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New U–Pb SHRIMP zircon age for the Schurwedraai alkali granite: Implications for pre-impact development of the Vredefort Dome and extent of Bushveld magmatism, South Africa

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Abstract

The Schurwedraai alkali granite is one of a number of prominent ultramafic-mafic and felsic intrusions in the Neoarchaean to Palaeoproterozoic sub-vertical supracrustal collar rocks of the Vredefort Dome, South Africa. The alkali granite intruded the Neoarchaean Witwatersrand Supergroup and has a peralkaline to peraluminous composition. A new zircon SHRIMP crystallization age of 2052 ± 14 Ma for the Schurwedraai alkali granite places it statistically before the Vredefort impact event at 2023 ± 4 Ma and within the accepted emplacement interval of 2050–2060 Ma of the Bushveld magmatic event. The presence of the alkali granite and associated small ultramafic-mafic intrusions in the Vredefort collar rocks extends the southern extremity of Bushveld-related intrusions to some 120 km south of Johannesburg and about 150 km south of the current outcrop area of the Bushveld Complex. The combined effect of these ultramafic-mafic and felsic bodies may have contributed to a pronouncedly steep pre-impact geothermal gradient in the Vredefort area, and to the amphibolite-grade metamorphism observed in the supracrustal collar rocks of the Vredefort Dome.

Keywords: SHRIMP; Bushveld; Vredefort; Witwatersrand; Schurwedraai

1. Introduction

The Vredefort Dome is located on the Kaapvaal Craton, some 120 km southwest of Johannesburg, South Africa (Fig. 1). It is an ovoid structure, over 70 km wide, and comprises a core of Archaean TTG-greenstone rocks (Lana et al., 2004) and a collar of overturned Neoarchaean to Palaeoproterozoic supracrustal rocks (Gibson and Reimold, 2001). Because the Vredefort Dome is located in the centre of the Witwatersrand Basin, the world's largest accumulation of exploitable gold, there has for many years been an intense focus on understanding the geological processes leading to the formation of this large structure.

Evidence for an impact origin is prevalent throughout the Vredefort Dome structure and includes (1) the occurrence of the high pressure silica polymorphs, coesite and stishovite, in some of the collar rocks (Martini, 1978, 1991), (2) planar deformation features (PDFs) in quartz throughout the entire structure (Grieve et al., 1990), (3) the widespread occurrence of shatter cones throughout the structure (Hargraves, 1961; Albat and Mayer, 1989), (4) the widespread occurrence of pervasive pseudotachylite veins throughout rocks of both the gneissic granite core and supracrustal collar sequences (e.g., Reimold and Colliston, 1994; Gibson et al., 1997), as well as (5) the presence of dykes of a xenolith-laden granophyric rock interpreted by Koeberl et al. (1996) as impact melt.

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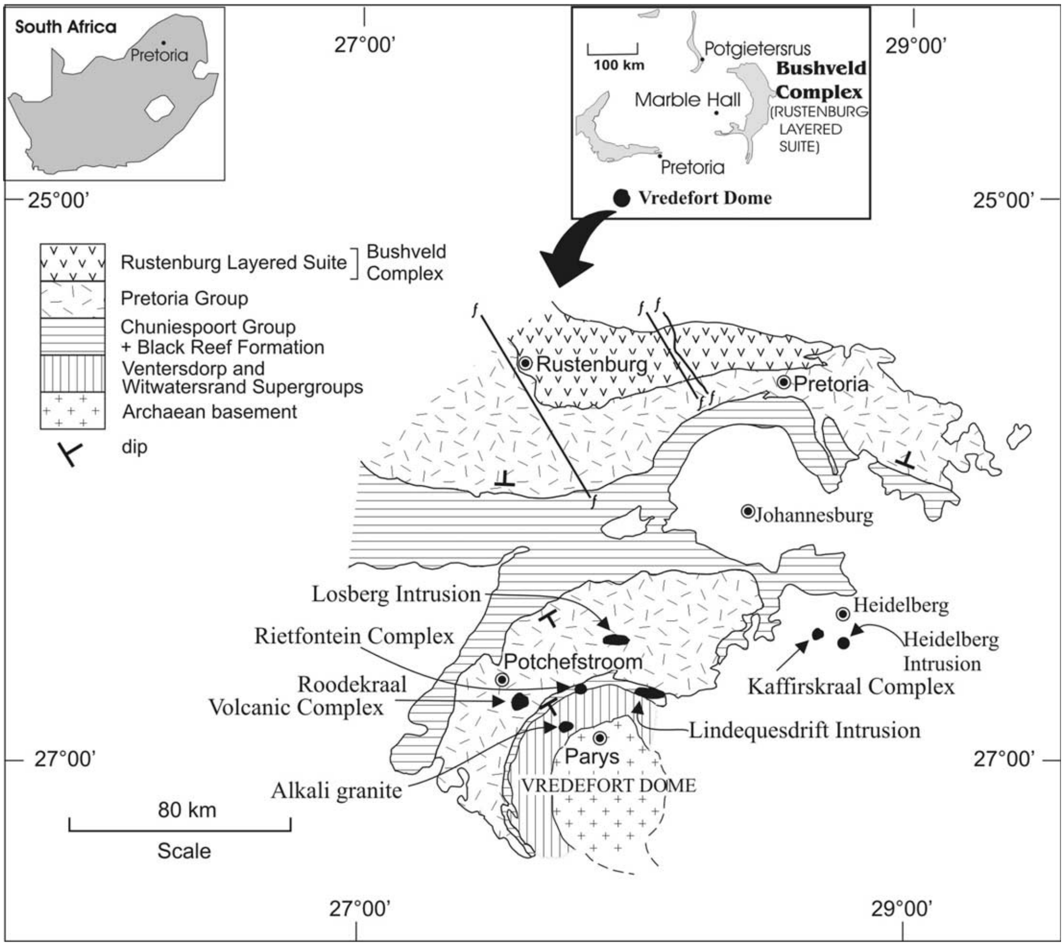

Fig. 1. Location of the Vredefort Dome and satellite intrusions related to the Bushveld magmatic event, South Africa.

