Volcanism of the Palaeoproterozoic Bushveld Large Igneous Province: the Rooiberg Group, Kaapvaal Craton, South Africa

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Abstract

The volcanic rocks of the Rooiberg Group represent the uppermost unit in the Palaeoproterozoic Transvaal Supergroup and form one of the largest provinces of silicic volcanic rocks in the world. Although stratigraphically associated with the Transvaal basin-fill, the Rooiberg Group is petrogenetically linked with the larger Bushveld magmatic event for which emplacement was preceded by the extrusion of the vast Rooiberg lava flows in the northern part of the Kaapvaal Craton. Like many silicic-dominated Large Igneous Provinces (LIPs), which are increasingly recognised in the rock record, the Rooiberg Group volcanics are intracontinental, subaerial, and are dominated by voluminous lava flows. Originally, the Rooiberg Group is inferred to have covered an area of more than 200,000 km^2 of which, after erosion, an area of 50,000 to 67,000 km^2 remains. The lava flows form a stratigraphic succession up to 6 km thick, and are divided into four formations in ascending order: Dullstroom, Damwal, Kwaggasnek and Schrikkloof. Due to a scarcity of reliable geochronologic data, the temporal span of the Rooiberg Group is poorly understood. The Rooiberg Group consists of basaltic to rhyolitic lava erupted from fissural volcanism with estimated eruption temperatures of the rhyolitic lavas exceeding 1000°C. Minor explosive eruptions are represented by pyroclastic rocks, and subordinate sedimentary interbeds originated from sandy fluvial and lacustrine processes. The rocks are essentially undeformed and have not been buried so that their original textures are well preserved. The Bushveld Complex and the associated Rooiberg Group lava flows are proposed to have formed as a result of partial melting of subcontinental lithosphere and lower crust by a mantle plume. This thorough review of the geochronology, physical volcanology, and geochemistry of the Rooiberg Group enables construction of a geodynamic model.

Keywords: Palaeoproterozoic; voluminous silicic volcanism; Large Igneous Province; Rooiberg Group; South Africa; volcanic evolution

1. Introduction

The Rooiberg Group is part of the Bushveld Large Igneous Province (LIP) (Ernst and Bell, 2010; Pankhurst et al., 2011) and represents the youngest, most silicic and most voluminous volcanic unit in the Transvaal Supergroup, that was deposited on the stable Kaapvaal Craton in northern South Africa. Although the Rooiberg Group is stratigraphically associated with the Transvaal Supergroup, it is petrogenetically linked with the larger Bushveld magmatic event (e.g., Twist and French, 1983; Eriksson et al., 1995). The extrusion of the vast, bimodal Rooiberg Group preceded the emplacement of the Bushveld Complex in the northern part of the craton. The Bushveld LIP as a whole, thus comprises the basaltic-rhyolitic Rooiberg Group (2061±2 Ma; Walraven, 1997), the mafic-layered rocks of the Bushveld Complex *per se* (the Rustenberg Layered Suite; 2058.9±0.8 Ma, Buick et al., 2001), the Lebowa Granite (2054±2 Ma; Walraven and Hattingh, 1993), and the Rashoop Granophyre Suites (2053±12 Ma; Coertze et al., 1978). The Rooiberg Group consists of four formations, which include in ascending order, the Dullstroom, Damwal, Kwaggasnek and Schrikkloof formations (Schweitzer, 1987; Schweitzer et al., 1995). In spite of its Palaeoproterozoic age, the Rooiberg Group is generally undeformed and relatively unmetamorphosed. The Rustenburg Suite intrusion thermally metamorphosed the lower two formations, and the Lebowa Suite metasomatically altered (deposition of secondary cassiterite, tourmaline and carbonate) the entire Group, particularly in its northwestern part (Buchanan, 2006). To date, no associated dyke swarms have been identified (Kinnaird, 2005).

Despite its importance with respect to the formation of the Bushveld LIP as a whole and considering that the Rooiberg Group is one of the oldest and largest provinces of silicic volcanic rocks known (c.f., Twist and French, 1983), the group has not yet been studied in detail. Most previous studies have involved local field mapping in separate areas, together with minor petrology and several sets of geochemical analyses (Sharpe et al., 1983; Twist, 1985; Myers et al., 1987; Crow and Condie, 1990; Harmer and von Gruenewaldt, 1991; Hatton and Schweitzer, 1995; Buchanan et al., 2002). No stratigraphic markers have been identified, as yet, that are suitable for regional to basin-wide correlation (Twist and French, 1983).

The Rooiberg Group has been interpreted as consisting of several thousand metres of lava flows erupted from fissural volcanism with minor units of shale and greywacke (Twist and French, 1983; Twist, 1985; Harmer and Farrow, 1995; Schweitzer et al., 1995; Hatton and Schweitzer, 1995). Three hypotheses have been proposed for the origin of the Rooiberg Group. First, several authors (Rhodes, 1975; Elston, 1992) attributed the Rooiberg Group and the Bushveld Complex to the simultaneous impact of several comets or asteroids, a hypothesis which was later opposed by Buchanan and Reimold (1998). Second, Hatton (1988) proposed that the Rooiberg Group formed as a result of subduction-related processes associated with a nearby plate margin along the northern Kaapvaal edge. Third, several authors (Sharpe et al., 1981; Harmer and von Gruenewaldt, 1991; Hatton, 1995; Hatton and Schweitzer, 1995) attributed the Rooiberg Group and the associated Bushveld Complex to partial melting of subcontinental lithosphere and lower crust by a mantle plume. The latter hypothesis is today agreed upon by most authors, including Ernst and Buchan (2001) who interpreted the Bushveld Magmatic Province as a LIP (cf., Coffin and Eldholm, 1994; Sheth, 2007; Bryan and Ernst, 2008). According to Allen et al. (2008) only a few examples of silicic volcanic LIPs have been documented worldwide. Of those, four are Proterozoic and were formed during supercontinent assembly: the ~2450 Woongarra Province rhyolites, North West

Australia (Trendall, 1995; Barley et al., 1997), the ~2061 Ma Rooiberg Group (Walraven, 1997), the ~1592 Ma Gawler Range Volcanics, South Australia (Creaser and White, 1991; Creaser, 1995; Allen and McPhie, 2002; Allen et al., 2008), and the ~1100 Ma rhyolites of the North Shore Volcanic Group, Minnesota (Green and Fitz, 1993). Younger examples include the Snake River Plain (Bonnichsen and Kauffman, 1987; Manley, 1996; Branney et al., 2008), Trans-Pecos Texas (Henry et al., 1989, 1990), Yellowstone National Park (Christiansen and Hildreth, 1989), and the Etendeka Igneous Province in Namibia (Milner, 1986; Milner et al., 1992).

The aim of this paper is to provide a comprehensive review of the Rooiberg Group because no similar study has been conducted since that of Twist and French (1983; see also, a short review by Buchanan, 2006). A new mapping program focusing on the physical volcanology of the Rooiberg Group was begun in 2010, and preliminary field data from this work will be combined with extant literature to provide an up-to-date overview of the nature of Rooiberg volcanism and its geodynamic origin. The focus of this paper is to provide, for the first time, properly constrained lithofacies interpretations of the Rooiberg Group, as well as to highlight initial results of eruption temperature and viscosity estimates based on new modeling data. This thorough review of the geochronology, physical volcanology, and geochemistry of the Rooiberg Group also enables the construction of a geodynamic model.

