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$^{40}Ar/^{39}Ar$ geochronology and structural data from the giant Okavango and related mafic dyke swarms, Karoo igneous province, northern Botswana

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Abstract

In NE Botswana, the Karoo dykes include a major N110° dyke swarm known as the Okavango giant dyke swarm (ODS/N110°) and a second smaller set of N70° dykes belonging to the Sabi-Limpopo dyke swarm (SLDS/N70°). New $^{40}Ar/^{39}Ar$ plagioclase dating of Karoo dolerites of the giant ODS/N110° and the SLDS/N70° in NE Botswana yield plateau ages between 179.6 ± 1.2 and 178.4 ± 1.1 Ma. Our data are concordant with previous $^{40}Ar/^{39}Ar$ ages for Northern Karoo dykes and lava flows exposed in western Zimbabwe. The data are tightly clustered, indicating a short-lived (179–181 Ma) flood basalt magmatism in this region. The new radiometric dates allow the definition of a diachronous Jurassic flood basalt activity in southern Africa. A significant south to north younging at the scale of the Karoo igneous province correlates with a chemical zonation from low-Ti (south) to high-Ti (north) mafic rocks. Structural measurements on the ODS/N110° and SLDS/N70° Karoo dykes of NE Botswana suggest that: (1) most of the host fractures are inherited Precambrian structures; (2) dyke emplacement occurred under unidirectional tensional stresses; (3) significant syn- and post-volcanic extensional tectonics are lacking. Combined with regional geology, these geochronological and structural data do not confirm unambiguously the triple-junction hypothesis usually put forward to support a mantle plume model for the evolution of the Karoo igneous province, prior to Gondwana breakup. © 2002 Published by Elsevier Science B.V.

Keywords: Ar-40/Ar-39; absolute ages; dike swarms; mantle plumes; Gondwana; Karoo Basin

1. Introduction

The Karoo-Ferrar/Antarctica large igneous province (KFA-LIP hereafter) covers 6×10^6 km^2 and is one of the greatest continental flood basalt provinces in the world (Fig. 1a). It is linked

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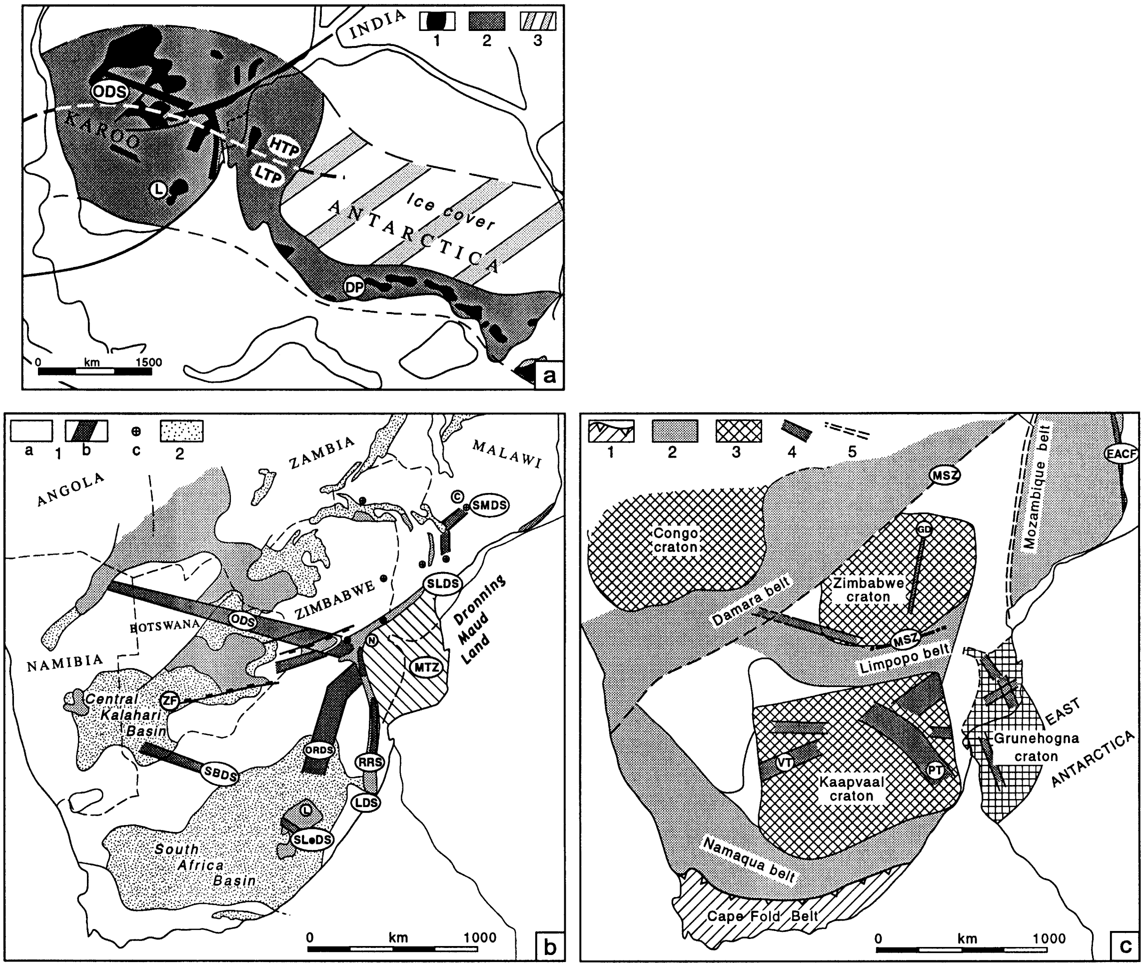

