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THE DULLSTROOM BASALT FORMATION AND THE ROOIBERG GROUP: VOLCANIC ROCKS ASSOCIATED WITH THE BUSHVELD COMPLEX

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The Dullstroom Basalt Formation and the Rooiberg Group: volcanic rocks associated with the Bushveld Complex

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I, Joachim-Klaus Schweitzer, declare that, unless specifically acknowledged, this dissertation represents my own, unaided work. It is submitted for the degree of Doctor of Philosophy to the University of Pretoria. It has not been submitted before for any degree or examination at any other university.

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The Dullstroom Basalt Formation and the Rooiberg Group:
volcanic rocks associated with the Bushveld Complex

Abstract

The aims of this study are twofold. First is to investigate the potential link between the predominantly volcanic Dullstroom Basalt Formation and the Rooiberg Group (both units formerly considered as part of the Transvaal Supergroup), now prised apart by the mafic rocks of the Rustenburg Layered Suite (RLS) and, second, to establish the possible relationship of these volcanic rocks with the Bushveld Complex. Field, petrographic, and geochemical investigations cover identified and potential Dullstroom volcanic rock occurrences (southeastern Bushveld Complex, Makeckaan and Rooiberg Fragments), as well as outcrops of the Rooiberg Group (Bothasberg Plateau, and Tauteshoogte, Rooiberg, and Loskop Dam areas). The Dullstroom volcanic rocks in the southeastern portion of the Complex are mapped documented and interpreted in detail, which also results in the first compilation of a comprehensive geological map. Extrusive volumes and mode of eruption are deduced for individual magma types. Three depressions in the vicinity of potential eruption centers are documented. A sand sheet overlies the generally flat unconformity that marks the top of the Transvaal Supergroup. Interaction between this sheet and the first extrusions is pronounced.

The primary chemical composition of the rocks under consideration has been modified, in part as a consequence of their age but mostly by their proximity to major, acidic and mafic intrusive rocks. Field, petrographic and geochemical evidence are employed to identify mobile and immobile element concentrations. The floor rocks of the RLS (Dullstroom Basalt Formation) were subjected to thermal metamorphism and accompanying dehydration. Si, Mn, Ca, Na, K, Fe, Mg, Sr, Th, Ba, U, Hf, Ni, Cu, Zn, Pb, Nb, Zr, and Y were mobile in the roof rocks (Rooiberg Group). There, the mode and degree of alteration depends on the geological setting and the distance from major intrusions. Ti, Al, P, Ga, Sc, and heavy rare earth elements proved inert. Hydrothermal convection cells, active in the roof rocks, are expressed as a 1.4 kilometer thick zone of upward increasing hydration, topped by maximum concentrations of Pb (335 ppm), Zn (929 ppm), and Mn (0.45 wt.%). Alteration also affected the color of the rocks. Therefore color can not be utilized for stratigraphic subdivision nor to draw inferences about the evolution of the Proterozoic atmosphere.

Employing immobile element concentrations it is deduced that one magma type, the High-Mg Felsite (HMF), is common to the volcanic floor and roof successions of the RLS, unequivocally establishing that the volcanic rocks were continuous before separation by the mafic rocks. The Dullstroom Formation therefore represents the basal portion of the Rooiberg Group and this fact creates the potential to establish a

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regionally applicable stratigraphy for the Rooiberg Group. This incorporates the regional review of previous field and geochemical work.

It is recommended that the Rooiberg Group be redefined to include the Dullstroom Formation and that it is regionally subdivided into the Dullstroom, Damwal, Kwaggasnek, and Schrikkloof Formations (bottom to top). The Loskop Formation, overlying the Rooiberg Group, could potentially be included in the Rooiberg Group, but this awaits detailed study.

Regionally persistent marker horizons, readily visible in the field, support the proposed subdivision. These are (i) a zone of quartzite xenoliths in the uppermost portion of the Kwaggasnek Formation, (ii) the Union Tin Member, which constitutes the top of the Kwaggasnek Formation, and (iii) the strongly flow-banded Schrikkloof Formation, commonly topped by a tuffaceous deposit. The lowermost Dullstroom succession is also present in the Makeckaan and Rooiberg Fragments. In the Rooiberg Fragment this succession is overlain by LMF flows of the Schrikkloof Formation, identifying intra-Rooiberg unconformities that onlap towards the north and northwest. The uppermost Dullstroom Formation is preserved in the Loskop Dam area. Synthesis of all available data facilitates the classification of previously undefined Rooiberg occurrences and a regional map of the Rooiberg Group detailing the distribution of the four formations is consequently compiled. It is suggested that the basal Rooiberg succession is also preserved beyond the present-day outcrop of the Bushveld Complex, e.g. in the Molopo Farms Complex.

Six interstratified magma types constitute the Dullstroom Formation and these are named, in order of their extrusive sequence: Low-Ti (LTI) Basaltic Andesite, Basal Rhyolite, High-Ti (HTI) Basalt, High-Mg Felsite (HMF), High-Fe-Ti-P Andesite, and Low-Mg Felsite (LMF). The latter two are continuous into the Damwal Formation, with the last HMF extrusion defining the top of the Dullstroom Formation. Two compositionally distinct LMF's constitute the Kwaggasnek and Schrikkloof Formations. In total then, eight magma types define the Rooiberg Group, with individual magma types exhibiting only minor signs of fractional crystallization. Sr_i is elevated and high concentrations of elements characteristically enriched in the crust are encountered. The HMF has a Proterozoic, upper crustal composition.

The anomalously high Zn and Pb concentrations in the massive volcanic rocks in the roof zone of the RLS lead to consideration of the economic potential of the Rooiberg Group. Previously described deposits can be related to the newly established stratigraphic subdivision of the Rooiberg Group. Four mineralizing events, two linked to the intrusions of the RLS and one each to the intrusion of the Rashoop Granophyre and Lebowa Granite Suites, appear to have affected the Rooiberg Group. Initial intrusions of the RLS are proposed to have pneumatolytically-hydrothermally concentrated base metals, especially copper, into the Dullstroom floor succession (first mineralizing event). Pyrite and arsenopyrite in sedimentary rocks at the base of the Kwaggasnek Formation could be due to shallow granophyre intrusions (second mineralizing

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event), subsequently overprinted by base metal mineralization (mainly Pb and Zn), constituting the third mineralizing event. Fourthly, the Lebowa granites introduced tin and fluorspar, and this type of mineralization is restricted to the upper Kwaggasnek and Schrikkloof Formations. Sinter deposits, present at the top of the Schrikkloof Formation, are interpreted to be the surface expression of the hydrothermal convection cell, and may be considered for their gold concentrations.

Currently available age data suggest that the Rooiberg Group (2061±2Ma) is more closely associated with the Bushveld Complex (2054±2Ma for the Rustenburg Layered and Lebowa Granite Suites, 2053±12Ma for the Rashoop Granophyre Suite, and 2060±2Ma for the Rooikop Granite Porphyry) than the Transvaal Supergroup (about 2.4 – 2.6Ga). This is supported by a close geographic association of the volcanic and intrusive rocks, leading to consideration of the potential link between the acidic Bushveld suites and the Rooiberg Group. Comparison of granophyre and Rooiberg rhyolite chemistry confirms that the granophyre, by and large, is the shallow intrusive equivalent of the rhyolite, rather than remelted rhyolite or melted sedimentary rocks. The Rooikop Granite Porphyry is the shallow intrusive equivalent of the most evolved, and youngest Rooiberg magma. Further evidence supporting the notion that the Rooiberg Group forms part of the Bushveld Complex is found in the fact that the youngest Rooiberg rhyolite compositions compare favorably with those of published Bushveld granites. The Rooiberg rhyolites, Rashoop granophyre and Lebowa granite are therefore all derived from a source similar to upper crustal composition. Granite intrusion terminated the Bushveld magmatic event, but may have overlapped in time with the last extrusions of the Rooiberg rhyolites.

Considering available evidence, a plume origin of the Complex is favored over a meteorite impact. It is concluded that a mantle plume initiated the Bushveld magmatic event, with volcanic extrusions and silicic (Rashoop Granophyre and Lebowa Granite Suites) intrusions being related. The presence of Bushveld satellite intrusions, together with the Bushveld metamorphic event affecting large portions of the Kaapvaal Craton, suggests that Bushveld magmatism was regional. Since evidence of uplift is absent from the main body of the Complex and uplift probably occurred towards the north and northwest, it is suggested that the Bushveld plume was positioned towards the north of the present-day outcrop of the Complex. Intraplating, by plume-derived magma at the lower-upper crustal boundary, of the Kaapvaal Craton at 2054Ma is proposed to have caused the Bushveld magmatic event. This also resulted in the strong upper crustal signature for the majority of Bushveld magma types.

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Die Dullstroom Basaltformasie en die Rooiberggroep: vulkaniese gesteentes geassosieer met die Bosveldkompleks.

Opsomming

Die doel van die studie is tweeledig. Eerstens is dit om die potensiële skakel tussen die oorwegend vulkaniese Dullstroom Basaltformasie en die Rooiberggroep te beskryf (beide eenhede is voorheen as deel van die Transvaal Supergroep gesien en word nou geskei deur basiese gesteentes van die Rustenburg Gelaagde Suite (RLS)), en tweedens is dit om die moontlike verband tussen hierdie twee vulkaniese rotsopeenvolgings en die Bosveldkompleks vas te stel.

Veld-, petrografiese-, en geochemiese navorsing dek die voorkomste van positief geïdentifiseerde en potensiële Dullstroom vulkaniese gesteentes (suidoos Bosveldkompleks, Makeckaan- en Rooibergfragmente), asook dagsome van die Rooiberggroep (Bothasbergplato, Tauteshoogte-, Rooiberg- en Loskopdamgebiede). Die Dullstroom vulkaniese gesteentes in die suidoostelike gedeelte van die Bosveldkompleks is gekarteer, gedokumenteer en volledig geïnterpreteer. Gevolglik is ook die eerste samestelling van 'n omvattende geologiese kaart gedoen. Ekstrusiewe volumes en ekstrusiemeganismes word afgelei vir die individuele magmatipes. Drie versakkings in die omgewing van moonlike ekstrusiepunte is gedokumenteer. 'n Sandlaag is teenwoordig op die diskordansie wat die top van die Transvaal Supergroep aandui. Tekens van interaksie tussen die sandlaag en die eerste lawauitvloeiings is teenwoordig.

Die primêre chemiese samestelling van die gesteentes onder bespreking toon verandering - gedeeltelik as gevolg van die lang tydsverloop, maar hoofsaaklik as gevolg van hul nabyheid aan belangrike suur- en basiese intrusiegesteentes. Veld-, petrografiese- en geochemiese gegewens is gebruik om die mobiele en nie-mobiele elementkonsentrasies te identifiseer. Die gesteentes onder die RLS (d.i. Dullstroom Basaltformasie) is onderwerp aan termale metamorfose en gepaardgaande dehidrasie. In teenstelling was Si, Mn, Ca, Na, K, Fe, Mg, Sr, Th, Ba, U, Hf, Ni, Cu, Zn, Pb, Nb, Zr, en Y mobiel in die dakgesteentes (Rooiberggroep) van die RLS. In die gesteentes is die meganisme en graad van verandering afhanklik van die geologiese ligging en afstand van groot intrusiegesteentes. Daar is vasgestel dat Ti, Al, P, Ga, Sc, sowel as swaarder seldsame aarde elemente nie mobiel was. Hidrotermale konveksieselle, aktief in die dakgesteentes, word illustreer deur 'n 1.4 kilometer dik sone wat opwaarts toeneem in graad van hidrasie. Maksimum konsentrasies van Pb (335ppm), Zn (929ppm) en Mn (0.45wt.%) word aan die bokant van die sone bereik. Verandering het ook die kleur van die rots aangetas. Gevolglik kan kleur nie gebruik word vir

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stratigrafiese onderverdeling of om afleidings te maak ten opsigte van die evolusie van die Proterosoïese atmosfeer nie.

Uit 'n studie van die nie-mobiele elementkonsentrasies is die afleiding gemaak dat een magmatipe - die Hoë Mg-felsiet (HMF), algemeen voorkom in die vloer- en dakopeenvolgings van die RLS. Dit is onteenseglik vasgestel dat die vulkaniese gesteentes van die Dullstroom Basaltformasie en die Rooiberggroep aaneenlopend was voordat dit deur die basiese gesteentes van die RLS geskei is. Die Dullstroomformasie stel gevolglik die basale gedeelte van die Rooiberggroep voor. Hierdie feit het die geleentheid geskep om 'n regionaal-toepaslike stratigrafie vir die Rooiberggroep daar te stel. Inligting verkry uit vorige veld- en geochemiese werk is hierby ingesluit.

Dit word aanbeveel dat die Rooiberggroep herdefinieer word om die Dullstroom Basaltformasie in te sluit, en dat die nuutgedefinieerde Rooiberggroep as volg onderverdeel word (van onder na bo) : Dullstroom-, Damwal-, Kwaggasnek- en Schrikkloofformasie. Die Loskopformasie wat bo-op die Rooiberggroep voorkom kan moontlik ook by die Rooiberggroep ingesluit word, maar verdere studie word hiervoor benodig.

Regionaal-standhoudende horisonne, geredelik herkenbaar in die veld, verleen ondersteuning aan die voorgestelde onderverdeling. Hieronder tel (i) 'n sone van kwartsietinsluitsels in die boonste deel van die Kwaggasnekformasie, (ii) die Union Tin Lid, wat die top van die Kwaggasnekformasie verteenwoordig, en (iii) die sterk vloeigebande Schrikkloofformasie wat algemeen bedek word deur 'n tuffagtige afsetting. Die onderste Dullstroomopeenvolging is ook sigbaar in die Makeckaan- en Rooibergfragmente. In die Rooibergfragment is die opeenvolging bedek deur 'n vloei van Lae Mg-felsiet (LMF) van die Schrikkloofformasie. Dit definieer die intra-Rooiberg diskordansie wat na die noorde en noordweste van die betrokke gebied voorkom. 'n Sintese van al die beskikbare data het die klassifikasie van die voorheen ongedefinieerde Rooiberg gebeurtenis vergemaklik. 'n Regionale kaart van die Rooiberggroep, wat die verspreiding van die vier formasies detaileer, is gevolglik saamgestel. Daar word voorgestel dat die basale Rooibergopeenvolging ook verder gepreserveer is as die hedendaagse grense van die Bosveldkompleks (byvoorbeeld in die Molopo Farms-kompleks in Botswana).

Ses tussengelaagde magmatipes vorm die Dullstroomformasie. In volgorde van uitvloeiing staan hulle bekend as: Lae Ti-basaltiese andesiet (LTI), Basale rioliet, Hoë Ti-basalt (HTI), Hoë Mg-felsiet (HMF), Hoë Fe-Ti-P-andesiet, and Lae Mg-felsiet (LMF). Laasgenoemde kom ook voor onder die Damwalformasie bokant die RLS waar die laaste HMF-uitvloeiing die bopunt van die Dullstroomformasie definieer. Twee tipes LMF, wat op grond van hul samestelling onderskei word, vorm die Kwaggasnek- en Schrikkloofformasies. In totaal definieer agt magmatipes die Rooiberggroep, waar individuele magmatipes slegs klein tekens van

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fraksionele kristalisasie toon. In die magmas is Sr_I verhoog en hoë konsentrasies van elemente, kenmerkend verryk in die kors, is teenwoordig. Die HMF het Proterosoïese bo-kors samestelling.

Die anomale hoë Zn- and Pb-konsentrasies in die vulkaniese gesteentes in die daksone van die Rustenburg Gelaagde Suite noodsaak die oorweging van die ekonomiese potensiaal van die Rooiberggroep. Die voorheen-beskryfde mineraalafsetting kan in verband gebring word met die nuut-geskepte stratigrafiese onderverdeling van die Rooiberggroep. Vier mineraliseringsperiodes, waarvan twee gekoppel kan word aan die indringing van die Rustenburg Gelaagde Suite en een elk onderskeidelik aan die indringing van die Rashoop Granofier en die Lebowa Graniet Suites, is teenwoordig. Dit word voorgestel dat die aanvanklike indringing van die Rustenburg Gelaagde Suite, pneumatolities-hidrotermale onedelmetale, veral koper, in die Dullstroom opeenvolging gekonsentreer het (eerste mineralisasieperiode). Piriet en arsenopiriet in die sedimentêre gesteentes aan die basis van die Kwaggasnekformasie kan toegeskryf word aan vlak granofierindringings (tweede mineralisasieperiode), wat daarna oorskryf is deur onedelmetaalmineralisasie (hoofsaaklik Pb en Zn) van die derde periode. Vierdens, het die Lebowagraniet tin- en vloeispaatmineralisasie veroorsaak. Laasgenoemde is beperk tot die boonste Kwaggasnek- en Schrikkloofformasies. Sinterafsettings, aanwesig aan die bokant van die Schrikkloofformasie, word gesien as oppervlakmanifestasies van hidrotermale konveksieselle, en mag oorweeg word vir goudkonsentrasie.

Ouderdomsdata, wat tans beskikbaar is, stel voor dat die Rooiberggroep (2061$\pm$2Ma) eerder verwant is aan die Bosveldkompleks (2054$\pm$2Ma vir die Rustenburg Gelaagde en Lebowa Graniet Suites, 2053$\pm$12Ma vir die Rashoop Granofier Suite, en 2060$\pm$2Ma vir die Rooikop Granietporfier) as aan die Transvaal Supergroep (ongeveer 2.2 – 2.6Ga). Die stelling word ondersteun deur die noue assosiasie van die vulkaniese en plutoniese gesteentes. Dit gee weer aanleiding tot die moontlike skakeling tussen die suur Bosveld suites en die Rooiberggroep. 'n Vergelyking van die chemiese samestellings bevestig dat die granofier in die algemeen die vlak indringingsekwivalent van die rioliet is, eerder as wat dit hersmelte rioliet is. Die Rooikop Granietporfier is die vlak intrusiewe ekwivalent van die mees ontwikkelde en daarom jongste Rooiberg magma. Verder, wat die idee ondersteun dat die Rooiberggroep deel uitmaak van die Bosveldkompleks, is gevind dat die jongste Rooiberg riolietsamestellings gunstig vergelyk met dit wat oor die Bosveldgraniet gepubliseer is. Die Rooibergrioliet, Rashoopgranofier en Lebowagraniet is dus almal afkomstig van 'n bron soortgelyk aan die bo-kors. Granietintrusie het die Bosveld magmatiese gebeurtenis ge-eindig, maar dit mag, in tyd, met die laaste ekstrusies van die Rooiberg rioliet oorvleuel het.

Met al die beskikbare gegewens word 'n pluimoorsprong bo die van 'n meteorietimpakoorsprong vir die Bosveldkompleks verkies. Daar word tot die gevolgtrekking gekom dat 'n mantelpluim die Bosveld magmatiese gebeurtenis begin het, met verwantee vulkaniese ekstrusie en intrusie van suur gesteentes (Rashoop Granofier Lebowa Graniet Suites). Die teenwoordigheid van Bosveld satelietindringings tesame

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met grootskaalse metamorfose het groot dele van die Kaapvaalkraton geaffekteer, wat impliseer dat die Bosveld magmatisme streeksgebonde was. Aangesien daar geen bewyse van opheffing in die grootste gedeelte van die Kompleks teenwoordig is nie en aangesien opheffing waarskynlik in die noorde en noordweste voorgekom het, word voorgestel dat die Bosveldpluim noord van die hedendaagse dagsoom van die Kompleks was. Intraplatering van die Kaapvaalkraton deur pluim-verwante magma om en by 2054Ma, word gesien as die oorsaak van die Bosveld magmatiese gebeurtenis. Dit het ook aanleiding gegee het tot die sterk bo-kors karakter van die meerderheid van die magmatipes van die Bosveldkompleks.

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Appendix B: Abstracts

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Appendix C: Co-authored Manuscripts

Appendix D: Isotope Data

Appendix E: Sampling and Sample Localities

Appendix F: Mineral Analyses

Appendix G: Whole Rock Analyses

Appendix H: CIPW-Norm

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Appendix I: Rare Earth Element Analyses

Appendix J: Analytical Methods

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The Dullstroom Basalt Formation and the Rooiberg Group: volcanic rocks associated with the Bushveld Complex

1. Introduction

The Transvaal Supergroup is composed of a 12 to 15 km thick succession of sedimentary and volcanic rocks (SACS, 1980). The Dullstroom Basalt Formation (or Dullstroom Formation in short) and the Rooiberg Group were, prior to this study, regarded as the terminal members of the Transvaal Supergroup. A brief overview of Transvaal volcanism is therefore provided before the Dullstroom and Rooiberg events are considered in more detail.

The oldest volcanic rocks of the Transvaal Supergroup are preserved in the Abel Erasmus Basalt Formation, which is part of the Wolkberg Group. This Formation (up to 500 m thick), is restricted to the northeastern margin of the Transvaal Basin, and rests unconformably on older Swazian rocks (SACS, 1980). However, the most pronounced volcanic activity in the Transvaal Supergroup is found in the Pretoria and Rooiberg Groups. Basaltic lava of the Bushy Bend Member (part of the Timeball Hill Formation, basal portion of the Pretoria Group) are present in the southern area of the Pretoria Group Basin (Eriksson et al., 1994). Pyroclastic rocks are encountered at the equivalent stratigraphic level elsewhere in the Transvaal Basin. The generally 150 to 300 m thick Hekpoort Andesite Formation is developed over an extensive area and circumscribes the Bushveld Complex. Lahar deposits (Eriksson and Twist, 1986) have been described, with andesitic lavas being the dominant rock type. A whole rock, Rb/Sr isochron age of 2224$\pm$21Ma was obtained from lavas in the southeastern portion of the Transvaal Basin (Burger and Coertze, 1975; also see Cornell et al., 1996). Recent age determinations (Beukes, pers. communication, 1998) suggests that the Hekpoort volcanic rocks are more likely to be 2.4Ga old. The, up to 400 m thick, predominantly pyroclastic and volcaniclastic Machadodorp Member, separating the Boven and Lydenburg Members of the Silverton Shale Formation, is restricted to the eastern portion of the Transvaal Supergroup. Subdivision considers a basal pyroclastic and an upper basalt unit (Button, 1974). Basalt lavas exhibit comparable compositions over some 200 km distance, and resemble those of present-day oceanic tholeiites (Button, 1974; Sharpe et al., 1983).

The Dullstroom Formation, in the southeastern area of the Bushveld Complex, represented in the old classification (SACS, 1980) the upper part of the Pretoria Group, and was the thickest basalt to andesite package in the Transvaal Supergroup. In spite of its significant outcrop area of approximately 400 km^2, it had received little attention in the past. The terminal package of volcanic rocks in the Transvaal Supergroup was

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regarded as the very extensive, siliceous eruptives of the Rooiberg Group, with proposed eruptive volumes of 300 000 km^3 over an area of 50 000 km^2 (SACS, 1980; Twist, 1985; Twist and French, 1983).

Mafic intrusions of the Rustenburg Layered Suite (RLS) separate the outcrop areas of the Dullstroom Formation and the Rooiberg Group. The possibility that the Dullstroom and Rooiberg volcanic rocks originally formed one continuous succession is suggested by the outcrop pattern. Recent findings, to be more fully elaborated on in this treatise, question the classification of the Dullstroom Formation and the Rooiberg Group as integral parts of the Transvaal Supergroup. Evidence strongly suggests that the volcanic package is part and parcel of the Bushveld magmatic event.

It is important to note that this study also identifies a sequence of Dullstroom Formation in the roof of the RLS. To avoid confusion, this sequence will hereafter be referred to as the Dullstroom roof succession as opposed to the better known Dullstroom floor succession beneath the RLS.

1.1 Aims and scope of investigation

This investigation has two major aims. First is to examine the physical and chemical characteristics of the Dullstroom and Rooiberg volcanic rocks in order to evaluate the possible link between these successions, and secondly, their relationship with the Bushveld Complex has to be established.

Two major hypotheses are therefore considered:

a) The Dullstroom Basalt Formation and the Rooiberg Group are genetically and temporarily unrelated.

b) These volcanic successions, individually or together, do not form an integral part of the Bushveld magmatic event.

In order to achieve these aims, seven areas were investigated (Appendix A, page A13, Fig. 1, localities 1 to 7): Dullstroom Basalt Formation (Dullstroom area, detailed mapping and sampling); a volcanic xenolith in the RLS (mapping and sampling); Tauteshoogte area (reconnaissance sampling); Bothasberg Plateau (sampling traverse employing the map of Clubley-Armstrong, 1977); Loskop Dam (reconnaissance field visits; geochemical analyses provided by Twist, unpublished data; Twist, 1985); Makeckaan Fragment (mapping and sampling); Rooiberg Fragment (mapping and sampling).

The Dullstroom Formation (Dullstroom area), the volcanic xenolith, and the Rooiberg felsite of the Bothasberg Plateau, Tauteshoogte, and Loskop Dam areas , together, represent the most continuous

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composite section through the relevant volcanic successions. The volcanic rocks of the Makeckaan and Rooiberg Fragments are also important because previous workers have reported conformable contacts between the Pretoria Group and the overlying Rooiberg Group, in both these areas (e.g. Wagner, 1921; Boardman, 1946). Some analyses of granophyre and Rooikop Granite Porphyry intrusions are also considered, as is a database containing published granophyre and granite compositions, for comparative purposes.

Sampling procedure, sample localities, and rock types are provided in Appendix E. Appendices F to I list the analytical data that are utilized during this study. The analytical methods are described in Appendix J.

