Basement control on dyke distribution in Large Igneous Provinces: Case study of the Karoo triple junction

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Abstract

Continental flood basalts consist of vast quantities of lava, sills and giant dyke swarms that are associated with continental break-up. The commonly radiating geometry of dyke swarms in these provinces is generally interpreted as the result of the stress regime that affected the lithosphere during the initial stage of continental break-up or as the result of plume impact. On the other hand, structures in the basement may also control dyke orientations, though such control has not previously been documented. In order to test the role of pre-dyke structures, we investigated four major putative Karoo-aged dyke swarms that together represent a giant radiating dyke swarm (the so-called "triple-junction") associated to the Jurassic Kano continental flood basalt (>3 x 10^6 km^2; southern Africa). One of the best tests to discriminate between neoformed and inherited dyke orientation is to detect Precambrian dykes in the Jurassic swarms. Accordingly, we efficiently distinguished between Jurassic and Precambrian dykes using abbreviated low resolution, ^{40}Ar/^ {39}Ar incremental heating schedules.

Save-Limpopo dyke swarm samples (n = 19) yield either apparent Protozoic (728–168 Ma) or Mesozoic (131–179 Ma) integrated ages; the Olifants River swarm (n = 20) includes only Protozoic (851–1731 Ma) and Archaean (2470–2872 Ma) dykes. The single age obtained on one N–S striking dyke (1464 Ma) suggests that the Lebombo dyke swarm includes Protozoic dykes in the basement as well. These dates demonstrate the existence of pre-Karoo dykes in these swarms as previously hypothesized without supporting age data. In addition, aeromagnetic and air-photo interpretations indicate that: (1) dyke emplacement was largely controlled by major discontinuities such as the Zimbabwe and Kaapvaal craton boundaries, the orientation of the Limpopo mobile belt, and other pre-dyke structures including shear zones and (2) considering its polygenetic, pre-Mesozoic origin, the Olifants River dyke swarm cannot be considered part of the Kano magmatic event.

This study, along with previous results obtained on the Okavango dyke swarm, shows that the apparent "triple junction" formed by radiating dyke swarms is not a Jurassic structure; rather, it reflects weakened lithospheric pathways that have controlled dyke orientations over hundreds of millions of years. One consequence is that the "triple-junction" geometry can no

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1. Introduction

Continental flood basalts (CFB) are the result of huge magmatic events that are particularly abundant during the Phanerozoic (see a review in [1]). Most of them are linked to the Pangaea mega-continent fragmentation (e.g. Central Atlantic, Paraná-Etendeka, Deccan), and are characterized by the occurrence of giant dyke swarms emplaced in a radial pattern (e.g. [2]). Dyke swarms are significant in part because their geometries are generally considered to be paleo-stress and strain markers and as such they are useful for recognizing mantle plume impact sites [3].
However, dyke swarms are also known as plate discontinuity markers [4] and more recent investigations support the preponderant role played by the pre-existing structure of the lithosphere in controlling dyke-swarm emplacement [5-7] and/or CFB-related rift settings [8,9]. Consequently, the dyke distributions may not reflect a “primary” structural signature but would highlight preexisting lithospheric weaknesses. Nevertheless, few studies have focused on this issue, and the possible influence of various basement structures (e.g., edges of the cratons, mobile belts, shear zones, older dyke swarms) on CFB emplacement is still poorly constrained.

The Karoo CFB formed during a 180 Ma magmatic event occurring prior to the southern冈德温 break-up and the opening of the Indian Ocean. It consists of tholeiitic lava-flows, sills and dykes covering a paleosurface in excess of 3 x 10^6 km^2 [10]. Huge dyke swarms (the N110° striking Okavango, the N70° striking Sava-Linopo, the knee-shaped Okavango River and the N-S Lebombo dyke swarms; Fig. 1; e.g., [11]) appear to converge at the eastern edge of the province defining a four-branch structure (the so-called “triple-junction”; Fig. 1). Although the Karoo “triple junction” has been regarded as a Jurassic, CFB-related structure and a classical example of a mantle plume impact site marker (e.g., [3,12]), it appears that (1) prior to the present work the ages of the dyke swarms were poorly constrained, and (2) the field and petrographic evidence contained in published geological maps suggests that some of these dykes are pre-Karoo [13]. Additionally, a recent study demonstrates that the N110°-striking branch (i.e., Okavango swarm) includes approximately 17% Proterozoic dykes and there is not a reformed structure [7]. Therefore the Karoo “triple junction” provides an excellent opportunity to investigate the influence of basement structures during CFB emplacement and also the validity of the widely presumed