Fig. 1. Major Precambrian and Karoo structural features of West Gondwana. (a) Distribution of continental flood basalt and related intrusive rocks of the Karoo-Ferrar/Antarctica large igneous province in a pre-drift Gondwana reconstruction. 1, exposed complexes; 2, extrapolated magmatic rocks; 3, inferred magmatic units beneath ice cover in western Antarctica. HTP and LTP, high- and low-Ti tholeiitic province, respectively. (b) Karoo tectono-magmatic framework of southern Africa. 1, magmatic complexes with 1a, flood basalt; 1b, dykes and sills; 1c, eruptive centres; 2, sedimentary basins. C, Chilwa; L, Lesotho; LDS, Lebombo dyke swarm; MTZ, Mozambique thinned zone; N, Nuanetsi; ODS, Okavango dyke swarm; ORDS, Olifants River dyke swarm; RRS, Rooi Rand Suite; SBDS, South Botswana dyke swarm; SLDS, Sabi-Limpopo dyke swarm; SLeDS, South Lesotho dyke swarm; SMDS, South Malawi dyke swarm; ZF, Zoetfontain fault. (c) Major basement boundaries in southern Africa. 1, palaeozoic belt; 2, proterozoic belts; 3, craton; 4, dyke swarms; 5, suture lines. EACF, East African coastal fault; GD, Great Dyke; MSZ, Magogaphate shear zone; PT, Pongola rift trend; VT, Venterdorp rift trend.

to the initial Jurassic breakup of Gondwana. The African section of this LIP, the Karoo igneous province, consists of flood basalts, sills and giant dyke swarms that together cover more than 3×10^6 km^2 in southern Africa (Fig. 1b). The evolution of the Karoo igneous province has been largely documented with emphasis on the petrology of igneous rocks [1], thermo-mechanical and geotectonic evolution related to either mantle plume or subduction processes [2,3]. However, limited field structural data and precise geochronological data (e.g. [4,5] have been integrated to

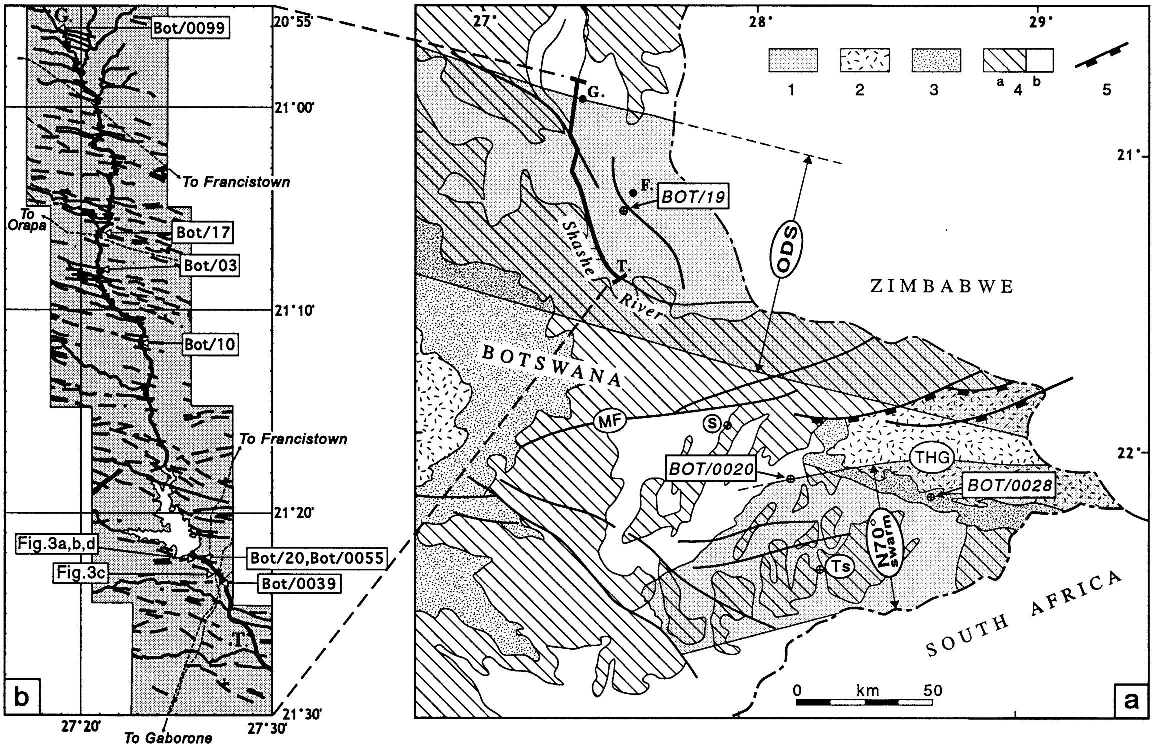

Fig. 2. The Karoo dyke system in NE Botswana. (a) Simplified geological map showing the location of the N110° (Okavango) and N70° (Sabi-Limpopo) dyke swarms. The studied areas, including the Shashe reference section, Tsetsebjwe (Ts) and Tuli (THG), as well as isolated dated samples are shown. 1, regional envelop of the N110° and N70° dyke swarms; 2, flood basalt; 3, Karoo basins; 4, Precambrian basement with 4a, dominantly gneissic rocks; 4b, granites; 5, major extensional faults. F, Francistown; G, Gulubane; MF, Magogaphate fault; ODS, Okavango dyke swarm; T, Tonotha. (b) Location of dated rocks along the Shashe section. The distribution of dykes is according to published geological maps of the Geological Survey of Botswana. Location of Fig. 3 is also shown.