2. Synthesis and discussion

The research on which this thesis is based has been conducted over a period of 6 years, and this compilation is an amalgamation of the published manuscripts, manuscripts under review or revision, and extended abstracts (Table 1).

The writer performed fieldwork, sampling, sample preparation, petrographical, and geochemical analyses (except for the REE). Manuscripts listed in Appendix A were all written by the candidate including, for example, literature reviews, compilation of the figures, and data analyses. C.J. Hatton is first author on the Hatton and Schweitzer (1995), (Appendix A36 to A51) manuscript because he initially proposed the plume origin for the Bushveld Complex. It is in Appendix A where the writer's major contributions are to be found.

Appendix B (B1 to B17) presents symposia abstracts. The candidate wrote all abstracts, except for Verryn et al. (1995). Abstracts are presented for completeness, but also contain some information and interpretation that are not part of Appendix A. The Schweitzer and Hatton (1997) abstract, for example, compares the sedimentary record at the base of the Ventersdorp and Bushveld plume events, and makes deductions concerning the geographic position of the plume.

Co-authored manuscripts are provided in Appendix C (C1 to C69). The contribution to the Eriksson et al., (1993; C1 to C27) is a preliminary, regional stratigraphic correlation of the Rooiberg Group and a complete geochemical profile thereof. The stratigraphic setting of the Loskop Formation is also discussed. The flood rhyolite manuscript by Twist et al. (1998, C28 to C69), has been included because it reviews the worldwide occurrence of voluminous rhyolites, and discusses eruption mechanisms of the rhyolitic rocks of the Rooiberg Group.

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Appendix D (D1 to D8) summarizes the majority of the available isotope information on the Rooiberg Group, including Rb/Sr isotopic data of the Dullstroom Formation LTI Basaltic Andesite, HTI Basalt, and Basal Rhyolite. The Rb/Sr isotopes were measured and detailed by Schweitzer (1986), but is not included in the author list due to differences in interpretation advanced by Harmer and Farrow (1995, Appendix D).

Table 1: Summary of manuscripts, abstracts, co-authored manuscripts, and isotope data (provided in the same sequence as listed in the Appendices A to D).

Appendix A: Manuscripts

Schweitzer, J.K., Hatton, C.J., and de Waal, S.A., 1995. Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Sequence: a proposed new subdivision. South African Journal of Geology, 98, 245-255.

Schweitzer, J.K. and Hatton, C.J., 1995. Chemical alteration within the volcanic roof rocks of the Bushveld Complex. Economic Geology, 90, 2218-2231.

Schweitzer, J.K., Hatton, C.J., and de Waal, S.A., 1995. Economic potential of the Rooiberg Group - volcanic rocks in the floor and roof of the Bushveld Complex. Mineralium Deposita, 30, 168-177.

Hatton, C.J. and Schweitzer, J.K., 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. Journal of African Earth Sciences, 21, 579-594.

Schweitzer, J.K., Hatton, C.J., and de Waal, S.A., 1997. Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa. Journal of African Earth Sciences, 24, 95-104.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1998 (submitted). The basal portion of the Rooiberg Group, South Africa: the onset of Bushveld magmatism. Journal of Volcanology and Geothermal Research.

Appendix B: Abstracts

Schweitzer, J.K. and Hatton, C.J., 1995. Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex. Extended Abstract, Centennial Geocongress, Rand Afrikaans University, Johannesburg, 532-535.

Hatton, C.J. and Schweitzer, J.K., 1997. The World's largest platinum, chromitite, and gold deposits, South Africa: Mantle plume in origin? Extended Abstract, Plumes Plates and Mineralization Symposium (PPM'97), 14-18 April, University of Pretoria, 45-46.

Schweitzer, J.K., Hatton, C.J., and de Waal, S.A., 1997. The Rooiberg Group: missing link to the understanding of the Bushveld Igneous Complex? Extended Abstract, University of Pretoria - Research Seminar, 26 September, 28-29.

Schweitzer, J.K. and Hatton, C.J., 1997. Sedimentary rocks at the base of the Ventersdorp and Bushveld plume events. Extended Abstract, Symposium on Precambrian Sedimentation Systems, Council for Geosciences, Pretoria, 23 October, unpaginated.

Verryn, S.M.C., de Waal, S.A., Schweitzer, J.K. and Hatton, C.J., 1995. The contact metamorphic aureole of the Rustenburg Layered Suite of the Bushveld Complex: Zn concentration as characterized by an x-ray diffraction study. Extended Abstract, Centennial Geocongress, Rand Afrikaans University, Johannesburg, 936-939.

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Appendix C: Co-authored Manuscripts

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., van Deventer, J.L. and Hatton, C.J., 1993. The Transvaal Sequence: an overview. Journal of African Earth Sciences, 16, 25-51.

Twist, D., Cheney, E.S., Schweitzer, J.K., de Waal, S.A. and Bristow, J.W., 1998 (under revision). Flood rhyolites in the Rooiberg Group of South Africa. South African Journal of Geology.

Appendix D: Isotope Data

Harmer, R.E. and Farrow, D., 1995. An isotope study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. Mineralium Deposita, 30, 188-195.

The purpose of the following sections is to guide the reader through the work that has been conducted. The reader is continuously referred to the individual manuscripts and abstracts, listed in Appendices A-D, for more detail.

2.1 Preliminary investigation: Extent of alteration

The chemical composition of the volcanic rocks under consideration plays an important role during this study. Element mobility pattern must therefore be established initially (Appendix A, A12-A25 and A26-A30; also see Appendix B, B13-B17). Element redistribution could be pronounced by virtue of the age of the volcanic rocks and their proximity to major mafic and siliceous intrusions. However, the identification of primary and secondary element concentrations is essential in fulfilling the major aims of this study.

The volcanic rocks under consideration are located in three distinct geological settings (Fig. 1, A13), in relation to the Rustenburg Layered Suite (RLS) and the Lebowa Granite Suite (LGS). Some are underlying the mafic rocks of the RLS (Fig. 1, A13; locality 1), others are overlying the RLS (Fig. 1, A13; localities 3, 4 and 5), whereas still others are preserved in fragments that are imbedded in granite (Fig. 1, A13; localities 6 and 7). Differing element redistribution pattern have therefore to be expected.

The volcanic rocks of the Dullstroom Formation, beneath the RLS (Fig. 1, A13, locality 1) are subdivided (according to rock texture) into three metamorphic zones (Fig. 7, A18):

Upper Metamorphic Zone (<400 m beneath RLS): Granoblastic textures; partial melting close to contact; amphibolite to granulite facies.

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Middle Metamorphic Zone (400-1000 m beneath RLS): Original textures; tremolite-actinolite neoformation, sericite and quartz, upper greenschist facies.

Lower Metamorphic Zone (>1000 m beneath RLS): Original textures; chlorite is present; lower greenschist facies.

Amphibole of the Middle Metamorphic Zone has low (<1 wt.%) Na_2O contents (Appendix F, F4) suggesting low metamorphic grade. Coexisting amphibole and clinopyroxene in the Upper Metamorphic Zone have comparable FeO/MgO ratios, which, in turn, are similar to the whole rock ratios, suggesting that these elements were inert. Evidence supports the notion that the volcanic floor rocks of the Dullstroom Formation were dehydrated by the RLS, confirming a previous study in the western Bushveld Complex (Fig. 1, A13; locality 8). Loss on ignition (LOI) values are low in the Dullstroom floor succession (Fig. 8, A20), normative corundum is almost completely absent (Fig. 9, A20), and positive correlations between CaO and FeO or MgO, as typical for unaltered igneous rocks, are observed. Element redistribution associated with the Dullstroom floor succession is therefore linked to dehydration, with a pronounced, long-term hydrothermal system having been absent. It is therefore deduced that element redistribution within these rocks is minor.

Towards (1-2 km) the contact with the RLS the roof felsites are transformed into biotite hornfelse. Above this zone, devitrified glass is altered to quartz, chlorite and epidote. LOI and normative corundum (Figs. 8 and 9, A20) are highly variable in the roof rocks, indicating varying degrees of alteration.

Comparison of the immobile (Fig. 4B, A16) and the rare earth elements (REE, Appendix I, I1), confirms that the High-Mg Felsite (HMF) is common to the floor and roof successions. The Basal Rhyolite is only present in the Dullstroom floor succession and in the Makeckaan Fragment (Fig. 4A, A16).

Regional comparison of magma types shows that the felsite succession at Tauteshoogte and the Bothasberg Plateau are less altered than those at Loskop Dam (Figs. 4C-E, A16) and in the Rooiberg and Stavoren/Makeckaan Fragments (Fig. 4E, A16). At Loskop Dam some samples of felsite have anomalously high SiO_2 (>76 wt.%; Fig. 13, A22), high LOI (Fig. 8, A20), high normative corundum (Fig. 9, A20), and high Zn and Pb (Figs. 11 and 12, A21) concentrations. Zn contents are correlated with the abundance of secondary chlorite (B13 to B17). CaO exhibits a pronounced secondary correlation with LOI (Fig. 10, A21). In spite of these complicating factors, immobile element concentrations (e.g. Fig. 14, A22) clearly distinguish the felsite magma types above the RLS.

It is concluded that the volcanic rocks beneath the RLS show minor signs of element redistribution. The felsite succession above the RLS has been severely altered, with associated changes in element concentrations. There, Ti, P, Al, Ga, Sc, and the HREE are the same at all localities, have remained inert

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and can be utilized for regional correlations. The roof rocks are regionally depleted in Sr, Na and Th, and enriched in LOI, Ni, and Zn (Fig. 15, A23). Nb, Zr, and Y, which are commonly taken as immobile, have been depleted in the upper felsite succession. Element redistribution is the result of the RLS hydrothermal convection cell, which is also responsible for a 1.4 km thick zone of increasing base metal enrichment (Fig. 17, A24) immediately above the RLS.

It was also established in this study that felsite color can not be employed during stratigraphic subdivision. This has previously resulted in erroneous classifications. Felsite color, in addition, should also not be utilized to identify the nature of the Proterozoic atmosphere

2.2 Testing of hypotheses

2.2.1 Hypothesis 1: The Dullstroom Formation and Rooiberg Group are genetically unrelated

The Dullstroom Basalt Formation (SACS, 1980) was previously thought to consist almost entirely of mafic volcanic rocks and a link to the dacitic and rhyolitic Rooiberg rocks was questioned. This necessitates that the Dullstroom Formation, as preserved in the southeastern area of the Bushveld Complex (Fig. 1, A13; Fig. 6, A7), receives more detailed attention.

Mapping confirms that the Dullstroom Formation was emplaced on a pronounced unconformity, which is underlain by the sedimentary rocks of the Houtenbek and Steenkampsberg Quartzite Formations (Fig. 3, A107). An unconsolidated unconformity sand sheet interacted with initial lava eruptions (Figs. 14g and i, A121 and A122). Three depressions are found on the basal unconformity (Fig. 3, A107; Fig. 5, A109; Figs. 6a and b, A110; Fig. 10, A114). These are associated with rhyolite lava flows (Fig. 7, A111; Figs. 8a and b, A112; Fig. 9, A113; Fig. 14h, A122) that flowed for up to 7km, attain thicknesses of 200 m, possess irregular flow tops, and have estimated eruptive volumes of 20 km^3. The depressions are interpreted to have formed close to eruption centers.

Four distinct magma types are identified in the Dullstroom floor succession (Fig. 3, A107; Fig. 6, A7). These magmas extruded as fluidal lava flows. Initial extrusions of individual magma types carry abundant sedimentary fragments of the Transvaal Supergroup (Fig. 14d, A119; Fig. 14e, A120). Inspection of the Dullstroom map (Fig. 3, A107) reveals that the magma types are intercalated, do interfinger, and extruded in no specific order. However, the dacitic HMF's increase in abundance towards the top of the volcanic pile (Fig. 4, A108; Fig. 11, A115). The floor succession consists to 41 vol.% of HTI Basalt, 30 vol.% LTI Basaltic Andesite, 28 vol.% dacite (HMF), and 1 vol.% Basal Rhyolite and its definition as "Basalt Formation" (SACS, 1980) appears inappropriate (Table 2, A102). Compositional variations, linked to different eruption centers,

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are observed within individual magma types (Fig. 12, A116; Fig. 13, A117), providing scope for further subdivision.

The predominance of siliceous lava flows in the upper portion of the volcanic floor succession suggests a progressive transition into the siliceous, volcanic roof . The uppermost portion of the Dullstroom Formation is preserved as the volcanic xenolith, separating the Main and Upper Zones of the RLS, and as the basal portion of the felsite pile at Loskop Dam (Fig. 5, A109).

No regionally applicable stratigraphic subdivision existed for the Rooiberg Group, having been a succession without a base. However, this has changed with the identified link between the volcanic floor and roof packages. Review of previous field and geochemical work (Fig. 3, A4; Figs. 7a to c, A8) identifies regionally persistent marker horizons and magma types. The four, newly defined formations, from base to top, are termed: Dullstroom, Damwal, Kwaggasnek and Schrikkloof (Fig. 4, A5). Eight magma types are defined. Six are present in the Dullstroom Formation (i.e. the Dullstroom floor and roof successions) out of which two are continuous into the Damwal Formation. Two, compositionally distinct LMF's are the sole magma types of the Kwaggasnek and Schrikkloof Formations. The presence of prominent sedimentary intercalations commonly mark the formational contacts. However, some quartzites, are discontinuous, such as the one separating the Damwal from the Kwaggasnek Formation. A laterally persistent, prominent shale horizon, which may locally be developed as a tuff and is commonly underlain by an agglomerate, terminates the Kwaggasnek event. It is recommended that this prominent marker horizon be included in the Kwaggasnek Formation as the Union Tin Member. Some of the best exposure of parts of the Damwal and Kwaggasnek Formations is present in a road-cut towards the east of the Loskop Dam dam-wall (Fig. 5, C63). The uppermost Kwaggasnek in this exposure consists of a prominent lapilli tuff (Fig. 6, C64).

The transition from the volcanic floor into the roof succession has been established. When combining the newly established, regionally applicable stratigraphic subdivision (Fig. 4, A5) with previous studies, and own findings where of regional significance, it is possible to compile a map featuring the distribution of the four Rooiberg Formations (Fig. 3, A15). Andesitic lavas of the Rooiberg and Makeckaan/Stavoren Fragments , for example, compositionally compare to LTI Basaltic Andesite as preserved in the Dullstroom floor succession (Fig. 8, A9). Rhyolite in the Makeckaan Fragment is identified as Basal Rhyolite (Fig. 7c, A8). The basal Dullstroom succession is therefore also present in the two fragments under consideration. The Rooiberg Group is thickest in the southeastern Bushveld Complex and thins towards the north, where only the uppermost Schrikkloof Formation is present (e.g. Rooiberg Fragment, where the Schrikkloof immediately overlies the Dullstroom Formation; Fig. 3, A4; Fig. 2, A106). Volcanic flows are intercalated with the Loskop Formation, which has, to date, received little attention. Future work has to confirm whether the inclusion of the Loskop as a fifth formation into the Rooiberg Group (Fig. 14, C21) is justified.

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Altogether, eight magma types are classified for the redefined Rooiberg Group (Fig. 4, A5; Fig. 3, A39; Table 1, A40), taking in account that the LMF of the Dullstroom and Damwal Formations are comparable in composition. Distinct Fe, Ti, P, and V concentrations define the various magma types. Zr contents, in contrast, vary widely within the four Rooiberg Formations. In the HMF (G8, G9, C13, G14) and Basal Rhyolite (G5, G6) of the Dullstroom Formation, Zr concentrations vary between 144-272 ppm and 174-309 ppm, respectively. These variations are increasingly pronounced towards the top of the succession with Zr ranging in between 276-431 ppm, 385-573 ppm, and 420-714 ppm in the LMF's of the Dullstroom/Damwal (G9, G10, G14-G19), Kwaggasnek (G11, G12, G20), and Schrikkloof (G12, G21, G23, G25) Formations, respectively. The cause of these variations has not yet been determined.

The incompatible elements Zr, Nb and Y generally increase towards the top of the succession, whereas the reverse is observed for P_2O_5, TiO_2, and Sc. This is especially pronounced for the LMF (Fig. 4, A42). Al_2O_3 tends to cluster, implying subordinate plagioclase fractionation. Sc and FeO exhibit limited variations within individual magma types, suggesting that fractional crystallization of mafic mineral phases was subordinate. The upward increase of incompatible elements is accompanied by an increase in the REE (Fig. 5, A43). Flat, heavy REE pattern shows that garnet was absent in the source region. The weight of evidence suggests that partial melting is the predominant factor controlling magma composition.

The LTI Basaltic Andesite, Basal Rhyolite, High-Ti Basalt, HMF, and the high Fe-Ti-P Andesite (Table 1, A40) are interpreted as to have extruded as fluidal lava flows. The depositional nature of the remaining LMF rhyolite flows of the Rooiberg Group is debated. Dullstroom, Damwal, Kwaggasnek and Schrikkloof LMF rhyolites could have flowed over distances of 40 km, have thicknesses of up to 400 m, regular flow-tops, with areal extents and eruptive volumes that increase towards the top of the succession (Table 2, A102).

Transitions from lava- to pyroclastic flows have been documented, in space and time (Branney et al., 1992). Similar to the Bad Step Tuff (Branney et al., 1992), the uppermost Schrikkloof Formation exhibits pyroclastic features at its base, with lava-like characteristics being more pronounced towards the top. Care must therefore be taken not to oversimplify by proposing one extrusive mechanism for, for example, all the rhyolites of the Rooiberg Group. A spectrum of flow types could be represented by the rhyolites under consideration, ranging from base to top from lava flows, lava-like ignimbrites, rheomorphic ignimbrites, to non-rheomorphic-welded ignimbrites (Schrikkloof Formation).

The Rooiberg Group has, to date, received little attention by geochronologists. Whole rock, Rb/Sr and Pb isotopes suggest that the Rooiberg Group is older than 2070Ma (Harmer and Farrow, 1995; Appendix D). Walraven (1997) derives a single zircon Pb evaporation age for the Kwaggasnek Formation of 2061Ma $\pm$2. Barley (pers. communication, 1997) analyzed rhyolites of the Schrikkloof Formation, yielding a zircon

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SHRIMP age of 2057$\pm$7Ma. All these suggest that the felsites are consistently older than the mafic rocks and the granites by about 5 to 10Ma.

In summary: One magma type, the HMF, is common to the volcanic floor and roof successions of the RLS, unequivocally establishing that at least the lower portion of the volcanic pile was continuous before separation by the RLS. The Dullstroom succession is the basal formation of the Rooiberg Group, which enables the establishment of a regionally applicable stratigraphic subdivision, and the compilation of a map featuring the distribution of the four Rooiberg formations. The previously undocumented volcanic floor succession is investigated in detail. The onset of volcanic activity, as observed above the unconformity topping the Transvaal Supergroup, is described, together with the field, petrographical and geochemical characteristics of the initial Rooiberg magma types. The transition from the floor succession to the roof is gradual, with the floor succession becoming increasingly siliceous towards its top. Eight magma types extruded within the Rooiberg Group, and their distribution, extrusive volumes and characteristics are identified. Transitional compositions in between the major magma types are absent. This, taken together with other geochemical characteristics, suggests that fractional crystallization was not pronounced in the evolution of the various magma types, which inherited a strong upper crustal signature and could have formed at crustal levels.

2.2.2 Hypothesis 2: The Dullstroom Formation, Rooiberg Group and Bushveld Igneous Complex are unrelated

In the previous section it has been established that the Dullstroom and Rooiberg volcanic rocks are related. The basal Dullstroom unconformity (e.g. Fig. 3, A107) is taken as supporting evidence for inclusion of the Dullstroom Formation into the Rooiberg Group. However, in the presence of a link between the Rashoop Granophyre- (RGS), Lebowa Granite- (LGS) and/or Rustenburg Layered (RLS) Suites and the Rooiberg Group, this basal unconformity would mark the termination of the Transvaal Supergroup and the onset of Bushveld magmatism.

Acid magmas are centrally placed within the Bushveld Complex with the mafic rocks located at the periphery (Fig. 1, A13). The Rooiberg Group exhibits a close spatial association with the RGS and LGS. The Dullstroom Formation is localized in occurrence, with the Damwal, Kwaggasnek and Schrikkloof Formations covering increasingly larger areas (Table 1, A101). The regional uniformity of magma types is noted. The Lower and Critical Zones of the RLS are nowhere in contact with the volcanic rocks. The Main and Upper Zones abut the Dullstroom and Damwal Formations, but are not found in contact with the Kwaggasnek and Schrikkloof Formations. The latter two are predominantly in contact with granite of the LGS or granophyres

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of the RGS in the western and northern areas of the Complex. Granite is intrusive into the mafic rocks of the RLS and therefore terminates the Bushveld event.

Work aimed at testing Hypotheses 2 concentrates on the establishment of a potential link between the volcanic rocks and those of the RGS and LGS. Hatton and Sharpe (1989) noted possible geochemical links between the RLS and the volcanic rocks.

The newly established stratigraphy of the Rooiberg Group (Fig. 4, A5) facilitates confident field and geochemical comparison of the Rooiberg magma types and the RGS and LGS. 140 granophyre compositions were compiled into a regional database and these were compared, by locality, to the associated Rooiberg magma types. In most cases, the granophyre composition differs from that of the abutting Rooiberg magma type, but matches Rooiberg magmas higher in the volcanic pile (Fig. 8, A47; Fig. 9, A47). Damwal-type granophyre, for example, intruded beneath the LMF of the Dullstroom Formation, and Schrikkloof-type granophyre intruded beneath the Kwaggasnek Formation LMF (Table 2, A46). Granophyres corresponding to progressively younger LMF magma compositions continuously intruded younger volcanic rocks. The majority of granophyres are therefore co-magmatic with the Rooiberg Group, representing the shallow intrusive equivalents of the various LMF magma types. The Rooikop Granite Porphyry (Table 2, A55), included in the RGS, intrudes the upper portion of the Rooiberg Group. The composition of this porphyry corresponds favorably with the Schrikkloof LMF magma, supporting the notion that the granophyres are shallow LMF intrusions.

A potential link between the LGS and the Rooiberg Group has been debated for several decades (see A52 to A61 for discussion of various viewpoints). Most recent workers prefer the interpretation that the Bushveld granites and the Rooiberg volcanic rocks are genetically unrelated. This also leads to statements such as "...it is not possible that the Rooiberg Group can represent the volcanic equivalent of the Lebowa Granites. Significant compositional differences exist between the volcanics and granites..." (see Harmer and Farrow, 1995; Appendix D, D2).

This study reveals that previous attempts at correlating rhyolite and granite compositions were seriously hampered due to the absence of a properly defined stratigraphic subdivision of the Rooiberg Group and its associated magma types. Several Rooiberg magma types, for example, were averaged to then compare to granite compositions. This led to the conclusion that the rhyolites and granites are unrelated. When comparing individual LMF magma types with Nebo compositions (Table 2, A55) it is deduced that the Schrikkloof LMF most favorably compares to the granites. This is documented with regard to REE (Fig. 2, A56), major and trace element concentrations (Fig. 4, A58), and in the Qz/Or/Ab system (Fig. 3, A57). It is consequently concluded that the Schrikkloof and granite magmas are derived from the same source.

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Geochronological information (Walraven, 1997) suggests that the Bushveld Complex developed over a short duration of time, some 7Ma. The most reliable ages are summarized as follows:

Rashoop Granophyre Suite:	2053Ma $\pm$12 (U/Pb, bulk zircon)
Lebowa Granite Suite:	2054Ma $\pm$ 2 (Pb evaporation)
Rooikop Granite Porphyry:	2060Ma $\pm$2 (Pb evaporation)
Rustenburg Layered Suite (Upper Zone):	2061Ma $\pm$27 (Rb/Sr)

Armstrong (pers. communication, 1997) recently reported a zircon SHRIMP age of 2054Ma$\pm$1.5 for the Critical Zone. With the limited age information on the Rooiberg Group (see previous section), it is probably safe to assume that the Rooiberg Group rocks are genetically and temporally related to the Bushveld magmatic event.

In summary: Compositional comparison between the Rooiberg volcanic rocks and the granophyres of the RGS reveals that the vast majority of granophyres are shallow intrusives of Rooiberg magmas with increasingly evolved granophyres encountered in the younging Rooiberg succession. The Rooikop Granite Porphyry is the shallow intrusive equivalent of most evolved and youngest Rooiberg magma. In addition, Nebo Granite compositions compare favorably with that of the youngest Rooiberg magma types, supporting that the Bushveld event was relatively short-lived. Findings strongly recommend inclusion of the Rooiberg Group into the Bushveld Complex.

2.3 Logical Consequences

2.3.1 New proposed subdivision

During the course of this study it became evident that the newly defined stratigraphic subdivision of the Rooiberg Group (Fig 3, A4) held the key to improved understanding of not only the Rooiberg Group, but also the Bushveld Complex. Without the stratigraphic subdivision the following contributions, for example, could not have been achieved successfully:

a) Definition of magma type versus stratigraphic level, and associated extrusive volumes (Fig. 3, A4; Table 1, A101; Table 2, A102),
b) Compilation of a regional map featuring the distribution of the four formations (Fig. 3, A15),
c) Granophyre/Rooiberg magma type comparison (Figs. 8 and 9, A47),
d) Granite/Rooiberg magma type comparison (Figs. 2 to 4, A56 to 58),
e) Evaluation of mineralizing events for individual stratigraphic level (Fig. 2, A28; Fig. 3, A29).

