U–Pb geochronology and paleomagnetism of the Westerberg Sill Suite, Kaapvaal Craton – Support for a coherent Kaapvaal–Pilbara Block (Vaalbara) into the Paleoproterozoic?

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ABSTRACT

Precise geochronology, combined with paleomagnetism on mafic intrusions, provides first-order information for paleoreconstruction of crustal blocks, revealing the history of supercontinental formation and break-up. These techniques are used here to further constrain the apparent polar wander path of the Kaapvaal Craton across the Neoarchean–Paleoproterozoic boundary. U–Pb baddeleyite ages of 2441 ± 6 Ma and 2426 ± 1 Ma for a suite of mafic sills located on the western Kaapvaal Craton in South Africa (herein named the Westerberg Sill Suite), manifests a new event of magmatism within the Kaapvaal Craton of southern Africa. These ages fall within a ca. 450 Myr temporal gap in the paleomagnetic record between 2.66 and 2.22 Ga on the craton. Our older Westerberg Suite age is broadly coeval with the Woongarra magmatic event on the Pilbara Craton in Western Australia. In addition, the Westerberg Suite on the Kaapvaal Craton intrudes a remarkably similar Archean–Proterozoic sedimentary succession to that on the Pilbara Craton, supporting a stratigraphic correlation between Kaapvaal and Pilbara (i.e., Vaalbara). The broadly coeval Westerberg–Woongarra igneous event may represent a Large Igneous Province. The paleomagnetic results are more ambiguous, with several different possibilities existing. A Virtual Geomagnetic Pole obtained from four sites on the Westerberg sills is 18.9°N , 285.0°E , $A_{95} = 14.1^\circ$, $K = 43.4$ (Sample based VGP, $n = 34$: 16.8°N , 2879.9°E , $dp = 4.4^\circ$, $dm = 7.7^\circ$). If primary (i.e., 2441–2426 Ma), it would provide a further magmatic event within a large temporal gap in the Kaapvaal Craton's Paleoproterozoic apparent polar wander path. It would suggest a relatively stationary Kaapvaal Craton between 2.44 Ga and 2.22 Ga, and ca. 35° of latitudinal drift of the craton between ca. 2.66 Ga and 2.44 Ga. This is not observed for the Pilbara Craton, suggesting breakup of Vaalbara before ca. 2.44 Ga. However, it is likely that the Woongarra paleopole represents a magnetic overprint acquired during the Ophthalmian or Capricorn Orogeny, invalidating a paleomagnetic comparison with the Westerberg Sill Suite. Alternatively, our Westerberg Virtual Geographic Pole manifests a 2.22 Ga magnetic overprint related to Ongeluk volcanism. The similarity between Ongeluk and Westerberg paleopoles however may also infer magmatic connections if both are primary directions, despite the apparent 200 million year age difference.

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1. Introduction

A fundamental question concerning the arrangement of late Archean continental blocks is whether they were amalgamated into a single supercontinent, Kenorland, or if they were dispersed

into several smaller supercratons such as Superia, Sclavia and Vaalbara (e.g., Bleeker, 2003). Paucity of the paleomagnetic record for most Archean continental crust, and a lack of reliable geochronology on units with paleomagnetic constraints are the main problems preventing resolution of this question. Precise emplacement ages from igneous units of different ages, together with paleogeographic studies can be used to construct magmatic barcodes and apparent polar wander paths (APWPs) of these Archean crustal blocks. Similar magmatic barcode and APWPs indicate if the cratons were a part of a common crustal framework, whereas divergent magmatic barcodes and APWPs indicate the

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Fig. 1. Geological map of the Kaapvaal Craton, showing the major >2.0 Ga units (simplified after Keyser, 1997). The spatial subdivision of the Transvaal Supergroup successions into the Transvaal, Griqualand West and Kanye (in Botswana) basins is shown. The schematic division into three tectonic blocks is based on Eglington and Armstrong (2004). Abbreviation SG = Supergroup.

cratons were presumably dispersed during this time interval (e.g. Bleeker and Ernst, 2006).

The Kaapvaal Craton of southern Africa has long attracted the attention of research, and it is one of the best-studied Archean cratons. This is partly due to the extraordinary preservation of >2.0 Ga supracrustal successions, such as the Witwatersrand and Transvaal supergroups, as well as the Bushveld Complex, with the associated deposits of gold, iron, diamonds, manganese, platinum, chromium and vanadium (Fig. 1). The most studied connection regarding the Kaapvaal Craton during the Archean and Paleoproterozoic is with the Pilbara Craton of Western Australia. The Neoproterozoic-Paleoproterozoic continuity of these two cratons (i.e., Vaalbara) was first proposed by Cheney et al. (1988). The exact configuration of the two cratons at this time has since been tested (Smirnov et al., 2013; De Kock et al., 2009a; Strik et al., 2003; Wingate, 1998; Zegers et al., 1998). Vaalbara is currently paleomagnetically well constrained between ca. 2.78 Ga and 2.66 Ga during Ventersdorp volcanism on the Kaapvaal Craton (e.g., De Kock et al., 2009a). After this volcanism, a remarkable stratigraphic match between the Ghaap Group (Transvaal Supergroup) on the Kaapvaal Craton and the Hamersley Group, Pilbara Craton, suggests a cohesive Vaalbara into the Paleoproterozoic (e.g., Beukes and Gutzmer, 2008). However, the next youngest well-constrained paleopoles from either

craton, are from rocks in which correlation is much more problematic. For the Kaapvaal Craton, the next youngest paleopole is dated at ca. 2.22 Ga, or ca. 2.43 Ga (Evans et al., 1997), due to contradicting age determinations discussed below; whereas for the Pilbara Craton they are between 1.75 and 1.95 Ga (Schmidt and Clark, 1994; Li et al., 1993). A primary paleomagnetic record for the lower part of the Ghaap Group and the Hamersley Group has so far proved elusive (De Kock et al., 2009b; Schmidt and Clark, 1994; Li et al., 1993).

This study reports U–Pb geochronology and paleomagnetism for the newly identified Westerberg Sill Suite, which forms semi-continuous outcrops in the Griqualand West sub-basin of the Transvaal Supergroup on the western margin of the Kaapvaal Craton. These mafic intrusions occur in the upper parts of the 2465 ± 6 Ma Kuruman Iron Formation, in the Ghaap Group (Pickard, 2003). If the Westerberg Sill Suite is coeval with the 2449 ± 3 Ma dolerites that intrude the Weeli Wolli Iron Formation near the top of the Hamersley Group on the Pilbara Craton (Barley et al., 1997), the geochronological magmatic “barcode” match and similar stratigraphies could support the existence of Vaalbara as a continuous cratonic block well into the Paleoproterozoic Era. This may also refine relative positions of these cratons using paleomagnetic studies at this time.

2. Geological setting

2.1. Regional geology

The Kaapvaal Craton in southern Africa is composed of ca. 3.6–2.7 Ga granitoid-greenstone basement overlain by ca. 3.1–1.7 Ga supracrustal cover successions. The Neoproterozoic Ventersdorp Supergroup (which provides paleomagnetic constraints used to support Vaalbara), and the Paleoproterozoic Transvaal Supergroup (that matches the Pilbara Craton temporally and stratigraphically), are two such cover successions that developed across the ca. 3.6 and 2.7 Ga crustal basement (Fig. 1).

Following the extensive volcanism and sedimentation that resulted in the deposition of the Ventersdorp Supergroup, deposition of clastic and carbonate sedimentary rocks (with subordinate volcanic rock units) of the Transvaal Supergroup began. The Transvaal Supergroup is today preserved in three 'basins' or erosional remnants. These remnants consist of the Transvaal Basin on the central and eastern parts of the Kaapvaal Craton, and the Griqualand West Basin on the western Kaapvaal Craton (both occurring in South Africa), while the isolated and largely Kalahari sand-covered occurrences in Botswana are referred to as the Kanye Basin (Fig. 1). The spatially separated remnants share a similar geological evolution and stratigraphy. Geological units have therefore been defined representing similar lithologies that can span over more than one basin. An estimate for the onset of sedimentation is provided by volcanic rocks in the Vryburg Formation in the Griqualand West Basin, which is dated to 2642 ± 3 Ma (Walraven and Martini, 1995). This is temporally similar to the 2664 ± 6 Ma age reported for the Wolkberg Group further to the east (Barton et al., 1995), which is considered to be a protobasinal fill of sedimentary and volcanic rocks before the onset of sedimentation in the main Transvaal Basin. The Wolkberg Group is overlain by the Black Reef Formation in both the Transvaal and Kanye basins. The Vryburg Formation is an equivalent of the Black Reef Formation, and forms the base of the Transvaal Supergroup in the Griqualand West Basin. The carbonate to banded iron formation (BIF) platform successions (Chuniespoort, Ghaap and Taupone groups in the Transvaal, Griqualand West and Kanye basins, respectively), and the overlying mixed clastic and chemical sedimentary rocks (Pretoria, Postmasburg and Segwagwa groups), are widespread and present in all three basins (Eriksson et al., 2006). The Ghaap Group of the Griqualand West Basin hosts the Westerberg Sill Suite, which is the focus of this study (Fig. 2).