constrain the geotectonic models. Furthermore, though mafic dyke swarms are known to be crucial indicators for mantle dynamics and crustal palaeostress regimes, precise geochronological and structural information related to the giant Okavango dyke swarm are still missing. Fig. 1b indicates that the Karoo intrusive complex is dominated by four different dyke sets, namely the Okavango (N110°), Sabi-Limpopo (N70°), Lebombo (N-S) and Olifants River (N20–40°) systems. These four dyke arrays converge towards the Nuanetsi area, in southern Zimbabwe, which is considered to be a rift triple-junction formed above a mantle plume [2,6–8]. However, the following critical issues were not addressed in that interpretation: (1) the temporal relationships between the various dyke swarms is not yet established, and (2) the inherited or newly formed origin of the involved fractures was not documented.

This paper is focused on: (1) the giant N110° Okavango dyke swarm (ODS/N110°) which represents one of the greatest fissural intrusive complexes in the world [9]. It forms a 1500-km-long and 100-km-wide tectono-magmatic structure extending from Nuanetsi in western Zimbabwe through northern Botswana up to northern Namibia (Fig. 1b). (2) The N70° dyke swarm (SLDS/N70°) exposed south of the ODS/N110° and corresponding to the SW tip of the Sabi-Limpopo dyke system [10]. Except for one $^{40}Ar/^{39}Ar$

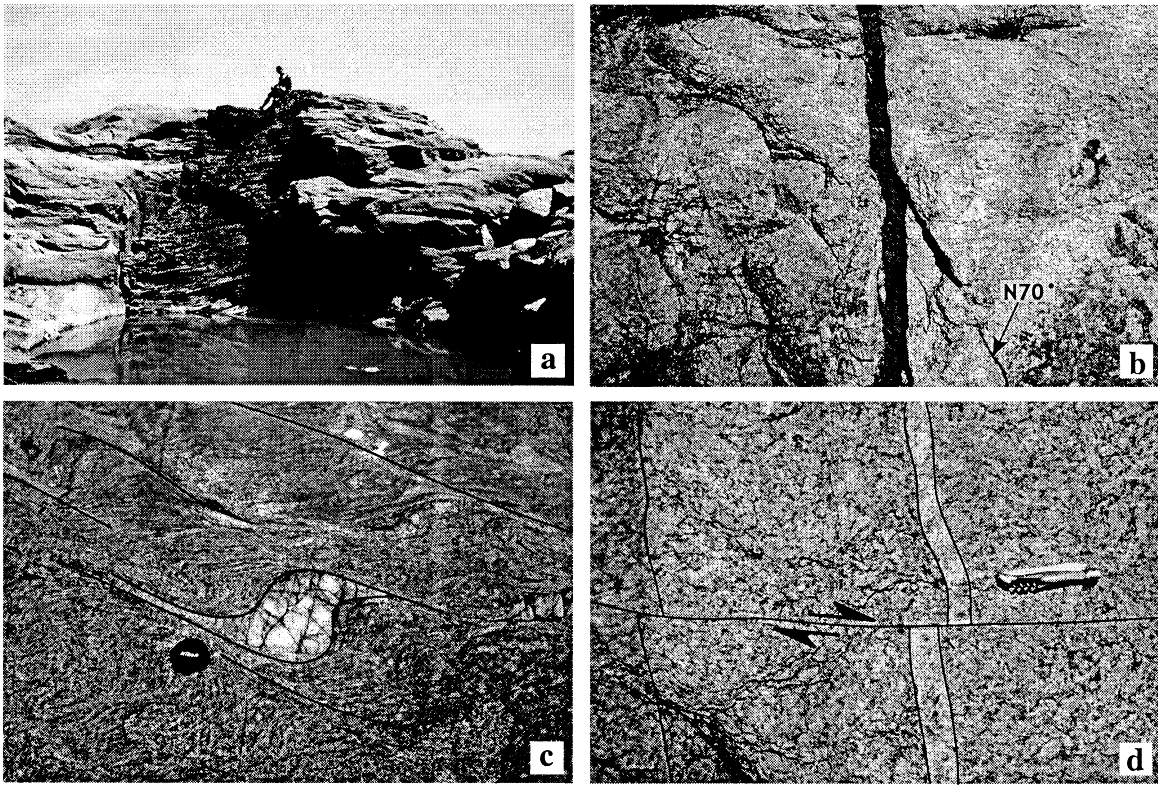

Fig. 3. Structural features of the Karoo ODS/N110° swarm and its Proterozoic basement host-rocks (see location in Fig. 2b). (a) Vertical attitude of a N70° segmented dyke at the Shashe Dam (sample BOT/0055). (b) Small-scale segmentation of a N110° dyke (10 cm thick) caused by a basement-related N70° brittle fracture. (c) N70° brittle shear planes in orthogneiss from the Shashe Dam-Tonotha area. (d) N70° granite veins and epidote-filled cracks dextrally offset by a N110° (dyke-parallel) basement fault, Shashe Dam area.

whole-rock age determination on a mafic dyke from the external part of the swarm [11], the ODS/N110° and SLDS/N70° have never been dated and their structural setting never been fully documented.