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A composite profile through the Rooiberg Group suggests a maximum thickness of 9 km. The Dullstroom Formation is best developed in the eastern portion of the Complex (4.9 km {2.5 km and 2.4 km in the floor and roof, respectively}), with the thickness of the Damwal (1.5 km), Kwaggasnek (1.4 km), and Schrikkloof (1.2 km) Formations being fairly constant. The areal extent of the Formations increases towards the top of the Rooiberg Group, which is indicative of larger eruptive volumes. The newly defined Dullstroom Formation comprises 20 vol.% basalt, 15.5 vol.% basaltic andesite, 19 vol.% dacite, and 45.5 vol.% rhyolite, and is far from being a basalt formation, sensu strictu. A conservative estimate of total eruptive volume for the Rooiberg Group is 112 000 km^3 (Table 1, A101), out of which 94 vol.% are dacites and rhyolites.

2.3.2 Plume-related origin of the Bushveld Igneous Complex

The Bushveld components (RLS, RGS, LGS, Rooiberg Group) are chemically and spatially related, and age dating suggests that the related magmatic event was relatively short-lived. It is therefore proposed that the Bushveld magmatic event is the result of a short-lived geological process such as either a mantle plume or a meteorite impact.

Workers preferring a meteorite impact origin for the Complex argue that the thermal effects eliminated all evidence of high pressure. Bushveld magma types (Table 1, A53) emplaced at high temperatures (LGS >900°C, RLS >1200°C, Rooiberg Group >1000°C, see A53 for various references), justifying this statement. The findings of this study, however, lead to prefer a mantle plume origin rather than a meteorite impact origin for the Complex (see A75-A77 for detailed discussion).

It is noted that compositional similarities exist between the rhyolites and basalts of the Yellowstone area, proposedly plume-related, and the volcanic rocks of the Bushveld Complex (Fig. 6, A44; Fig.7, A45). Compositional and depositional similarities are also noted when comparing Rooiberg rhyolites to those of the plume-originated Jozini and Etendeka (Table 3, C57; Table 4, C58; Fig. 3, C61). Hot, large volume rhyolites that flowed for long distances are, in addition, commonly related to mantle plume settings (see C28ff).

The initial proposal of a plume ascending through the lithosphere and into the crust at the present site of the Bushveld Complex was subsequently discarded (Fig. 10, A48). The plume initiation model considers significant uplift prior to first magma emplacement. The unconformity beneath the Rooiberg Group is undisturbed and evidence of uplift is not detected (also see B9 to B12). Flow directions of early Rooiberg sediments are from north to the south. Is this taken together with the uplift that occurred towards the north,

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possibly along the Thabazimbi Murchison Lineament, it is deduced that a mantle plume was positioned towards the north of the present-day outcrop of the Complex.

None of the Rooiberg magma types can be regarded as a primitive mantle melt (Table 1, A40). Mafic Rooiberg magmas have MgO contents generally <5 wt.%, SiO2 >53 wt.%, and Ni and Cr concentrations varying between 16-158 ppm, and <367 ppm, respectively. Sr_i ratios are 0.705 (LTI Basaltic Andesite) and 0.709 (LMF, Dullstroom Formation; see Appendix D, D1 to D8). Youngest rhyolites have MgO of <1 wt.%, Ni <35 ppm, and Cr <19 ppm. The HMF, and to some extent the Basal Rhyolite, have compositions that closely resemble Proterozoic upper crustal compositions (Table 1, A40). This upper crustal signature could have been caused by intraplating at the lower-upper crustal boundary. This is deduced from the chemistry of the intrusive mafic rocks (Hatton, 1995), and the composition of the initial, silicic extrusions. The Basal Rhyolite and the HMF are interpreted to represent the crustal melts that formed above the intraplated mafic magma. The LTI Basaltic Andesite and HTI Basalt are probably mixtures of mantle and crustal material. Intraplating must have occurred in pulses and these are also reflected in the periodic evolution of the Complex. Multiple intraplating events probably resulted in the melting of higher, upper crustal levels, expressed by the various LMF magma types that have, for example, a rare earth element pattern similar to the Basal Rhyolite and HMF (Fig. 2, A56).

The Bushveld magmatic event affected a major portion of the Kaapvaal Craton. This is manifested in regional metamorphism and several synchronous satellite intrusions and extrusions (e.g. Fig. 2, A106). Bushveld parental magmas are also associated with the Uitkomst Complex (de Waal and Gauert, 1997).

2.3.3 Economic potential

The mineralization that occurs in the Rooiberg Group is related to the stratigraphic subdivision (Fig. 2, A28). It is noted that individual types of mineralization are not only confined to distinct stratigraphic levels, but also to distinct geographic regions. Tin and fluorspar mining, for example, is restricted to the central, western and northern regions of the Complex (Fig. 3, A29), where the granites are closely associated with the Rooiberg volcanic rocks.

It is deduced that the Rooiberg Group underwent four major mineralizing events, based on which a regional exploration model is established. Two of the events are linked to the RLS, one is attributed to granophyre intrusion, and the final event produced exogranitic fluorspar and tin deposits. Major volcanogenic ore deposits appear to be absent from the Rooiberg Group, possibly due to its intracratonic setting.

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First Mineralizing Event

Localized Cu diggings are present in the Dullstroom floor succession. Cu occurrences are present in epidotized zones along fault planes. This type of mineralization is tentatively linked to the initial intrusions of the RLS.

Second Mineralizing Event

Localized arsenic pyrite and pyrite occur at the base of the Kwaggasnek Formation (Fig. 2, A28). This mineralization is associated with later base metal enrichment (see Third Mineralizing Event). Arsenic mineralization is associated with sericitization and silicification. This style of mineralization is tentatively attributed to contact metamorphism associated with shallow granophyre intrusion.

Third Mineralizing Event

A hydrothermal convection system driven by the RLS heat source concentrated Pb and Zn into the roof rocks of the RLS. This gave rise to elevated Zn concentrations over the entire roof succession with maximum Pb (Fig. 12, A21) and Zn (Fig. 4, A31) enrichment towards the base of the Kwaggasnek Formation, some 1.4 km above the contact with the RLS. Increasing Pb and Zn enrichment is accompanied by increasing hydration (Fig. 8, A20). Maximum Zn contents represented by samples of the massive, interior portions of rhyolite flows, exceed 900 ppm, whereas unaltered rhyolite typically has Zn concentrations of about 50 ppm. It is proposed that Zn originated from the RLS, whereas Pb could have been derived from the volcanic rocks. As stated above, significant Zn concentrations are encountered in the massive portions of the flows. Porous layers, such as sedimentary intercalations or flow top breccias represent targets for potentially economic Zn and Pb concentrations.

Sinter deposits towards the top of the volcanic roof rocks, testify that the hydrothermal system affected the complete roof package. Surface sintering is accompanied by pronounced silicification, which is also expressed by a high paleoweathering index (Fig. 8, A33). These sinter deposits are potential targets for gold exploration.

Fourth Mineralizing Event

Tin and fluorspar mineralization in the volcanic and sedimentary Rooiberg rocks are exogranitic, and are found between 2 and 10 km from the granite. A review of the tin production (Tables 2 to 4, A30) only considers the Bushveld rock types (including the Rooiberg Group), and reveals that the majority of the tin was derived from the Rooiberg Group (about 69%). This anticipates that the tin derived from sedimentary

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rocks predominantly originated from the Union Tin Shale and the associated agglomerate. It is noted that the newly defined stratigraphic subdivision (Fig. 4, A5) and the map featuring the distribution of the four Rooiberg formations (Fig. 3, A29) enables to regionally target the Union Tin Member as a potential host for tin and fluorspar.

3 Conclusions

On the strength of the evidence obtained in this study, it is concluded that the Dullstroom Basalt Formation (SACS, 1980) forms the basal succession of the Rooiberg Group. The Rooiberg Group, in turn, is spatially, geochemically and temporally related to the Bushveld Complex and not to the Transvaal Supergroup as hitherto considered (SACS, 1980). Both hypotheses, as defined at the beginning of this study, have thereby been falsified. It is furthermore concluded that the Rooiberg Group should be redefined and subdivided, from bottom to top, into four formations i.e. Dullstroom, Damwal, Kwaggasnek and Schrikkloof Formations. The name Dullstroom Basalt Formation accordingly becomes redundant.

The granophyre of the RGS, compositionally identical to the silicic magma types of the Rooiberg Group represents the shallow intrusive equivalents of the rhyolites. The succession of LMF magma is compositionally mimicked by the granophyre intrusions. The granophyre intrusions must therefore be synchronous with the extrusion of the Rooiberg Group.

The Schrikkloof LMF correspond chemically to the granites of the LGS, implying that these rocks were derived from the same source. Granite intrusion may have overlapped in time with the last LMF extrusions, or represent a continuation of the Rooiberg event.

The relationship between the Rooiberg Group and the RLS is not fully established yet. The RLS intruded in four major pulses, i.e. the Lower Zone, Lower and Upper Critical Zone and the Main Zone. These events must reflect events of the source area that triggered crustal melting and the extrusion of Rooiberg lavas.

Magma intraplating, due to a plume positioned towards the north of the Complex, is suggested to have triggered the Bushveld magmatic event. Such intraplating could have occurred along the lower-upper crustal boundary (Conrad discontinuity). Melting of upper crust accounts for the huge amounts of silicic Bushveld magmas. Intraplating effected the majority of the Kaapvaal craton, also causing the formation of several satellite intrusions, and a regional metamorphic event.

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References

Boardman, L.G., 1946. The geology of a portion of the Rooiberg Tinfields. Trans. Geol. Soc. S. Afr., 49, 103-133.

Branney, M.J., Kokelaar, B.P. & McConnell, B.T. (1992). The Bed Step Tuff: A lava-like rheomorphic ignimbrite in a calc-alkaline Piecemeal Caldera, English Lake District. Bull. Volcanol., 54, 187-199.

Burger, A.J. and Coertze, F.S., 1975. Age determinations: April 1972 - March 1974. Ann. Geol. Surv. S. Afr., 10, 135-141.

Button, A., 1974. Low-potash basalts in the Pretoria Group, Transvaal Supergroup. Trans. Geol. Soc. S. Afr., 77, 99-104.

Clubley-Armstrong, A.R., 1977. The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome. Unpubl. M.Sc. thesis, Univ. Pretoria, 107pp.

Cornell, D.H., Schutte, S.S. and Eglington, B.L., 1996. The Ongeluk Basaltic Andesite Formation in Griqualand West, South Africa: Submarine alteration in a 2222Ma Proterozoic sea. Prec. Res., 79, 101-123.

de Waal, S.A. and Gauert, C.D.K., 1997. The basal gabbro unit and the identity of the parental magma of the Uitkomst Complex, Badplaas, South Africa. S. Afr. J. Geol., 100, 349-361.

Eriksson, P.G. and Twist, D., 1986. A note on a lahar deposit in the Hekpoort Formation, Transvaal Sequence, near Pretoria. Trans. Geol. Soc. S. Afr., 89, 415-418.

Eriksson, P.G., Engelbrecht, J.P., Res, M. and Harmer, R.E., 1994. The Bushy Bend lavas, a new volcanic member of the Pretoria Group, Transvaal Sequence. S. Afr. J. Geol., 97, 1-7.

Hatton, C.J. and Sharpe, M.R., 1989. Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: *Boninites and related rocks* (Edited by Crawford, A.J.), pp174-208, Unwin, Hyman, London.

Hatton, C.J., 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. J. Afr. Earth Sci., 21, 571-577.

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Schweitzer, J.K., 1986. The geochemical transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group. Inst. Geol. Res. Bushveld Complex. University of Pretoria, Annual Report, 72-81.

Sharpe, M.R., Brits, R. and Engelbrecht, J.P., 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3 Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. Institute Geological Research Bushveld Complex, University of Pretoria Research Report, 40, 63pp.

South African Committee for Stratigraphy (SACS), 1980. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. Handbook Geol. Surv. S. Afr., No 8, 633pp.

Twist, D., 1985. Geochemical evolution of the Rooiberg siliceous lavas in the Loskop Dam area, southeastern Bushveld. Econ. Geol., 80, 1153-1165.

Twist, D. and French, B.M., 1983. Voluminous acid volcanism in the Bushveld Complex: a review of the Rooiberg Felsite. Bull. Volcanol., 46-3, 225-242.

Wagner, P.A., 1921. The Mutue Fides - Stavoren Tinfields. Dept. of Mines and Industries, S. Afr., 16, 160pp.

Walraven, F. (1997). Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. Econ. Geol. Res. Unit, Inf. Circ. 316, 21pp.

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Appendices

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Appendix A: Manuscripts

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Regional lithochemical stratigraphy of the Rooiberg Group upper Transvaal Sequence: a proposed new subdivision

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S.Afr.J.Geol.,1995,98(3),245–255

Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Supergroup: A proposed new subdivision

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The regional stratigraphy of the Rooiberg Group is re-evaluated in terms of lithology, geochemistry, and new information on the Dullstroom Formation and the Rooiberg and Stavoren Fragments. On the strength of this study a new subdivision for the Rooiberg Group is proposed; the Rooiberg Group should be divided into the Dullstroom, Damwal, Kwaggasnek, and Schrikkloof Formations. The Union Tin Member marks the top of the Kwaggasnek Formation and is comprised of a succession of pyroclastic and sedimentary rock types. Employing this subdivision the Rooiberg Group may be further subdivided into a western Nylstroom Package (comprising Kwaggasnek and Schrikkloof Formations) and an eastern Bothasberg Package (comprising the complete Rooiberg succession). The basal Dullstroom succession is also preserved in the Stavoren Fragment. In the Rooiberg Fragment the Dullstroom Formation is overlain by the Kwaggasnek and Schrikkloof Formations and the Damwal Formation is absent.

Die regionale stratigrafie van die Rooiberg Groep is herevalueer in terme van litologie, geochemie, en nuwe inligting oor die Dullstroom Formasie en die Rooiberg- en Stavorenfragmente. Op grond van hierdie studie word 'n nuwe onderverdeling van die Rooiberg Groep voorgestel, naamlik dat die Rooiberg Groep onderverdeel word in die Dullstroom, Damwal, Kwaggasnek, en Schrikkloof Formasies. Die Union Tin Lid maak die bokant van die Kwaggasnek Formasie uit en bestaan uit 'n opeenvolging van piroklastiese en sedimentêre gesteentetipes. Om hierdie onderverdeling te implementeer, kan die Rooiberg Groep verder onderverdeel word in 'n westelike Nylstroompakket (bestaande uit die Kwaggasnek en Schrikkloof Formasies) en 'n oostelike Bothasbergpakket (bestaande uit die hele Rooibergopeenvolging). Die basale Dullstroomopeenvolging is ook bewaar in die Stavorenfragment. In die Rooibergfragment word die Dullstroom Formasie oorlê deur die Kwaggasnek en Schrikkloof Formasies, en die Damwal Formasie is afwesig.

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Introduction

The Rooiberg Group, previously regarded as the uppermost portion of the Transvaal Supergroup, is preserved over a vast area and is encountered throughout the Transvaal (Figure 1). This Group has been identified as a major, acid volcanic succession, covering at least 50 000 km^2 with an estimated erupted volume that, according to Twist & French (1983), may have exceeded 300 000 km^3.

The stratigraphic subdivision which is currently accepted by SACS (1980) is shown in Figure 2. Rocks of the Rooiberg Group are largely confined to the roof of the Bushveld Complex, and show a discordant contact with the acid and basic rocks of the complex. This relation has hampered the lateral correlation of previous subdivisions and the establishment of a regionally applicable stratigraphy. In addition, previous studies on the Rooiberg Group were isolated in nature and incorporated different approaches in subdividing this succession. Subdivisions were frequently based on texture, structure, or colour. These features are, however, likely to vary significantly on a regional scale due to primary differences in the style of deposition and alteration processes prevailing in the various depositional settings (Eriksson & Cheney, 1992; Schweitzer & Hatton, 1995).

The need for the modification of the current stratigraphic subdivision (Figure 2) has recently been emphasized by Eriksson *et al.* (1993) and Schweitzer & Hatton (1995). Revision of the upper Transvaal stratigraphy is required because it has been shown (e.g. Schweitzer & Hatton, 1995) that the Dullstroom Formation and the Rooiberg Group were one continuous succession prior to dislocation by the intrusive rocks of the Bushveld Complex. This is supported by the existence of an unconformity beneath the Dullstroom Formation (Cheney & Twist, 1991). The Dullstroom Formation therefore, represents the lowermost portion of the Rooiberg Group.

The terms 'Rooiberg Felsite' or 'felsite' are commonly applied to the predominantly dacitic and rhyolitic volcanic rocks encountered in the roof of the Bushveld Complex. This term is potentially misleading as not only basaltic and andesitic magma types, but also dacites and rhyolites, constitute a significant portion of the Dullstroom Formation. The term felsite is considered to be obsolete (IUGS, 1989), but is retained in this paper to refer to the dacites and rhyolites as preserved in the roof of the Bushveld Complex (e.g. Twist, 1985). It is noted, for clarity, that the volcanic flows referred to as high magnesium felsite (HMF) are dacites in composition. The majority of the low magnesium felsites (LMF) represent rhyolites with some LMF dacites which are encountered towards the base.

In this study the lithological and geochemical characteristics of the Rooiberg Group are employed to show that this Group exhibits regionally persistent characteristics. This approach has resulted in the present proposal of a regionally applicable stratigraphic subdivision for the Rooiberg Group.

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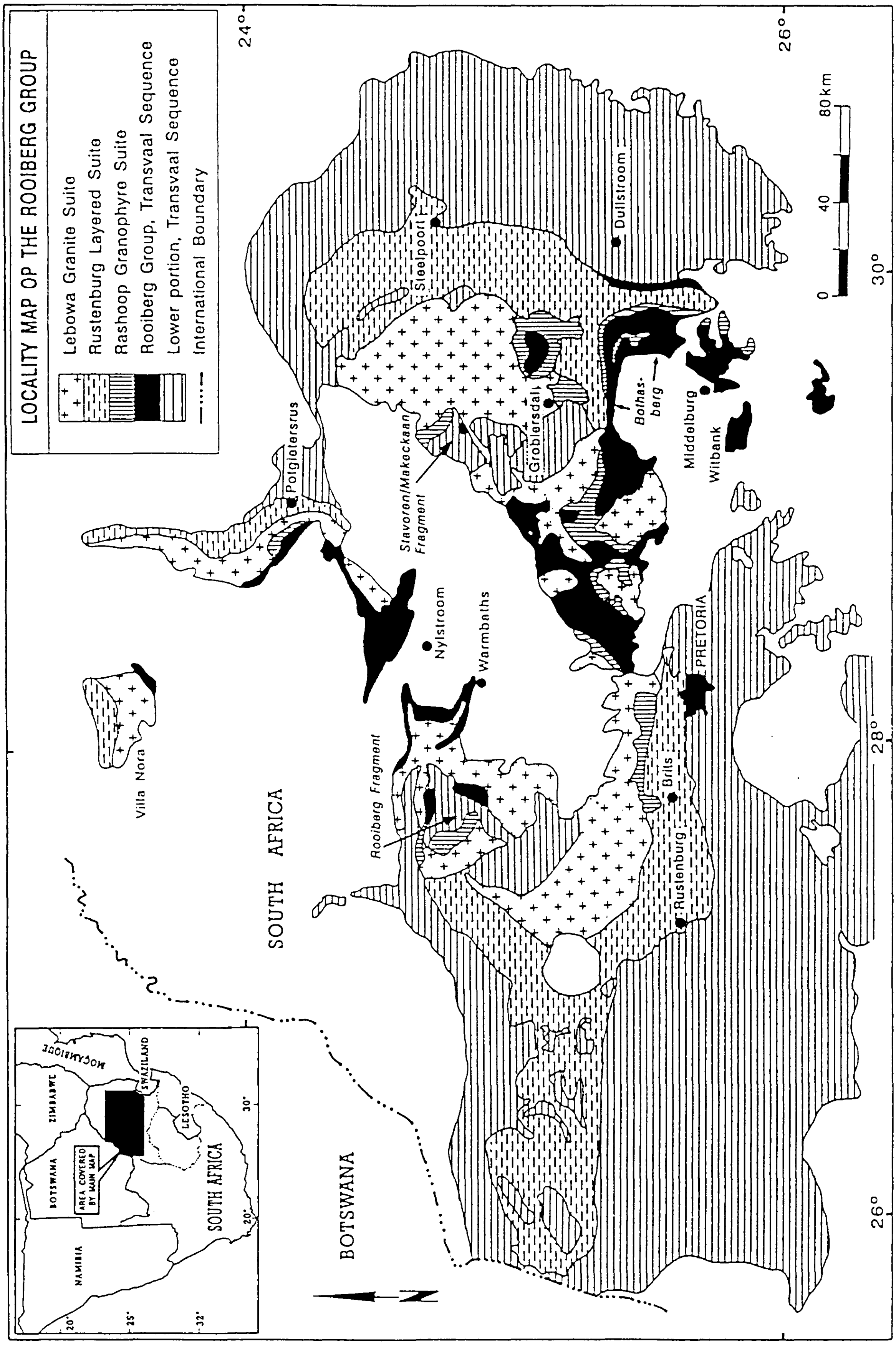

Figure 1 Geological map of the Bushveld Complex and the distribution of the Rooiberg Group (modified after Walraven, 1982).

Previous stratigraphic subdivisions

Stratigraphic subdivision of the Rooiberg Group using textural and structural features was undertaken by early workers (e.g. Lombaard, 1932; Wolhuter, 1954; Glathaar, 1956). These subdivisions cannot be employed for regional stratigraphic correlations, due to the lateral variability of the criteria used (e.g. Du Plessis, 1976; Twist & French, 1983).

Strauss (1954) and Menge (1963) examined rocks of the

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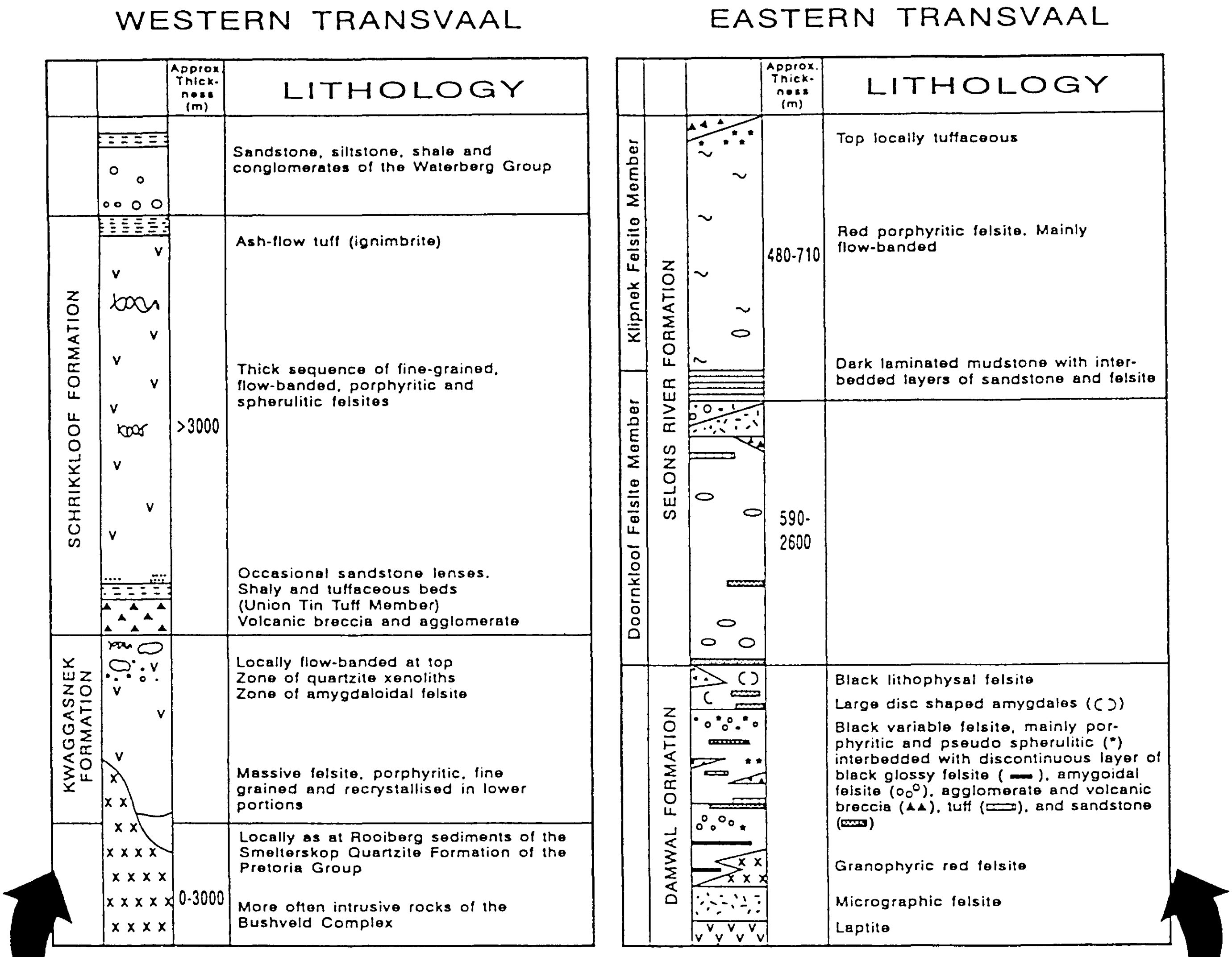
Rooiberg Group in the northern Transvaal (Figure 3), identifying a lower and an upper succession. These successions are separated by a volcaniclastic unit, overlain by a shale or thinly bedded, acid tuff. A comparable stratigraphic subdivision was proposed by Coetzee (1970), Rhodes & Du Plessis (1976), and Du Plessis (1976) for the Rooiberg Group occur-



		WESTERN TRANSVAAL	CROCODILE RIVER FRAGMENT	MARBLE HALL FRAGMENT	EASTERN TRANSVAAL
		FORMATION	FORMATION	FORMATION	FORMATION
	ROOIBERG GROUP	Schrikkloof			Selons River
	ROOIBERG GROUP	Kwaggasnek			Damwal
	PRETORIA GROUP				Dullstroom Basalt
					Houtenbek
					Steenkampsberg Quartzite
					Nederhorst
		Rayton	Smelterskop Quartzite	Makeckaan Quartzite	Lakenvalei Quartzite
			Leeuwpoort		Vermont Hornfels

Figure 2 Currently defined stratigraphic subdivision of the upper Transvaal Supergroup (after SACS, 1980).