Although some researchers have until recently argued for a multiple deformation origin (e.g. Lilly, 1981; Reimold, 1990; Reimold et al., 1990), the impact origin for the structure (e.g. Boon and Albritton, 1936; Dietz, 1961; French and Nielsen, 1990; Grieve et al., 1990) seems now to be largely accepted (Gibson and Reimold, 2001; Reimold and Gibson, 1996). Hart et al. (1991) proposed a modified impact-related model with post-impact tectonic modification.

In spite of the generally converging ideas on the impact origin of the Vredefort Dome, a debate on the metamorphic history of the collar rocks still remains, particularly in relation to the timing of the various metamorphic events. Some investigators (e.g. Bisschoff, 1982; Schreyer, 1983) contend that the development of hornfelsed metasedimentary rocks in the collar is due to the intrusion of basic plutons belonging to the Bushveld magmatic event, while others (Gibson, 1993) argue that because these rocks contain at least two planar foliations, they cannot be classified as hornfels senso stricto. Gibson (1993) ascribed the development of the metamorphism to a regional event that affected the Witwatersrand Basin as a whole, possibly during Bushveld emplacement before the Vredefort impact episode.

The Schurwedraai alkali granite intruded supracrustal rocks of the Witwatersrand Supergroup in the inner collar (Fig. 2). The granite represents one of a number of minor intrusions, which in terms of emplacement ages and their potential roles as heat sources, could have contributed substantially to the heat flow pattern in the Vredefort structure. In this paper we present new zircon SHRIMP geochronological data for the Schurwedraai granite and discuss the implication of these data in terms of pre-impact magmatism, the timing of the metamorphism within the Vredefort Dome structure, and the extent of the Bushveld magmatic event.

2. Analytical techniques

For U–Pb SHRIMP dating, a sample of alkali granite of the Schurwedraai intrusion was obtained from the farm Koedoeslaagte 516 IQ (26°51′30″ S and 27°20′30″ E). Approximately 30 kg of the granite was selected and crushed to ensure a representative zircon sample. Some of the individual rock fragments contained narrow (<0.05 in maximum width) cross-cutting pseudotachylite veinlets, which were removed.

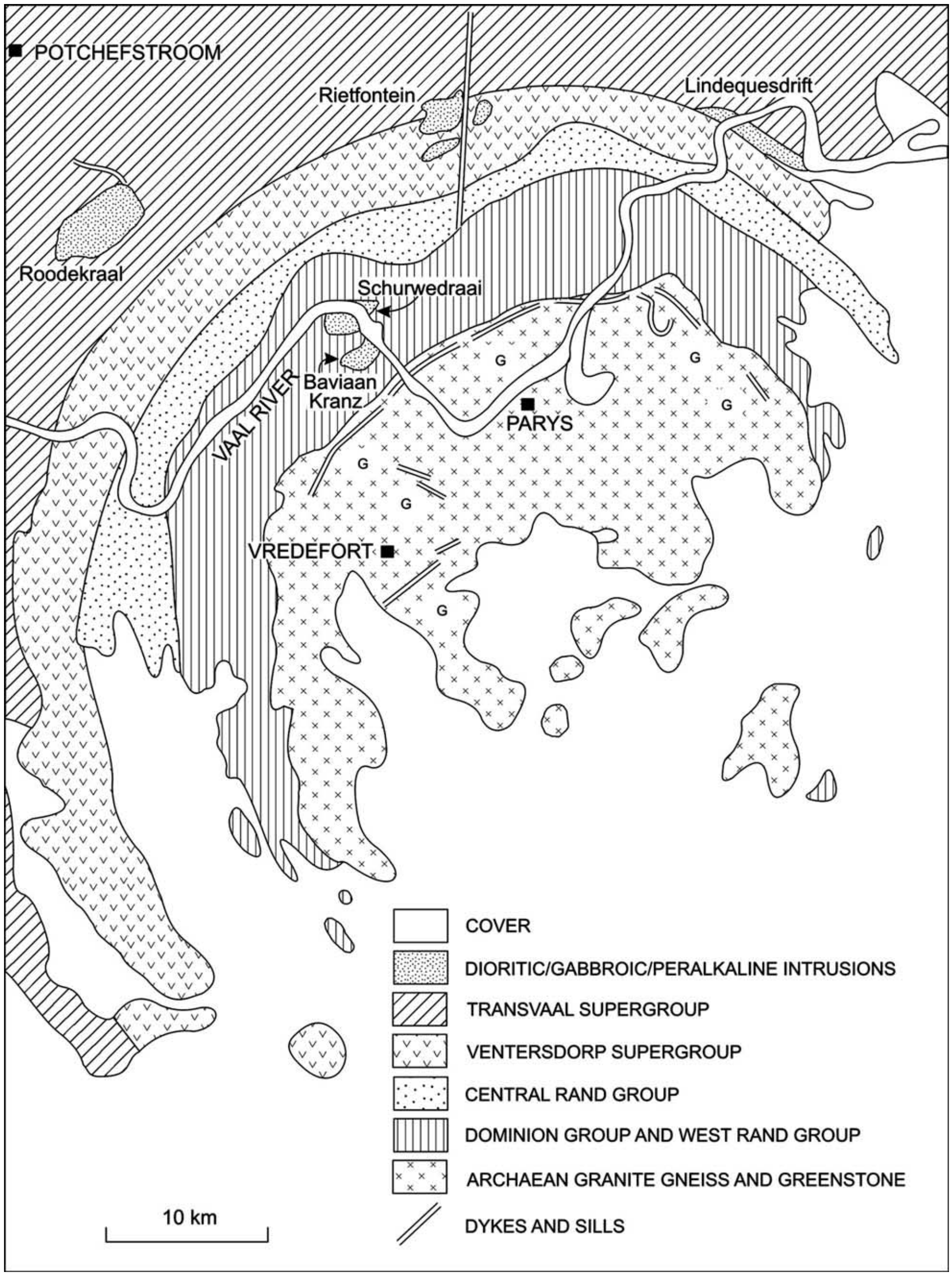

Fig. 2. Geological map of the Vredefort Dome, showing location of minor intrusions (G = granophyre) in the collar rocks. Numerous sills related to the Ventersdorp and Bushveld magmatic events not shown.

