Paleomagnetism of the 1.1 Ga Umkondo large igneous province in southern Africa

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[1] The Umkondo dolerites are present over a wide area in the Kalahari craton, southern Africa. Thirty-nine sampling sites in Botswana and South Africa yielded tightly grouped paleomagnetic directions due south with shallow inclinations and three sites of opposite polarity. The dolerites have U-Pb single-crystal baddeleyite or zircon crystallization ages of 1112 ± 0.5 to 1108 ± 0.9 Ma. These results can be combined with published data from 39 additional Umkondo sites and 33 sites in the Grunehogna Province of Antarctica after restoring East Antarctica to its position next to southern Africa. Grouping the sites geographically yields 10 site mean poles with mean at 64.0°N, 38.8°E, A_{95} = 3.7°. This Umkondo pole can be correlated with Keweenawan poles from Laurentia. Because both sets of poles are precisely of the same age as well as predominantly of one polarity, the relative orientation of the two cratons within the Rodinia supercontinent is fixed. This implies that the Namaqua-Natal-Maud belt which rims the southern part of the Kalahari craton, faced away from Laurentia. The Umkondo pole combined with published poles suggest that the Kalahari craton remained distinctly south of the Laurentian craton between 1.1 and 1.0 Ga, making it highly unlikely that the two cratons collided.

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1. Introduction

[2] In the mid-1960s, M. W. McElhinny and coworkers published a series of papers on the Precambrian Umkondo dolerites and lavas of southern Africa [*McElhinny and Opdyke*, 1964; *McElhinny*, 1966; *Jones and McElhinny*, 1966]. They demonstrated by paleomagnetic means that the widespread Umkondo sills in eastern Zimbabwe could be correlated with similar mafic intrusions in Botswana and South Africa. Subsequent work by *Wilson et al.* [1987], *Allsopp et al.* [1989], and *Hargraves et al.* [1994] expanded the known extent of the Umkondo province which also includes a detached fragment now located in East Antarctica as part of the Grunehogna terrane [*Peters*, 1989; *Groenewald et al.*, 1995; *Jones et al.*, 2003]. The age of the type Umkondo sills in Zimbabwe was constrained by Rb-Sr isotopic data as consistent with emplacement at ~1100 Ma [*Allsopp et al.*, 1989]. More recently, U-Pb geochronological studies by *Hanson et al.* [1998] and *Wingate* [2001] have confirmed and refined this age assignment.

[3] In order to better constrain the areal extent of the province and the absolute age and the duration of magmatism, we collected paleomagnetic samples at 91 additional sites in Botswana and South Africa, mostly from mafic intrusions known or presumed to belong to the Umkondo province. Thirtyone of these sites did not yield usable results mainly because of lightning. This work was carried out in conjunction with detailed U-Pb geochronological studies. Eleven intrusions in Zimbabwe, Botswana, and South Africa have yielded U-Pb zircon or baddeleyite ages ranging from 1112 to 1108 Ma [*Hanson et al.*, 2004a]. Some of the results and implications of the paleomagnetic work have been briefly discussed by *Hanson et al.* [2004a]. Here we present results from additional paleomagnetic sites and provide a thorough analysis of the paleomagnetic data for the entire Umkondo province. We also review the Mesoproterozoic paleomagnetic database for southern Africa and discuss possible relations between the Kalahari and Laurentian cratons within the Rodinia supercontinent.

[4] An unexpected result of the present project was the discovery that, in parts of the province, Umkondo dolerite intrusions occur in close spatial association with lithologically similar but much older, Paleoproterozoic dolerites [*Hanson et al.*, 2004b]. We present paleomagnetic data

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from two additional sites in rock units belonging to this Paleoproterozoic intraplate province.

2. Geological Setting

[5] The Umkondo igneous province is named for extensive dolerite sills that intrude Proterozoic strata of the Umkondo Group in eastern Zimbabwe and adjacent parts of Mozambique (Figure 1a) [*McElhinny and Opdyke*, 1964; *Munyanyiwa*, 1999]. Other mafic intrusions present over a wide area in the Kalahari craton in Zimbabwe, Botswana, and South Africa also belong to the province [*Hanson et al.*, 2006]. In southeastern Botswana and parts of South Africa, the intrusions consist primarily of numerous dolerite sills and sheets emplaced into Proterozoic cover sequences of the Palapye and Waterberg groups, as well as older cratonic rocks (Figure 1b). The extension of the Umkondo province in East Antarctica occurs in the Grunehogna crustal province (Figure 1a), where widespread dolerite sills and other intrusive bodies of the Borgmassivet suite penetrate the cratonic Ritscherflya Supergroup and underlying Archean basement [*Groenewald et al.*, 1995; *Jones et al.*, 2003]. That supergroup and the Umkondo Group are both capped by erosional remnants of flood basalts genetically related to the sills [*McElhinny*, 1966; *Munyanyiwa*, 1999; *Groenewald et al.*, 1995]. Other members of the province in southern Africa include the Timbavati Gabbro in eastern South Africa [*Hargraves et al.*, 1994], large, mafic/ultramafic intrusions in the subsurface of Botswana [*Key and Mapeo*, 1999; *Hanson et al.*, 2004a], and bimodal magmatic assemblages in western Botswana. The bimodal rocks have yielded U-Pb zircon crystallization ages of 1107.5 ± 0.5 to 1106.1 ± 2.0 Ma [*Schwartz et al.*, 1996; *Singletary et al.*, 2003]. They bear a Neoproterozoic greenschist-facies dynamothermal metamorphic overprint and are therefore less suitable for paleomagnetic studies than the undeformed mafic intrusions listed earlier. The total extent of the Umkondo province is inferred to be ca. 2×10^6 km^2, making it comparable to other major intraplate large igneous provinces (LIPs).

3. Paleomagnetic Analyses

3.1. Rock Magnetic and Petrographic Analyses

[6] The majority of our paleomagnetic sites (Figure 1b) come from dolerite sills up to 120 m thick intruded into the Palapye and Waterberg groups. Additional sites come from similar dolerites intruding older Paleoproterozoic and Archean rocks. We also sampled the Timbavati Gabbro, which comprises a series of arcuate, composite sheets up to 480 m thick intruded into Archean crystalline rocks near the eastern border of South Africa. Details on the geological setting of many of the sampling sites are given by *Pancake* [2001] and *Seidel* [2004].

[7] All samples were collected with a gasoline-powered drill. Wherever possible, the bedding attitude of nearby sedimentary strata was used for tilt corrections. For many sites that was not possible; however, regional dips are typically <10° in those parts of the Waterberg and Palapye groups where many of our samples come from. It has also not been possible to apply a tilt correction to sites from intrusions emplaced into Archean crystalline rocks, but there is no structural evidence for significant postemplacement tilting in these areas. Karoo strata unconformably overlying the Timbavati Gabbro in Kruger Park typically dip eastward at <5–20°. As noted by *Hargraves et al.* [1994], because the characteristic remanence directions from the gabbro are oriented north-south at shallow angles, the structural correction for the post-Karoo tilting in this case is negligible.

[8] The sampled dolerites consist of fine- to medium-grained (<2 to 3 mm) plagioclase, augite, pigeonite, generally minor enstatite and biotite, variable amounts of interstitial micrographophyre, and sparse olivine. Pyroxene is rimmed by hornblende and biotite, and all three minerals are variably altered to very fine grained chlorite-actinolite-epidote-smectite assemblages. Olivine is partly to completely serpentinized, and plagioclase is partly altered to sericite and minor prehnite. The alteration is sporadically developed within individual intrusions and, in some samples, occurs in localized pockets <5 mm across. Its intensity correlates with grain size of the primary igneous phases. Finer grained samples near chilled margins typically show the least alteration, whereas pegmatitic pockets in the centers or upper parts of sills show the most intense replacement of primary phases. These observations are consistent with the interpretation that the alteration is deuteric in origin and developed during progressive cooling from magmatic temperatures.

[9] The composite Timbavati Gabbro sheets in part consist of dolerite similar to that described above. Coarser grained gabbros also occur, with poikilitic diopside up to 1.5 cm across enclosing plagioclase and olivine. Deuteric alteration is similar to that in the dolerite sills described above, but many of the Timbavati samples show only minor alteration.

[10] In the analyzed samples, opaque phases consist predominantly of magnetite, with minor pyrite in some cases. Primary magnetite grains are typically <2 mm across and are intergrown with other igneous phases. Finer magnetite granules ranging down to <0.001 mm are intergrown

Figure 1. (a) Extent of Umkondo igneous province (indicated by heavy dashed line) in southern Africa and adjacent parts of East Antarctica, restored to pre-Mesozoic position in Gondwana after *Reeves et al.* [2002]. Kalahari craton is delimited by 0.65–0.45 Ga orogenic belts. Lighter dashed lines show southern extent of Archean and Paleoproterozoic cratonic basement in subsurface and, farther south, tectonic boundary between Namaqua-Natal orogen and younger terranes. Paleomagnetic sites discussed in text: K, Koras Group; J, Jannelsepan amphibolite; Ok, Okiep district; PE, Port Edwards Charnockite. Cratonic cover sequences: PG, Palapye Group; SG, Soutpansberg Group; UG, Umkondo Group; WG, Waterberg Group. Modified from *Hanson et al.* [2004a]. Inset shows country outlines: B, Botswana; M, Mozambique; N, Namibia; SA, South Africa; Zi, Zimbabwe. (b) Sites sampled by us in the central part of Umkondo province in southeastern Botswana and South Africa. Geology from *Mortimer* [1984], *Zimbabwe Geological Survey* [1994], and *Keyser* [1997].

