Coeval Large-Scale Magmatism in the Kalahari and Laurentian Cratons During Rodinia Assembly

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We show that intraplate magmatism occurred 1106 to 1112 million years ago over an area of two million square kilometers within the Kalahari craton of southern Africa, during the same magnetic polarity chron as voluminous magmatism within the cratonic core of North America. These contemporaneous magmatic events occurred while the Rodinia supercontinent was being assembled and are inferred to be parts of a single large igneous province emplaced across the two cratons. Widespread intraplate magmatism during Rodinia assembly shows that mantle upwellings required to generate such provinces may occur independently of the supercontinent cycle.

Formation of large igneous provinces (LIPs) involves the emplacement of enormous volumes (typically millions of cubic kilometers) of mantle-derived magmas in geologically short time frames [<1 to 2 million years (My)] (*1*, *2*). Most of the better known LIPs are less than 300 My old and typically comprise flood basalts, generally less abundant felsic volcanic rocks, and associated dike swarms, sill networks, and mafic and ultramafic layered intrusions (*3*). Here we employ paleomagnetic correlation and single-crystal U-Pb baddeleyite and zircon dating to show that a 1106- to 1112-My-old LIP, the Umkondo province, can be traced over much of the Kalahari craton and was emplaced synchronously with widespread intraplate magmatism in Laurentia, the cratonic core of North America.

Umkondo igneous province. The Umkondo province is named for extensive diabase sills, up to hundreds of meters thick, that intrude Proterozoic strata of the Umkondo Group in eastern Zimbabwe and adjacent parts of Mozambique (Fig. 1) (*4*–*7*). Comparable sills are widespread within other Proterozoic successions in the Kalahari craton, including the Soutpansberg, Palapye, and Waterberg Groups in southern Africa and the Ritscherflya Supergroup in the Grunehogna crustal province of East Antarctica (Fig. 1), which is interpreted as a detached portion of the Kalahari craton (*8*). The present limits of these sedimentary successions are generally erosional, implying that the associated diabase sills were originally more extensive. Other intrusions belonging to the Umkondo province cut older cratonic rocks and include the Timbavati Gabbro in South Africa and the large (up to 300 km long), subsurface Tshane and Xade mafic and ultramafic layered complexes in Botswana (Fig. 1). Erosional remnants of flood basalts genetically related to the sills cap the Umkondo Group and the Ritscherflya Supergroup (*7*–*9*). Mafic rocks throughout the province have compositions typical of continental tholeiites (*7*, *8*, *10*, *11*).

Pole positions from different parts of the Umkondo province are statistically indistinguishable from the mean pole for the Umkondo sills in eastern Zimbabwe (Table 1 and fig. S3), implying that the magmatism occurred within a narrow time interval. We determined U-Pb baddeleyite and zircon crystallization ages of diabase sills and gabbroic intrusions that cut the Umkondo, Waterberg, and Palapye Groups and older cratonic rocks in Zimbabwe, South Africa, and Botswana (Fig. 1, fig. S4, and table S2) (*12*). The ages range between 1108 and 1112 million years ago (Ma) (*13*). Thirteen samples yield ages of 1108 to 1109 Ma, and 10 come from intrusions that have paleomagnetic poles statistically indistinguishable from the pole for the Umkondo sills in eastern Zimbabwe. Published, precise crystallization ages for other parts of the province in Botswana are as young as 1106.1 ± 2 Ma (Fig. 1).

We interpret the paleomagnetic and geochronologic data to indicate the presence of a Mesoproterozoic LIP defined by scattered erosional remnants traceable over an area of $\sim 2 \times 10^6$ km^2 in the Kalahari craton (Fig. 1). Our ages for the Umkondo province suggest that a large proportion of the mafic magmatism occurred in less than 3 My and perhaps in as little as 1 million years (1109.0 ± 1.3 to 1109.8 ± 0.8 Ma). Sedimentary cover and extensive erosion make it difficult to estimate the total volume of magma represented by the Umkondo province, but its inferred areal extent is the same order of magnitude as typical Phanerozoic LIPs, such as the Jurassic Karoo-Ferrar province (3.1×10^6 km^2) or the Cretaceous Paraná-Etendeka province ($>2 \times 10^6$ km^2) (*2*). On the basis of comparison with younger LIPs where the basalts have been partly stripped away to reveal an array of feeder dikes and sills (*3*), we infer that the shallow-level Umkondo intrusions supplied flood lavas that were originally more widespread than the limited remnants of basalt preserved in parts of the province.