The ODS/N110° has been variously interpreted as: (1) a failed arm of a triple rift junction above a starting mantle plume which led to the breakup of Gondwanaland [2,12,13]; (2) the result of a plume impinging a subducting lithosphere [3]; (3) a South Atlantic ocean-related magmatism emplaced along a Cretaceous continental transverse fracture [14].

The objectives of this paper are: (1) to present new $^{40}Ar/^{39}Ar$ ages on plagioclases from N110° and N70° dyke sets in northern Botswana; (2) to present field structural observations for both dyke systems; and (3) to integrate our data in the regional framework in order to generate constrained interpretations on the rift triple-junction model.

2. Geological framework and structural analysis

The Pre-Kalahari basement is well exposed in NE Botswana and primarily comprises foliated Archaean rocks of the Zimbabwe craton and Limpopo belt and unconformably overlying Permo-Jurassic Karoo sedimentary and volcanic sequences of the Central Kalahari basin and Tuli half-graben [15–18] (Figs. 1b and 2a).

The average length of individual dykes within the ODS/N110° is 10 km with a mean N110° azimuth parallel to the swarm trend (Fig. 2b). The highest exposed dyke density occurs in the Francistown area which is drained by the Shashe River. The nearly unbroken exposures along the Shashe River allow a complete sampling of all the dykes of the ODS/N110° within a ca. 80-km-long continuous section, at high angle to the swarm trend (Fig. 2b). Along the section, the ODS/N110° comprises more than 170 regularly spaced vertical dykes, 18 m thick on average (140 data), with generally simple, planar, parallel-sided walls (Fig. 3a). The most common deviations from this simple geometry are 'en echelon' apophyses indicating a sinistral shearing component during dyke emplacement.

The SLDS/N70° dyke set is poorly exposed to the SW in the Tsetsebjwe area (Fig. 2a). It defines a ca. 50-km-wide dyke swarm which is parallel to the northern border fault of the Tuli half-graben (Fig. 2a). The mean thickness of the N70° dykes (7 data) is 35 m which is nearly twice the average value for the N110° dykes measured along the Shashe section.

Since the two dyke swarms do not benefit from similar exposure conditions, the resulting discrepancy in the quality and quantity of data (140 and seven measured dykes for the N110° and N70° swarms, respectively) makes it difficult to compare the corresponding cumulative dilatations of 20% (SLDS/N70°) and 5% (ODS/N110°). In both cases, crustal extension is exclusively accommodated by dyke injection and associated vertical jointing without concomitant extensional faulting.

On the other hand, a dense network of steep preexisting faults/fractures is observed within the dominantly granitoid country-rocks of both N110° and N70° dyke swarms. A number of these steep brittle structures are parallel to the dyke margins. Field relationships show that mafic dykes intrude along preexisting fractures (Fig. 3b) that typically have various origins, i.e. strike-slip faults (Fig. 3c,d), reverse fault-related fractures, or joints. In the Tuli area, the ODS/N110° and SLDS/N70° dyke networks show cross-cutting relationships that do not provide a definite chronological template [14].

3. Geochronology

3.1. Sample description and analytical procedures

Ten samples of mafic dykes intruding into Archaean gneissic granites (nine samples) and Karoo sediments (one sample) in NE Botswana were selected for $^{40}Ar/^{39}Ar$ dating. They are representative of both the ODS/N110° (BOT/03-10A-17-19-20, BOT/0028-39-55-99) and SLDS/N70° (BOT/0020) dyke sets. Note that (1) sample BOT/0055 is from a N70°-trending segment of a N110° dyke, and (2) the trend of the dyke BOT/0020 was not directly measured in the field; it was deduced from a previous map of the Geological Survey of Botswana (Tsetsebjwe 1:50 000 sheet). The sampled dykes cover a broad area and various structural and geographical zones of the Karoo igneous complex in northern Botswana (see Fig. 2 for sample location). The N110° dykes were sampled along the Shashe section (BOT/0099-17-03-10A-20-0039) and in isolated localities such as the Francistown quarry (BOT/19) and the Tuli basin (BOT/0028).

All the rocks (except BOT/17) consist of fine- to medium-grained dolerites, with intergranular/intersertal texture. The dominant minerals are plagioclase and augite with minor olivine and Ti-magnetite. The sample BOT/0055 contains large (up to 2 cm) phenocrysts of zoned plagioclase, oriented parallel to the margins of the dyke. In some dolerites, plagioclase and sometimes augite form glomeroporphyritic clusters. The groundmass contains fresh glass or cryptocrystalline minerals, feathery augite and skeletal plagioclase and Ti-magnetite. The mineral phases are fresh except olivine which is moderately serpentinized. Some plagioclase crystals are locally cut by sericite-filled cracks.