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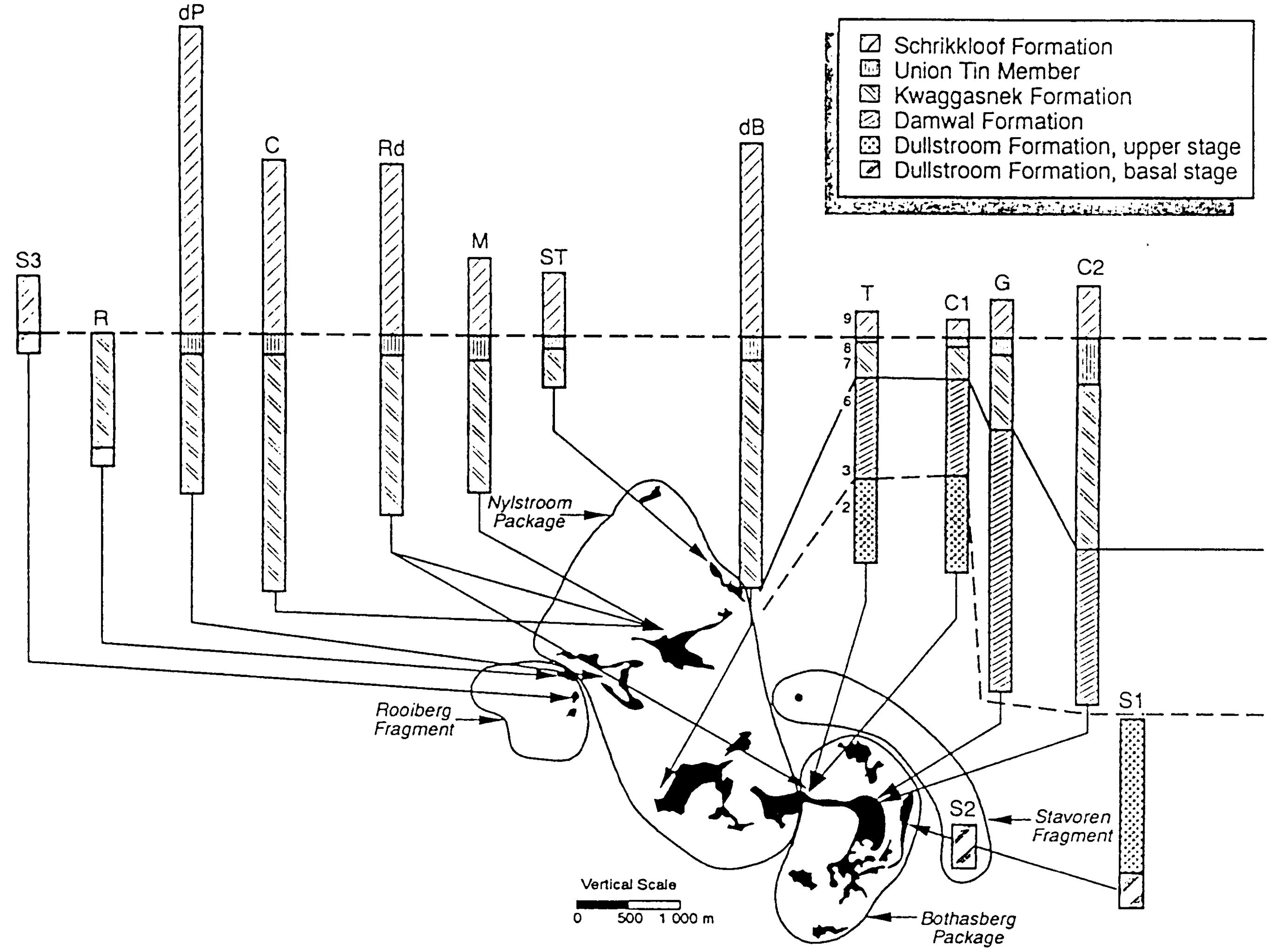

Figure 3 Stratigraphic subdivisions for the various Rooiberg Group occurrences obtained from the literature. The nomenclature is as proposed in this paper. The stratigraphic information of the various horizons comprising the Rooiberg Group in the various regions has been deduced from the following sources: C1 and C2 = Clubley-Armstrong (1977); C = Coetzee (1970); dB = De Bruiyn (1980); dP = Du Plessis (1976); G = Von Gruenewaldt (1968); M = Menge (1969); Rd = Rhodes & Du Plessis (1976); R = Richards (1987); ST = Strauss (1954); S1, S2, and S3 = this study; T = Twist (1985).

rences towards the west of those examined by Strauss (1954) and Menge (1963) (Figure 3). The latter authors all used an agglomerate and the overlying tuffaceous shale to distinguish a lower and upper felsite succession (Figure 3). A prominent zone of quartzite xenoliths is encountered beneath the agglomerate in the lower felsite occurrences towards the north of Nylstroom and Warmbaths and west of Potgietersrus. An additional feature of the volcanic rocks common in the above areas is the strongly flow-banded nature of the upper rhyolite succession. These flows are commonly overlain by an ash-flow tuff.

Rooiberg Group occurrences towards the north of Pretoria (De Bruiyn, 1980) and those of the Bothasberg Plateau (Middelburg area, Von Gruenewaldt, 1968; Rhodes & Du Plessis, 1976; Clubley-Armstrong, 1977; 1980; Twist, 1985) are preserved more than 200 km towards the southwest of those described above (Figure 3). North of Pretoria a prominent agglomerate, overlain by shaly tuffaceous beds, separates a lower Kwaggasnek from an upper Schrikkloof Formation (De Bruiyn, 1980). Characteristics of the volcanic flows beneath and above the agglomerate and shale horizons are similar to those observed in the Warmbaths, Nylstroom, and Potgietersrus areas, namely a prominent zone of quartzite xenoliths (1 – 3m in length) towards the upper portion of the lower succession (i.e. Kwaggasnek Formation), and pronounced flow-banding in the upper rhyolites (i.e. Schrikkloof Formation), terminated by an ash-flow tuff.

The volcanic succession at the Bothasberg Plateau has been intensively studied. Near Loskop Dam, Rhodes & Du Plessis (1976) identified a succession similar to the one observed towards the north of Nylstroom (Figures 1 and 3). A more detailed description of the 4 to 5 km-thick package in this area was given by Von Gruenewaldt (1968), Clubley-Armstrong (1977), and Twist (1985) (Figure 3). Von Gruenewaldt identified a lower, middle, and upper felsite zone on the basis of textural characteristics in the various volcanic flows. The middle and upper zones are separated by an agglomerate/shale succession, which is overlain by flow-banded rhyolite, similar to the succession described in the central, western, and northern Transvaal. Subsequent workers, studying the Rooiberg Group towards the west and east of Loskop Dam, also identified the agglomerate/shale succession as volcanic

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breccia or tuff overlain by a lithology interpreted as mudstone, sandstone, shale, and/or tuff. This horizon was used by Clubley-Armstrong (1977) to subdivide the upper Selons River Formation into a lower Doornkloof and an upper Klipnek Member. The latter author employed, in addition, a prominent quartzite further towards the base of the succession (Figure 2) to separate a lower Damwal from an upper Selons River Formation.

The stratigraphic subdivision proposed by Clubley-Armstrong (1977) was adopted by Twist (1985), who further subdivided the volcanic succession into 9 units (Figure 3). Using the geochemical units defined by Twist (1985) the Damwal/Selons River Formation contact in Clubley-Armstrong's section is at the unit 6/7 contact (Schweitzer & Hatton, 1995), where a major compositional break and a marked change in the amount of phenocrysts is observed (Twist, 1985). The volcanic succession of the Bothasberg Plateau has various features that compare to the previously described localities. These are the agglomerate and tuffaceous shale horizon, a prominent zone of quartzite xenoliths beneath this agglomerate, and the strongly flow-banded nature of the uppermost rhyolites, which are capped by an ash-flow tuff.

The Rooiberg Group occurrences of the Stavoren and Rooiberg Fragments and those of the Dullstroom Formation (Figure 1) have, to date, received little attention. The Dullstroom succession represents an integral part of the Rooiberg Group

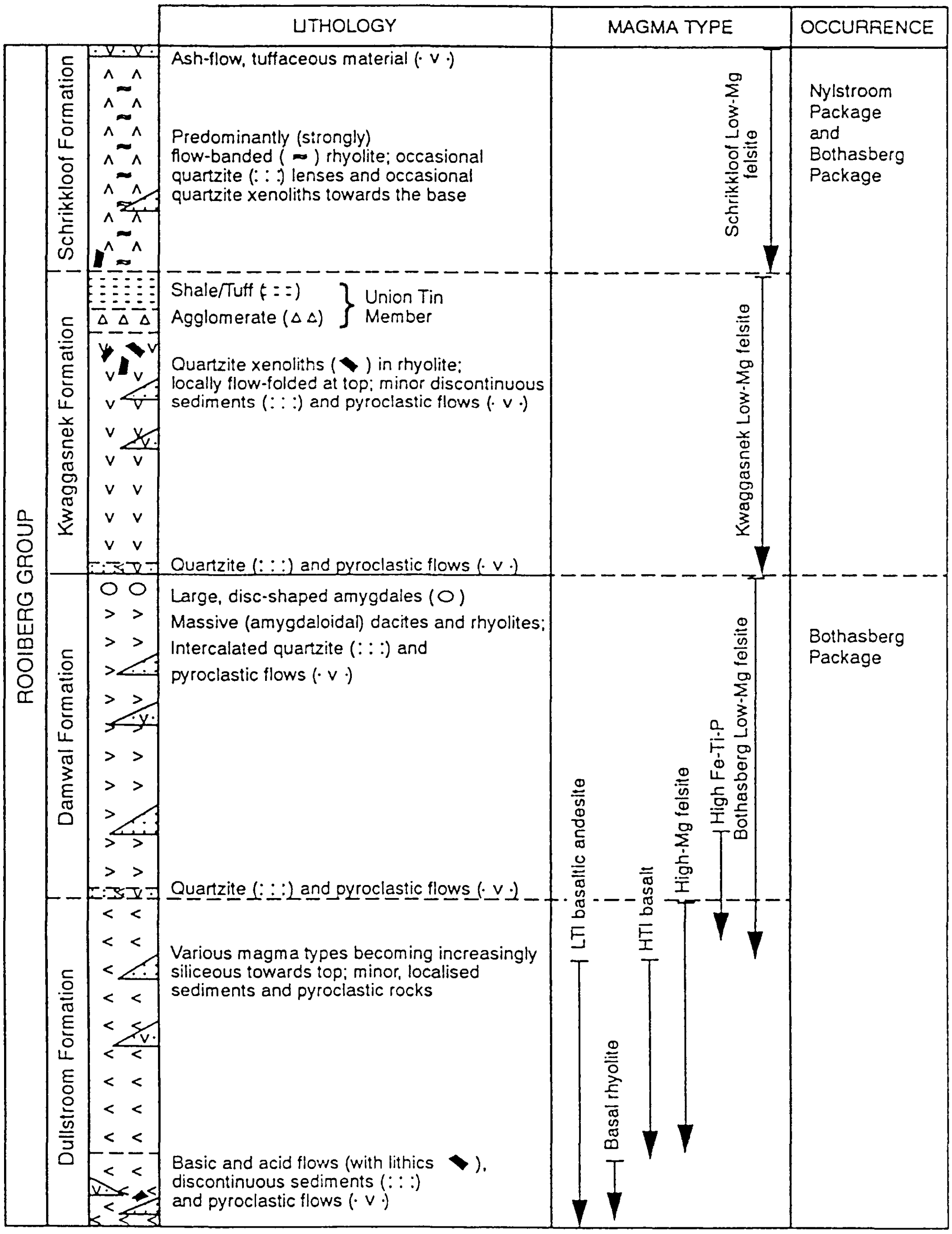

Figure 4 Regional stratigraphy of the Rooiberg Group as deduced from lithological and geochemical characteristics.

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(Schweitzer, 1986; Eriksson *et al.*, 1993; Schweitzer & Hatton, 1995; Schweitzer *et al.*, 1995) and is subdivided into a basal and an upper stage on the basis of magma types and the abundance of sedimentary intercalations (Figure 4). High magnesium felsites (HMF) of the upper stage are continuous into the lower portion of the succession above the Rustenburg Layered Suite (Figure 5). They represent the majority of the flows contained within units 1 and 2 as described at Loskop Dam (Twist, 1985); (Figure 5).

Volcanic rocks of the Rooiberg Fragment (e.g. Recknagel, 1908; Stear, 1977) have previously been assigned to the Kwaggasnek Formation (Richards, 1987; Richards & Eriksson, 1988). Acid flows of the Stavoren Fragment (Figure 1) were first described by Mellor (1905) and Wagner (1921; 1927). A detailed study of the sedimentary and volcanic rocks of this fragment still needs to be undertaken.

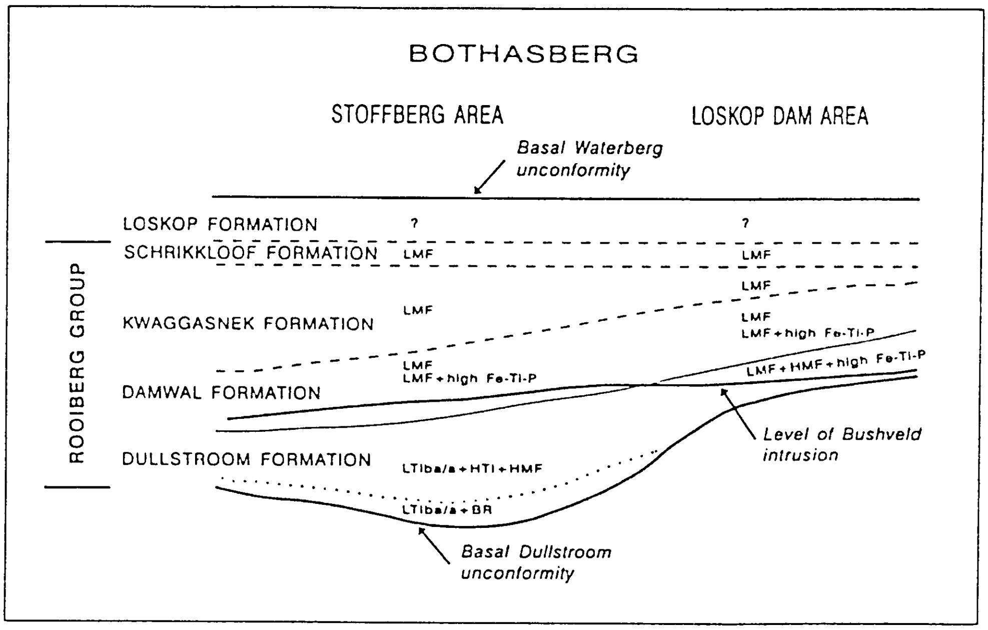

Figure 5 Reconstructed emplacement level of Rustenburg Layered Suite for the eastern portion of the Bushveld Complex using the lithological and geochemical characteristics of the volcanic rocks of the Rooiberg Group. Magma types within the Loskop Formation possess exceptionally high TiO_2 (>4wt.%) and P_2O_5 (>1wt.%) and their possible link to the underlying Rooiberg magma types still needs to be investigated. Also shown are the distribution of the various magma types throughout the proposed formations.

LTI_{ba} = Low-Ti basaltic andesite; BR = Basal Rhyolite; HTI = High-Ti basalt; HMF = High-Mg felsite; LMF = Low-Mg felsite; High Fe–Ti–P = High Fe–Ti–P andesite.

It should be clear from the above that certain marker horizons are persistent over the entire extent of the volcanic rocks under consideration, which are:

- Top of Schrikkloof Formation/Klipnek Member: pyroclastic flow;
- Throughout Schrikkloof Formation/Klipnek Member: pronounced flow-banding;
- Top of Kwaggasnek Formation/Doornkloof Member: shale/tuff horizon;
- Top of Kwaggasnek Formation/Doornkloof Member: agglomerate and/or volcanic breccia; and
- Top of Kwaggasnek Formation/Doornkloof Member: quartzite xenoliths.

Large disc-shaped amygdales have been described towards the top of the Damwal Formation (Figures 2 and 4; Von Gruenewaldt, 1968; Clubley-Armstrong, 1977). However, the question of their regional persistence warrants further attention.

Table 1 Proposed new subdivision for the Rooiberg Group

GROUP	FORMATION	MEMBER
ROOIBERG	Schrikkloof	
	Kwaggasnek	Union Tin
	Damwal	
	Dullstroom	

A regionally applicable stratigraphic subdivision of the Rooiberg Group employing lithological characteristics appears to be justified. Accordingly a new subdivision as outlined in Figure 4 is proposed (Table 1). The Rooiberg Group is proposed to be comprised of four formations, namely Dullstroom, Damwal, Kwaggasnek, and Schrikkloof. The formation status is assigned due to the complexity of the lithologies and magma types encountered in these formations. This facilitates the establishment of members within these formations, such as the proposed Union Tin Member (Figure 4). The name Union Tin Member is preferred to the 'Sterk River Shale' or Member, the name originally given to this horizon by Mellor (1909). A Sterk River Formation has previously been recognized by SACS (1980).

Kwaggasnek, Schrikkloof, Doornkloof, and Klipnek are terms previously applied to the upper Rooiberg (Figure 2), and were proposed to SACS within the same year (SACS, 1980). Kwaggasnek and Schrikkloof are proposed as the names for the two uppermost Rooiberg Formations. Firstly, both already possess formation status (Figure 2), and the upper Rooiberg succession was assigned these names over the majority of the Transvaal. The terms Doornkloof and Klipnek have only been applied locally in the eastern Transvaal and, considering their correspondence to the Kwaggasnek and Schrikkloof, these terms are redundant.

The incorporation of the Dullstroom and Damwal Formations into one subgroup is not justified due to the diversity of lithologies encountered within these formations (M. Johnson, pers. comm., 1994). Similar lithologies are, in contrast, encountered in the Kwaggasnek and Schrikkloof Formations.

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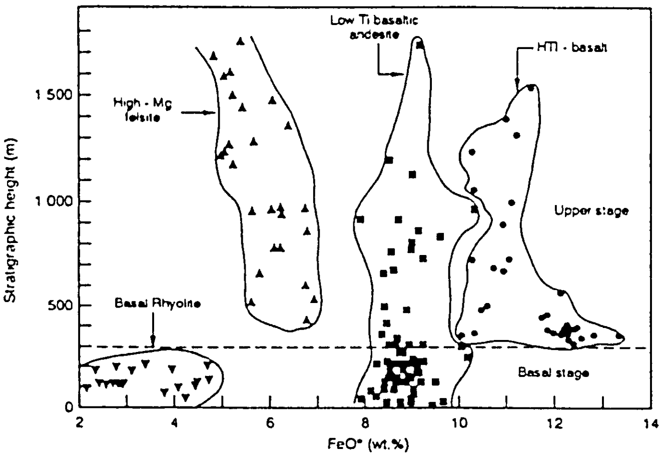

Figure 6 Total FeO versus stratigraphic height for the four magma types of the Dullstroom Formation as preserved in the floor of the Rustenburg Layered Suite. FeO represents an inert element within the Bushveld floor volcanic rocks (Schweitzer & Hatton, 1995).

However, the authors regard the Union Tin Member as representing a major break in Rooiberg evolution and, therefore, do not propose to include the uppermost Rooiberg formations into a subgroup at this stage. This renders the term 'Selons River' obsolete.

The newly proposed stratigraphic subdivision will be applied in the following section.

Regional geochemical comparison

It has previously been shown that the volcanic rocks of the Damwal, Kwaggasnek, and Schrikkloof Formations are geochemically distinct (Clubley-Armstrong, 1977; De Bruiyn, 1980; Twist, 1985). The compositional variations as observed in the various Rooiberg Group occurrences are, in the following, utilized to establish their relationship to the newly proposed stratigraphic subdivision. The compositions of flows of the Dullstroom Formation are also utilized to identify possible occurrences of the magma types in other parts of the Bushveld roof rocks.

The regional lithological correlations are confirmed using the geochemical characteristics of the Rooiberg volcanic rocks. More than 600 whole-rock analyses of volcanic flow units have been considered during the regional chemostratigraphic comparison (see Appendix for the source of data). In this comparative exercise only elements known to be immobile (Schweitzer & Hatton, 1995) are utilized. The average compositions of the various magma types in terms of these immobile elements are provided in Table 2.

TiO_2 and Zr concentrations were found to be the most useful for the regional geochemical comparison. Not all of the 600 samples were analysed for their TiO_2 and Zr contents, so about 400 analyses were employed for the regional comparison.

Bothasberg and Nylstroom Packages

The combination of lithological and geochemical characteristics results in the recognition of an eastern Bothasberg and a western Nylstroom Package (Figure 4), which delineate the distribution of the various Rooiberg Formations. Volcanic flows of the Bothasberg Package are, according to the current evidence, encountered in the floor of the Rustenburg Layered Suite (Figure 5), the Bothasberg Plateau, and the Angeweezen Basin (east of Groblersdal). Four compositional magma types of the basal Dullstroom Formation, are preserved beneath the Rustenburg Layered Suite (Figure 6). Low titanium basaltic andesites (LTI_{ba}), high titanium basalts (HTI basalt), and Basal Rhyolites are not encountered towards the top of the Dullstroom Formation (Figure 4). The High Fe–Ti–P magma type is the only basic magma type in the Rooiberg Group above the Rustenburg Layered Suite and is compositionally distinct from the remaining basic magma types of the Dullstroom Formation (Table 2). The basic magma types of the

Table 2 Average (Avg) concentrations and standard deviations (Std) of TiO_2, P_2O_5, Nb, Zr, and Y for the major magma types of the Rooiberg Group

Dullstroom Formation

	TiO_2		P_2O_5		Nb		Zr		Y		
	Av	Std	Av	Std	Av	Std	Av	Std	Av	Std	N
$LTI_{ba/a}$	0.62	(0.09)	0.12	(0.03)	3	(3)	130	(42)	21	(5)	77
BR	0.31	(0.06)	0.08	(0.01)	6	(1)	228	(33)	25	(5)	24
HTI	1.87	(0.22)	0.23	(0.05)	13	(3)	206	(51)	30	(6)	35
HMF	0.60	(0.04)	0.13	(0.01)	8	(2)	214	(33)	28	(4)	54
LMF	0.64	(0.07)	0.16	(0.03)	16	(1)	328	(20)	50	(7)	29
High-Fe -Ti-P	1.02	(0.06)	0.35	(0.03)	14	(2)	282	(19)	49	(3)	5

Damwal Formation

	TiO_2		P_2O_5		Nb		Zr		Y		
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	N
LMF	0.57	(0.06)	0.15	(0.03)	15	(2)	330	(32)	51	(13)	86
High-Fe -Ti-P	1.19	(0.07)	0.38	(0.04)	13	(1)	271	(24)	43	(4)	3

Kwaggasnek Formation

	TiO_2		P_2O_5		Nb		Zr		Y		
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	N
	0.34	(0.07)	0.05	(0.01)	22	(3)	447	(53)	67	(7)	39

Schrikkloof Formation

	TiO_2		P_2O_5		Nb		Zr		Y		
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	N
	0.25	(0.01)	0.03	(0.01)	24	(4)	486	(93)	71	(9)	20

Only analyses of stratigraphically well constrained samples were taken. The stratigraphic position of these magma types is shown in Figure 4. N refers to number of analyses

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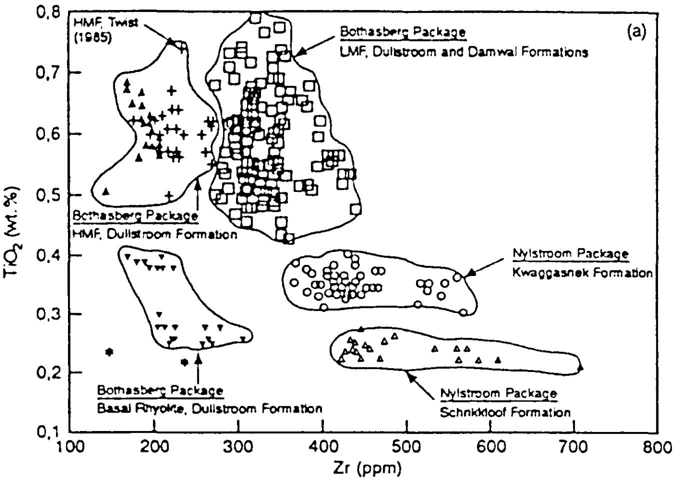

Figure 7a Compositional variations of 261 samples of volcanic rocks of the Rooiberg Group as preserved in the Bothasberg Package. Basic magma types which occur in the lower and middle portion of the Dullstroom Formation are not shown. Stars identify samples that cannot be stratigraphically placed using their TiO_2 and Zr concentrations. A magma type previously classified as high Fe-Ti-P (Twist, 1985) locally occurs towards the base of the Bothasberg Package but is not considered here. The average composition of this flow-type is given in Table 2.

