Lyon. Analytical uncertainties vary from 1 to 2% and from 10 to 15% for major and trace element, respectively (depending on the concentration).

5. Results

[13] We got ten plateau and four mini-plateau ages (Figure 4 and Tables 1 and S1). In the northern Lebombo (Figure 2c), the N–S (SA27) and N125° (SA30) oriented dikes yielded well defined plagioclase plateau ages of 178.0 ± 1.0 and 178.1 ± 1.1 Ma similar to the age of the Okavango dike swarm ($\sim 179 \pm 1$ Ma [Le Gall *et al.*, 2002; Jourdan *et al.*, 2004, 2005a]).

[14] In southern Lebombo (Figure 2d), the Jozini rhyolite (SA2) displays one plateau age of 177.8 ± 0.7 Ma, while the Sabie River basalt (SA 3) failed to provide a plateau age on plagioclase probably because of some alteration by sericite (as suggested by the severely perturbed $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ spectrum; Figure 4). Plagioclase from the three southern Lebombo Rooi Rand dikes (SA5, 7, 8) display

more or less disturbed age spectra relatively difficult to interpret. The two samples SA5 and SA8 are probably affected by excess ^{40}Ar (saddle shaped age spectra), and we observe three mini-plateau ages of 173.9 ± 3.8 , 172.1 ± 2.3 , and 164.7 ± 3.2 Ma, significantly younger than all other dated Karoo mafic dikes. The plateau fraction of SA5 may be affected by some alteration as shown by the $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ ratio. For SA7 (younger than the two others, from field relationships), the emplacement age may be given by the four high temperature steps (179.4 ± 1.6 Ma), or more probably by the intermediate temperature mini-plateau age of 172.1 ± 2.3 Ma, which corresponds to high $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ ratios. We shall see that the sample SA41 may help us to interpret this discrepancy. Plagioclase from the N–S dike (SA41) considered being (or similar as) a Rooi Rand dike despite its northern position (see above) yielded a plateau age of 173.9 ± 0.7 Ma. This particularly young age cannot be attributed to subsequent alteration in view of both the high quality of the plateau age and the almost flat $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ spectrum, and is thus geologically significant. This reliable age is concordant with the SA5 and SA7 mini-plateau ages (173.9 ± 3.8 and 172.1 ± 2.3 Ma, respectively). Nevertheless, the younger mini-plateau age of SA8 (164.7 ± 3.2 Ma) is not easily understandable as field relationships show that it is crosscut by the SA7 dike. Although this is not evidenced by the $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ spectrum, this age may be affected by alteration (or partial $^{40}\text{Ar}^*$ loss).

[15] Plagioclases from the three gabbros from the Northern Ring complex (Figure 2b) provide two reliable and concordant plateau ages of 177.2 ± 0.8 (Z18) and 178.2 ± 1.7 (Z21) Ma, corresponding to flat $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ ratio spectra (Figure 4). Z16 plagioclase sample shows continuously increasing apparent ages, with the highest temperature age at 183.5 Ma, not concordant with Z16 and Z18 samples. The biotite single grain from the doleritic dike (Z22) from the same region shows a plateau age of 176.8 ± 0.7 Ma. Plagioclase from the nearby picritic dike (Z33) failed to provide an age probably because of a high alteration and maybe excess ^{40}Ar . Plagioclase of Z35 sample displays a saddle shaped age spectrum probably due to excess ^{40}Ar . The age of 177.2 ± 2.4 Ma calculated on the four younger steps (36.5% of ^{39}Ar released), cannot be considered as a robust age and will not be used in our discussion but we note that it corresponds to high $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ ratios, and therefore it may represent a good approximation of the emplacement age.

¹Auxiliary materials are available in the HTML. doi:10.1029/2006GC001392.

