ECONOMIC GEOLOGY
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GEOCHRONOLOGY OF THE ROOIBERG GROUP, TRANSVAAL SUPERGROUP, SOUTH AFRICA

F. WALRAVEN

INFORMATION CIRCULAR No. 316

UNIVERSITY OF THE WITWATERSRAND
JOHANNESBURG

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by

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November, 1997

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ABSTRACT

Single-grain zircon Pb-evaporation age determinations have been made of acid volcanic rocks from the Rooiberg Group, Transvaal Supergroup, as well as the Rooikop Granite Porphyry, which forms extensive sills within the Rooiberg Group. Crystallisation ages of 2061±2 and 2060±2 Ma have been obtained for the Rooiberg Group and Rooikop Granite Porphyry respectively. Within the uncertainty limits, these ages are consistent with existing age determinations of the Rooikop Granite Porphyry and other rock units with known relationships to the Rooiberg Group. These results constitute the first precise age determinations for the uppermost part of the Transvaal Supergroup and define the completion of sedimentation and volcanism in the Transvaal basin. Together with existing age data for the base of the Transvaal Supergroup, the Rooiberg age also demonstrates the extreme longevity of the Transvaal sedimentary basin–close to 600 Ma. In addition, the new age data demonstrate that the Rooiberg volcanism, followed first by the emplacement of the basic layered rocks of the Bushveld Complex and finally by the intrusion of the Bushveld Complex granites, occurred in a time span of only 7 Ma. It is considered highly likely that the Rooiberg Group volcanism, together with that of the immediately preceding Dullstroom Formation, formed an integral part of the same major magmatic event which affected the Kaapvaal Craton at this time and caused the emplacement of the Bushveld Complex. It is proposed that this event was cyclic in nature and involved two basic to acid cycles. Of these the Dullstroom-Rooiberg volcanism represents the first cycle while the second cycle, which was plutonic instead of volcanic, is represented by the basic layered rocks and granites of the Bushveld Complex.

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Published by the Economic Geology Research Unit
Department of Geology
University of the Witwatersrand
1 Jan Smuts Avenue
Johannesburg 2001
South Africa

ISBN 1-86838-1978

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INTRODUCTION

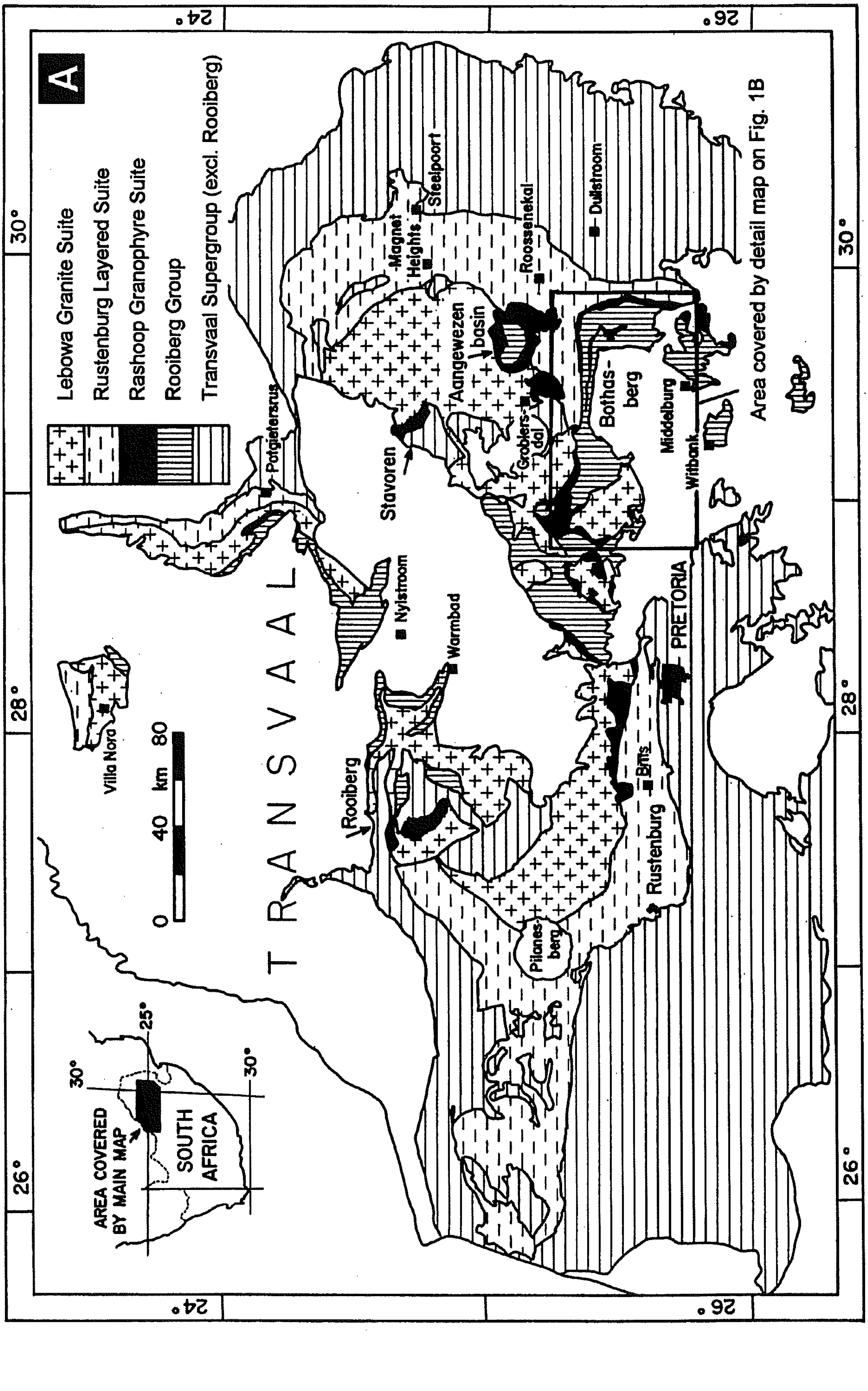
The Rooiberg Group is a thick succession of acid volcanic rocks which occurs throughout the Transvaal sedimentary basin (Fig. 1A) and forms the upper third of the Transvaal Supergroup (Eriksson *et al.*, 1993). The age of extrusion of the volcanic rocks has long been a point of interest because, apart from subordinate local sediments overlying the Rooiberg Group, the volcanic rocks define the last major event in the history of the Transvaal basin. Attempts in the past to date the volcanic rocks were limited to whole-rock techniques and, largely because of isotopic disturbance, have met with little success. Consequently, until now no precise, reliable age determinations were available for the Rooiberg Group.

It is known from field relationships that the Rooiberg Group precedes the Bushveld Complex. The latter is a major plutonic complex of basic layered rocks and granites, which intruded the Transvaal strata at a general level between the Rooiberg Group and the underlying Pretoria Group. This level has been considered by some authors to represent a palaeo-unconformity between the Pretoria and Rooiberg Groups (Cheney and Twist, 1991). In the south-eastern Transvaal basin, the Rooiberg Group was also directly underlain by volcanic rocks of the Dullstroom Formation prior to the emplacement of the Bushveld Complex. Possible genetic relationships have been considered between the three units (e.g. Twist and French, 1984; Harmer and von Gruenewaldt, 1991). While the age of the Bushveld Complex is well-established (Walraven *et al.*, 1990; Walraven and Hattingh, 1993; Table 1), the lack of reliable age data for the Rooiberg Group, or the Dullstroom Formation, impedes the evaluation of genetic relationships between the volcanic units and the Bushveld Complex.

In an attempt to address these problems, single-grain zircon Pb-evaporation age determination was undertaken of two samples of rhyolite from the Selons River Formation of the Rooiberg Group, in the east-central part of the Transvaal basin. Additionally, Pb-evaporation analyses have also been made of zircons from the Rooikop Granite Porphyry. This intrusive rock, for which an earlier U-Pb bulk zircon age determination of 2066±10 Ma is available (Faurie, 1977; Table 1), forms extensive sills within the Rooiberg Group in the Loskop Dam area, in the eastern part of the Transvaal basin. The results of these age determinations are presented in this paper together with their implications for the chronostratigraphy of the Transvaal basin and possible genetic relationships between the Bushveld Complex, Rooiberg Group and Dullstroom Formation.

GEOLOGICAL BACKGROUND

A geological sketchmap is shown in Fig. 1A illustrating the distribution of the Rooiberg Group in relation to the Bushveld Complex and other parts of the Transvaal Supergroup in the Transvaal.