![Diagram](image-url)  

Fig. 2. Maps showing locations of dated samples. The rose diagrams indicate the orientations of the dated dykes in each location (A) Western Tuli basin, n = 6. Ages equivalent are from (a) [11]; (b) [13]. (B) Eastern Tuli basin (Botswana), n = 12. (C) Northern Lebombo (Mozambique), n = 17. (D) Northern Lebombo (Zambia); n = 17. Dashed squares correspond to areas delimited by air photos and cited in Fig. 8 with (B) Botswana and (D) Zambia.
relation between dyke-defined triple-junctions and
mantle plumes.

In this paper, we provide age data on the Save-
Limpopo (19 dates), Olifants River (20 dates) and
Lebombo (1 date) dyke swarms, in order to determine
if they include Jurassic dykes, pre-Karoo dykes or both
(i.e. if the branches are a reformed or inherited struc-
ture; see [7]). Radiometric dating is the only way to
clearly determine if the dykes belong to the Karoo
event, because it is generally impossible to do so with
field or petrographic observations. Plagioclase was
dated rapidly using the 40Ar/39Ar technique with rela-

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Both integrated and high temperature ages (excluding pre-degassing step) are given. Analytical uncertainties are ±2σ.
tively few heating steps; nevertheless, we were able to unambiguously distinguish between Jurassic and older dykes.

Possible basement control on dyke swarm emplacement was also investigated using the southern Africa dyke database [14] and air-photo interpretation. Our results provide new constraints on the Karoo CFB geodynamics and question models relating the Karoo radiating dyke swarm to mantle plume-head impact. We suggest that our results may have general application to relations between CFB-related dyke swarms and basement structures.

2. Geological background

A general description of the province is given by [10]. The N70°-oriented Save-Limpopo dyke swarm is generally poorly exposed and extends over ca. 800 km (Fig. 1) from south-eastern Botswana (Tuli basin) to the north-eastern margin of the Limpopo orogenic belt in eastern Zimbabwe. The swarm consists of a 50-100 km-wide corridor of vertical to sub-vertical dykes with a mean thickness of 27 m [15], although the number of dykes measured (n = 13) is low. The dykes crosscut the Archaean to Proterozoic metamorphic Limpopo belt and the Karoo-Permian-Jurassic sedimentary sequence and lavas, in both the Tuli basin and the Save-Limpopo monoclone. Most of the studied dykes are located within the eastern end of the Tuli basin (n = 12; Fig. 2B; Table 1) near Deutsch where they intrude the basement. Six dykes were also sampled near the western part of the Tuli basin (Fig. 2A). Plagioclase from two dykes yielded plateau (>70% of 39Ar released) and miniplateau (between 50% and 70% of 39 Ar released) ages of 178.9±0.8 (2σ) (Bot0020) and 180.4±0.7 Ma (Bot48), respectively [11,16] (Fig. 2A). Two dykes (Z44, Z46) intruding the Karoo Save-Limpopo monoclone were sampled farther to the east, near the Mutandahe area (Fig. 2C).

The sigmoidally shaped Olikants River dyke swarm is up to 200 km wide [17] and extends from the south-west, where few dykes intrude the Karoo sediments [18], to the north-east, where most (but not all) of the Olikants River dykes stop at the limit between the basement and the Karoo sequence of the Lebombo monoclone (formed by Karoo sedimentary, basaltic and tholithic sequences; Figs. 1 and 2D). The dyke swarm is composed of three successive segments. From south-west to north-east, the dominant direction of the swarm changes from ~N45° to ~N35° (in the ~2.7 Ga Transvaal Supergroup) and rotates back to ~N60° (in the ~3.5 Ga granitoid-greenstone termin; Figs. 1 and 3). Based on different aeromagnetic signatures, the northern Olikants River swarm segment was divided into two sub-swarms [14], a N68° striking minor segment and the N50° striking Palabora segment. We have chosen to investigate a ~10 km section of dykes (n = 18; Table 1 and Appendix A) cropping out along the Letaba River in the northern segment (ca. 21.5°S and 31°E; Fig. 2D). This section comprises not only dykes with a typical Olikants River swarm direction (~N60°, n = 12) but also includes dykes striking E-W (n = 1), N130° (n = 4) and N-S (n = 1); more likely belonging to the Lebombo swarm. In addition, three dykes (SA9-10-11) from the N35°-oriented segment farther to the south (26°S and 30.5°E; Fig. 3) were also investigated. SA9 shows a N70° trend whereas the SA10 and SA11 have a N-S orientation.