Comparison with Laurentian igneous province. Widespread intraplate magmatism ~1100 Ma in Laurentia is represented by the voluminous Keweenawan tholeiites and less abundant alkaline rocks in the Midcontinent rift, which are inferred to have originated from a mantle plume (*14*). U-Pb geochronology from exposures of the rift in the Lake Superior region indicates that most of the magmatism occurred 1094 to 1108 Ma, with minor late-stage activity as young as 1087 Ma (Fig. 2). An estimated 50 to 80% of the magmatism (by volume) occurred 1108 ± 1 Ma, with rates of magma production decaying rapidly over the next 1 to 3 My (*14*, *15*).

Most of the rocks emplaced during the initial magmatic episode 1105 to 1108 Ma in the Midcontinent rift record a single magnetic polarity (with the exception of minor, short reversals of uncertain exact age), whereas most of the younger rocks show the opposite polarity (Fig. 2). These two polarity chrons have been referred to as "reversed" and "normal," respectively, based on comparison with the present-day field, although their true polarity is unknown (*16*).

U-Pb geochronology indicates that the bulk of the Umkondo igneous province was emplaced at the same time as the first main magmatic episode in the Midcontinent rift (Fig. 2). The polarity of 58 out of 67 Umkondo sites in southern Africa is reversed with respect to the present-day field; all Umkondo sites in Antarctica have

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reversed polarity (Table 1). Given these data and the similarity in U-Pb ages, we infer that the majority of the Umkondo province was emplaced during the same reversed polarity chron that is recorded in the Midcontinent rift. The only Umkondo igneous units with opposite polarity that have been precisely dated have crystallization ages of ~1108 to 1109 Ma (Fig. 2), suggesting these intrusions were emplaced during one of the brief intervals of normal polarity recorded in the Midcontinent rift within the longer reversed polarity chron.

Mafic intrusions in Saskatchewan, ~1400 km northwest of the Midcontinent rift, have a U-Pb baddeleyite age of 1109 ± 2 Ma, increasing the known geographic extent of intraplate magmatism comparable in age to the main Keweenawan episode (*17*). Other members of the Laurentian intraplate igneous province include extensive diabase sills and locally preserved basalt lavas in the southwestern United States. U-Pb crystallization ages for the diabases range from 1069 ± 3 to 1100 ± 2 Ma (*18*–*20*). Paleomagnetic poles from a larger sample suite overlap with Keweenawan poles from the Midcontinent rift, suggesting that magmatism in the two regions was contemporaneous (*21*, *22*).

Implications. Precise U-Pb geochronology and extensive paleomagnetic data show that voluminous Umkondo and Laurentian intraplate magmatism was synchronous (Fig. 2). One possible explanation for the data is that the two provinces represent coeval but spatially unrelated LIPs emplaced on separate cratons. Given the scale of the magmatism, this could imply a global event affecting Earth's mantle ~1100 Ma. An alternate, more testable model, which we prefer, is that the Laurentian and Umkondo magmatic events were spatially linked within a single LIP during assembly of the late Mesoproterozoic–early Neoproterozoic Rodinia supercontinent (*23*, *24*). Evidence for Rodinia assembly is provided by widespread Mesoproterozoic orogenic belts that record terminal phases of orogenesis ~1150 to 950 Ma (supporting online text), but the configuration of the supercontinent is uncertain (*25*, *26*).

Correlation of the Umkondo and Laurentian igneous provinces constrains the relative positions of Kalahari and Laurentia within Rodinia. A previous model (*6*) juxtaposed the Kalahari craton against the southwestern margin of Laurentia (directions are relative to present-day coordinates), aligning the Laurentian and Umkondo igneous provinces behind a continuous Mesoproterozoic orogen represented by the coeval Grenville and Namaqua-Natal-Maud belts (Fig. 3, position H). In a contrasting model (*27*), the Kalahari craton faced in the opposite direction from Laurentia (Fig. 3, position D), and the Umkondo and Laurentian igneous provinces were emplaced as the two cratons collided during Rodinia assembly. The first model is inconsistent with paleomagnetic data that require substantial separation between the two cratons