A
Lebowa Granite Suite
Rustenburg Layered Suite
Rashoop Granophyre Suite
Rooiberg Group
Transvaal Supergroup (excl. Rooiberg)
Area covered by detail map on Fig. 1B
TRANSVAAL
0 40 km 80
AREA COVERED BY MAIN MAP
SOUTH AFRICA
Villa Nora
Rooiberg
Warmbad
Nylstroom
Potgietersrus
Stavoren
Aangewezen basin
Magnet Heights
Steelpoort
Roossenekal
Dullstroom
Groblersdal
Bothasberg
Middelburg
Witbank
PRETORIA
Brits
Rustenburg
Pilanesberg
24°
26°
28°
30°
25°

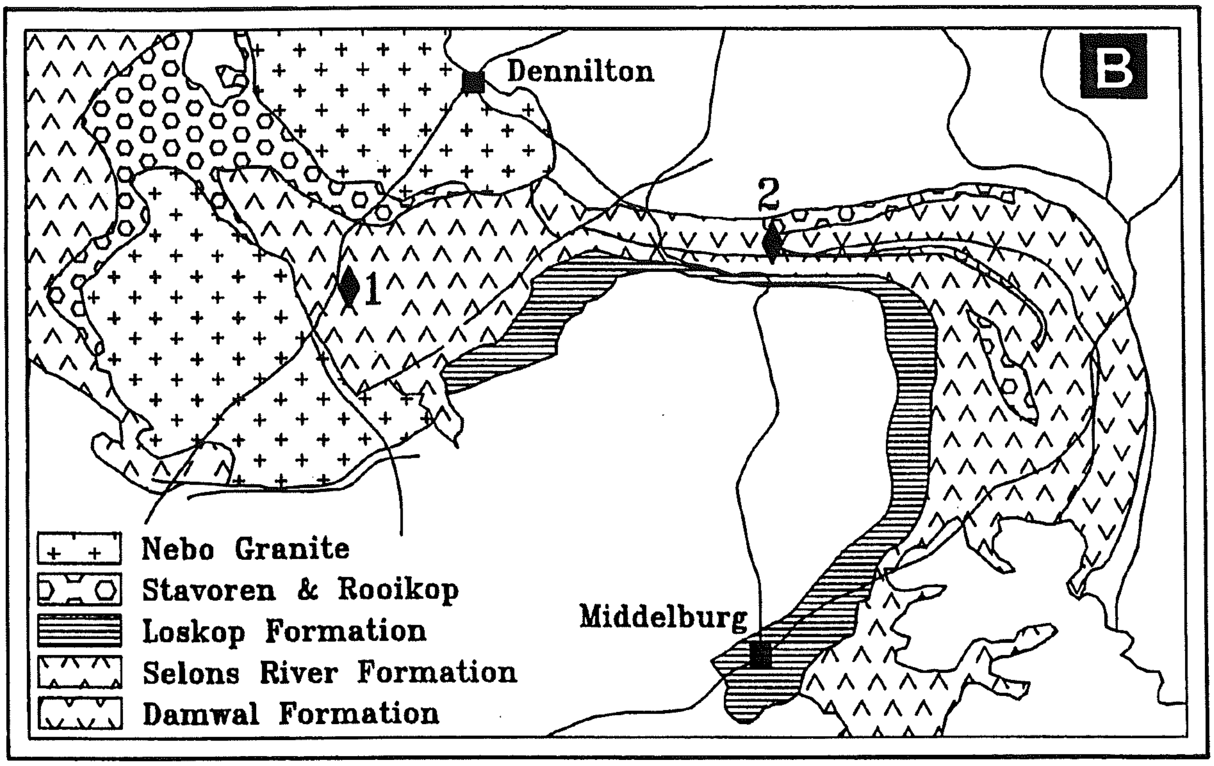


Figure 1 (previous page and above). A. Geological sketch map of the Transvaal basin showing the distribution of the Rooiberg Group and the main components of the Bushveld Complex. B. Detailed map showing the location of the samples analysed in this study.

Stratigraphy

The South African Committee for Stratigraphy (SACS) has divided the Transvaal Supergroup into three groups: the Chuniespoort, Pretoria and Rooiberg Groups (Fig. 2), which consist of chemical sediments, clastic sediments and volcanics rocks, respectively. The very base of the Transvaal Supergroup is formed by the Black Reef Formation, a basin-wide arenite unit which stands apart from the Chuniespoort Group. A number of sedimentary units of restricted extent and thickness overlie the Rooiberg Group. These include the Loskop, Rust de Winter and Glentig Formations. Underlying the Transvaal Supergroup in various parts of the basin, are protobasinal successions such as the Godwan Formation, Wolkberg, Groblersdal and Buffelsfontein Groups (Fig. 2).

The Rooiberg Group varies from rhyodacitic at the base to rhyolitic at the top. Two formations are recognised in the eastern and central Transvaal basin; they are the lower, rhyodacitic Damwal Formation and the upper, rhyolitic Selons River Formation. The Damwal Formation is confined to the south-eastern part of the Transvaal basin. In the central and eastern parts of the Transvaal basin the Selons River Formation has been subdivided into two members: the lower Doornkloof Member and the upper Klipnek Member. A persistent fine-grained sedimentary unit marks the base of the Klipnek Member while the top of the Doornkloof Member consists of black rhyolite, amygdaloidal and porphyritic volcanics and local pyroclastic rocks. The Selons River Formation extends basin-wide but in the western part of the basin, in the Rooiberg area, the two members have been given formation status and are called the

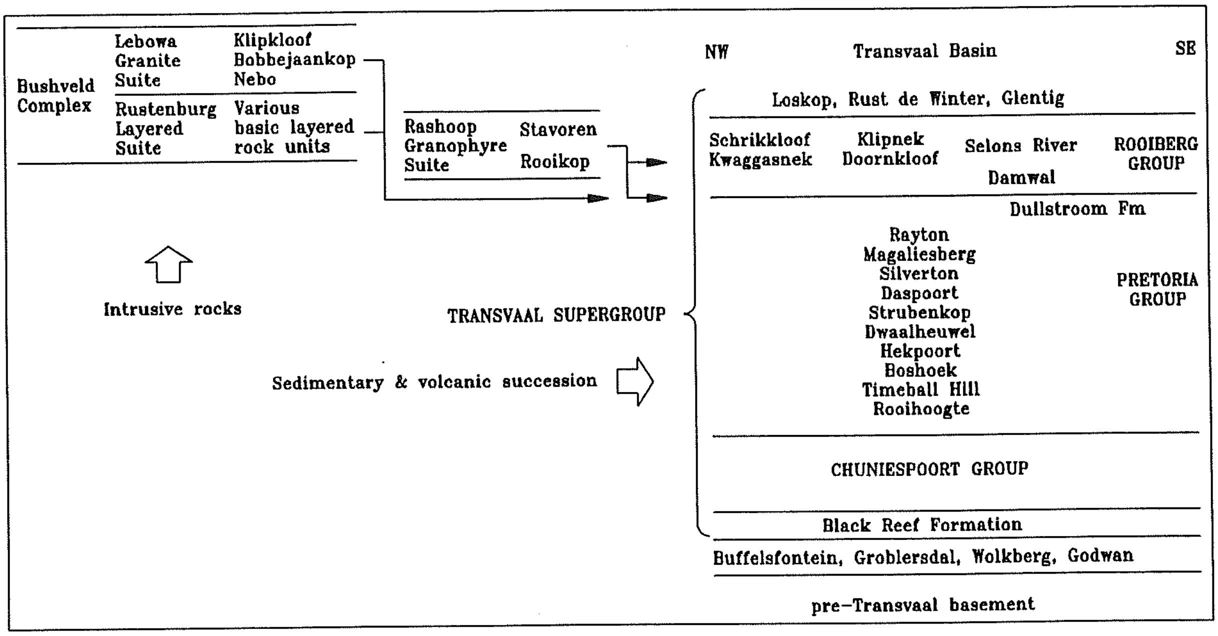


Figure 2. Schematic profile illustrating the stratigraphy of the Transvaal Supergroup and the intrusive relationships with the Bushveld Complex.

Kwaggasnek (lower) and Schrikkloof Formations (upper) (SACS, 1980; Eriksson *et al.*, 1993).