The Lebombo dykes have a mean orientation of ~175°N and mainly intrude the Lebombo monoclone (Fig. 1) where they cut the whole Karoo basalt sequence. Two plateau ages of 181.4±0.7 and 182.3±1.7 Ma on plagioclase from these dykes were
provided by [16]. Scarse N-S oriented dykes also occur in the basement, west of the Lebombo [17]. The three N-S oriented dykes are located at about 50 km (SA10 11) and 30 km (SA47) from the Lebombo monolite. It is difficult to determine if these dykes belong to the Lebombo or Olifants River dyke swarm.

3. Petrography

The investigated Jurassic dykes (n=5) belong to the Save-Limpopo swarm (Fig. 2A and C) and consist of dolerites containing clinopyroxene and plagioclase with minor amounts of opaque minerals and olivine phenocrysts (except Z46). They are generally fine to medium grained and are relatively fresh with minor evidence of alteration (mainly sericite, serpentine and chlorite). Proterozoic dykes generally display a coarsen-grained texture. Proterozoic dykes from west of Tuli (n=4; Fig. 2A) show the same paragenesis as Jurassic dykes from which they are hardly distinguishable. On the other hand, Proterozoic dykes from the Save-Limpopo swarm (n=14; Fig. 2B), the Olifants River (n=20; Figs. 2D and 3) and the Lebombo (n=1; Fig. 2D) swarms differ from the Jurassic dykes by the absence of olivine and the occurrence of significant amounts of amphibole, chlorite, ± pyrite and interstitial micro-pyroxene. The Proterozoic rocks are more strongly altered compared to Jurassic dykes and plagioclase is more significantly sericitized. Proterozoic dykes are therefore often but not systematically (as illustrated by West Tuli Proterozoic dykes) characterized by amphibole, chlorite and pyrite, as already mentioned for the Okavango swarm [7]. Therefore, petrographic observations may provide potential clues about the age of the dykes but are not sufficient to discriminate conclusively between Proterozoic and Jurassic dykes.

4. Analytical method

Most analyses were performed using a relatively fast method so-called “speedy step-heating” [7]. It compromises accuracy but decreases the time spent on each sample relative to 40Ar/39Ar conventional method. This is appropriate in this study because we aim only to discriminate between Jurassic and Proterozoic dykes. For each sample, five visibly fresh grains (except Bo46 where we used ~10 mg) were carefully selected using a binocular microscope. The first Ar degassing step (5–27% of 39Ar released) was performed in order to reduce atmospheric Ar and any Ar from secondary minerals. We measured 3, 6, 4, 5 and 9 additional steps for samples SA11, SA47, SA53, SA55 and SA58, respectively (Fig. 4A and Appendix A). We also performed one more detailed Ar/Ar step-heating experiment on the sample Bo46 from the Save-Limpopo swarm (Fig. 4B and Appendix A).

Samples were irradiated for ~70 h in the Hamilton McMaster University nuclear reactor (Canada) in the position 3c with the Bb3gr amphibole standard (1072 Ma. [19,20]; unpublished analyses performed in Nice and Berkeley; cf. discussion in [7,16]). Gas extraction was performed with a CO2 laser 46-9 laser and isotopic measurement carried out with a VG3-600 mass spectrometer using a Daly-photomultiplier system.

![Fig. 4](image-url)
at the University of Nice. Ages are given at the 2σ confidence level. Errors in the age of the monitor are not included in the age calculation. More complete description is given in [7].

It is worth noting that these ages are not meant to be interpreted in detail, as the speedy step-heating method does not allow us to distinguish alteration or excess or loss of argon. Moreover, the appearance of the plagioclase separates and shapes of age spectra suggest that most samples underwent variable perturbations, and so, we report integrated ages for whole samples rather than selected high-temperature steps. Therefore, the ages provided in this study must be used only to differentiate Jurassic and Precambrian dykes (i.e. Karroo-aged or older) and do not provide precise emplacement ages.