2. Regional geologic setting

By ca. 2.6 Ga, the Kaapvaal Craton was a predominantly granitic, stable Archaean block that was characterized in the Archaean - Palaeoproterozoic by the development of large volcano-sedimentary intracratonic basins on an evolving stable platform. These basins include the ca. 3.1-2.8 Ga Witwatersrand Supergroup and the ca. 2.7 Ga Ventersdorp Supergroup basin-fills, both of which formed during late cratonisation (e.g., Eriksson et al., 2005), and the Transvaal

(Supergroup) basin (~2.66-2.1 Ga), which developed following cratonisation. The latter basin contains one of the thickest (ca. 15 km; Button, 1986) and most complete successions of Neoarchaean-Palaeoproterozoic volcano-sedimentary rocks, which form the floor rocks to the entire Bushveld LIP (Eriksson and Reczko, 1995). The Transvaal rocks underwent regional-scale compressive deformation prior to the Bushveld LIP event (Bumby et al., 1998; Eriksson et al., 1998), thus indicating a time gap between the end of Transvaal sedimentation and the onset of Rooiberg–Bushveld magmatism. The Bushveld LIP was part of a widely-distributed coeval Proterozoic magmatism in the Kaapvaal Craton in southern Africa, including the Molopo Farms layered intrusion, intrusions into the Okwa basement complex (both in Botswana), and smaller intrusions of the Bushveld high-Ti suite near the Vredefort impact complex in South Africa (e.g. Reichhardt, 1994; Kinnaird, 2005; Mapeo et al., 2006).

2.1. Geochronology

The majority of isotopic ages (single-grain zircon Pb-evaporation) determined from samples of the Rooiberg Group and the Bushveld Complex range from 2061±2 to 2052±48 Ma (Table 1) (e.g., Walraven et al., 1987, 1990; Walraven, 1997; Buick et al., 2001). More recently, Buchanan et al. (2004) determined Rb-Sr ages of 2071+94/-65 Ma for the Dullstroom and Damwal Formations. Furthermore, based on all available geochronological data from the Rooiberg Group and the Bushveld Complex, it was suggested that the best estimate for the age of the Kwaggasnek Formation is 2057.3±3.8 Ma (Harmer and Armstrong, 2000). The duration of Rooiberg Group volcanism is thus not well constrained.

2.2. Structural relationships between the Bushveld Complex, the Transvaal Supergroup floor and the Rooiberg Group

The stratigraphy of the Rooiberg Group has been disrupted by the intrusion of three suites of the Bushveld Complex, which include the Rustenburg (layered mafic rocks), Rashoop (granophyres) and Lebowa (granitic) suites. The lowermost Dullstroom Formation, which occurs only in the SE part of the Rooiberg Group, lies unconformably (Cheney and Twist, 1991) over Pretoria Group sedimentary rocks of the Transvaal Supergroup and beneath Bushveld lithologies (e.g., Eriksson et al., 1995). The remaining three formations of the Rooiberg Group as well as the upper part of the Dullstroom Formation were detached by the Bushveld intrusion (Rustenburg Suite), and elevated to form the roof of the Bushveld Complex (Hatton and Schweitzer, 1995; Schweitzer et al., 1995 and references therein). All four formations, with the lower part of the Dullstroom detached from the rest of the group, occur in the SE of the Rooiberg Group (Fig. 1). The Damwal Formation is also restricted to this general area and immediately to the west. The upper Kwaggasnek and Schrikkloof formations are much more widespread in the south-central and northwestern parts of the Rooiberg Group where they lie unconformably on Transvaal sedimentary strata in the so-called Rooiberg Fragment. The Rooiberg lava flows in the east are spatially associated with the Rustenburg Suite of the Bushveld Complex, and the upper two Rooiberg formations in the west, with the Lebowa Granite Suite (Hatton and Schweitzer, 1995). The Rooiberg deposits are thickest in the area of Loskop Dam, just to the south of the proposed Kanye axis (a postulated crustal architectural feature of at least Transvaal age; Eriksson et al., 1996), immediately southeast of the Dennilton Fragment (Fig. 2).

There are five “fragments” (a term which is well entrenched in local and global literature on the Bushveld LIP) of Transvaal-Rooiberg lithologies enclosed within the much wider spread Bushveld intrusives. The Rooiberg and Crocodile fragments lie in the west of the Bushveld LIP and are interpreted as large roof pendants. The Dennilton, Marble Hall and Makeckaan/Stavoren fragments are located in the east (Fig. 2) and are interpreted as floor-attached domes (Hartzer, 1995). Further complications in spatial relations are presented by evidence for a catastrophic event between the end of Transvaal sedimentation and the onset of Rooiberg volcanism. Eriksson et al. (1995, and references therein) attribute the immature nature of the uppermost Transvaal Supergroup sedimentary rocks within the Makeckaan and Rooiberg fragments, and gravity slumping of Pretoria Group sedimentary and volcanic rocks in eastern Botswana (Crockett, 1972) to possible updoming of the craton during upwelling of the Bushveld LIP plume.

The Kwaggasnek and Schrikkloof formations within the Rooiberg fragment unconformably overlie (Schweitzer et al., 1995) texturally and mineralogically immature sedimentary rocks of the Smelterskop Formation (Richards, 1987). The stratigraphic placement of this unit as well as the underlying Leeuwpoort Formation, and the Makeckaan Formation in the fragment of the same name, is uncertain – they are all thought to be immature sedimentary deposits related to rapid sedimentation from igneous updoming preceding Rooiberg Group eruption, rather than being part of the Pretoria Group (e.g., Eriksson et al., 1995).

In the southeastern area of greatest exposure, the Rooiberg Group grades conformably into 1100 m of red shale intercalated with conglomerate overlain by mainly impure recrystallised sandstone of the overlying Loskop Formation (Clubley-Armstrong, 1977; Martini, 1998). Contact metamorphism of the Rooiberg Group rocks, which now essentially form the roof of the Bushveld Complex, led to partial melting of the lava flows and to the formation of fine-grained granulitic rocks (c.f., French and Twist, 1983). Recent age data (U–Pb sphene concordant age on a calc-silicate xenolith within Rustenburg Suite mafic rocks) for the Bushveld Complex indicates a minimum emplacement age of 2058±0.8 Ma (Buick et al., 2001). A thermal model of the emplacement and crystallisation of the Bushveld Complex by Cawthorn and Walraven (1998) indicates that the magmas injected into the complex were emplaced within roughly 75,000 years. More recently, Letts et al. (2009) suggested a minimum emplacement time of 1.4 My, determined by means of seven magnetic reversals found in the Bushveld Complex. The mean palaeomagnetic pole from the Bushveld Complex yields a palaeolatitude of ~45° N (Letts et al., 2009) and would thus correspond to the location of present-day northern Africa.

Group	Formation	Main lithologies	Thickness (m)
	Loskop	Red shale, sandstone, conglomerate	0-1000
Rooiberg	Schrikkloof	Rhyolite	200-3000
Rooiberg	Kwaggasnek	Rhyolite, shale	500-2500
Rooiberg	Damwal	Dacite, rhyolite	1000-2500
Rooiberg	Dullstroom	Basalt to rhyolite	Up to 2000
Pretoria (Upper part)	Rayton	Quartzite, shale	1200
Pretoria (Upper part)	Magaliesberg	Orthoquartzite	300
Pretoria (Upper part)	Silverton	Black shale	600
Pretoria (Upper part)	Dasport	Orthoquartzite	80-95
Pretoria (Upper part)	Strubenkop	Quartzite, shale	105-120

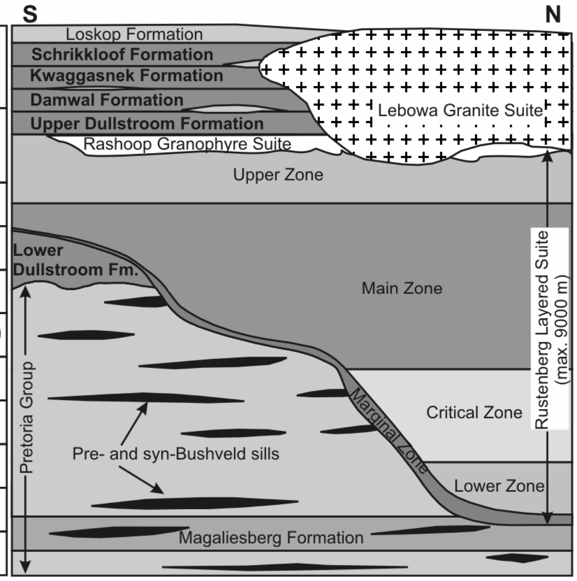

Figure 1. Schematic north-south section in the Loskop Dam area showing the relationship between the Rooiberg Group, the underlying Pretoria Group (Transvaal Supergroup), and the intrusions of the Rustenberg and Lebowa Granite Suites (modified after SACS, 1980; Walraven, 1982; Harmer and Sharpe, 1985; Schweitzer et al., 1995).