From the points of view of volcanic activity, the Rooiberg Group is the final and largest volcanic episode in the development of the Transvaal basin and it ranks among the world's largest accumulations of siliceous volcanic rocks (Twist and French, 1984). Basic and acid volcanic eruptions are also interspersed in the chemical and clastic sedimentation at various stages throughout the history of the basin, starting with the protobasins (Figs. 2 and 3). Within the Wolkberg Group these are the basalts of the Abel Erasmus Formation; the Godwan Formation contains basaltic lava flows; acid and basic volcanic units form part of the Buffelsfontein Group and the Groblersdal Group includes acid and intermediate volcanic rocks. The Serala Member is a thin basalt unit within the Black Reef Formation (SACS, 1980) although Bosch *et al.* (1993) confine the Black Reef Formation to the quartzite overlying the Serala Member and groups the latter and underlying quartzite with the Wolkberg Group.

Prominent, basin-wide volcanics form the Hekpoort Andesite Formation which is correlated with the Ongeluk Formation in the Griqualand West basin (Sharpe *et al.*, 1983; Walraven *et al.*, 1990). The Machadodorp Member of the Silverton Formation is a largely pyroclastic unit confined to the eastern Transvaal basin. At the top of the Pretoria Group, the Dullstroom Formation is a bimodal volcanic unit of alternating acid and basic volcanics (Schweitzer, 1984). In pre-Bushveld reconstructions the Dullstroom Formation immediately underlies the Rooiberg Group and combination of the two units into one magmatic event seems logical and has in fact been implied in various studies (e.g. Schweitzer, 1984; Harmer and von Gruenewaldt, 1991).

SACS (1980) subdivided the Bushveld Complex into three suites: the Rustenburg Layered Suite, Lebowa Granite Suite and Rashoop Granophyre Suite. These represent the basic layered rocks, granites and granophyres of the complex respectively. The SACS classification

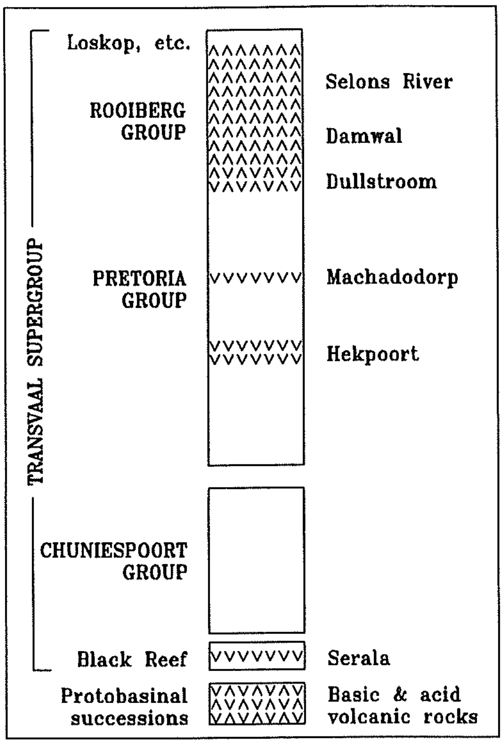


Figure 3. Schematic section illustrating the main occurrences of volcanic strata within the Transvaal Supergroup.

is a purely lithostratigraphic one, however, and not all of the components of the Rashoop Granophyre Suite genetically form a part of the Bushveld Complex. Walraven (1985) interpreted the bulk of the granophyric rocks (Stavoren Granophyre) as resulting from shallow intrusion of acid magmas immediately following, and forming a plutonic extension of, the Rooiberg volcanic event. Other granophyre types are closely linked to the Bushveld granites and basic layered rocks and were formed by metamorphism of Rooiberg Group volcanics (Von Gruenewaldt, 1972) or Pretoria Group sediments (Strauss, 1943) or by differentiation and assimilation of acid material by the basic layered rocks (Diepkloof Granophyre; Walraven, 1985).

The Bushveld Complex has demonstrably intrusive relationships with the Transvaal basin fill (Fig. 2). The general sequence of events, based on the field relationships, is as follows: after deposition of the Pretoria Group sediments (and its various volcanic intercalations) voluminous volcanism produced the Dullstroom Formation and the Rooiberg Group. Initially this volcanism was bimodal and areally restricted to the south-eastern Transvaal basin (the Dullstroom Formation) but soon became acid and, after extrusion of the Damwal Formation, extended across the entire Transvaal basin. The Rashoop Suite granophyre, largely situated at the base of the volcanic succession, was emplaced towards the end, or immediately after, the Rooiberg volcanism. The Rooikop Granite Porphyry probably intruded at this stage as well. This was followed by the emplacement of the basic layered rocks of the Bushveld Complex (the Rustenburg Layered Suite) and subsequently, the intrusion of the Bushveld granites (Lebowa Granite Suite). Locally transgressive relationships bring Bushveld granites into contact with the Selons River Formation in the central Transvaal basin and in the area north-west of Potgietersrus.

Geochronology

Although the lithostratigraphy of the Transvaal basin is well established, comparatively little chronostratigraphic information is available. Recent studies have demonstrated that the base of the Transvaal Supergroup is significantly older than was previously considered (Walraven, 1994; Walraven and Martini, in press; Walraven *et al.*, in press). On the basis of geochemical and field evidence the upper part of the Transvaal Supergroup, in particular the volcanic rocks of the Dullstroom Formation and the Rooiberg Group, is considered to be close to the Bushveld Complex in age, i..e. only slightly older than ca 2060 Ma (Schweitzer, 1984; 1986; Walraven *et al.*, 1990). However, until now no precise and reliable age determinations were available for this part of the succession. In addition to the poor chronostratigraphic control, this lack of information also hampered interpretations of the genesis of the Rooiberg Group and its possible relationships to the Bushveld Complex.

Those geochronological data that are available for the Rooiberg Group are listed on Table 1 together with the age data for rock units relevant to the age of the Rooiberg Group. Those ages directly relevant to the Rooiberg Group are schematically illustrated on Fig. 4. The whole-rock isotope systems (both Rb-Sr and Pb-Pb) of the acid volcanic rocks have been severely affected by open-system behaviour, among other reasons due to the emplacement of the Bushveld Complex, and dates that are up to 500 Ma younger than the 2066 Ma minimum (see below) have been obtained from such determinations (Walraven, 1987). Up to now, the oldest date reported for the Rooiberg Group is the 2030±50 Ma Rb-Sr whole-rock age reported by Burger and Coertze (1975) for Rooiberg Group samples from the vicinity of Loskop Dam. Unfortunately these authors provide no analytical data to recalculate their results, so that direct comparisons of their age and uncertainties are not possible. Burger and Coertze (1975) suggested that their samples may have undergone resetting during the emplacement of the Bushveld Complex and reflect a Bushveld age. More recently Farrow (1988) reported a 2018+58/-60 Ma Pb-Pb whole-rock isochron for the Rooiberg Group.

A minimum age for the Rooiberg Group can be inferred from the age data available for demonstrably post-Rooiberg rock units. These include the Bushveld Complex, the Rooikop Granite Porphyry and the Rust de Winter Formation, central Transvaal basin. Walraven *et al.* (1990) proposed 2061±27 Ma as the preferred age of the basic layered rocks of the complex; this date is based on numerous Rb-Sr determinations of Upper Zone magnetite gabbro from various sources. Walraven and Hattingh (1993) reported a single-grain zircon Pb-evaporation age of 2054±2 Ma for the Nebo Granite, the main component of the granitic part of the Bushveld Complex.

Open-system behaviour has also been found on a whole-rock scale in the Stavoren Granophyre and the only reliable indication of its age is available from U-Pb zircon data. Coertze *et al.* (1978) reported a U-Pb bulk zircon age for the Stavoren Granophyre from the eastern Bushveld Complex: 2053±12 Ma. An age of the same order of magnitude was found by Faurie (1977) but this author also obtained a large degree of scatter in his data and did not report an exact age.