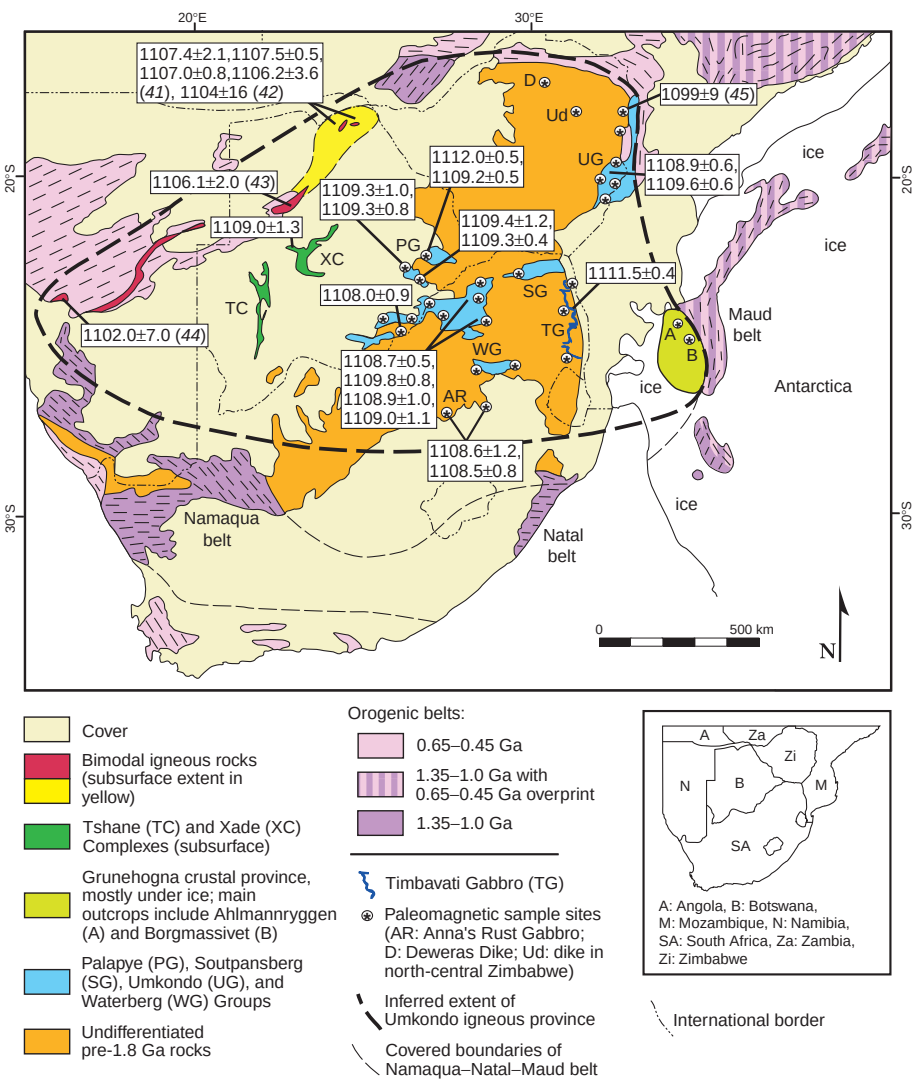


Fig. 1. The Umkondo igneous province in southern Africa and Antarctica, restored to pre-Mesozoic position after (*38*); the Precambrian geological framework follows (*39*, *40*). U-Pb baddeleyite and zircon ages (in Ma) in boxes are from the present work and (*41*–*45*). Most of our ages are from diabase sills that intrude the Palapye, Umkondo, and Waterberg Groups. Published ages come primarily from anorogenic rhyolites and associated subsurface intrusions within bimodal assemblages in western Botswana and Namibia. Symbols for paleomagnetic sites in many cases represent multiple sites in different intrusions or lava flows. Present-day coordinates are shown for Africa.

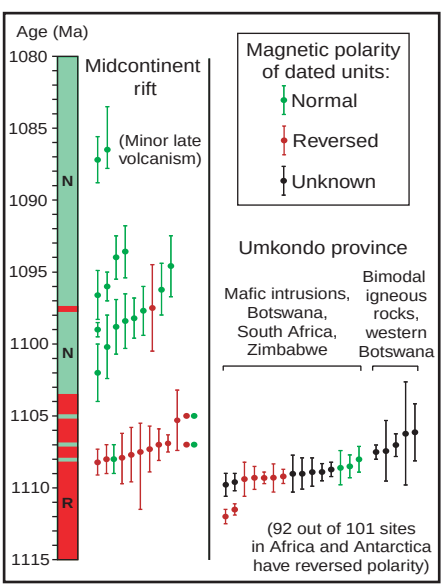
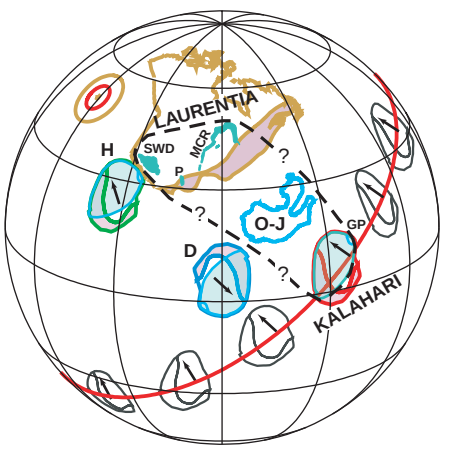