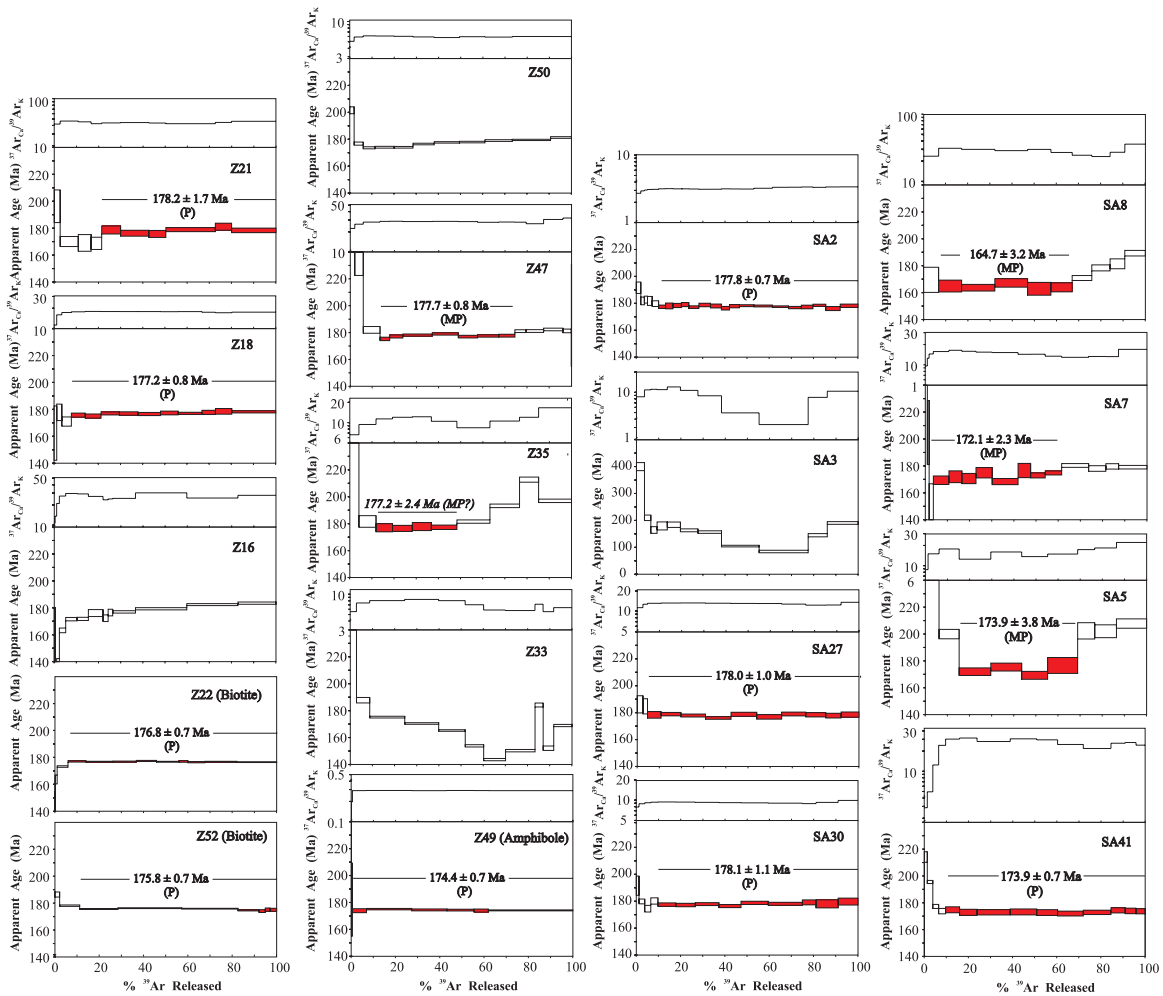


Figure 4. $^{40}\text{Ar}/^{39}\text{Ar}$ age and related $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ ratio spectra of the plagioclase separates versus the cumulative percentage of ^{39}Ar released. Errors on plateau (P; $>70\%$ ^{39}Ar released) ages are quoted as 2σ and do not include systematic errors (i.e., uncertainties on the age of the monitor and on the decay constant).

[16] In the Mutandawhe region (Figure 2a), amphibole single grain from the syenitic (Z49) and biotite single grain from the granitic (Z52) plutons yielded well defined concordant plateau-ages of 174.4 ± 0.7 and 175.8 ± 0.7 Ma, respectively. Plagioclase from Z50 sample from the “Main granophyre” shows a saddle shaped age spectrum, and did not provide a plateau-age. Finally plagioclase from the N80° dike (Z47) yielded a slight saddle shaped age spectrum characterized by one mini-plateau (61.1% ^{39}Ar released) age of 177.7 ± 0.8 Ma at intermediate temperature (in agreement with the two previous ages of 178.9 ± 0.8 and 180.4 ± 0.7 Ma obtained on the Save-Limpopo dike swarm; Table S2) [Le Gall et al., 2002; Jourdan et al., 2005a]. Because of the flatness of the $^{37}\text{Ar}_{\text{Ca}}/^{39}\text{Ar}_{\text{K}}$ spectrum, this mini-plateau fraction is probably not affected by alteration.

[17] Data corresponding to the plateau steps were systematically plotted in an inverse correlation diagram (i.e., $^{39}\text{Ar}/^{40}\text{Ar}$ versus $^{36}\text{Ar}/^{40}\text{Ar}$, not shown) and yielded isochron ages mostly concordant with the plateau ages presented above (Table 1). However, we chose to use the plateau age as the inverse isochron diagrams show poorly defined $^{40}\text{Ar}/^{36}\text{Ar}$ initial ratios and low mean squared weighted deviates (MSWD), both because of the strong clustering of the data near the $^{39}\text{Ar}/^{40}\text{Ar}$ axis (Table 1).

6. Discussion

6.1. Dating of the Easternmost Karoo Magmatism

[18] We obtained new reliable age data on four groups of the Karoo province: (1) the Jozini

rhyolitic formation which caps the main basic lava flows sequence of the Lebombo monocline, (2) the intrusive gabbroic to granitic ring complexes which intrude the basic volcanic rocks of the Mwenezi basin, (3) dikes from the Lebombo monocline (mostly NS oriented) and from the Save Limpopo (mostly NE–SW oriented) which intrude the Lebombo basalts, and (4) the MORB-akin Rooi Rand dikes which intrude the Lebombo sedimentary and basaltic sequences.

6.1.1. Age of the Mwenezi Intrusives

[19] The investigated Mwenezi intrusive complexes include (1) plutons (Z16, Z18, Z21, Z49, Z52) accompanied by a radiating “coronae” of dikes, (2) dikes possibly related to plutonic activity (Z22, Z35), and (3) a large sill of granophyre (the so-called “Main Granophyre”, Z50) (Figures 2a and 2b). The ages obtained for these samples (ranging from 178.2 ± 1.7 to 174.4 ± 0.7 Ma), represent so far the youngest dates of the whole Karoo province, Rooi Rand dikes excepted (Figure 5 and Table S2). The Z18 (177.2 ± 0.8 Ma) and Z21 (178.2 ± 1.7 Ma) samples from the gabbroic Northern Ring Complex show indistinguishable ages possibly attesting to a brief emplacement of this complex. The biotite-dolerite dike (Z22) from the Buby River turf complex shows akin age of 176.8 ± 0.7 Ma. The syenitic (Z49; 174.4 ± 0.7 Ma) and granitic (Z52; 175.8 ± 0.7 Ma) differentiated plutons show both concordant younger ages, when compared to the basic intrusions. One doleritic dike (Z35), possibly related to an intrusive complex, has a chemical composition similar to the Mwenezi gabbros and dolerites. It yielded an ambiguous weighted mean age (36.5% ^{39}Ar released) of 177.2 ± 2.4 Ma that could be considered as valid as it is fully concordant with the other chemically similar intrusions mentioned above. The N70°/Save-Limpopo doleritic dike (Z47) gave a mini-plateau age of 177.7 ± 0.8 Ma which is indistinguishable from both (1) other Save-Limpopo dikes [Le Gall *et al.*, 2002; Jourdan *et al.*, 2005a] and (2) the gabbroic intrusions mentioned above. Altogether, the Mwenezi intrusives span from 178 to 174 Ma and therefore postdate the main peak of basaltic flooding of the Karoo province (184–178 Ma [Jourdan *et al.*, 2005a]).