Table 1. Age determinations relevant to the Transvaal Supergroup and the Bushveld Complex

Rock Unit	Age (Ma)	Ro	MSWD	No	I/E	Method	Material	Reference	Comment
Bushveld Complex and post-Transvaal intrusives									
Nebo Granite, Lebowa Granite Suite	2054±2					Pb-Pb	single zircon	Walraven and Hattingh (1993)	
Upper Zone, Rustenburg Layered Suite	2061±27	0.70731±0.00004	1.36	33	I	Rb-Sr	whole rock	Walraven *et al.* (1990)	
Stavoren Granophyre, Rashoop Granophyre Suite	2053±12					U-Pb	bulk zircon	Coertze *et al.* (1978)	
Rooikop Granite Porphyry	2066±10		1.57	8	I	U-Pb	bulk zircon	Faurie (1977)	Intrudes Damwal Fm
Rooikop Granite Porphyry	2060±2					Pb-Pb	single zircon	This work	
Transvaal Supergroup									
Rhyolite intercalation, Rust de Winter Formation	2060					U-Pb	bulk zircon	Walraven (1981)	Estimated age only
Rhyolite, Rooiberg Group	2030±50					Rb-Sr	whole rock	Burger and Coertze (1973)	No analytical data
Rhyolite, Selons River Formation, Rooiberg Group	2061±2					Pb-Pb	single zircon	This work	
Rhyolite and rhyodacite, Rooiberg Group	1605±28	0.732	3.75	12	E	Rb-Sr	whole rock	Walraven (1987)	Reset age
Rhyolite and rhyodacite, Rooiberg Group	2003+289/-360	10.2+0.7/-0.8	9.43	12	E	Pb-Pb	whole rock	Walraven (unpublished data)	Same samples as above
Rooiberg Group	2018+58/-60	10.5±0.1	0.77	8	I	Pb-Pb	whole rock	Farrow (1988)	
Dullstroom Basalt Formation	2234±443	0.7052±0.0035	15.78	9	E	Rb-Sr	whole rock	Walraven (1987)	
Dullstroom Basalt Formation	2101±28					Various	whole rock	Schweitzer (1986)	
Hekpoort Andesite Formation	2224±21					Rb-Sr	whole rock	Burger and Coertze (1973)	
Timeball Hill Formation, Pretoria Group	2208±63	0.704±0.003	8.42	10	E	Rb-Sr	whole rock	Hunter and Hamilton (1978)	
Oak Tree Formation, Chuniespoort Group	2550±3		6.48	32		Pb-Pb	single zircon	Walraven and Martini (in press)	
Abel Erasmus Formation, Wolkberg Group	2138+46/-47	8	1.34	6	I	Pb-Pb	whole rock	Armstrong (1987)	
Godwan Formation	2325+69/-73	9.1	0.85	9	I	Pb-Pb	whole rock	Armstrong (1987)	

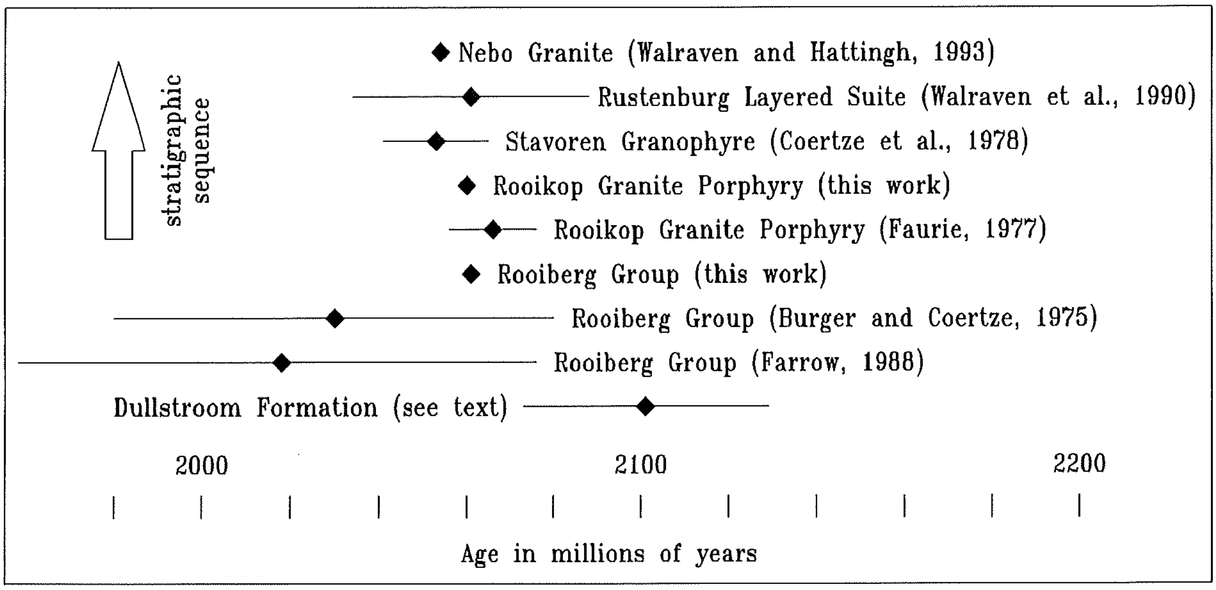


Figure 4. Diagrammatic illustration of the age relationships of the Dullstroom Formation, Rooiberg Group and Bushveld Complex based on the available geochronological information. The uncertainty limits of the age determinations are shown as horizontal lines (in some cases obscured by the markers).

Within the uncertainty limits of the determinations, these ages are indistinguishable from the U-Pb bulk zircon age of 2066±10 Ma reported by Faurie (1977) for the Rooikop Granite Porphyry. These ages are also of the same order as the 2060 Ma U-Pb bulk zircon $^{207}Pb/^{206}Pb$ ratio age estimate reported by Walraven (1981) for rhyolite intercalated in the Rust de Winter Formation. All of these data are mutually consistent and support a credible minimum age limit of 2066±10 Ma for the Rooiberg Group volcanism.

A similarly well-defined maximum age limit is lacking for the Rooiberg Group. The Dullstroom Formation immediately underlies the Rooiberg Group and its age should provided an upper age limit for the Rooiberg volcanism. However, although age determinations have been carried out on the Dullstroom volcanics, no definitive results have yet emerged. Walraven (1987) reported a Rb-Sr whole-rock errorchron of 2234±442 Ma which, because of its very large uncertainty provides no usable age information. J. Schweitzer (personal communication) undertook Rb-Sr and Pb-Pb whole-rock age determinations on the Dullstroom Formation and obtained dates ranging from 1871±176 Ma to 2186±234 Ma. Schweitzer (1986) proposed 2101±28 Ma as a reliable age for the Dullstroom extrusive event. Although probably of the correct order-of-magnitude, this date is based on the combination of basaltic andesite and rhyolite in the regression calculation. Since these rocks are likely to have had different initial isotopic compositions, this date is problematic and cannot be used to obtained an unequivocal age of extrusion for the Dullstroom volcanics.

The Hekpoort Andesite Formation is the next closest stratigraphic unit underlying the Rooiberg Group for which age data are available, but this unit is separated from the Rooiberg Group by some 2.2 km of intervening clastic sediments in the central Transvaal basin and even more in the eastern Transvaal (Eriksson *et al.*, 1993). A Rb-Sr isochron age of 2224±21 Ma was reported for the Hekpoort Formation by Burger and Coertze (1975). Although this age is within the uncertainty limits of a Pb-Pb whole-rock isochron of 2238+87/-92 Ma (Armstrong,

1987) for the Ongeluk Formation (a correlate of the Hekpoort Formation in the Griqualand West basin), additional geochronological data is required before the 2224±21 Ma can be accepted as reliable. It is clear that the Hekpoort age does not constitute an effective maximum age limit for the Rooiberg Group.

ISOTOPIC DATA

Single-grain zircon Pb-evaporation age determinations have been carried out on samples collected from the Rooiberg Group and the Rooikop Granite Porphyry. The location of the samples are indicated on Fig. 1B. The analytical techniques and the interpretation of Pb-evaporation data have been discussed in detail elsewhere (Kober, 1986, 1987; Grobler and Walraven, 1993) and will not be repeated here. It should be noted, however, that the analytical uncertainties of the ages and the $^{207}Pb/^{206}Pb$ ratios are quoted at the 95% confidence level.

