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Direct Mesoproterozoic connection of the Congo and Kalahari cratons in proto-Africa : Strange attractors across supercontinental cycles

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1 Direct Mesoproterozoic connection of Congo and Kalahari
2 cratons in proto-Africa: Strange attractors across
3 supercontinental cycles

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18 **ABSTRACT**

19 Mobilistic plate-tectonic interpretation of Precambrian orogens requires that two
20 conjoined crustal blocks may derive from distant portions of the globe. Nonetheless,
21 many proposed Precambrian cratonic juxtapositions are broadly similar to those of
22 younger times (so-called “strange attractors”), raising the specter of bias in their

construction. We evaluate the possibility that Congo and Kalahari cratons were joined together prior to their amalgamation along the Damara-Lufilian-Zambezi orogen in Cambrian time by studying diabase dikes of the Huila-Epembe swarm and sills in the southern part of the Congo craton in Angola and in Namibia. We present geologic, U-Pb geochronologic and paleomagnetic evidence that these two cratons were directly juxtaposed at ca. 1.1 Ga, but in a slightly modified relative orientation compared to today. Recurring persistence in cratonic connections, with slight variations from one supercontinent to the next, may signify a style of supercontinental transition similar to the northward motion of Gondwana fragments across the Tethys-Indian oceanic tract, reuniting in Eurasia.

INTRODUCTION

Efforts to reconstruct the paleogeographies of Precambrian landmasses have intensified in recent decades (summarized by Evans, 2013), although there is no consensus on the arrangements of cratons in supercontinents such as Rodinia (~900–700 Ma) and Nuna (~1600–1400 Ma). Methods of cratonic reconstruction include tectonostratigraphic comparisons, paleomagnetism and matching fragments of large igneous provinces (LIPs) on now-separated crustal blocks (Bleeker and Ernst, 2006; Li et al., 2008). Ideally, a favored model would be supported by several independent lines of evidence.

Meert (2014) noted the frequent occurrence of hypothesized Precambrian cratonic connections that approximate those of Pangea. Calling such examples “strange attractors,” he suggested the possibility that implicit bias might favor familiar reconstruction models over more exotic possibilities. An alternative explanation might be

lack of plate-tectonic mobility for most of Precambrian time (e.g., Stern, 2005), but mobilistic interpretations are bolstered by many lines of evidence. This evidence include paleomagnetic support for the independent lateral motion of the lithospheric blocks, magmatic arc activity and associated ore deposits related to subduction of oceanic-type lithosphere, and well-documented ophiolites and eclogites back at least to ~2.0 Ga (Cawood et al., 2006; Boniface et al., 2012).

The Ediacaran-Cambrian Damara-Lufilian-Zambezi orogen (DLZO) in southern Africa has been interpreted variously to have formed by closure of a wide ocean basin (e.g., Goscombe et al., 2018) or at most a narrow oceanic seaway (Miller, 1983; Hanson, 2003). One recent argument in favor of the latter hypothesis comes from recent U-Pb dating of the Huila gabbro-norite dikes (Congo craton), which provides a temporal match with the extensive Umkondo LIP (Kalahari craton) at ca. 1110 Ma (Ernst et al., 2013). Nonetheless, evidence in the Damara belt of fully-fledged rifts and passive margins, and an accretionary prism and orogenic foreland basin (Hoffman and Halverson, 2008; Miller, 2008), testify to ocean opening and closure between 750–500 Ma. Can these observations be reconciled in a single tectonic model?

METHODS AND RESULTS

In order to constrain the relative positions of Congo and Kalahari cratons, we conducted a paleomagnetic and U-Pb geochronological investigation of the ca. 1.1 Ga Huila-Epembe (HE) dikes and related mafic rocks across the Congo craton in Angola and northernmost Namibia (Fig. 1), the results of which can be compared to the well-established paleomagnetic pole from the coeval Umkondo LIP from Kalahari (Swanson-Hysell et al., 2015). Methods are fully described in the GSA Data Repository¹. As part of