Fig. 2. U-Pb zircon and baddeleyite crystallization ages (with 2σ error bars, unless not given in the original reference) for igneous rocks from the Midcontinent rift (*14*, *36*, *37*, *46*) and Umkondo province (Fig. 1). Ages with errors of >2 My from the Umkondo province are not shown, except for bimodal rocks in western Botswana. Two major polarity chrons for the Midcontinent rift are shown at left; the main reversal separating them occurred between 1102 ± 2 and 1105 ± 2 Ma (*14*). Exact ages and the total number of short intervals of opposite polarity within the main polarity chrons are unknown and are shown schematically. The reversal time scale for the Midcontinent rift is based on paleomagnetic data for many more rock units than have been dated.

Table 1. Summary of paleomagnetic data for the Umkondo igneous province. Latitude and longitude give the pole position as transferred to the northern hemisphere; Antarctic poles have been rotated to Africa with the Euler pole (latitude –10.18°, longitude –31.04°, and rotation angle 58.73°) of Reeves *et al.* (*38*). A95, radius in degrees of the 95% circle of confidence; R, reversed; N, normal.

Rock unit and sampling area	Number of sites	Polarity	North latitude	East longitude	A95	Reference
Umkondo diabase sills, eastern Zimbabwe	9	9R	66.0	34.0	3.7	(*4*)
Umkondo lavas, eastern Zimbabwe	9	9R	63.4	16.4	13.7	(*9*)
Umkondo dike, north-central Zimbabwe*	1	1R	64.1	34.7	7.9	(*49*)
Deweras Dike, northwestern Zimbabwe*	1	1N	65.1	55.6	11.6	(*49*)
Diabase sills, Botswana and South Africa	13	12R, 1N	65.2	50.6	4.5	(*50*)
Diabase sills, Botswana	12	11R, 1N	61.1	38.5	4.9	(*12*)
Diabase sills, South Africa	11	11R	55.4	37.6	10.6	(*12*)
Anna's Rust Gabbro (in Vredefort dome), South Africa	6	6N	68.5	29.0	10.5	(*5*)
Timbavati Gabbro, South Africa	5	5R	62.6	46.8	3.6	(*51*)
Lavas and diabase sills, Ahlmannryggen, Antarctica	11	11R	66.1	41.7	5.3	(*52*)
Diabase sills, Ahlmannryggen, Antarctica	23	23R	62.3	28.2	3.0	(*53*)
Mean of all poles			63.6	36.2	3.8	

*Not included in the mean Umkondo pole because of inadequate sampling statistics.



Mesoproterozoic Grenville belt in Laurentia; Namaqua–Natal–Maud belt in Kalahari)

1.1 Ga Laurentian intraplate magmatic rocks (MCR = Midcontinent rift; P = Pecos intrusive suite; SWD = southwestern U.S. diabases)

1.1 Ga Umkondo intraplate magmatic rocks (GP = Grunehogna crustal province, Antarctica)

Fig. 3. Alternate proposed positions of the Kalahari craton relative to Laurentia (shown in present-day coordinates); other cratons within Rodinia are not shown. Mean 1108-Ma poles and their 95% circles of confidence for Kalahari (Table 1) and Laurentia (*47*) are shown in red and brown, respectively (upper left). Alignment of the mean Umkondo pole with the mean pole for coeval rocks of the Midcontinent rift permits Kalahari to occupy any position on the larger circle shown in red (about the same as the paleoequator in this case). Our preferred position for Kalahari is outlined in red; the bold dashed line indicates the inferred extent of the Umkondo-Laurentian LIP. Other proposed positions for Kalahari are labeled H (*6*) and D (*27*); the arrow on the craton points north in each case. An outline of the Cretaceous Ontong-Java plateau (O-J) is shown for comparison. Laurentian intraplate magmatic rocks include the examples discussed in the text and the Pecos intrusive suite in the subsurface of west Texas and New Mexico (*48*).

~1100 Ma (*24*, *26*, *27*). The second model was viable in the absence of a constraint on the polarity of the Umkondo pole (*28*). However, because almost all the Umkondo rocks have the same polarity in present-day coordinates as coeval parts of the Midcontinent rift, models that rotate Kalahari by 180° relative to Laurentia are now precluded. The temporal correlation between these paleomagnetically well-studied provinces provides one of the few available constraints on relative polarity between the cratons that made up Rodinia (*25*).