The Ghaap Group (Schröder et al., 2006), is a ca. 1.5 km thick carbonate and BIF succession, with a four-fold subdivision (i.e., the Schmidtsdrif, Campbellrand, Asbestos Hills, and Koegas subgroups). The Koegas Subgroup has alternatively been placed into the Ghaap and Postmasburg groups (Eriksson et al., 2006). The Schmidtsdrif Subgroup, which can include the 2642 ± 3 Ma Vryburg Formation (Walraven and Martini, 1995), is a mixed clastic-carbonate ramp succession that is conformably overlain by the Campbellrand Subgroup. The Malmani Subgroup in the main Transvaal Basin represents laterally equivalent strata of carbonate rocks (Beukes, 1987). This carbonate strata consists of a thin basinal deep water succession near the south-west margin of the craton in the Griqualand West Basin, and a relatively thick continental shelf succession deposited in shallower water on the craton in both the Griqualand West and Transvaal basins. Chert and BIF of the Asbestos Hills Subgroup conformably overlie the Campbellrand Subgroup, representing drowning of the platform at about 2.5 Ga (Pickard, 2003; Sumner and Bowring, 1996). The ca. 950 m thick Asbestos Hills Subgroup comprises of the 2464 ± 6 Ma Kuruman Iron Formation and the conformably overlying Griquatown/Daniëlskuil Iron Formation (Beukes and Gutzmer, 2008; Pickard, 2003; Eriksson et al., 2006). Dolerites intrude the finely

laminated micritic iron formation of the Westerberg Member in the upper stratigraphic levels of the Kuruman Iron Formation (e.g., the Westerberg Sill near Prieska; Fig. 2). Discontinuous intrusive dolerite sills have been mapped along strike from north-east of Prieska all the way to Kuruman with decreasing occurrences. Iron formations and clastic rocks of the Koegas Subgroup conformably overlies the Griqualand/Daniëlskuil iron formations, and represent the stratigraphic top of the Ghaap Group. These iron formation successions are progressively cut down into toward the north-east by a regional glacial unconformity overlain by the Makganyene Formation diamictites. Extrusion of the Ongeluk Formation volcanic rocks followed conformably over the Makganyene Formation at 2222 ± 13 Ma, according to a Pb–Pb whole-rock isochron age by Cornell et al. (1996). The reliability of this age, however, is under debate because of the altered nature of the volcanic rocks, and subsequent whole-rock Pb–Pb and U–Pb isochron age determinations of 2394 ± 26 Ma and 2392 ± 26 Ma, respectively on the overlying Moodraai Formation dolomite in the upper Postmasburg Group (Bau et al., 1999; Faurey et al., 2013). This presents an alternative, significantly older, minimum age for the Ongeluk and Makganyene formations, with implications discussed by Hoffman (2013) and Kirschvink et al. (2000). In addition, a stratigraphic correlation of rocks of the Postmasburg Group with rocks of the Pretoria Group in the Transvaal Basin remains contested (e.g., Moore et al., 2001, 2012). Deposition of the Transvaal Supergroup sedimentary rocks ended abruptly with the emplacement of the Bushveld Complex (Fig. 1) at ca. 2.05 Ga.

At ca. 1.20 Ga, the Namaqua-Natal Mobile Belt started to form by successive accretion of terranes to the western margin of the Kaapvaal Craton. Accretion and collision of these terranes with the Kaapvaal Craton continued until approximately 1.02 Ga according to Eglington and Armstrong (2004), resulting in orogenesis and regional metamorphism along the western and southern margins of the craton (Fig. 1).

2.2. Local geology

The Westerberg Sill near Prieska on the western margin of the Kaapvaal Craton (Prieska study area, Fig. 2b), intruded in close proximity to the region that was thoroughly reworked and metamorphosed between ca. 1.20 and 1.02 Ga during the Namaqua-Natal Orogeny (Figs. 1 and 2; Eglington, 2006). Extensive folding of the Transvaal Supergroup stratigraphy on this western margin of the craton, including the Kuruman Iron Formation and the Westerberg Sill, however, is related to deformation during an older (pre-1.9 Ga) tectonic event. This folding is expressed in the Prieska study area as a large synclinal structure with a north–south axis and smaller parasitic folds (Altermann and Hålbich, 1990). Toward the north and east of Prieska (Kuruman study area, Fig. 2a), dolerite bodies that are less deformed and metamorphosed intrude into the cratonic hinterland. These intrusions, now linked in this study to the Westerberg Sill near Prieska, define a more extensive sill suite (Fig. 2), with a regional tilt of bedding $<10^\circ$ to the west.

The intermittent intrusive dolerite bodies have varying overall thicknesses of 50–200 m, and are composed of fine- to medium-grained gray-green dolerite. Sericitisation of plagioclase is common, indicating a secondary event of alteration which increases with proximity to the craton margin in the south and west. Magnetite occurs throughout the groundmass as small, euhedral crystals ca. 0.1–0.3 mm in diameter. The outer surfaces of the crystals are slightly altered. Almost all primary pyroxenes have undergone varying amounts of uraltisation, although relict pyroxene rafts are occasionally preserved. The BIF that hosts the dolerite shows clear evidence of contact metamorphism up to ca. 0.5 m away from the intrusive contacts. The preservation of the original

Fig. 2. Simplified geological map of the study area modified from 1:250 000 maps produced by the Council for Geoscience, South Africa. Inset maps show sample localities A (Kuruman study area) and B (Prieska study area) in the north-east and south-west respectively.

sedimentary layering in the BIF indicates that the intrusion of the sills occurred after the sediments were lithified.

Although there have been several studies on the geology of the study area (Fig. 2), none have focused on the dolerite intrusions. Dreyer (1982) interpreted the Westerberg dolerite intrusions as sills, whereas Altermann and Hälbig (1990) described the intrusions as dyke-like bodies intruding at a low angle to the bedding of the host sedimentary rock. A correct classification of the Westerberg intrusions in relation to the host lithology is crucial, since it controls the structural correction used during paleomagnetic studies. As no foliation in the dolerite themselves has been observed, the contact zone to the surrounding BIFs was examined at several outcrops in the Prieska study area. No signs of angular discordance were observed in the field. Columnar jointing of the dolerite

perpendicular to bedding of the iron formation in the country rock further confirms that the intrusions should be classified as sills rather than dykes.

3. Methodology

3.1. Baddeleyite ID-TIMS U–Pb geochronology

The center of the Westerberg dolerite (sample M03WA, collected on the Naauwte Farm in the Prieska study area; Fig. 2b), was sampled for U–Pb geochronology, along with sample TGS-01 further to the north in the Kuruman study area (Fig. 2a). Sample processing and dissolution were done at Lund University, Sweden. The highest quality baddeleyite grains were identified under the

Fig. 3. Field localities along the Orange River illustrating various structural relationships between the intrusion and the country rocks. Sedimentary bedding data from the Westerberg area (Dreyer, 1982), was used to calculate the fold axis of the regional syncline with an azimuth of 19.1° and a plunge of 19.4° . Maps are simplified after Dreyer (1982).

optical microscope and divided into five fractions from each sample, comprising 1–5 grains each. Further details on the water-based separation technique used in this study are given in Söderlund and Johansson (2002).

Mass spectrometry analysis was done using a Finnigan Triton Thermal Ionization Mass Spectrometer in the Department of Geosciences at the Swedish Museum of Natural History in Stockholm. Regressions were carried out using Isoplot (Ludwig, 1991), with U decay constants taken from Jaffey et al. (1971). The initial common Pb correction was done using the isotopic compositions from the global common Pb evolution model by Stacey and Kramers (1975). Further details on the methodology are given in Olsson et al. (2010).

3.2. Paleomagnetic studies

Samples were drilled and collected from two localities (three sites) in the Westerberg Sill itself along the banks of the Orange River in the Prieska study area (Figs. 2 and 3), and from two sites further to the north-east in the Kuruman study area (Fig. 2). One of the localities in the Prieska study area is located in the vicinity of the abandoned asbestos mining village of Westerberg, where two parallel sills intrude the Kuruman Iron Formation (Fig. 3a). Samples were collected from the thick interior of a sill outcropping in the Orange River, and from its finer-grained upper contact (TKWA). Additional samples were collected from a second sill that intrudes stratigraphically higher in the succession and outcrops along the R383 provincial road above the river (TKWB/TKWE/MO3WD). Samples from this locality constitute two sites on the western limb of a north-east plunging syncline (Fig. 2). The remaining sample

specimens from the Prieska study area were from outcrops situated east of Westerberg on the Naauwte Farm, and are representative of a single thick sill (Fig. 3b). These constitute one site on the eastern limb of the same syncline. As shown (Fig. 3), samples were also collected from near the fine-grained basal contact of the sill (TKWD), from its coarser central portion (TKWC/MO3WC/MO3WA), as well as from its finer-grained upper contact with the iron formation (MO3WB). Sampling along these two limbs allows for evaluation of the paleomagnetic fold test. From the Kuruman study area (Fig. 2a), samples were collected from medium-grained dolerite bodies forming scattered outcrops on the Simbambala Game Farm (FYL), and from the Kranzkop Farm (MDK03).