a broader study on numerous dike swarms exposed in the area, we identified 25 sites (i.e. separate cooling units) in mafic igneous rocks that preserve either a shallow SW or a less common NE characteristic magnetic remanence vector (Fig. 2). Most of these sites are in the generally N- or NNW-trending Huila dikes, including the dike dated by Ernst et al. (2013), which yielded a U-Pb baddeleyite age of 1110 ± 3 Ma. We obtained three new ID-TIMS U-Pb baddeleyite ages (Fig. 3): one from our southernmost region where dolerite dikes near Epembe trend NW (1109 ± 10 Ma), one from a Huila dike with a NE-directed magnetic remanence vector (ca. 1104 Ma), and one from a mafic sill intruding redbeds of the Chela Plateau (1127 ± 8 Ma). The Chela sill yields a virtual geomagnetic pole that is similar to, but predates, our new ca. 1.1 Ga HE dikes paleomagnetic pole; the latter result (34.7°S , 256.5°E , $K = 12.1$, $A_{95} = 8.7^\circ$) is demonstrated to be primary via a positive baked-contact test on a 100-m-wide Epembe dike intruded into host gneiss (Fig. S3). In the baked contact test, host rocks within 1–20 m of the contact show complete remagnetization at the time of dike intrusion, whereas host rocks 33–130 m from the contact exhibit a distinct stable magnetic remanence direction. Additional baked-contact tests were inconclusive (Fig. S4; [see footnote 1](#)). Sites in proximity to the Kaoko belt, which is contiguous with the Damara belt (Fig. 1), bear distinct WSW or NW downward magnetic remanence directions interpreted as Ediacaran-Cambrian overprints by comparison to the Congo craton's apparent polar wander path from that time interval (Rapalini, 2018). The new HE pole fulfills all seven of the Van der Voo (1990) reliability criteria and can be called a paleomagnetic keypole (Buchan, 2013).

PALEOGEOGRAPHIC IMPLICATIONS

91 The HE paleomagnetic pole yields a relatively low latitude for the Congo craton
92 at ca. 1.1 Ga, and permits a direct connection between Congo and Kalahari cratons (Fig.
93 4b), the latter of which remained in tropical low latitudes throughout late
94 Mesoproterozoic time (Gose et al., 2013). Data presented by Ernst et al. (2013) and de
95 Kock et al. (2014) show that the Huila dikes are fractionated continental tholeiites with
96 compositions similar to much of the Umkondo LIP, and those workers hypothesized that
97 the dikes represent a radial arm of the LIP emanating from a focus in the Kalahari craton.
98 Like the majority of published Umkondo paleomagnetic data, the HE remanence
99 directions are southerly and upward, favoring the same-hemisphere polarity option for
100 those two suites as shown in Figure 4b. Following Swanson-Hysell et al. (2015) we
101 propose that south-seeking magnetic remanences represent normal polarity for the Congo
102 and Kalahari data; this allows the ca. 1.1 Ga reconstruction to be more consistent with
103 both the final arrival of Kalahari in Rodinia (Swanson-Hysell et al., 2015; Kasbohm et
104 al., 2016) as well as the derivation of Congo from the breakup of Nuna (Salminen et al.,
105 2016). Based on the distribution of Umkondo igneous rocks in the Kalahari craton,
106 including two well-constrained dike swarms, de Kock et al. (2014) inferred the existence
107 of a major magmatic center for the LIP near the northwest edge of the craton.
108 Significantly, the HE dikes point directly to that magmatic center in the reconstruction in
109 Fig. 4b, which was arrived at independently using our new paleomagnetic data.

110 The simplest possible kinematic evolution from the proposed ca. 1.1 Ga relative
111 reconstruction of Congo and Kalahari cratons to that of post-Damara time would be a
112 ~45° pivot around a local Euler pole. If the reconstructed relative position of Congo and
113 Kalahari persisted through Rodinia breakup, then the Damaran evolution between the two

cratons might be comparable to the evolution of the Pyrenees in the Cretaceous (Visser and Meijer, 2012). This scenario would support models for the DLZO involving a narrow ocean basin (Miller, 1983; Hanson, 2003). We propose, however, that the two cratons became far separated after ca. 1.1 Ga. Kalahari converged toward Laurentia across a distance of ~6000 km to arrive in Rodinia by ca. 1.0 Ga (Loewy et al., 2011). Congo's post-1.1 Ga motion and eventual location relative to Rodinia are less clear, but its moderate-high latitude at ca. 0.92 Ga (Evans et al., 2016) is incompatible with Kalahari's low-latitude position within Rodinia at that time. Such a scenario suggests a cause-and-effect relationship between emplacement of the Umkondo LIP and initial separation of the Congo and Kalahari cratons.

Our kinematic model through the Rodinia-Gondwana supercontinental cycle thus proposes that Congo and Kalahari were "strange attractors" in Meert (2014) terminology; their relative positions were similar before and after a large separation across the globe. We consider the age overlap and paleomagnetic data from the HE dikes and Umkondo LIP, together with alignment of the HE dikes with a major focus of Umkondo igneous activity on the Kalahari craton, as compelling support for the proposed 1.1 Ga reconstruction. How can cratons separate by large distances in a mobilistic plate-tectonic scenario, and then return to rejoin each other?