Sample BOT/17 differs from other samples. It is a olivine-free medium-grained gabbro made of plagioclase, augite, pigeonite, Ti-magnetite, interstitial micropegmatite and biotite. Secondary minerals are more abundant than in other samples and consist of chlorite and sericite (interstitial patches or infilling veins in plagioclases) and uralite after pyroxenes.

Representative major and trace element analyses of dated samples were performed by X-ray fluorescence spectrometry at Lyon, and are listed in Table 1 (**Background Data Set**[1]). All the dolerites, except sample BOT/17, are high-Ti tholeiites ($2.1 < TiO2 < 3.9\%$) containing 150–360 ppm Zr. They show chemical similarities with dykes from the southern periphery of the ODS [11] and lava flows from the Zambezi Gorge in Zimbabwe [5]. Their chemical composition is similar to that of high-Ti Karoo igneous mafic rocks (Fig. 1a) which define an igneous sub-province geographically centred on the study area [19,20]. The gabbro BOT/17 contains a lower (0.5%) TiO_2 concentration and lower Zr (61 ppm), Nb (<4 ppm) and Y (<14 ppm) abundances, and most probably is genetically unrelated with the other ODS dykes, despite its N110° trend and its location within the Okavango dyke swarm (Fig. 2b).

Twenty to 30 mg of fresh transparent plagioclase (grain size in the range 125–250 μm) were separated using a Frantz magnetic separator, and then carefully selected under a binocular microscope. The samples were irradiated in the nuclear reactor at McMaster University in Hamilton, Canada, in position 5C. The total neutron flux density during irradiation (deduced from a nominal value for the reactor) was 9.0×10^{18} n cm^{-2}. We used the Hb3gr hornblende as a flux monitor, with an age of 1072 Ma [21]. Eleven clusters of five grains of hornblende monitor were included in a 69-mm-long irradiation canister, and the distances between them were lower than 6 mm (corresponding to a flux gradient of about 0.3%). The single grains of hornblende monitor were measured individually. The J values applied to samples were deduced from the $^{40}Ar^*/^{39}Ar_K$ gradient measured on the monitors along the canister. The maximum error bar on the corresponding $^{40}Ar^*/^{39}Ar_K$ ratio is $\pm0.2\%$ in the volume where the samples were included. The plagioclase bulk samples were step heated with a double vacuum high radiofrequency furnace, directly connected to a stainless steel purification line and a 120°-12 cm MASSE mass spectrometer working with a Baür-Signer source and a Balzers SEV 217 electron

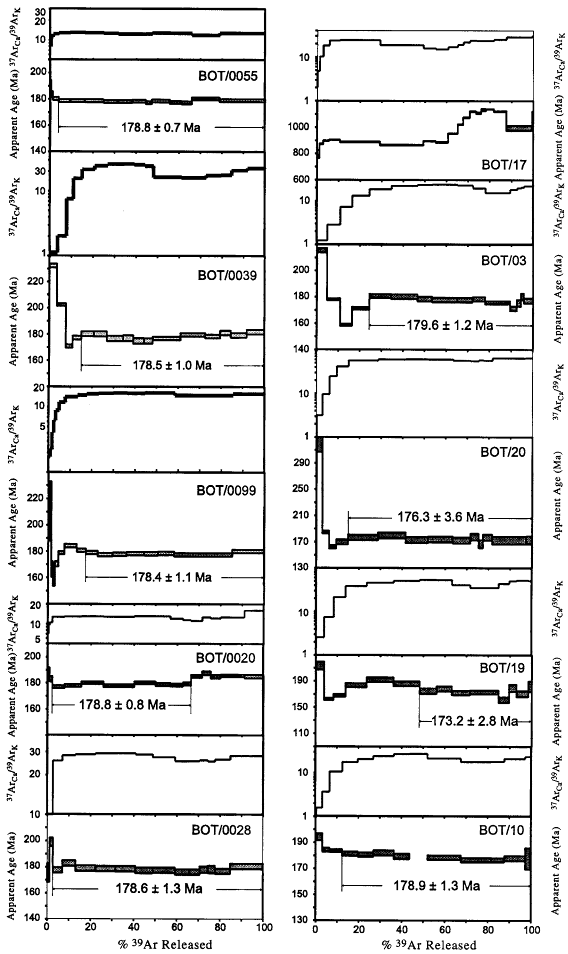

Fig. 4. Ages and $^{40}Ar_{Ca}/^{39}Ar_K$ ratio spectra for plagioclase bulk samples from the dyke swarms of NE Botswana. Apparent ages and plateau ages are given at the 1σ and 2σ level, respectively.

multiplier. Argon isotopes were of the order of 260–430, 740–4600, 800–5800 and 3–40 times the blank level for masses 40, 39, 37 and 36, respectively. The criteria for defining plateau ages were the following: (1) at least 70% of released ^{39}Ar; (2) at least three successive steps in the plateau; and (3) the integrated age (error-weighted mean) of the plateau should agree with each apparent age of the plateau within a 2σ confidence interval. Uncertainties on the apparent ages on each step are quoted at the 1σ level (Fig. 4) and do not include the uncertainties on the age of the monitor. Plateau ages are given at the 2σ level (Fig. 4).