For the XRF analyses, the samples were ground to <75 μm in a tungsten carbide mill and analyzed at the Department of Geology, University of Pretoria, South Africa. Loss on ignition was determined at 1000 °C and major element analysis was performed on the fused Li borate beads using an ARL9400XP^{+} spectrometer. Another aliquot of the sample was pressed into a powder briquette for the trace element analysis.

The samples collected for the U–Pb zircon SHRIMP analysis were initially crushed to <250 μm at the Department of Geology, University of Pretoria. The sample was then processed with a superpanner and the heavy mineral concentrate collected. Further concentration was made using heavy liquids at the University of Pretoria and the Research School of Earth Sciences (RSES), the Australian National University, Canberra, Australia, finally leading to a relatively clean zircon concentrate. Zircon grains were then handpicked under a binocular microscope and the grains mounted in epoxy together with the SHRIMP zircon standards AS3 (gabbroic anorthosite from the Duluth Complex, Minnesota, USA; Paces and Miller, 1989) and SL13 (RSES, the Australian National University). This zircon grain mount was sectioned, polished and photographed in transmitted and reflected light.

To provide information on zonation, radiation damage and presence of inherited cores and metamorphic overgrowths, the zircon grain mount was examined and photographed under a scanning electron microscope fitted with a cathodoluminescence imaging facility. The zircons were analyzed using the SHRIMP II spectrometer during a single session. Each analysis consisted of 6 scans through the mass range. The SHRIMP data were reduced following Williams (1998), Williams and Claesson (1987), and Compston et al. (1992) and using the SQUID Excel Macro of Ludwig (2000). U/Pb in the unknowns was normalized to a $^{206}Pb/^{238}U$ value of 0.1859 (equivalent to an age of 1099.1 Ma) for AS3 (Paces and Miller, 1989). The U and Th concentrations were determined relative to those measured in the SL13 standard. Ages were calculated using the radiogenic $^{207}Pb/^{206}Pb$ ratios, with the correction for common Pb made using the measured ^{204}Pb and the appropriate common Pb composition, assuming the model of Cumming and Richards (1975). Uncertainties in the individual isotopic ratios and ages are reported at the 1σ level, unless otherwise stated in the text, and the final weighted mean ages are reported as 95% confidence limits. The concordia plots and weighted mean age calculations were carried out using Isoplot/Ex (Ludwig, 1999).

3. Geological setting of the Schurwedraai alkali granite

The Vredefort impact structure, estimated to have had an original diameter of 250–300 km (Gibson and Reimold, 2001), has been dated at 2023 ± 4 Ma by Kamo et al. (1996), using U–Pb SHRIMP techniques on accessory zircon grains from the pseudotachylitic breccias. This structure is, thus, the oldest known impact structure on earth. Also, since an estimated 8–11 km of overlying rocks have been removed by erosion since the impact event, it is the world's most deeply eroded impact structure (Gibson et al., 1998).

The Vredefort Dome, in the central part of the impact structure, is well exposed along its northwestern margins, but towards the southeast is covered by shale and dolerite sills of the Phanerozoic Karoo Supergroup (≈300–180 Ma). The dome consists of two main parts, i.e. a 40 km wide core region of Mesoarchaean crystalline basement, and a 15–20 km wide collar zone of overturned sub-vertical Neoarchaean to Palaeoproterozoic supracrustal rocks (Fig. 2). Outside of this collar, the dip of the strata shallows and defines a broad 90-km-wide arching synclinal structure, termed the Potchefstroom Synclinorium, the outer limits of which broadly define the boundary of the Witwatersrand Basin (Gibson and Reimold, 2001).

The rocks of the core region consist of amphibolite to granulite facies granite gneiss as well as mafic and felsic gneiss (protolith age of 3.5 Ga, with metamorphic overprint at 3.1 Ga; Hart et al., 1981, 2004). The latter have experienced at least two deformational events, which accompanied the metamorphism prior to the deposition of the supracrustal rocks of the collar (Gibson and Reimold, 2001). A third group of rocks (Greenlands Formation) comprises an amphibolite-grade granite-greenstone lithology and is separated from the granulite facies rocks by an inferred fault or shear zone (Hart et al., 2004). With the exception of the high metamorphic grade, the rocks of the core zone resemble typical Archaean TTG-greenstone sequences developed elsewhere on the Kaapvaal Craton (Lana et al., 2004; Hart et al., 2004).

The collar rocks comprise a series of unconformity-bounded sedimentary and volcanic sequences deposited between 3.07 and 2.25 Ga in a succession of basins on the Kaapvaal Craton (Clendennin et al., 1988). They are now overturned and young away from the core of the dome structure. The oldest rocks in the collar are the 3.074 ± 0.027 Ga Dominion Group (Armstrong et al., 1991), a sequence of bimodal basaltic andesite and felsic lavas, along with minor rift-related clastic sedimentary rocks (Jackson, 1994). These are followed by the 2.9 to 2.7 Ga sequence of clastic sedimentary rocks of the Witwatersrand Supergroup (Central and West Rand Groups, Fig. 2). The deposition of the Witwatersrand Supergroup was abruptly terminated at 2.714 Ga (Armstrong et al., 1991) by the eruption of tholeiitic flood basalts of the Ventersdorp Supergroup. Deposition of the Transvaal Supergroup began at approximately 2.6 Ga, when a shallow sea covered much of the Kaapvaal Craton. Cessation of deposition within the Transvaal Supergroup occurred at approximately 2.25 Ga (Walraven, 1997; Clendennin et al., 1988). The Bushveld magmatic event initiated at approximately 2.06 Ga (Walraven, 1997) with the extrusion of the dominantly silicic volcanic rocks of the Rooiberg Group, followed by the intrusion of mafic and ultramafic magmas (Rustenburg Layered Suite, Fig. 1), and finally, the emplacement of a voluminous granite mass (Lebowa Granite Suite). Although most of the rocks of the Bushveld magmatic event occur to the north of the Witwatersrand Basin, a small outlier of mafic-ultramafic rocks, known as the Losberg Complex, is situated 30 km north of the Vredefort Dome. Forming an oval-shaped body, it intruded into Pretoria Group rocks and has a marginal sill facies that is similar to some of the marginal sills of the Bushveld Complex (Cawthorn, 1983). Coetzee and Kruger (1989) performed detailed Rb–Sr and Pb–Pb whole rock and mica geochronology on a series of samples representing most of the rocktypes found throughout the sequence and concluded that the best age estimate for the Losberg Complex was a combined Rb–Sr mica and whole rock age of 2041 ± 41 Ma obtained on a harzburgite sample. In addition, they found initial Sr ratios for the Losberg that correspond to those of the Bushveld sequence, suggesting the southerly extension rocks related to the Bushveld magmatic event well beyond the current outcrop of the Bushveld Complex.