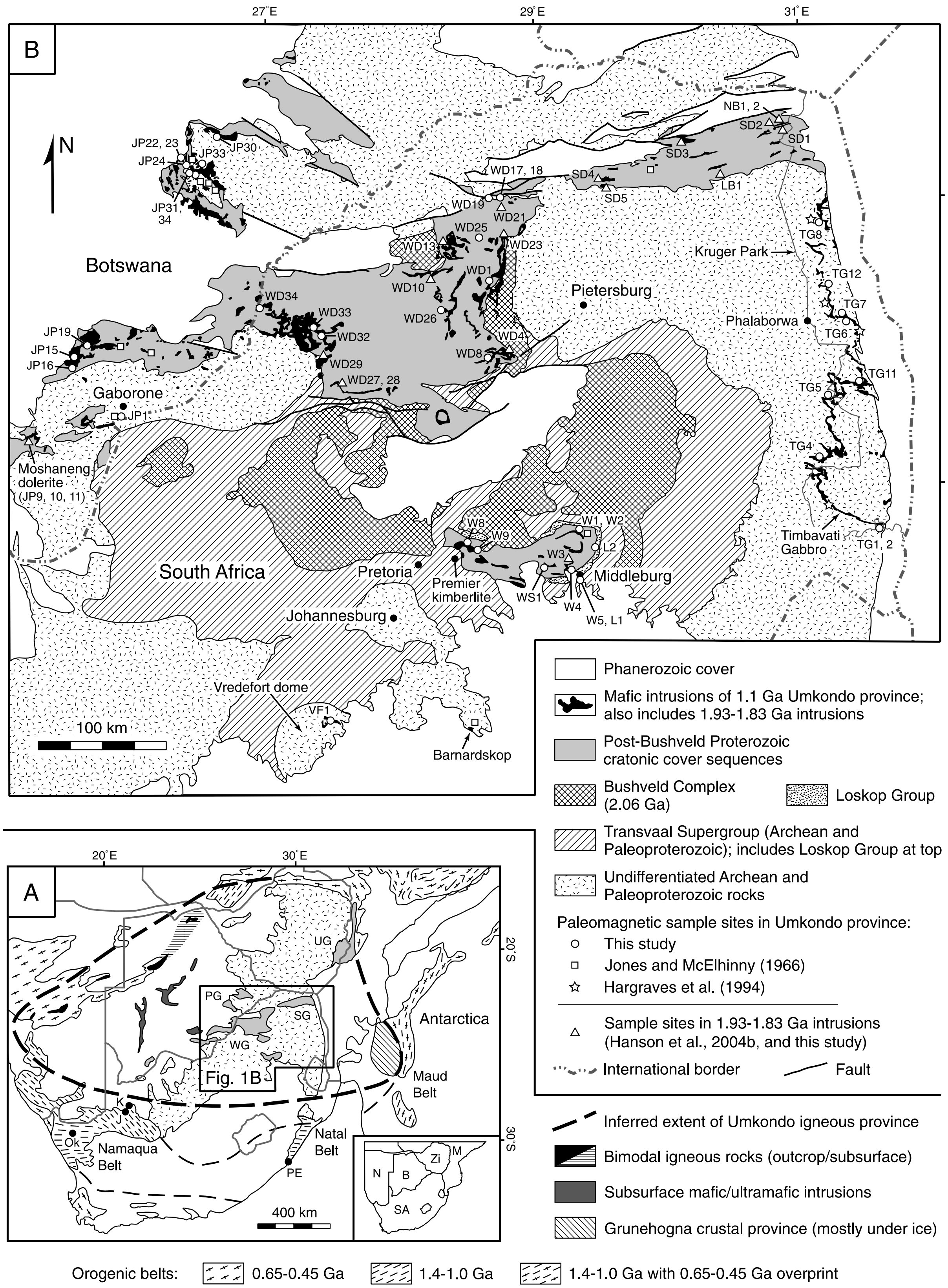
B
27° E
29° E
31° E
23° S
25° S
N
Botswana
South Africa
Gaborone
Pretoria
Johannesburg
Pietersburg
Phalaborwa
Middleburg
Kruger Park
Premier kimberlite
Vredefort dome
Barnardskop
Timbavati Gabbro
Moshaneng dolerite (JP9, 10, 11)
100 km
Phanerozoic cover
Mafic intrusions of 1.1 Ga Umkondo province; also includes 1.93-1.83 Ga intrusions
Post-Bushveld Proterozoic cratonic cover sequences
Bushveld Complex (2.06 Ga)
Loskop Group
Transvaal Supergroup (Archean and Paleoproterozoic); includes Loskop Group at top
Undifferentiated Archean and Paleoproterozoic rocks
Paleomagnetic sample sites in Umkondo province:
This study
Jones and McElhinny (1966)
Hargraves et al. (1994)
Sample sites in 1.93-1.83 Ga intrusions (Hanson et al., 2004b, and this study)
International border
Fault
A
20° E
30° E
20° S
30° S
UG
PG
SG
WG
Fig. 1B
Antarctica
Maud Belt
Natal Belt
Namaqua Belt
Ok
K
PE
N
B
Zi
M
SA
400 km
Inferred extent of Umkondo igneous province
Bimodal igneous rocks (outcrop/subsurface)
Subsurface mafic/ultramafic intrusions
Grunehogna crustal province (mostly under ice)
Orogenic belts:
0.65-0.45 Ga
1.4-1.0 Ga
1.4-1.0 Ga with 0.65-0.45 Ga overprint

Figure 1

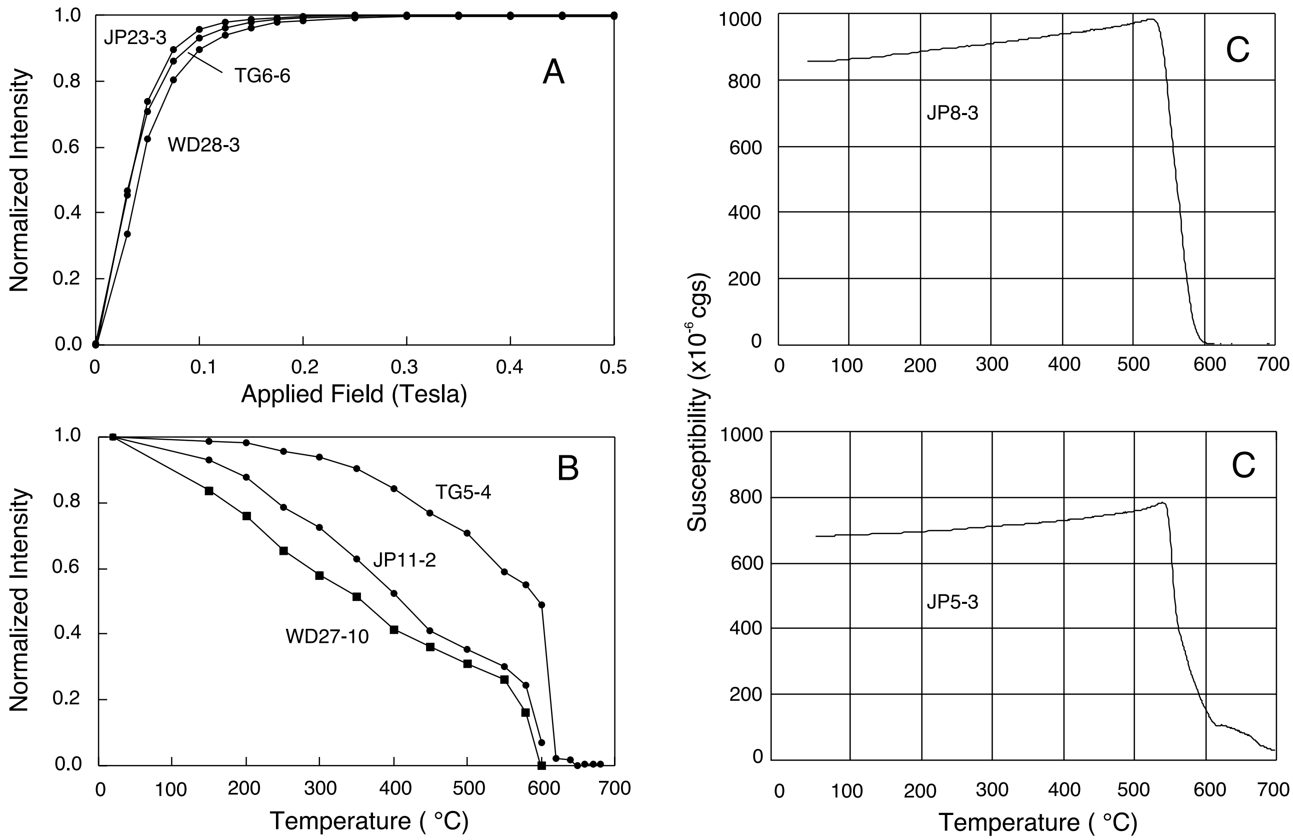

Figure 2. (a) Isothermal remanent magnetization (IRM) acquisition for three dolerites identifies magnetite as the sole carrier of the magnetic remanence. (b) Thermal demagnetization confirms magnetite as the dominant magnetic carrier but also shows a contribution by hematite in some samples (e.g., sample TG5-4). (c) Temperature dependence of the susceptibility shows the dominance of magnetite but also clear evidence of hematite in some samples.

with secondary alteration products of the primary silicate phases. Hematite occurs in some samples as a minor alteration product of magnetite or forms particles <0.001–0.03 mm in size within aggregates of fine-grained secondary minerals.

[11] All samples were oriented with a sun compass and the readings were converted to magnetic angles using the SUNDEC program of *Tauxe* [1998]. This was indeed necessary as many samples were extremely strongly magnetized with intensities of the natural remanent magnetization (NRM) of up to 10^{+4} A/m. In the laboratory, the samples were stored in a magnetically shielded room where they remained throughout the measuring procedure. Pilot samples indicated that the samples responded better to alternating field demagnetization (AFD) than thermal demagnetization and most samples were subjected to progressive AFD in at least seven steps up to 100 mT. A few sites were also subjected to thermal demagnetization. The data were analyzed by the principal component method [*Kirschvink*, 1980]. After measuring the NRM and before proceeding with alternating field demagnetization, the samples from Botswana were heated to 200°C in order to eliminate a possible overprint carried by goethite.

[12] In their magnetic characteristics, the dolerites from all sampling sites were very homogeneous. Figure 2 shows some examples of rock magnetic analyses. Isothermal remanent magnetization (IRM) acquisition experiments identify magnetite as the sole magnetic mineral. The temperature dependence of the susceptibility reveals magnetite as the dominant phase but also indicates the presence of hematite in some samples. Thermal demagnetization confirms that magnetite is the main carrier of the remanent magnetization. These results are consistent with the petrographic observations.

[13] Upon alternating field demagnetization, many samples lost 80% to 90% of their NRM intensity after demagnetization to only 10 or 20 mT. The directions of this low-stability component were randomly oriented. Representative vector component diagrams are depicted in Figure 3. Sample JP19-3 shows the typical behavior, namely that the characteristic direction of magnetization is revealed only at the higher demagnetization steps, usually above 60 mT. Samples JP1-3 and VF1-6 are from the only two sites that were of opposite polarity to all our other sites.

[14] Figure 4a demonstrates a feature observed at most sites, namely that one or several samples have significantly different directions. Almost inevitably, these samples are the most strongly magnetized samples. The same observation is true when one looks at the mean site intensities (Figure 4b). In general, the sites that gave similar directions and yielded good clusters are less strongly magnetized than the sites that did not provide useful data. The extraordinarily high mag-

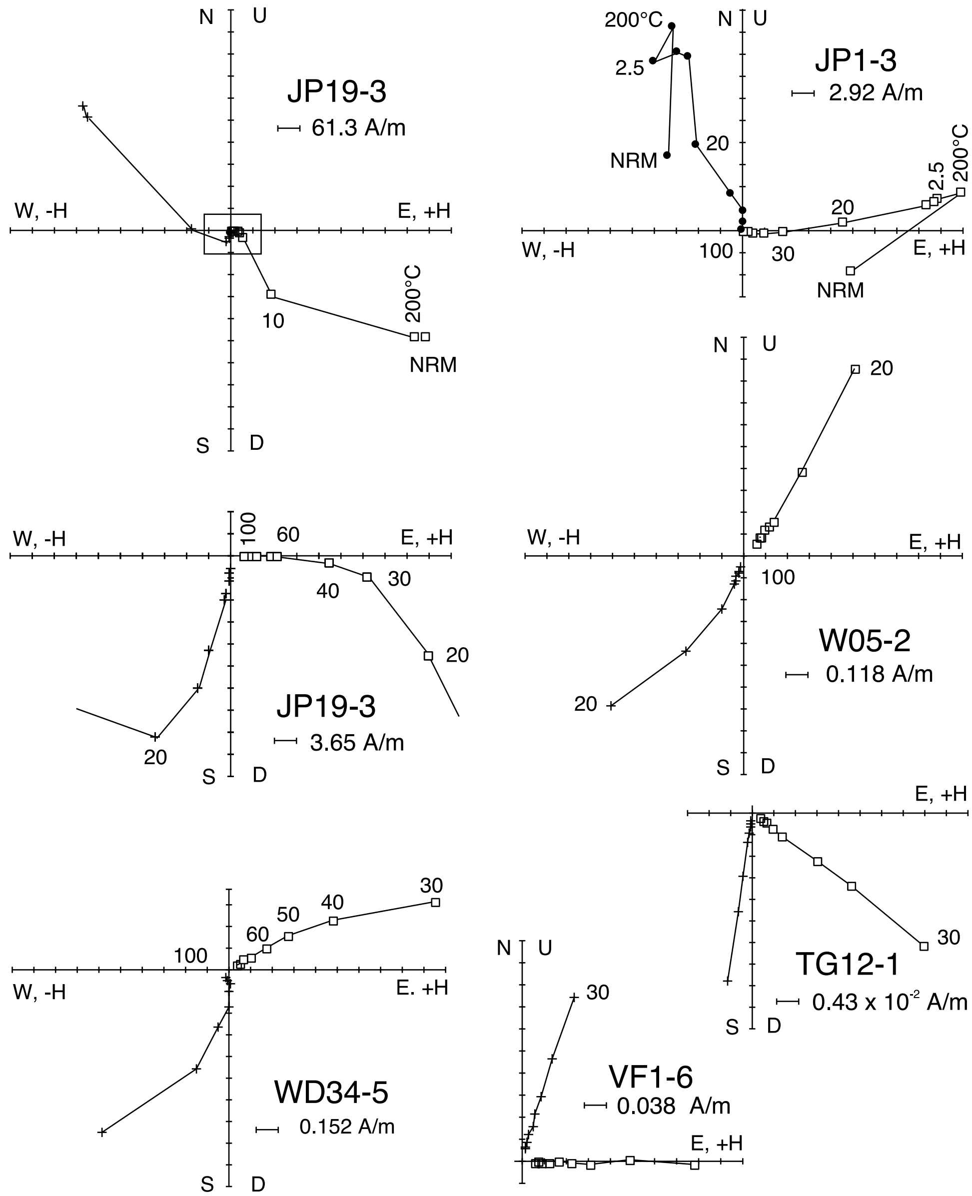

Figure 3. Vector component diagrams for representative samples. Most samples revealed their characteristic directions only at higher demagnetization levels (see sample JP19-3). Crosses are the projection onto the N-S/E-W plane, and open squares are in the up-down-horizontal plane. Numbers indicate demagnetization field in millitesla.

netizations (>10^3 A/m) are most likely due to lightning strikes, a phenomenon also noted by *McElhinny and Opdyke* [1964] and *Jones and McElhinny* [1966].