Core samples were collected using a portable petrol-powered drill and oriented using both a magnetic and a sun compass. Attitudes of the intrusions were derived from bedding of the host BIF, and determinations of paleo-vertical from columnar cooling joints in the sill were plotted on a stereographic projection. All measurements of magnetic remanence were made by using the superconducting rock magnetometer at the University of Johannesburg (a vertical 2G Enterprises DC-4K magnetometer), and at Yale University (a vertical 2G Enterprises DC SQUID magnetometer), both equipped with similar automatic sample changers (Kirschvink et al., 2008). Selected specimens were submerged in liquid nitrogen before further demagnetization was undertaken. All specimens were exposed to stepwise demagnetization including an alternating-field (AF) pre-treatment from 2 to 10 mT, followed by thermal demagnetization using an ASC Model TD48 shielded oven in 12 steps from 100°C to 550°C in decreasing temperature intervals. Specimens from sites FYL and TGS-03 were demagnetized

Fig. 4. Concordia diagrams of samples M03WA and TGS-01. The inset is a SEM-BSE image of a polished cross-section through a representative baddeleyite grain revealing thin zircon alteration along parts of the rim. White arrows point out zircon domains (Zr), which show up as brighter domains than the baddeleyite phase in BSE imaging.

via stepwise AF demagnetization from 2 to 100 mT. The process was abandoned when sample intensity dropped below instrument noise level (below ca. 1 pAm^2), or when samples started to show erratic behavior.

Magnetic components were quantified via the least-squares component analysis of Kirschvink (1980), and using the software Paleomag 3.1b2 (Jones, 2002). Linear fits were included in subsequent analyses if they had a Mean Angle Deviation (MAD) $\leq 10^\circ$. Additional digital handling was conducted with the PmagPy software of Tauxe (2010). Paleomagnetic pole calculations are based on the assumption of a geocentric axial-dipole field, and a stable Earth radius throughout geological time that equals the present day radius. Visualization of pole positions and paleogeographic reconstructions was achieved with GPlates (Williams et al., 2012).

4. Results

4.1. U–Pb geochronology

Extracted baddeleyite grains from M03WA were ca. 30–50 μm in length, elongated and brown in color. The grains have ‘frosty’ surfaces when viewed under the optical microscope, indicative of partial replacement of baddeleyite by zircon as a result of late- or post-magmatic reaction of baddeleyite with a silica-rich melt or fluid (e.g. Heaman and LeCheminant, 1993; Söderlund et al., 2013). Back scattered electron microscopy reveals the presence of zircon in ca. 0.5 μm thick semi-continuous rims and also in fractures (Fig. 4). Baddeleyite grains extracted from sample TGS-01 are >50 μm in length, dark brown and crystalline, without any signs secondary zircon. Data is presented in Table 1 with Concordia diagrams shown in Fig. 4.

For M03WA, the $^{207}\text{Pb}/^{206}\text{Pb}$ dates of five fractions range from 2405.8 ± 1.8 to 2420.2 ± 1.9 Ma and plot 2–4% discordant (Fig. 4). The $^{207}\text{Pb}/^{206}\text{Pb}$ date of the “oldest” fraction (2420.2 Ma) is taken as the minimum age of this sample. Free regression including all fractions yields an upper intercept age of 2434 ± 16 Ma and a lower intercept age of 920 ± 450 Ma (MSWD = 2.6). For various reasons discussed below, a forced lower intercept of 1100 ± 100 Ma is preferred in the regression, which results in a slightly older age of 2441 ± 6 Ma (MSWD = 2.9).

The $^{207}\text{Pb}/^{206}\text{Pb}$ dates for five fractions of TGS-01 range from 2424.1 ± 4.9 to 2426.5 ± 1.7 Ma, and all fractions plot less than 1% discordant. Using a free regression yields a lower intercept of -230 Ma. We prefer to use the weighted mean of $^{207}\text{Pb}/^{206}\text{Pb}$ dates,

which is 2426.0 ± 1.2 Ma (MSWD = 0.35), as the best age estimate of this intrusion (Fig. 4).

4.2. Paleomagnetism

4.2.1. Demagnetization result(s)

A summary of the demagnetization results is provided here. All components are given in geographic (not tilt-corrected) coordinates. During demagnetization there was a clear distinction in the behavior of coarse-grained dolerite from the central parts of the thick sills (Fig. 5a and c), and that of samples from the finer grained contact zones or medium-grained thinner sills and intrusive bodies (Fig. 5b, d and e). Identified components are summarized in Table 2.

In the Prieska study area, coarse-grained samples from the lower sill at Westerberg (samples TKWA 1–8) are poor magnetic recorders and rapidly demagnetize to lose all significant magnetization by a demagnetization step as low as 350°C . However, in some cases magnetization persists up to 545°C . Besides a very low-coercivity random component of magnetization removed from these samples in the first couple of AF demagnetization steps, they are dominated by randomly oriented single linear components of magnetization that demagnetize toward the origin (Fig. 5a). The eight samples from this site are thus not given any further attention. Demagnetization of samples from near the upper contact of the lower sill, as well as from the stratigraphically upper sill at Westerberg proved to be more successful. Here once again a low-coercivity component of magnetization was removed from most samples (Fig. 5b). While being quite scattered, these low-coercivity components form a poorly constrained south-westerly cluster of data. After removal of this component, samples demagnetize along linear trajectories toward the origin, and are labeled “HIG” according to their higher stability. These trajectories generally define a moderate negatively inclined, north–northwesterly magnetization in geographic coordinates (Fig. 6b). This component is comparable to characteristic components seen in two samples from the lower sill (Decl. = 281.8° , Incl. = -55.1° seen in Fig. 6b). Characteristic components from samples TKWB 1 to 7 define significantly steeper and more scattered set of directions (average inclination = -76.0° ; Fig. 6a), and there exists a distinct, but untested possibility that the nearby north-west trending dyke magnetically affected these samples (Fig. 3a). It is also possible that these samples have experienced greater alteration due to modern weathering compared to other samples, and that they may represent a present field-like magnetization. These components are labeled “PF” despite their persistence at high temperature demagnetization steps. Exclusion

Fig. 5. Representative demagnetization behavior of selected coarse-grained and fine-grained samples from the investigated sites in the Kuruman (north-east) and the Prieska (south-west) study areas.

Table 1
U–Pb ID-TIMS isotopic data.

Analysis no. (number of grains)	U/Th	Pbc/Pbtot ^a	²⁰⁶ Pb/ ²⁰⁴ Pb raw ^b	²⁰⁷ Pb/ ²³⁵ U	±2s % err	²⁰⁶ Pb/ ²³⁸ U	±2s % err	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb	±2s % err	Concordance
				[corr] ^c	[age, Ma]							
<i>M03WA</i>												
a (3 grains)	21.1	0.013	4623.5	9.3118	0.34	0.43470	0.32	2369.2	2326.9	2405.8	1.8	0.967
b (3 grains)	35.0	0.007	9006.7	9.5794	0.26	0.44414	0.25	2395.2	2369.2	2417.4	1.4	0.980
c (3 grains)	54.1	0.015	3969.7	9.6460	0.34	0.44650	0.32	2401.6	2379.7	2420.2	1.9	0.983
d (4 grains)	31.5	0.031	1898.7	9.5003	0.38	0.44061	0.36	2387.6	2353.4	2416.9	2.0	0.974
e (4 grains)	27.2	0.042	1320.1	9.4373	0.33	0.43858	0.29	2381.5	2344.3	2413.5	2.4	0.971
<i>TGS-01</i>												
a (5 grains)	22.3	0.048	1274.7	9.7785	0.39	0.45106	0.38	2414.1	2400.0	2426.1	2.2	0.989
b (5 grains)	11.9	0.027	2291.2	9.7747	0.31	0.45078	0.30	2413.8	2398.7	2426.5	1.7	0.989
c (1 grain)	−34.9	0.079	798.3	9.7839	0.80	0.45167	0.80	2414.6	2402.7	2424.7	3.9	0.991
d (2 grains)	−1.9	0.283	214.0	10.0422	1.25	0.46348	1.19	2438.7	2454.9	2425.1	8.0	1.012
e (2 grains)	−10.0	0.112	569.1	9.9282	1.05	0.45850	1.05	2428.1	2432.9	2424.1	4.9	1.004

^a Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).^b measured ratio, corrected for fractionation and spike.^c isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (6 pg Pb and 0.06 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 sample.**Table 2**
– Summary of least-squares component analysis.

Component			In situ coordinates				Tilt-corrected coordinates			
Site	Region	n/N	Decl. in°	Incl. in°	A ₉₅ in°	k	Decl. in°	Incl. in°	α ₉₅ in°	k
<i>PF</i>										
TKWB	Westerberg upper sill	7/7	333.2	−76	20.2	8.4	263.2	−58.4	20.2	8.4
TKWD/M03WB	Naauwte sill	15/15	14.2	−69	8.0	23.8	158.8	−87.4	8.0	23.7
<i>INT</i>										
MDK03	Kuruman	6/6	83.9	31.6	20.1	10.1	90.6	42.5	20.1	10.1
VGP based on 6 in situ samples							2.8°N	275.5°E	dp = 12.7°	dm = 22.6°
VGP based on 6 tilt-corrected samples							11.8°N	271.1°E	dp = 15.3°	dm = 24.8°
<i>HIG</i>										
M03WD/TKWE (a)	Westerberg upper sill	14/17	296.6	−39.1	6.4	39.4	278.3	−35.1	6.6	37.2
TKWA	Westerberg lower sill	2/10	281.8	−55.1	34.6	27.1	308.6	−50.1	34.6	27.1
TKWD (b)	Naauwte sill	6/7	300.2	−12.4	6.2	116.2	294.5	−19	6.2	115.9
FYL	Kuruman	7/8	257.2	−53.4	23.2	6.6	258.5	−45.4	23.2	6.6
MDK03	Kuruman	5/6	282.2	−29.2	19.5	13	289.9	−36.7	19.5	13.1
Combined samples		n = 34	288.9	−37.4	7.8	11	279.2	−34.9	6.7	14.5
Combined as sites		N = 4	286.7	−34.5	26.6	12.9	281.7	−34.8	19.5	23.3
VGP based on 34 tilt-corrected samples							16.8°N	279.9°E	dp = 4.4°	dm = 7.7°
VGP based on 4 tilt-corrected sites (exclude site TKWA)							18.9°N	285.0°E	A ₉₅	K
									14.1°	43.4

Site coordinates: M03WD, TKWA, TKWB & TKWE = 29.3°S 22.3°E; M03WB, TKWC & TKWD = 29.4°S 22.6°E; MDK03 = 28.0°S 23.4°E; FYL = 27.8°S 23.4°E.