5. Geochronological results

Five of nineteen Save-Limpopo dykes yield mostly Jurassic (and one Cretaceous) semi-quantitative apparent ages (Fig. 5A) ranging from 131 ± 2 to 179 ± 4 Ma (2σ error confidence level); the remaining 14 dykes yield substantially older ages ranging from 723 ± 3 to 1863 ± 18 Ma. The sample Bo46 displays a highly disturbed detailed age spectrum (Fig. 4B) with strong evidence of excess argon (as shown by its saddle shape) and alteration, demonstrated by the corresponding variation in $^{37}$Ar/$^{39}$Ar ratio. The Precambrian ages cannot be attributed to excess Ar affecting the Jurassic dykes as (1) there is no intermediate age between Jurassic and Precambrian dykes and (2) the dykes mostly show some petrographic differences (e.g. amphibole and pyrite occurrence).

Twenty dykes located in the northern and southern part of the Okavango River dyke swarm display integrated ages ranging from 851 ± 5 to 2862 ± 6 Ma (Fig. 5B; Table 1 and Appendix A). Although these data do not represent geologically significant ages, two relatively distinct populations appear. The first one, ranging from 700 to 1700 Ma, displays the same apparent age span as the Precambrian dykes and sills (ranging from 850 to 1700 Ma) and the Save-Limpopo dykes. The second population displays older ages between 2.3 and 2.9 Ga showing a noticeable age gap with the first population. No Jurassic age was obtained. More detailed spectra (Fig. 4A) are greatly disturbed showing quasi-symmetric mixture of excess Ar (saddle shaped age spectra) and alteration degassing phases (variable

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Fig. 5  (A-C) "Speedy step-heating" ages for (A) the Save-Limpopo (SLDS; black diamond), (B) the Okavango River (ORDS; empty circle) dyke swarm and (C) comparison between the Okavango (ORDS, empty) data from [7,11], Save-Limpopo and Okavango River dyke swarms; x axis shows number of analyses, (y) apparent ages of the Limpopo dykes vs. x-axis respective orientation; here the cluster in westerly-southerly dykes with Archaean apparent ages and ~7 Ma orientations-fast they were previously attributed to the ~2.7 Ga (?) Pabba dyke swarm. These dates are low-resolution and should only be used to differentiate among Jurassic, Precambrian and possibly Archaean dykes.
$^{37}$Ar/$^{39}$Ar ratio spectra. One N10° oriented dyke, sampled close to the Lebombo and suspected to belong to the Lebombo dyke swarm yielded a date at 12.64 ± 7 Ma (Fig. 2D, Table 1).

6. Discussion

6.1. Geometry of the dyke swarms

Broad-scale observations show that the so-called 'dyke junction' is a more complicated structure than portrayed in some oversimplified sketch maps. First, the Okavango and Save-Limpopo dyke swarms, though both of Karoo age (~179 Ma [7,11,16] and unpublished data) and referred to as a radiating structure, do not radiate from Mwenezi area, but rather consist of two crosscutting swarms [3,21]; Figs. 1 and 6B,C which partially overlap in the Tuli basin area (Figs. 1, 6 and 9). Secondly, the Olimpus River swarm does not converge near Mwenezi but actually stops against the Lebombo monoclinc hundreds kilometers to the south (Figs. 1, 3 and 9). Chavez Gomez [14] provided a summary of main dyke swarm orientations in southern Africa produced by digitizing geological and geophysical maps and investigating magnetic data and published literature. This database does not discriminate between Proterozoic and Jurassic dykes; nevertheless, it does reveal the effect of basement control on dyke emplacement. The results have been reported in Figs. 1, 3, 6 and 7. Subsequently, we used air photos (focused on our sampling area; cf. Fig. 2B,D) to investigate the distribution and orientation of the four branches at more detailed scale (Fig. 8).

6.1.1. The Save-Limpopo and Okavango dyke swarms

Statistical analysis of dyke orientations performed on 1942 dykes from the Save-Limpopo swarm shows a roughly constant direction with a mean strike of 66° ± 16° (1σ, Figs. 6B and 7A) parallel to the Limpopo belt/Zimbabwe craton limit as well as the eastemost (SW–NE oriented) Limpopo structures (Fig. 6A) [22]. On closer inspection, one can observe (1) a subtle rotation of dyke directions from the southwestern (70° ± 18°; n = 900) part of the swarm, seemingly following (and likely influenced by) the Limpopo belt overall orientation and (2) a difference in direction between the dykes intruding the Limpopo belt and the Zimbabwe craton (Fig. 6C).