Material Analysed

Two samples of agglomeratic rhyolite (samples FW94 012 and FW94 013) were collected for age determination from the uppermost part of the Doornkloof Member of the Selons River Formation in the central Transvaal basin. In this area the Nebo Granite of the Bushveld Complex has discordantly intruded the underlying Stavoren Granophyre and Rooiberg Group to within an estimated 500 m from the sample locality. A single population of zircons was recovered from sample FW94 012, with individual grains ranging in length from 50 to about 250 µm. The zircons are very clear, pale pink and devoid of internal structure such as multiple

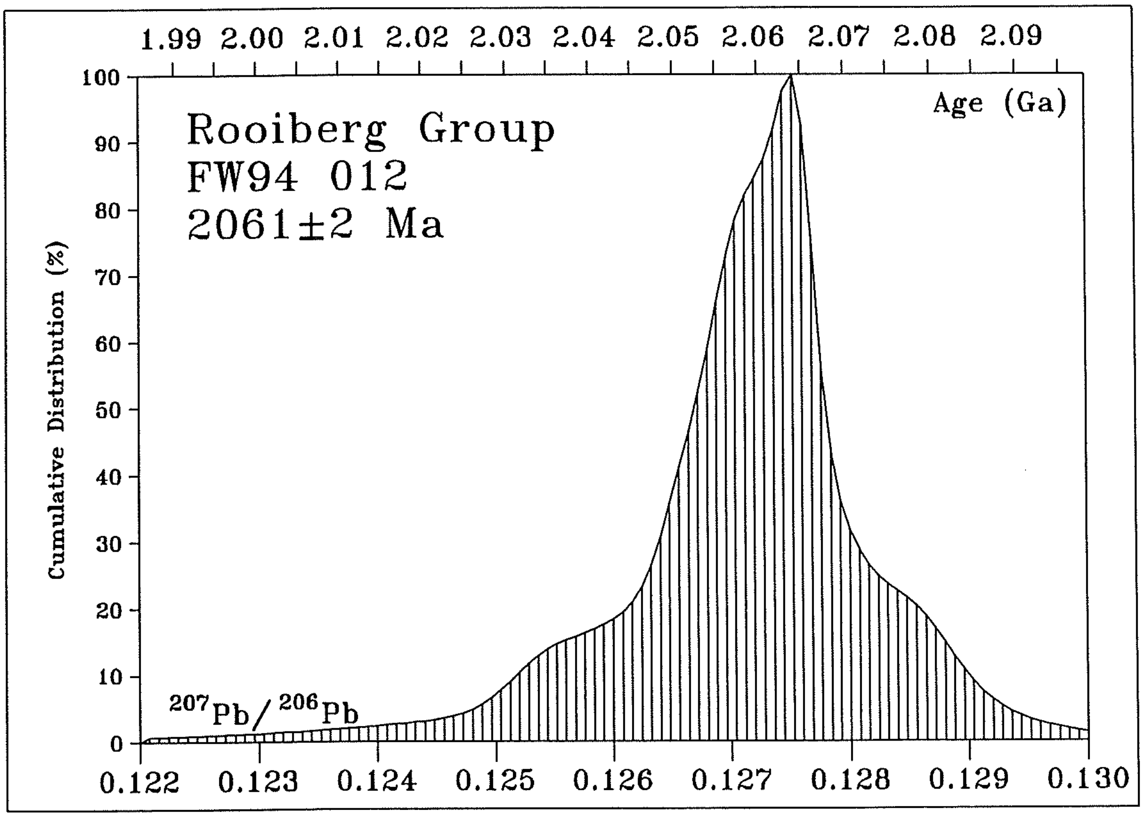


Figure 5. Cumulative distribution plot of $^{207}Pb/^{206}Pb$ ratios and corresponding ages for Rooiberg Group rhyolite sample FW94 012.

growth zoning or overgrowths. A few needle-shaped inclusions and small fluid or gas bubbles are present in some of the grains. The zircons have simple morphologies; they are euhedral with slightly frosted surfaces and consist primarily of first-order prism and pyramid faces accompanied by second-order {1,1,1} faces in many grains. The grains selected for analysis ranged from 200 to 250 μm in length.

Multiple populations of zircons were recovered from sample FW94 013. These include a homogeneous population of grains which, although in many respects similar to, are slightly smaller (less than 200 μm in length) and contain more inclusions and bubbles than the zircons from sample FW94 012. Some of the grains are very slightly cloudy also. Simple crystal shapes again predominate–prism and pyramid faces–but some grains display small, high-order facets. The zircons are euhedral and display no internal structure. This population is considered to be primary magmatic in origin and to have crystallised from the volcanic magma. Grains selected from this population for analysis were mostly about 150 μm in length. The other zircons separated from sample FW94 013 are heterogeneous and include many rounded, dark-coloured grains. These zircons are taken to be xenocrystic in origin and none were selected for analysis.

The sample of Rooikop Granite Porphyry (FW94 014) was collected from the Loskop Dam area, from the same locality used by Faurie (1977) for his age determination of this unit. A bimodal population of zircons was recovered from this sample with the majority of the zircons forming one population varying only in terms of the grain size which reaches a maximum of about 250 μm in length. The grains are extremely clear, colourless and contain a small number of needle-like inclusions and some fluid or gas bubbles. No internal structure is visible and the grains are euhedral and made up of first-order prism and pyramid faces only. Grains were primarily selected for analysis from this population. Some clear pale brown zircon grains form

Table 2. Summary of Pb-evaporation data from the Rooiberg Group and Rooikop Granite Porphyry

Sample	Zircon grain	Temperature (°C)	$^{207}Pb/^{206}Pb$	Age(Ma)	MSWD	#
Selons River Formation, Rooiberg Group						
FW94 012	All	1425-1480	0.12728±0.00005	2060.8±2.5	3.36	37
FW94 013	1	1445	0.12697±0.00004	2056.5±1.2	0.68	16
	2	1445-1480	0.12693±0.00009	2055.9±3.0	0.55	5
	1 & 2	1445-1480	0.12697±0.00003	2056.4±1.1	0.66	21
	3	1445	0.12620±0.00016	2045.7±5.0	2.75	10
	4	1445-1480	0.12734±0.00014	2061.1±4.4	2.17	12
	5	1445	0.12735±0.00011	2061.7±4.3	0.82	5
	6	1445-1480	0.12716±0.00024	2059.1+9.4/-9.5	1.23	5
	4-6	1445-1480	0.12733±0.00009	2061.4±2.5	1.67	22
Rooikop Granite Porphyry						
FW94 014	1	1445-1480	0.12727±0.00004	2060.6±3.4	0.082	3
	2	1445-1480	0.12729±0.00012	2060.9±3.4	1.63	16
	3	1445-1480	0.12721±0.00013	2059.8±4.0	1.98	11
	1-3	1445-1480	0.12725±0.00007	2060.4±2.0	1.61	30
	4	1445-1480	0.12595±0.00017	2042.2±5.3	2.25	14
	6	1445-1480	0.12565±0.00008	2038.0±6.1	0.11	5

NOTE: detailed analytical data are to be found in Appendix 1.

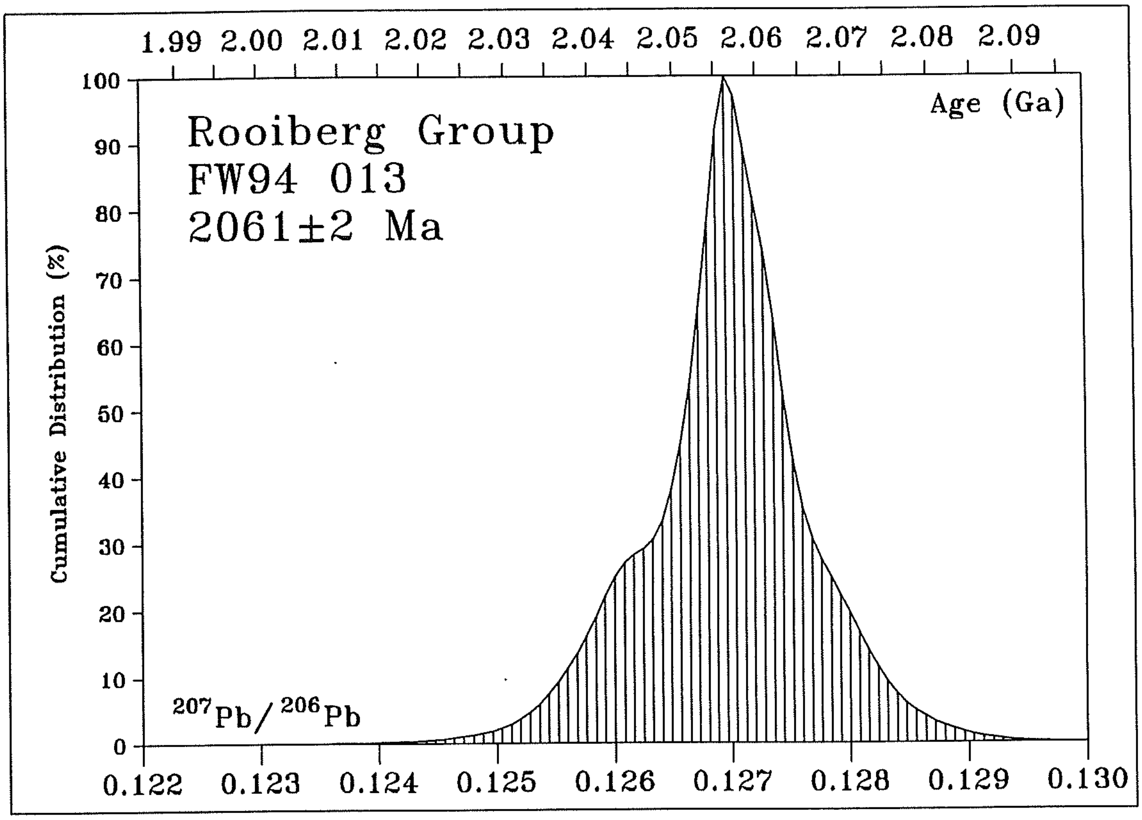


Figure 6. Cumulative distribution plot of $^{207}Pb/^{206}Pb$ ratios and corresponding ages for Rooiberg Group rhyolite sample FW94 013.

a second population in sample FW94 014. In addition to their brown colour, these grains contain fewer inclusions than the grains from the first population. One grain from the pale brown population was included for analysis.