Abbreviations: Decl. = declination, Incl. = inclination, α₉₅ = radius of 95% confidence cone about the mean direction, k = precision parameter for direction, VGP = virtual geomagnetic pole, dp and dm = semi-axes of 95% confidence about the mean, A₉₅ = radius of 95% confidence about the mean pole, K = precision parameter for pole. Sample based VGP was calculated for site coordinates at 28.5°S 23.0°E.

of these components (i.e., TKWB 1–7) from the HIG components identified in other samples yields a tight clustering mean for the upper sill in geographic coordinates (Decl. = 296.6°, −39.1°, k = 39.4, α₉₅ = 6.4°, n = 14; [Fig. 6b](#)). Samples M03WD 7–9 are the exception to the behavior described above. These samples display single linear, north-westerly and upward directed magnetic components, not seen in any other of the samples, and were removed during demagnetization up to 570 °C. These anomalous, possibly lightning-induced magnetizations are excluded from further evaluation.

On the Naauwte Farm (Prieska study area), coarse-grained dolerite samples appeared to be poor recorders of the Earth's past magnetic field. Samples collected here were from the interior of the sill (M03WA/M03WC/TKWC; [Fig. 3b](#)). As was the case at Westerberg, these coarse-grained samples generally lost their

magnetization quite rapidly ([Fig. 5c](#)). These samples can be characterized by randomly directed low-coercivity components, and randomly directed linear components that are not evaluated further ([Fig. 5c](#)). Again, finer-grained dolerite in proximity of the contact with the iron formation yielded better results. Samples M03WB 1–8 were collected from more weathered exposures from the track along the hillside above the Orange River, while samples TKWD 1–7 were collected from a fresh exposed outcrop within the river bed itself ([Fig. 3b](#)). Samples from both outcrops displayed randomly directed low-coercivity components during low-field AF demagnetization ([Fig. 5d](#)). The samples from the track exposure displayed northerly and upward directed linear components that demagnetized toward the origin. These PF components are near parallel to the present-day magnetic field of the Earth at the locality ([Fig. 6a](#)), and probably were acquired during recent

Fig. 6. Summary of means for identified magnetic components PLF and INT in A with corresponding bootstrap fold test of Tauxe et al. (1991) using PmagPy in Tauxe (2010), both in geographic and tilt-corrected coordinates. B shows HIG.

weathering. Samples TKWD 1–7 also display similar northerly present field-like (or PF) components within the 200 °C to 500 °C stepwise demagnetization range (Figs. 5d and 6a), but here a third magnetic component (HIG) is identified at demagnetization steps above 500 °C, as shallow easterly zero-seeking demagnetization trajectories in six of the seven samples (Fig. 5d). A mean was calculated for these six samples at a Decl. = 300.2°, Incl. = −12.4°, $k = 116.2$, $\alpha_{95} = 6.2^\circ$, $n = 6$ (Fig. 6b).

Samples from sites FYL and MDK03 in the Kuruman study area behaved similarly during demagnetization (Fig. 5e). Samples from both sites displayed randomly directed low-coercivity components that were removed during the first couple of demagnetization steps. Hereafter all samples displayed a magnetic component of medium- to low-coercivity (7.5–30 mT). In samples from FYL, these components were randomly directed, but for samples from MDK03 these intermediate components form an easterly and downward directed cluster labeled “INT” (Decl. = 83.9°, Incl. = 31.6°, $k = 10.07$,

$\alpha_{95} = 20.07^\circ$, $n = 6$; Fig. 6a). The INT component is near antipodal to the HIG component identified elsewhere, but it is clearly of lower coercivity. At demagnetization steps above 30 mT, and up to 85 mT (i.e., high-coercivity), samples from both sites revealed easterly and upward directed characteristic remanence directions. These directions are similar to that seen at the southern localities, and thus labeled HIG (Fig. 6b).

4.2.2. Structural correction, paleomagnetic fold test and pole calculation

A consistent characteristic remanence (i.e., component HIG) was identified from sites TKWA and TKWE/M03WD along the western limb of a gently north-east plunging syncline. Only two samples from site TKWA yielded the HIG component, while 21 samples recorded the HIG component at TKWE/M03WD. In addition, the HIG component was identified from two sites from the Kuruman study area. In order to restore bedding to paleo-horizontal, the

regional fold axis (i.e., azimuth = 19.1° and plunge = 19.4°) in the Prieska study area first had to be restored to horizontal, and all identified components from the Westerberg and Naauwte areas had to be corrected accordingly. The plunge-corrected bedding data for samples from the Prieska study area (Westerberg and Naauwte), and the bedding data for samples from the Kuruman study area (FYL and MDK03) was then used to restore all components to horizontal (Fig. 6). Means of structurally corrected components were then calculated and are shown in Table 2.

The PF directions from the Prieska study area (Westerberg and Naauwte), become more disparate during the unfolding as set out above (Fig. 6). This suggests that the acquisition of this magnetization occurred after folding. Formal evaluation of the fold test of McFadden and Jones (1981) is not possible because the two groups do not share a common precision. We therefore make use of the bootstrap evaluation of the fold test from Tauxe et al. (1991) instead (Fig. 6a). This shows clearly that the PF component from the 22 samples was acquired after folding because 95% confidence limits on the degree of untilting required for maximizing concentrations of the data (i.e., maximum eigenvalue of τ_1 of the orientation matrix), include 0% unfolding. The maximum concentrations of data are reached between –10% and 24% unfolding (Fig. 6a).

A slight visual improvement of grouping of HIG components is observed during unfolding (Fig. 6b). The HIG groups from the western limb (from the Westerberg upper sill), and the eastern limb (site TKWD at Naauwte Farm) in the Prieska study area do not share a common precision. We thus again use the bootstrap evaluation of the fold test following Tauxe et al. (1991) for all identified HIG components. The HIG component from 34 samples appears to have been locked in prior to folding because 95% confidence limits on the degree of untilting required for maximizing fits of the data (i.e., maximum eigenvalue of τ_1 of the orientation matrix) occurs between 70% and 149% unfolding (Fig. 6b).

A VGP calculated for 34 tilt-corrected samples is situated at 16.8°N, 279.9°E ($dp = 4.4^\circ$, $dm = 7.7^\circ$). The tilt-corrected site-based ($N = 4$) is comparable at 18.9°N, 285.0°E, $A_{95} = 14.1^\circ$, $K = 43.4$.

5. Discussion

5.1. Emplacement age of the Westerberg Sill

The upper intercept date of 2434 ± 16 Ma for sample M03WA using a free regression, yields a lower intercept date of 920 ± 450 Ma, the latter of which can be interpreted to reflect the time of disturbance of the U–Pb isotopic system in primary zirconium-bearing minerals. We assume that most of the discordance relates to the event causing partial transformation of baddeleyite to zircon (Fig. 4), at an approximate time given by the lower intercept. According to Colliston and Schoch (2013), the Namaqua-Natal Orogeny ended at ca. 1030 Ma in a phase of comprehensive folding and shearing, and we assume that metamorphism at zeolite to greenschist facies in the area west of the town of Prieska relates to this metamorphic event (Cornell et al., 2006). Hence, we prefer to use a 1100 ± 100 Ma as a proxy for the lower intercept, since ca. 1100 Ma is normally referred to as the general time of metamorphism for the Namaqua-Natal Orogeny (e.g., Eglington, 2006). This approach results in an upper intercept age of 2441 ± 6 Ma, which is interpreted as the best estimate of the emplacement age of the Westerberg Sill in the Prieska study area. A multi-stage disturbance of the U–Pb isotopic system would theoretically bias both the upper and lower intercept dates in a discordant data set. The MSWD value of 2.9 indicates scatter beyond analytical uncertainty and we cannot rule out that a more recent Pb-loss event (younger than the Namaqua-Natal orogeny), may be superimposed.

The age results of M03WA and TGS-01 agree with previously obtained radiometric dates from the Kuruman BIF into which the Westerberg Sill intrudes. An unpublished single-grain zircon U–Pb age of 2480 ± 6 Ma for tuffaceous units at the base of the Kuruman BIF by Trendall et al. (1995) is thought to reflect the onset of BIF sedimentation according to Eriksson et al. (2006). U–Pb zircon ages of 2465 ± 6 Ma (Pickard, 2003), and an unpublished age of 2465 ± 7 Ma (cited in Martin et al., 1998) from the upper Kuruman Formation, are probably a good age estimate of the transition to a shallower depositional environment. This transitional depositional environment characterizes the deposition of the Griquatown Iron Formation (Beukes, 1984). Additionally, an unpublished age of 2432 ± 31 Ma is often cited for tuffaceous mudstone at the base of the Griquatown Iron Formation (Martin et al., 1998). Unpublished work cited in Kirschvink et al. (2000) for zircons from a tuffaceous bed near the top of the overlying Koegas Subgroup gave an age of 2415 ± 6 Ma. This suggests that the Westerberg Sill Suite may have been broadly coeval with the felsic magmatism during deposition of the Griquatown Iron Formation. However, field observations and thermal alteration of the surrounding country rock support the assertion that the Kuruman BIF was already lithified when the intrusion occurred. Consequently, the age range of 2441 ± 6 Ma to 2426 ± 1 Ma for the Westerberg Sill Suite reflects a minimum age for the Kuruman Iron Formation, in agreement with previously published age constraints.