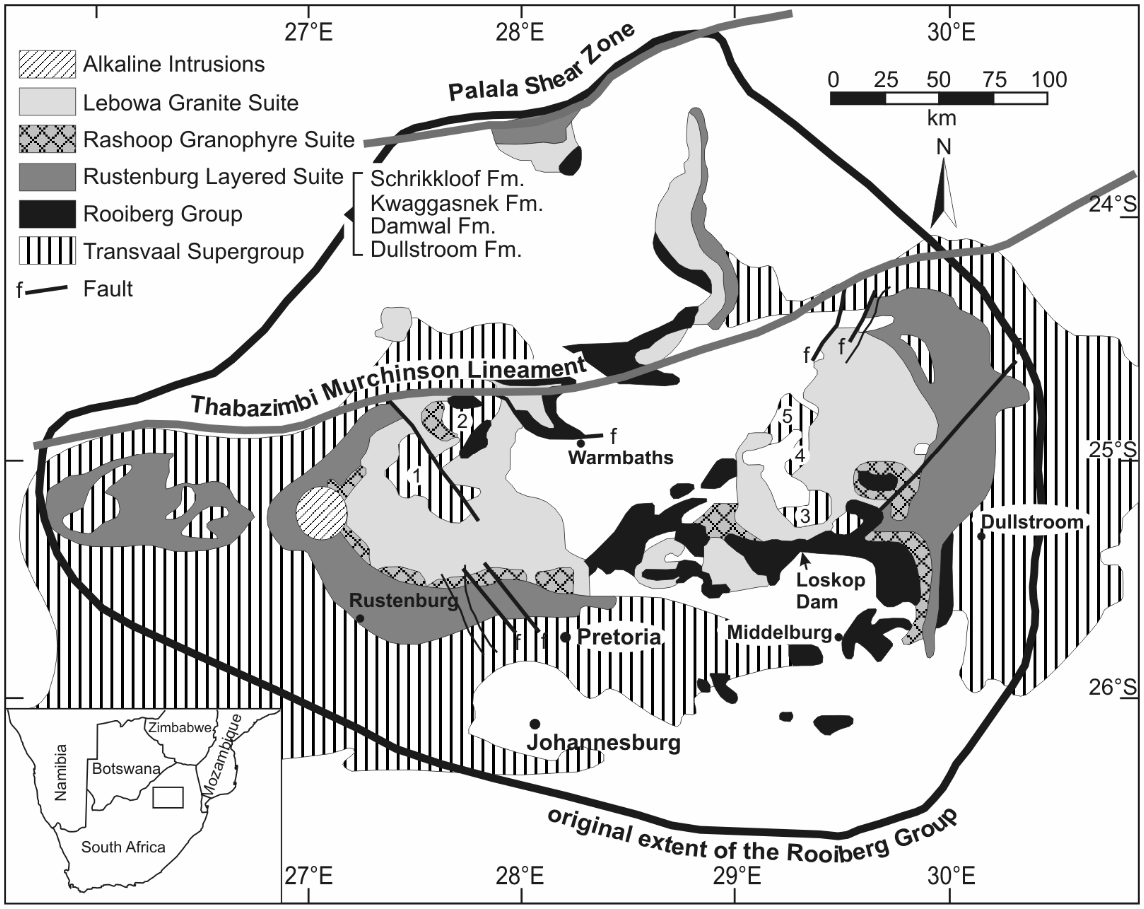

Figure 2. Simplified geological map of the Bushveld Large Igneous Province, including the Rustenburg Layered Suite, the Rooiberg Group, the Rashoop Granophyre Suite and the Lebowa Granite Suite. Also shown is the postulated extent of the original Rooiberg volcanic suite. The inset in the lower left corner shows the location of the area in South Africa. 1, Crocodile River fragment; 2, Rooiberg fragment; 3, Dennilton fragment; 4, Marble Hall fragment; 5, Stavoren (Makeckaan) fragment. Modified after Hartzer (1995), Kinnaird (2005) and Kruger (2005).

3. Stratigraphy and lithology

De Bruiyn (1980) studied the Rooiberg Group north of Pretoria. In the Warmbaths area, where the Rooiberg Group is unconformably overlain by Waterberg Group sedimentary rocks, Rhodes and Du Plessis (1976) described the Rooiberg Group as a 3-km-thick volcanic succession. A similar study was done near Villa Nora by van der Walt (1980) who described comparable field relations to those at Warmbaths with thicknesses of up to 4.5 km for the Rooiberg Group. The most complete and best exposed lithostratigraphic section is in the southeastern Bushveld around the borders of the Middelburg basin (filled mainly with Loskop Formation and Waterberg Group sedimentary strata) (e.g., Mellor, 1907; Wolhuter, 1954; von Gruenewaldt, 1966, 1968; Clubley-Armstrong, 1977; Twist, 1985). Here, Twist (1985) described a ca. 3520 m-thick section immediately north of the Loskop Dam, on the northern flank of the preserved Middelburg basin (Fig. 2). To the east, on the northeastern rim of the Middelburg basin, the succession gradually thickens to 5110 m (Clubley-Armstrong, 1977). The Rooiberg lithostratigraphic section is dominated by thick lava flows that are intercalated with minor volcaniclastic and siliciclastic layers. Twist (1985) distinguished nine units of lava flows within the sequence, based on colour, texture, phenocryst content, internal structure, and relationship to the intercalated sedimentary units (Fig. 3). Schweitzer et al. (1995) assigned the nine lava units to the four formations of the Rooiberg Group: (1) the Dullstroom Formation (upper stage) which equates to lava units 1-2 of Twist (1985); (2) the Damwal Formation with lava units 3-6; (3) the Kwaggasnek Formation with lava units 7-8; and (4) the Schrikkloof Formation, correlated with lava unit 9. Figure 4 illustrates the correlations between the nine lava units of Twist (1985 and his earlier work; Table 1), the formations defined by Schweitzer et al. (1995), and data from Eriksson et al. (1994) concerning intercalated sedimentary beds. Our preliminary volcano-sedimentary analysis uses rock composition, texture (coherent *versus* clastic) and grain size, to define eight lithofacies. These lithofacies include the: (1) mafic coherent volcanic lithofacies (ML), felsic coherent volcanic lithofacies (FL), massive tuff lithofacies (mT), peperitic breccia lithofacies (Gp), tuffaceous breccia lithofacies (Gms), cross-bedded sandstone lithofacies (St, Sp), rippled sandstone lithofacies (Sr), and mudstone lithofacies (Fh) (Table 2).