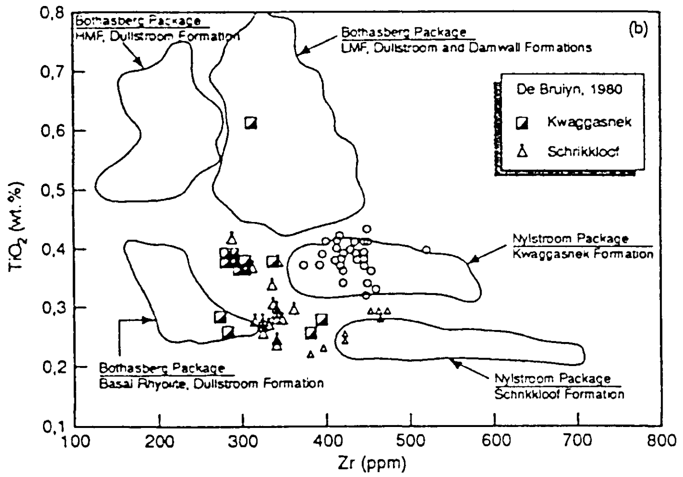

Figure 7b Compositions of the volcanic rocks of the Rooiberg Group in the Nylstroom Package (82 analyses) compared to the compositional fields of the acid magma types as observed within the Bothasberg Package. The analyses of De Bruiyn (1980) are identified due to their comparably lower Zr concentrations. The source of the remaining analyses is listed in the Appendix under Nylstroom Package.

Dullstroom Formation underlying the Rustenburg Layered Suite are, therefore, only utilized for comparison with the basic volcanic flows within the Rooiberg and Stavoren Fragments.

The chemostratigraphic subdivision of the acid magma types of the Bothasberg Package is given in Figure 7a. Low magnesium felsite flows (LMF) are characterized by decreasing TiO_2 and increasing Zr concentrations towards the top of the Rooiberg Group. Distinct breaks, especially notable in terms of TiO_2, separate the LMF of the Dullstroom and

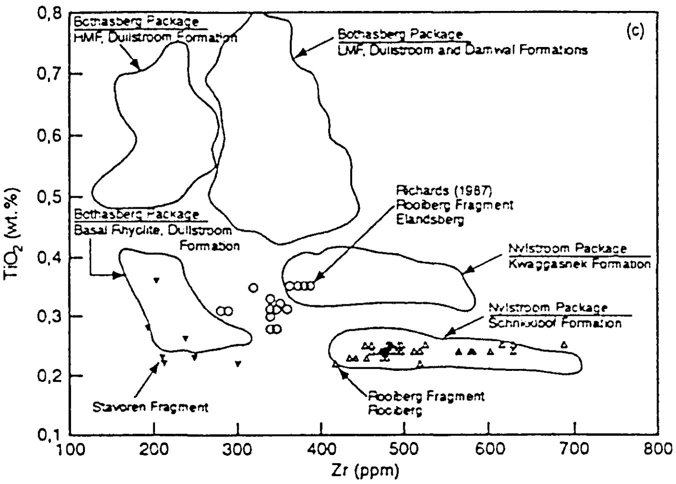

Figure 7c TiO_2 versus Zr concentrations of the acid volcanic flows preserved in the Rooiberg (64 analyses) and Stavoren Fragments. Also shown are the compositional fields for the acid magma types of the Bothasberg Package. See Appendix for the source of analyses.

Damwal Formations from the magmas of the Kwaggasnek and Schrikkloof Formations (Figure 7a). High magnesium felsite (HMF) above and below the layered mafic sequence is compositionally comparable. HMF and Basal Rhyolites have lower Zr concentrations than the other acid magma types encountered in the Rooiberg Group (Figure 7a).

The Nylstroom Package is geochemically defined by analyses of volcanic flows sampled towards the north of Pretoria, northwest of Warmbaths and Groblersdal, towards the west of Naboomspruit, and in the vicinity of Potgietersrus and Villa Nora. The compositions indicate that the magma types encountered within the Dullstroom and Damwal Formations are absent in the Nylstroom Package (Figure 7b). Therefore, only volcanic rocks of the Kwaggasnek and Schrikkloof Formations are preserved in the central, western, and northern Transvaal.

Volcanic rocks of the Rooiberg and Stavoren Fragments

Previous stratigraphic correlations of the rocks of the Rooiberg and Stavoren Fragments suggested that these rocks correspond to upper Transvaal Supergroup deposits (e.g. Stear, 1977; Schreiber *et al.*, 1991; Eriksson *et al.*, 1993).

Rhyolite flows on the eastern edge of the Rooiberg Fragment (Figure 1) correspond to compositions observed in the Schrikkloof Formation (Figure 7c). Richards (1987) examined the volcanic rocks along the Elandsberg which are preserved along the northern rim of the fragment. TiO_2 concentrations indicate that flows belonging to the Kwaggasnek Formation are the majority of the Elandsberg. An agglomerate/shale horizon at the base of the volcanic succession has previously been described (Rozendaal *et al.*, 1986) and has been mapped at the Rooiberg.

Basic flows which underlie the rhyolites in the Rooiberg Fragment are intercalated with sedimentary rocks of the Smelterskop Formation (Stear, 1977). The composition of these basic flows correspond best with those of the LTI_{ba} (Figure 8), confined to the basal Dullstroom Formation (Figure 4). The fact that the basic flows of the Rooiberg Fragment are intercalated with sedimentary layers implies that the Smel-

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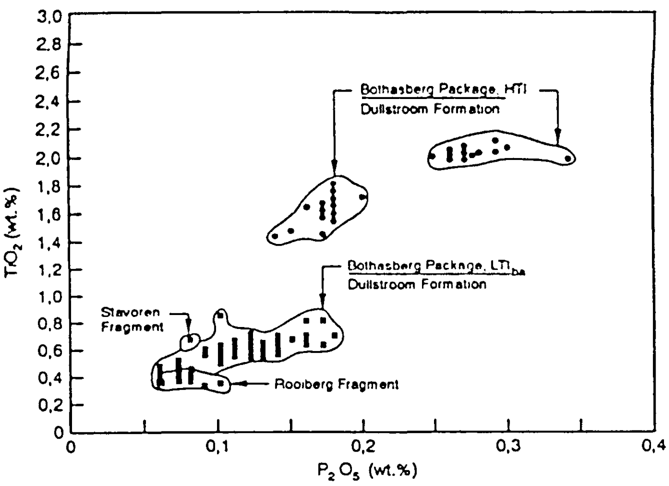

Figure 8 TiO_2 versus P_2O_5 plot illustrating the similar compositions of the LTI_{ba} and the basic magma types preserved in the Rooiberg (9 analyses) and Stavoren (1 analysis) Fragments.

terskop Formation may be correlated with the basal stage of the Dullstroom Formation (Figures 3, 4, and 6).

Compositions of the acid flows of the Stavoren Fragment compare with those of the Basal Rhyolite, observed towards the base of the Dullstroom Formation (Figures 4, 6, and 7c). As in the Rooiberg Fragment, basic volcanic flows are intercalated with sedimentary rocks in the strata beneath the Basal Rhyolite. Only one analysis is available from these flows, and this compares favourably with LTI_{ba} compositions (Figure 8). The volcanic succession as observed within the Stavoren Fragment, therefore, may be correlated with rocks of the basal stage of the Dullstroom Formation (Figure 3).

In conclusion, volcanic flows of the basal Rooiberg Group are preserved in both fragments. This succession is overlain by the Kwaggasnek and Schrikkloof Formations within the Rooiberg Fragment.

Summary and discussion

Regional stratigraphic characteristics and geochemical variations of volcanic flows of the Rooiberg Group provide the basis for a regionally applicable stratigraphic sub-division as proposed in Figure 4. The lowermost two formations of the Rooiberg Group are largely confined to the eastern Transvaal and regionally persistent marker horizons appear to be absent. Stratigraphic subdivision in this area has to be made on the macroscopic features in the various magma types and their corresponding geochemical characteristics. The HMF magma type is a mappable unit and is confined to the Dullstroom volcanic rocks in the floor and roof of the Rustenburg Layered Suite. This defines the Dullstroom/Damwal Formation contact. Since basic flows intercalated with the Smelterskop Formation of the Rooiberg Fragment compare to a magma type of the basal Dullstroom Formation, unconformities must be present. These are positioned beneath the Kwaggasnek and Schrikkloof Formations (Figure 3, profiles R and S3).

The Kwaggasnek and Schrikkloof Formations are the upper Rooiberg Group. Volcanic and sedimentary rocks of these Formations are widespread and found throughout the Transvaal. The correlation of the previously defined Kwaggasnek and Schrikkloof Formations with the Damwal and Selons River Formations (Coertze *et al.*, 1977; SACS, 1980) is unsubstantiated. This confirms De Bruiyn's (1980) findings.

The newly proposed subdivision of the lower Rooiberg Group results from the finding that the volcanic flows previously assigned to the Pretoria Group (i.e. the Dullstroom Formation) are the basal portion of the Rooiberg Group. The stratigraphic subdivision of the upper Rooiberg Group represents a combination of previous stratigraphic proposals, made for the western and eastern Transvaal, respectively (see SACS, 1980 for more detailed discussion).

The previous correlation of the Kwaggasnek and Schrikkloof with the Damwal and Selons River, respectively, resulted from the fact that regionally persistent marker horizons are largely confined to the Kwaggasnek and Schrikkloof Formations. The relevant regional marker horizons are a zone of quartzite xenoliths in the uppermost portion of the Kwaggasnek Formation, the Union Tin Member which constitutes the top of the Kwaggasnek Formation, and the strongly flow-banded nature of the Schrikkloof Formation, frequently terminated by a tuffaceous deposit. The lateral persistence of these marker horizons and the regional occurrence of chemically comparable magma types strongly suggests that similar processes were active over the entire area considered in this study.

Other incompatible, immobile trace elements and element ratios can be used to chemically subdivide the Rooiberg Group, and the TiO_2 and Zr ratio has been chosen as an example. Variations in this ratio are attributed to processes such as fractional crystallization and partial melting, which were controlled on a regional scale. The identification of these processes and their possible link to the Bushveld magmatic events will receive more detailed attention in the future.

Acknowledgements

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References

Cheney, E. & Twist, D. (1991). The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. *Precambrian Res.*, 52, 115–132.

Clubley-Armstrong, A.R. (1977). *The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome.* M.Sc. thesis (unpubl.), Univ. Pretoria, 107 pp.

---- (1980). Petrochemistry of the Rooiberg Felsite Group and overlying Loskop Formation, north of Middelburg, southeastern Transvaal. *Ann. geol. Surv. S. Afr.*, 14/2, 11–28.

Coertze, F.J., Jansen, H. & Walraven, F. (1977). The transition from the Transvaal Sequence to the Waterberg Group. *Trans. geol. Soc. S. Afr.*, 80, 145–156.

Coetzee, G.L. (1970). The Rooiberg Felsite series north of Nylstroom. *Symp. on the Bushveld Igneous Complex and other layered intrusions*, Spec.

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Publ., Geol. Soc. S. Afr., 1, 312–325.
Daly, R.A. (1928). Bushveld Igneous Complex of the Transvaal. *Bull. geol. Soc. Am.*, 39, 703–763.
De Bruiyn, H. (1980). *The geology of the acid phase of the Bushveld Complex, north of Pretoria – a geochemical statistical approach.* Ph.D. thesis (unpubl.), Univ. Orange Free State, 171 pp.
Du Plessis, M.D. (1976). *The Bushveld granites and associated rocks in the are north-west of Warmbaths, Transvaal.* M.Sc. thesis (unpubl.), Univ. Pretoria, 85 pp.
Eriksson, P.G. & Cheney, E.S. (1992). Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the lower Proterozoic sequences of southern Africa. *Precambrian Res.*, 54, 257–269.
----, Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., Van Deventer, J.L. & Hatton, C.J. (1993). The Transvaal Sequence: An overview. *J. Afr. Earth Sci.*, 16, 25–51.
Fourie, P.J. (1969). *Die geochemie van granitiese gesteentes van die Bosveldstollingskompleks.* D.Sc. thesis (unpubl.), Univ. Pretoria, 289 pp.
Glathaar, C.W. (1956). *Die verysterde piroklaste en 'n Na-Waterbergse graniet suidoos van die dam Rust der Winter.* M.Sc. thesis (unpubl.), Univ. Pretoria, 80 pp.
Hall, A.L. (1932). The Bushveld Igneous Complex of the central Transvaal. *Mem. geol. Surv. S. Afr.*, 28, 560 pp.
IUGS (International Union of Geological Sciences) (1989). *A Classification of Igneous Rocks.* Subcommittee on Systematics of Igneous Rocks, Le Maitre, R.W. (Ed.), Blackwell scient. Publ., 35–139.
Kleemann, G.J. (1985). *The geochemistry and petrology of the roof rocks of the Bushveld Complex, east of Groblersdal.* M.Sc. thesis (unpubl.), Univ. Pretoria, 178 pp.
Lenthal, D.H. & Hunter, D.R. (1977). The geology, petrology, and geochemistry of the Bushveld granites and felsites in the Potgietersrus tin-field. *Inf. Circ., Econ. Geol. Res. Unit, Univ. Witwatersrand*, 110, 91 pp.
Liebenberg, C.J. (1961). The trace elements of rocks of the Bushveld Igneous Complex, part 2. The different rock types. *Publ. Univ. Pretoria*, 13, 65 pp.
Lombaard, B.V. (1932). *Felsites and their relations in the Bushveld Complex.* Ph.D. thesis (unpubl.), Univ. Zurich, 106 pp.
---- (1934). On the differentiation and relationships of the rocks of the Bushveld Complex. *Trans. geol. Soc. S. Afr.*, 37, 5–52.
Mellor, E.T. (1905). The geology of a portion of the Springbok Flats and the adjacent areas. *Transvaal Mines Dept., Rep. Geol. Surv.*, 27–36.
---- (1909). On a portion of the Waterberg District west of Potgietersrust. *Ann. Rep. geol. Surv. Transvaal*, 25–50.
Menge, G.F. (1963). *The cassiterite deposits on Doornhoek 342 KR and vicinity, west of Naboomspruit Transvaal.* M.Sc. thesis (unpubl.), Univ. Pretoria, 56 pp.
Niemand, N. (1982). *Die Geologie en geochemie van'n gebied op die grens van die landdrosdistrikte Groblersdal en Middelburg, Transvaal.* B.Sc. (hons.) Project (unpubl.), Univ. Pretoria, 26 pp.
Recknagel, R. (1908). On some mineral deposits in the Rooiberg district. *Trans. geol. Soc. S. Afr.*, 11, 83–106.
Rhodes, R.C. & Du Plessis, M.D. (1976). Notes on some stratigraphic relations in the Rooiberg Felsite. *Trans. geol. Soc. S. Afr.*, 79, 183–185.
Richards, R.J. (1987). *A geological investigation of upper Transvaal Sequence rocks in the northern portion of the Rooiberg Fragment.* M.Sc. thesis (unpubl.), Univ. Pretoria, 79 pp.
---- & Eriksson, P.G. (1988). The sedimentology of the Pretoria Group in selected areas of the northern portion of the Rooiberg Fragment. *S. Afr. J. Geol.*, 91, 498–508.
Rozendaal, A., Toros, M.S. & Anderson, J.R. (1986). The Rooiberg tin deposits, West-Central Transvaal. *In*: Anhaeusser, C.R. & Maske, S. (Eds.) *Mineral Deposits of Southern Africa*, II. Geol. Soc. S. Afr., 1307–1327.
Schreiber, U.M., Eriksson, P.G. & Snyman, C.P. (1991). A provenance study of the sandstones of the Pretoria Group, Transvaal Sequence (South Africa): petrography, geochemistry, and palaeocurrent directions. *S. Afr. J. Geol.*, 94, 288–298.
Schweitzer, J.K. (1986). Field and geochemical investigations of the Dullstroom and Rooiberg volcanic rocks. *Ext. Abstr., Geocongress '86*, Geol. Soc. S. Afr.,Johannesburg, 873–876.
---- & Hatton, C.J. (1995). Chemical alteration within the volcanic roof rocks of the Bushveld Complex. *Econ. Geol.* (in press).
----, ---- & De Waal, S.A. (1995). Economic potential of the Rooiberg Group – volcanic rocks in the floor and roof of the Bushveld Complex. *Mineralium Deposita*, 30, 168–177.
SACS (South African Committee for Stratigraphy) (1980). Stratigraphy of South Africa. Part 1 (Comp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. *Handbk. Geol. Surv. S. Afr.*, 8, 690 pp.
Stear, W.M. (1977). The stratigraphy and sedimentation of the Pretoria Group at Rooiberg, Transvaal. *Trans. geol. Soc. S. Afr.*, 80, 53–65.
Strauss, C.A. (1954). The geology and mineral resources of the Potgietersrus tin-fields. *Mem. Geol. Surv. S. Afr.*, 46, 241 pp.
Twist, D. (1985). Geochemical evolution of the Rooiberg siliceous lavas in the Loskop Dam area, southeastern Bushveld. *Econ. Geol.*, 80, 1153–1165.
---- & French, B.M. (1983). Voluminous acid volcanism in the Bushveld Complex: a review of the Rooiberg Felsite. *Bull. Volcanol.*, 46-3, 225–242.
Van Der Walt, W.A. (1978). *Die geologie van 'n gebied in die omgewing van Villa Nora, Noord Transvaal.* M.Sc. thesis (unpubl.), Rand Afrikaans Univ., Johannesburg, 106 pp.
Von Gruenewaldt, G. (1968). The Rooiberg Felsite north of Middelburg and its relation to the layered sequence of the Bushveld Complex. *Trans. geol. Soc. S. Afr.*, 71, 153–172.
---- (1972). The origin of the roof-rocks of the Bushveld Complex between Tauteshoogte and Paardekop in the Eastern Transvaal. *Trans. geol. Soc. S. Afr.*, 75, 121–134.
Wagner, P.A. (1921). The Mutue Fides - Stavoren Tinfields. *Dept. Mines Ind., S. Afr.*, 16, 160 pp.
---- (1927). The geology of the north-eastern part of the Springbok Flats and surrounding country. Expl. of sheet 17 (Springbok Flats), *Geol. Surv. S. Afr., Dept. Mines Ind.*, 104 pp.
Walraven, F. (1982). *Textural, geochemical and genetical aspects of the granophyric rocks of the Bushveld Complex.* Ph.D. thesis (unpubl.), Univ. Witwatersrand, Johannesburg, 251 pp.
Watson, M.D. (1967). *Die Vloeispaatvoorkomste op Buffelsfontein 347 en omstreke, nordwes van Naboomspruit, Transvaal.* M.Sc. thesis (unpubl.), Univ. Pretoria, 112 pp.
Wolhuter, L.E. (1954). *The geology of the country surrounding Loskop Dam, Transvaal.* M.Sc. thesis (unpubl.), Univ. Pretoria, 66 pp.

Appendix

Source of geochemical analyses

Nylstroom Package		Number of analyses
Wagner (1927)	Potgietersrus area	2
Lombaard (1931) (in Wolhuter (1954))	Pretoria area	1
Lombaard (1932) pp. 142, 150–152	Pretoria area	9
Lombaard (1934)	Middelburg area	1
Watson (1967) p. 36	Naboomspruit area	1
Fourie (1969)	Potgietersrus, Rooiberg, and Nylstroom areas	4
Coetzee (1970) p. 317	Nylstroom area	2
Du Plessis (1976) p. 56	Warmbaths area	3
Lenthal & Hunter (1977) pp. 89, 90	Potgietersrus area	14
Van der Walt (1978) pp. 18, 22	Villa Nora Area	10
De Bruiyn (1980) pp. 44–47	Pretoria area	32
Walraven (1982) pp. 223, 224	Potgietersrus area	11

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Appendix (continued)

Richards (1987) p. 41	Northern Rooiberg Fragment	20
This study	Eastern Rooiberg Fragment	43
Bothasberg Package		Number of analyses
Daly (1928)	Middelburg area	1
Hall (1932)	Middelburg area	2
Lombaard (1932)	East of Groblersdal	1
Wolhuter (1954) p. 13	Witbank area	1
Liebenberg (1961) (in Von Gruenewaldt (1972)	East of Groblersdal	1
Von Gruenewaldt (1968) p. 1966	East of Groblersdal	2
Von Gruenewaldt (1972) p. 128	East of Groblersdal	2
Clubley-Armstrong (1980) pp. 14, 15	Bothasberg Plateau	23

Appendix (continued)

Niemand (1982) pp. 18, 19	Loskop Dam area	18
Walraven (1982) pp. 159, 162, 163	East of Groblersdal	8
Kleeman (1985) pp. 159, 162, 163	East of Groblersdal	26
Twist (1985)	Loskop Dam area (analyses courtesy of Pretoria University, D. Twist)	167
This study	Bothasberg Plateau	43
This study	East of Groblersdal	8
This study	Dullstroom area	157
Basic magma types of the Rooiberg and Stavoren Fragments		
Richards (1987) p. 31	'Smelterskop lavas', Northern Rooiberg Fragment	4
This study	'Smelterskop lavas', Eastern Rooiberg Fragment	4
This study	Stavoren Fragment	8

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Chemical alteration within the volcanic roof rocks of the Bushveld Complex

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Chemical Alteration within the Volcanic Roof Rocks of the Bushveld Complex

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Abstract

Field relations, petrography, and geochemistry identify mobile and immobile elements within the Rooiberg volcanic rocks of the floor and roof of the mafic Rustenburg Layered Suite of the 2.06 Ga Bushveld Complex. The floor rocks show thermal metamorphism accompanied by dehydration. Two major alteration processes affected the roof rocks. The first followed extrusion of the felsic Damwal Formation and is marked by veins of pyrite and arsenopyrite. The second is related to the intrusion of the Rustenburg Layered Suite, which produced an aureole 1.4 km thick in the overlying felsic rocks. Pb, Zn, and Mn attain maximum concentrations of 335 ppm, 929 ppm, and 0.45 wt percent, in the metasomatized roof rocks. The economic significance of elevated Pb and Zn concentrations at the top of the aureole deserves future attention. Primary concentrations of Si, Mn, Ca, Na, K, Fe, Mg, Sr, Th, Ba, U, Hf, Ni, Cu, Zn, Pb, Nb, Zr, and Y were modified to varying degrees, depending on locality and distance from the Bushveld intrusions. Ti, Al, P, Ga, Sc, and heavy REE were immobile; concentrations of these elements in the Rooiberg volcanic rocks indicate that at least one geochemically distinct magma type is present in both the floor and the roof sequences. This confirms that the volcanic floor and roof successions originally formed as a continuous sequence.

The color of the roof rocks is controlled by the contact metamorphic processes and cannot be used for stratigraphic subdivision, nor should the red color of these rocks be used for inferences about the evolution of the Proterozoic atmosphere. Hydrothermal alteration was also responsible for the aberrant radiometric dates in the Rooiberg Group.

Introduction

STUDIES considering alteration processes in the floor and, especially the roof zone, of mafic intrusions are scarce. The volcanic rocks of the Rooiberg Group are exceptionally well preserved in the roof of the 2.05 to 2.06 Ga Bushveld Complex (Fig. 1), providing the opportunity to study alteration processes. Schweitzer et al. (1995a) successfully used geochemical characteristics, combined with field evidence, to establish the stratigraphy of the Rooiberg Group, but the geochemical and petrogenetic relationships between the volcanic rocks can only be properly evaluated after the effects of alteration have been determined.

The geochemistry of the Rooiberg Group has been modified by the Rustenburg Layered Suite. This paper describes the geochemical and textural characteristics of this alteration in the volcanic suite, identifying which elements were mobilized during the alteration processes. Some mobile elements may have been concentrated to economic levels (Schweitzer et al., 1995b). Four major mineralizing events caused enrichment of Cu in the volcanic rocks of the floor, and of As, Pb, Zn, Sn and F in the roof zone of the complex (Schweitzer et al., 1995b). The alterations that accompanied the enrichment of the roof by As, Pb, and Zn are the concern of this study.

Geologic Setting

Regional geology

The Bushveld Complex is of enormous extent (Fig. 1). The Complex comprises the mafic Rustenburg Layered Suite, the Rashoop Granophyre Suite, and the Lebowa Granite Suite. The intruded rocks consist of a number of >2.7 to <2.1 Ga major unconformity-bounded units and >3.0 Ga crystalline basement (Cheney and Winter, 1995). The Bushveld Complex predominantly intruded the regional unconformity below the Rooiberg Group, so that the most common footwall rocks are the largely clastic rocks of the Pretoria Group (Cheney and Twist, 1991). Subsequently, the Bushveld Complex and its enclosing rocks were deformed to produce the map pattern of Figure 1.