5.2. Paleomagnetism – comparison with Paleoproterozoic paleopoles

The ca. 1.1 Ga Namaqua-Natal Orogeny was likely responsible for a significant disturbance of the U–Pb isotopic system in baddeleyite from the Westerberg Sill. None of our calculated poles however suggest that this event affected the magnetization of samples. Instead our paleopoles compare well with published paleomagnetic poles and VGPs, as well as known magnetic overprints from the Kaapvaal Craton during the Paleoproterozoic (Fig. 7). For this comparison we also included Neoproterozoic poles from the Kaapvaal Craton (all poles used in this comparison are listed in Table 3).

Our pre-fold high stability VGP (i.e., HIG) from the Westerberg Sill Suite plots well within an existing gap in the apparent polar wander path of the Kaapvaal Craton between ca. 2.66 Ga and the time of extrusion of the Ongeluk volcanics (Fig. 7). The HIG component VGP plots near the ca. 2.22 Ga Ongeluk Formation paleopole of Evans et al. (1997), and is indistinguishable from the intermediate component pole (i.e., INT) that was removed in some samples. This intermediate component is opposite in polarity to the HIG direction, and is clearly a younger magnetization. Besides being indistinguishable from the HIG pole, the INT pole is also very similar to the pole determined from the weathering profile that developed below the unconformity at the base of Gamagara-Mapedi Formation (Fig. 7). The age of the Gamagara-Mapedi Formation was recently revised to post-date the intrusion of the 2054 Ma Bushveld Complex based on a younger U–Pb age population of detrital zircon grains (Dreyer, 2014). It is interesting to note that such a young age was considered, but not preferred, by Evans et al. (2002).

This comparison of paleopoles allows for several possible interpretations. Although the magnetization of the Westerberg Sill Suite clearly pre-dates ca. 2.0 Ga deformation of the Postmasburg and Campbellrand groups, we have no further constraints on the timing of remanence acquisition. The magnetization could represent a ca. 2.22 Ga magnetic overprint associated with the extrusion of the Ongeluk volcanic rocks. However, this is unlikely given the lack of observations for a wider metamorphic and metasomatic influence of the Ongeluk Formation. A second, option would be that the HIG magnetization pre-dates deformation, and that it is a primary magnetization acquired at ca. 2.43 Ga during the

Fig. 7. Possible apparent polar wander path for the Kaapvaal Craton (black) and Pilbara Craton (blue) using known paleopoles for the Neoproterozoic–Paleoproterozoic (including component INT and HIG of this study). References for the Pilbara poles (blue): P1 = 2772 Ma Pilbara Flood basalt Package 1 (Strik et al., 2003), BR = 2772 ± 2 Ma Black Range dykes (Embleton (1978), P2 = 2767 Ma Pilbara Flood basalt Package 2 (Strik et al., 2003), P4-5 = 2739 Ma Pilbara Flood basalt Package 4–5 (Strik et al., 2003), P8-10 = 2717 ± 2 Ma Pilbara Flood basalt Package 8–10 (Strik et al., 2003), WOON = 2449 ± 3 Ma Woongarra Rhyolite (Evans, 2007; Evans, pers. comm., 2012). (For interpretation of reference to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Summary of VGP and paleopoles for the Kaapvaal Craton in the Neoproterozoic to Paleoproterozoic.

Rock unit	Code	Age (Ma)	Age reference	Pole °N	Pole °E	A ₉₅ or <i>dp</i> (°)	<i>dm</i> (°)	Pole reference
<i>Neoproterozoic poles</i>								
Derdepoort Basalt	DB	2782 ± 5	Wingate (1998)	−39.6	4.7	17.5		Wingate (1998)
Modipe Gabbro	MG	2784 ± 1	Denysyn et al. (2013)	−47.6	12.4	8.6	9.3	Denysyn et al. (2013)
Allanridge Formation	AR	ca. 2700	De Kock et al. (2009a)	−69.8	345.6	5.8		De Kock et al. (2009a)
Rykoppies Dykes	RYK	2700–2660	Olsson et al. (2010)	−62.1	336	3.5	4.2	Lubnina et al. (2010)
<i>Paleoproterozoic poles</i>								
Sample-based HIG component (VGP), Westerberg Sill Suite	HIG	2441–2426	This study	16.8	279.9	4.4	7.7	This study
Tilt-corrected INT component, Westerberg Sill Suite	INT _{tc}		This study	11.8	271.1	15.3	24.8	This study
In situ INT component, Westerberg Sill Suite	INT _{is}		This study	2.8	275.5	12.7	22.6	This study
Ghaap SD component	Ghaap SD	2500–2300	De Kock et al. (2009b)	−48	65.6	14.7	17.3	De Kock et al. (2009b)
Ongeluk Lava	ONG	2222 ± 13 ^a	Cornell et al. (1996)	−0.5	100.7	5.3		Evans et al. (1997)
Mamatwan Ore component 1	MAM-1	ca. 2200	Evans et al. (2001)	−8.2	111.1	5.6	11.1	Evans et al. (2001)
Gamagara/Mapedi Formation	BGM	ca. 2200	Evans et al. (2002)	2.2	81.9	7.2	11.5	Evans et al. (2002)
Ghaap W component	G W	ca. 2200	De Kock et al. (2009b)	−3.2	104.1	15		De Kock et al. (2009b)
Phalaborwa Complex	PB	2060 ± 4	Wu et al. (2011)	27.7	35.8	6.6		Letts et al. (2011)
B-1 Bushveld Sills	B1	2058 ± 6	Wabo et al. (2011)	13.1	44	14.3		Wabo et al. (in press)
Bushveld Complex	BC	2054.4 ± 1.3	Scoates and Friedman (2008)	19.2	30.8	5.8		Letts et al. (2009)
Waterberg unconformity bounded sequence 1	WUBS-1	2054 ± 4	Dorland et al. (2006)	36.5	51.3	10.9		De Kock et al. (2006)
Witwatersrand overprint	WITS	1945 ± 40	Lager et al. (1988)	19.1	45.6	7.8		Lager et al. (1988)
Ghaap ND component	G-ND	2000–1900	De Kock et al. (2009b)	26.5	22.8	7		De Kock et al. (2009b)
Vredefort	VRED	2023 ± 4	Kamo et al. (1996)	21.8	44.5	11.3	15.4	Carporzen et al. (2005)

A₉₅ (in degrees) is the radius of the 95% confidence cone about a mean based on site poles, while *dp* and *dm* (in degrees) are semiaxis of the 95% confidence cone about a mean based on site direction.

^a Reliability of age determination under debate (see text).

intrusion and subsequent cooling of the Westerberg Sill Suite. If correct, this suggests a relatively stationary Kaapvaal Craton for some 200 million years (i.e., between 2.43 Ga and 2.22 Ga). There is however a third option that we consider here, which suggests that the age of the Ongeluk Formation is not ca. 2.22 Ga as commonly accepted, but much closer in age to that of the Westerberg Sill Suite (i.e., ca. 2.43 Ga). An older age has been suggested for the Ongeluk volcanic rocks before (Moore et al., 2001, 2012; Bau et al., 1999), but requires a challenging revision of stratigraphic correlations between the various basins preserving the Transvaal Supergroup. If correct, the Westerberg Sill Suite may be a stratigraphically deeper, intrusive equivalent of the Ongeluk Formation volcanic rocks. This option remains speculative until conclusive geochronological data is presented for the Ongeluk Formation itself.

The INT magnetization or intermediate opposite polarity overprint was only observed from northerly sampling sites in the Kuruman study area, further away from the edge of the Kaapvaal Craton. Apart from being situated deeper into the interior of the craton, the sites are stratigraphically closer to the Ongeluk Formation due to the unconformity at the base of the Postmasburg Group. This unconformity cuts down into the Koegas Formation in the south-western extreme of the craton near Westerberg, but cuts out increasingly older stratigraphic units toward the north-east nearer Kuruman. The Postmasburg Group rests unconformably on top of the Griquatown Iron Formation. There is thus a possibility that the Ongeluk Formation could have overprinted the magnetization of the Westerberg Sill Suite in the Kuruman study area, where there is much less intervening rock units compared to the Prieska study area. Alternatively the INT magnetization may be related to the deep oxidative weathering experienced before the deposition of the Gamagara-Mapedi Formation at ca. 2.0 Ga. This second interpretation is currently favored based on the rather ambiguous results of the fold test for the INT component.