3.2. Dolerite Intrusions in Southeastern Botswana

[15] Eleven sites in dolerite intrusions belonging to the Umkondo province in Botswana (Figure 1b) yielded a stable remanence. The site mean directions are depicted in Figure 5, and their statistical parameters are listed in Table 1. Site JP1 is the only site of this suite that has a northerly, shallow direction, antipodal to the other sites. In the same area, *Jones and McElhinny* [1966] sampled 9 sites; their results are in excellent agreement with our data (Figure 5).

[16] The Moshaneng Dolerite, which consists of several faulted sills and irregular intrusive bodies southwest of Gaborone (Figure 1b), was previously considered to be part of the Umkondo suite [e.g., *Carney et al.*, 1994]. However, three separate samples from different parts of the Moshaneng Dolerite have yielded U-Pb baddeleyite ages of 1927.7 ± 0.5 to 1927.1 ± 0.7 Ma [*Hanson et al.*, 2004b]. Two sites (JP9 and JP10) yielded magnetization directions markedly different from the directions for the Umkondo intrusions in the region (Figure 5) [*Hanson et al.*, 2004b]. A third site in the Moshaneng Dolerite (JP11), which has yielded a U-Pb baddeleyite age of 1927.3 ± 0.7 Ma, has a well-clustered magnetization direction statistically identical to directions for other dolerites in southeastern Botswana assigned to the Umkondo province (Table 1). It is likely that the dolerite at site JP11 was remagnetized during the Umkondo event, although no Umkondo intrusions are exposed in the

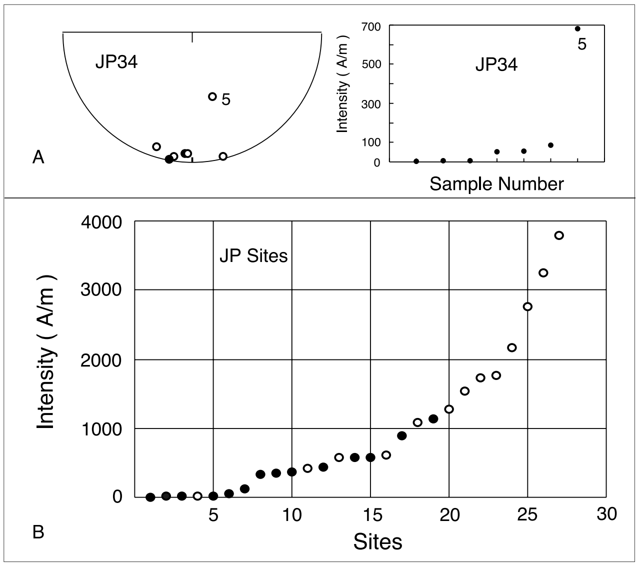

Figure 4. (a) Schmidt net for samples from Botswana site JP34. Open symbols are in the upper hemisphere and closed ones in the lower. The stray sample 5 is significantly more strongly magnetized than the other samples from the same site, suggesting remagnetization by lightning. (b) Botswana sampling sites ordered by their average intensity of magnetization. Solid symbols represent sites that yielded typical Umkondo directions. Open symbols are for sites that did not yield useful data and are inferred to have been affected by lightning.

vicinity. *Jones and McElhinny* [1966] reported a K-Ar date of 1110 ± 44 Ma (recalculated to currently recommended constants) for a plagioclase-pyroxene fraction from a sample of the Moshaneng Dolerite collected near our sites JP9 and JP10, which suggests that these older dolerites were thermally disturbed during the Umkondo event.

3.3. Dolerite Intrusions in South Africa

[17] Eleven dolerite sites in the main Waterberg basin west of Pietersburg in northern South Africa (Figure 1b) yielded Umkondo-type directions as did six dolerites in the southeastern part of the Waterberg Group near Middleburg. The site mean directions are shown in Figure 6 and are listed in Table 1.

[18] Six additional dolerites in the Waterberg Group west of Pietersburg that during the field work were considered to be members of the Umkondo suite yielded distinctly different directions of magnetization (Figure 6). One of the sampled sills (sites WD27 and WD28) has a U-Pb baddeleyite crystallization age of 1871.9 ± 1.2 Ma. Two other dolerites in the same region have yielded U-Pb baddeleyite ages of 1878.8 ± 0.5 and 1873.7 ± 0.8 Ma. Five dolerite sills intruding the Soutpansberg Group to the northeast of Pietersburg (sites SD1-5 in Figure 1b) and two basalt lavas within that group (LB1, NB1) yielded exactly antipodal directions. These data, combined as the WSD pole (Waterberg-Soutpansberg Dolerite) in Figure 6, have been reported by *Hanson et al.* [2004b]. To these data we can add another basalt flow in the Soutpansberg Group (site NB2) and sill site W3 from the Middleburg area. The revised site mean pole position lies at 17.4°N, 17.2°E with an error of A_{95} = 8.2°. The two directional groups are antipodal at the 1% significance level. These data indicate the existence of a Paleoproterozoic intraplate igneous province within part of the same area that was later the site of Umkondo magmatism. Without geochronological or paleomagnetic evidence, it is difficult to assign Proterozoic dolerite sills in this region to one or the other of these magmatic episodes.

[19] Site WD28, from one of the Paleoproterozoic sills in the main Waterberg basin, has a high-coercivity magnetization that agrees with data from the other sites in Paleoproterozoic sills in the area. However, it has a well-defined low-coercivity component that clearly indicates remagnetization during Umkondo igneous activity (Figure 6). As is the case for remagnetized parts of the Moshaneng Dolerite in Botswana, there is no evidence for the presence of Umkondo intrusions nearby, suggesting that the remagnetization may have been caused by migrating fluids driven by regional Umkondo magmatism.

[20] We also sampled dolerite intrusions cutting Archean rocks south of the Waterberg Group, within the Vredefort dome (Figure 1b). The dolerite intruding the Vredefort dome comprises several separate exposed masses inferred by *Coetzee et al.* [1995] and *Bisschoff* [1999] to belong to a single intrusive sheet. Site VF-1 comes from one of the main dolerite exposures and is only the second of our sites that is of normal polarity. Two additional sites from the dolerite also seem to be of normal polarity, but these data are statistically not acceptable. *McDonald and Andersen* [1973], quoted by *Allsopp et al.* [1989], obtained a mean direction from six sites in the same intrusion that is also of normal polarity. *Jones and McElhinny* [1966] obtained an Umkondo-type direction of normal polarity from a dolerite sheet at Barnardskop (Figure 6) to the east of the Vredefort dome.

[21] At site WS-1, west of Middleburg, a dolerite sill of inferred Umkondo age intrudes sandstones of the Wilgerivier Formation of the Waterberg Group. The sandstones

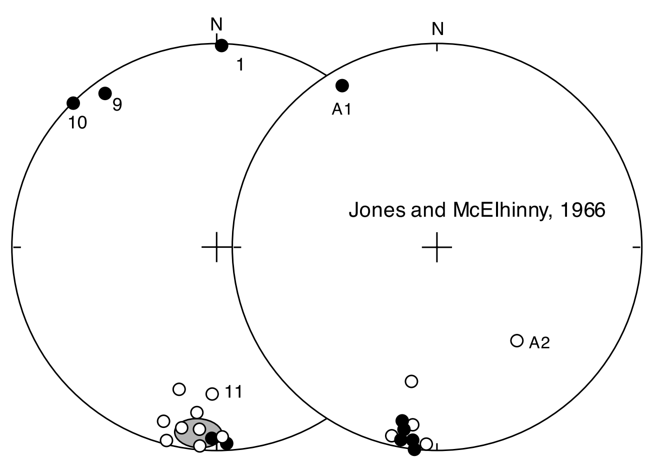

Figure 5. Schmidt equal-area projection of the site mean directions from Botswana. Shaded ellipse represents the 95% error of the mean of the site means. The second net displays mean directions observed by *Jones and McElhinny* [1966] from sites in the same area. Open (solid) symbols are in the upper (lower) hemisphere.

Table 1. Statistical Parameters of Paleomagnetic Data[a]