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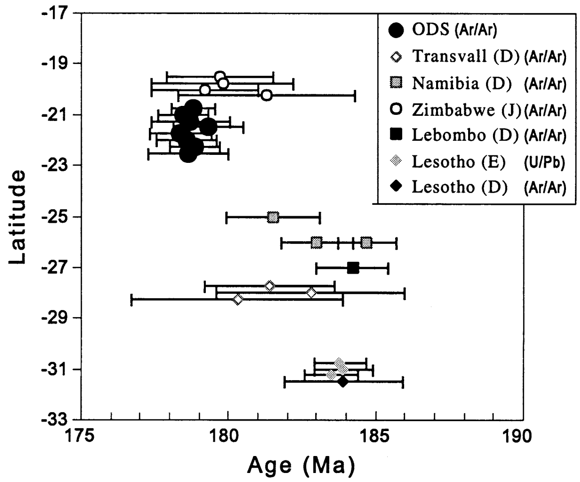

Fig. 5. Diagram showing age versus latitude of basalts and dolerite dykes from the Karoo igneous province. Source of $^{40}Ar/^{39}Ar$ age data: (1) Sabi-Lebombo, part of Lesotho, Transvaal and Namibia [4] (D in inset); (2) Zimbabwe [5] (J in inset); (3) Okavango dyke swarm (this study). U/Pb zircon ages from Lesotho are from [23] (E in inset). Only $^{40}Ar/^{39}Ar$ plagioclase ages and U/Pb zircon ages are plotted with their 2σ confidence levels.

The uncertainties on the $^{40}Ar^*/^{39}Ar_K$ ratios of the monitor are included in the calculation of the plateau age uncertainty. Correction factors for interfering isotopes were $(^{39}Ar/^{37}Ar)_{Ca} = 7.06 \times 10^{-4}$, $(^{36}Ar/^{37}Ar)_{Ca} = 2.79 \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_K = 2.97 \times 10^{-2}$. Decay constants are those of [22]. Detailed analytical data given in Table 2 can be obtained in the **Background Data Set**[1] and the main results are compiled in Table 3 (**Background Data Set**[1]). We only report age spectra data because the $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isochron plot displays data strongly clustered near the abscissa axis, due to atmospheric contaminations mostly lower than 5%. A summary of previous and new Karoo igneous province age data is compiled in Fig. 5 [4,5,23].

3.2. Results

If we exclude one high temperature apparent age (representing 3% of ^{39}Ar for the sample BOT/03) that is not concordant with the plateau age, seven concordant plateau ages ranging from 178.4 ± 1.1 to 179.3 ± 1.2 Ma (with a less precise age of 175.5 ± 3.6 Ma) are obtained on plagioclase from mafic dykes sampled along the Shashe River (BOT/03-10-20, BOT/0039-55-99) and in the Tuli basin area (BOT/0028) (Fig. 2). The sample BOT/19 displays a more complicated age spectrum with concordant apparent ages at high temperature (52% of ^{39}Ar), corresponding to a weighted mean age of 172.6 ± 2.8 Ma. The sample BOT/0020 from the SLDS/N70° dyke swarm does not display a plateau age but instead a flat section of the age spectrum, representing 64.2% of ^{39}Ar released, which indicates a weighted mean age of 178.8 ± 0.8 Ma. The existence of significantly higher (internally concordant) apparent ages at high temperature is not clearly understood, but could correspond to low amounts of excess argon.

In most cases, the low temperature fractions displaying variable ages higher or lower than the remaining flat part of the spectra correspond to low and increasing $^{37}Ar_{Ca}/^{39}Ar_K$ ratio, hence suggesting that this fraction corresponds to potassic alteration phases (probably sericite filling small cracks as observed under the microscope) whereas the higher temperature gas fractions correspond to nearly pure plagioclase, as shown by more regular and higher $^{37}Ar_{Ca}/^{39}Ar_K$ ratios. The lower ages obtained at low temperature clearly result from younger alteration phases. On the other hand, the highest ages are more difficult to explain. They could result from excess argon due to contamination of basaltic magma by the basement host-rocks as commonly described for basaltic dykes crossing much older and K-rich host-rocks. However, in that case a clear saddle shape is usually observed, that is not the case here, the high temperature apparent ages being included in the plateau ages (sample BOT/0020 excepted). Alternatively, they may result from ^{39}Ar loss from tiny secondary potassium-rich mineral fractions included in the plagioclase by recoil during the irradiation. In any case, it must be outlined that the plagioclases from these dykes are not, or slightly, affected by excess argon, that is crucial to obtain a precise chronology of the Karoo dyke swarms. This could be due to the superficial levels where these dykes were emplaced, as attested by the existence of Karoo lava flows in the region (see Fig. 2), hence allowing a sufficient degassing of radiogenic argon eventually incorporated into the magma from host-rocks at deeper levels.

Sample BOT/17 shows a disturbed age spectrum characterized by a nearly flat section (but without concordant apparent ages) corresponding to a weighted mean age of 883 ± 4 Ma. The remaining part of the spectrum gives higher apparent ages probably caused by excess ^{40}Ar. It is clear that the corresponding dyke does not belong to the Karoo igneous suite and is part of a much older Proterozoic mafic dyke system, though there are no obvious field features allowing to discriminate the Proterozoic and Jurassic dykes in the ODS/N110°.