5.3. Implications for Vaalbara

5.3.1. Vaalbara so far

Based on analyses of sequence stratigraphy, lithostratigraphy and lithofacies, Cheney (1996, 1990) produced a reconstruction placing the Pilbara Craton at the southern margin of the Kaapvaal Craton. This reconstruction also included the Yilgarn and Zimbabwe cratons in the delimitation of Vaalbara. The relationships between these four cratons have recently been discussed in Smirnov et al. (2013). Similar time-stratigraphic development is present in both Kaapvaal and Pilbara cratons (Fig. 8). The volcanic rocks of the Ventersdorp Supergroup and the sedimentary rocks of the successive Transvaal Supergroup (Kaapvaal Craton), can be correlated with the volcanic rocks of the Fortescue Group and the sedimentary rocks of the Mount Bruce Supergroup (Pilbara Craton), respectively (Cheney, 1990). A comparison between similar poles of the Neoarchean Usushwana Complex on the Kaapvaal Craton, and the Millindina Complex (Pilbara Craton), in addition to correlation between Archean tectonic architecture of the respective cratons, led Zegers et al. (1998) to propose an alternative reconstruction with the Pilbara Craton on the eastern margin of the Kaapvaal Craton. Published paleomagnetic data disproved the traditional “Cheney-fit” scenario; De Kock et al. (2009a) revised paleomagnetic results for the 2.78–2.70 Ga interval, and also presented new data from the Ventersdorp Supergroup volcanic rocks. Based on this, a third reconstruction (herein referred to as the “de Kock-fit”), places the Pilbara Craton to the north-west of the Kaapvaal Craton. The alignment of platform sedimentary rocks, together with the overlapping paleopoles and parallel APWPs for the ca. 2.78–2.66 Ga time interval favor this model. In addition, new U–Pb baddeleyite ages of ca. 2990–2978 Ma for the Usushwana Complex (Gumsley et al. 2015) also contradicts the link to the

2860 ± 20 Ma Millindina Complex, although it may be related to the Hlagothi Complex (Schmidt and Embleton, 1985; Gumsley et al., 2013).

The Vaalbara hypothesis is corroborated by geology, geochronology and paleomagnetism until ca. 2.66 Ga. The next possible pair of paleopoles of comparable age is at ca. 1.9 Ga, but a general paleolatitudinal comparison of the Kaapvaal and Pilbara cratons at this time rules out the possibility of a connection due to a poleward drift of the Kaapvaal Craton, and the low-latitude position of the Pilbara Craton. The Pilbara Craton is at ca. 12° latitude for remagnetization seen during the Capricorn Orogeny, and Kaapvaal is at ca. 55° latitude for the post-Waterberg dolerites and Hartley-Tsineng volcanic rocks and dolerites (Alebouyeh Semami, 2014; Hanson et al., 2004). A possible break-up scenario at ca. 2.2 Ga is supported by the “barcode” age match between the 2222 ± 13 Ma Ongeluk volcanic rocks in the Kaapvaal Craton from Cornell et al. (1996) and 2208 ± 10 Ma volcanism in the Turee Creek Group of the Pilbara Craton (Müller et al., 2005). However, there is controversy concerning the ca. 2.22 Ga age of the Ongeluk volcanic rocks by Cornell et al. (1996). Two new indirect minimum age determinations at ca. 2394 Ma on the overlying Moodraai Formation dolomites suggest this unit to be at least 200 Ma older (Fairey et al., 2013; Bau et al., 1999). Combined with the work of Moore et al. (2001, 2012), there is the possibility that the Westerberg Sill Suite may indeed reflect sub-volcanic intrusions linked to the Ongeluk volcanic event itself, which is supported by paleomagnetism presented in this study, unless this indeed reflects a magnetic overprint tied to the ca. 2.22 Ga Ongeluk volcanism.

5.3.2. A new barcode match at ca. 2.44 Ga?

The new age of 2441 ± 6 Ma age for the Westerberg Sill coincides within error with the zircon U–Pb SHRIMP age of 2449 ± 3 Ma for the Woongarra Rhyolite of the Pilbara Craton (Barley et al., 1997). This extrusive suite overlies the BIF successions of the Weeli Wolli Formation. Zircons from a tuffaceous sandstone layer in the Weeli Wolli Formation also yield the age of 2449 ± 3 Ma (Barley et al., 1997). Therefore, the Woongarra volcanism has been interpreted as representing a Large Igneous Province (LIP). There are also numerous doleritic and basaltic units intruding within the Weeli Wolli strata. These magmatic units likely reflect later magmatic episodes of the same LIP, which may date to 2426 ± 1 Ma, the same age as obtained for sample TGS-01 in this study.

The Woongarra Rhyolite at the top of the Weeli Wolli Formation is a felsic unit thought to have been emplaced in two magmatic pulses (Trendall et al., 1995). Although a directly equivalent unit is absent in the Griqualand West Basin of the Kaapvaal Craton, there are several coeval porphyroclastic stilpnomelane pelite beds in the upper part of the Kuruman Iron Formation which are thought to be derived from felsic volcanic activity (Beukes, 1984). Tuffaceous horizons can also be found within a sedimentary unit in the overlying Bolgeeda Iron Formation in the Pilbara Craton. Unpublished zircon U–Pb dating cited in Gutzmer and Beukes (1998) from one of these volcanic layers yielded an age of ca. 2440 Ma. We therefore suggest a major Westerberg–Woongarra LIP event may have taken place on the contiguous cratons of the Kaapvaal and Pilbara from approximately 2425–2445 Ma, despite the paleomagnetic discrepancy. The similarities between the geological histories during the ca. 2.8 to 2.2 Ga time interval are significant (e.g., Beukes and Gutzmer, 2008). Trendall (1968) and Button (1976) were the first to point out these resemblances between the sedimentary successions and basin configurations of the Transvaal Supergroup (Kaapvaal) and the Hamersley Group (Pilbara). Button (1976) concluded that the two largely coeval sedimentary successions represented spatially distinct basins, but probably shared similar depositional histories as part of a larger continental block.

Baddeleyite U–Pb dating of the Westerberg Sill near the south-western margin of the Kaapvaal Craton and a dolerite sill suite further to the north-west in the cratonic hinterland yield

crystallization ages of 2441 ± 6 Ma and 2426 ± 1 Ma, respectively. These two U–Pb ages date a new event of mafic magmatism on the craton, which may represent a new Large Igneous Province. These new ages define the herein named Westerberg Sill Suite which is similar in age to the 2449 ± 3 Ma Woongarra

volcanic rocks of the Pilbara Craton, possibly indicating a common Westerbeg–Woongarra LIP. However, if the Westerbeg characteristic magnetization is primary, a comparison to coeval Pilbara Craton poles does not allow for a Vaalbara (Kaaapvaal–Pilbara) reconstruction at 2.44–2.43 Ga, indicating crustal break-up before this time. It is important to bear in mind the primary nature of paleopoles on both cratons may be in doubt, as resetting by either the Ongeluk volcanism in the Kaaapvaal Craton, or the Capricorn Orogeny in the Pilbara Craton may be apparent. In our preferred interpretation, despite the paleomagnetic discrepancy, the Kaaapvaal and Pilbara cratons formed a single crustal block between 2449 and 2426 Ma. The magmatic barcode match, combined with similar depositional histories recorded in underlying carbonates and BIFs argue strongly for a shared history between these two cratonic blocks. This would extend the crustal association between these two blocks from 2.78 Ga, all the way through to 2.22 Ga.