Mafic sills and dykes are common within the collar rocks of the Vredefort Dome and have been variously interpreted as hypabyssal equivalents of the Ventersdorp lavas (Bisschoff, 1972a; Pybus et al., 1995), the Bushveld Complex (Bisschoff, 1972a,b), or younger magmatic events (Bisschoff, 1972a). Dykes of unusual clast-ridden granophyric rocks occur along the core-collar contact and in the western part of the core. These have been interpreted as impact melt (Koeberl et al., 1996). Recently, Reimold et al. (2000) presented results on the Anna's Rust Sheet, a suite of tholeiitic gabbroic intrusions which occur in both the core and collar regions of the Vredefort Dome, and which have not been cross-cut by pseudotachylite veinlets. They reported Ar–Ar mineral separate ages of approximately 1000 Ma for the intrusions. Karoo-age (i.e. 180 Ma; Allsopp et al., 1984) dolerite sills and dykes are of widespread occurrence in the eastern and southern parts of the Vredefort Dome (e.g. Nel, 1927; Pybus, 1995) and these represent the final emplacement of igneous rocks within this region.

Folding as well as concentric and vertical radial faults complicate the structure of the Vredefort Dome. Although the large folds developed within the Witwatersrand Supergroup strata appear to be pre-impact in age, the faults show both pre- and syn-impact displacement (Colliston et al., 1999). Further from the core, folding within the Pretoria Group of the Potchefstroom Synclinorium verges away from the Vredefort Dome (Simpson, 1978). Further away, the folds decrease in amplitude and are associated with concentrically arranged imbricate fault systems, which generally dip towards the Vredefort Dome structure (Gibson and Reimold, 2001). Some of these faults appear to be linked with intense brecciation, which Brink et al. (1997) attributed to the formation of the dome. A similar timing has been suggested for smaller-scale thrust faults and associated folds, which occur in the vicinity of Johannesburg, up to 150 km from the Vredefort Dome (McCarthy et al., 1986, 1990; Gibson et al., 1999).

The Schurwedraai alkali intrusion (comprising both alkali granite and nepheline syenite rocks) is one of a number of small, chemically related, alkali granitic bodies (the others comprising the Baviaanskranz alkali granite and granite related to the Rietfontein Complex) which have intruded into the inner and outer collar rocks (Fig. 2) on the northwestern side of the Vredefort Dome structure (Bisschoff, 1982). Along with various mafic intrusions (e.g. Lindequesdrift and Rietfontein) which Bisschoff (1972b) interpreted to be comagmatic, the emplacement of these alkali intrusions may be fault-controlled (e.g. Bisschoff, 1988).

Metamorphic isograds in the collar rocks follow a concentric pattern, decreasing in intensity away from the center of the dome. The upper Witwatersrand Supergroup, the Ventersdorp lava, the rocks of the Transvaal Supergroup, as well as the mafic sills contained within these rocks, display only a greenschist grade of metamorphism. In contrast, the lower Witwatersrand, the Dominion Group and the intercalated mafic sills have been metamorphosed up to the amphibolite facies (Bisschoff, 1982; Gibson and Stevens, 1998; Gibson and Reimold, 2001). Two superimposed metamorphic events seem to have caused this concentric pattern. The first predates the Vredefort impact and is ascribed to a period of high heat flow connected to the Bushveld magmatic event (Gibson and Wallmach, 1995; Gibson and Reimold, 2001). The second event, contemporaneous with and resulting from the impact episode, caused transient thermal effects that overprint the existing mineralogical and structural features (Gibson et al., 1997, 1998; Gibson, 2002).

4. Previous age determinations

Walraven and Elsenbroek (1991) obtained Rb–Sr and Pb–Pb whole rock and mineral separate ages from both the granitic rocks and nepheline syenites. However, for both the alkali granites and nepheline syenites there is a large scatter in their results resulting in large uncertainties in the ages. They ascribed this to isotopic disturbance possibly due to metamorphism associated with either the Bushveld magmatic or Vredefort impact events. Excluding the Rb–Sr whole rock data of the Schurwedraai granite, they reported an age of crystallization (weighted mean of both the granitic and syenitic age data) of 2210 Ma, with a standard error of 31 Ma. In contrast, Moser and Hart (1996) determined a single zircon U–Pb age of 2078 ± 12 Ma on nepheline syenite from the Schurwedraai intrusion.

5. Contact relationships with the surrounding rock units

According to Bisschoff (1982), the roofs of the alkali granite intrusions dip towards the east at a low angle. In places, on what is believed to be original basal contacts, the alkali granite contains relatively abundant rounded quartz grains and metasedimentary xenoliths that can be equated to the surrounding metasedimentary rocks of the West Rand Group (Elsenbroek, 1991, 1993; Bisschoff, 1982). The nepheline syenite (i.e. mariupolite) dykes of the Schurwedraai alkali intrusion only occur within the roof zones of the granite bodies. Based on field relationships, Elsenbroek (1991) proposed that the nepheline syenites intruded as sills prior to the emplacement of the main granite mass. Thus, the nepheline syenite would appear to be at least marginally older than the granitic rocks.

Both the granitic and, locally developed, syenitic rocks of the Schurwedraai alkali intrusion are cut by pseudotachylite veinlets ranging in width from <0.05 mm up to 10 cm (Fig. 3). They also contain abundant multiply striated joint surfaces and shatter cones (Nicolaysen and Reimold, 1999). These features confirm their pre-impact age. Also, on the basis of palaeomagnetic studies, (1970) showed that the alkali granite had intruded into the surrounding rocks of the Witwatersrand Supergoup prior to their overturning during the impact event.