6.1.2. Age Differences Between Silicic and Basic Magmatism

[20] Silicic magmatism occurs in two areas of the eastern Karoo province; in the Mwenezi area as

intrusive complexes and along the Lebombo monocline as rhyolitic lava flows, sills and dikes. We examine the time relationship between the basaltic and silicic magmatism in these two regions.

[21] 1. The Mwenezi intrusive complexes show unambiguous younger ages on differentiated rocks (174.4 ± 0.7 Ma and 175.8 ± 0.7 Ma on syenite and granite) than on gabbros (177.2 ± 0.8 Ma and 178.2 ± 1.7 Ma). This is consistent with field relationships observed on the Marangudzi complex where the silicic intrusives generally crosscut the initial gabbroic intrusion. However, in the case of the Marangudzi complex, the emplacement duration seems much shorter [Landoll *et al.*, 1989] compared to other intrusions.

[22] 2. In the Lebombo series, the rhyolitic lava from southern Lebombo has an age of 177.8 ± 0.7 Ma, sensibly younger than the plagioclase plateau age at 184.2 ± 1.2 Ma obtained by Duncan *et al.* [1997] on the underlying Sabie River basalts (located in northern Lebombo, Figure 1). This age difference (5–7 Ma) can be real, but as previously mentioned, the Lebombo basalt age may be affected by slight excess ^{40}Ar (saddle shaped age spectrum) that would increase the age difference. Nevertheless, N–S mafic dikes intruding the Lebombo basalts dated at 182.3 ± 1.7 and 181.4 ± 0.7 Ma (northern Lebombo [Jourdan *et al.*, 2005a]) confirm that the Lebombo basalts at this location are significantly older than the rhyolite lava flows from the south and possibly suggest that the Lebombo basalts (Sabie River formation) were emplaced in a short time span (2–3 Myr). Two doleritic dikes (SA27, SA30) dated at 178.1 ± 1.1 and 178.0 ± 1.0 Ma (Figure 6) are apparently coeval with the rhyolitic activity but we cannot estimate if they represent an important local basaltic episode. Our age on the southern Lebombo Jozini rhyolite is slightly younger, although in agreement within uncertainties, with the SHRIMP U/Pb isochron age of 180.2 ± 2.7 Ma obtained on a northern Lebombo rhyolite interbedded with the upper sequence of the Sabie River basalts [Riley *et al.*, 2004]. Taking into account the possibly $\sim 1\%$ relative bias between the $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb techniques [e.g., Min *et al.*, 2000], the SHRIMP U/Pb age could be recalculated (for comparison purpose only) to 178.4 ± 2.7 Ma, and is thus indistinguishable from the age obtained in this study. Therefore, in both cases, the silicic magmatism postdates the end of the basaltic magmatic activity by 4–5 Myr (Figure 6).