The reunion of Gondwana-derived terranes in Asia serves as an example of how such moderate reshuffling can occur from one supercontinent to the next, despite wide oceans having once intervened (e.g., Metcalfe, 2011). Figure 5 shows Arabia and Australia reconstructed in their positions relative to India during mid- to late Mesozoic time, utilizing the model of Seton et al. (2012). The difference between ca. 160 Ma and

present-day locations of Arabia might appear as a simple ca. 60° pivot around a local Euler pole, but the ca. 80 Ma reconstruction divulges a history of ocean widening and narrowing between Arabia and India. A more dramatic set of motions is demonstrated by Australia. If current convergence relative to Eurasia continues (e.g., DeMets et al., 1994), the Australian continent will collide with Korea and Japan ~80 million years into the future, and the ensuing positions of India and Australia will superficially resemble their Gondwanan ancestry. Depending on the degree of lateral escape of the once-intervening island arcs during collision, there may be scant evidence of the ~5000 km-wide ocean that currently separates those two landmasses.

A dynamic explanation for this process appeals to long-term stability of circum-supercontinental subduction systems, with that surrounding Pangea as the best understood example (Richards and Engebretson, 1992). In a mantle reference frame, Australia's late Mesozoic motion had a significant eastward component. However, for the last 45 million years, an abrupt change to northward motion along the ancient pan-Pacific subduction system suggests that it has become confined to that system (Yoshida, 2016). If, more generally, the fragments of supercontinents have motions that are similarly restricted to ~90° from the host landmass centroid—then one might expect only limited reshuffling of cratons through supercontinental cycles. Thus, the “strange attractor” phenomenon may have a plausible physical basis, even within a mobilistic, plate-tectonic conceptual framework.

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FIGURE CAPTIONS

Figure 1. Site locality map with a Google Earth™ background. Boundary of Kaoko belt allochthons from Goscombe et al. (2018). Inset abbreviations: DLZO = Damara-Lufilian-Zambezi orogen, Kala = Kalahari craton, SF = São Francisco craton, W.Afr. = West African craton. U-Pb baddeleyite age for site S1642 is from Ernst et al. (2013); other baddeleyite ages farther south are from this work.

Figure 2. (A) Equal-area projection of paleomagnetic results from the studied mafic intrusions in Angola and Namibia (Table DR2; [see footnote 1](#)). Geochronological data for the dated dikes are listed in Tables S1 and S2.

Figure 3. Wetherill U–Pb ID-TIMS concordia diagrams for analyzed baddeleyite from dikes S1601 (sample: S1601G) and W1518 (sample: W1518) and from sill S1608

(sample: S1608G) with the error ellipses demarcating individual fractions analyzed at 2σ ;
for details see Table DR1 (see footnote 1).

Figure 4. Paleogeographic relationships between Congo and Kalahari cratons. (A) Present-day configuration with discordant paleomagnetic results from the HE dikes (C1; this work) and Chela sill (this study) versus the Umkondo LIP (K1; Swanson-Hysell et al., 2015). (B) Kalahari craton and the Umkondo pole rotated to present-day Congo craton (Euler rotation -12.8°N , 019.0°E , -43.2°) in the proposed relative configuration at 1.1 Ga. In this reconstruction the HE dikes on the Congo craton (HE), the Dibete (D) and the Proterozoic Okavango (PO) dikes on the Kalahari craton (red lines) represent a radial arm of the Umkondo LIP emanating from a focus near the edge of the Kalahari craton (red star) previously inferred by de Kock et al. (2014). (C) 1.1-Ga paleogeographic reconstruction of Congo, Kalahari, and Laurentia (poles listed in Table S3). Euler rotations: Congo to rotation axis (-05.7°N , 007.1°E , -124.2°) and Laurentia to rotation axis (49.7°N , 168.6°E , $+66.2^\circ$). Blue arrow indicates relative motion of the Kalahari craton toward its subsequent collision with Laurentia in Rodinia.

Figure 5. Reconstructed Gondwana-derived cratons in a fixed-India reference frame, using the rotation model of Seton et al. (2012). Orange = Arabia, Purple = India, Red = Australia.

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317 1GSA Data Repository item 2018xxx, methods and detailed results description,
318 geochronology and paleomagnetic data tables, and additional data figures, is available
319 online at <http://www.geosociety.org/datarepository/2018/>, or on request from
320 editing@geosociety.org.

Salminen et al. Figure 1

Salminen et al. Figure 2.