The volcanic rocks of the Rooiberg Group are predominantly preserved in the roof of the Bushveld Complex. These volcanic rocks are geochemically related to the Rashoop Granophyre Suite (Walraven, 1985; Schweitzer and Hatton, 1995) and the Rustenburg Layered Suite (Hatton and Sharpe, 1988; Schweitzer and Hatton, 1995). The Lebowa Granite Suite intrudes the Rooiberg Group, Rashoop Granophyre Suite and Rustenburg Layered Suite. The 2061 ± 2 Ma age of the Rooiberg Group (Walraven, 1995) is indistinguishable from the age of the Rustenburg Layered Suite (2060 ± 27 Ma; Walraven et al., 1990) but is older than the Lebowa Granite Suite (2054+2 Ma; Walraven and Hattingh, 1993). The Rooiberg Group is, therefore, cogenetic with the Bushveld igneous episode (Schweitzer and Hatton, 1995). Sedimentary and volcanic xenoliths occur in the Rustenburg Layered Suite. The most prominent xenolith is a 70-km-long screen of the Dullstroom Formation in the eastern portion of the Rustenburg Layered Suite (Fig. 1).

The Rooiberg Group is one of the most extensive siliceous volcanic successions in the world. Eruptions exceed 300,000 km^3 and cover about 50,000 km^2 (Twist and French, 1983). Many of the Rooiberg units appear to be felsic lava flows of great extent, resembling flood basalts (Twist et al., 1995; writ. commun.). West of Belfast and Dullstroom (Fig. 1), volcanic

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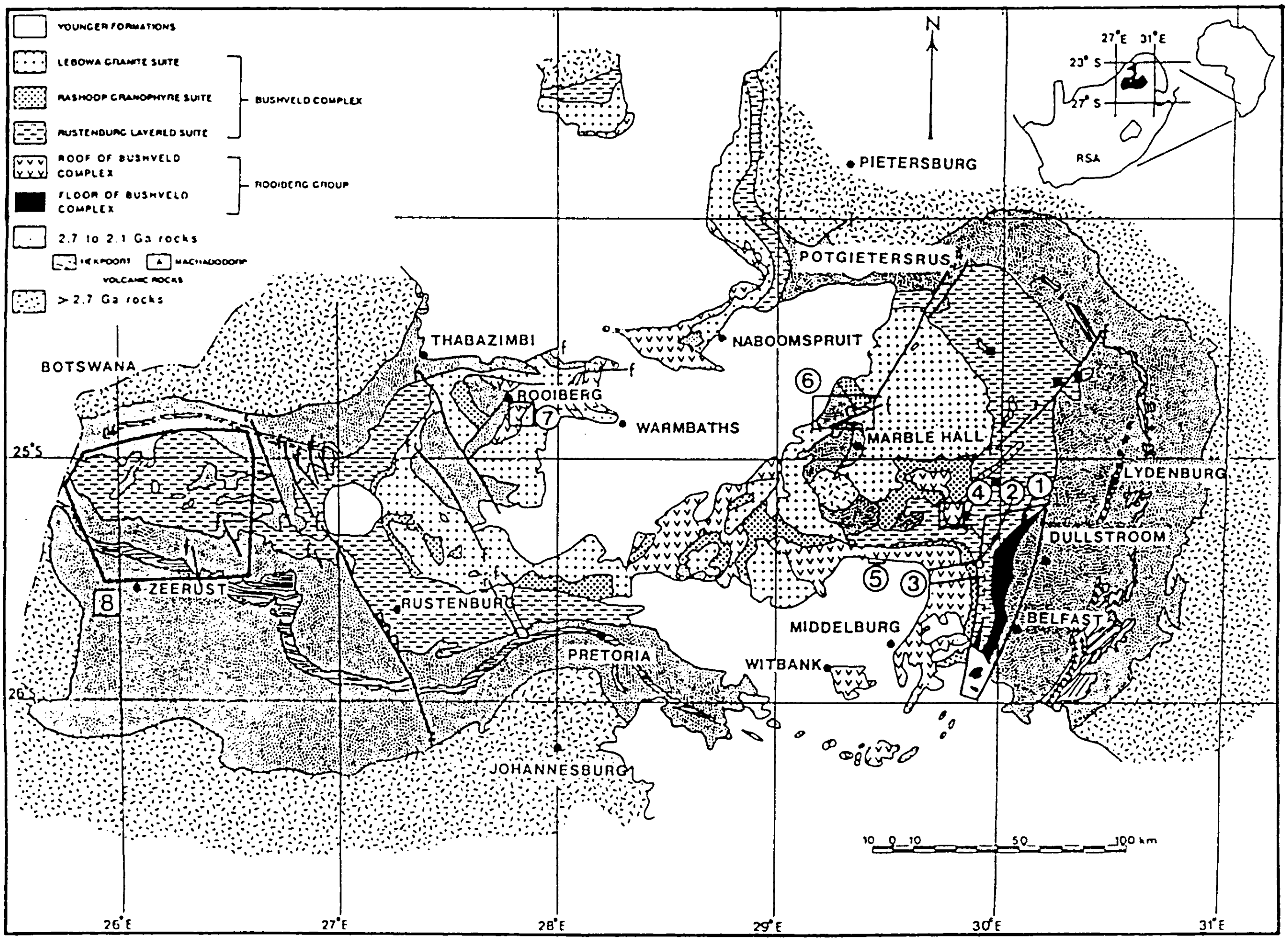

FIG. 1. Geologic map showing the geographic distribution of the volcanic rocks forming the floor and roof of the Bushveld Complex. Localities: 1 = Dullstroom Formation, 2 = Dullstroom xenolith, 3 = Bothasberg plateau, 4 = Tautes-hoogte, 5 = Loskop Dam, 6 = Stavoren fragment, 7 = Rooiberg fragment. Also shown are the study areas of Engelbrecht (1990), locality 8) and Wallmach (1988, squares in eastern lobe of the Rustenburg Layered Suite mark the location of calc-silicate xenoliths).

rocks of the Dullstroom Formation underlie the Rustenburg Layered Suite, whereas elsewhere the Rooiberg Group is the roof of the Bushveld Complex. The Rooiberg Group in the roof has only low-grade metamorphic characteristics (Martini, 1988), and the striking freshness of these old rocks is one of their most conspicuous features (Twist and French, 1983).

Schweitzer et al. (1995a), building on the findings of Clubley-Armstrong (1977, 1980), De Bruiyn (1980), Rhodes and Du Plessis (1976), and, especially, Twist (1985), used the distribution of eight magma types to subdivide the Rooiberg Group stratigraphically. Four magma types are in the Dullstroom Formation, in the floor of the Rustenburg Layered Suite, and five are in the roof of the Rustenburg Layered Suite, in the Dullstroom, Damwal, Kwaggasnek, and Schrikkloof Formations (Table 1, Figs. 2, 3, and 4). These magma types are defined by titanium and other high field strength elements. One magma type, the high Mg felsite, is common to both roof and floor (Fig. 5), establishing that the floor and roof volcanic rocks are the same succession (Fig. 6).

The Dullstroom Formation in the Rustenburg Layered Suite floor consists of massive lava flows. Pyroclastic flows and sedimentary rocks occur toward the base (Fig. 2). Pyroclastic intercalations are more abundant in the formations overlying the Dullstroom, some being strongly kaolinitized. The majority of the flows above the Rustenburg Layered Suite possess thick, massive interior zones, and much thinner flow-banded (and commonly flow-brecciated) basal and upper portions (Twist and Bristow, 1990). The flows are up to 400 m thick. The porous pyroclastic horizons and basal and upper portions of flows may have facilitated the circulation of hydrothermal fluids. The geochemical analyses employed in this study were, however, taken from the dense (nonporous) portions of the volcanic flows.

Metamorphism

Engelbrecht (1990) stressed that in the western Bushveld the thermal effect of the Rustenburg Layered Suite on the underlying sedimentary rocks (Fig. 1, locality 8) was domi-

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TABLE 1. Comparison of Stratigraphic Subdivisions as Defined by South African Committee for Stratigraphy (SACS, 1980) and Schweitzer et al. (1995a) for the Volcanic Rocks of the Floor and Roof of the Bushveld Complex

SACS (1980)			Schweitzer et al. (1995a)		
Group	Formation	Member	Group	Formation	Member
Rooiberg	Selons River	Klipnek	Rooiberg	Schrikkloof	
		Doornkloof		Kwaggasnek	Union Tin
	Damwal			Damwal	
				Dullstroom	
Pretoria	Dullstroom				

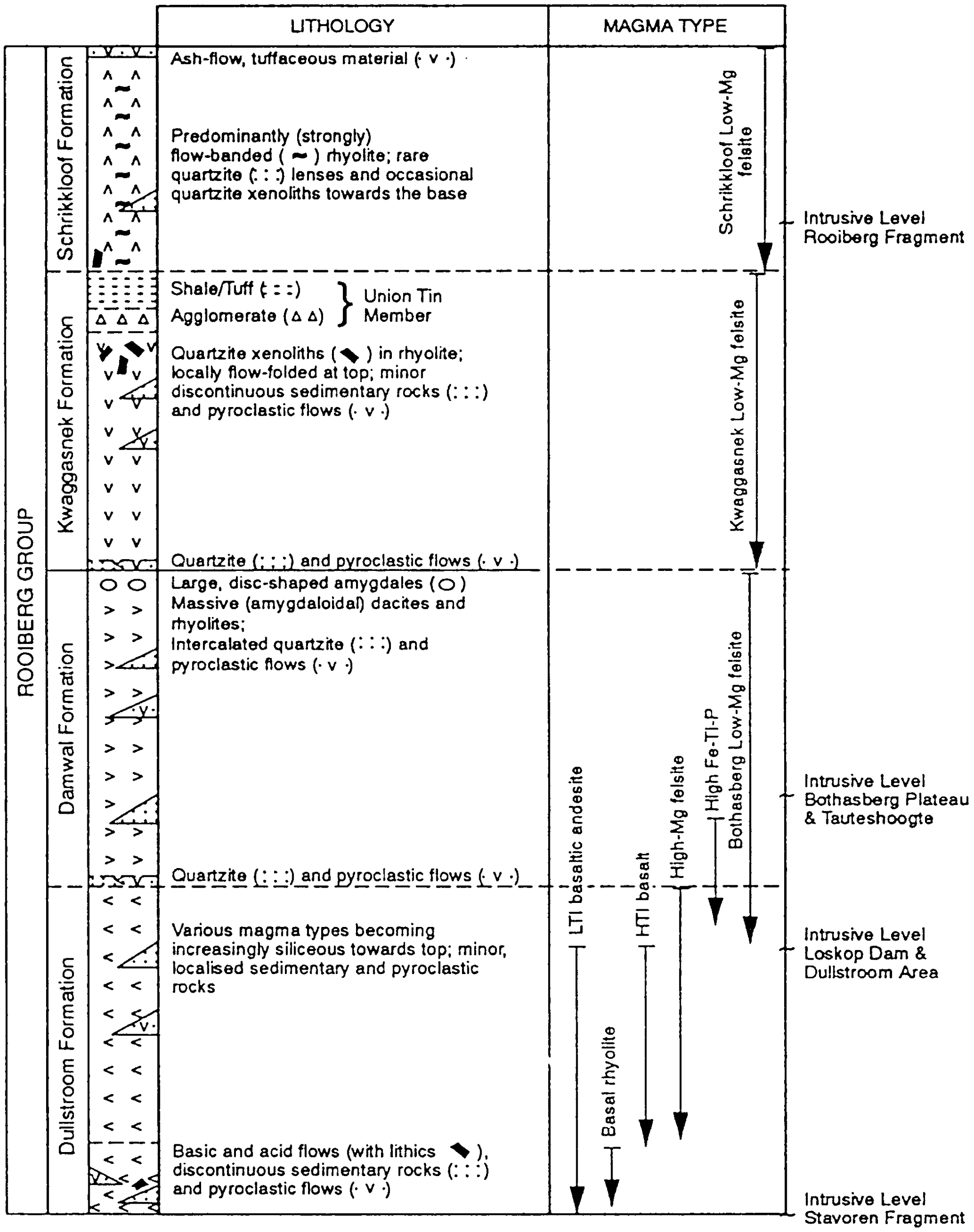

FIG. 2. Regional stratigraphic subdivision of the Rooiberg Group as deduced from lithological and geochemical characteristics (modified after Schweitzer et al., 1995a).

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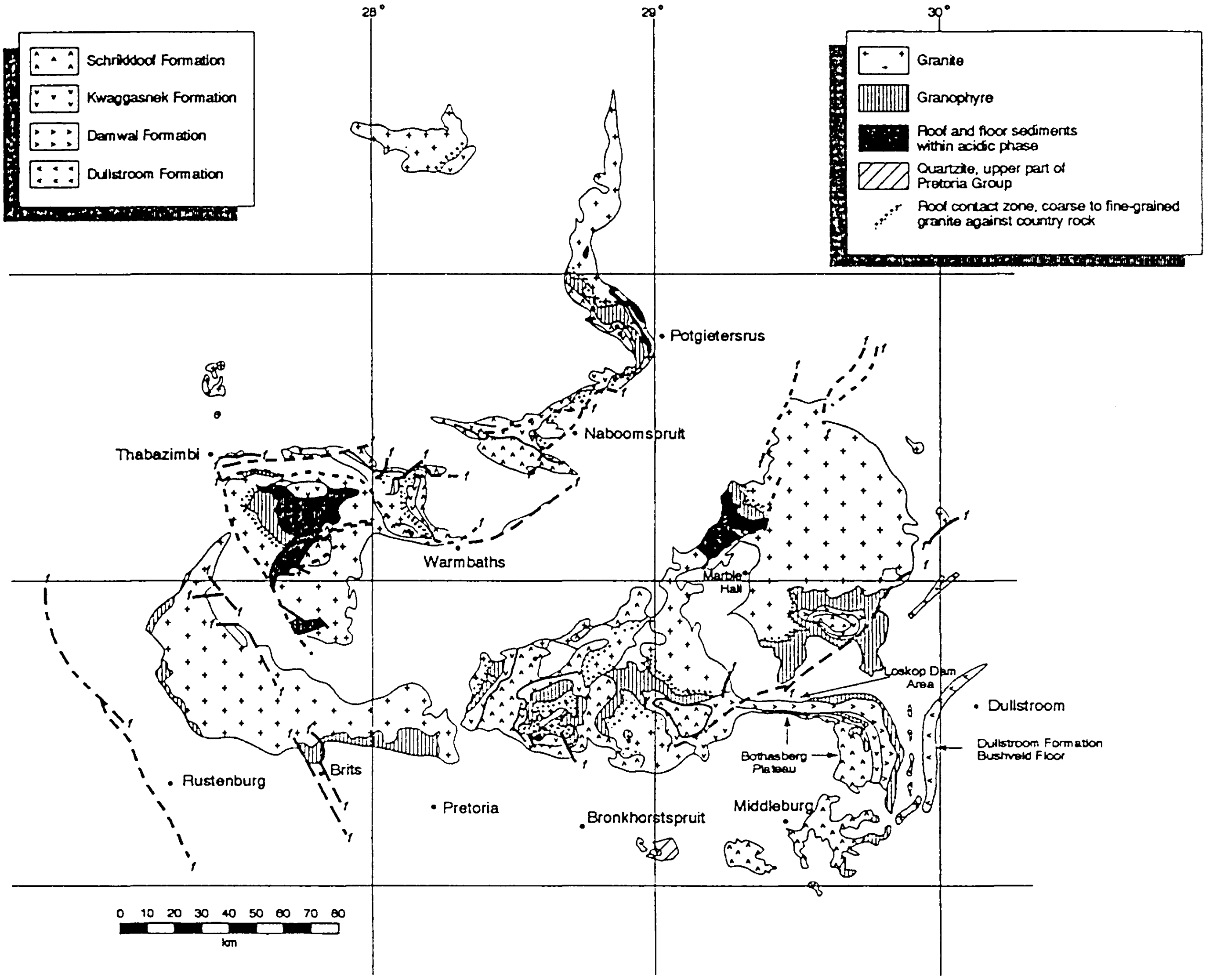

FIG. 3. Geographic distribution of the four Rooiberg Group formations (modified after Schweitzer et al., 1995b).

nantly dehydration. He found no differences in the compositions of the hornfelses in the floor compared to the average shale of Blatt et al. (1972).

In the eastern Bushveld in the lower (>1,000 m below the Rustenburg Layered Suite) and middle (1,000–400 m below the Rustenburg Layered Suite) portions of the Dullstroom Formation, secondary minerals include tremolite-actinolite, sericite, and quartz (Schweitzer, 1987; Fig. 7A and B). Chlorite is confined to the lower portion. The amphiboles have low Na_2O contents (<1 wt %), which indicates low to medium metamorphic grades (e.g., Harte and Graham, 1975; Gelinas et al., 1982). Less than 400 m below the mafic rocks, granoblastic textures completely overprint the original volcanic textures (Fig. 7C). Actinolite is transformed to hornblende, a transition that takes place at about 500°C (Winkler, 1979). Coexisting amphiboles and clinopyroxenes in the upper portion of the Dullstroom Formation have similar FeO/MgO ratios, which are, in turn, similar to whole-rock ratios, suggesting that these elements have not been remobilized. On the contact with the Rustenburg Layered Suite pegmatitic zones contain prismatic and euhedral plagioclase and amphibole. Where the Dullstroom Formation is not present, similar temperatures are recorded in calc-silicate assemblages (Sharpe and Foertsch, 1981).

For 1 to 2 km above the contact with the Rustenburg Layered Suite, felsite is biotite hornfels (von Gruenewaldt, 1972). About 1.4 km above the contact, on the Bothasberg plateau (Fig. 3), is a hydrothermally altered zone (Martini, 1988) of silicification and sericitization with distal chlorite, epidote, and calcite (Fig. 7D). Between 2 and 3 km above the contact are intergrowths of quartz and sericitized albite in felsitic and granophyric rocks. Devitrified glass in the felsic rocks is altered to quartz, chlorite, and epidote; mafic phenocrysts are usually altered to hornblende and/or chlorite. In

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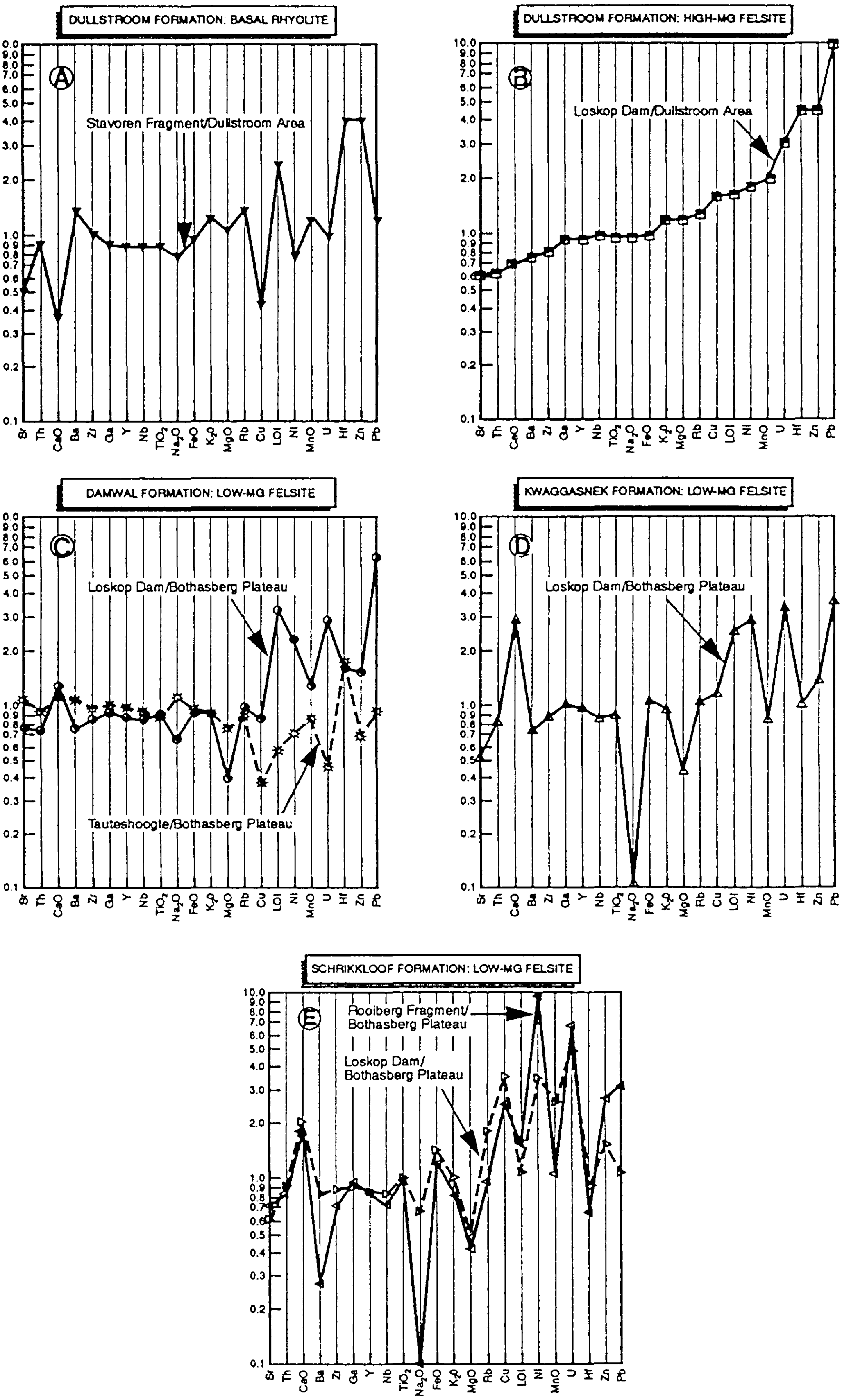

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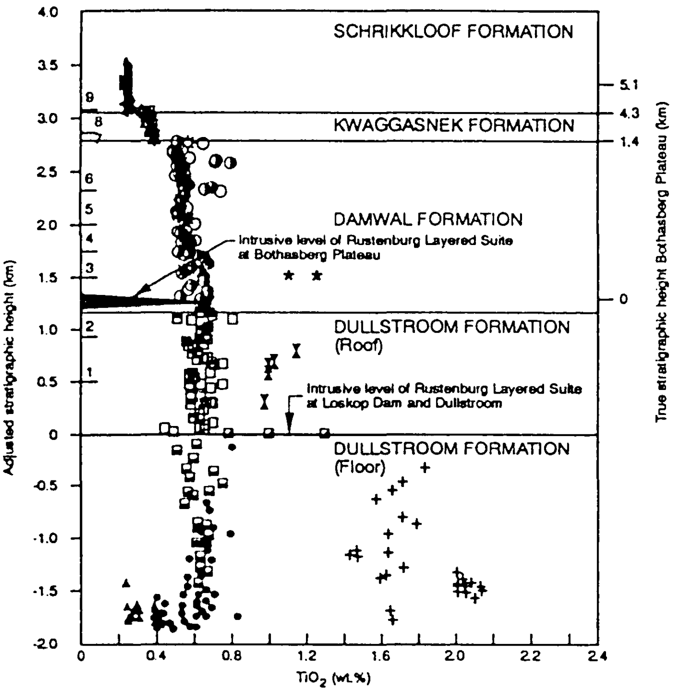

Symbol	Magma Type	Locality	Formation
◁	Low Magnesium Felsite (LMF)	Loskop Dam	Schrikkloof
◊	Low Magnesium Felsite (LMF)	Bothasberg Plateau	
▷	Low Magnesium Felsite (LMF)	Rooiberg Fragment	
△	Low Magnesium Felsite (LMF)	Loskop Dam	Kwaggasnek
▽	Low Magnesium Felsite (LMF)	Bothasberg Plateau	
◑	Low Magnesium Felsite (LMF)	Loskop Dam	Damwal
○	Low Magnesium Felsite (LMF)	Bothasberg Plateau	
✡	Low Magnesium Felsite (LMF)	Tauteshoogte	
x	High Fe-Ti-P Lava	Loskop Dam	
★	High Fe-Ti-P Lava	Bothasberg Plateau	Damwal
□	Low Magnesium Felsite (LMF)	Loskop Dam	Dullstroom
▭	High Magnesium Felsite (HMF)	Loskop Dam	
I	High Fe-Ti-P Lava	Loskop Dam	
◪	Xenolith	Dullstroom Area	
⊟	High Magnesium Felsite (HMF)	Dullstroom Area	
+	High Titanium Basalt (HTI)	Dullstroom Area	
▲	Basal Rhyolite	Dullstroom Area	
●	Low Titanium Basaltic Andesite	Dullstroom Area	

FIG. 5. Variations in TiO_2 with stratigraphic height for the volcanic rocks of the Dullstroom and Rooiberg successions. Stratigraphic heights for felsite occurrences from the Bothasberg plateau (locality 3), the Tauteshoogte area (locality 4), and the Rooiberg fragment (locality 7) are adjusted to allow stratigraphic comparison with Loskop Dam (locality 5). Localities are shown in Figure 1. Y axis right = uncorrected stratigraphic height for Bothasberg plateau; Y axis left = stratigraphic units at Loskop Dam. The numerical subdivision of units at Loskop Dam (after Twist, 1985) on the left Y axis allows stratigraphic comparison with the formations of the Bothasberg plateau. Although TiO_2 concentrations for low Ti basaltic andesite and high Mg felsite compositions are comparable, these flows differ in other elements (Schweitzer et al., 1995a).

felsites more than 3 km above the Rustenburg Layered Suite, silicification is associated with calcite, quartz, epidote, and hornblende. In the Rooiberg fragment (Fig. 1, locality 7) these features are even more prominent than in the Loskop Dam area (Fig. 1, locality 5). There, plagioclase phenocrysts and matrix are almost entirely replaced by chlorite, calcite, and sericite.

Geochemical Effects of Alteration

The degree of alteration is indicated by volatile contents (L.O.I., loss on ignition) of the rocks, normative compositions (particularly normative corundum), variation in compositions with stratigraphic height, and comparison of the geochemistry of the equivalent magma types recognized by Schweitzer et al. (1995a) in different settings (Table 2, Fig. 4A–E).