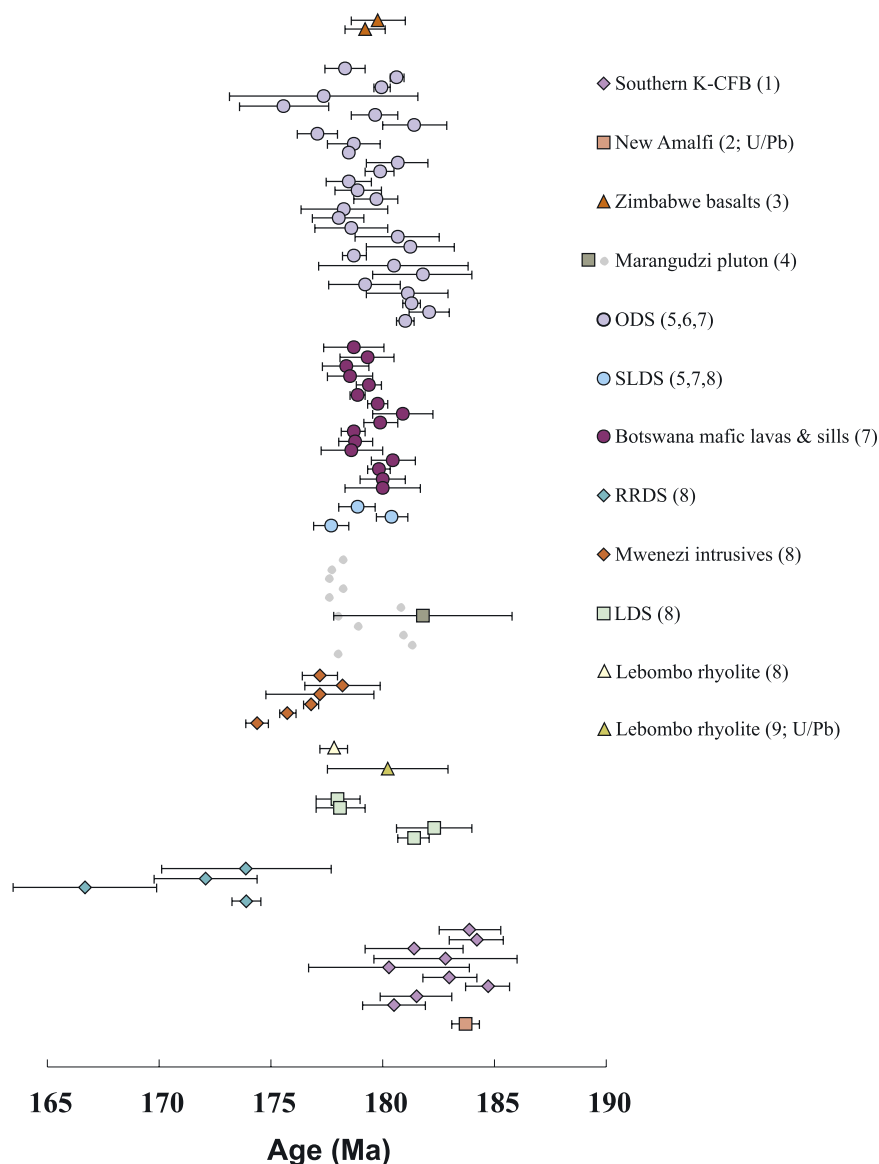


Figure 5. Compilation of 76 mineral separate plateau and mini-plateau $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb ages (errors 2σ) of the Karoo CFB. The data are approximately classified from north (top) to south (bottom), but the y axis does not represent the exact latitude for clarity. All $^{40}\text{Ar}/^{39}\text{Ar}$ ages are intercalibrated against the 28.02 Ma-aged Fish Canyon sanidine as recommended by *Renne et al.* [1998]. (1) *Duncan et al.* [1997]; (2) *Encarnacion et al.* [1996]; (3) *Jones et al.* [2001]; (4) *Landoll et al.* [1989]; (5) *Le Gall et al.* [2002]; (6) *Jourdan et al.* [2004]; (7) *Jourdan et al.* [2005a]; (8) present study; and (9) *Riley et al.* [2004]. The mean age for Marangunzi pluton is recalculated relative to FCs standard, but the single ages are provided as reported by *Landoll et al.* [1989].

6.1.3. Origin of the Late-Stage Magmatism

[23] *Betton et al.* [1984], *Cox* [1988], and *Harris and Erlank* [1992] proposed that the Jozini rhyolites, in regard to their mantle-like isotopic signature, resulted from the remelting of Karoo gabbros suspected to have been previously underplated at the base of the crust. These gabbros are supposed to be coeval with the main phase of basaltic magmatism. In this case, their remelting would

necessarily postdate the peak of the basaltic activity. This is in accordance with the younger $^{40}\text{Ar}/^{39}\text{Ar}$ age that we obtained on the silicic lava flows. The remelting event is interpreted as a response to the progressive crustal thinning in the Lebombo-Save area, prior to the continental break-up [*Cox*, 1988]. Similarly, the younger ages of the Mwenezi silicic plutons compared to the gabbroic plutons are in agreement with an origin in response to the ongoing crustal thinning, a few million years

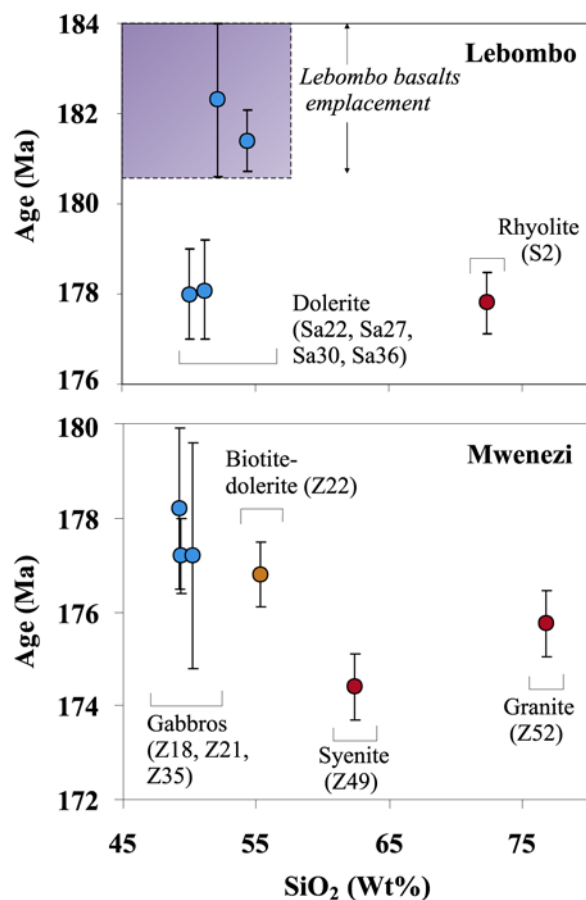


Figure 6. Age (Ma, error bars 2σ) versus SiO_2 (wt%) of plutons of the Mwenezi area and dikes and rhyolite of the Lebombo area. Plain blue circle, basic rocks; plain orange circle, moderately evolved rocks; plain red circle, evolved rocks. The shaded purple area represents the probable age of the Lebombo lava pile emplacement, with the younger age limit based on the ages of two dikes dated by *Jourdan et al.* [2005a]. Note the late silicic activity respective to most of the mafic activity in the two regions.

later than in the Lebombo region. Although in agreement with the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained in this study, these hypotheses need to be further tested by additional isotopic investigations.

[24] The relatively young Rooi Rand basaltic dikes have a very specific composition and differ from other Karoo basaltic rocks by their depletion in the most incompatible trace elements and their E-MORB affinities (e.g., positive ϵ_{Nd} and negative ϵ_{Sr} [Hawkesworth *et al.*, 1984; Duncan *et al.*, 1990]). The Rooi Rand dikes are therefore considered as representing the transition between the enriched tholeiitic within-plate basalts and the asthenosphere-derived MORBs marking the very first inception of the oceanization process. The robust age of SA41 (173.9 ± 0.7 Ma) and the

concordant mini-plateau ages (173.9 ± 3.8 and 172.1 ± 2.3 Ma) obtained on the southern SA5-7 dikes, assess that Rooi Rand dikes (including SA41 dike) occurred after (or possibly coevally with) the end of the Karoo magmatism. Therefore we speculate that the formation of the first oceanic crust could be contemporaneous or slightly post-date the end of the Karoo magmatism as early as circa 170 Ma (see discussion hereafter).

[25] While the whole region is supposed to have been in extension since at least 290 Ma as monitored by extensional basins filled by the Karoo sedimentary sequence (e.g., Main Karoo, Tuli and Lebombo basins [Bangert *et al.*, 1999; Catuneanu *et al.*, 2005]), the Lebombo-Mwenezi area would nicely illustrate the latest axis of continental extension (and related magmatism) just prior to the onset of oceanization.