4. Interpretation

4.1. Timing of Karoo magmatism

The new ^{40}Ar/^{39}Ar ages presented in this paper indicate that the ODS/N110° and SLDS/N70° dyke sets of northern Botswana were emplaced between 179.3 ± 1.2 Ma and 178.4 ± 1.1 Ma. This age range represents the best estimate for the ODS/N110°, firmly establishing a mid-Jurassic age to the giant dyke complex of NE Botswana and hence excluding a Cretaceous age proposed by [14]. Although the number of dated dykes of both directions is low, our data suggest a synchronous emplacement of the ODS/N110° and the SLDS/N70° Karoo dyke swarms converging at Nuanetsi. Additional age determinations (in progress), especially on the SLDS/N70° dyke system, are required to further constrain this interpretation. The lack of age differences between the peripheral (BOT/0099-20-0039-0028) and central (BOT/03-10-19) dykes across the 80-km-wide ODS/N110° dyke swarm (Fig. 2b) further indicates that this latter has been emplaced either during one single short-lived igneous event or as the result of successive magma injections within a very short time, i.e. within the analytical margin of error of geochronological data.

The new age data presented here are similar to: (1) the ^{40}Ar/^{39}Ar age of 178.9 ± 1.4 Ma measured on a whole-rock sample at the southern periphery of the N110° dyke set [11], and (2) four ^{40}Ar/^{39}Ar whole-rock and plagioclase ages obtained further north in Zimbabwe, on lava flows near Victoria Falls, that range from 179.8 ± 1.2 Ma to 179.2 ± 0.9 Ma (plagioclase) and from 181.3 ± 1.5 Ma to 179.2 ± 0.9 Ma (whole-rock and plagioclase) [5] (Fig. 5). Thus, the ^{40}Ar/^{39}Ar ages for both dykes and lava flows are tightly clustered around 178–181 Ma and indicate a short time-span for the bulk of the magmatic activity over the northern Karoo igneous province of southern Africa. These clustered data are from three different laboratories using distinct monitors (FCT-3 biotite for [5], Hb3gr amphibole for this study, and unspecified for [11]). Nevertheless, the two ages of 28.04 and 1072 Ma chosen for the two monitors FCT and Hb3gr, respectively, are in agreement with the intercalibration performed by [24]. Therefore, based on these ages and the geographical distribution of the dated rocks, the N110° Okavango dyke complex, and possibly the N70° Sabi-Limpopo dyke swarm represent the feeders of the high-Ti tholeiites among the North Karoo lava pile. In the Tuli half-graben (Fig. 2a), N110° dykes intrude basaltic lavas flows that are assumed to represent the lowermost part of the partly eroded Karoo flood basalt succession. The emplacement ages for the southern Karoo igneous sub-province of the KFA-LIP (Fig. 5) are in the interval 185–180 Ma when only precise ^{40}Ar/^{39}Ar and U–Pb zircon ages are compiled

[4,25,26]. Thus, taking into account the analytical uncertainties, the Karoo igneous province was most probably emplaced in ca. 5 Ma. At the regional scale, the onset of Karoo magmatism seems to be younger in the northern igneous sub-province. Indeed, mineral separates (mostly plagioclase) $^{40}Ar/^{39}Ar$ ages from (1) Lesotho and Lebombo Karoo lava flows; (2) Transvaal Karoo dykes and sills; and (3) central/southern Namibia Karoo flood basalts display plateau ages ranging from 184.7 ± 0.7 Ma to 180 ± 1.8 Ma [4], compared to the interval 179 ± 1.2 to 178.4 ± 1.1 Ma for Karoo mafic rocks in Botswana and Zimbabwe (5, and this work). This N–S diachronism for the onset of Karoo igneous activity correlates with a large-scale geochemical zonation involving a (younger) high-Ti basalt sub-province to the north and an (older) low-Ti basalt sub-province to the south [19,20] (Fig. 1a).

4.2. Structural and geotectonic implications

The origin of the linearity of the giant Okavango dyke swarm, with a constant N110° strike over more than 1500 km, is poorly understood, since it is not concordant with any mapped basement structures [27]. Indeed, in NE Botswana, the ODS/N110° aeromagnetic anomalies intersect at high angle the NE–SW tectonic grain of the Damara/Ghanzi-Chobe Neoproterozoic belt (Fig. 1b,c) whilst across the Shashe River section, the N110° dyke array cuts sharply through complexely folded Archaean ductile fabrics (Fig. 2a).

The $^{40}Ar/^{39}Ar$ (minimum) age of 884 ± 4 Ma obtained on a N110° mafic dyke along the Shashe transect (sample BOT/17, this work) demonstrates that part of the Okavango Karoo dyke system was emplaced along a reactivated N110° Proterozoic or older dyke/fracture zone. NW–SE-elongated granitic bodies dated at 1022 ± 6 Ma (U–Pb SHRIMP single zircon) [28] along the same tectonic zone belong to this inferred Proterozoic dislocation zone that probably extends over > 1500 km between the Kaapvaal and Zimbabwe cratons (Fig. 1c). Therefore, the Okavango Karoo dyke swarm is likely to have exploited a major Precambrian crustal/lithospheric-scale discontinuity at depth that was reactivated during the emplacement of Karoo dykes. The structural significance of this major basement fault/dyke zone within the Proterozoic framework of southern Africa remains to be precisely determined.