The basement intruded by the Okavango swarm (109° ± 12°, n = 2129; Fig. 1) is not well known west of the Tuli basin (mainly due to lack of exposure in the Kalahari Desert) but a recent gravimetric study [23] suggests that the Okavango dykes and the Limpopo monoclinc belt largely overlap (Fig. 1). In its easternmost part (east of 28°E), the Okavango dyke swarm displays a small but noticeable rotation from 110° ± 12° (n = 1656) to ~106° ± 14° (n = 604; due to the occurrence of NW–oriented dykes) which might be associated with the more pronounced rotation (U-shaped) of the Limpopo belt (Fig. 6B). Therefore, the Save-Limpopo and Okavango dyke swarms mimic the U-shape of the Limpopo belt that therefore appears to have influenced the dyke emplacement.
Fig. 7. Rose diagram indicating the dyke orientations of the four radiating dyke swarms after [14]. Strike direction is shown by 6° intervals. (A) Save–Limpopo (SLDS). Number of measurements: 1984; largest p-value=375 values (19%); mean orientation=68°±16° (19). B) Okavango (ODS). Number of measurements: 2320; largest p-value=567 values (25%); mean orientation=119°±12°. (C) Ofiants River (ODS) and Palabora (PDS). (1) Ofiants River. Number of measurements: 4775; largest p-value=384 values (8%); mean orientation=52°±27° and (2) Palabora. Number of measurements: 522; largest p-value=139 values (50%); mean orientation 15±18°. (D) Lebombo (LDS). Number of measurements: 650; largest p-value=109 values (17%); mean orientation 177°±16°.

Air photo analysis of a restricted part (see inset in Fig. 2B) of the eastern Tuli basin has been subsequently used to provide a "field-scale" picture of dyke distributions and orientations in this area. The identified and digitized dykes are plotted in rose diagrams (Fig. 8A,B). We split the dykes into two groups: (1) dykes intruding the basement (n=3226; Fig. 8A) and (2) those intruding the Karoo formation (n=945; Fig. 8B). Both groups show similar dominant directions. In the basement, dykes follow variable orientations but mainly strike between N70° and N110°. Dykes intruding the Karoo formation are more scarce than those intruding the basement and their orientations are more clustered, with most striking between N85° and N105°. In both cases, a secondary N–S direction is also apparent (Fig. 8B). We interpret this difference as possibly reflecting the strong contribution of the Precambrian dykes in the basement (Fig. 8A). Additionally, the predominant N90°-oriented dykes similarly follow the Limpopo structure (Fig. 6B); these dykes may belong to the Okavango swarm, and may have been influenced by the Limpopo belt structure (see above), or may represent a distinct E–W dyke swarm as illustrated by the presence of a vast quantity of N90°-oriented dykes in the Letaba region (Fig. 8C–E).

6.1.2. The Ofiants River dyke swarm

The Ofiants River dykes database [12] includes more than 5000 dykes and shows a wider range of dyke orientations than other branches of the radiating structure (Figs. 1, 3 and 7). The dykes strike 45°±21° in the southern zone, 35°±25° in the middle zone and 68±16° in the northern zone [14]. Uken and Watkeys [17] have interpreted the northermost orientation as reflecting (1) a change of the basement nature (Fig. 3) and (2) the existence of multiple dyke generations.

The air photos study is focused on the northern portion of the swarm (Figs. 1 and 2D) in the Letaba region, near the Lebombo. Therefore, the two dyke swarms of Ofiants River and Lebombo appear in this area and in the rose diagrams of Fig. 8C–D. We defined three groups of dykes intruding either basement (n=913), Karoo sandstones of the Clarens formation
(n=87), and the Karoo basalts (n=409). In the basement, the dykes display three dominant orientations with a strike of ∼N50° being most common (Fig. 8C). In the Karoo sediments and lavas (Fig. 8D,E), the dyke directions are more variable with an E–W primary direction. The N50° orientation also exists here as well but is very weakly represented. Air-photo analysis shows that most dykes reported in the basement do not intrude the Jurassic sequence. Therefore, the northern portion of the Olifants River swarm is mainly Precambrian, although a few Jurassic dykes exist.