Salminen et al. Figure 3

Salminen et al. Figure 4

Salminen et al., Figure 5

GSA Data Repository

Direct Mesoproterozoic connection of Congo and Kalahari cratons in proto-Africa: Strange attractors across supercontinental cycles

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S1. METHODS

S1.1 Geochronological methods

Baddeleyite is a common accessory phase in mafic intrusions and a proven U-Pb geochronometer. Therefore, the separation of baddeleyite was attempted on several mafic dolerite dike samples that were the least altered due to metamorphism, and were sufficiently coarse-grained. This separation

procedure was done at the Department of Geology, Lund University. The water-based separation technique of Söderlund and Johannsson (2002) was employed from cut and crushed rock, and was successful in yielding sufficient baddeleyite from samples W1518, S1601G and S1608G. These samples were studied for U-Pb geochronology, employing the same techniques as described by Gumsley et al. (2015) using isotope dilution thermal ionization mass spectrometry (ID-TIMS).

After handpicking, three fractions of the best-quality baddeleyites grains from each of the three samples were assembled. One to five grains per fraction were transferred to Teflon capsules in ethanol. The fractions were then rinsed repeatedly in ultrapure 7 M HNO₃ and H₂O to improve the Pb blank during measurement. For dissolution, an ultrapure HF:HNO₃ (10:1) solution was added to the individual Teflon capsules with a ²⁰⁵Pb-²³³⁻²³⁶U tracer solution. The capsules were placed for 3 days in an oven running at 190°C. After dissolution, the capsules were cooled and dried on a hot plate at 100°C. Ultrapure 6 M HCl together with 0.25 M H₃PO₄ was added to each capsule, and once again, the capsules were placed on a hot plate to dry down. The remaining droplet containing the sample fractions was dissolved in 2 uL silica gel before being loaded onto outgassed Re filaments.

The U and Pb isotopic compositions were measured at the Department of Geosciences in the Swedish Museum of Natural History using a Thermo Scientific - Finnigan TRITON mass spectrometer. The Pb isotope compositions of the samples were measured in dynamic (peak jumping) mode using a secondary electron multiplier at temperatures between 1210°C to 1240°C. Pb isotopes (²⁰⁴Pb, ²⁰⁵Pb, ²⁰⁶Pb and ²⁰⁷Pb) were measured for between 80 and 120 cycles. U isotopes (²³³U, ²³⁶U and ²³⁸U) were measured for between 40 and 120 cycles at temperatures between 1310°C and 1360°C, also in dynamic mode. The procedural blank in the isotope laboratory at the Swedish Museum of Natural History was determined to be 0.05 pg for U and 0.5 pg for Pb. Mass fractionation for Pb was determined by replicate analyses of the common and radiogenic NIST standard reference materials SRM 981 and SRM 983. The determination of U fractionation was obtained directly from the measured ²³³U/²³⁶U isotopic ratio. The Stacey and Kramers (1975)

modelled common Pb evolution curve was used to estimate the initial Pb compositions at the age of the sample. The decay constants used were 1.55125×10^{-11} (^{238}U) and 9.8485×10^{-10} (^{235}U), with the isotopic composition of U being $^{238}\text{U}/^{235}\text{U} = 137.88$ (Jaffey et al., 1971; Steiger & Jäger, 1977).

The uncertainty in age includes ± 0.04 in Pb fractionation and $\pm 50\%$ in Pb and U blank concentration. Uncertainties in Pb blank composition are 2.0% for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.2% for $^{207}\text{Pb}/^{204}\text{Pb}$. The final treated analytical results were calculated and plotted using the Microsoft Excel Macro, Isoplot (Ludwig, 2003), excluding decay constant errors.

S1.2 Paleomagnetic methods

For paleomagnetic studies, we sampled 35 sites representing 34 separate cooling units (33 dikes and one sill) in the southern part of the Congo craton in Angola and in Namibia (Table S2). Sampled dikes trend from N-S to NNW-SSE. The dikes show vertical to subvertical dips at sites where the contacts between dikes and host rocks are visible. Sill S1608 intrudes quartzite (bedding 33° toward 025°); an apophysis from the sill penetrates the overlying quartzite, confirming an intrusive relationship. Samples were mainly taken with the portable water-cooled gasoline field drill. Block samples were taken from one of the dikes (site S1646). Six to twelve oriented 2.5-cm-diameter core samples were collected from each cooling unit. Baked host and unbaked host rock at eight sites were sampled (at site S1610 only block samples were taken) for baked contact tests (Everitt and Clegg, 1962). Six to 25 samples were collected from each baked contact test site. Cored samples were oriented using solar and magnetic compasses, whereas block samples were oriented using magnetic orienting. We screened possible effects of lightning strikes on outcrops with a magnetic compass. Due to limited sizes of outcrops, minor deflections were unavoidable at a few sites. Cored samples were cut into several specimens with a non-magnetic dual-blade saw at Yale University. Specimens were split into two parts, which were measured in the magnetically shielded room of the paleomagnetic laboratory at the Department of Geology and Geophysics at Yale