Analytical Results

Table 2 presents a summary of the age data obtained during this study.

Rooiberg Group–Sample FW94 012. Six zircon grains were analysed from sample FW94 012. Homogeneous Pb-isotopic compositions were found in all six of the grains, both at different temperatures within the grains as well as between different grains (Table 2). The weighted mean $^{207}Pb/^{206}Pb$ ratio for all the data from sample FW94 012 is 0.12728±0.00009, which corresponds to a date of 2061±2 Ma (Fig. 5). The limited spread of isotopic compositions between the analysed grains is interpreted to reflect concordancy of the analysed grains or, if Pb-loss did occur, this took place during geologically recent times. In either case the data have age significance and the 2061±2 Ma date can be interpreted as the crystallisation age of the zircons. Because the zircons form the only population recovered from sample FW94 012, it is further concluded that the zircons crystallised from the rhyolite melt and that their age represents the age of extrusion of the rhyolite.

Rooiberg Group–Sample FW94 013. The six zircon grains selected for analysis from the clear, homogeneous population, although each internally of homogeneous Pb-isotopic composition, yielded Pb with different isotopic ratios between grains. Fig. 6 illustrates the data obtained from all the grains analysed. Three of the six grains (nos 4, 5 and 6) contained Pb with compositions indistinguishable from each other and very similar to that of the FW94 012 zircons. The weighted mean $^{207}Pb/^{206}Pb$ ratio of the three grains is 0.12733±0.00009 and corresponds to a date of 2061±2 Ma. Pb from grains 1 and 2 had slightly lower $^{207}Pb/^{206}Pb$ ratios averaging 0.12697±0.00003 (corresponding to a date of 2056±1 Ma). Grain 3 released Pb with still lower isotopic ratios (0.12620±0.00016) indicating a date of 2046±5 Ma (Table 2).

Because of their internal agreement as well as the close resemblance between their weighted mean date and the age of sample FW94 012, grains 4, 5 and 6 of sample FW94 013 are also considered to be concordant or to have lost Pb during geologically recent times only. Small but varying degrees of Pb-loss have affected the other zircon grains from this sample at some stage in the geological past. Although the emplacement of the Bushveld Complex could be considered as a possible cause of the open-system behaviour, this is not completely consistent with the somewhat lower date indicated by grains 3 (2046±5 Ma compared to the 2054±2 Ma age of the Nebo Granite).

Rooikop Granite Porphyry–Sample FW94 014. The Pb-isotopic ratios obtained from the zircons analysed from the Rooikop Granite Porphyry are shown in Fig. 7. Three of the five population one grains from the Rooikop Granite Porphyry released Pb of homogeneous isotopic composition at all temperature ranges (Table 2). The weighted mean $^{207}Pb/^{206}Pb$ ratio of these three grains is 0.12725±0.00005 which corresponds to a date of 2060±2 Ma. Although internally homogeneous, Pb with slightly lower isotopic ratios was obtained from grain 4 (0.12595±0.00017; 2042±5 Ma) and from grains 6 (0.12565±0.00008; 2034±6 Ma). The

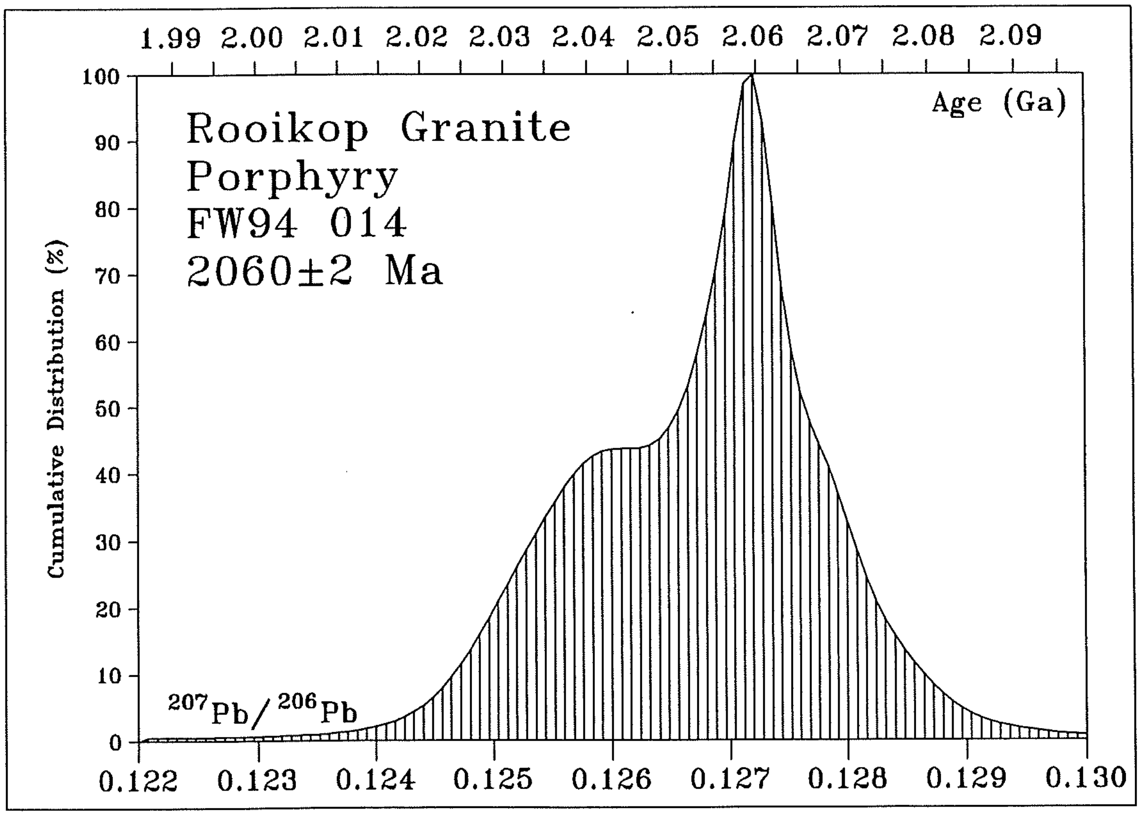


Figure 7. Cumulative distribution plot of $^{207}Pb/^{206}Pb$ ratios and corresponding ages for Rooikop Granite Porphyry sample FW94 014.

amount of Pb released by grain 5, the pale brown population two grain, was insufficient to yield useable analytical data.

Because of the agreement between the data from grains 1, 2 and 3, these are considered to be concordant or to have lost Pb only during geologically recent times. Their dates are therefore considered to represent the crystallisation age of the zircons. The lower dates indicated by grains 4 and 6 are interpreted to be a result of Pb loss at some stage in the geological past. As in the case of the Rooiberg Group (sample FW94 013), the Bushveld Complex is probably not the sole cause of the open-system behaviour.

DISCUSSION

The new Rooiberg Group data provide, for the first time, a reliable chronostratigraphic marker in the upper part of the Transvaal succession, enabling improved estimates to be made of sediment and rock accumulation rates in the Transvaal basin. Although an age close to that of the Bushveld Complex was previously considered for the Rooiberg Group (Walraven *et al.*, 1990), this was based on genetic considerations and lacked reliable geochronological support. Such support has now been found and as a result the Rooiberg Group, and the upper part of the Transvaal Supergroup, can be firmly placed at 2061±2 Ma. Accepting the age of the Black Reef Formation at the base of the succession to be similar to that found for the Vryburg Formation, its correlate in the Griqualand West basin (dated at 2643±2 Ma, Walraven *et al.*, in press), this means that the total life span of the Transvaal basin is close to 600 Ma.

Apart from their chronostratigraphic significance, the single most striking aspect of the results obtained in this study is the similarity of the ages found for the Rooiberg Group and the Rooikop Granite Porphyry. This means that the Rooikop Granite Porphyry was intruded almost immediately after, or even contemporaneous with the later stages of, the extrusion of the Rooiberg Group. The age data therefore support a model in which the Rooikop Granite Porphyry represents a shallow, intrusive phase of the Rooiberg magmatism which occurred after the major part of the volcanic pile had accumulated. This mode of origin is identical to that which has been proposed for the Stavoren Granophyre (Walraven, 1987) and it is therefore suggested that the Stavoren Granophyre and the Rooikop Granite Porphyry were formed in very similar manners and are both related to the Rooiberg magmatic event.