	Site												
	S Lat	E Long	N	R	Dec	Inc	k	α_{95}	Lat	Long	dp	dm	Reference
						Botswana South							
JP1	24.69	25.87	5/1	4.765	1.2	−0.8	17.0	19.1	65.7	28.9	9.5	19.1	*Pancake* [2001] and this study
JP15	24.32	25.53	8/2	7.914	194.4	−2.2	81.8	6.2	61.0	56.4	3.1	6.2	*Pancake* [2001] and this study
JP16	24.37	25.52	9/1	7.794	194.8	−28.2	6.6	21.6	48.0	47.1	13.0	23.7	*Pancake* [2001] and this study
JP19	24.23	25.64	5/1	4.738	196.8	−11.4	15.3	20.2	55.9	56.5	10.4	20.5	*Pancake* [2001] and this study
JP9 (Moshaneng)	24.96	25.25	14/0	13.677	324.1	7.2	40.2	6.3	45.0	329.4	3.2	6.4	*Pancake* [2001] and this study
JP10 (Moshaneng)	24.90	25.25	13/0	12.261	315.0	0.9	31.6	7.5	39.6	318.5	3.7	7.5	*Pancake* [2001] and this study
JP11 (Moshaneng)	24.94	25.3	10/10	9.871	182.3	−27.3	69.6	5.8	50.6	28.8	3.5	6.4	*Pancake* [2001] and this study
7	24.33	26.13	6	5.970	193.5	−5.5	165.0	5.2	59.9	54.2			*Jones and McElhinny* [1966]
8	24.23	25.87	7	6.545	191.0	−33.0	13.2	17.0	46.5	41.3			*Jones and McElhinny* [1966]
9	24.67	25.88	6	5.987	187.5	−13.0	379.0	3.4	57.7	40.3			*Jones and McElhinny* [1966]
A1	24.93	25.30	4	3.988	329.5	8.5	244.0	5.9	48.2	335.5			*Jones and McElhinny* [1966]
						Botswana North							
JP22	22.92	26.38	6/1	5.676	176.9	3.3	15.4	17.6	68.6	17.9	8.8	17.6	*Pancake* [2001] and this study
JP23	22.92	26.37	4/1	3.792	178.0	−7.3	14.4	25.0	63.4	22.0	12.7	25.2	*Pancake* [2001] and this study
JP24	22.91	26.39	5/1	4.831	185.4	−10.8	23.7	16.0	61.1	37.6	8.2	16.3	*Pancake* [2001] and this study
JP30	22.70	26.61	5/1	4.898	181.3	6.9	39.3	12.3	70.7	30.6	6.2	12.4	*Pancake* [2001] and this study
JP31	23.00	26.48	8/2	7.954	190.8	−10.2	152.6	4.5	59.9	48.3	2.3	46.0	*Pancake* [2001] and this study
JP33	22.94	26.44	6/4	5.815	186.8	−19.1	27.1	13.1	56.6	38.6	7.1	13.7	*Pancake* [2001] and this study
JP34	22.98	26.46	6/1	5.894	184.7	−2.1	47.4	9.8	65.5	37.9	4.9	9.8	*Pancake* [2001] and this study
1	23.10	26.60	8	7.961	190.5	14.0	180.0	4.2	70.7	62.7			*Jones and McElhinny* [1966]
2	23.05	26.55	7	6.991	190.5	9.5	674.0	2.3	69.1	56.6			*Jones and McElhinny* [1966]
3	23.00	26.41	8	7.991	190.5	4.0	796.0	2.0	66.6	53.7			*Jones and McElhinny* [1966]
4	23.00	26.41	6	5.981	187.0	5.0	254.0	6.7	68.5	46.1			*Jones and McElhinny* [1966]
5	23.00	26.41	7	6.981	187.0	5.0	323.0	3.3	38.4	45.7			*Jones and McElhinny* [1966]
6	22.90	26.40	8	7.992	186.5	0.5	897.0	1.8	66.4	42.8			*Jones and McElhinny* [1966]
						Waterberg							
WD1	23.81	28.74	9/3	8.490	184.0	−8.5	15.7	13.4	61.7	37.3	6.8	13.5	this study
WD8	24.28	28.71	12/0	11.489	171.4	−26.3	21.5	9.6	50.9	15.4	5.6	10.4	this study
WD17	23.15	28.75	10/0	9.664	189.5	−18.8	26.8	9.5	55.9	45.6	5.2	9.9	this study
WD18	23.15	28.75	5/4	4.817	190.3	−11.5	21.8	16.8	59.3	49.1	8.6	17.0	this study
WD19	23.16	26.68	10/2	9.402	190.5	−43.5	15.1	12.9	40.4	41.2	10.0	16.0	this study
WD25	23.42	28.65	8/4	7.013	205.6	11.9	7.1	22.4	59.9	87.4	11.5	22.7	this study
WD26	23.95	28.39	13/0	12.456	171.7	10.6	22.1	9.0	69.8	4.0	4.6	9.1	this study
WD28H[b]	24.5	27.56	11/1	10.396	340.8	72.0	16.6	11.6	6.9	17.1	18.0	20.4	*Hanson et al.* [2004b]
WD28L	24.5	27.56	7/3	6.943	179.8	−38.3	104.4	5.9	44.0	27.3	4.2	7.0	*Hanson et al.* [2004b]
WD32	24.14	27.41	6/8	5.657	181.4	3.7	14.6	18.1	67.7	31.2	9.1	18.2	this study
WD33	24.05	27.32	10/2	9.218	206.9	−36.2	11.5	14.9	38.7	60.3	10.1	17.3	this study
WD34	23.84	26.93	7/4	6.560	158.6	−27.2	13.6	16.9	46.3	355.9	10.0	18.5	this study
10	22.92	29.93	5	4.940	194.0	24.0	66.5	9.5	73.1	84.2			*Jones and McElhinny* [1966]
						Middleburg							
W01	25.49	29.46	16/0	15.762	175.3	−0.5	63.1	4.7	63.9	18.8	2.3	4.7	*Seidel* [2004] and this study
W02	25.47	29.44	9/9	8.265	199.1	−19.6	10.9	16.3	49.9	59.4	8.9	17.1	*Seidel* [2004] and this study
W03[b]	25.70	29.41	9/3	8.340	337.5	71.8	12.1	15.4	5.5	29.4	23.8	27.1	*Seidel* [2004] and this study
W04	25.75	29.45	13/0	12.693	174.9	−10.0	39.1	6.7	58.8	19.6	3.4	6.8	*Seidel* [2004] and this study
W05	25.76	29.48	11/2	10.718	174.0	−12.8	35.5	7.8	57.3	18.4	4.0	7.9	*Seidel* [2004] and this study
W08	25.59	29.58	9/3	8.901	201.2	12.3	80.6	5.8	61.9	78.5	3.0	5.9	*Seidel* [2004] and this study
W09	25.65	28.60	11/1	10.585	197.7	9.2	24.1	9.5	63.0	70.4	4.8	9.6	*Seidel* [2004] and this study
L-1	25.76	29.48	19/0	18.414	188.0	14.5	30.7	6.2	70.1	53.4	3.2	6.3	*Seidel* [2004] and this study
L-2[b]	25.60	29.62	11/0	10.984	6.9	49.1	636.4	1.8	34.0	36.9	1.6	2.4	*Seidel* [2004] and this study
WS-1	25.71	29.21	11/0	10.853	189.0	−0.5	67.9	5.6	62.6	49.2	2.8	5.6	*Seidel* [2004] and this study
11 Mooiplaats	25.50	29.46	6	5.633	188.0	6.0	13.6	19.0	66.2	50.2			*Jones and McElhinny* [1966]
12 Barnardskop	26.90	28.53	6	5.983	16.0	−14.5	292.0	3.9	65.3	69.3			*Jones and McElhinny* [1966]
13 Premier	25.70	28.53	10	9.878	183.0	−3.0	73.5	5.7	62.7	34.6			*Jones and McElhinny* [1966]
						Timbavati							
TG01	25.35	31.81	11/13	10.933	191.1	0.9	150.1	3.7	62.9	56.8	1.9	3.7	*Seidel* [2004] and this study
TG01-K			13/10	12.985	324.7	−68.1	820.5	1.4	52.8	248.9	2.0	2.4	*Seidel* [2004] and this study
TG02	25.35	31.79	11/1	10.629	193.6	0.1	26.9	9.0	61.5	61.3	4.5	9.0	*Seidel* [2004] and this study
TG04	24.94	31.30	10/2	9.446	188.5	7.9	16.2	12.4	67.5	53.9	6.3	12.4	*Seidel* [2004] and this study
TG05-AF	24.55	31.35	8	7.448	20.5	−3.7	12.7	16.2	59.9	75.5	8.1	16.2	*Seidel* [2004] and this study
TG05-TD			13/2	12.228	210.6	1.6	15.5	10.9	52.0	87.2	5.4	10.9	*Seidel* [2004] and this study
TG05B			12/2	11.479	326.9	4.4	21.1	4.4	50.8	39.7	5.6	11.2	this study
TG06	23.91	31.45	11/1	10.529	194.5	−1.3	21.2	10.1	61.8	63.1	5.1	10.1	*Seidel* [2004] and this study
TG07	23.90	31.46	9/3	8.958	181.6	−3.5	191.6	3.7	64.3	35.2	1.9	3.7	*Seidel* [2004] and this study
TG08	23.23	31.23	11/1	10.400	184.0	−20.3	16.7	11.5	56.0	38.3	6.3	12.1	*Seidel* [2004] and this study
TG11	24.40	31.59	7/2	6.978	182.3	0.7	274.0	3.7	65.9	37.1	1.8	3.7	*Seidel* [2004] and this study
TG12	23.72	31.31	12/1	10.928	176.9	20.8	10.3	14.2	76.7	17.9	7.9	15.0	*Seidel* [2004] and this study
KD01	25.35	31.81	12/5	11.717	345.4	−67.0	38.9	7.0	63.2	233.0	9.7	11.7	*Seidel* [2004] and this study

Table 1. (continued)

	Site												
	S Lat	E Long	N	R	Dec	Inc	k	α_{95}	Lat	Long	dp	dm	Reference
10	25.20	31.20	8		190.6	−4.9	170.0	4.3	61.6	54.2			*Hargraves et al.* [1994]
H	24.00	31.30	4		185.0	1.0	70.0	11.0	66.0	43.9			*Henthorn* [1981]
						Vredefort							
VF1	25.84	27.52	11/1	10.399	22.6	−15.3	16.6	11.5	61.9	81.5	6.1	11.8	*Seidel* [2004] and this study
2	27.0	27.4			14.4	−9.5		26.5	63.8	61.6			*McDonald and Andersen* [1973]
4	27.1	27.6			15.4	−6.7		13.0	62.1	62.0			*McDonald and Andersen* [1973]
6	26.8	27.5			353.3	−19.2		14.0	71.7	6.1			*McDonald and Andersen* [1973]
7	27.0	27.4			354.2	−12.6		13.0	68.6	11.6			*McDonald and Andersen* [1973]
10	27.0	27.6			344.8	−3.4		23.0	60.7	−4.9			*McDonald and Andersen* [1973]
11	27.1	27.6			1.7	−14.1		22.0	70.0	32.4			*McDonald and Andersen* [1973]
						Soutpansberg							
NB2[b]	22.56	30.86	8/3	7.602	173.4	−53.7	17.6	13.6	32.9	24.4	13.3	19.0	this study
						Umkondo Dolerites, Zimbabwe							
A	18.00	32.80	9/1	8.757	186.0	−17.0	33.0	9.0	63.0	49.5			*McElhinny and Opdyke* [1964]
B	18.10	32.90	5/0	4.985	171.5	−10.0	267.0	4.5	65.5	12.0			*McElhinny and Opdyke* [1964]
C	18.20	32.85	8/0	7.671	184.5	−8.0	21.0	12.5	67.5	44.5			*McElhinny and Opdyke* [1964]
D	18.45	32.76	10/0	9.288	168.0	−5.5	12.6	14.0	66.0	21.0			*McElhinny and Opdyke* [1964]
E	19.53	32.63	10/0	9.902	185.0	−3.5	92.0	5.0	68.0	46.0			*McElhinny and Opdyke* [1964]
F	19.60	32.80	8/0	7.966	179.5	−13.0	206.0	4.0	64.0	31.5			*McElhinny and Opdyke* [1964]
H	19.85	32.95	10/0	9.576	185.0	−2.5	21.0	10.5	68.5	46.5			*McElhinny and Opdyke* [1964]
I	19.90	32.80	8/0	6.755	176.0	−14.0	5.7	25.5	62.5	24.0			*McElhinny and Opdyke* [1964]
J	20.53	32.66	7/1	6.570	180.5	−10.0	14.0	16.5	64.5	34.0			*McElhinny and Opdyke* [1964]
						Umkondo Lavas, Zimbabwe							
1	20.70	32.46	2		173.0	−11.0			63.0	17.0			*McElhinny* [1966]
2	20.70	32.50	1		178.0	−8.0			65.0	27.5			*McElhinny* [1966]
3	20.71	32.50	3		159.0	−19.0			53.0	356.5			*McElhinny* [1966]
4	20.53	32.66	7		180.5	−10.0			64.5	34.0			*McElhinny* [1966]
5	20.33	32.15	3		200.0	−5.0			60.0	75.0			*McElhinny* [1966]
6	20.25	32.15	1		177.0	14.0			76.5	45.0			*McElhinny* [1966]
7	20.16	32.18	1		142.0	−36.0			69.5	65.5			*McElhinny* [1966]
8	20.06	31.29	2		142.0	−36.0			35.5	349.5			*McElhinny* [1966]
9	19.70	32.45	1		164.0	−38.0			46.0	336.5			*McElhinny* [1966]

[a]N, number of samples included/excluded in the statistics; R, resultant vector; Dec, east declination; Inc, inclination; k, Fisher's precision parameter; α_{95} radius of 95% circle of confidence; Lat, Long, latitude and east longitude of pole position transferred to the Northern Hemisphere; dp, dm, semiaxes of ellipse of 95% confidence.

[b]Sites yielding Paleoproterozoic magnetization directions.

were sampled over a distance of 5 m from the intrusive contact above the sill; the base of the sill is not exposed. The sill did not yield usable data, but the host sandstone samples indicate remagnetization during Umkondo time (Figure 6).

[22] At site W05 near Middleburg a dolerite sill intrudes the Loskop Formation, a Paleoproterozoic red bed sequence which unconformably underlies the Waterberg Group. We could only sample the dolerite and the sedimentary strata overlying the dolerite (site L-1). The Loskop samples have directions of magnetization very similar to the intruding dolerite (Figure 6), but even those Loskop samples that were drilled within half a meter of the dolerite contact have a mean direction that is statistically distinct from the direction of the sill. The majority of the Loskop samples were collected away from the contact (up to 25 m), expecting that these samples would yield the original Loskop direction. It seems clear, though, that all the samples were remagnetized during Umkondo time. The directional dispersion of the Loskop data suggests that the remagnetization event was not the result of a short thermal pulse due to sill intrusion but instead occurred over a longer time period, possibly due to circulating hydrothermal fluids driven by Umkondo igneous activity.