University, USA, and in the Solid Earth Geophysics Laboratory at the University of Helsinki, Finland. At Yale University after measurement of the natural remanent magnetization (NRM), the samples were cycled through the Verwey transition at $\sim 120^\circ \text{ K}$ (Verwey, 1939) by immersing them in liquid nitrogen in order to reduce the viscous component carried by larger magnetite grains (Schmidt, 1993). The specimens were then thermally demagnetized using a nitrogen-atmosphere ASC Scientific model TD-48SC furnace. At the University of Helsinki part of the specimens underwent stepwise demagnetization using the in-line static 3-axis alternating field (AF) system paired to a 2G cryogenic magnetometer, and part were thermally demagnetized using an argon-atmosphere ASC Scientific model TD-48SC furnace. Demagnetization was continued until the magnetic intensity of the specimens dropped below system noise level or until the measured directions became erratic and unstable. Both the thermal and AF (for most of the samples) methods were effective and results from both laboratories are comparable.

Principal-component analysis (Kirschvink, 1980; Jones, 2002) was used to isolate the characteristic remanent magnetization (ChRM) for specimens displaying near-linear demagnetization trajectories. The best-fit line was used if defined by at least five consecutive demagnetization steps that trended toward the origin. The maximum angle of deviation (MAD) was less than 10° for most of the accepted specimens. At sites S1601, S1602, S1604, and S1605 MAD as high as 25° was accepted for some of the specimens if the obtained direction was in line with the directions of the specimens with lower MAD from the same cooling unit. The mean directions were calculated using Fisher statistics (Fisher, 1953) to compute a site mean, giving unit weight to each sample (in cases of two specimens per sample each specimen was assigned 0.5 weight). The site mean was accepted for further calculation if it was obtained from four or more separate samples. We used the constant cutoff angle of 45° commonly used to exclude transitional virtual geomagnetic poles (VGPs) (e.g., Johnson et al., 2008). The maximum deviation of VGPs from the mean paleopole was 41° .

S2. RESULTS

S2.1 Geochronological results

The extracted baddeleyite grains from the samples were between 20 μm and 50 μm in length and are medium brown in color. In sample W1518, a total of three baddeleyite fractions were analyzed (Bd1–3; Table S1), with each fraction being composed of between two and three grains. Regression comprising the three fractions yields upper and lower intercepts of 1109 ± 10 Ma and 447 ± 270 Ma, respectively (with a MSWD < 0.1 ; Fig. 3). Concordance varies between $\sim 96\%$ and $\sim 99\%$, with the most concordant baddeleyite fraction having a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 1101 ± 3 Ma (2σ). We interpret the upper intercept age of 1109 ± 10 Ma to date crystallization of this intrusion. A subordinate fraction of baddeleyite in all these samples have frosty surfaces, indicative for secondary zircon formed during a later event of alteration or metamorphism. We thus attribute the lower intercept of 447 ± 270 Ma to a younger Cambrian (possibly Pan-African) event during which baddeleyite was partly converted to zircon in the presence of silica.

The three fractions of sample S1601G plot moderately discordant (2-3 %), and have scattered $^{207}\text{Pb}/^{206}\text{Pb}$ dates between 1115 Ma and 1097 Ma which precludes meaningful linear regression and a conclusive age interpretation for this sample. The weighted $^{207}\text{Pb}/^{206}\text{Pb}$ mean is 1104 ± 4 Ma (2σ) but is associated with a high MSWD value of 7.1. If discordance of individual fractions was the result of a Pan-African thermal event combined with younger (recent?) diffusional Pb-loss, as depicted in Figure 3 by the two dotted reference lines from 1110 Ma to 550 Ma and from 1110 Ma to 0 Ma, that could explain the scattered analyses. We admit the ambiguous result of this sample and therefore only an approximate age of ~ 1104 Ma (the weighted mean of $^{207}\text{Pb}/^{206}\text{Pb}$ dates) can be assigned to this sample.

Three fractions (Bd1–3), with between 1 and 3 baddeleyite grains in each fraction, were analyzed for sample S1608G (Table S1). These fractions produced $^{207}\text{Pb}/^{206}\text{Pb}$ dates between 1129 Ma and 1097 Ma. We favor the weighted mean of $^{207}\text{Pb}/^{206}\text{Pb}$ dates of the two near-concordant fractions Bd-1 and Bd-2, i.e. 1127 ± 8 Ma, as the most reliable age estimate for this sample (Fig. 3).