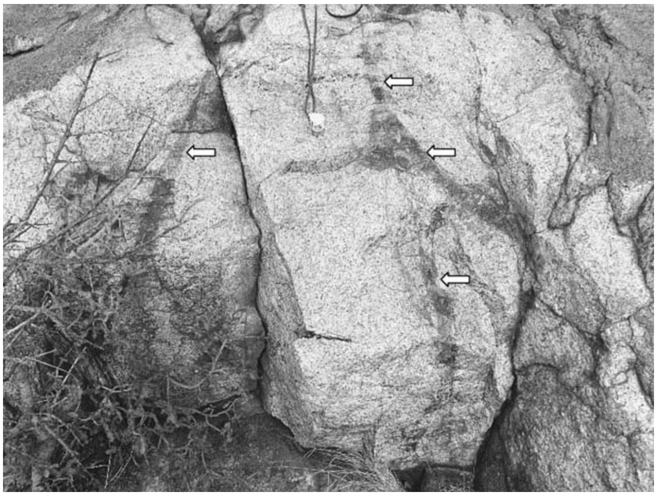

Fig. 3. Pseudotachylite veins (arrows) cross-cutting the Schurwedraai alkali granite.

6. Petrography

6.1. Alkali granite

The Schurwedraai alkali granite and associated nepheline syenite rocks have been previously described by a number of workers (e.g. Hall and Molengraaff, 1925; Bisschoff, 1969; Elsenbroek, 1991, 1993). The alkali granite generally exhibits a hypidiomorphic granular texture defined by strongly interlocking anhedral, sub-hedral, and euhedral grains of the constituent phases. The main variety is a massive fine- to medium-grained sodium-rich leucocratic granite. This has a modal composition of quartz (25%), albite (43%), K-feldspar (22%), aegirine/arfvedsonite (9%) and mica (1%; Fe-rich biotite to Mg-rich lepidomelane) (Elsenbroek, 1991, 1993), along with accessory zircon, apatite, magnetite, ilmenite and very rare chalcopyrite. Locally, where the alkali granite contains large numbers of nepheline syenite xenoliths, the granite grades into syenite (quartz 2%, albite 59%, K-feldspar 19%, aegirine/arfvedsonite 20%). Hornblende pegmatite veins are also locally developed.

Albite generally occurs as relatively large sub-hedral equant to sub-prismatic, highly embayed grains which are cross-cut by narrow veins of fine-grained plagioclase and quartz. Close to pseudotachylite veinlets they are micro-faulted (with common lateral displacements up to 0.5mm), have moderately bent multiple twin lamellae, and subgrain development along their margins. They are also moderately fractured and brecciated (though with no fragment rotation) and are traversed by the pseudotachylite veinlets. Quartz forms relatively large ragged, strongly embayed, elongate grains, which are composed of multiple lenticular subgrain lamellae and exhibit strong to extreme undulose extinction. In places, these grains are cross-cut by tiny equant polygonal quartz aggregates with well-developed triple-junction grain boundaries. The K-feldspar grains are strongly embayed and have ragged grain boundaries against the quartz and smaller plagioclase grains. They also exhibit moderate undulose extinction.

6.2. Nepheline syenite

Alkali nepheline syenites (termed 'mariupolite' by Bisschoff, 1982) dominate this group. They are generally coarser-grained than the granitic rocks and have a well-developed allotriomorphic granular texture defined by strongly interlocking non-aligned grains of the constituent phases. They have a modal composition of albite (55%), nepheline (25%), microcline (15%) and aegirine (4%), along with minor hornblende, Na-mica and sodalite, and accessory magnetite, ilmenite and sphene. In places, they are pegmatitic, and nepheline may occur as monomineralic veinlets up to 3cm in width. The nepheline and sodalite grains are moderately embayed and contain common inclusions of albite, aegirine and hornblende. The microcline is partially replaced by the fine-grained colourless Na-mica while the aegirine is partially replaced by the hornblende. The albite grains are commonly micro-faulted and deformed (defined by twin lamellae which are bent by up to 30°).

7. Geochemistry

The chemistry of the alkali granite and related syenite and nepheline syenite are taken from Elsenbroek (1991, 1993) and listed in Table 1. On the basis of Na + K to Al ratios, Elsenbroek (1991, 1993) classifies the alkali granite as peraluminous to peralkalic. He also suggested that the observed enrichment of the alkali granites in Rb, Th and Y was due to assimilation of quartzite and shale of the West Rand Group during emplacement. This interpretation is supported by pseudo-layering within the granite along its contacts with the sedimentary rocks, the occurrence of rounded quartz grains and quartzite xenoliths within the granite, and the relative enrichment of the granite in trace elements in close proximity to the metasedimentary xenoliths (Elsenbroek, 1991, 1993).

8. U–Pb SHRIMP geochronology

The CL images clearly define two distinct zircon populations within this sample (Fig. 4). The dominant zircon type (comprising over 95% of the zircon population) consists of sharp, commonly doubly terminated, equant to short prismatic grains with well-developed face-parallel growth zoning and common rounded inherited cores. These zircon crystals are up to 300 μm in maximum dimension, may have relatively large inherited cores (comprising up to 75% of the zircon surface area), and in places, show well-developed Maltese cross-shaped sector zoning (Fig. 5). These "magmatic" zircons correspond well with the

Table 1
Geochemistry of the Schurwedraai alkali granite and related rocks

	A	B	C
Major (%)			
SiO_2	71.18	74.02	57.51
TiO_2	0.26	0.21	0.30
Al_2O_3	12.85	12.90	21.18
Fe_2O_3	0.92	0.52	2.18
FeO	1.37	1.47	1.06
MnO	0.09	0.01	0.04
MgO	0.89	0.86	0.85
CaO	0.01	0.27	0.01
Na_2O	6.56	4.99	9.85
K_2O	3.04	4.05	3.82
P_2O_5	0.01	0.01	0.01
Cr_2O_3	0.07	0.06	0.01
H_2O^+	0.20	0.31	0.41
H_2O	0.01	0.02	0.02
CO_2	0.33	0.33	0.05
Minor (ppm)			
Rb	68	143	63
Sr	162	117	62
Ba	626	497	682
Zr	275	191	120
Y	10	17	2
Nb	33	25	15
Ga	27	25	30
Zn	80	77	73
Th	11	23	2
n	9	9	12

A: Schurwedraai alkali granite.
B: Baviaanskranz alkali granite.
C: Nepheline syenite (mariupolite).
From Elsenbroek (1991).