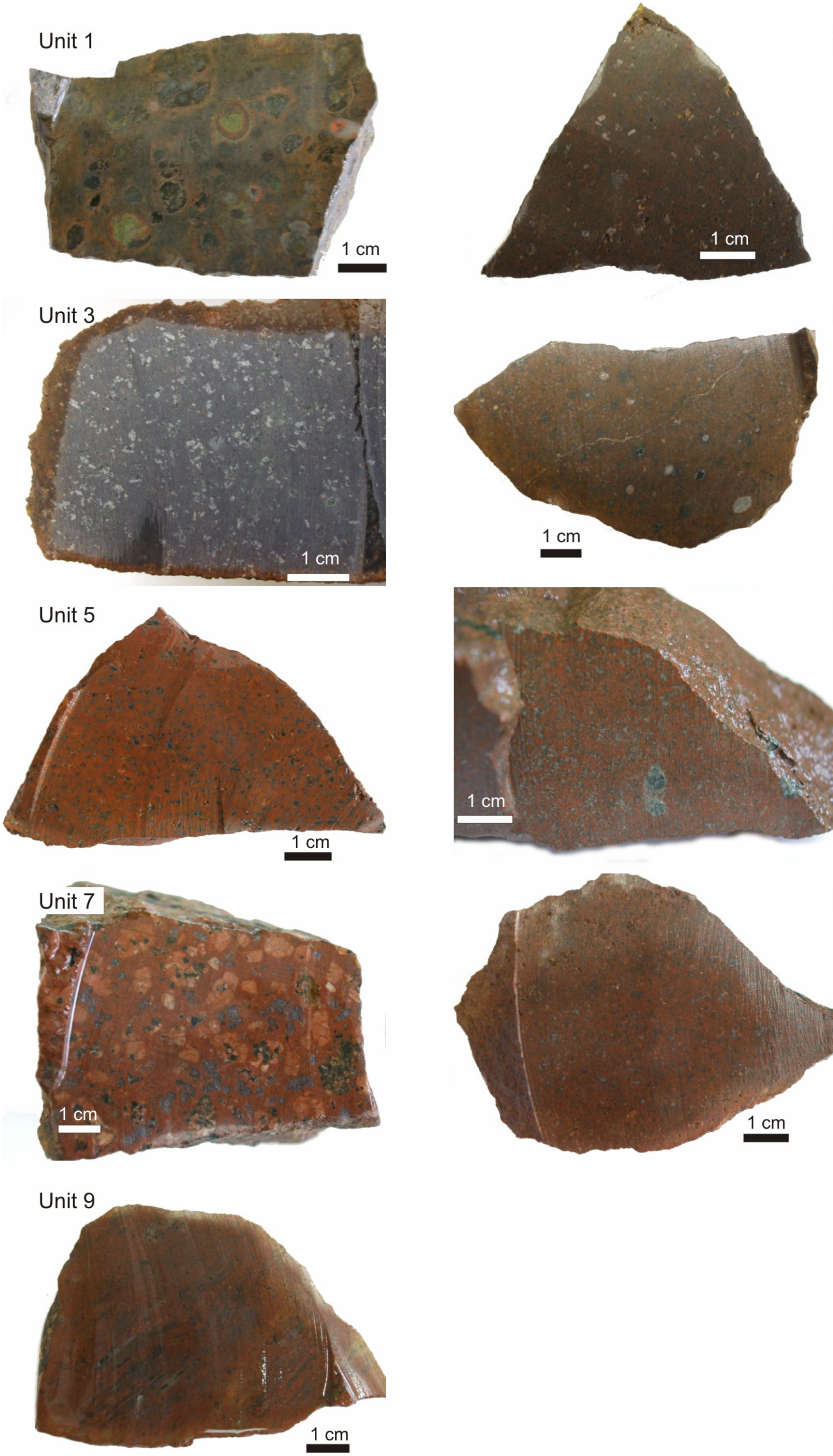
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Figure 3. Examples of hand specimen from the nine different lava units of the Rooiberg Group as described by Twist (1985). Samples were all taken from the Loskop Dam area (Fig. 2 for locality).

Table 1. Description of the nine different lava units of the Rooiberg Group in the Loskop Dam region as described by Twist (1985) and Schweitzer et al. (1995).

Formation	Unit[1]	Description[1]	Rock type[2]
Schrikkloof	9	Sparsely porphyritic to non-porphyritic pinkish-red felsites. Generally flow-banded, feldspars invariably sericitized.	Low-Mg felsite
Kwaggasnek	8	Very sparsely porphyritic and very flaggy pinkish-red felsite. Commonly flow-banded.	–
	7	Red porphyritic and non-porphyritic lavas.	Low-Mg felsite
Damwal	6	Generally massive porphyritic red felsite with local flow-banding and amygdaloidal layers. Sometimes light grayish to greenish.	–
	5	Brick-red to purple slightly porphyritic felsite. Very flaggy and commonly flow-banded.	–
	4	Typically amygdaloidal and lithophysal dark brown felsites, sometimes with coarse, prominent flow-banding.	Low-Mg felsite
	3	Dense, dark brown, grey and black porphyritic felsites, often glassy with strong conchoidal fracture. Strongly spherulitic towards the top. Often amygdaloidal.	High Fe-Ti-P andesite
Dullstroom	2	Massive, crystalline microporphyritic black, dark brown and dark green felsites. Sometimes amygdaloidal and flow-banded. Augite phenocrysts are abundant.	High Fe-Ti-P andesite Low-Mg felsite High-Mg felsite High-Ti basalt Basal rhyolite
	1	Massive, dark-red and grey porphyritic felsites, rarely amygdaloidal or flow-banded. Widely spaced spherulites. Typically hornblende (and chlorite) -bearing, becoming more pervasively altered downwards.	Low-Ti basaltic andesite

[1]Twist (1985); [2]Schweitzer et al. (1995); –, no data available.

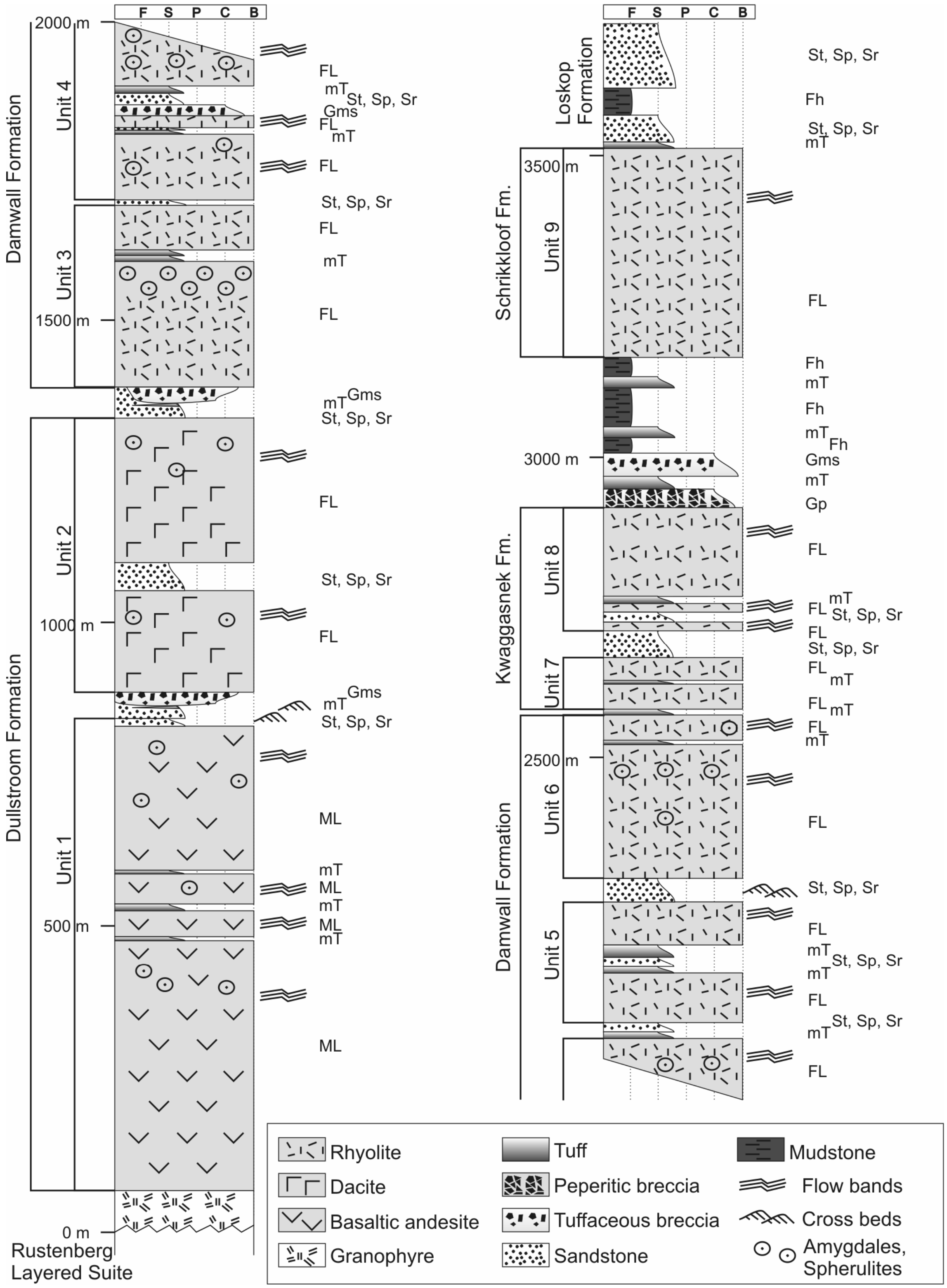


Figure 4. Idealized stratigraphic section through the Rooiberg Group near Loskop Dam (Fig. 2 for location) (modified after Twist (1985) and Schweitzer et al. (1995)). F, Fines (clay and silt); S, Sand; P, Pebbles; C, Cobbles; B, Boulders. ML, mafic coherent volcanic lithofacies;

FL, felsic coherent volcanic lithofacies; mT, massive tuff lithofacies; Gp, peperitic breccia lithofacies; Gms, tuffaceous breccia lithofacies; St, Sp, cross-bedded sandstone lithofacies; Sr, rippled sandstone lithofacies; Fh, mudstone lithofacies.