The SLDS/N70° dyke system follows a fabric which is known to represent a fundamental tectonic feature of the southern African sub-continent [29]. In NE Botswana, the northern edge of the Kaapvaal craton strikes roughly N70° (Fig. 1c), and several faults having the same trend within this craton were rejuvenated during Karoo extension, e.g. the Zoetfontain fault [30] (Fig. 1b). Further north, the Magogaphate N70° ductile shear zone (Fig. 1c) also forms a major Archaean discontinuity within the Limpopo belt [31]. This shear zone has been successively reactivated during the Palaeoproterozoic Ubendian–Eburnean orogeny [31,32] and during Karoo extension (Fig. 1b). Karoo-age basement-controlled N70° extensional faults also define the northern boundary of the Tuli half-graben [33] and extend further to the NE along the Sabi-Lebombo dyke swarm from NE Botswana to the Mozambican coast (Fig. 1b). From the structural considerations above, the ODS/N110° and SLDS/N70° Karoo dyke systems exposed in NE Botswana were emplaced along reactivated Precambrian fracture zones. Similar conclusions were reached by [34] for NS Karoo dykes of the Rooi Rand Suite along the eastern boundary of the Kaapvaal craton (Fig. 1b,c). Thus, during Jurassic times, the Karoo extension rejuvenated a previously faulted Precambrian continental crust as already pointed out by some authors [35,36]. Once subjected to Karoo extension, concentration of extensional strain and magmatism should have preferentially occurred along preexisting discontinuities that may fortuitously mimic a triple-junction pattern in the Nuanetsi area. The junction zones between both inherited and/or newly formed Karoo active faults could have yielded vertical pathways for Karoo magma, hence forming nodes or eruptive centres within the KFA-LIP (Fig. 1b), e.g. Chilwa, Nuanetsi, Dufek and Beardmore Glacier [37–39]. These fault-controlled feeder centres, from which the dyke arrays are likely to have propagated laterally, may give the appearance of plume head impact zones. In particular, the Nuanetsi triple-junction-like fracture/dyke pattern can no longer be used as unequivocal evidence for reconstructing Karoo palaeostress directions and radial stress induced by a plume-related uplift (Fig. 1b). Instead, comparing the structure of the N70° and N110° dyke swarms exposed in NE Botswana rather suggests a unidirectional extension oriented at N160° (perpendicular to the SLDS/N70°) that could account for (1) marked thickness variations between the N110° and N70° dyke swarms (18 m and 35 m in average, respectively) and (2) the shearing component documented along N110° dykes.

Furthermore, an exhaustive review of Karoo dyke systems in southern Africa (cf. SE Botswana, S. Malawi, S. Lesotho) and Antarctica (West Dronning Maud Land) [40–42] (Fig. 1b) leads to a much more complex dyke swarm distribution that does not support the plume-induced triple-junction model. In a pre-drift reconstruction of Gondwanaland, the Karoo-age dykes of the KFA-LIP do not converge systematically towards the inferred Nuanetsi triple-junction assumed to occur above the KFA-LIP plume head [2,6,8]. Though a single giant plume head with several distinct magmatic foci structurally controlled by inherited basement features is still a viable model, the appropriateness of a mantle plume model requires further extensive structural investigations of the Okavango, Sabi-Limpopo and Lebombo dyke/fracture arms, with particular attention paid to stress conditions that prevailed during dyke injection. Additionally, the fact that the onset of Karoo crustal extension starts and generates rift basins more than 50 Ma before the emplacement of Karoo magmatism throughout southern Africa [43–44] does not support an active mantle plume model for the extensional development of the Gondwana Karoo rift basins.

5. Conclusion

Integration of $^{40}Ar/^{39}Ar$ analyses of plagioclase from Karoo dolerites and geological field observations, enables us (1) to evaluate the relationship between magmatism and crustal extension, and (2) to precisely address the duration of the Okavango and Sabi-Limpopo giant dyke swarms in the Karoo igneous sub-province of NE Botswana. Our main conclusions are as follows:

1. The plateau ages for the Okavango N110° dykes are clustered between 179 ± 1.2 Ma and 178.4 ± 1.1 Ma. They show that the ODS/N110° forms a major short-lived magmatic event within the KFA-LIP, pre-dating Gondwana dispersal. The geochemical data reveal that this dyke swarm includes high-Ti tholeiitic mafic magmas.
2. One (and possibly two) dyke of the SLDS/N70° was emplaced at 178.8 ± 0.7 Ma and thus is coeval with the ODS/N110° Karoo dykes.
3. The new ages obtained in the present work are similar to previous ages related to dykes and lava flows from northern Botswana and Zimbabwe. Altogether, the geochronological data related to the northern Karoo igneous sub-province indicate its emplacement between 181 and 178 Ma.
4. Reliable mineral ages from the southern Karoo igneous province in South Africa and Namibia are older than the ages for the northern Karoo igneous sub-province, suggesting that there was a diachronous south to north onset of Karoo magmatism in southern Africa.
5. One mafic dyke from the ODS/N110° yields a minimum age of 883 ± 4 Ma; it is chemically distinct (low-Ti tholeiite) from other N110° dykes. Thus, it shows that the Okavango giant dyke swarm includes both Proterozoic and Jurassic dykes.
6. The role of preexisting basement brittle fabrics on the emplacement of the N110° and N70° Karoo dyke swarms in NE Botswana is emphasized.
7. The appropriateness of previous models assigning the triple-junction-like pattern of Karoo dykes in Nuanetsi to a mantle plume head is questioned by our data.

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