S2.2 Paleomagnetic results

Most dike sites exhibited one or two components of remanent magnetization (Fig. S1). Based on thermomagnetic analyses and unblocking temperatures ($\sim 500\text{--}580^\circ\text{C}$) the ChRM is typically carried by (titano)magnetite. The ChRM of sill S1608 is carried by both magnetite and hematite (Fig. S1) and due to age difference from the dikes this is excluded from the mean. Twenty-three of the accepted sites show consistent ChRM with shallow to intermediate, mainly upward directions, generally with SW declination, and two of the accepted sites show ChRM with shallow downward directions with NE declination (Table S2; Fig. S2). The mean directions of these two polarity groups pass the reversal test of McFadden and McElhinny (1990), but the classification level is indeterminate due to low number of sites showing the NE declination (obtained angle between the directions: 18.2° and critical angle: 25.2° ; Table S2). Two of the most westerly Angolan sites (S1629 and S12EN) and one site from Namibia (JS1508) show NW-down and WSW-down directions, which are interpreted to date from regional low-grade metamorphism of Ediacaran-Cambrian age (possibly related to the adjacent Kaoko orogen). Site S12EM, which shows scattered ChRM directions, is one of the most westerly Angolan sites and samples were moderately weathered. Site S1654 also shows scattered ChRM directions: low- to moderate-temperature and low-coercivity remanent magnetization components for these samples were scattered and not coherent enough to produce clustered means for mean calculations.

Host rocks at eight sites were sampled for baked contact tests (Figs. S3 and S4). Reliability of the new HE dikes pole is supported by a baked-contact test on site L14E07 in Namibia (Fig. S3). The $\sim 100\text{-m}$ wide dike yields intermediate SW-upward ChRM typical for the HE swarm. Several baked foliated mafic gneiss samples 1.3–50 m from the dike margin show ChRM directions similar to the dike. Samples between 35 m and 100 m from the dike margin commonly show steep upward NW directions. For a second test, sill site S1608 yields a shallow SW-downward ChRM, and baked

154 quartzite in contact with the top of the sill shows a similar shallow SW subhorizontal magnetization
155 direction; subhorizontal purple mudstones ~100m higher in the sedimentary succession show a
156 similar direction, but it is not certain whether this indicates pervasive remagnetization of the
157 sedimentary strata, or whether they are only slightly older than the sill. Attempted baked contact
158 tests for sites S1602, S1655, L14E05, and L14E06 were inconclusive mainly due to scattered
159 ChRM directions in the host rock. The ChRM for dike D1604 is horizontal with SW declinations,
160 but baked host-rock samples show both horizontal East (unblocking below 580°C) and horizontal
161 West (unblocking below 350°C) directions.

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TABLES

TABLE S1. ID-TIMS BADDELEYITE ISOTOPIC DATA FROM THE DIKES W1518 AND S1601 AND FROM THE SILL S1608

Analysis number (number of grains)	U/Th	Pbc/ Pbtot [*]	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²³⁵ U	± 2σ % err.	²⁰⁶ Pb/ ²³⁸ U	± 2σ % err.	Rho	²⁰⁷ Pb/ ²³⁵ U abs. err.	± 2σ	²⁰⁶ Pb/ ²³⁸ U abs. err.	± 2σ	²⁰⁷ Pb/ ²⁰⁶ Pb abs. err.	± 2σ	Concordance
			raw [†]	[corr] [§]				[age, Ma]							
<i>S1608G - 1127 ± 8 Ma (weighted mean ²⁰⁷Pb/²⁰⁶Pb)</i>															
Bd-1 (1 grain)	13.8	0.702	48.3	1.9996	2.2498	0.1876	1.2925	0.61	1115.4	15.2	1108.4	13.2	1129.0	35.6	98.2
Bd-2 (2 grains)	10.4	0.245	223.8	1.9828	0.7743	0.1862	0.6494	0.82	1109.7	5.2	1100.8	6.6	1127.1	8.9	97.7
Bd-3 (3 grains)	0.6	0.093	466.3	1.8682	0.6123	0.1781	0.5315	0.85	1069.9	4.0	1056.5	5.2	1097.3	6.5	96.3
<i>S1601G - ca. 1104 Ma</i>															
Bd-1 (3 grains)	7.9	0.139	443.2	1.9392	0.9692	0.1832	0.8979	0.90	1094.7	6.5	1084.5	9.0	1115.1	8.6	97.3
Bd-2 (3 grains)	0.6	0.067	682.3	1.9026	0.9353	0.1813	0.8718	0.90	1082.0	6.2	1074.3	8.6	1097.6	8.1	97.9
Bd-3 (5 grains)	9.3	0.064	1005.3	1.9110	0.6205	0.1822	0.5732	0.90	1084.9	4.1	1079.1	5.7	1096.6	5.4	98.4
<i>W1518 - 1109 ± 10 Ma (upper intercept)</i>															
Bd-1 (2 grains)	48.0	0.123	375.4	1.8058	1.5939	0.1736	1.5295	0.92	1047.6	10.4	1031.7	14.6	1080.7	12.5	95.5
Bd-2 (2 grains)	47.1	0.044	982.7	1.9311	0.3398	0.1837	0.3022	0.87	1091.9	2.3	1087.2	3.0	1101.4	3.4	98.7
Bd-3 (3 grains)	35.0	0.164	261.2	1.9055	0.7891	0.1815	0.6589	0.82	1083.0	5.3	1075.3	6.5	1098.7	9.0	97.9

Note: Sample S1608G is from the sill S1608; sample S1601G is from the dike S1601, sample W1518 is from the dike W1518

^{*} Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).