Floor rocks

Chayes (1966) and Irvine and Baragar (1971) considered igneous rocks with L.O.I. > 2.5 wt percent to be altered. Only five of the 162 massive lava flows of the Dullstroom volcanic rocks have L.O.I. greater than this value (Fig. 8). Nonetheless, the criterion of Irvine and Baragar (1971) is for low-grade, regionally metamorphosed terranes, whereas the Rooiberg Group has undergone high contact metamorphic grades. However, Figure 8 illustrates that some high Mg felsite magma types in the roof of the Rustenburg Layered Suite have higher L.O.I. than equivalents in the floor.

Normative corundum in mafic rocks is an indication of metasomatism (Hatch et al., 1972) or alteration (Chayes, 1969). Most of the Dullstroom lavas in the floor lack norma-

FIG. 4. Comparison of element concentrations of stratigraphically corresponding magma types: A. Basal rhyolite—Dullstroom Formation. The basal rhyolite occurrences from the Stavoren fragment (n = 7) are normalized to their equivalents from the Dullstroom area (n = 24). B. High Mg felsite—Dullstroom Formation. This magma type in the roof (n = 28) is normalized to its equivalent from the floor, in the Dullstroom area (n = 26). C. Low Mg felsite—Damwal Formation. Loskop Dam (n = 75) and Tauteshoogte (n = 8) areas normalized to their stratigraphic equivalents from the Bothasberg plateau (n = 11). D. Low Mg felsite—Kwaggasnek Formation. Loskop Dam occurrences (n = 15) normalized to their equivalents from the Bothasberg plateau (n = 24). E. Low Mg felsite—Schrikkloof Formation. Loskop Dam (n = 14) and Rooiberg fragment (n = 43) occurrences normalized to their equivalents from the Bothasberg plateau (n = 6). Al_2O_3, P_2O_5, and Sc compare favorably for the various localities under consideration. The sequence of elements was determined by sorting the normalized element concentrations, in ascending order, for the high Mg felsite magma type from the Loskop Dam. The average compositions of magma types that are considered in this study, but which have no equivalent at another locality, are given in Table 2.

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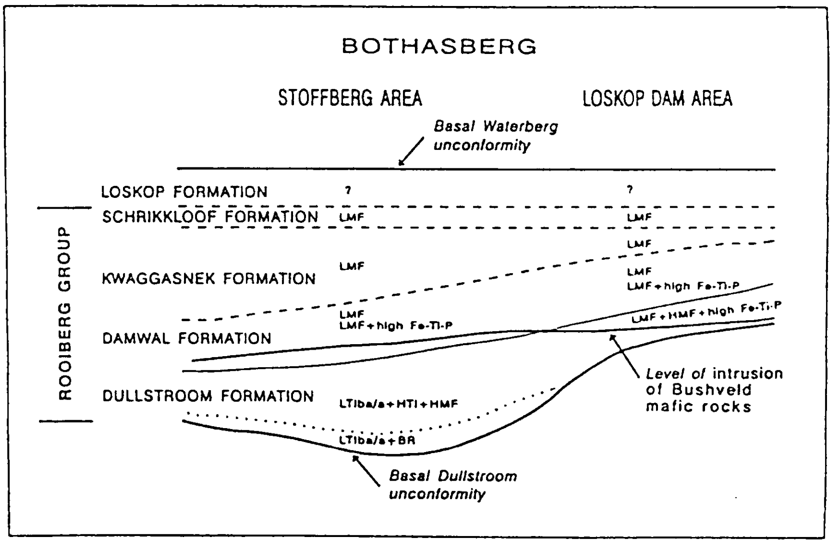

FIG. 6. Reconstructed intrusive level of the Rustenburg Layered Suite for the eastern Bushveld Complex (after Schweitzer et al., 1995a). The stratigraphic distribution of the following magma types are shown: $LTI_{ba/a}$ = low Ti basaltic andesite, BR = basal rhyolite, HTI = high Ti basalt, HMF = high Mg felsite, LMF = low Mg felsite, and high Fe-Ti-P = high Fe-Ti-P andesite. Note that the high Mg felsite magma type is preserved beneath and above the Rustenburg Layered Suite. Damwal, Kwaggasnek, and Schrikkloof low Mg felsite magma types are compositionally distinct (e.g., Fig. 5).

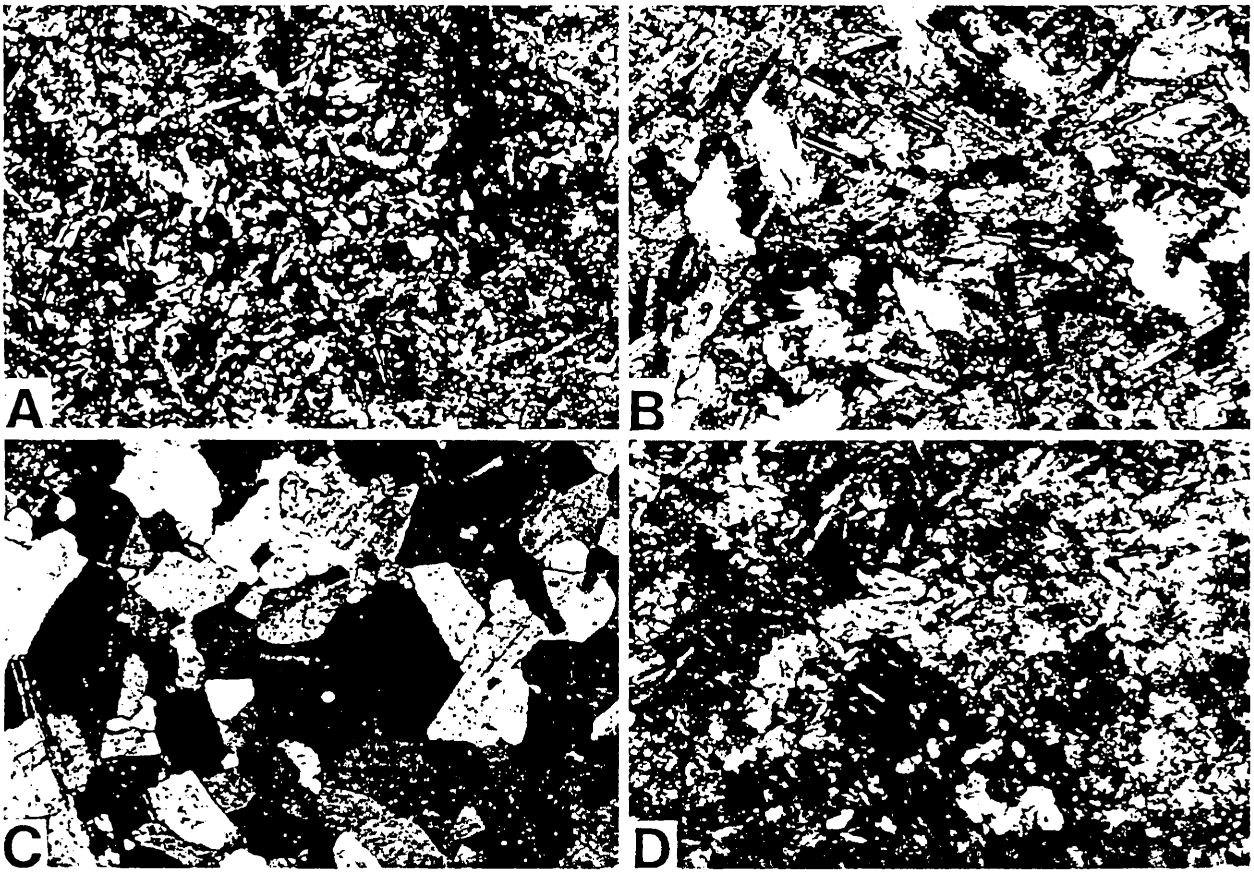

FIG. 7. A. Alteration texture and mineral assemblage in a low Ti basaltic andesite in the lower Dullstroom zone (>1,000 m distance to the Rustenburg Layered Suite). Chlorite is present but the original ophitic texture is preserved. B. Tremolite-actinolite associated with plagioclase in a low Ti basaltic andesite 400 to 1,000 m below the Bushveld mafic rocks; chlorite is absent. C. Granoblastic texture in a low Ti basaltic andesite <400 m from the contact with the Bushveld mafic rocks. Interlocking plagioclase (74 vol %), biotite (8 vol %), pyroxene (8 vol %), hornblende (2 vol %), quartz (5 vol %), and magnetite (3 vol %) are the predominant minerals. D. High Mg felsite of the Rooiberg Group about 1,000 m above the intrusive contact. Chlorite (black patches), epidote, and calcite are abundant in the rocks <1.4 km from the Bushveld contact. Long dimension for A to D is 1.4 mm.

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TABLE 2. Average Geochemical Analyses of the Magma Types of the Dullstroom Formation

	Dullstroom Formation							
	LTI_{ba}		HTI		High Fe-Ti-P		LMF	
n	77	Std	35	Std	5	Std	29	Std
SiO_2	57.30	2.30	53.90	2.20	61.30	1.60	67.90	1.10
TiO_2	0.62	0.09	1.87	0.22	1.02	0.06	0.63	0.07
Al_2O_3	14.70	0.60	13.60	0.70	12.00	0.20	12.00	0.30
FeO^*	8.87	0.44	11.50	1.22	10.69	1.20	7.16	0.65
MnO	0.16	0.02	0.17	0.02	0.28	0.05	0.21	0.27
MgO	5.06	1.14	4.62	0.54	0.81	0.21	0.53	0.20
CaO	7.92	0.84	8.37	1.21	3.56	0.25	2.04	0.80
Na_2O	2.28	0.41	3.00	0.45	2.86	0.41	2.81	0.63
K_2O	1.43	0.40	1.38	0.38	3.25	0.26	4.43	0.86
P_2O_5	0.12	0.03	0.23	0.05	0.35	0.04	0.16	0.03
L.O.I.	1.38	0.56	0.95	0.39	1.95	0.49	1.19	0.50
Total	99.90		99.50		98.10		99.10	
Nb	3	3	13	3	14	2	16	1
Zr	130	42	206	51	282	19	328	20
Y	21	5	30	6	49	2	49	7
Sr	252	47	389	58	159	16	136	60
Rb	58	22	50	20	126	11	169	36
Zn	79	17	94	22	407	131	246	168
Cu	60	199	55	49	52	38	46	36
Ni	81	32	90	28	13	4	14	9
Ba	394	109	336	125	431	26	659	226
Sc	30	3	24	3	20	3	12	2
Ca	14	1	19	1	19	1	16	2
Hf	1	3	1	4			7	3
U	0	2	0	1	4	0	8	12
Th	12	8	10	3	15	3	18	2
Pb	7	13	4	2	98	68	48	48

Magma types listed are those not compared to stratigraphic equivalents from other locations (Fig. 4A–E); data from Schweitzer (1987) and Twist (1985); major elements in wt percent, trace elements in ppm, FeO^* = total iron as FeO

Abbreviations: High Fe-Ti-P = high Fe-Ti-P andesite, HTI = high Ti basalt, LMF = low Mg felsite, LTI_{ba} = low Ti basaltic andesite, Std = standard deviation

tive corundum (Fig. 9) and have positive correlations between CaO and FeO^* or MgO (Schweitzer, 1987). These relations are typical of unaltered igneous rocks (Gelinas et al., 1982). Thus, any metasomatism or alteration in the floor rocks was limited to dehydration with little, if any, mobilization of the major rock-forming elements.

Roof rocks

The roof volcanic rocks have increasingly higher normative corundum with increasing height above the Rustenburg Layered Suite (Fig. 9), suggesting a much greater degree of alteration than in the floor. The almost twofold increase in Ca and generally higher Sr concentrations in flows without normative corundum (Table 3), suggests that Ca and Sr were removed from the corundum-normative flows. Corundum-normative flows are especially prominent at Loskop Dam, where the Ca concentration of low Mg felsite flows above the Dullstroom Formation correlates positively with L.O.I. (Fig. 10).

The striking increase in volatiles in the roof away from the Rustenburg Layered Suite (Fig. 8) is accompanied by a general increase in Zn, Pb (Figs. 11 and 12), and to a lesser extent, Mn (Schweitzer et al., 1995b). Alteration in the lower 1.4 km of felsites occurs irrespective of magma type (Figs. 8, 11, and 12).

Zn contents decline in the middle portion of the roof rocks but are higher than in the floor rocks (Fig. 11). L.O.I. is generally high (Fig. 8). Thus, this portion of the pile appears to be pervasively altered.

At the top of the succession, Zn contents decline (Fig. 11), normative corundum contents are variable (Fig. 9), and silica commonly exceeds magmatic values (Fig. 13). These characteristics indicate that leaching and silicification were the dominant processes at the top of the succession.

Concentrations of mobile elements have been modified to varying degrees at the localities under consideration (Figs. 11, 12, and 13). Immobile elements, such as Ti and P, exhibit limited scatter and comparable concentrations for the various localities (Fig. 14).

Regional Variations in Alteration

Stavoren fragment

Zn and Hf enrichment is pronounced in the Dullstroom volcanic rocks of the Stavoren fragment (Fig. 1, locality 6), when compared with the equivalent magma type in the floor of the Rustenburg Layered Suite in the eastern Bushveld

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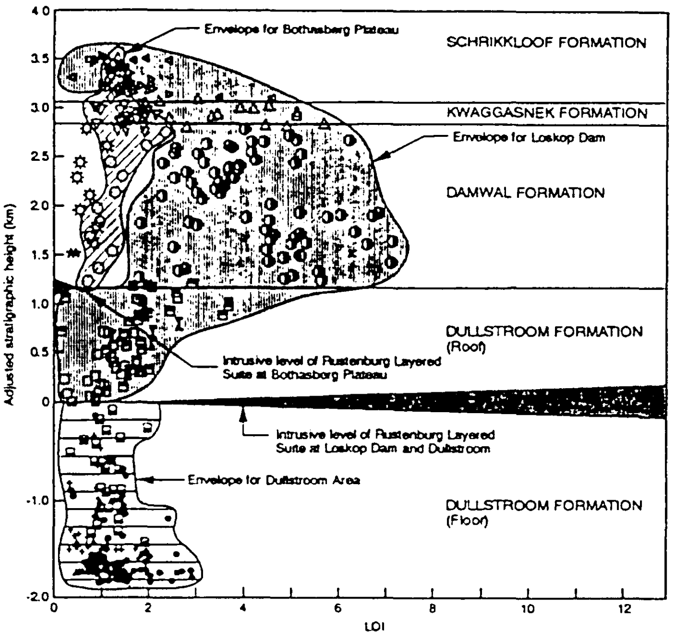

FIG. 8. Variation of L.O.I. with stratigraphic height for Dullstroom and Rooiberg volcanic rocks. See Figure 5 for legend.

(Fig. 4). Normative corundum, which is almost completely absent in the Dullstroom basal rhyolite, is characteristic of the rhyolites of the Stavoren fragment. The basal rhyolite of the Stavoren fragment has relatively higher K, Rb, Ba, L.O.I., Hf, Zn (Fig. 15A), and Si, and lower Na, Sr, Cu, and Ca (Fig. 15B) concentrations than its equivalents in the Dullstroom area, suggesting that the Stavoren flows are severely altered.

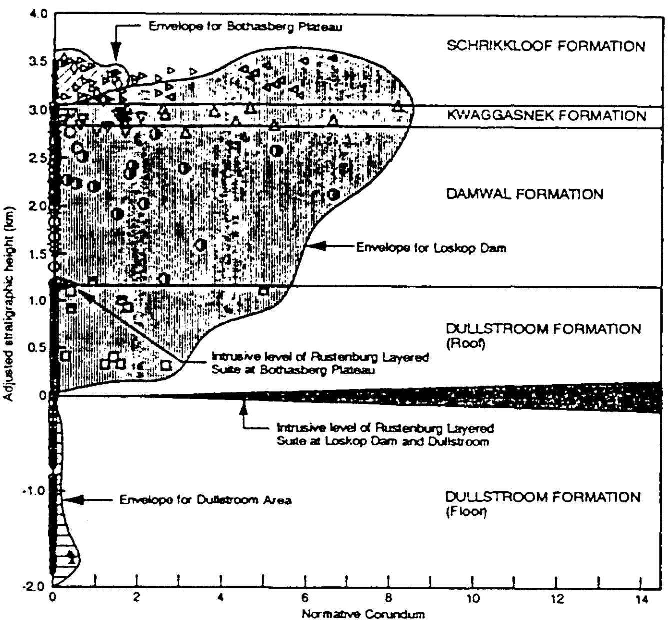

FIG. 9. Variations in normative corundum with stratigraphic height in the Rooiberg volcanic rocks. Immobile elements indicate that low Mg felsite with and without normative corundum occurs within regionally comparable stratigraphic horizons. See Figure 5 for legend.

Loskop Dam area

A comparison between the high Mg felsite magma type in the Dullstroom Formation, below (Dullstroom area) and above (Loskop Dam area) the Rustenburg Layered Suite, suggests an increase of, in increasing order, K, Mg, Rb, Cu, L.O.I., Ni, Mn, U, Hf, Zn (Fig. 15A), and Pb and a depletion in Ba, Ca (Fig. 15B), Th, and Sr at Loskop Dam (Fig. 1, locality 5; Fig. 4). Corundum occurs in the norm of some high Mg felsites of the Loskop Dam succession but not in the same magma type in the Rustenburg Layered Suite floor (Fig. 9).

At Loskop Dam, the low Mg felsites in the Damwal Formation have higher concentrations of Ca, Mn, Zn, Ni, L.O.I., and Pb and lesser Ba, Na (Fig. 16), Th, Sr, Mg, and Si (Fig. 13) than stratigraphic and compositional equivalents in the Bothasberg plateau (Fig. 4E).

A comparison of the low Mg felsite magma type of the Kwaggasnek Formation at Loskop Dam with its equivalent in the Bothasberg plateau (Fig. 4D shows that the Loskop Dam occurrences are severely altered. The very low Na contents of Loskop Dam low Mg felsites (Fig. 16) are accompanied by low Zr, Ba, Th, Sr, and Mg (Fig. 4D). The Loskop Dam area shows a relative increase in Zn, L.O.I., Ca, Ni, U, and Pb.

The Schrikkloof Formation in the Loskop Dam area has

TABLE 3. Comparison of Low Mg Felsite Compositions (unit 6 of Twist, 1985) with and without Normative Corundum

	Low Mg felsite magma type—Damwal Formation			
	Without normative corundum (n = 19)		With normative corundum (n = 9)	
		Std		Std
SiO_2	65.97	1.05	67.77	1.27
TiO_2	0.54	0.07	0.58	0.08
Al_2O_3	11.31	0.30	11.62	0.25
FeO*	6.96	0.73	7.31	0.98
MnO	0.16	0.03	0.15	0.05
MgO	0.50	0.16	0.59	0.16
CaO	3.28	0.55	1.85	0.76
Na_2O	1.90	0.75	1.84	1.01
K_2O	3.97	0.50	3.88	0.68
P_2O_5	0.17	0.03	0.18	0.03
L.O.I.	4.16	0.82	3.08	0.61
Nb	14	2	15	2
Zr	316	25	316	19
Y	50	9	54	14
Sr	92	23	73	27
Rb	160	31	158	41
Zn	207	70	236	101
Cu	31	24	26	18
Ni	13	9	15	8
Ba	752	230	799	224
Sc	13	1	14	2
Ga	17	1	17	1
Hf	7	2	7	1
U	3	0	3	0
Th	17	2	17	2
Pb	52	94	34	19

Std = standard deviation; major elements in weight percent, trace elements in ppm, FeO* = total iron as FeO

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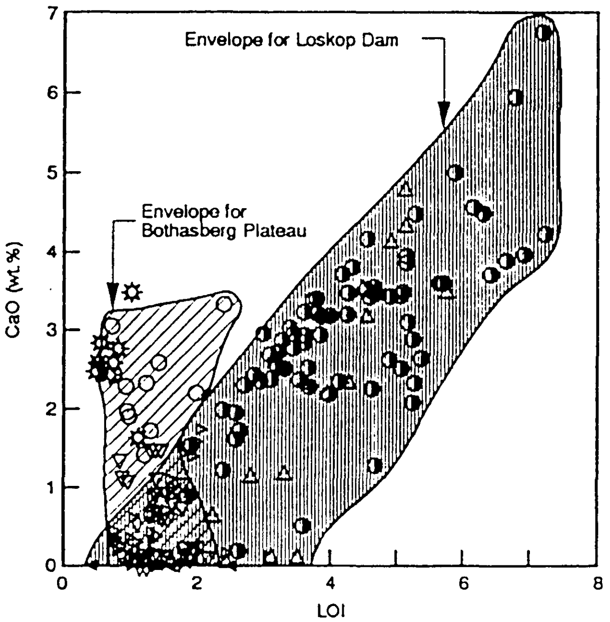

Symbol	Locality	Formation
◁	Loskop Dam	Schrikkloof
◊	Bothasberg Plateau	
▷	Rooiberg Fragment	
△	Loskop Dam	Kwaggasnek
▽	Bothasberg Plateau	
◑	Loskop Dam	Damwal
○	Bothasberg Plateau	
✡	Tauteshoogte	

FIG. 10. CaO/L.O.I. correlation of low Mg felsite flows of the Damwal, Kwaggasnek, and Schrikkloof Formations. CaO concentrations of low Mg felsite flows from the Loskop Dam exhibit a pronounced (rc = 0.836) correlation with L.O.I.

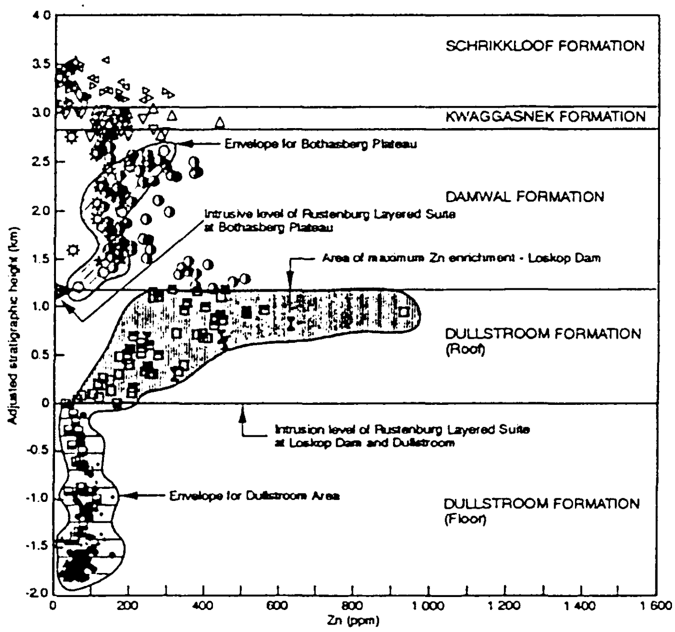

FIG. 11. Variations in Zn within Dullstroom and Rooiberg volcanic rocks related to the distance to the Bushveld intrusion. See Figure 5 for legend.

exceptionally low Na (Fig. 16) and correspondingly high Si (Fig. 13) compared to other areas. Silicification and secondary calcite, epidote, and hornblende also indicate that the Schrikkloof Formation in the Loskop Dam area is severely altered. Geochemically the Schrikkloof Formation at Loskop Dam is relatively enriched in Fe, Ca, Zn, Pb, U, Ni and Si and depleted in Y, Nb, Zr, Th, Sr, Hf, Mg, Ba, and Na, compared to equivalents from the Bothasberg plateau (Fig. 4E).

Rooiberg fragment

In the Rooiberg fragment (Fig. 1, locality 7) leaching of Na in some flows of the Schrikkloof Formation (Fig. 16) is almost as pronounced as in the Loskop Dam area. Silicification, however, is not as severe (Fig. 13); Si is higher than in stratigraphically equivalent flows of the Bothasberg plateau. These flows exhibit an alteration pattern similar to the uppermost flows from the Loskop Dam and are characterized by Fe, Zn, Rb, Ca, Mn, Ni, and U enrichment and by Zr, Y, Nb, Ba, Na, Sr, and Mg depletion (Fig. 4E).

Bothasberg plateau and Tauteshoogte area

The lavas of the Bothasberg plateau (Fig. 1, locality 3) have Si and Na contents which are consistent with magmatic origins (Figs. 13 and 16). Mildly elevated normative corundum (Fig. 9), Zn values (Fig. 11), and low L.O.I. values (Fig. 4C–E) indicate that these rocks are moderately altered. Low Mg felsites from Tauteshoogte possess comparable concen-

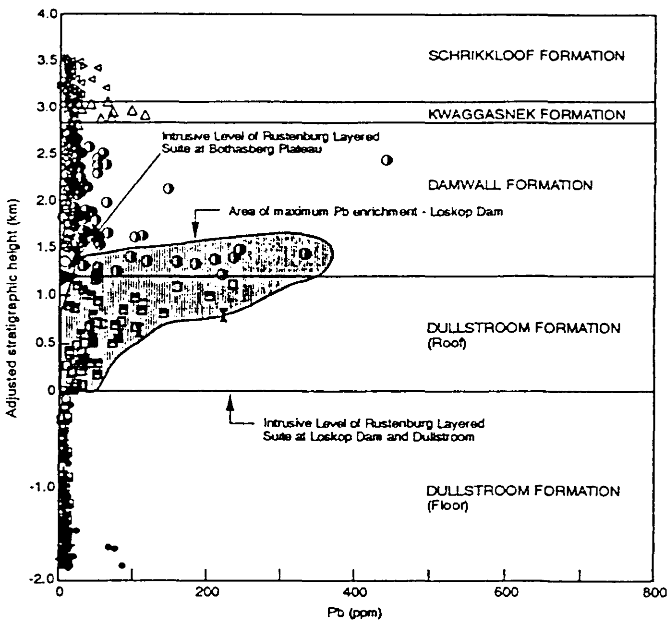

FIG. 12. Pb concentrations in the Rooiberg volcanic rocks beneath and above the Rustenburg Layered Suite. See Figure 5 for legend.