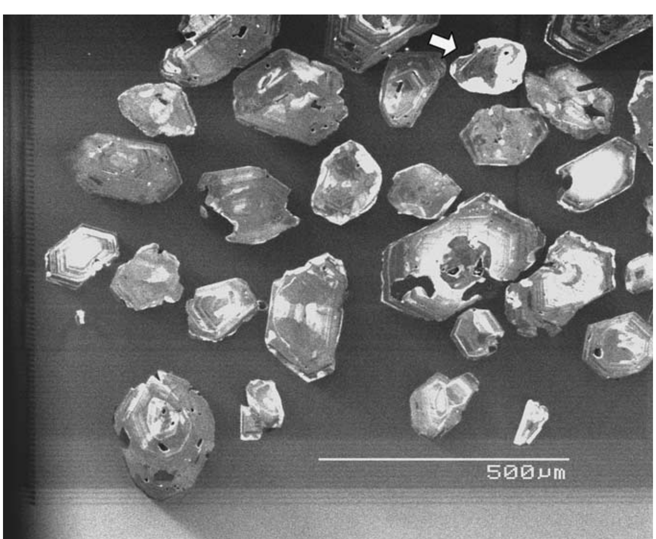

Fig. 4. CL image of zircon population from the Schurwedraai alkali granite, showing the dominant population of angular short to prismatic magmatic grains, and a small population (arrow) of rounded equant grains.

type S5 zircons of Pupin (1980), which he correlates with zircons originating from alkaline and hyperalkaline granitic magmas derived from mantle melts, with the zircon crystallization occurring below 650 °C (Pupin and Turco, 1972).

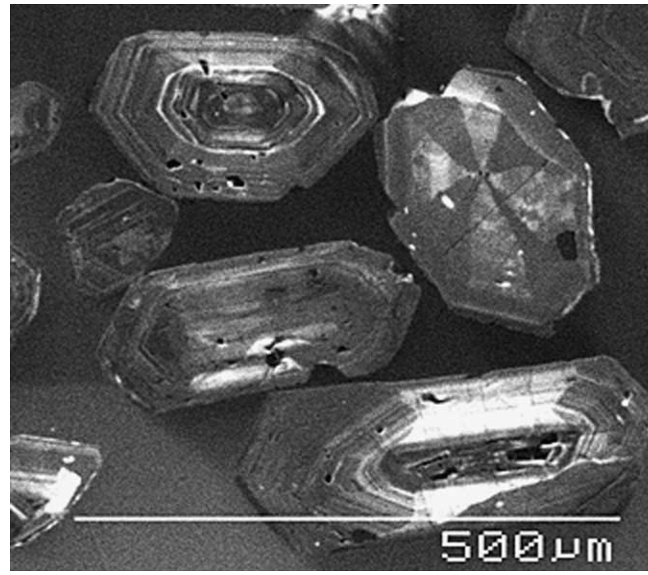

Fig. 5. Close-up CL image of zoned zircon crystals and one showing a Maltese cross.

The second, subordinate, zircon population comprises rounded, anhedral, moderately embayed, ovoid-shaped grains with very bright luminescent edges and sector zonation around the rims. These grains are commonly of the order of 50–100 μm in maximum dimension (Fig. 4).

Some of the zircon grains also displays PDFs and have small bright-CL zones and rims indicating some recrystallization (Figs. 4 and 5). These features along with the presence of rare embayments suggest some post-emplacement alteration or metamorphism, probably related to the Vredefort impact event.

Eighteen analyses were made on 15 different zircon grains, with the data being presented in Table 2 and plotted as a Wetherill U–Pb concordia diagram in Fig. 6. Many of the zircons are highly discordant and have high common Pb contents, both being consistent with the altered nature of the zircons. The presence of these common Pb-enriched zircons would help to explain the anomalously 'older' age for the alkali granites determined by Walraven and Elsenbroek (1991), using whole-rock Rb–Sr and Pb–Pb techniques. If only the "magmatic" grains are used in the regression, an age of 2044.1 ± 8.7 Ma is indicated. A regression of the least altered zircons, i.e. those that are less than 10% discordant, yields an age of 2052 ± 14 Ma (Fig. 7) and a weighted mean of the same zircons gives an age of 2044.7 ± 7.7 Ma (MSWD = 0.42; prob. = 0.91). Based on the latter data, we propose that the age of crystallization of the Schurwedraai alkali granite is 2052 ± 14 Ma, which spans the range of 2038–2066 Ma at a 95% level of confidence.

Table 2
Summary of SHRIMP U–Pb data on zircons from the Schurwedraai alkali granite