[†] Measured ratio, corrected for fractionation and spike.

[§] Isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (0.5 pg Pb and 0.05 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample.

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TABLE S2. PALEOMAGNETIC DATA FOR EACH SITE IN HUILA-EPEMBE MAFIC INTRUSIONS

Site	Age (Ma)	SLat (°S)	SLon (°E)	N/n	B	D (°)	I (°)	k	a95 (°)	PLat (°N)	PLon (°E)
S1608*†	1127±8§	16.71205	13.14839	4/7	0	237.3	17.4	24.9	18.8	-34.2	283.0
										K=31.5	A95=16.6
S1601#	ca. 1104§	17.33856	13.92666	10/13	1	024.4	20.7	18.0	11.7	52.7	056.2
S1605#		17.32328	13.89552	6/8	1	039.1	08.7	07.2	26.7	45.3	078.3
S1602†		17.33205	13.87869	6/7	1	212.5	-15.1	11.8	20.4	-49.4	250.3
S1604		17.33114	13.88415	6/8	1	231.5	-34.5	19.0	15.8	-27.7	250.0
S1606		17.29864	13.92193	6/8	1	204.1	-37.6	11.2	20.9	-43.2	223.1
S1607*		16.99194	13.72447	5/9	0	306.2	10.2	06.8	31.7	-	-
S1629*		15.68298	12.26259	8/12	0	252.2	46.3	07.0	22.6	-	-
S1637		15.52762	13.31250	6/9	1	242.1	-09.3	17.3	16.6	-25.4	270.0
S1638, S12EK		15.51881	13.34103	8/12	1	232.7	20.3	12.4	16.4	-38.9	285.2
S1642	1110 ± 3**	15.26252	13.55929	6/11	1	234.3	-09.4	16.4	17.0	-32.9	267.2
S1646		15.05847	13.22374	8/13	1	214.1	-22.2	67.5	06.8	-46.9	246.8
S1647		14.87991	13.13260	9/9	1	206.0	-05.8	10.4	16.7	-58.5	250.7
S1650		14.72857	13.34138	8/12	1	213.6	-05.7	24.1	11.5	-52.5	258.7
S1651*		14.71335	13.33191	7/8	0	152.9	19.7	13.7	16.9	-	-
S1654*§§		14.67431	13.35023		0	-	-			-	-
S1655†		14.67432	13.35103	7/7	1	221.3	-15.6	57.4	08.0	-43.2	257.0
S1659		14.71807	13.39359	8/13	1	266.4	-13.1	26.5	11.0	-01.7	275.9
S12EI†		15.56163	13.26660	5/6	1	218.6	-18.1	29.8	14.2	-44.2	252.8
S12EJ main*		15.52745	13.30506	7/7	0	166.5	05.2	63.2	07.7	-	-
S12EJ satellite		15.52745	13.30506	6/6	1	266.9	-15.9	161.2	05.3	-00.7	274.6
S12EM*§§		15.88349	12.23204		0	-	-			-	-
S12EN*		15.88396	12.25305	5/5	0	347.0	61.3	103.5	07.6	-	-
JS15A07		17.22023	13.64281	10/10	1	263.8	-06.0	28.5	09.2	-05.0	278.8
JS15A08*		17.21996	13.64217	5/5	0	260.4	73.3	11.2	23.9	-	-
L14E05+D1607†		17.55524	13.57151	12/12	1	246.2	-34.7	46.4	06.4	-15.6	256.7
L14E06†		17.55206	13.58556	6/6	1	271.7	-34.4	46.7	09.9	07.2	265.6
L14E07††		17.55484	13.58333	8/8	1	221.8	-36.9	84.5	06.1	-33.9	242.5
W1516		17.52081	13.53650	10/10	1	216.3	-40.8	17.3	11.9	-35.1	233.9
W1517		17.52904	13.53037	8/8	1	216.6	02.1	28.0	10.7	-50.5	262.9
W1518	1109 ± 10§	17.52966	13.52843	7/7	1	232.0	-52.8	52.4	8.4	-18.0	237.1
D1603		17.54996	13.57063	10/10	1	240.3	-32.3	51.0	6.8	-21.2	255.8
D1604†		17.60256	13.65184	5/5	1	230.9	-09.5	33.8	13.3	-35.0	264.4
D1606		17.57945	13.66880	10/10	1	184.8	-26.0	6.6	20.3	-55.2	201.9
MEAN				191/228	25	228.3	-20.7	10.0	9.6	-34.7	256.5
										K=12.1	A95= 8.7
Means for reversal test***											
MEAN NE (polarity inverted)				12/15	2	212.1	-14.9			-49.7	248.3
MEAN SW				179/213	23	229.9	-21.1	9.6	10.3	-33.1	257.1
Obtained angles of reversal test										γ=18.2	γ _c =25.2