6.1.3. The Lebombo dyke swarm
The Lebombo dykes are mainly distributed along the Lebombo monocline where they crosscut the Karoo basalt sequence (Fig. 1). They show clustered orientations with a mean of N175°±17° (n=630). In the Karoo basalts and sediments (Fig. 8D,E) the so-called Letaba restricted area shows the N–S dominant direc-
tion of dykes related to the Lebombo dyke swarm. Based on study of air photos (Fig. 8C-E), dykes striking N165°-180° are present in the basement and probably represent a western extension of the Lebombo dyke swarm. N-S dykes also exist within the Limpopo belt (Fig. 8A, B). Therefore, although the Lebombo has probably channeled the main concentration of the N-S dykes, they are more sparsely distributed in the basement to the west (Fig. 8C) and north (Fig. 8A, B) of the Lebombo. We thus suggest that the Lebombo area has possibly constituted a preferential path for magmatic upwelling according to its position at the eastern edge of the Kaapvaal craton. Unfortunately, we cannot evaluate the proportion of Precambrian dykes for this swarm.

6.2. The Karoo dyke swarms: evidence for inherited orientation

$^{40}Ar/^{39}Ar$ “speedy” dating performed on 19 dykes (plus 3 dykes dated in [11, 16], including either basement or Karoo sequences, show that the Save-Limpopo swarm includes both Proterozoic (700-1700 Ma; $\eta=4$) and Jurassic dykes (131-180 Ma; $\eta=8$; Fig 5A). The youngest apparent age of 131 Ma more likely reflects alteration rather than a Cretaceous emplacement age since the “conventional” $^{40}Ar/^{39}Ar$ dates available on the Save-Limpopo dykes reveal a concordant age of ~179 Ma ([11, 16], unpublished data). Therefore, the Karoo-aged N70°/Save-Limpopo swarm shows evidence of structural inheritance from a Proterozoic dyke swarm, along with basement influence marked by discernable rotation of the swarm contiguous to the Limpopo architecture (cf discussion above, Fig 6B).

The Olifants River swarm was investigated in its southern and northern regions. The ages obtained seem to indicate two distinct Precambrian dyke events, ranging from 850 to 1700 Ma and from 2500 to 2900 Ma. Although the ages obtained are not precise emplacement ages, the apparent ages nevertheless define two populations consistent with the two different aero-magnetic dyke signatures reported within this portion of the swarm [17, 14]. No ages consistent with the Karoo event were obtained, although scarce Karoo dykes are probably present in the Olifants River swarm as shown by a few dykes that crosscut Karoo sediments (see above). Therefore, the Olifants River swarm is likely to include two dominant generations, Archaean and Proterozoic, and possibly a minor component of Jurassic dykes. Thus, the Olifants River dyke swarm can no longer be considered as a Karoo-aged dyke swarm, confirming field observations previously mentioned in [13], and the oldest dykes in the swarm define a weakened pathway that was subsequently followed by younger generations of dykes.

The last major branch of the Karoo radiating swarm studied is the N-S Lebombo dyke swarm which also includes the Rood Rand dyke swarm (e.g. [18]). Unfortunately, because the number of outcropping dykes crossing the basement is low, it is difficult to test the effect of inheritance in this dyke swarm. Nevertheless, some dykes intrude the basement on the west side of the Lebombo monocline (Fig. 1; see also [18]). This is the case for (1) the SA47 N-S oriented dyke sampled in the Letaba River (Fig. 2D) that yield an apparent age of 1464 ± 7 Ma (Table I) and (2) two N-S dykes sampled in southern extremity of the Olifants River swarm, showing similar Proterozoic ages but for which relations with Lebombo (and Olifants River) swarms are uncertain.

The inheritance demonstrated for the Olifants, Save-Limpopo and possibly the Lebombo dyke swarms is in agreement with similar data obtained on the N110°-oriented Okavango dyke swarm for which the occurrence of a ca. 1 Ga old N110° oriented dyke swarm clustered in the center of the Jurassic swarm was highlighted [7].

In summary, our results indicate that the Jurassic Save-Limpopo, Lebombo and Okavango dyke swarms parallel Proterozoic dyke swarms, suggesting that dyke emplacement in this region has been repeatedly controlled by features of its ancient basement including craton boundaries and, more subtly, basement belt fabrics. Furthermore, the Olifants River dyke swarm cannot be considered to be dominantly of Karoo age, contrary to previous suggestions [3]. Therefore, the apparent “triple-junction” geometry of these polygenetic dyke swarms cannot be used to infer stress patterns at the time of Karoo magmatism. Rather, the apparent triple junction geometry is actually an artifact that is ultimately imposed by the control of pre-Karoo basement structures on dyke emplacement, as suggested by [13].