Grain spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	(1) $^{206}Pb/^{238}U$ Age		(1) $^{207}Pb/^{206}Pb$ Age		% Discordant	(1) $^{207}Pb^*/^{206}Pb$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{207}Pb^*/^{238}U$	±%	Err corr
1.1	4.05	106	180	1.75	18.8	1163.9	±9.8	2066	±37	44	0.1277	2.1	3.484	2.3	0.1979	0.92	0.406
2.1	24.36	125	94	0.78	16.8	720.4	±8.1	2108	±110	66	0.1307	6.1	2.13	6.2	0.1182	1.2	0.192
2.2	35.01	119	85	0.74	26.7	1014	±15	2169	±160	53	0.135	9.2	3.18	9.4	0.1703	1.6	0.167
3.1	0.86	228	416	1.88	67.0	1879	±13	2042	±10	8	0.12590	0.58	5.873	0.96	0.3383	0.77	0.796
4.1	42.99	328	569	1.79	39.5	495.4	±6.1	1915	±190	74	0.117	11	1.29	11	0.0799	1.3	0.118
5.1	1.33	226	480	2.19	72.9	2028	±14	2048	±12	1	0.12639	0.69	6.444	1.0	0.3698	0.78	0.751
5.2	8.45	188	227	1.25	56.5	1790	±14	2045	±33	12	0.1261	1.9	5.57	2.1	0.3201	0.88	0.428
6.1	0.96	56	56	1.03	16.5	1875	±16	2057	±22	9	0.1270	1.2	5.912	1.6	0.3376	0.97	0.618
7.1	1.71	270	351	1.34	71.0	1694	±17	1978	±15	14	0.12148	0.82	5.033	1.4	0.3005	1.1	0.804
8.1	0.13	311	864	2.87	94.5	1948	±12	2040.9	±5.9	5	0.12586	0.33	6.122	0.80	0.3528	0.73	0.910
9.1	0.91	342	563	1.70	87.4	1667	±11	1977	±19	16	0.1214	1.1	4.941	1.3	0.2952	0.74	0.566
10.1	0.33	78	69	0.92	25.3	2065	±16	2058	±15	0	0.1271	0.87	6.618	1.3	0.3777	0.91	0.723
10.2	1.42	120	192	1.66	35.0	1865	±13	2032	±16	8	0.1253	0.93	5.795	1.2	0.3355	0.83	0.667
11.1	1.80	107	130	1.26	31.8	1891	±14	2043	±25	7	0.1260	1.4	5.921	1.6	0.3409	0.84	0.517
12.1	1.08	103	155	1.55	27.1	1703	±13	2038	±18	16	0.1257	10	5.237	1.3	0.3023	0.85	0.649
13.1	0.15	51	42	0.85	16.9	2082	±18	2060	±15	−1	0.1272	0.84	6.690	1.3	0.3813	1.0	0.772
14.1	1.20	101	103	1.06	23.1	1502	±11	2039	±19	26	0.1257	1.1	4.547	1.4	0.2623	0.86	0.620
16.1	0.89	113	117	1.07	36.4	2035	±15	2048	±18	1	0.1263	1.0	6.465	1.3	0.3711	0.86	0.639

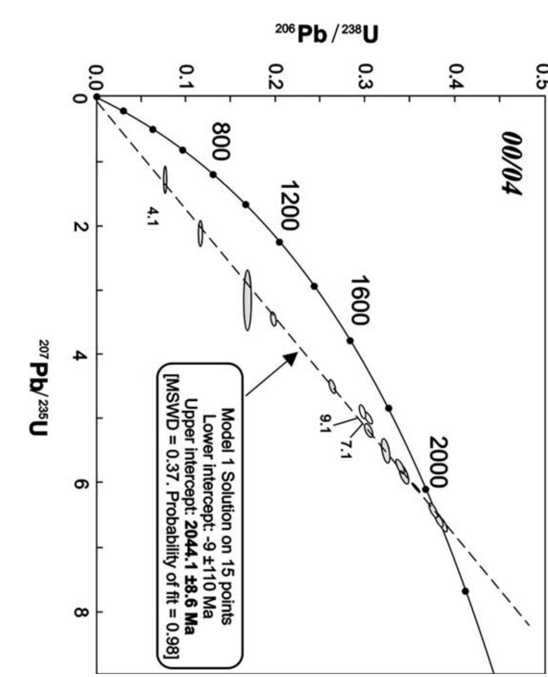

Fig. 6. Wetherill U–Pb concordia plot for all SHRIMP zircon analyses from the Schurwedraai alkali granite.

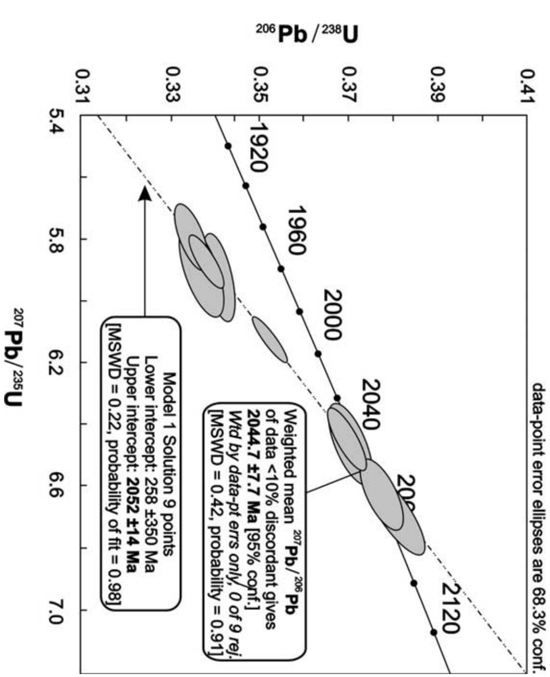

Fig. 7. Enlarged view of Wetherill U–Pb concordia plot showing the ages calculated from the least discordant data.

9. Discussion

9.1. Metamorphism

The pre-impact amphibolite-grade metamorphism of the collar rocks (Bisschoff, 1982; Gibson and Wallmach, 1995; Gibson and Reimold, 2001) has been a source of contention. Early workers (e.g. Hall and Molengraaff, 1925; Nel, 1927; Bisschoff, 1969, 1982, 1988; Schreyer, 1983; Stepto, 1990) invoked localized magmatic heat sources to produce hornfelsic rocks typical of the inner collar rocks. Gibson (1993) argued that these hornfelsic rocks have well preserved, though variably developed, foliation fabrics and hence cannot have been produced by a localized heat source.

Although there are many small mafic and felsic intrusions within the collar sequences of the Vredefort Dome, Gibson (op. cit.) argued that their volume is insufficient to explain the regional-scale metamorphism observed and that there is no geophysical evidence for a larger sub-surface magmatic body. Instead, he suggested that the metamorphism was simply part of a much larger regional metamorphic event. Gibson and Wallmach (1995) demonstrated that the amphibolite-grade metamorphism in the inner collar rocks followed an anti-clockwise P-T path, consistent with syn-metamorphic thickening of the overlying sequences during metamorphism. They argued that the peak geothermal gradient within the region during this metamorphic event was 40–50 °C/km, and the peak pressure 0.4–0.45 GPa. They proposed that this metamorphism was not consistent with a diapiric model which should involve decompression during heating, and instead was related to regional-scale metamorphism associated with the Bushveld magmatic event. Gibson and Stevens (1998) echoed this finding.