[23] In order to compare the magnetic characteristics of this remagnetized Loskop site with pristine Loskop strata we sampled a small outcrop about 20 km north of Middleburg, well removed from any mapped Umkondo sills (site L-2, Figure 1b). Thermal demagnetization identifies hematite as the carrier of the remanence for sites L-1 and WS-1, whereas the magnetization for the L-2 samples is carried largely by magnetite with lesser contribution from hematite (Figure 7). The dominance of magnetite is a strong indication that the remanence is primary. Vector component diagrams reveal at least two magnetizations in the remagnetized samples, but the L-2 samples contain only one component (Figure 7). The directions of magnetization from site L-2 cluster very tightly with a precision parameter k = 636 (Table 1). Such large values imply that the data do not average secular variation. This is most likely due to the fact that all samples were drilled in one bedding plane because of limited exposure and thus the samples are all of the same age. The 95% error ellipse of the virtual geomagnetic pole position (VGP) derived from site L-2 (Figure 7) falls within

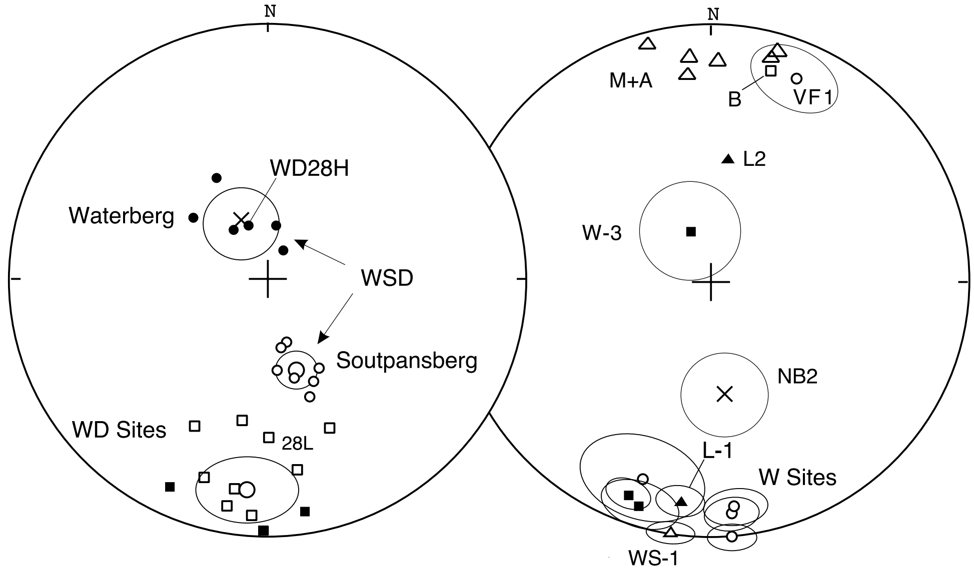

Figure 6. Stereonets for sites in northern South Africa. See Figure 1 for site location. Sites labeled WSD are Paleoproterozoic sites published by *Hanson et al.* [2004b]. M + A are site means from dolerites intruding the Vredefort dome [*McDonald and Andersen*, 1973], and B is the mean for a site at Barnardskop [*Jones and McElhinny*, 1966]. Open (solid) symbols are in the upper (lower) hemisphere.

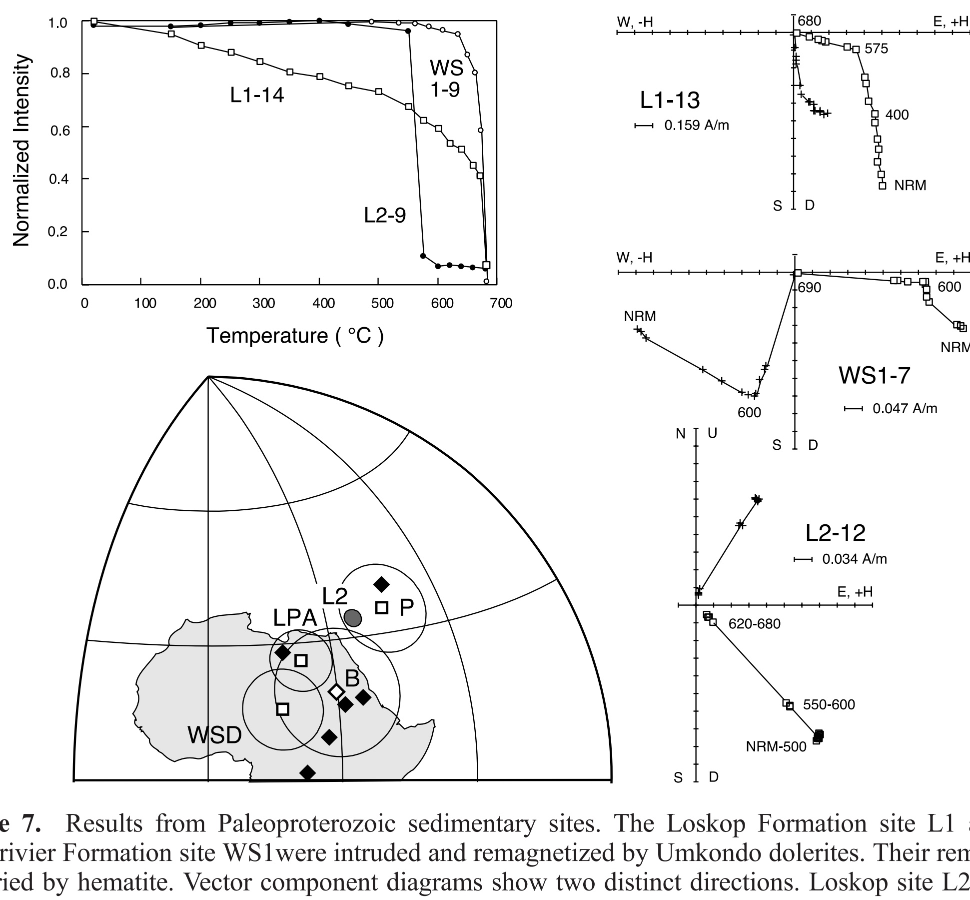

Figure 7. Results from Paleoproterozoic sedimentary sites. The Loskop Formation site L1 and the Wilgerivier Formation site WS1were intruded and remagnetized by Umkondo dolerites. Their remanence is carried by hematite. Vector component diagrams show two distinct directions. Loskop site L2 is well removed from any Umkondo intrusives. Its remanence is carried by magnetite. The pole position of site L2 falls close to the pole from the Phalaborwa Complex (P [*Morgan and Briden*, 1981]), dated at 2.06 Ga. Also shown are the poles from various Bushveld outcrops (diamonds [after *Hanson et al.*, 2004b]), the ~1.98 Ga Limpopo gneiss group A pole (LPA [*Morgan*, 1985]), and the ~1.9 Ga WSD pole of *Hanson et al.* [2004b].

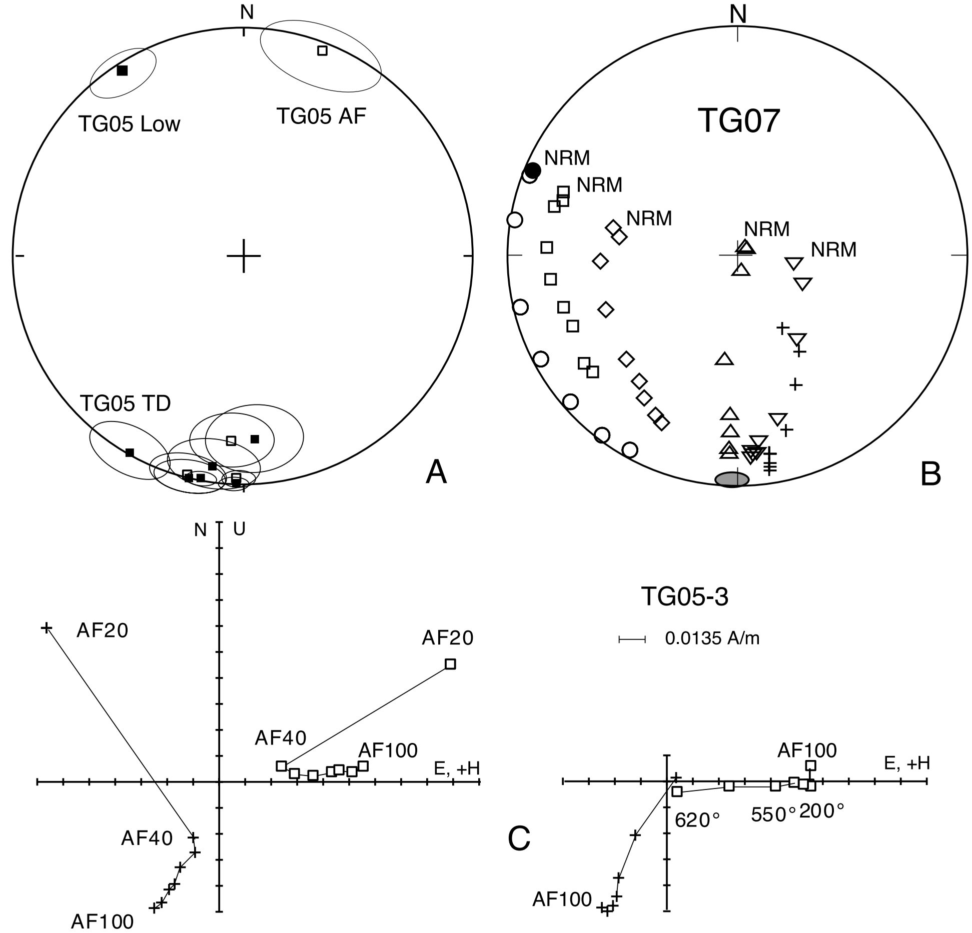

Figure 8. (a) Site mean directions from the Timbavati Gabbro. (b) Samples from site TG07 yielded great circle paths during alternating field demagnetization. After additional thermal demagnetization, principal component analyses established a well-defined mean direction (shaded oval, see Table 1). Different symbols represent individual samples. (c) Site TG05 yielded a normal polarity during AF and a reversed polarity upon subsequent thermal demagnetization.

the error circle of the mean pole derived from sites in the Phalaborwa Complex [*Morgan and Briden*, 1981] which has U-Pb baddeleyite ages of 2059.6 ± 0.4 to 2060.6 ± 0.5 Ma [*Reischmann*, 1995; *French et al.*, 2002], closely similar to the age of the Bushveld Complex (2.06 Ga [*Eglington and Armstrong*, 2004]). Our results are in full agreement with the arguments of *Martini* [1998] that the Loskop Formation was deposited during emplacement of parts of the Bushveld Complex.

3.4. Timbavati Gabbro

[24] We sampled the Timbavati Gabbro at 11 sites near and within Kruger National Park (Figure 1b), two of which did not yield usable results. The site means are shown in Figure 8 and listed in Table 1. Several of the precision parameters, k, are large, indicating that these sites did not average out secular variation. However, the dispersion among the sites is very close to the expected value assuming that secular variation in the Precambrian was similar to Mesozoic and Cenozoic variations [*Butler*, 1992].

[25] The samples from site TG07 did not reach stable endpoints upon AF demagnetization but rather their directions defined great circle paths heading toward the typical Timbavati direction (Figure 8b). Upon subsequent thermal demagnetization the characteristic directions were revealed in the range from 350°C to 620°C. They agree well with the directions from the other sites.