6.3. Implication for the mantle plume hypothesis

The origin of the Karoo CFB is still matter of debate, particularly concerning the possible presence of a mantle plume beneath the province (e.g. [24,25]). In the mantle plume model (as defined for instance by [24,25]), hot buoyant mantle rises from deep mantle and upwells into the base of the lithosphere. This impact is predicted to trigger (1) crustal doming and (2) the propagation of magma by fracturing crustal to
supra-crustal levels from a central point (likely to represent the central axis of the plume; for instance, the Mwenze-Tuli region for the Kamo case). Based initially on the outcrop pattern of lavas (i.e. no dykes were yet considered), Cox [28] and Burke and Dewey [29] mentioned the possible link between the Kamo architecture and a mantle plume impact within the Mwenze area (Fig. 1). Subsequent studies on the Kamo giant dyke swarms have led Ernst et al. [2] and Ernst and Buchan [3,12] to propose that the Kamo radiating structure (considering the Save-Limpopo, the Olifants River and the Lebombo swarms as the radiating branches) was consistent with a mantle plume impact.

In this study (and in [7]), we show that the “triple junction” structure is probably an artifact characterized by (1) a strong basement control, (2) the occurrence of Precambrian dykes within at least two (and possibly three) branches (Save-Limpopo and Okavango swarms and possibly the Limpopo swarm), (3) a branch (Olifants River) which is not Jurassic in age contrary to previous suppositions (e.g.,[3,30]) and (4) a branch (the Save-Limpopo) which does not really radiate from the (Mwenze area) focal point. Therefore, the apparent radiating structure is not sufficient to infer the existence of a Jurassic mantle plume impact, because Proterozoic dykes, which cannot be related to a plume impact in Kamo time, define a similar pattern (Fig. 9). It is therefore likely that during Jurassic magmatism, basement structures acted to control the orientation of Kamo dykes. Thus, the Kamo dyke swarm geometry should no longer be used to support the Kamo mantle plume hypothesis; nevertheless, a mantle plume origin for Kamo magmatism remains a possibility.

6.4. The Kamo triple junction and other CFB related dyke swarms

CFB and contemporaneous regional dyke swarms generally associated with continental breakup are considered to provide evidence for plume-induced structure ([12] and references therein), but little consideration is generally given to the idea that basement control is generally given to the idea that basement control could constrain dyke swarm (and CFB) geometry. For instance, rifting events apparently take place preferably along pre-existing orogenic fabrics ([9] and references inside). One of the best examples concerns the breakup of Gondwana and the opening of the Atlantic Ocean occurring along the Hveinynian, Caledonian and Pan-African belts [5]. Here we provide a brief overview of the relations between selected major dyke swarms associated with the Gondwana breakup (Fig. 10) and their basement structures.

Fig. 9. Sketch map of the four radiating dyke swarms based on Ar/Ar ages, aeromagnetic data, and field observations. Plain lines correspond to segments of the swarms in which measurements and observations have been made (this study, [71,16]), dashed lines represent inferred dyke swarm extensions. Densities of dykes within the swarms are not shown. Grey shows the discontinuous intrusion of dykes making up each swarm; dykes intruded prior to the Kamo volcanism (A), and contemporaneously with the ~180 Ma Kamo CFB (B).

Most dykes located on the circum Central Atlanticcontinents are related to the 200 Ma Central Atlantic Magmatic Province (e.g.,[31–34]). Among these dykes, considered to converge towards a focal zone around Florida [35], one of the best-defined swarms consists of WNW-ESE dykes in Liberia and their counterpart in French Guyana. The trend of these swarms follows the Pan-African belt separating the West African and Amazonian cratons. The South Atlantic opening was preceded by intense magmatic activity at 120 Ma forming the Parana Etendeka CFB associated with several major dyke swarms [36]. Among them, the most striking feature is the triple junction formed by the Rio de Janeiro, Minas Gerais and Posto-Guiana dyke swarms in Brazil [37,38]. The two first branches ap-
parenthetically. The Pan-African Ribiers and Kaoko belt directions and the third branch follows the Paleozoic Ponta Grossa arch [39]. To the North, the Rio-Cent-Mirinu dyke swarm [49] is also Paraná-related [41] and extends on the northern wedge of the Sao Francisco craton, in a direction parallel to the Pan-African Paranaiba (and its African counterpart) shear zones [42] which may have controlled the swarm orientation. Another Paraná-Entendes related dyke swarm is the 100-km-wide Henties-Bay-Otjo dyke swarm in Namibia [6] which intrudes (and generally follows) the SW–NE oriented Damara mobile belt. Interestingly, the dykes fan out as they leave the Damara belt and intrude the Congo craton at the easternmost extremity of the swarm [Fig. 10] [6].