Good agreement (within analytical uncertainty) exists between the age found here for the Rooikop Granite Porphyry and the previous U-Pb bulk zircon age determination of Faurie (1977): 2060±2 Ma compared to 2066±10 Ma respectively. The new age is also within the analytical uncertainty of the 2053±12 Ma U-Pb bulk zircon age reported by Coertze *et al.* (1978) for the Stavoren Granophyre, thereby providing further evidence supporting the similar origins of the Rooikop Granite Porphyry and Stavoren Granophyre.

Another striking aspect of the Rooiberg Group age is its closeness to the age of the Bushveld Complex. Table 3 summarises the best current age estimates for the Bushveld Complex, Rooiberg Group and related rock units and shows that the new age for the Rooiberg Group is indistinguishable from that of the basic layered rocks (Upper Zone) of the Bushveld Complex. The age of the Rustenburg Layered Suite is also indistinguishable from the new age obtained for the Rooikop Granite Porphyry.

Table 3. Best current age estimates of the Rooiberg Group, Bushveld Complex and related rock units

Rock Unit	Age (Ma)	Method[1]	Reference
Nebo Granite, Lebowa Granite Suite, Bushveld Complex	2054±2	ZE	Walraven and Hattingh, 1993
Upper Zone, Rustenburg Layered Suite, Bushveld Complex	2061±27	Rb-Sr	Walraven *et al.*, 1990
Stavoren Granophyre	2053±12	ZB	Coertze *et al.*, 1978
Rooikop Granite Porphyry	2060±2	ZE	This work
Selons River Formation, Rooiberg Group	2061±2	ZE	This work
Dullstroom Formation	2101±28	Rb-Sr, Pb.Pb	See note 2

NOTES:
[1] ZE: single-grain zircon Pb-evaporation; ZB: U-Pb bulk zircon chemistry.
[2] The age of the Dullstroom Formation is based on unpublished data of J.K. Schweitzer, recalculated by the author.

Although no direct field relationships have been observed between the Rustenburg Layered Suite and the Rooikop Granite Porphyry, it can be demonstrated that the basic layered rocks were emplaced after the completion of the Rooiberg Group magmatism and the intrusion of the Stavoren Granophyre. Walraven (1987) described remnants of granophyric xenoliths in the uppermost portion of the Upper Zone in the eastern Bushveld Complex which support the intrusive relationship of the basic layered rocks into the Stavoren Granophyre. Accepting a late syn- or immediately post-Rooiberg age for the Rooikop Granite Porphyry therefore implies that the plutonism of the Bushveld Complex took place after the intrusion of the Rooikop Granite Porphyry. The currently accepted age of the basic layered rocks, 2061±27 Ma, therefore seems slightly high and should be reduced.

The field relationships and chronostratigraphic data point to the following sequence of main events that took place during the final stages of evolution of the Transvaal basin (NB keep in mind the reservations associated with the 2101±28 Ma Dullstroom Formation age and the 2061±27 Ma Rustenburg Layered Suite age refered to above) :

- before ca 2100 Ma – completion of clastic sedimentation in the Transvaal basin, i.e. the Pretoria Group,
- at or after ca 2101±28 Ma – basic volcanism in the south-eastern part of the Transvaal basin to form the Dullstroom Formation,
- 2061±2 Ma – acid volcanism extending across the entire Transvaal basin to form the Rooiberg Group,
- 2060±2 Ma – intrusion of the Rooikop Granite Porphyry as sills within the Rooiberg Group and intrusion of the Stavoren Granophyre at the base of the Rooiberg Group,
- 2061±27 Ma – intrusion of the basic layered rocks of the Rustenburg Layered Suite of the Bushveld Complex,
- 2054±2 Ma – intrusion of the Nebo Granite of the Bushveld Complex.

The final point brought out by the new age data is the short duration of the magmatic activity of the Rooiberg Group and Bushveld Complex. A total of only 7 Ma separates the Rooiberg Group from the Nebo Granite. Admittedly the Rooiberg Group samples were obtained from the central part of the Rooiberg succession and slightly older ages can be expected for the base of the Selons River Formation, the Damwal Formation and the Dullstroom Formation. Nevertheless, it is evident that the total time span remains extremely short. Thus the new Rooiberg Group age provides evidence that magmatic events of the magnitude of the Rooiberg Group volcanism and Bushveld Complex plutonism can take place within a very short geological time span.

Furthermore, the extremely short time span separating the volcanism of the Rooiberg Group from the plutonism of the Bushveld Complex makes it highly probable that the two episodes formed part of one major magmatic event which affected the Kaapvaal Craton towards the end of the life of the Transvaal sedimentary basin. As suggested by other studies (Schweitzer, 1984; 1986; Eriksson *et al.,* 1993) extrusion of the Dullstroom Formation was probably an immediate precursor to the Rooiberg Group volcanism and should be included with the latter. It therefore also formed part of the Rooiberg-Bushveld event. Seen in this view, the Rooiberg-Bushveld event appears cyclic in nature and consisted of two cycles, each starting out with basic magmatism and ending with acid magmatism. The first cycle, Dullstroom–Rooiberg, was volcanic while the second, basic layered rocks–granites, was plutonic.

Although volcanic-plutonic rock associations are not unusual, recognition of the Dullstroom–Rooiberg–Bushveld association as one is important. Previous and current genetic models of the Bushveld Complex tend to ignore the preceding volcanic successions, probably because their close temporal association was not demonstrated. Yet the generation and extrusion of extremely large volumes of basic and acid magmas immediately prior to the emplacement of the Bushveld Complex cannot be without implications for the origin of the latter. Estimated total thicknesses for the Rooiberg Group plus Bushveld Complex in the order of 15 km are involved and their formation must have affected crust–mantle relationships and geothermal gradients beneath the Transvaal basin. Significantly higher ambient temperatures must have been encountered during the emplacement of the Bushveld Complex as a result of the preceding volcanism and these would have affected magma transport and cooling tempos. All these aspects are, however, beyond the scope of this paper and cannot be dealt with here.

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Appendix 1. Analytical data obtained for samples FW94 012, 013 and 014

Sample	Grain	Block	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	Ratios	Temp (°C)
FW94 012	1	1	0.12734±0.00124	0.15865±0.00147	9	1425
	1	2	0.12710±0.00029	0.15859±0.00059	9	1425
	2	1	0.12871±0.00063	0.16142±0.00120	9	1425
	2	2	0.12663±0.00069	0.16127±0.00130	9	1425
	2	3	0.12765±0.00063	0.15647±0.00105	9	1460
	2	4	0.12768±0.00034	0.15738±0.00086	9	1460
	2	5	0.12745±0.00015	0.15695±0.00052	8	1460
	2	6	0.12754±0.00014	0.15751±0.00072	6	1460
	2	7	0.12739±0.00044	0.15643±0.00047	9	1460
	2	8	0.12747±0.00023	0.15700±0.00073	8	1460
	2	9	0.12759±0.00030	0.15731±0.00060	9	1460
	2	10	0.12759±0.00011	0.15739±0.00044	7	1460
	2	11	0.12697±0.00093	0.15690±0.00109	10	1460
	2	12	0.12787±0.00083	0.15794±0.00080	9	1460
	3	1	0.12801±0.00060	0.15712±0.00101	9	1425
	3	2	0.12720±0.00031	0.15550±0.00104	8	1425
	3	3	0.12737±0.00047	0.15678±0.00053	9	1425
	3	4	0.12541±0.00031	0.15999±0.00014	9	1460
	3	5	0.12857±0.00030	0.16415±0.00064	8	1460
	3	6	0.12688±0.00030	0.16216±0.00026	9	1460
	3	7	0.12733±0.00023	0.16312±0.00053	9	1460
	3	8	0.12818±0.00051	0.16431±0.00149	9	1460
	4	1	0.12625±0.00086	0.14964±0.00199	9	1445
	5	1	0.12543±0.00277	0.14404±0.00536	9	1425
	5	2	0.12484±0.00120	0.14561±0.00337	9	1425
	5	3	0.12568±0.00440	0.14781±0.00608	9	1425
	5	4	0.12758±0.00191	0.14672±0.00364	9	1425
	5	5	0.12680±0.00103	0.14740±0.00129	9	1480
	6	1	0.12611±0.00044	0.15789±0.00081	9	1445
	6	2	0.12691±0.00022	0.15911±0.00048	8	1445
	6	3	0.12656±0.00019	0.15930±0.00060	9	1445
	6	4	0.12713±0.00021	0.15966±0.00053	9	1445
	6	5	0.12709±0.00022	0.15942±0.00042	9	1445
	6	6	0.12736±0.00037	0.15990±0.00045	9	1445
	6	7	0.12690±0.00025	0.15953±0.00049	9	1445
	6	8	0.12626±0.00042	0.15908±0.00067	8	1445
	6	9	0.12760±0.00057	0.16026±0.00193	8	1445
FW94 013	1	1	0.12633±0.00043	0.17108±0.00088	9	1445
	1	2	0.12673±0.00071	0.17018±0.00141	9	1445
	1	3	0.12753±0.00053	0.16907±0.00104	9	1445
	1	4	0.12705±0.00034	0.16599±0.00064	9	1445
	1	5	0.12694±0.00037	0.16595±0.00010	9	1445
	1	6	0.12696±0.00010	0.16604±0.00039	7	1445
	1	7	0.12679±0.00040	0.16617±0.00042	9	1445
	1	8	0.12679±0.00033	0.16581±0.00042	9	1445
	1	9	0.12719±0.00015	0.16617±0.00028	8	1445
	1	10	0.12725±0.00040	0.16640±0.00031	9	1445
	1	11	0.12714±0.00012	0.16606±0.00018	10	1445