Table 2. Volcanic, volcaniclastic and siliciclastic lithofacies of the Rooiberg Group.

Lithofacies code	Lithofacies	Facies, characteristics	Inferred process	Interpreted setting
ML	Mafic coherent volcanic (thickness of multiple units: up to 400 m)	Massive aphyric to porphyritic flows; vesicle/ amygdale content variable but concentrated at flow margins.	Effusive lava flow	Subaerial flows
FL	Felsic coherent volcanic (thickness of multiple units: up to 200 m)	Massive aphyric to porphyritic flows; local flow banding; vesicles/ amygdales concentrated at flow margins.	Effusive lava flow	Subaerial flows
mT	Massive tuff (thickness of single units: 1-50 m)	Massive, matrix-supported; matrix consisting of well preserved cuspate shard textures and crystal fragments (original glass replaced by calcite or cryptocrystalline silica); clasts consisting of lava and pumice fragments.	Pyroclastic flow (High concentration density current deposition)	Subaerial deposits
Gp	Peperitic breccia (thickness of single units: 1-10 m)	Clast- to matrix-supported, non-stratified breccia containing monomictic, blocky, ragged clasts of lava; clasts do not have chilled margins and include angular and shard-like clasts with curviplanar margins that often show jigsaw-textures, separated by a matrix of pale-grey massive siltstone.	Mingling of magma with poorly consolidated wet sediment, at the margins of intrusions (Kano, 1989; Goto and McPhie, 1996, 1998; Hanson and Hargrove, 1999) or bases of lavas (Schmincke, 1967; Hunns and McPhie, 1999).	Subaerial to shallow water deposits, possibly near lakes, ponds and rivers
Gms	Tuffaceous breccia (thickness of single units: 1-10 m)	Massive, matrix-supported, poorly sorted; lava clasts, a few mm to more than 20 cm across (outsized clasts can be as large as 1 m across), set in a matrix of sand-sized fragments and commonly cemented by silica.	Debris flows, lahars (c.f., Johnson and Rodine, 1984; Rodolfo and Arguden, 1991).	Volcanic fans fringing flanks of volcanic edifice

Table 2. Continued.

Lithofacies code	Lithofacies	Facies, characteristics	Inferred process	Interpreted setting
St, Sp	Cross-bedded sandstone (thickness: 1-10 m)	Planar or trough cross-bedding; coarse to fine sandstones with poor sorting and well rounded grains (quartz, feldspar, rock fragments and opaque mineral phases).	Sinuously crested and linguoid (3D) dunes, channel deposits (Miall, 1996).	Braided stream
Sr	Rippled sandstone (thickness: 1-5 cm)	Very fine- to medium-grained sandstones with variable crystal-lithic fragments very similar to cross-bedded sandstone lithofacies; symmetrical and asymmetrical ripples can be observed; symmetrical ripples characterized by linear, bifurcating crest in plan view; asymmetrical ripples have distinct stoss and lee sides with well-defined foresets.	Symmetrical ripples: oscillatory water currents generated by wave action in shallow water conditions (Reineck and Singh, 1980). Asymmetric ripples: migration of small bedforms under the influence of unidirectional tractional currents under lower flow regime conditions (Collinson and Thompson, 1982).	Flood plain
Fh	Mudstone (thickness: 1-5 m)	Planar bedded, graded.	Background sedimentation settling through the water column, probably with a felsic vitric ash component (e.g. Fritz and Vanko, 1992).	Shallow water: pond or lake

4. The nature of Rooiberg Group Volcanism

4.1. Sedimentary interbeds

The early volcanism of the Rooiberg Group (preserved in the Dullstroom Formation) was apparently continuous, forming thick successions of massive lavas with only minor pyroclastic layers and sedimentary interbeds (French and Twist, 1983). We interpret the scarcity of sedimentary interbeds as reflecting either rapid accumulation, or the constructional nature of the volcanic units (cf., volcanic geomorphic landscape elements that build rapidly and positively, normally at faster rates than sedimentary deposits). Later Rooiberg volcanism (preserved in the Damwal to Schrikkloof Formations) was less continuous, with hiatuses being indicated by more abundant interbedded sandstone and shale (Fig. 4). The sandstone indicates a non-volcanic erosional source. At least for the lower part of the Rooiberg Group, it can be argued that the quiescent breaks in volcanism were of short duration. We base this premise on the observation (Eriksson et al., 1994) that only siliciclastic Pretoria Group detritus from nearby source areas was deposited during most of these hiatuses, implying that time was too short for weathered volcanic detritus to become available. Only the uppermost sandstones bear evidence of a silicic volcanic component (cf., Eriksson et al., 1994) thereby suggesting longer hiatuses. Although Twist (1983, 1985) interpreted these sandstones to have been deposited in a littoral environment, more recent work suggests that deposition took place within sandy braided rivers, draining low-lying source areas and spreading erratically over the lava flow surfaces during quiescent breaks in volcanic activity (Eriksson et al., 1994). The nature of the shales is less certain as they may contain a large amount of primary or reworked volcanic material (French and Twist, 1983).

4.2. Areal extent and eruptive volume

Willemse (1969) recorded an areal extent of the Rooiberg Group of between 50,000 and 67,000 km^2. More recent work, however, showed that the Rooiberg Group originally covered an area of more than 200,000 km^2 (Fig. 2) (Cawthorn and Walraven, 1997). The volume left after erosion is approximately 350,000 km^3 (Eriksson et al., 1995; Cawthorn and Walraven, 1997), and thicknesses range from 3 to more than 5 km (von Gruenewaldt, 1968, 1972; du Plessis, 1976; Clubley-Armstrong, 1977). This volume is comparable with that of the Rustenburg Layered Suite of the Bushveld Complex and makes the Rooiberg Group one of the largest provinces of silicic volcanic rocks known (Twist and French, 1983). Harmer and Armstrong (2000) suggested that the Bushveld LIP as a whole produced between 0.7 and 1 million km^3 of magma within 1-3 My, which would require magma generation rates between 1 and 0.3 x 10^6 km^3 per Ma, respectively.