[26] Alternating field demagnetization to 40 mT reduced the intensity of magnetization of the samples from site TG05 to 1% of their NRM value. This low-stability component is not a recent overprint but clusters with a mean declination of 333°E, an inclination of 5°, and α_{95} = 12°. The significance of this direction is not readily apparent. Upon further demagnetization the intensity steadily increases (Figure 8c). Nine of the 15 samples from this site yielded a well-defined normal direction of magnetization. From the vector component diagram it is clear that the samples contain yet a third component of magnetization. It was identified in subsequent thermal demagnetization (Figure 8c) and is of reversed magnetic polarity. The *F* test shows that the two components are antiparallel at the 95% significance level ($F = 1.091 \ll F_{95} = 3.23$). Eight "B" samples, i.e., those parts of the core closest to the surface, were thermally demagnetized in 16 steps up to 680°C with the

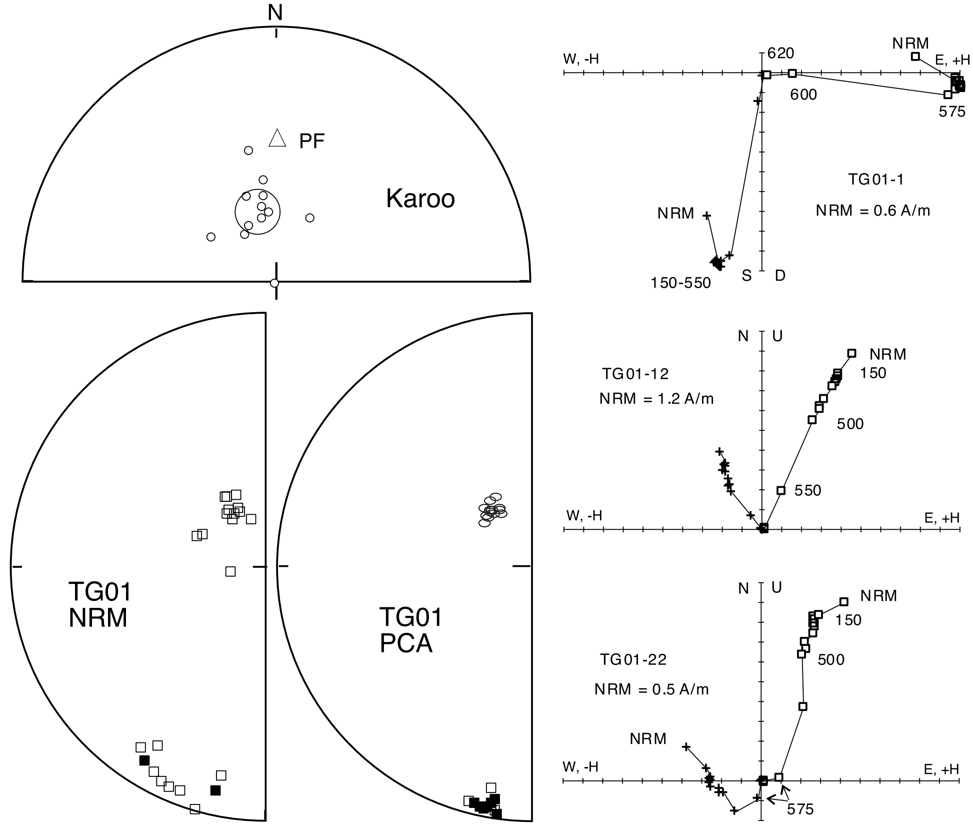

Figure 9. Stereonet of samples from a Jurassic Karoo dike that intruded the Timbavati Gabbro at site TG01. The NRM as well as the characteristic directions of the Timbavati host rock are either a Karoo direction or the typical Umkondo direction of magnetization. No transitional directions were observed. Only one sample, TG01-22, revealed both directions during demagnetization.

goal of establishing the relative age of the normal and reversed magnetizations. Surprisingly, this procedure identified only one component of magnetization with a mean declination of 334°, an inclination of 7°, and α_{95} = 16.5°. This is the same direction as the low-stability direction identified by alternating field demagnetization and will be discussed later.

[27] In fresh outcrops in the bed of the Crocodile River (site TG01), the Timbavati Gabbro is intruded by a 12-m-thick Karoo dolerite dike which afforded the opportunity to perform a contact test. Samples were collected along a profile perpendicular to the dike. The contact zones on either margin of the dike were deeply eroded and not visible. The dike yielded a mean direction of magnetization in good agreement with published Karoo data (Figure 9) [*Hargraves et al.*, 1997]. The NRM directions of the host rock fall into two groups, one close to the Karoo direction and one in agreement with the typical Timbavati-Umkondo direction (Figure 9). No transitional directions between the two clusters were observed and the same duality persisted throughout the thermal demagnetization procedure. Principal component analyses yielded either Umkondo-type directions or Karoo directions (Figure 9). The distribution of remagnetized samples is very asymmetrical. On one side of the dike, only samples collected within 0.5 m of the contact are remagnetized, whereas the zone of remagnetization extends to 5 m on the other side. Only one sample (TG01-22 in Figure 9) which was collected 5 m away from the dike, carried a Karoo direction up to 550°C and the primary Timbavati direction from 575 to 620°C. These results constitute a positive baked contact test but demonstrate only that the characteristic Timbavati remanence was acquired prior to the emplacement of the Karoo dike in the Jurassic.

[28] The Timbavati Gabbro has been previously studied by *Henthorn* [1981] and *Hargraves et al.* [1994]. The data from sites 2 and 3 of Hargraves et al. were analyzed using convergent circles and no error estimates were provided; also, their site 7B has an α_{95} of 28.1°. These results have been excluded from calculating the mean Timbavati direction. Using previously available Rb-Sr dates from rock units with similar pole positions, together with $^{40}Ar/^{39}Ar$ dates from the Timbavati Gabbro, *Hargraves et al.* [1994] suggest an age of 1100 Ma for the gabbro. *Hanson et al.* [2004a] reported a precise crystallization age of 1111.5 ± 0.4 Ma based on U-Pb analyses of individual baddeleyite crystals from site TG07.

4. Age of Magnetization

[29] An important aspect of this project was to collect samples for U-Pb single-crystal baddeleyite or zircon dating from the same intrusions that were sampled for paleomagnetic studies. The geochronological analyses were performed at the MIT Isotope Geology Laboratory, and the

results were reported by *Hanson et al.* [2004a]. Samples from 14 sites in the area of Figure 1b yielded crystallization ages ranging from 1112.0 ± 0.5 to 1108.0 ± 0.9 Ma. Nine of these samples come from intrusions that gave a well-defined Umkondo magnetization direction in this study (sites JP1, JP24, JP30, JP31, JP33, JP34, TG07, WD8, and VF1). Another dated sample is from the Barnardskop dolerite, where *Jones and McElhinny* [1966] obtained an Umkondo-type direction. In addition, *Hanson et al.* [2004a] provided ages of 1108.9 ± 0.6 and 1109.6 ± 0.6 Ma for two Umkondo dolerite sills from eastern Zimbabwe, the area of the original studies by *McElhinny and Opdyke* [1964] and *McElhinny* [1966].

[30] These ages establish the time of igneous crystallization which is not necessarily the time when the magnetization was acquired. Several lines of evidence suggest that the magnetization at most sites is indeed primary, dating to the time of initial cooling. The Umkondo pole position is different from any younger pole position for southern Africa [e.g., *McElhinny and McFadden*, 2000; *McElhinny et al.*, 2003]. The remanence in the Umkondo rocks is carried dominantly by magnetite. Over 30% of this magnetization has unblocking temperatures >500°C. A thermal event capable of remagnetizing these rocks has to be of similar temperature. Because the sampling sites are distributed over a very large area this event would have to be craton-wide; there is no evidence for such an event on this scale. *Jones and McElhinny* [1966] reported a positive baked contact test at their site 13 in the Premier kimberlite mine. Ten sites in South Africa yielded a direction of magnetization antipodal to most Umkondo sites, which is further evidence in support of a primary magnetization.

[31] *Jones et al.* [2003] provided evidence that the Borgmassivet intrusions they collected in the Grunehogna crustal province of Antarctica, which are part of the Umkondo LIP, also carry a primary magnetization. Jones et al. assigned an age of ~1130 Ma to the Borgmassivet intrusions, based on an unpublished U-Pb zircon age for a tuff within the host Ritscherflya Supergroup, and field evidence that the intrusions were emplaced while the host sediments were still poorly consolidated. Two other tuff samples from the Ritscherflya Supergroup have also yielded U-Pb zircon ages of ~1130 Ma [*Frimmel*, 2004]. However, using these results to date the Borgmassivet intrusions conflicts with the fact that the group mean Borgmassivet pole, after restoration of the Grunehogna terrane adjacent to the Kalahari craton, is statistically identical to the Umkondo pole from southern Africa, well dated at 1112–1108 Ma. Importantly, one of the Borgmassivet dolerites has yielded an unpublished U-Pb zircon and baddeleyite age of 1107 ± 2 Ma (R. Tucker, personal communication, 2003). We therefore infer that the Borgmassivet intrusions and the Umkondo mafic rocks in southern Africa acquired their characteristic remanence at the same time.

[32] However, some sites in southern Africa have been remagnetized. Site JP11 has been dated at 1927.3 ± 0.7 Ma but its magnetization is clearly of Umkondo age. The nearby site JP10 has a similar crystallization age but its pole position is very different. The significance of this pole will be discussed later. Site WD28 has a well-defined low-coercivity component similar to other Umkondo sites but its high-coercivity magnetization agrees with sites that have been dated near 1875 Ma. In addition, a significant number of sites were remagnetized by lightning.

5. Mystery Direction

[33] Two sampling sites in the Moshaneng Dolerite in Botswana (JP-9 and JP-10) yielded well-defined directions of magnetization that are distinctly different from the directions of Umkondo sites. The same anomalous direction was also obtained by *Jones and McElhinny* [1966] from the dolerite (their site A1). A subset of samples from a site in the Timbavati Gabbro (TG-5B), about 670 km to the east, carries a very similar magnetization. In Zimbabwe, about 725 km to the north of the JP sites, *Bates and Jones* [1996] obtained a similar direction from one of the Sebanga dikes, which are of Paleoproterozoic age. All these sites are located on the Kalahari craton. *Meert et al.* [1995] reported data on 10 sites in the ~750 Ma Mbozi syenite and gabbro complex in Tanzania that also have a northwesterly shallow direction of magnetization. The complex lies near the eastern edge of the Congo craton and is over 1700 km to the north of the JP sites. Also within the Congo craton, *Wingate et al.* [2004] have reported the same direction from ~765 Ma volcanic rocks in northwest Zambia.

[34] The pole positions of these sites are shown in Figure 10. Clearly, the poles are not of Umkondo age nor are they due to a recent overprint. The Moshaneng Dolerite has been dated at 1929–1928 Ma. However, if that were also the time of magnetization then one would expect the pole to lie between the 2.06 Ga Phalaborwa pole (PA1) and the 1.87 Ga WSD pole. The pole from the Timbavati Gabbro at site TG05 also falls in this group. This gabbro has yielded a U-Pb baddeleyite age of 1111.5 ± 0.4 Ma. Thus the age of magnetization must be younger. *Meert et al.* [1995] used a K-Ar biotite date of 743 ± 30 from the Mbozi syenite [*Brock*, 1968] to argue that the Mbozi pole implies that the Congo craton was not yet part of East Gondwana. This age of the Mbozi complex is supported by a recently obtained U-Pb age of 748 ± 6 Ma [*Mbede et al.*, 2004]. However, the agreement of the Mbozi pole with the other poles in Figure 10 is striking and suggests that these rocks were magnetized at the same time and in the same relative position as they are today. Without a good determination of the age of magnetization of these poles, their tectonic significance remains a mystery.