6.1.4. Episodic Diking Along the Lebombo?

[26] In contrast to the Okavango dike swarm that was emplaced in a very short time (probably on the order of 1 Ma), the ages obtained on the eight dikes intruding the Lebombo cover most of the Karoo province history, ranging from 182 to 172 Ma. Three distinct periods (182–181 Ma, 179–178 Ma and 174–172 Ma) could exist, although the small data set is probably insufficient to determine whether dike intrusions were episodic or continuous. The activity of the Lebombo may have begun before 182–181 Ma, more or less contemporaneously with basaltic lava flows and sills in different regions of the province (Botswana, Namibia and southern South Africa [Duncan *et al.*, 1997; Jourdan *et al.*, 2005a]). The Lebombo was still active during the emergence of both the Okavango (N110°) and Save-Limpopo (N70°) dike swarms, at around 179 Ma and apparently ended with the Rooi Rand dikes emplacement (174–172 Ma), discussed above.

6.2. On the duration of the Karoo Magmatism Event

[27] CFBs are mostly considered as brief events with their main magma volumes possibly emplaced in a time frame shorter than 1 Ma [Courtillot and Renne, 2003]. On the basis of a relative low number of age data mostly localized in the southern and western part of the province, Duncan *et al.* [1997] also speculated that the Karoo CFB could have been emplaced in such a short time span, at around 183–184 Ma. More recently, Jones *et al.*

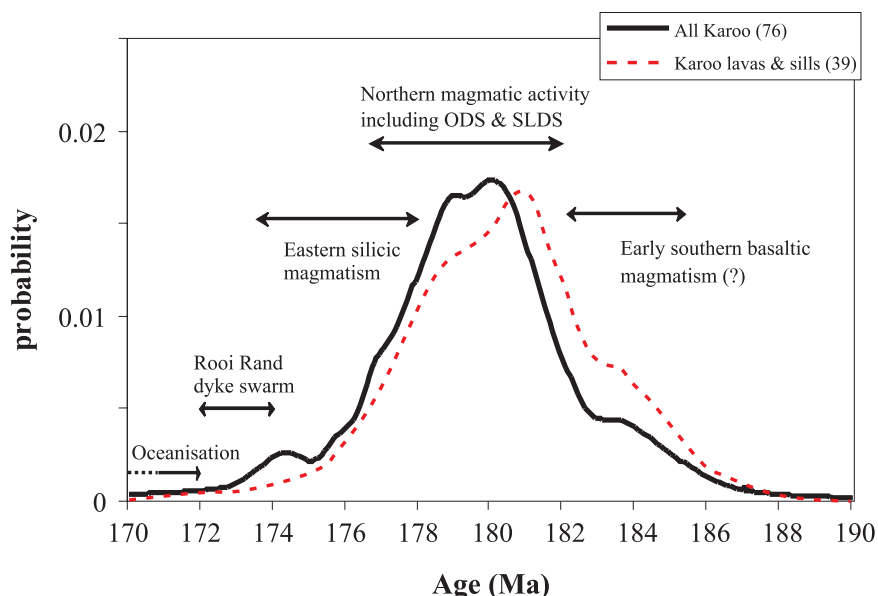
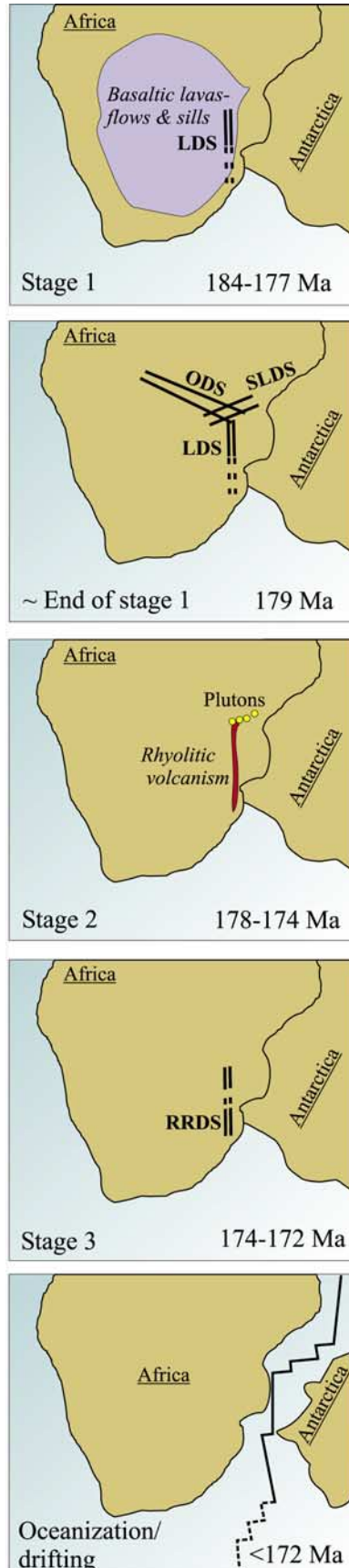


Figure 7. Age probability density distribution diagram (PDD) for the Karoo CFB rocks calculated using *Sircombe* [2004]. PDD curve for the whole Karoo age database (black plain line; $n = 76$) and the basaltic lavas and sills only (red dashed line; $n = 39$). Interpretations of the curves are given in the text. Data sources are provided in Figures 1 and 5.

[2001] and *Jourdan et al.* [2005a] showed that the emplacement of the Karoo basalts occurred between 184 and 177 Ma, over a longer period compared to other CFBs and without any unique and dominant peak activity. During this relatively long basalt flooding, several brief events were recognized such as the intrusion of the huge high-Ti Okavango dike swarm at 179 ± 1 Ma (15 age data) and the low-Ti 800-m-thick lava pile in Botswana (Shadi-Shadi borehole) at 178 ± 1.5 Ma (7 age data) (on the basis of plagioclase $^{40}\text{Ar}/^{39}\text{Ar}$ data [*Le Gall et al.*, 2002; *Jourdan et al.*, 2004, 2005a]) and the 1.6 km Lesotho lava pile (on the basis of paleomagnetic data [*Marsh et al.*, 1997]).