4.3. Petrology and Geochemistry

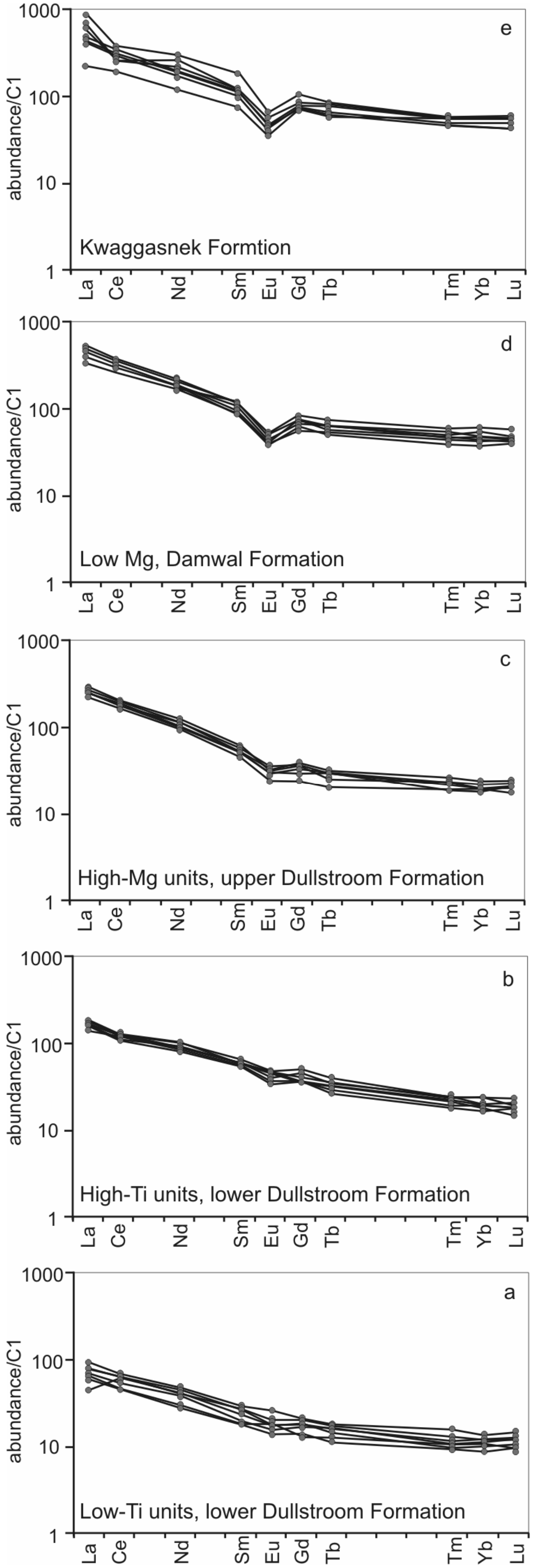
The Rooiberg Group consists of nine magma types, with the greatest variety of magma types occurring in the basal Dullstroom Formation (Table 1) (Hatton and Schweitzer, 1995). The lower to middle Dullstroom Formation is composed of interbedded low-Ti (TiO_2 <1.0 wt.%; SiO_2 <60 wt.%), high-Ti (TiO_2 >1.0 wt.%; SiO_2 <60 wt.%) and high-Mg (2.0 wt.% on average; Twist, 1985; Schweitzer et al., 1995) volcanic units, ranging from basalt to andesite (Buchanan et al., 1999, 2004). Younger volcanic units range from andesite to dacite in the upper Dullstroom Formation and are predominantly rhyolite in the overlying Damwal, Kwaggasnek and Schrikkloof formations (Buchanan et al., 2002).

Above the basal rhyolite of the Dullstroom Formation there is a general increase in SiO_2 and decrease in MgO towards the top of the volcanic succession. The Damwal Formation, composed predominantly of dacites and rhyolites, contains lower proportions of MgO (1.09 wt.%) than the upper Dullstroom Formation, whereas the rocks of the Kwaggasnek Formation contain on average 0.66 wt.% MgO (Hatton and Schweitzer, 1995). Abundances of Al_2O_3 decrease with increasing stratigraphic height in the Rooiberg Group from an average of 15.2 wt.% for low-Ti lavas of the Dullstroom Formation to an average of 11.5 wt.% for the Kwaggasnek Formation (Buchanan et al., 1999, 2002; Buchanan, 2006).

Incompatible trace elements, including rare earth elements (REE), increase in abundance with increased stratigraphic height and SiO_2 content (Fig. 5) (Buchanan, 2006). Magnitudes of negative Eu anomalies, as measured by decreasing values of Eu/Eu* (measured/ projected Eu values), also increase with stratigraphic height. Average abundances of Sc decrease from 34.2 ppm for low-Ti units of the Dullstroom Formation to 1.35 ppm for the Kwaggasnek Formation (Buchanan et al., 1999, 2002; Buchanan, 2006).

The compositional data indicate that the dacites and rhyolites were derived from low-Ti melts by fractional crystallization and assimilation in a mid-crustal magma chamber before emplacement (Buchanan et al., 1999, 2002, 2004). Recently, comparisons of experimentally derived liquid compositions from mafic mantle and crustal sources carried out by Turner and Rushmer (2009) in several LIPs revealed key discriminants between those two sources (Al_2O_3, total FeO and water content), and favour a mafic mantle source for low-Ti rhyolites which bear striking chemical resemblance to A-type granites (such as the Lebowa Granite Suite in the case of the Rooiberg Group; Buchanan et al., 2004). The Rooiberg Group is given as a key example of an origin due to fractional crystallisation, which lends support to Turner and Rushmore's (2009) theory (c.f., Pankhurst et al., 2011). Average SiO_2/Al_2O_3 ratios of 2.068 and average K_2O/Na_2O ratios of 5.830 for the Rooiberg deposits (Twist, 1985) could be another piece of evidence supporting crystal fractionation. According to Pankhurst et al. (2011) high SiO_2/Al_2O_3 ratios (~5-7) and high K_2O/Na_2O ratios (>1.5) are diagnostic characteristics of the rhyolites observed within mafic LIPs that are primarily the products of efficient fractional crystallization from a mafic mantle source. In contrast, rhyolites with lower SiO_2/Al_2O_3 ratios (~4) and lower K_2O/Na_2O ratios (<1.5) appear to occur more in response to lithospheric extension, during rifting or back-arc evolution (Pankhurst et al., 2011).

Van Tongeren et al. (2010) went a step further by leaving out the underlying Dullstroom Formation and considering only the Damwal, Kwaggasnek and Schrikkloof formations in their calculations. Based on their results, Van Tongeren et al. (2010) suggest that the Bushveld Complex was initially a hypabyssal intrusion, where the overburden grew significantly thicker as the erupted Rooiberg lava (forming together with the RLS from a single parent magma in the same magma chamber) issued from the chamber late in the crystallization process and was deposited on the initially thin roof. Volcanic units of the high-Ti suite of the Dullstroom Formation, however, are enriched in incompatible trace elements and were derived, at least in part, from a different source and resided in a different magma chamber (Buchanan et al., 2002). Rb-Sr and Sm-Nd isotopic compositions are similar to those indicated for melts that crystallized to form the Rustenberg Layered Suite (RLS) of the Bushveld Complex (Buchanan et al., 2004). Therefore, several authors (e.g. Sharpe et al., 1986; Maier et al., 2000; Buchanan et al., 2004) propose that Rooiberg Group melts may have resided in the same magma chamber(s), considered an intermediate residence for the magmas of the RLS, before the melts separated, started to rise to higher elevations in the crust, and, were eventually expelled onto the surface.



1000
100
10
1
abundance/C1
e
Kwaggasnek Formtion
La Ce Nd Sm Eu Gd Tb Tm Yb Lu
d
Low Mg, Damwal Formation
c
High-Mg units, upper Dullstroom Formation
b
High-Ti units, lower Dullstroom Formation
a
Low-Ti units, lower Dullstroom Formation

Figure 5. Chondrite-normalised REE diagram for the volcanic units of the Rooiberg Group: a) low-Ti units of the lower Dullstroom Formation; b) high-Ti units of the lower Dullstroom Formation; c) high-Mg units of the upper Dullstroom Formation; d) low-Mg units of the Damwal Formation; and e) silicic volcanic units of the Kwaggasnek Formation (after Buchanan et al., 1999, 2002; Buchanan 2006). Abundances are normalised to those of C1 chondrites from Anders and Grevesse (1989).

4.4. Intensive parameters of magma (temperature and viscosity)

4.4.1. *Phenocryst contents of Rooiberg lavas*

We conducted a preliminary study on four samples of Rooiberg lava flows, with the aim of making an initial interpretation of the intensive parameters and therefore modelling their possible eruption temperatures and viscosities at the time of their eruption**.** In thermodynamics, exchanges within a system, such as a magma chamber, and the outside are controlled by intensive parameters such as temperature, viscosity, pressure, oxygen fugacity, mole fraction, and specific volume. These data are the basis for inferences on the changing conditions of crystallisation and the dynamics of the magma chamber (Agangi, 2011).