6. Discussion

6.1. Umkondo Pole and Its Laurentian Counterpart

[35] There are now 71 sampling sites from the Umkondo province in the Kalahari craton in southern Africa that have yielded similar directions of magnetization, approximately due south with shallow inclinations, and 10 sites of opposite polarity. To this data set one can add the results from 33 sites in Antarctica [*Peters*, 1989; *Jones et al.*, 2003] after restoring East Antarctica to its position next to southern Africa using the parameters given by *Reeves et al.* [2002]. Giving equal weight to each site pole yields a site mean pole at 63.5°N, 38.2°E, A_{95} = 2.1°. It seems more appropriate, though, to group the sites geographically. Most of the sites sampled by *Jones and McElhinny* [1966] are in the same area as our sites in Botswana, and the Timbavati Gabbro was sampled by

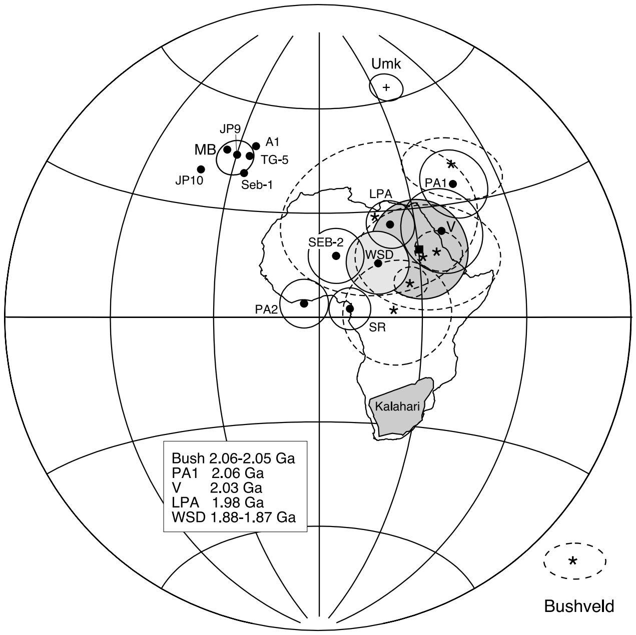

Figure 10. Comparison of "mystery directions" with dated Precambrian pole positions. A1, Moshaneng Mine dolerite [*Jones and McElhinny*, 1966]; MB, Mbozi Complex [*Meert et al.*, 1995]; Seb-1, SEB-2, Sebanga dikes [*Bates and Jones*, 1996]; JP9, JP10, TG−5, this study; PA1, PA2, Phalaborwa Complex [*Morgan and Briden*, 1981]; LPA, Limpopo Gneiss group A [*Morgan*, 1985]; V, Vredefort [*Carporzen et al.*, 2005; *Hargraves*, 1970; *Pesonen et al.*, 2003]; SR, Sand River dikes [*Morgan*, 1985]; WSD, Waterberg−Soutpansberg dolerites [*Hanson et al.*, 2004b; this study]; solid square is the mean of the Bushveld Complex data [*Hattingh and Pauls*, 1994]; its error circle is shaded grey.

Hargraves et al. [1994] as well as by us. This classification yields 10 groups of data summarized in Table 2. In the computation of the group means, sites with $\alpha_{95} > 20°$ have been omitted. The mean pole lies at 64.0°N, 38.8°E, A_{95} = 3.6°.

[36] *Jones and McElhinny* [1966] first demonstrated the utility of paleomagnetic techniques for correlating widely separate dolerite intrusions in parts of southern Africa, within what is now considered the Umkondo LIP. The present study emphasizes the role paleomagnetism can play in delimiting the total extent and timing relations of Precambrian LIPs represented by erosional remnants scattered over a wide region, particularly when the paleomagnetic data are coupled with robust geochronological studies.

[37] Precise U-Pb crystallization ages for mafic intrusions from different parts of the Umkondo province in southern Africa indicate emplacement in a narrow time frame at 1112−1108 Ma. The close similarity in pole positions (Figure 11) for the much larger suite of undated Umkondo intrusions and lavas demonstrates that an enormous volume of mafic magma was emplaced throughout the province in the same narrow time frame. These results are consistent with work in other, better known LIPs, where detailed geochronology, supported in many cases by paleomagnetic data, indicates that much of the magmatism occurred over time intervals <1−2 m.y. [e.g., *Courtillot and Renne*, 2003].

[38] An important aspect of the paleomagnetic data for the Umkondo province is that the great majority of sites have yielded a single polarity that is reversed with respect to the present-day field. Out of a total of 114 sites in southern Africa and the Grunehogna province in Antarctica, only 10 have normal polarity. These data raise the possibility that most of the province was emplaced during a single reversed polarity chron.

[39] Independent constraints on the temporal significance of the polarity data for the Umkondo province come from comparison with coeval magmatism in the Midcontinent rift in Laurentia, for which an extensive paleomagnetic database exists. There, the voluminous Keweenawan igneous suite was emplaced primarily at 1108−1094 Ma, based on U-Pb geochronology. An early, major pulse of magmatism occurred at 1107.5 + 4/−2 to 1105.3 ± 2.1 Ma [*Davis and Sutcliffe*, 1985; *Davis and Green*, 1997], which coincides, within error, with widespread magmatism in the Umkondo province. With a few exceptions, units emplaced during the first Keweenawan magmatic pulse have reversed magnetic polarity, whereas most of the younger Keweenawan igneous rocks have the opposite polarity [*Halls and Pesonen*, 1982; *Davis and Green*, 1997; *Nicholson et al.*, 1997]. These two major polarity chrons have long been used for regional correlation in the Midcontinent rift. Because of the close temporal overlap between the initial pulse of Keweenawan magmatism and emplacement of the Umkondo province, *Hanson et al.* [2004a] inferred that the great majority, if not all, of the latter province was emplaced during the reversed polarity chron recorded in the Midcontinent rift. Such an inference allows the reversal sequence established in the Midcontinent rift, and calibrated by U-Pb geochronology, to be used in intercontinental correlation of 1.1 Ga magmatic events within the Kalahari and Laurentian cratons.

[40] Shorter, normal polarity intervals have been documented within the longer reversed polarity chron in the older part of the Keweenawan suite, although the total number and exact ages of these normal polarity intervals are generally unclear [e.g., *Symons et al.*, 1994; *Nicholson et al.*, 1997]. For example, different parts of the Coldwell,

Table 2. Site Mean Pole Positions[a]

	N	R	k	Lat	Long	A_{95}
Botswana North	12	11.931	159.5	66.4	43.0	3.4
Botswana South	7	6.923	78.0	57.3	43.6	6.9
Waterberg	11	10.527	21.1	57.3	34.4	10.2
Middleburg	11	10.801	50.2	63.6	47.0	6.5
Vredefort	4	3.897	29.2	69.3	45.9	17.3
Timbavati	12	11.823	62.1	64.1	54.7	5.6
Umkondo dolerite, Zimbabwe	8	7.964	191.1	66.4	35.5	4.0
Umkondo lavas, Zimbabwe	9	8.473	15.2	63.4	16.4	13.7
Antarctica-Peters	10	9.848	59.1	66.1	41.7	5.3
Antarctica-Jones	23	22.788	103.6	62.2	28.2	3.0
Mean of area means	10	9.948	172.2	64.0	38.8	3.7
Revised Paleoproterozoic pole	15	14.384	22.7	17.4	17.2	8.2

[a]N, number of sites; R, resultant vector; k, Fisher's precision parameter; Lat, Long, latitude and east longitude of pole position; A_{95}, radius of 95% circle of confidence.

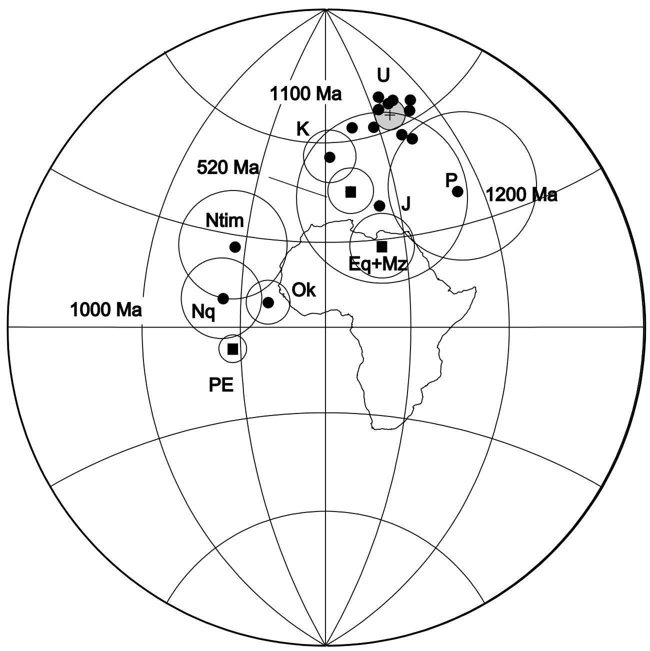

Figure 11. Pole positions for 10 Umkondo sampling areas (U), the Kalkpunt Formation (K, *Briden et al.* [1979]) and the Namaqua–Natal Belt (Ok, *Muller et al.* [1978]; Nq, *Onstott et al.* [1986]; Ntim, *Maré and Thomas* [1998]; PE and Eq + Mz, *Gose et al.* [2004]). P, Premier Kimberlite [*Doppelhammer and Hargraves*, 1994]; J, Jannelsepan and related rocks [*Onstott et al.*, 1986]. The pole for 520 Ma is the Gondwana pole of *McElhinny et al.* [2003].

Nemegosenda, and Lackner Lake alkaline complexes show both normal and reversed polarity [*Symons et al.*, 1994]. These three complexes have yielded U-Pb ages of 1108 ± 1, 1107, and 1105 Ma, respectively [*Heaman and Machado*, 1992] (error bars not reported for latter two ages). In the Umkondo province, sites with normal polarity include our site JP1 from a dolerite sheet in southeastern Botswana, the Barnardskop dolerite in South Africa [*Jones and McElhinny*, 1966], and dolerite intruding the Vredefort dome (our site VF1 and six sites sampled by *McDonald and Andersen* [1973]). These dolerites have yielded U-Pb ages ranging from 1108.6 ± 1.2 to 1108.0 ± 0.9 Ma [*Hanson et al.*, 2004a]. They are inferred to have been emplaced during one (or more) of the short intervals of normal polarity documented within the main reversed polarity chron in the Midcontinent rift.

[41] It has been argued that the Keweenawan paleomagnetic data provide evidence for asymmetric reversals of the geomagnetic field [*Pesonen and Halls*, 1983; *Nevanlinna and Pesonen*, 1983]. This conclusion has been disputed by *Symons et al.* [1994], based on recognition of symmetric reversals recorded by Keweenawan alkaline complexes [see also *Ernst and Buchan*, 1993; *Gallet et al.*, 2000]. In the Umkondo province, 10 sites with normal polarity come from intrusions whose crystallization ages are within error of ages for intrusions showing the opposite polarity. An *F* test establishes that the two groups of samples are antiparallel at the 95% confidence level. Thus we find no evidence for asymmetric reversals in this time frame.

[42] *Hanson et al.* [2004a] used a mean Umkondo pole located at 63.6°N, 36.2°E, A_{95} = 3.8° when they argued that the Umkondo igneous province and the contemporaneous magmatic activity on the North American craton could be parts of a single large igneous province (LIP). The angular difference between the pole used by those authors and our new Umkondo pole is 1.2° and thus does not change the conclusions of those authors.

6.2. Southern African Poles Relevant to Rodinia Reconstructions

[43] There is wide agreement that many, if not all, of Earth's cratons were assembled near the end of the Mesoproterozoic within a supercontinent that is generally called Rodinia; the configuration of that supercontinent, however, remains controversial because there are few or no reliable paleomagnetic data from most cratonic blocks to test this hypothesis. The Umkondo pole position provides a robust anchor point for the relative positions of the Laurentian and Kalahari cratons during Rodinia assembly at ∼1100 Ma. The location of the Kalahari craton before and after this time is, however, only poorly constrained (Figure 11). Toward younger ages, there are several pole positions from the Namaqua-Natal orogenic belt. *Muller et al.* [1978] obtained a pole position from 10 sites in mafic intrusions in the Okiep copper district. *Onstott et al.* [1986] reported results from an additional five intrusions in the same area. The latter authors performed thermochronological studies and obtained ages ranging from 1010 to 1075 Ma for the time when the rocks cooled below 500°C. Further analyses on the same samples refined the age to 1000 ± 25 Ma [*Renne et al.*, 1990].

[44] In the Natal sector of the belt, the Port Edward Charnockite (1025 ± 8 Ma [*Eglington et al.*, 2003]) was sampled by *Onstott et al.* [1986] (1 site, 6 samples) and *Gose et al.* [2004] (4 sites, 30 samples). *Maré and Thomas* [1998] obtained a similar pole position from the Ntimbankulu pluton, a member of the same Oribi Gorge suite. The $^{40}Ar/^{39}Ar$ ages on hornblende [*Jacobs et al.*, 1997] imply that the sampling area, the Mzumbe terrane, cooled through the 500° isotherm at 1004 ± 5 Ma, setting the magnetization of the Port Edward and Ntimbankulu plutons at that time. Combining the results from the four studies yields a mean pole position at 9.4°N, 329.5°E, A_{95} = 17.8°.