[28] The present data show that the magmatism did not end near 177 Ma as previously thought, but pursued (although volumetrically much more restricted) with the intrusion of the Mwenezi-Mutandawhe complexes during ~ 4 My (from 178.2 ± 1.7 to 174.4 ± 0.7 Ma) and apparently ended with the intrusion of the Rooi Rand dike swarm (172–174 Ma). Therefore the presently known total duration of the whole province deduced from the available age data, is likely to extend from ~ 184 Ma [*Duncan et al.*, 1997] to 174 Ma (Figure 7). This duration should not be mistaken with the duration of the major volume (represented by the basaltic lava flows and sills) which was emplaced over a shorter period (~ 4 –5 Myr; Figure 7) [*Jourdan et al.*, 2005a]. Prob-

bility curves are often used to determine magmatism duration of a province. However, they are generally built as based on the number of $^{40}\text{Ar}/^{39}\text{Ar}$ analyses and not the volume of the magma emplaced. If the distribution of the ages measured is not representative of the total volume of the Karoo province and/or the precision obtained on the individual ages are uneven, then the apparent duration of the magmatism can be biased. In order to detect some eventual bias, we performed two distinct probability curves (Figure 7), based on either all selected Karoo age data ($n = 76$, including lava flows, dykes, sills and various intrusives) or lava flows and sills only ($n = 39$). The second curve concerns a sampling that is geographically more uniformly distributed over the province (Figure 1). These two curves are quasi-indistinguishable (except for ages younger than 175 Ma where only dikes and plutonic rocks have been found) with a peak slightly older for the curve that includes the lava flows and sills only. The match between the two curves and the fact that the plotted data concern most of the main magmatic formations of Karoo suggest that the magmatic duration of the main volume derived from these curves is not biased by an inappropriate sampling distribution and does not represent an over-interpretation of our data set. We must nevertheless outline that the much extended sill complex in



southern South Africa (Figure 1, dating in progress) is underestimated in both of these curves.

[29] Because of both (1) the particularly good exposure of all types of formations (basic and silicic lava flows, sills, dikes, basic and silicic plutons) and (2) the high number of age data when compared to most other CFBs, we may question whether the Karoo province is really such an atypical “long-lasting” province or instead some of the other provinces are not sufficiently constrained in term of age data and/or data coverage.

6.3. Geodynamic Evolution of the Karoo Province

[30] Here we propose four main emplacement stages for the Karoo CFB (Figure 8) followed by continental breakup and sea floor spreading.

6.3.1. Stage 1 (185–177 Ma): Main Karoo Magmatism

[31] According to the limited data available, the eruptions apparently began at 185–184 Ma in the southern (Lesotho lava pile and granophyric sills) [Duncan *et al.*, 1997; Encarnacion *et al.*, 1996] and eastern (Lebombo monocline) part of the province and lasted at least until 181 Ma. Around 182 Ma, magmatism started in the northern part of the province (Botswana-Zimbabwe), where it occurred until ~177 Ma [Jones *et al.*, 2001; Jourdan *et al.*, 2005a]. During the late stage of the north-western basaltic magmatism (circa 179 Ma), two of the Karoo prominent dike swarms synchronously emerged (i.e., the N110°/Okavango and N70°/Save-Limpopo dike swarms [Le Gall *et al.*, 2002; Jourdan *et al.*, 2004, 2005a; present data]) probably in a short time span (i.e., 1–2 Ma, although the Save-Limpopo dike swarm is not yet extensively dated). Detailed structural observations on Okavango and Save-Limpopo dike swarms [Le Gall *et al.*, 2005] demonstrate that their emplacements might have been triggered by a single broad NNW-SSE extension. The high-Ti composition and young age of these swarms preclude them being the feeder of the low-Ti lavas of Botswana [Jourdan *et al.*, 2005b]. Contemporaneously, the

Figure 8. Simplified sketch maps illustrating the interpretative three main emplacement stages for the Karoo province plus the drifting stage. Dike swarms are represented by thick lines; basic lavas are represented by purple field; plutons are represented by yellow plain circles; and rhyolites are represented by the red field. Dike swarm abbreviations as in Figure 1.

Lebombo dike swarm continued to build-up as shown by the two dates at 178 Ma obtained in this study (Figure 1; Table 1).

6.3.2. Stage 2 (178–174 Ma): Late Eastern Activity

[32] From 178 to 174 Ma, the easternmost part of the province (i.e., the Lebombo and Mwenzi/Save-Limpopo regions) remained active possibly as the result of a still active crustal thinning (see discussion above). During this stage, a dominantly silicic magmatism occurred, as represented by the Jozini rhyolite, at 177.8 ± 0.7 Ma and by the ‘basic then silicic’ Mwenzi plutons intruded from 178 to 174 Ma. We note that our stages 1 and 2 fit nicely with the recent model of CFB volcanism proposed by *Jerram and Widdowson* [2005].

6.3.3. Stage 3 (174–172 Ma): Final Rooi Rand Dike Swarm

[33] Radiometric age data on the chemically specific (see above) SA41 and Rooi Rand dikes (one robust age of 173.9 ± 0.7 Ma and two possibly significant ages around 172 and 174 Ma; Figure 4; Table 1) suggest the appearance of asthenosphere-derived magmas during the final stage of the Karoo magmatism, along its eastern edge. These dikes likely represent the very first initiation of the oceanization process.