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References

- Alebouyeh Semami, F., (M. Sc thesis) 2014. U–Pb geochronology of the Tsineng dyke swarm and paleomagnetism of the Hartley Basalt Formation, South Africa: evidence for two separate magmatic events at 1.93–1.92 and 1.88–1.84 Ga in the Kalahari craton. Lund University, Lund, Sweden.
- Altermann, W., Hålbich, I.W., 1990. Thrusting, folding and stratigraphy of the Ghaap Group along the southwestern margin of the Kaaapvaal Craton. *South Afr. J. Geol.* 93, 553–566.
- Altermann, W., Nelson, D.R., 1998. Sedimentation rates, basin analysis and regional correlation of three Neoproterozoic and Paleoproterozoic subbasins of the Kaaapvaal craton as implied by precise SHRIMP U–Pb zircon ages from volcanic sediments. *J. Sediment. Geol.* 120, 225–256.
- Anbar, A.D., Duan, Y., Lyons, T.W., Arnold, G.L., Kendall, B., Creaser, R.A., Kaufman, A.J., Gordon, G.W., Scott, C., Gavin, J., Buick, R., 2007. A whiff of oxygen before the great oxidation event? *Science* 317, 1903–1906.
- Barley, M.E., Pickard, A.L., Sylvester, P.J., 1997. Emplacement of a large igneous province as a possible cause of banded iron formation 2.45 billion years ago. *Nature* 385, 55–58.
- Barton, J.M., Blignaut, E., Salnikova, E.B., Kotov, A.B., 1995. The stratigraphical position of the Buffelsfontein Group based on field relationships and chemical and geochronological data. *South Afr. J. Geol.* 98, 386–392.
- Bau, M., Romer, R.L., Lüders, V., Beukes, N.J., 1999. Pb, O, and C isotopes in silicified Mooidraai dolomite (Transvaal Supergroup, South Africa): implications for the composition of Paleoproterozoic seawater and ‘dating’ the increase of oxygen in the Precambrian atmosphere. *Earth Planet. Sci. Lett.* 174, 43–57.
- Beukes, N.J., 1984. Sedimentology of the Kuruman and Griquatown Iron-formations, Transvaal Supergroup, Griqualand West, South Africa. *Precambrian Res.* 24, 47–84.
- Beukes, N.J., 1987. Facies relations, depositional environments and diagenesis in a major early Proterozoic stromatolitic carbonate platform to basinal sequence, Campbellrand Subgroup, Transvaal Supergroup, Southern Africa. *Sediment. Geol.* 54, 1–46.
- Beukes, N.J., Gutzmer, J., 2008. Origin and paleoenvironmental significance of major iron formations at the Archean–Paleoproterozoic boundary. In: Hagemann, S., Rosiere, C., Gutzmer, J., Beukes, N.J. (Eds.), *Banded Iron Formation-Related High-Grade Iron Ore*. Society of Economic Geologists, Denver, pp. 5–47.
- Bleeker, W., 2003. The late Archean record: a puzzle in ca 35 pieces. *Lithos* 71, 99–134.
- Bleeker, W., Ernst, R.E., 2006. Short-lived mantle generated magmatic events and their dyke swarms: The key unlocking Earth’s paleogeographic record back to 2.6 Ga. In: Hanski, E., Mertanen, S., Rämö, T., Vuollo, J. (Eds.), *Dyke Swarms – Time Markers of Crustal Evolution*. Taylor & Francis, London, pp. 3–26.
- Button, A., 1976. Transvaal and Hamersley Basins – review of basin development and mineral deposits. *Miner. Sci. Eng.* 8, 262–290.
- Carporzen, L., Gilder, S.A., Hart, R.J., 2005. Palaeomagnetism of the Vredefort meteorite crater and implications for craters on Mars. *Nature* 435, 198–201.
- Cheney, E.S., 1990. Evolution of the “Southwestern” continental margin of Vaalbara. In: *Geocongress’90*. Geological Society of South Africa, Cape Town, pp. 88–91.
- Cheney, E.S., 1996. Sequence stratigraphy and plate tectonic significance of the Transvaal succession of southern Africa and its equivalent in Western Australia. *Precambrian Res.* 79, 3–24.
- Cheney, E.S., Roering, C., Stettler, E., 1988. *Geocongress’88*. Geological Society of South Africa, Durban, pp. 85–88.
- Colliston, W.P., Schoch, A.E., 2013. Wrench-shearing during the Namaqua Orogenesis—Mesoproterozoic late stage deformation effects during Rodinia assembly. *Precambrian Res.* 233, 44–58.
- Cornell, D.H., Schütte, S.S., Eglinton, B.L., 1996. The Ongeluk basaltic andesite formation in Griqualand West, South Africa: submarine alteration in a 2222 Ma proterozoic sea. *Precambrian Res.* 79, 101–123.
- Cornell, D.H., Thomas, R.J., Moen, H.F.G., 2006. The Namaqua-Natal Province. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), *The Geology of South Africa*. Geological Society of South Africa/Council of Geoscience, Johannesburg/Pretoria, pp. 325–379.
- Denyszyn, S.W., Feinberg, J.M., Renne, P.R., Scott, G.R., 2013. Revisiting the age and paleomagnetism of the Modipe Gabbro of South Africa. *Precambrian Res.* 238, 176–185.
- De Kock, M.O., Evans, D.A.D., Dorland, H.C., Beukes, N.J., Gutzmer, J., 2006. Paleomagnetism of the lower two unconformity-bounded sequences of the Waterberg Group, South Africa: Towards a better-defined apparent polar wander path for the Paleoproterozoic Kaaapvaal Craton. *South Afr. J. Geol.* 109, 157–182.
- De Kock, M.O., Evans, D.A.D., Beukes, N.J., 2009a. Validating the existence of Vaalbara in the Neoproterozoic. *Precambrian Res.* 174, 145–154.
- De Kock, M.O., Evans, D.A.D., Kirschvink, J.L., Beukes, N.J., Rose, E., Hilburn, I., 2009b. Paleomagnetism of a Neoproterozoic–Paleoproterozoic carbonate ramp and carbonate platform succession (Transvaal Supergroup) from surface outcrop and drill core, Griqualand West region, South Africa. *Precambrian Res.* 169, 80–99.
- Dorland, H.C., Beukes, N.J., Gutzmer, J., Evans, D.A.D., Armstrong, R.A., 2006. Precise SHRIMP U–Pb zircon age constraints on the lower Waterberg and Soutpansberg Groups South Africa. *South Afr. J. Geol.* 109, 139–156.
- Dreyer, D., (M.Sc thesis) 2014. Geochronology and correlation of Paleoproterozoic red beds of the Elim Group in the Griqualand West Northern Cape Province. University of Johannesburg, Johannesburg, South Africa.
- Dreyer, C.J.B., (PhD thesis) 1982. Amphibole Asbestos in South Africa. Rand Afrikaans University, Johannesburg, South Africa, pp. 301.
- Eglinton, B.M., 2006. Evolution of the Namaqua-Natal Belt, southern Africa – a geochronological and isotope geochemical review., *J. Afr. Earth Sci.* 46, 93–111.
- Eglinton, B.M., Armstrong, R.A., 2004. The Kaaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton. *South Afr. J. Geol.* 107, 13–32.
- Embleton, B.J.J., 1978. The paleomagnetism of 2400 M.Y. old rocks from Australian Pilbara Craton and its relation to Archean–Proterozoic tectonics. *Precambrian Res.* 6, 275–291.
- Eriksson, P.G., Altermann, W., Hartzler, F.J., 2006. The Transvaal Supergroup and its precursors. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (Eds.), *The Geology of South Africa*. Geological Society of South Africa/Council of Geoscience, Johannesburg/Pretoria, pp. 237–260.
- Evans, D.A.D., 2007. Key Paleomagnetic pole from the Woongarra/Weeli Wolli large igneous province, Pilbara Craton, Australia: A link between supercratons? *Geol. Soc. Am. Abstr. Programs* 39, 285.
- Evans, D.A.D., Beukes, N.J., Kirschvink, J.L., 1997. Low-latitude glaciation in the Paleoproterozoic era. *Nature* 386, 262–266.
- Evans, D.A.D., Gutzmer, J., Beukes, N.J., Kirschvink, J.L., 2001. Paleomagnetic Constraints on Ages of Mineralization in the Kalahari Manganese Field, South Africa. *Econ. Geol.* 96, 621–631.
- Evans, D.A.D., Beukes, N.J., Kirschvink, J.L., 2002. Paleomagnetism of a lateritic paleoweathering horizon and overlying Paleoproterozoic red beds from South Africa: implications for the Kaaapvaal apparent polar wander path and a confirmation of atmospheric oxygen enrichment. *J. Geophys. Res.* 107, 2–22.
- Fairey, B., Tsikosa, H., Corfu, F., Polteau, S., 2013. U–Pb systematics in carbonates of the Postmasburg Group, Transvaal Supergroup, South Africa: primary versus metasomatic controls. *Precambrian Res.* 231, 194–205.
- Gumsley, A.P., Olsson, J.R., Söderlund, U., de Kock, M.O., Hofmann, A., Klausen, M., 2015. Precise U–Pb baddeleyite age dating of the Usushwana Complex, southern Africa – Implications for the Mesoproterozoic magmatic and sedimentological evolution of the Pongola Supergroup, Kaaapvaal Craton. *Precambrian Res.* 267, 174–185.
- Gumsley, A.P., de Kock, M.O., Rajesh, H.M., Knoper, M.W., Söderlund, U., Ernst, R.E., 2013. The Hlogoth Complex: the identification of fragments from a Mesoproterozoic large igneous province on the Kaaapvaal Craton. *Lithos* 174, 333–348.
- Gutzmer, J., Beukes, N.J., 1998. High-grade manganese ores in the Kalahari manganese field: characterization and dating of the ore forming events. Rand Afrikaans University Johannesburg, South Africa 221, Unpublished Report.