[45] *Briden et al.* [1979] obtained a pole position from the Kalkpunt Formation, the youngest member of the Koras Group, which has been widely used to define the apparent pole wander path for the Kalahari craton between 1.1 and 1.0 Ga [e.g., *Weil et al.*, 1998; *Powell et al.*, 2001; *Evans et al.*, 2002; *Meert and Torsvik*, 2003; *Pesonen et al.*, 2003; *Pisarevsky and Natapov*, 2003]. *Onstott et al.* [1986] argued that the age of this pole is <1049–1032 Ma, based on $^{207}Pb/^{206}Pb$ dates for two highly discordant multigrain zircon fractions from felsic dikes that intrude all members of the Koras Group except the Kalkpunt Formation [*Barton and Burger*, 1983]. They also cited U-Pb zircon dates of ∼1085 and 1050 Ma from felsic volcanic rocks in the group and from genetically related granites; these dates are based on discordant, multigrain zircon analyses obtained in the 1960s (see discussion by *Cahen et al.* [1984]). On the basis of the same data, *Renne et al.* [1990] gave the age of the Kalkpunt pole as <1065 ± 20 Ma. More recent age deter-

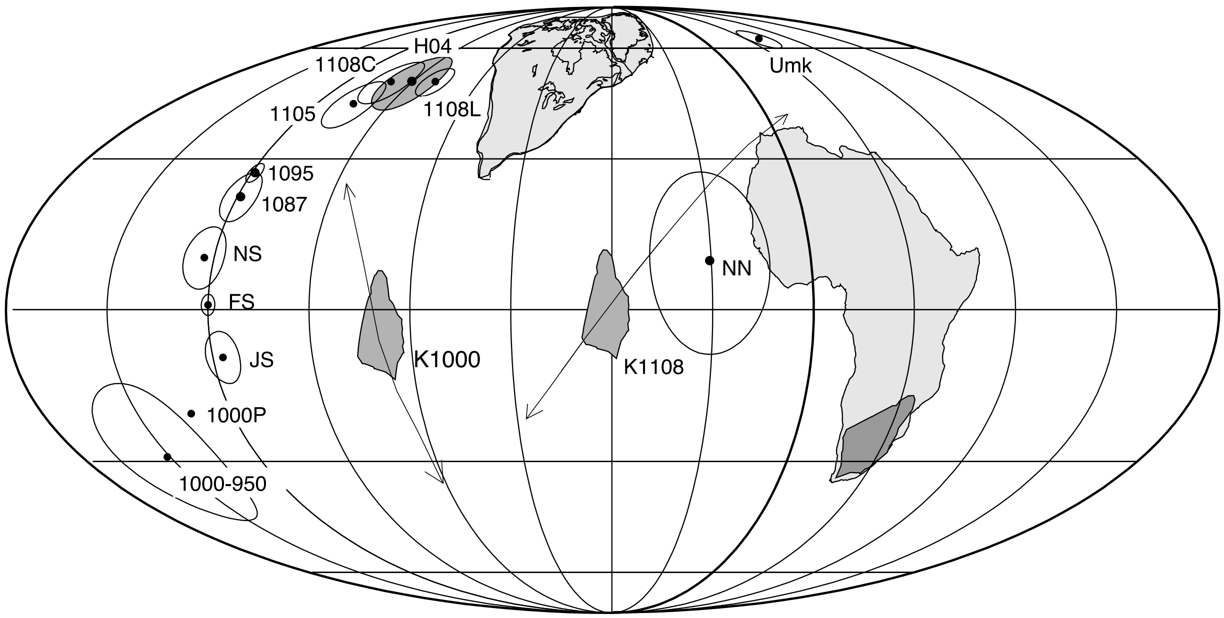

Figure 12. Possible positions of the Kalahari craton relative to Laurentia at 1108 Ma (K1108) and 1000 Ma (K1000). Pole H04 (shaded ellipse) is the mean Laurentia pole for 1108 Ma as also used by *Hanson et al.* [2004a]. Pole identification: 1108L, Logan Sills; 1108C, Coldwell combined; 1105, reversed upper Osler lavas; 1095, Portage Lake lavas; 1087, Lake Shore traps; NS, Nonesuch shales; FS, Freda sandstone; JS, Jacobsville sandstone; 1000P, estimated pole by *Pesonen et al.* [2003]; 1000-950, Grenville A overprint. Pole references: *Buchan et al.* [2001] and *Meert and Torsvik* [2003]; Umk, mean Umkondo; NN, Namaqua-Natal.

minations have superseded these previous data. *Gutzmer et al.* [2000] reported a U-Pb zircon SHRIMP age of 1171 ± 7 Ma for volcanic rocks near the base of the Koras Group and separated from the Kalkpunt Formation by an unconformity. Felsic volcanic rocks that conformably underlie the Kalkpunt Formation have yielded a U-Pb zircon ion-microprobe age of 1093 ± 9 Ma [*Pettersson and Cornell*, 2005; A. Pettersson, personal communication, 2005]. This result provides the best current constraint on the age of the Kalkpunt pole.

[46] *Doppelhammer and Hargraves* [1994] reported paleomagnetic data from the Franspoort and Schuller pipes within the Premier kimberlite swarm. They combined their results with poles from the National and Premier pipes [*Jones*, 1968; *Hargraves and Onstott*, 1980]. Samples from individual pipes cluster well but the means differ by as much as 37°. *Doppelhammer and Hargraves* [1994] cite seven age determinations on the Premier pipe and two on the National pipe. The ages range from 1223 to 1140 Ma. Three ages are quoted without error estimates and the others have errors ranging from ±16 to ±72 Ma. Recognizing the limitations of the age determinations and the streaked distribution of their data, *Doppelhammer and Hargraves* [1994] suggest that the mean pole may provide the best estimate for a pole for the Kalahari craton at ~1200 Ma. Using the same data, *Powell et al.* [2001] list the age of the Premier kimberlites as 1165 ± 10 Ma but do not explain how they arrived at that age and error limit.

[47] From the eastern part of the Namaqua belt, *Onstott et al.* [1986] report additional pole positions from four sites, including the Jannelsepan amphibolite. This unit yielded an ^{40}Ar/^{39}Ar cummingtonite date of 1244 ± 30 Ma, considered by *Onstott et al.* [1986] to constrain the age of magnetization. *Evans et al.* [2002] used this age to date the time of magnetization of some of their sampling sites in the Northern Cape Province. A plagioclase separate from the Jannelsepan Formation, however, gave an ^{40}Ar/^{39}Ar date of 547 ± 9 Ma [*Onstott et al.*, 1986]. The mean pole position of *Onstott et al.* [1986] falls precariously close to the 520 Ma pole for the Gondwana apparent polar wander path [*McElhinny et al.*, 2003; *Meert and van der Voo*, 1997] and the 530 Ma Equeefa/Mzumbe pole from the Natal area [*Gose et al.*, 2004]. This raises serious doubt about the age of magnetization of the Jannelsepan Formation and related rocks.

[48] Thus the only reasonably well-dated paleomagnetic poles from the Kalahari craton that are of direct use in Rodinia reconstructions are the ~1.1 Ga Umkondo and Kalkpunt poles and the ~1.0 Ga poles from the Namaqua-Natal Belt.

6.3. Implications for Rodinia Reconstructions

[49] For the time period from 1108 to 1087 Ma, there are several excellent pole positions from Laurentia from Keweenawan rocks, all but one of which are listed as “key poles” by *Buchan et al.* [2001]. They are shown in Figure 12 which also depicts the mean Coldwell pole of *Meert and Torsvik* [2003]. The next younger pole for Laurentia is the Grenville A metamorphic overprint pole, considered to represent the magnetic field direction between 950 and 1000 Ma [*Berger et al.*, 1979; *Buchan et al.*, 2001]. Several pole positions derived from sedimentary rocks seem to fill the gap in the polar wander path, but the age of these poles is poorly constrained. The poles are depicted in

Figure 12. On the basis of these data, *Pesonen et al.* [2003] estimated the Laurentian pole position for 1000 Ma. Their estimate and the pole position used by *Hanson et al.* [2004a] for their Laurentia-Kalahari reconstruction at 1108 Ma are also shown.

[50] Because many of the Umkondo dolerites are precisely of the same age as the early part of the Keweenawan igneous suite in Laurentia, the magnetic polarity of both data sets must be the same, thereby determining the relative orientation of the two cratons, a point argued in more detail by *Hanson et al.* [2004a]. The position of Kalahari at 1108 Ma (K1108) shown in Figure 12 was obtained by superposing its pole on the Laurentian pole for the same age. The Laurentian pole is the mean of the Logan sills, Coldwell Complex, Powder Mill Group, and North Shore Volcanic Group poles which have ages ranging from 1107.9 ± 1.8 to 1108 ± 1 Ma [see *Hanson et al.*, 2004a, and references therein]. The position of Kalahari in Figure 12 is the one advocated by *Hanson et al.* [2004a] in order to maintain a spatial link between the coeval Laurentian and Umkondo igneous provinces but the lack of paleolongitudinal control allows Kalahari to be situated anywhere along a small circle centered on pole H04 as schematically indicated by the double-ended arrow. Because there is no dated pole position for Laurentia at 1000 Ma, we use the pole estimated by *Pesonen et al.* [2003] to determine the relative position of Kalahari at that time. The polarity of the 1000 Ma Kalahari pole is not known nor is its paleolongitude but the configuration shown in Figure 12 (K1000) yields the simplest drift history for Kalahari. We do not use the Koras pole in Figure 12 because the relatively large error on the age of the pole (±9 Ma) makes it difficult to compare precisely with the Laurentian poles.

[51] In the interpretation shown in Figure 12, Kalahari remains distinctly south of Laurentia (present coordinates) between 1108 and 1000 Ma, in contrast to models invoking collision between the two cratons along the Namaqua-Natal-Maud and Grenville belts during Rodinia assembly [e.g., *Dalziel et al.*, 2000]. In the most recent of these collisional models, *Jacobs et al.* [2003] argued that juxtaposition of the two cratons occurred at 1090–1060 Ma, based on geochronological constraints from coeval parts of the Namaqua-Natal-Maud and Grenville belts. It is geometrically possible to combine our proposed positions for Kalahari at 1108 and 1000 Ma with the model of *Jacobs et al.* [2003], but such a scenario would require rotation of Kalahari by nearly 180° as it approached Laurentia. Following collision, the two cratons would have to rift apart, with Kalahari moving to the southwest of Laurentia coupled with a large rotation (Figure 12) by 1000 Ma. As far as we are aware, there is no evidence in either craton for such a rift event in the required time frame.

[52] It should be noted that our suggested configuration does not take account of the errors in the pole positions used for either Laurentia or Kalahari, so they could have been closer than we show by some 10 degrees. Indeed Laurentia appears to have been moving rather rapidly during latest Mesoproterozoic times, so the errors in individual poles may be exacerbated by the errors in the age of the poles [*Buchan et al.*, 2001].

[53] The separation of Kalahari and Laurentia at 1100–1000 Ma is such that reconstructions that place parts of East Gondwana to the southwest or south of Laurentia are geometrically possible [e.g., *Meert and Torsvik*, 2003; *Pesonen et al.*, 2003]. In the reconstruction of *Powell and Pisarevsky* [2002], Kalahari is separated from Laurentia by the Australia-Mawson cratons. Those workers noted that ~1080 Ma deformation in the Darling belt along the western Australian margin might link with coeval deformation in the Natal and Maud belts along the southeastern margin of Kalahari. Such an interpretation is possible within the framework of Figure 12. However, *Fitzsimons* [2003] has questioned the existence of a Mesoproterozoic orogenic belt in this time frame along the margin of west Australia, and has interpreted Mesoproterozoic terranes in that region as allochthonous blocks brought into position during Neoproterozoic–early Paleozoic tectonism.

[54] There is presently no consensus on which cratons were positioned next to southern Laurentia within Rodinia [e.g., *Tohver et al.*, 2005]. In order to rigorously test different models for Rodinia configurations, well-dated apparent polar wander paths for the various components of Rodinia for the appropriate time frames are needed. Obtaining such data will likely require prolonged efforts.

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