The indicated crystallization age of 2052 ± 14 Ma shows that the Schurwedraai alkali granite was emplaced approximately 30 Ma before the Vredefort impact event, dated at 2023 ± 4 Ma (Kamo et al., 1996), and well within the age bracket 2.05 to 2.06 Ga of the Bushveld magmatic event (Rustenburg Layered Suite, 2054.4 ± 2.8 Ma: Armstrong, unpublished; Lebowa Granite Suite, 2054 ± 2 Ma: Walraven and Hattingh, 1993; Rooiberg Group, 2061 ± 2 Ma: Walraven, 1997; Phalaborwa Carbonatite Complex, 2060.6 ± 0.5 Ma: Reischmann, 1995; Marble Hall sills, 2055.6 ± 3.1 Ma: De Waal and Armstrong, 2000; Uitkomst Complex, 2044 ± 8 Ma: De Waal et al., 2001). In addition, field evidence and geochemistry (Elsenbroek, 1991; Bisschoff, 1988) suggest that alkali granite at Schurwedraai and Baviaanskranz as well as that in the Rietfontein Complex are co-eval and comagmatic. Furthermore, recent SHRIMP dating and supporting geochemical studies (De Waal, data to be published elsewhere) also confirms that the Lindequesdrift and Heidelberg Intrusions and the Roodekraal Complex are temporally connected to the Bushveld magmatic event. All this information attests to a major intrusive/extrusive event in the Vredefort Dome region at about 2.05–2.06 Ga. Although these bodies individually are small (km-sized), their combined thermal effect added to that of numerous Bushveld-related sills and dykes of tholeiitic affinity (Bisschoff, 1972a,b, 1999; Nel, 1927) must have been considerable. We propose that these intrusions are, at least in part, responsible for the high geothermal gradient noted by Gibson and Wallmach (1995) and the resultant amphibolite-grade metamorphism of the inner collar rocks of the Vredefort Dome.

9.2. Implications for the extent of the Bushveld magmatic event

In this paper we have now pointed to the existence, in the Vredefort Dome area, of several igneous bodies (e.g. Schurwedraai, Lindequesdrift, Roodekraal) with SHRIMP zircon ages equivalent to that of the Bushveld magmatic event. This finding conclusively expands the southern extremity of the Bushveld magmatism beyond the locality of the Losberg Intrusion and as far south as the Vredefort Dome. It also explains the observations of Allsopp et al. (1991) of a well-defined $^{40}Ar/^{39}Ar$ plateau age of 2054 ± 11 Ma for biotite grains within the Archaean basement of the Vredefort Dome, which they attributed to argon loss caused by heating related to either the Bushveld or to the Vredefort event. With the current improved geochronological constraints, the plateau age of 2054 ± 11 Ma can now safely be interpreted as representing thermal resetting due to the Bushveld magmatic event. Also, the finding of Gibson et al. (2000) that most of the apparent $^{40}Ar/^{39}Ar$ ages of biotite and sericitic mica grains from the Witwatersrand Supergroup fell between 2100 and 1900 Ma, with a peak at 2060 Ma, most probably largely reflect the effects of the Bushveld magmatic event.

9.3. Summary

By way of summary we list, in reversed chronological order, the major geological events in the Vredefort Dome area:

10. Intrusion of Karoo-age dolerite at 180 Ma (e.g. Allsopp et al., 1984).
9. Intrusion of the Anna's Rust Sheet and related gabbroic intrusions at 1.05 Ga (Reimold et al., 2000).
8. Vredefort impact event at 2.023 Ma (Kamo et al., 1996) with resultant shock and transient thermal metamorphism (Gibson et al., 1997, 1998; Gibson, 2002), and development of granophyric impact melt (French and Nielsen, 1990; Koeberl et al., 1996).
7. Intrusion of the alkali granite and Bushveld-related ultramafic-mafic intrusions within the, then buried, sub-horizontal collar sequence of the Vredefort Dome, and widespread metamorphism of the Kaapvaal Craton at approximately 2055 Ma (this paper; Bisschoff, 1972a,b; De Waal and Armstrong, 2000; Allsopp et al., 1991; Gibson and Reimold, 1991 and references therein; Gibson, 2002; Hart et al., 2004 and references therein).
6. Folding and faulting of the entire sequence (by inference based on Elsenbroek, 1993; Cheney and Twist, 1991; and De Waal and Armstrong, 2000).
5. Deposition of the Transvaal Supergroup from 2.6–2.25 Ga (Armstrong et al., 1991; Walraven, 1997; Clendennin et al., 1988).
4. Eruption of the Ventersdorp flood basalts at 2.71 Ga (Armstrong et al., 1991).
3. Deposition of the Witwatersrand Supergroup from 2.98–2.71 Ga (Armstrong et al., 1991; Robb et al., 1990).
2. Deposition of the Dominion Group from 3.12–3.07 Ga (Armstrong et al., 1991).

1. Development of the granite-greenstone basement protolith at 3.5 Ga and metamorphic overprint at ~3.1 Ga (Hart et al., 2004; Kamo et al., 1996).

10. Conclusions

The zircon SHRIMP age of the Schurwedraai alkali granite (2052 ± 14 Ma) reported here, confirms that the intrusion is temporally unrelated to the Vredefort impact event, but instead forms part of the larger Bushveld magmatic event. The southern extremity of known Bushveld-related intrusions is thus extended as far south as the Vredefort Dome, some 120 km south of Johannesburg. We also show that numerous small, km-sized, intrusive and extrusive bodies (both mafic and felsic in composition) intruded the Vredefort Dome during the Bushveld magmatic event (2.05–2.06 Ga). These bodies are probably collectively, at least in part, responsible for the high geothermal gradient reported by Gibson and Wallmach (1995) for the Vredefort region at that time, as well as for the observed regional-scale pre-impact amphibolite-grade metamorphism within the collar rocks of the Vredefort Dome.

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