6.3.4. Stage 4 (<172 Ma): Drifting Between Africa and Antarctica

[34] At last, Karoo-related magmatism apparently vanished and continental breakup between Africa and Antarctica occurred possibly as early as circa 170 Ma. The precise timing between asthenospheric upwelling and onset of sea floor spreading is not well constrained yet and remains to be investigated in detail. However, this age is more in agreement with the ~ 164 Ma age obtained on altered plagioclase grains from the Dronning Maud Land basaltic province (conjugate to the African Karoo CFB) and considered to represent a minimum age for the sea floor spreading [*Zhang et al.*, 2003]. These ages are much older than the ~ 156 Ma (from timescale of *Gradstein et al.* [2004]) oldest magnetic anomaly (M25) evidenced in this region. Nevertheless, this anomaly is sufficiently distant from the edge of the continent to infer that the oceanization should have been significantly older (~ 10 – 15 Myr [*Lawver et al.*, 1992; *Roeser et al.*,

1996]). The Africa-Antarctica continent broke up with an orientation roughly parallel to the presently N–S oriented Lebombo and $N70^\circ$ /Save-Limpopo dike swarms and more or less at high angle to the Okavango dike swarm (that formed a failed rift; Figure 8). The $N70^\circ$ [*Le Gall et al.*, 2005] and N–S directions coincide with the eastern limit of the Kaapvaal and Zimbabwe cratons, and are likely to have concentrated the stress field, as previously proposed by *Tommasi and Vauchez* [2001]. This ultimately led to continental disruption.

6.4. Timing Between Rifting, CFB, and Oceanization

[35] It has been long recognized that most of the Phanerozoic CFBs are closely associated with continental breakup and oceanization (e.g., Decan/Indian Ocean, Karoo-Ferrar/Indian Ocean, CAMP/Central Atlantic, Parana-Etendeka/Southern Atlantic) or at least aborted rifting (Siberia and Emeishan traps) [e.g., *Hawkesworth et al.*, 1999; *Courtillot et al.*, 1999]. Generally, the flood basalts activity is believed to precede the oceanization by a period ranging from ~ 30 to a few Myr [e.g., *Hawkesworth et al.*, 1999]. This assumption is based on the age difference between the oldest recorded magnetic anomaly of the sea floor and the related flood basalts peak activity. Here we briefly examine (on the basis of the most recent data) the chronological and tectonic relationships between selected major Phanerozoic CFBs and their respective continental breakup process (i.e., rifting and oceanization onsets).

[36] $^{40}\text{Ar}/^{39}\text{Ar}$ data on the Central Atlantic Magmatic Province (CAMP) suggest that the province was mainly emplaced between 199–200 Ma [e.g., *Deckart et al.*, 1997; *Marzoli et al.*, 1999; *Knight et al.*, 2004] with a magmatic activity lasting until ~ 190 Ma as recorded by dikes from Mali [*Verati et al.*, 2005] and lava flows from Brazil [*Marzoli et al.*, 1999]. The occurrence of numerous precursor Triassic rift basins [*Olsen et al.*, 2002] preceding CAMP of about 30 Myr suggests that the region was already in extension well before the initiation of the magmatism. The first asthenospheric manifestation was recorded at 196.6 ± 0.6 Ma by the compositionally MORB-akin recurrent lava flow in Morocco [*Verati et al.*, 2006]. The age of the first oceanic crust was generally estimated at ~ 175 Ma but a recent central Atlantic reconstruction [*Sahabi et al.*, 2004] suggests that it could have been as old as the late Sinemurian (~ 190 Ma according to the

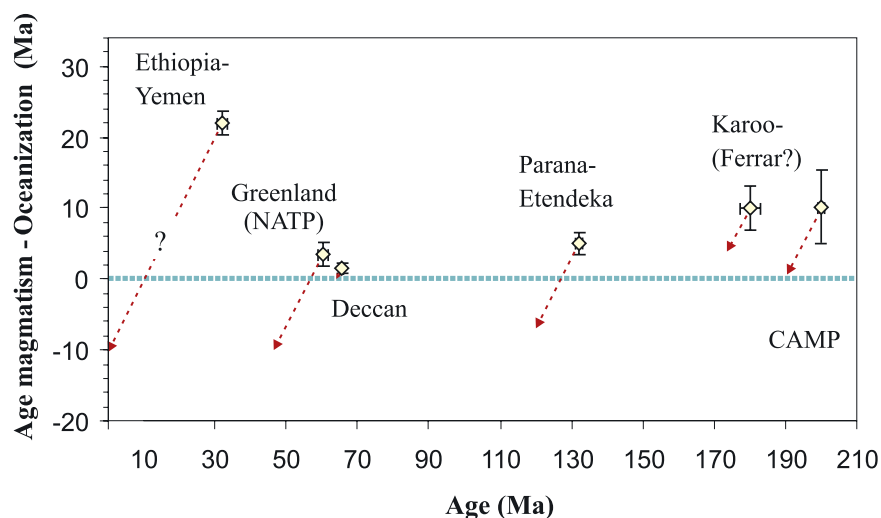


Figure 9. Ages of CFB versus the age difference between the CFB-peak (open diamonds) and the late-CFB protracted magmatism (red dashed-line arrows) of flood basalts and the estimated age of oceanization. Note that for Karoo and CAMP the span between the CFB peak and the oldest ocean floor is much shorter than previously thought [Courtilot *et al.*, 1999, Hawkesworth *et al.*, 1999]. Total uncertainties reflect the duration of the CFB peak activity combined with estimated uncertainties on the age of the oceanization (compare to Table S3). The horizontal blue dashed line reflects the onset of oceanic crust formation relative to each CFB. References as quoted in the text for each CFB, respectively.

geological timescale of *Gradstein et al.* [2004]). If we accept the latter age, the CAMP magmatic peak and the first asthenospheric manifestation would have preceded the onset of sea floor spreading by ~ 10 Myr and ~ 7 Myr, respectively. A protracted minor magmatic activity would have persisted inland until the creation of the oldest oceanic crust (Figure 9).