- Hanson, R.E., Gose, W.A., Crowley, J.L., Ramezani, J., Bowring, S.A., 2004. Paleoproterozoic intraplate magmatism and basin development on the Kaapvaal Craton: Age, paleomagnetism and geochemistry of ~1.93 to ~1.87 Ga post-Waterberg dolerites. *South Afr. J. Geol.* 107, 233–254.
- Heaman, L.M., LeCheminant, A.N., 1993. Paragenesis and U–Pb Systematics of Baddeleyite (ZrO₂). *Chem. Geol.* 110, 95–126.
- Hoffman, P.F., 2013. The great oxidation and a Siderian snowball Earth: MIF-S based correlation of Paleoproterozoic glacial epochs. *Chem. Geol.*, 143–156.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bently, W.C., Essling, A.M., 1971. Precision Measurement of Half-Lives and Specific Activities of U²³⁵ and U²³⁸. *Phys. Rev. C* 4, 1889–1906.
- Jones, C.H., 2002. User-driven integrated software lives: “Paleomag” Paleomagnetic analysis on the Macintosh. *Comp. Geosci.* 28, 1145–1151.
- Kamo, S.L., Reimold, W.U., Krogh, T.E., Colliston, W.P., 1996. A 2.023 Ga age for the Vredefort impact event and a first report of shock metamorphosed zircons in pseudotachylitic breccias and Granophyre. *Earth Planet. Sci. Lett.* 144, 369–387.
- Keyser, N., 1997. Geological map of the Republic of South Africa and the Kingdoms of Lesotho and Swaziland, 1:1,000,000. Council for Geoscience, Pretoria.
- Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. Int.* 62, 699–718.
- Kirschvink, J.L., Gaidos, E.J., Bertani, L.E., Beukes, N.J., Gutzmer, J., Maepa, L.N., Steinberger, R.E., 2000. Paleoproterozoic snowball Earth: extreme climatic and geochemical global change and its biological consequences. *Proc. Natl. Acad. Sci. U. S. A.* 97, 1400–1405.
- Kirschvink, J.L., Kopp, R.E., Raub, T.D., Baumgartner, C.T., Holt, J.W., 2008. Rapid, precise, and high-sensitivity acquisition of paleomagnetic and rock-magnetic data: development of a low-noise automatic sample changing system for superconducting rock magnetometers. *Geochem. Geophys. Geosyst.* 9, <http://dx.doi.org/10.1029/2007GC001856>.
- Layer, P.W., Kröner, A., McWilliams, M., Clauer, N., 1988. Regional magnetic overprinting of Witwatersrand Supergroup Sediments, South Africa. *J. Geophys. Res.–Solid Earth* 93, 2191–2200.
- Li, Z.X., McArthur-Powell, C., Bowman, P., 1993. Timing and genesis of Hamersley iron-ore deposits. *Exploration Geophys.* 24, 631–636.
- Ludwig, K.R., 1991. Isoplot – a plotting and regression program for radiogenic isotopic data, Open File Report, pp. 445, USGS.
- Martin, D.M.B., Clendenin, C.W., Krapez, B., McNaughton, N.J., 1998. Tectonic and geochronological constraints on Late Archaean and Palaeoproterozoic stratigraphic correlation within and between the Kaapvaal and Pilbara cratons. *J. Geol. Soc.* 155, 311–322.
- McCadden, P.L., Jones, D.L., 1981. The fold test in palaeomagnetism. *Geophys. J. Int.* 67, 53–58.
- Moore, J.M., Polteau, S., Armstrong, R.A., Corfu, F., Tsikosa, H., 2012. The age and correlation of the Postmasburg Group, southern Africa: Constraints from detrital zircon grains. *J. Afr. Earth Sci.* 64, 9–19.
- Moore, J.M., Tsikos, H., Polteau, S., 2001. Deconstructing the Transvaal Supergroup, South Africa: implications for Palaeoproterozoic palaeoclimate models. *J. Afr. Earth Sci.* 33, 437–444.
- Müller, S.G., Krapež, B., Barley, M.E., Fletcher, I.R., 2005. Giant iron-ore deposits of the Hamersley province related to the breakup of Paleoproterozoic Australia: new insights from in situ SHRIMP dating of baddeleyite from mafic intrusions. *Geology* 33, 577–580.
- Nelson, D.R., Trendall, A.F., Altermann, W., 1999. Chronological correlations between the Pilbara and Kaapvaal Cratons. *Precambrian Res.* 97, 165–189.
- Olsson, J.R., Söderlund, U., Klausen, M.B., Ernst, R.E., 2010. U–Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. *Precambrian Res.* 183, 490–500.
- Lubnina, N., Ernst, R.E., Klausen, M.B., Söderlund, U., 2010. Paleomagnetic study of NeoArchean–Paleoproterozoic dykes in the Kaapvaal Craton. *Precambrian Res.* 183, 523–552.
- Letts, S., Torsvik, T.H., Webb, S.J., Ashwal, L.D., 2009. Palaeomagnetism of the 2054 Ma Bushveld Complex (South Africa): implications for emplacement and cooling. *Geophys. J. Int.* 179, 850–872.
- Letts, S., Torsvik, T.H., Webb, S.J., Ashwal, L.D., 2011. New Palaeoproterozoic palaeomagnetic data from the Kaapvaal Craton, South Africa. In: Hinsbergen, D.J.J., Buiter, S.J. H., Torsvik, T.H., Gaina, C., Webb, S.J. (Eds.), *The Formation and Evolution of Africa: A Synopsis of 3.8 Ga of Earth History*. Geological Society of London, London, pp. 9–26.
- Pickard, A.L., 2003. SHRIMP U–Pb zircon ages for the Palaeoproterozoic Kuruman Iron Formation, Northern Cape Province, South Africa: evidence for simultaneous BIF deposition on Kaapvaal and Pilbara Cratons. *Precambrian Res.* 125, 275–315.
- Schmidt, P.W., Clark, D.A., 1994. Palaeomagnetism and magnetic anisotropy of Proterozoic banded-iron formations and iron ores of the Hamersley Basin, Western Australia. *Precambrian Res.* 69, 133–155.
- Schmidt, P.W., Embleton, B.J.J., 1985. Prefolding and overprint magnetic signatures in Precambrian (~2.9–2.7 Ga) Igneous rocks from the Pilbara Craton and Hamersley Basin, NW Australia. *J. Geophys. Res.–Solid Earth Planets* 90, 2967–2984.
- Schröder, S., Lacassie, J.P., Beukes, N.J., 2006. Stratigraphic and geochemical framework of the Agouron drill cores, Transvaal Supergroup (Neoproterozoic–Paleoproterozoic, South Africa). *South Afr. J. Geol.* 109, 23–54.
- Scoates, J.S., Friedman, R.M., 2008. Precise age of the Plantiferous Merensky Reef, Bushveld Complex, South Africa, by the U–Pb Zircon chemical abrasion ID-TIMS technique. *Econ. Geol.* 103, 465–471.
- Smirnov, A.V., Evans, D.A.D., Ernst, R., Söderlund, U., Li, Z.-X., 2013. Trading partners: tectonic ancestry of southern Africa and western Australia, in *Archean supercratons Vaalbara and Zimgarn*. *Precambrian Res.* 224, 11–22.
- Söderlund, U., Ibanez-Mejia, M., El Bahat, A., Ernst, R.E., Ikenne, M., Soulaïmani, A., Youbi, N., Cousens, B., El Janati, M., Hafid, A., 2013. Reply to Comment on “U–Pb baddeleyite ages and geochemistry of dolerite dykes in the Bas-Drâa inlier of the Anti-Atlas of Morocco: Newly identified 1380 Ma event in the West African Craton” by André Michard and Dominique Gasquet. *Lithos* 174, 101–108.
- Söderlund, U., Johansson, L., 2002. A simple way to extract baddeleyite (ZrO₂). *Geochem. Geophys. Geosyst.* 3, 10029/2001GC000212.
- Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet. Sci. Lett.* 26, 207–221.
- Strik, G., Blake, T.S., Zegers, T.E., White, S.H., Langeris, C.G., 2003. Palaeomagnetism of flood basalts in the Pilbara Craton, Western Australia: Late Archaean continental drift and the oldest known reversal of the geomagnetic field. *J. Geophys. Res.–Solid Earth Planets* 108, 2551.
- Sumner, D.Y., Bowring, S.A., 1996. U–Pb geochronologic constraints on deposition of the Campbellrand Subgroup, Transvaal Supergroup, South Africa. *Precambrian Res.* 79, 25–35.
- Tauxe, L., 2010. *Essentials of Paleomagnetism*. University of California Press, Berkeley/Los Angeles/London, pp. 489.
- Tauxe, L., Kylastra, N., Constable, C., 1991. Bootstrap statistics for paleomagnetic data. *J. Geophys. Res.–Solid Earth Planets* 96, 11723–11740.
- Trendall, A.F., 1968. Three great basins of Precambrian iron formation deposition: a systematic comparison. *Geol. Soc. Am. Bull.* 79, 1527–1533.
- Trendall, A.F., Compston, W., Nelson, D.R., De Laeter, J.R., Bennet, V.C., 2004. SHRIMP zircon ages constraining the depositional chronology of the Hamersley Group, Western Australia. *Austr. J. Earth Sci.* 51, 621–644.
- Trendall, A.F., De Laeter, J.R., Nelson, D.R., 1995. Chronology of Gondwana BIFs: progress report from recent zircon U–Pb results. In: *Third Australian Conference on Geochronology*, pp. 1–3.
- Wabo, H., de Kock, M., Rajesh, H.M., Beukes, N.J., 2011. Paleomagnetism and geochemistry of Bushveld-related intrusions, eastern Kaapvaal craton. In: *AGU Fall Meeting, 2011*. American Geophysical Union, San Francisco.
- Walraven, F., Martini, J., 1995. Zircon Pb–evaporation age determinations of the Oak Tree Formation, Chuniespoort Group, Transvaal Sequence: implications for Transvaal–Griqualand West basin correlations. *South Afr. J. Geol.* 98, 58–67.
- Williams, S.E., Müller, R.D., Landgrebe, T.C.W., Whittaker, J.M., 2012. GSA Today 22 2012. An open-source software environment for visualizing and refining plate tectonic reconstructions using high-resolution geological and geophysical data sets.
- Wingate, M.T.D., 1998. A paleomagnetic test of the Kaapvaal–Pilbara (Vaalbara) connection at 2.78 Ga. *South Afr. J. Geol.* 101, 257–274.
- Wu, F.-Y., Yang, Y.-H., Li, Q.-L., Mitchell, R.H., Dawson, J.B., Brandl, G., Yuhara, M., 2011. In situ determination of U–Pb ages and Sr–Nd–Hf isotopic constraints on the petrogenesis of the Phalaborwa carbonatite Complex, South Africa. *Lithos* 127, 309–322.
- Zegers, T.E., de Wit, M.J., Dann, J., White, S.H., 1998. Vaalbara, Earth’s oldest assembled continent? A combined structural, geochronological and palaeomagnetic test. *Terra Nova* 10, 250–259.