The gabbroic dyke swarm of the Red Sea rift paralleling the rift structure was emplaced between 54 and 21 Ma [43]. No basement structural control is apparent for the dyke orientations, but this swarm includes both Neogene and Proterozoic dykes (H.B. and G.F., unpublished data), suggesting that the dyking event associated with the Red Sea opening followed an ancient Proterozoic direction.

Finally we mention the radiating dyke swarms (e.g., [2]) related to the 65 Ma [44] Deccan traps in India. One branch of the swarm intrudes and follows the Central Indian Tectonic Zone related to an Early Proterozoic collisional orogen between the southern and northern Indian blocks [45]. The two other branches are parallel to the western limit of the Indian craton. This brief overview shows that the most prominent dyke swarms related to Gondwana break-up (including those considered to define several triple junctions) mainly follow craton boundaries and are often parallel to mobile belts, shear zones and other pre-existing basement structures [Fig. 10]. The dykes were therefore possibly influenced by pre-existing structures with regard to both location and orientation, as we have shown in the Karoo case. Basement control of CFB-related dyke swarms therefore casts doubt on the “active role” of mantle plumes, if any, in causing the “triple junction” pattern marked by the occurrence of radiating dyke swarms. We suggest that a careful re-examination at field scale is required to better constrain the basement influence on giant dyke swarm emplacement.

7. Conclusions

At/At dating and structural analyses were performed on the radiating dyke swarms widely considered to be
related to the Karoo igneous province including the
Save-Limpopo, the Okavango River and the Limpopo
dyke swarm in order to assess controls on their loca-
tion and orientation. Our data are compared to those
recently obtained on the Okavango dyke swarm [7]. We
find that:

1. Statistical direction analysis suggests that Karoo
dyke orientations are largely controlled by pre-exist-
ing structures that also controlled emplacement of
Precambrian dykes. The general orientations of the
Save-Limpopo (N70°) and the Okavango (N110°)
dyke swarms vary according to the local direction of
the dothropic mobile belt, paralelling craton bound-
aries. N-S striking dykes of the Limpopo swarm are
rare in the Kaapvaal craton and Limpopo belt, but
more abundant at the eastern wedge of the Kaapvaal
craton. Varying orientation of the mostly Precambri-
an Olifants River dyke swarm is systematically asso-
ciated with changing basement lithology. It is thus
suggested that basement structures play a dominant
(but not exclusive) role in controlling the orientation
of these major dyke swarms.

2. The N45°–35°–60° sigmoidally shaped Olifants River
dyke swarm is polygenetic and consists mostly of
Archean and Proterozoic dykes though relatively rare
Karoo dykes are present. Thus, the Olifants River
swarm is not dominantly of Karoo age as previ-
sely speculated. Moreover, this example high-
lights that major extensional structures of the sou-
thern African lithosphere are often used several times
as they constitute favored weakened paths for mag-
matic injections.

3. Excluding the largely Precambrian Olifants River
dyke swarm, two (and possibly three) of the three
major Karoo-aged radiating dyke swarms ambig-
uously include Proterozoic dykes. Therefore, the
N70° (Save-Limpopo), the N110° (Okavango) [7],
and possibly the N-S (Limpopo) dyke swarms
(forming an apparent triple junction) indicate a
strong structural inheritance and preclude a neo-
formed Janusian radiating structure.

4. The apparent triple junction geometry was not in-
duced by the arrival of a deep mantle plume head but
is inferred from previous history of the Kaapvaal
and Zimbabwe cratons. Therefore, this “high
junction” should not longer be used as an argument
for demonstrating (although it does not exclude) the
existence of a Karoo mantle plume.

5. Consideration of regional dyke swarms related to
other Gondwana CFB shows that they too generally
follow pre-existing lithospheric structures such as
craton boundaries, mobile belt orientations, base-
ment fabrics and major shear zones. We conclude
that the location and orientation of dyke swarms
associated with the Gondwana break-up were gen-
erally controlled by ancient basement structures and
were not “forced” by plume head impact.

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Appendix A. Supplementary data

Supplementary data associated with this article can
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