The Rooiberg lava flow units differ significantly in phenocryst content and mineralogy, and range from porphyritic to aphyric in texture. The phenocryst-rich lavas contain between 10 and 30 vol.% of phenocrysts of plagioclase, sanidine, quartz, augite and rare pigeonite, set in a groundmass of plagioclase, clinopyroxene, magnetite and ilmenite. Most phenocrysts are 1 - 10 mm in size, but a few sanidine and quartz crystals are larger than 2 cm across. The aphyric lavas contain roughly 0-3 vol.% of euhedral phenocrysts of quartz, sanidine and plagioclase. Most phenocrysts are < 3 mm in size. Spherulites in the groundmass are composed of quartz and feldspar crystals radiating from a common nucleus.

4.4.2. Temperature estimates

The absence of hydrous phenocrysts in most Rooiberg rocks, and available mineral thermometry suggest that the Rooiberg magmas were unusually hot and water-undersaturated. We recently undertook preliminary studies of eruption temperatures based on four porphyritic Rooiberg lavas with phenocryst contents between 10 and 30 vol.% taken from the upper Dullstroom Formation and the Damwal Formation (Table 3), both cropping out in the Loskop Dam area. Compositions of phenocrysts were determined by wavelength-dispersive electron microprobe analysis of polished thin sections on a Cameca SX-100. An accelerating voltage of 25 kV, a beam current of 10 nA and a beam diameter of 0.1 microns were employed. Equilibration temperatures were determined by application of two-feldspar geothermometry with the help of the SOLVCALC 1.0 software of Wen and Nekvasil (1994) using the feldspar site mixing models of Nekvasil and Burnham (1987) and Elkins and Grove (1990). The Nekvasil and Burnham (1987) solid-solution model is very similar to that of Elkins and Grove (1990), and use of the latter model yields results in agreement with the eutectic data (Nekvasil and Carrol, 1993). Temperatures at the time of crystallization of the Dullstroom and Damwal Formations – and presumably at eruption – ranged from approximately 840-1200°C according to the Nekvasil and Burnham (1987) model, and from 880-1120°C according to the Elkins and Grove (1990) model (Table 3). Twist and Elston (1979) found that the Rooiberg eruption temperatures of the younger, more silica-rich formations exceeded 1000°C by application of similar mineral-pair geothermometers.

Table 3. Feldspar thermometry results for four samples of the Dullstroom and Damwal Formations of the Rooiberg Group.

Formation	Unit	Sample	Plagioclase			Alkali-feldspar			Temperature (°C)	
			Ab	Or	An	Ab	Or	An	Nekvasil & Burnham (1987)	Elkins & Grove (1990)
Dullstroom	U2	RG12	0.441	0.147	0.411	0.315	0.588	0.096	1193.2	1120.2
Damwal	U3	RG19	0.917	0.042	0.041	0.054	0.914	0.032	841.0	878.4
Damwal	U3	RG17	0.941	0.024	0.035	0.024	0.942	0.034	871.2	978.7
Damwal	U5	RG25	0.526	0.094	0.379	0.284	0.672	0.043	1002.0	926.9

4.4.3. *Viscosity estimates*

Viscosities of the Rooiberg Group lavas (Table 4) were calculated using the method of Shaw (1972) and Giordano et al. (2006), and the effect of suspended phenocrysts was determined by the method of Roscoe (as presented in McBirney and Murase, 1984). The pre-eruptive apparent viscosities of the four analysed samples were between $\log_{10}$ 5.37 Pa.s and $\log_{10}$ 10.02 Pa.s, after Giordano et al. (2006) and between $\log_{10}$ 4.81 Pa.s and $\log_{10}$ 8.27 Pa.s, after Shaw (1972). Including the effect of the phenocrysts gave effective viscosities between $\log_{10}$ 5.0 Pa.s and $\log_{10}$ 8.57 Pa.s.

Table 4. Viscosity calculation results for four samples of the Dullstroom and Damwal Formations of the Rooiberg Group.

Formation	Unit	Sample	Phenocryst content (%)	Viscosity ($\log_{10}$ Pa.s)		
				Shaw (1972)	Giordano et al. (2006)	Effective viscosity[1]
Dullstroom	U2	RG12	10	4.81	5.37	5.00
Damwal	U3	RG19	15	8.27	10.02	8.57
Damwal	U3	RG17	20	6.14	7.33	6.56
Damwal	U5	RG25	30	8.17	10.43	8.88

[1]Roscoe (as presented in McBirney and Murase, 1984).

5. Discussion

5.1. Emplacement mechanisms

Based on previous literature and new data from our preliminary work on the Rooiberg Group, we suggest that this volcanic-dominated succession belongs to a group of widespread felsic successions that lack pyroclastic units and that were derived from high temperature magmas (c.f., Allen and McPhie, 2002). This group of volcanic successions includes many examples from important intraplate provinces such as the volcanic rocks of the Proterozoic Midcontinent rift, Minnesota (Green and Fitz, 1993), the Gawler Range Volcanics, South Australia (Allen et al., 2008), the Tertiary Trans-Pecos volcanic field, Texas (Henry et al., 1988), and the Tertiary Snake River Plain volcanic province, Idaho (Bonnichsen and Kauffman, 1987; Manley, 1996).

Our geodynamic model illustrates the inferred evolution of the Rooiberg Group (Fig. 6). Following Transvaal Supergroup deposition, a set of shrinking basins characterised by relatively immature shallow marine and fluvial deposits (referred to as the post-Magaliesberg Formation succession) is inferred, and these are interpreted as forming part of an overall tectonically unstable setting (Schreiber and Eriksson, 1992; Eriksson et al., 1998). This setting was also affected by relatively gentle regional shortening and folding of Transvaal sedimentary strata as the Eburnean supercontinent, which included the Kaapvaal craton, began to amalgamate (Eriksson et al., 1998). The post-Magaliesberg Formation sedimentary succession points to rapid uplift and tectonic instability related to major and rapid thermal doming as the Rooiberg magmas ascended through the crust (Eriksson et al., 1993, 1995; Catuneanu and Eriksson, 1999). The uppermost Pretoria Group clastic depositional environment was thus disrupted by Rooiberg volcanism, with emplacement of extensive mafic to felsic lavas, and subordinate volcaniclastic strata and clastic sediments. The felsic lavas were probably hot (840-1200°C), and their relatively low effective viscosities ($\log_{10}\eta$ 5.0- 8.57 Pa.s) allowed relatively rapid discharge and extensive outflow. The flows' great thicknesses may have lead to relatively efficient heat retention to delay solidification and prolong mobility for many years following extrusion (cf., Manley, 1992). Given the preserved volumes of Rooiberg Group volcanic rocks and their inferred original volumes, a sufficient mass eruption rate from a voluminuous chamber is postulated, and hence the total erupted volume was most likely the limiting factor in how far the rhyolites would have travelled (cf., Manley, 1992).

The lavas erupted over large areas of land where active sandy braided river systems (Eriksson et al., 1994) and probably open water bodies such as ponds and small lakes existed (Fig. 6). The lavas preserved important information concerning these continental environments, including complete sedimentary structures and bedforms. The quiescent breaks in volcanism were of short duration, as only Pretoria Group detritus from nearby source areas was deposited, with time appearing to have been too short for weathered silicic volcanic detritus to become available (see discussion in Eriksson et al., 1994). Only the uppermost sandstones interbedded with the Rooiberg lava flows bear geochemical evidence of a silicic volcanic component (Eriksson et al., 1994). The presence of localized pumiceous, crystal-rich or fine-grained volcaniclastic beds (both primary and reworked) in the Rooiberg Group suggests that small-volume pyroclastic eruptions occurred throughout its evolution. In many cases, these volcaniclastic deposits separate single lava flows, suggesting that eruptive activity alternated between effusive and explosive during the development of the Rooiberg Group. Reworked volcaniclastic facies together with possible hyaloclastites interlayered with sandstones and shales formed where Rooiberg lavas encroached onto latest Pretoria Group sedimentary settings. Furthermore, our recognition of peperitic breccia in the Rooiberg volcanic succession (especially in and between the Kwaggasnek and Schrikkloof formations) provides an effective way of determining the contemporaneous nature of volcanism and active sedimentation (e.g. Hanson and Schweickert, 1982; Einsele, 1986; Kano, 1989; Maas, 1992; Dadd and van Wagoner, 2002).