167 Note: SLat, SLon are the site latitude and longitude. N (n) is the number of samples (specimens) used to calculate the
168 paleomagnetic declination (D) and inclination (I); a95 and k are the 95% confidence envelope and the concentration
169 parameter for the paleomagnetic direction. B is the number of sites used for a between-site mean direction, where 1(0)
170 indicates sites included (excluded) for calculation of the mean direction. PLat and PLon are the latitude and longitude of
171 the virtual geomagnetic pole (VGP). A95 and K are the 95% confidence envelope and the concentration parameter for
172 VGP distribution. γ (γ_c) is obtained (critical) angle between the mean directions of different polarities (McFadden and
173 McElhinny, 1990).

174 *Site excluded from the calculation of the mean direction.

175 †Site for attempted baked contact test.

176 §Age from this study.

177 #Polarity of the ChRM direction has been reversed for mean pole calculation

178 **Age from Ernst et al. (2013).

179 ††Site for positive baked contact test.
180 §§Significantly scattered within-site directions.
181 ***Reversal test of McFadden and McElhinny (1990) using software of Koymans et al. (2016)
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Pole	Plat (°N)	Plon (°E)	A95	Reference	Age (Ma)	Age references
Congo						
Huila-Epembe	-34.7	256.5	8.7	This work	1109 ± 10; 1110 ± 3; ca. 1104	This work; Ernst et al., 2013
Kalahari						
Umkondo mean	-64.0	222.1	2.6	Swanson-Hysell et al., 2015	1108.6 ± 1.2; 1112.0 ± 0.5	Hanson et al., 2004 (range of ages)
Laurentia						
Seagull intrusions	42.0	233.4	7.1	Borradaile and Middleton, 2006	1112.8 ± 1.4	Heaman et al., 2007
Coldwell Complex (R) centers A,B,C	46.8	203.1	4.2	Kulakov et al., 2014	1108 ± 1	Heaman and Machado, 1992
Mamainse Point volcanics–Lower R1	47.5	226.7	8.0	Swanson-Hysell et al., 2009	n/a	
Powder Mill Group (R) (Siemens Creek Formation)	45.8	214.0	9.2	Palmer and Halls, 1986	1107.3 ± 1.6	Davis and Green, 1997
Osler Volcanics–R	43.1	194.5	5.9	Halls, 1974	1107.4 +5/-4; 1105 ± 2	Davis and Green, 1997

184 Note: Plat – pole latitude; Plong – pole longitude; A95 – 95% confidence circle of the pole

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191 **Figure S1.** Typical orthogonal vector plots of demagnetization (vertical/horizontal projections
192 shown by open/filled symbols) from mafic intrusions in Angola and Namibia for samples from
193 eight dikes and for one sample from a sill (S1608I). Numbers (with mT) indicate thermal (AF)
194 demagnetization step.

Figure S2. Site-mean paleomagnetic remanence directions for twenty-five HE dikes and one sill in Angola and Namibia (Table S2). Sill site S1608 was excluded from the mean due to age difference with other included sites. Tilt correction for the sill S1608 was done according to the bedding of the overlying, intruded quartzite (strike 295°, dip 33°NE) (see section 1.2.). Stereoplots show the paleomagnetic directions with the 95% confidence circle for each site. Open/closed symbol indicate upper/lower hemisphere. U-Pb ages given for three sites are from Ernst et al. (2013) and this work.

Figure S3. Positive baked contact test for the Epembe dike L14E07; numbered points indicate host-rock distances in meters from the dike contact. Open/closed symbols indicate upper/lower hemisphere.

211 **Figure S4.** Paleomagnetic results of attempted baked contact tests for six of the HE dike sites and
212 for one sill in Namibia and Angola. Tilt correction for the sill S1608 was done according to the
213 bedding of the overlying, intruded quartzite (strike 295°, dip 33°NE). Bedding of the purple shale
214 100m stratigraphically higher than the quartzite is subhorizontal (strike 175°, dip 07°W).
215 Open/closed symbols indicate upper/lower hemisphere. Numbers for baked and unbaked host rock
216 samples denote the distance from the dike margin in meters.

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