[37] The Parana-Etendeka CFB was mainly emplaced at 131–133 Ma with a minor magmatic activity extending probably until at least ~ 120 Ma [e.g., *Renne et al.*, 1992, 1996a, 1996b; *Stewart et al.*, 1996]. This province was emplaced in a region already in extension [*Turner et al.*, 1994; *Hawkesworth et al.*, 1999]. The Horingbaai, E-MORB-like dikes of Namibia (~ 125 Ma [*Renne et al.*, 1997]) and the Brazilian coastal NE–SW striking Florianopolis dikes (129–116 Ma [*Raposo et al.*, 1998; *Deckart et al.*, 1998]) have been suggested to reflect the final stage of rifting at this latitude [*Raposo et al.*, 1998; *Duncan et al.*, 1990]. The South Atlantic opened first (magnetic anomaly M9) near Cape town [*Turner et al.*, 1994] around 133–134 Ma [*Gradstein et al.*, 2004], and then progressed northward, reaching the latitude of the traps around 127 Ma (anomaly M2), i.e., broadly at the same time as the intrusion of the Horingbaai and Florianopolis dikes mentioned above (however

the large uncertainties on available data preclude a more precise comparison).

[38] The Deccan traps of India apparently show an extremely brief emplacement age (for the main volume of the magma) at 65.5 ± 1 Ma [e.g., *Courtilot et al.*, 1988; *Hofmann et al.*, 2000, and references therein]. So far and according to the compilation of *Hofmann et al.* [2000], the volcanism started at 68.2 Ma and ended at 64.0 ± 0.6 Ma (recalculated relatively to FCs standard at 28.02 Ma). The breakup between Seychelles and India is believed to have started slightly before the time of chron 28 (64 Ma [*Gradstein et al.*, 2004]) and is thus coeval with the end of the Deccan traps emplacement.

[39] The North Atlantic Tertiary province (NATP) consists of three distinct pulses of magmatism: one pulse at around 62–59 Ma followed by a second pulse at 57–54 Ma (including both a CFB component and voluminous seaward dipping reflector) and a final pulse at 50–47 Ma [e.g., *Tegner et al.*, 1998; *Jolley et al.*, 2002, and references therein]. The age of the first oceanic crust is constrained by the C25n chron located at the ocean-continent boundary and can be estimated at ~ 57 Ma [*Gradstein et al.*, 2004]. The onset of oceanization therefore slightly preceded the end of the second

pulse and preceded the end of the activity of the North Atlantic province by ~ 10 Myr.

[40] The last and most “atypical” example concerns the Ethiopia-Yemen traps. The most reliable ages obtained for the traps cluster at 31–28 Ma [e.g., Hofmann *et al.*, 1997; Ukstins *et al.*, 2002]. Minor volcanic activities occurred until present but it is hard to tell if they are related to the traps activity or not. The rifting of the Red sea and of the Gulf of Aden has been proposed to be initiated as soon as 35–30 Ma [Courtilot *et al.*, 1999]. The true seafloor spreading started much later at ~ 10 Ma and ~ 5 Ma for the Gulf of Aden and the Red Sea, respectively.

[41] In summary, this brief review shows that all the CFBs erupted on regions apparently already in extension (e.g., CAMP, Karoo-Ferrar, Parana-Etendeka provinces) since several tens million of years. In most cases, oceanization is partially coeval (CAMP, Parana-Etendeka, NATP and possibly Ethiopia-Yemen) or shortly follows (Karoo-Ferrar and Deccan) the CFB or the late CFB protracted activity (Figure 9). However, the main volume of the traps is systematically emplaced a few million years before the onset of oceanization (except for Ethiopia-Yemen). The onset of oceanization can be preceded by precursor MORB-like magmatism (Rooi Rand dikes for the Karoo, Horingbaai dikes for the Parana and the recurrent lava flow for the CAMP). The age difference between CFB emplacement and onset of oceanization is therefore generally lower than previously assigned [e.g., Hawkesworth *et al.*, 1999].

7. Conclusions

[42] 1. New $^{40}\text{Ar}/^{39}\text{Ar}$ data show that the basaltic magmatism of the Karoo province previously dated between 185 and 177 Ma, was followed by the emplacement of rhyolitic lava flows (one age at 177.8 ± 0.7 Ma) and gabbroic to silicic plutons (Mwenezi region: 178.2 ± 1.7 to 174.4 ± 0.7 Ma). The progressive thinning of the crust along the eastern edge of the Karoo province may have focused the location of these late-stage magmatic events. The new ages obtained on these formations would document the response to this crustal stretching by (1) melting of gabbros underplated at the base of the crust (silicic volcanism and plutonism) and, as the stretching pursued, (2) decompression melting of the underlying asthenosphere (Rooi Rand and similar dikes).

[43] 2. The E-MORB-like Rooi Rand dikes are inferred to represent the very first witnesses of the asthenosphere upwelling that shortly preceded the oceanization (i.e., the opening of the Indian Ocean). One unambiguous plateau age at 173.9 ± 0.7 Ma (obtained on a dike located at the north of the classically known Rooi Rand swarm), along with two concordant mini-plateau ages (173.9 ± 3.8 and 172.1 ± 2.3 Ma) strongly suggest that the onset of oceanization slightly postdated the end of the Karoo magmatism.

[44] 3. The whole magmatic activity of the province span over ~ 10 Myr (even though the main basaltic volume is emplaced more briefly). Although we have not yet a complete view of the activity of the whole province, we are now able to distinguish between (1) short-lived events (e.g., the N110° Okavango and probably N70°/Save-Limpopo dike swarms (179 ± 1 Ma)) and (2) long-lived structures, such as the Lebombo (and to lesser extent Save) monoclines that remained active during most of the magmatic activity of the province (from around 184 to 174–172 Ma). During the last few Myr of the province lifetime, the magmatic activity occurred in the Lebombo area only.

[45] 4. Scrutinizing the available ages and geological data on CFBs and oceanization processes, it appears that in most cases, the onset of oceanization slightly followed (1–2 Myr) or was coeval with the late flood basalts activity.

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