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Sample	Grain	Block	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	Ratios	Temp (°C)
FW94 013	1	12	0.12682±0.00012	0.16552±0.00023	10	1445
	1	13	0.12700±0.00010	0.16543±0.00006	10	1445
	1	14	0.12694±0.00012	0.16527±0.00018	9	1445
	1	15	0.12681±0.00022	0.16499±0.00023	10	1445
	1	16	0.12685±0.00022	0.16492±0.00012	10	1445
	2	1	0.12715±0.00029	0.15922±0.00039	9	1445
	2	2	0.12710±0.00019	0.15052±0.00059	9	1445
	2	3	0.12676±0.00017	0.18542±0.00020	9	1480
	2	4	0.12669±0.00039	0.18744±0.00027	8	1480
	2	5	0.12696±0.00044	0.18911±0.00124	9	1480
	3	1	0.12555±0.00058	0.16466±0.00112	9	1445
	3	2	0.12564±0.00027	0.16446±0.00025	8	1445
	3	3	0.12598±0.00049	0.16512±0.00026	9	1445
	3	4	0.12584±0.00022	0.16464±0.00033	9	1445
	3	5	0.12607±0.00017	0.16465±0.00046	9	1445
	3	6	0.12614±0.00022	0.16442±0.00033	9	1445
	3	7	0.12696±0.00027	0.16527±0.00029	9	1445
	3	8	0.12660±0.00045	0.16508±0.00045	10	1445
	3	9	0.12704±0.00037	0.16580±0.00031	9	1445
	3	10	0.12698±0.00040	0.16539±0.00023	8	1445
	4	1	0.12766±0.00042	0.16662±0.00061	9	1445
	4	2	0.12719±0.00036	0.16190±0.00023	9	1445
	4	3	0.12791±0.00056	0.16300±0.00063	9	1445
	4	4	0.12842±0.00047	0.16282±0.00074	9	1445
	4	5	0.12728±0.00014	0.16165±0.00036	9	1445
	4	6	0.12645±0.00032	0.16070±0.00038	10	1445
	4	7	0.12692±0.00044	0.16036±0.00032	10	1445
	4	8	0.12749±0.00028	0.16000±0.00046	10	1445
	4	9	0.12659±0.00048	0.16055±0.00050	10	1445
FW94 013	4	10	0.12610±0.00109	0.17054±0.00280	9	1480
	4	11	0.12793±0.00025	0.17290±0.00118	9	1480
	4	12	0.12740±0.00058	0.17193±0.00121	9	1480
	5	1	0.12706±0.00045	0.17286±0.00082	9	1445
	5	2	0.12783±0.00031	0.17430±0.00120	9	1445
	5	3	0.12727±0.00026	0.17083±0.00061	9	1445
	5	4	0.12702±0.00038	0.17123±0.00038	9	1445
	5	5	0.12735±0.00014	0.17089±0.00060	7	1445
	6	1	0.12702±0.00043	0.16444±0.00175	8	1445
	6	2	0.12745±0.00069	0.16477±0.00070	9	1445
	6	3	0.12656±0.00034	0.16682±0.00177	9	1445
	6	4	0.12746±0.00070	0.16668±0.00080	9	1445
	6	5	0.12778±0.00036	0.16076±0.00110	7	1480
FW94 014	1	1	0.12738±0.00034	0.19501±0.00051	9	1445
	1	2	0.12726±0.00014	0.19594±0.00008	9	1445
	1	3	0.12716±0.00044	0.19451±0.00032	9	1445
	2	1	0.12750±0.00054	0.14754±0.00219	8	1445
	2	2	0.12774±0.00086	0.14620±0.00071	9	1445
	2	3	0.12756±0.00045	0.14509±0.00046	9	1445
	2	4	0.12797±0.00031	0.14540±0.00047	9	1445
	2	5	0.12712±0.00042	0.14476±0.00043	9	1445
	2	6	0.12698±0.00028	0.14462±0.00031	9	1445

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Sample	Grain	Block	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	Ratios	Temp (°C)
FW94 014	2	6	0.12698±0.00028	0.14462±0.00031	9	1445
	2	7	0.12691±0.00033	0.14474±0.00040	9	1445
	2	8	0.12783±0.00100	0.14522±0.00056	9	1445
	2	9	0.12710±0.00022	0.14553±0.00035	9	1445
	2	10	0.12719±0.00022	0.14570±0.00037	10	1445
	2	11	0.12736±0.00031	0.14662±0.00103	6	1445
	2	12	0.12697±0.00075	0.14258±0.00073	9	1480
	2	13	0.12785±0.00021	0.14365±0.00129	6	1480
	2	14	0.12647±0.00049	0.14223±0.00095	9	1480
	2	15	0.12602±0.00053	0.14221±0.00121	9	1480
	2	16	0.12661±0.00070	0.14371±0.00093	9	1480
	3	1	0.12841±0.00032	0.15546±0.00077	8	1445
	3	2	0.12707±0.00032	0.15495±0.00099	9	1445
	3	3	0.12715±0.00012	0.15673±0.00062	9	1445
	3	4	0.12679±0.00033	0.15653±0.00055	9	1445
	3	5	0.12723±0.00044	0.15645±0.00038	9	1445
	3	6	0.12732±0.00045	0.15747±0.00012	9	1445
	3	7	0.12666±0.00030	0.15667±0.00029	9	1445
	3	8	0.12727±0.00039	0.15364±0.00017	10	1445
FW94 014	3	9	0.12723±0.00026	0.15473±0.00031	10	1445
	3	10	0.12774±0.00040	0.15580±0.00061	9	1445
	3	11	0.12657±0.00114	0.13353±0.00189	9	1480
	4	1	0.12662±0.00049	0.14925±0.00083	8	1445
	4	2	0.12626±0.00024	0.14870±0.00086	9	1445
	4	3	0.12592±0.00026	0.14772±0.00046	9	1445
	4	4	0.12700±0.00084	0.14122±0.00078	10	1445
	4	5	0.12663±0.00047	0.14181±0.00025	10	1445
	4	6	0.12576±0.00066	0.14165±0.00053	10	1445
	4	7	0.12546±0.00032	0.14126±0.00049	9	1445
	4	8	0.12853±0.00102	0.13146±0.00039	9	1445
	4	9	0.12585±0.00065	0.13201±0.00155	9	1445
	4	10	0.12514±0.00035	0.13635±0.00129	8	1445
	4	11	0.12580±0.00120	0.13288±0.00098	9	1445
	4	12	0.12767±0.00075	0.13404±0.00112	9	1445
	4	13	0.12507±0.00043	0.13417±0.00144	8	1480
	4	14	0.12589±0.00032	0.13358±0.00036	9	1480
	6	1	0.12540±0.00096	0.22919±0.00317	7	1445
	6	2	0.12572±0.00077	0.22538±0.00052	9	1445
	6	3	0.12532±0.00059	0.18426±0.00113	8	1460
	6	4	0.12577±0.00032	0.18397±0.00065	9	1460
	6	5	0.12564±0.00040	0.18541±0.00111	9	1460

NOTE: ratios are shown with one σ standard deviations.