The geochronology for the Umkondo province allows a more precise reconstruction of the relative latitudinal positions of Kalahari and Laurentia 1108 Ma (Fig. 3). Paleolongitude is not constrained by paleomagnetism, so that Kalahari can occupy any position along a small circle drawn about its pole. In order to maintain a spatial link between the Umkondo and Laurentian igneous provinces, we suggest that at 1108 Ma Kalahari was located off eastern Laurentia, with the Umkondo and Laurentian intraplate magmatism occurring at either end of a single LIP that extended across both cratons (Fig. 3).

Our reconstruction requires that the Umkondo-Laurentian LIP developed across the Grenville belt during Rodinia assembly. This is possible if the LIP was generated by a mantle plume rising from deep levels and acting independently of lithospheric plate motions (*1*, *29*). Continent-continent collision during formation of the Grenville belt (supporting online text) implies that at least some of the space between Kalahari and Laurentia was occupied by a continental block. Part of the Umkondo-Laurentian LIP could also have developed in an oceanic setting (Fig. 3). One test of our reconstruction would be to identify other cratons with LIPs of an appropriate age that could occupy the gap between Kalahari and Laurentia.

Of perhaps more general significance is the recognition that mantle-derived LIPs similar to those documented in the Phanerozoic were emplaced during Rodinia assembly. In addition to the Laurentian and Umkondo LIPs, mention should be made of the 1070- to 1078-My-old Warakurna LIP in Australia (*30*), which is located southwest of Laurentia in some Rodinia reconstructions (*24*). These Mesoproterozoic LIPs contrast with many of the best known Phanerozoic LIPs, such as the Jurassic Central Atlantic and Karoo-Ferrar provinces, the Cretaceous Paraná-Etendeka and Deccan provinces, and the Tertiary North Atlantic province, which either directly preceded or formed during the breakup of parts of Pangea (*2*). The Phanerozoic examples have influenced the development of an array of geophysical models that relate continental LIP formation to a buildup of heat in the underlying mantle after supercontinent assembly. The models predict that the insulating effects of a supercontinent and/or the isolation of that part of the mantle from cooling by subduction will eventually lead to upwelling of hot mantle beneath the supercontinent, possibly contributing to its breakup (*31*, *32*), with LIPs forming from decompressional melting of uprising mantle before or as the continents rift apart (*32*, *33*). In some interpretations (*34*), there is no role for deep-seated mantle plumes in these processes. Instead, plate motions and changes in lithosphere thickness (*35*) govern convection in the shallow mantle and formation of LIPs, which again is predicted to occur in regions undergoing extension during episodes of plate reorganization or supercontinent breakup.

Emplacement of LIPs over wide areas within craton interiors while Rodinia was being assembled thus may require reevaluation of the relations between mantle convection and supercontinent evolution. Available data show that LIPs comparable to those produced during supercontinent breakup can also be generated during supercontinent assembly. This observation is consistent with models in which at least some LIPs record random impingement on the lithosphere of uprising, deep-seated mantle instabilities independent of surficial plate-tectonic processes or stages in the supercontinent cycle (*1*, *29*).

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Materials and Methods
SOM Text
Figs. S1 to S4
Tables S1 and S2
References and Notes

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Optical Signatures of the Aharonov-Bohm Phase in Single-Walled Carbon Nanotubes

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We report interband magneto-optical spectra for single-walled carbon nanotubes in high magnetic fields up to 45 tesla, confirming theoretical predictions that the band structure of a single-walled carbon nanotube is dependent on the magnetic flux ϕ threading the tube. We have observed field-induced optical anisotropy as well as red shifts and splittings of absorption and photoluminescence peaks. The amounts of shifts and splittings depend on the value of ϕ/ϕ_0 and are quantitatively consistent with theories based on the Aharonov-Bohm effect. These results represent evidence of the influence of the Aharonov-Bohm phase on the band gap of a solid.

When a magnetic flux, ϕ, passes through a mesoscopic ring, the quantum states and dynamics of electrons on the ring are influenced by the Aharonov-Bohm (AB) phase (*1*); that is, $2\pi\phi/\phi_0$, where $\phi_0 = h/e$ is the magnetic flux quantum (h is the Planck constant and e is the electronic charge). When the phase coherence length exceeds the circumference, quantum interference between loop trajectories of opposite sense induces magnetoresistance oscillations with period ϕ_0 (known as AB oscillations) and $\phi_0/2$ [known as Altshuler-Aronov-Spivak (AAS) oscillations (*2*)]. These oscillations have been observed in various metallic rings and tubes (*3*), including the recent observation of the AAS oscillations in multiwalled carbon nanotubes (*4*).

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