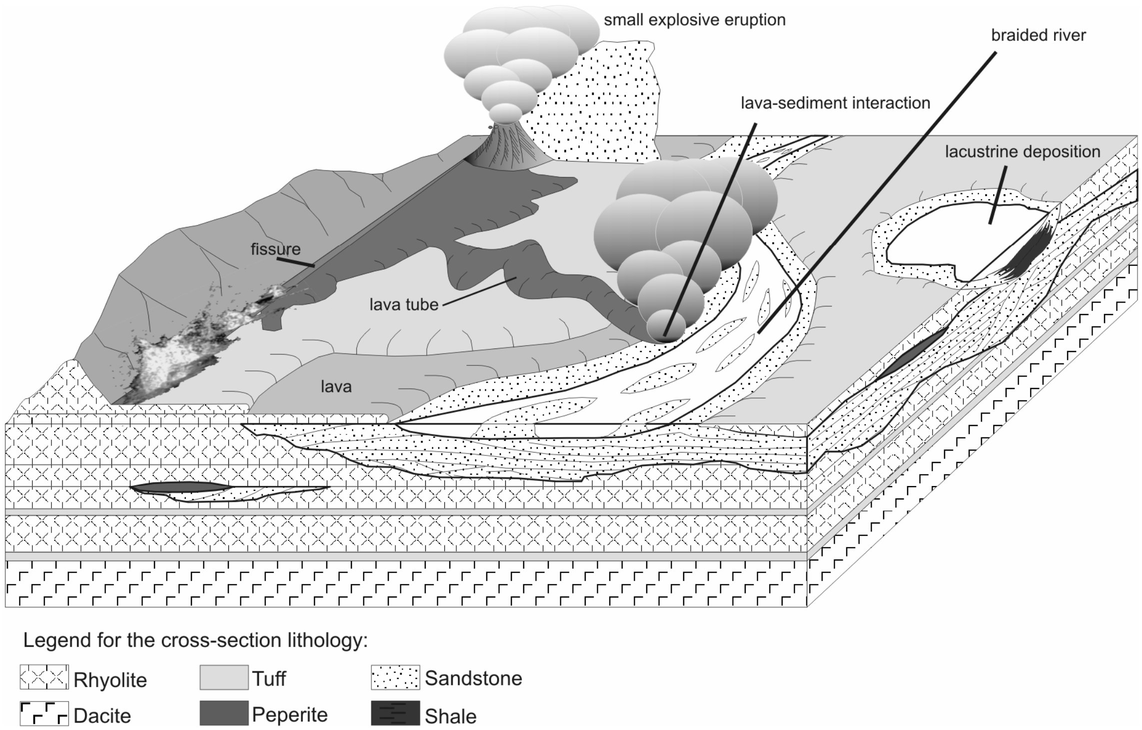


Figure 6. Reconstruction of the palaeoenvironment postulated for the Rooiberg Group. The model reflects the resurgence of Rooiberg volcanism after a relatively short hiatus during which localised clastic sedimentation derived from weathered Pretoria Group source areas adjacent to the volcanic basin, occurred within short-lived braided fluvial and localised lacustrine settings. The full inferred range of volcanic processes and products as well as possible interactions with the short-lived sedimentary environments are also shown, as the model is essentially schematic. Fissure eruptions with subordinate lava fountaining are presumed as the predominant volcanic style, with minor and localised pyroclastic eruptions; peperites formed where lavas locally impinged on wet sedimentary environments.

5.2. Cooling history

The cooling history of the Rooiberg deposits can be derived from the different textures found within the lava units (e.g. Lofgren, 1971a, b). Spherulite distribution sheds light on cooling and crystallisation whereas amygdales record part of the degassing history of a lava flow (Orth and McPhie, 2003). According to Lofgren (1974) spherulites may crystallize directly from the melt in response to large undercoolings. They can also occur through devitrification of a glass phase (i.e. crystallization below the glass transition temperature) although this is unlikely to occur under dry conditions, such as are inferred from the analysed Rooiberg Group lavas lacking hydrous mineral phases, because molecular diffusivities in the glass are too small (e.g. Manley, 1992). One exception for glass devitrification (in response to heating to 250-700°C and the presence of an alkali-rich fluid phase; Lofgren, 1971a) could be later hydrothermal-fluid circulation during vesicle-filling (Fowler et al., 2002). Within the Loskop Dam area (c.f., Twist, 1985) observed spherulite textures in the Rooiberg Group lava flows compare favourably with the two different cooling stages recognized by Lofgren (1971a) in his classic work**:** (1) widely spaced spherulites within glass, as have been observed mainly in unit 1 of the Dullstroom Formation (Table 1) suggest rapid cooling of water-undersaturated melt, with low-temperature (200°C) hydration in the presence of solutions with low alkali content (0.1 wt%); (2) abundant spherulites with a variety of shapes, forming a completely crystalline aggregate, as have been observed especially in units 3 and 4 of the Damwal Formation suggest higher water concentrations in the melt than in the underlying Dullstroom Formation, slower cooling and maintenance of higher temperatures than for the previous stage.

Abundant amygdales within the Rooiberg deposits attest to the exsolution of volatiles. Large amygdales (up to 5 cm across) are abundant in the upper parts of the Rooiberg lava flows but less abundant in lower parts close to the presumable flow bases. Crystallisation of the anhydrous minerals in the rhyolite probably expelled any volatile phases by diffusion and/or exsolution (e.g. Westrich et al., 1988; Toramaru, 1995). In the lower zone of the Rooiberg lava flows, the exsolved volatiles formed a few large bubbles. The relatively large size and low abundance imply that an early stage of bubble growth and coalescence in the high-temperature melt preceded solidification. The sparse number of amygdales in the lower zone of individual flows, which had the slowest cooling rate as it was beneath a considerable thickness of lava, could indicate that any earlier formed bubbles in this zone either migrated upwards or were resorbed into the melt (c.f. Orth and McPhie, 2003).

5.3. Source constraints

Identification of source volcanic centres is particularly difficult within the Rooiberg Group, given the very large area covered by these units. Moreover, single lava flows are typically relatively uniform in texture, composition, and thickness, with no easily mapped proximal-to-distal variations. Fissure vents are the most likely source, as they are for flood basalts and some moderate-volume felsic lavas (e.g., Manley, 1996) but have yet to be identified.

5. Conclusions

The Rooiberg Group volcanics, preceding the intrusion of the Rustenberg Layered Suite of the Bushveld Complex in the northern Kaapvaal Craton, belong to a group of widespread felsic successions that are increasingly recognised in the rock record, and which are intracontinental, subaerial, and are dominated by voluminous lavas. A thorough review of the geochronology, physical volcanology, and geochemistry of the Rooiberg Group, together with a first properly constrained lithofacies interpretation as presented here, have enabled the construction of a geodynamic model. New geothermometry data revealed that the lavas were probably hot and displayed relatively low viscosities, which, together with high eruption rates, were the main contributing factors to the extensive outflow and widespread distribution of the Rooiberg Group. The effusive volcanism was initially concomitant with active sedimentation in sandy braided river systems and possibly ponds and small lakes of late Transvaal Supergroup affinity, as shown by interlayered sedimentary rocks and peperites. Quiescent breaks in volcanism were only of short duration, based on the occurence of only localized, relatively thin interbedded sedimentary strata. Small-volume pyroclastic deposits are evidence for alternating effusive and explosive eruptions during development of the Rooiberg Group.

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