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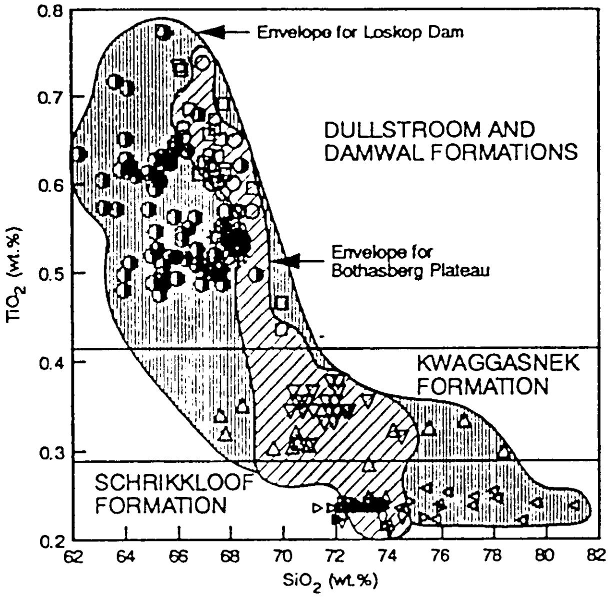

Symbol	Locality	Formation
◁	Loskop Dam	Schrikkloof
◊	Bothasberg Plateau	
▷	Rooiberg Fragment	
△	Loskop Dam	Kwaggasnek
▽	Bothasberg Plateau	
◑	Loskop Dam	Damwal
○	Bothasberg Plateau	
☼	Tauteshoogte	
□	Loskop Dam	Dullstroom

FIG. 13. TiO_2 and SiO_2 variations in low Mg felsite flows of the Rooiberg Group.

trations but have even lower Zn, L.O.I., Cu, and Mg, and higher Hf (Fig. 4C).

In summary, Ti, P, Al, Ga, and Sc concentrations are the same at all localities, whereas other elements scatter broadly or are relatively increased or depleted (Fig. 4A–E). Regionally, the roof rocks are depleted in Sr, Na, and Th and enriched in L.O.I., Ni, Zn. The lower portion of the roof rocks is depleted in Ca, with Ca enrichment in the upper portion of the volcanic pile. Mg has the reverse trend. The uppermost portion of the roof rocks has U and Fe enrichment. Nb, Zr, and Y reflect primary compositions in the lower portion of the Rooiberg Group, but depletion of these elements occurred in the Kwaggasnek and Schrikkloof Formations (Fig. 4D and E).

Discussion

Although heat from the Rustenburg Layered Suite devolatilized about 1 km of the floor volcanic rocks, elemental redistribution within these rocks was minor. A possible reason for this is that with the heat source above the fluid, cooling and recirculation of the fluid were impossible, with the water migrating into the Rustenburg Layered Suite magmas.

The primary compositions of the magma types in the Rooiberg Group overlying the Rustenburg Layered Suite were significantly modified. The degree of alteration varies from locality to locality and with stratigraphic height. Distinct magma types cannot be distinguished using mobile elements. Only a limited number of elements (Ti, Al, P, Ga, Sc, and heavy REE) were immobile during alteration. These can be regionally useful for lithochemical and petrogenetic studies. Other elements may be utilized selectively. Fe concentrations, for example, are comparable for the same floor and roof magma types, and stratigraphically equivalent roof rocks, for the lower portion of the succession (Fig. 4A–C). It is therefore deduced that primary Fe concentrations are encountered in the Dullstroom and Damwal Formations, whereas Fe enrichment occurred in the upper Rooiberg Group (Fig. 4D and E).

The zone of base metal concentration in the immediate roof zone is of special economic importance. Martini (1988) described two phases of mineralization at the transition from the Damwal to the Kwaggasnek Formation in the Bothasberg plateau. The first caused pyrite and arsenopyrite mineralization, which may have been initiated by shallow intrusion of granophyre (Martini, 1988). Because the arsenopyrite mineralization does not extend upward into the Kwaggasnek Formation, mineralization may have preceded the emplacement of the Kwaggasnek Formation.

Martini (1988) showed, in addition, that Pb and Zn were introduced later, but he could not explain this change in mineralization. Our results suggest that this second stage of mineralization is linked to the emplacement of the Rustenburg Layered Suite: fluids penetrated the bottom portion of the Rooiberg Felsite Group. In particular Zn, Pb, and Mn were introduced or redistributed into hydrated rocks. Aver-

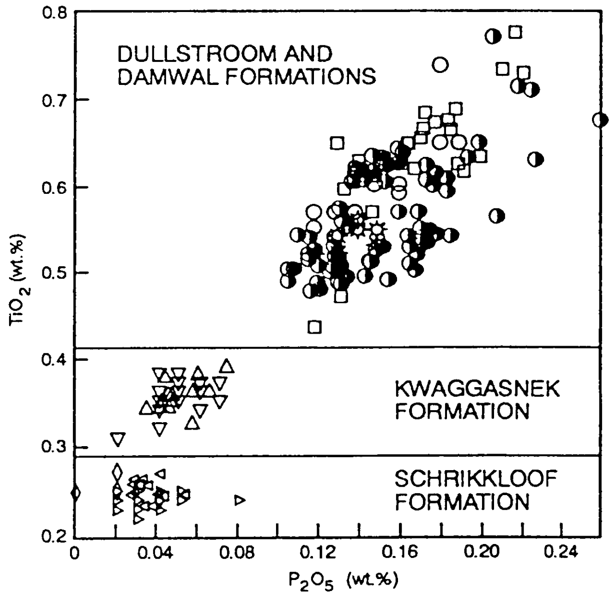

FIG. 14. Variations in TiO_2 and P_2O_5 within the various stratigraphic units of the Rooiberg Group. The distinctive ranges in concentration can be used to correlate units at different localities. See Figure 13 for legend.

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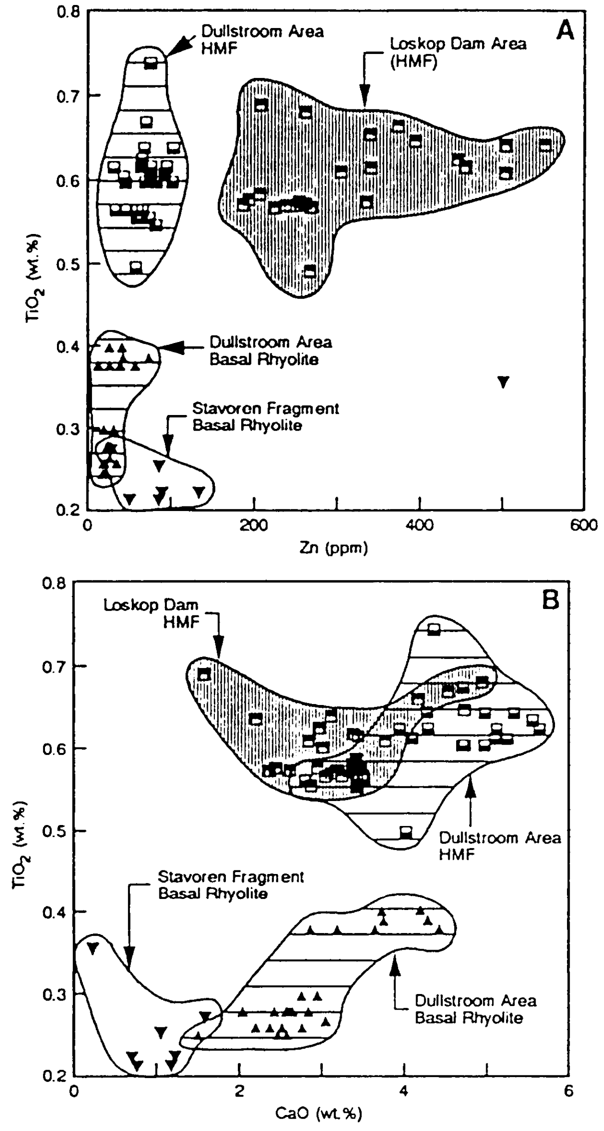

Symbol	Magma Type	Locality	Formation
▪	High Magnesium Felsite (HMF)	Loskop Dam	Dullstroom
▫	High Magnesium Felsite (HMF)	Dullstroom Area	
▲	Basal Rhyolite	Dullstroom Area	
▼	Basal Rhyolite	Stavoren Area	

FIG. 15. A and B. Geochemical comparison of corresponding floor and roof rocks.

age Zn contents of siliceous volcanic rocks normally are low (about 48–53 ppm), but the average concentration in massive Rooiberg felsite rocks from Loskop Dam is 318 ppm. The comparison of equivalent floor and roof magma types indicates that the majority of the Bushveld roof rocks show hydrothermal enrichment of Zn, Pb, and Mn, and that this enrichment is not restricted to intercalated quartzites as Martini (1988) suggested.

Volatiles are interpreted to have originated from the floor rocks and from xenoliths in the Rustenburg Layered Suite (Wallmach, 1988). A wide variety of saline fluids migrated through the Bushveld Complex (Schiffries and Skinner, 1987), and they could have transported appreciable amounts of dissolved metals. The formation of vesuvianite is a direct reflection of the availability of H_2O-rich fluids in xenoliths of the upper zone of the Rustenburg Layered Suite (Wallmach, 1988; see Fig. 1 for locality of various calc-silicate xenoliths). The hydration reactions to vesuvianite occur at low temperatures (<500°C) and are relatively insensitive to changes in pressure (Ito and Arem, 1970).

Figure 17 suggests that Zn was also redistributed in the upper portion of the Rustenburg Layered Suite. Fluids that percolated through the upper zone may have originated from wet magma underlying this zone. The lack of Pb enrichment within the upper zone of the Rustenburg Layered Suite supports the inference that the source for this element was the volcanic rocks.

The overall geochemical pattern of alteration of the volcanic roof rocks is consistent with fluid migration away from the Rustenburg Layered Suite with leaching at the top of the Rooiberg Group. Twist (1985) suggested pervasive alteration of the uppermost Rooiberg succession at Loskop Dam. He suggested that this feature resulted from a prolonged period of deep weathering during post-Rooiberg times. We propose that the severe alteration of the uppermost Rooiberg package could also be linked to the Bushveld hydrothermal system.

The color of the felsite in the roof has been one criterion to subdivide the felsite package stratigraphically (Clubley-Armstrong, 1977; Twist, 1985) and to mark the transition to an oxidizing atmosphere (Twist and Cheney, 1986). The color of stratigraphically equivalent volcanic rocks is regionally variable (Schweitzer et al., 1995a), resulting in erroneous stratigraphic correlations. This supports the alternative interpretation (Eriksson and Cheney, 1992) that the color of these rocks is the result of postdepositional processes and is unrelated to the evolution of atmospheric oxygen.

The hydrothermal redistribution of elements resulted in

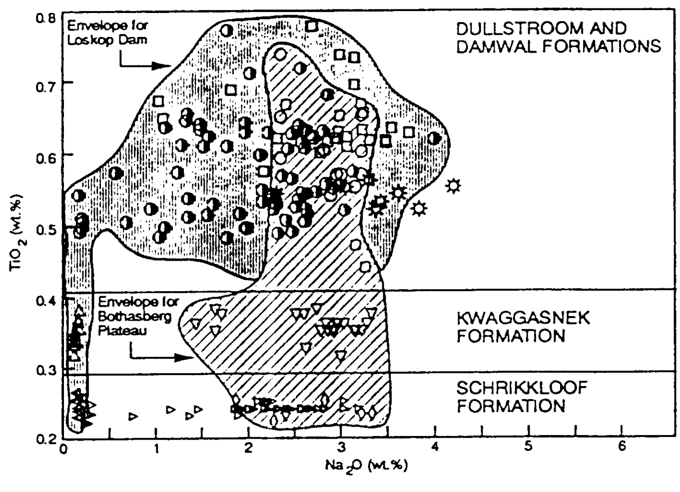

FIG. 16. Na_2O depletion and enrichment at different localities. See Figure 13 for legend.

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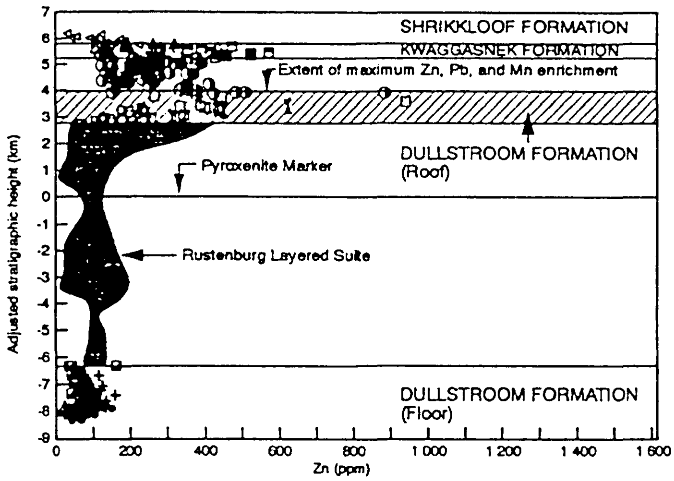

Symbol	Magma Type	Locality	Formation
◁	Low Magnesium Felsite (LMF)	Loskop Dam	Schrikkloof
△	Low Magnesium Felsite (LMF)	Loskop Dam	Kwaggasnek
◑	Low Magnesium Felsite (LMF)	Loskop Dam	Damwal
×	High Fe-Ti-P Lava	Loskop Dam	
□	Low Magnesium Felsite (LMF)	Loskop Dam	Dullstroom
▣	High Magnesium Felsite (HMF)	Loskop Dam	
⧗	High Fe-Ti-P Lava	Loskop Dam	
◪	Xenolith	Dullstroom Area	
⬓	High Magnesium Felsite (HMF)	Dullstroom Area	
+	High Titanium Basalt (HTI)	Dullstroom Area	
▲	Basalt Rhyolite	Dullstroom Area	
●	Low Titanium Basaltic Andesite (LTI)	Dullstroom Area	

FIG. 17. Zn variations within the Rustenburg Layered Suite and Rooiberg volcanic rocks relative to the stratigraphic position of the pyroxenite marker. Note the increase in Zn content within the upper portion (upper zone) of the Rustenburg Layered Suite.

aberrant, whole-rock, Rb/Sr and U/Pb ages for the Rooiberg Group in the roof zone of the Rustenburg Layered Suite (see Walraven, 1995, for review of ages). Economically viable elements could be enriched in porous Rooiberg rocks. Examples of economically viable deposits in pyroclastic rocks similar to those interbedded in the Rooiberg Group are Creede, Colorado; Round Mountain, Nevada; and McDermitt, Nevada (Hetherington and Cheney, 1985).

Conclusions

Primary and secondary geochemical concentrations in the Rooiberg Group are identifiable by comparing compositionally equivalent magma types of the floor and roof zone of the Bushveld Complex. This comparison reveals that the degree of geochemical alteration in the Rooiberg volcanic rocks is geographically variable. Ti, P, Al, Ga, Sc, and heavy REE, which were regionally immobile, indicate that the Dullstroom and Damwal Formations were a continuous succession, before being separated by the intrusions of the Rustenburg Layered Suite.

To date, studies have only considered the massive, welded portions of the volcanic succession. This led to the misperception, that the Rooiberg Group is "amazingly fresh." Studies on the permeable pyroclastic and nonwelded portions of the Rooiberg Group would contribute to a better understanding of the alteration processes and might lead to the discovery of economic deposits.

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February 7, 1994; July 12, 1995

REFERENCES

Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks: New York, Prentice Hall Inc., 634 p.

Chayes, F., 1966, Alkaline and subalkaline basalts: American Journal of Science, v. 264, p. 128–145.

——1969, On the occurrence of corundum in the norms of common volcanic rocks: Carnegie Institution of Washington, Year Book 74, p. 179–182.

Cheney, E.S., and Twist, D., 1991, The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa: Precambrian Research, v. 52, p. 115–132.

Cheney, E.S., and Winter, H. de la R., 1995, The late Archean and Early Proterozoic major unconformity-bounded units of the Kaapvaal province of southern Africa: Precambrian Research, v. 74, p. 203–223.

Clubley-Armstrong, A.R., 1977, The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton dome: Unpublished M.S. thesis, Pretoria, South Africa, Pretoria University, 107 p.

——1980, Petrochemistry of the Rooiberg Group and overlying Loskop Formation north of Middelburg, south-eastern Transvaal: South Africa Geological Survey Annals, v. 14, no. 2, p. 11–28.

De Bruiyn, H., 1980, The geology of the acid phase of the Bushveld Complex, north of Pretoria—a geochemical statistical approach: Unpublished Ph.D. thesis, Bloemfontein, South Africa, Orange Free State University, 171 p.

Engelbrecht, J.P., 1990, Contact metamorphic processes related to the aureole of the Bushveld Complex in the Marico district, western Transvaal, South Africa: South African Journal of Geology, v. 93, p. 339–349.

Eriksson, P.G., and Cheney, E.S., 1992, Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the lower Proterozoic sequences of southern Africa: Precambrian Research, v. 54, p. 257–269.

Gelinas, L., Mellinger, M., and Trudel, P., 1982, Archean mafic metavolcanics from the Rouyn-Noranda district, Abitibi greenstone belt, Quebec. 1. Mobility of the major elements: Canadian Journal of Earth Sciences, v. 19, p. 2258–2275.

Harte, B., and Graham, C.M., 1975, The graphical analyses of greenschist to amphibolite facies mineral assemblages in metabasites: Journal of Petrology, v. 16, p. 347–370.

Hatch, F.H., Wells, A.K., and Wells, M.K., 1972, Petrology of the igneous rocks: London, George Allen and Unwin Ltd., 551 p.

Hatton, C.J., and Sharpe, M.R., 1988, Significance and origin of boninite-like rocks associated with the Bushveld Complex, *in* Crawford, A.J., ed., Boninites and related rocks: London, Unwin Hyman, p. 299–311.

Hetherington, M.J., and Cheney, E.S., 1985, Origin of the opalite breccia at the McDermitt mercury mine, Nevada: ECONOMIC GEOLOGY, v. 80, p. 1981–1987.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classifica-

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tion of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.

Ito, J., and Arem, J.E., 1970, Idocrase: Synthesis, phase relations and crystal chemistry: American Mineralogist, v. 55, p. 279–288.

Martini, J.E.J., 1988, As-Zn mineralization associated with a Proterozoic geothermal system in the Rooiberg Group: South African Journal of Geology, v. 91, p. 337–345.

Rhodes, R.C., and Du Plessis, M.D., 1976, Notes on some stratigraphic relations in the Rooiberg Felsite: Geological Society of South Africa Transactions, v. 79, p. 183–185.

Schiffries, C.M., and Skinner, B.J., 1987, The Bushveld hydrothermal system: Field and petrologic evidence: American Journal of Science, v. 287, p. 566–595.

Schweitzer, J.K., 1987, The transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group, Transvaal Supergroup: A volcanological, geochemical and petrological investigation: Unpublished Ph.D. thesis, Pretoria, South Africa, Pretoria University.

Schweitzer, J.K., and Hatton, C.J., 1995, Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex [abs.]: Geocongress '95, Centennial, Johannesburg, April 3–7, 1995, p. 532–535.

Schweitzer, J.K., Hatton, C.J., and de Waal, S.A., 1995a, Regional lithochemical stratigraphy of the Rooiberg Group: A proposed new subdivision: South African Journal of Geology, v. 98/3, p. 245–255.

——1995b, Economic potential of the Rooiberg Group—volcanic rocks in the floor and roof of the Bushveld Complex: Mineralium Deposita, v. 30, p. 168–177.

Sharpe, M.R., and Foertsch, E., 1981, Grandite garnet in metamorphosed stromatolites from the Houtenbek Formation, eastern Transvaal: Geological Society of South Africa Transactions, v. 84, p. 245–250.

South African Committee for Stratigraphy (SACS), 1980, Stratigraphy of South Africa: South Africa Geological Survey Handbook 8, 633 p.

Twist, D., 1985, Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, southeastern Bushveld: ECONOMIC GEOLOGY, v. 80, p. 1153–1165.

Twist, D., and Bristow, W., 1990, Extensive lava-like siliceous flows in southern Africa: A review of occurrences: Pretoria, South Africa, Pretoria University, Institute for Geological Research on the Bushveld Complex, Research Report 82, 35 p.

Twist, D., and Cheney, E.S., 1986, Evidence for the transition to an oxygen-rich atmosphere in the Rooiberg Group, South Africa—a note: Precambrian Research, v. 33, p. 255–264.

Twist, D., and French, B.M., 1983, Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite: Bulletin of Volcanology, v. 46, p. 225–242.

Von Gruenewaldt, G., 1972, The origin of the roof-rocks of the Bushveld Complex between Tauteshoogte and Paardekop in the eastern Transvaal: Geological Society of South Africa Transactions, v. 75, p. 121–134.

Wallmach, T., 1988, The petrogenesis of high grade contact metamorphic mineral assemblages in calc-silicate xenoliths, eastern Bushveld Complex, South Africa: Unpublished Ph.D. thesis, Pretoria, South Africa, Pretoria University, 200 p.

Walraven, F., 1985, Genetic aspects of the granophyric rocks of the Bushveld Complex: ECONOMIC GEOLOGY, v. 80, p. 1166–1180.

——1995, Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa: Chemical Geology and Isotope Geosciences, in press.

Walraven, F., and Hattingh, E., 1993, Geochronology of the Nebo Granite, Bushveld Complex: South African Journal of Geology, v. 96, p. 31–41.

Walraven, F., Armstrong, R.A., and Kruger, F.J., 1990, A chronostratigraphic framework for the north-central Kaapvaal craton, the Bushveld Complex and the Vredefort structure: Tectonophysics, v. 171, p. 23–48.

Winkler, H.G.H., 1979, Petrogenesis of metamorphic rocks: New York-Heidelberg-Berlin, Springer Verlag, 349 p.

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Economic potential of the Rooiberg Group: volcanic rocks in the floor and roof of the Bushveld Complex

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Economic potential of the Rooiberg Group: volcanic rocks in the floor and roof of the Bushveld Complex

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Abstract. Volcanic rocks of the Rooiberg Group are preserved in the floor and roof of the mafic Rustenburg Layered Suite of the Bushveld Complex. Field and geochemical characteristics of these volcanic rocks imply that they are genetically related to the Rustenburg Layered Suite. Four major ore-forming events are identified in the Rooiberg Group. The first phase was accompanied by volcanic hosted, fault controlled, hydrothermal copper mineralisation, which is found in the lowermost portion of the Rooiberg Group, underlying the Rustenburg Layered Suite. This type of mineralisation is tentatively linked to initial Rustenburg Layered Suite intrusions. Stratabound arsenic mineralisation that possibly formed in response to contact metamorphism, characterises the second phase, and occurred after extrusion of the Damwal Formation, possibly due to shallow granophyric intrusion. The third mineralising event occurred in response to contact metamorphism during the final stages of the Rustenburg Layered Suite, where especially Pb and Zn were introduced into the felsite roof rocks. This type of mineralisation affected the majority of the Rooiberg Group, but is most pronounced towards the contact with the Rustenburg Layered Suite. The fourth phase is restricted to the Rooiberg Group in the Nylstroom area and is linked to the granite intrusions of the Lebowa Granite Suite, from which Sn and F were introduced into the uppermost felsite succession. Mineralisation in the Rooiberg Group appears to be controlled by the character and intrusion level of the associated Bushveld magmas. Different styles of mineralisation in Rooiberg Group volcanic rocks are encountered at various stratigraphic levels. Major primary volcanogenic ore deposits appear to be absent.

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The events comprising the Bushveld Complex (i.e. the Rustenburg Layered Suite, RLS; Lebowa Granite Suite, LGS; Rashoop Granophyre Suite, RGS; SACS, 1980) in southern Africa are of enormous spatial extent. Volcanic rocks comprising the Rooiberg Group of the Transvaal Sequence are closely associated with the Bushveld magmatic events, in time and space (e.g. Twist, 1985; Hatton and Sharpe, 1988; Schweitzer and Hatton, 1994b).

We first review the geological setting of the Rooiberg volcanic rocks as preserved beneath and above the RLS. Then we identify and categorise the mineralised zones contained in the Rooiberg Group, outline criteria to distinguish various styles of mineralisation, and link the deposits to the different phases of Bushveld magmatism. We conclude by considering the potential for undiscovered mineral deposits.

Geological setting

The Bushveld Complex predominantly overlies sedimentary rocks of the Transvaal Sequence (Fig. 1). In the southeast the RLS overlies a package of volcanic rocks, the Dullstroom Formation, which was long considered to be part of the Pretoria Group, Transvaal Sequence (SACS, 1980), and unrelated to the Rooiberg Group above the RLS (Table 1). Our investigations (Schweitzer, 1986; Eriksson et al., 1993; Schweitzer and Hatton 1994a; Schweitzer et al., 1994) established that one magma type is common to the volcanic floor and roof rocks of the RLS. It is therefore clear that the RLS intruded into the Dullstroom-Rooiberg volcanic pile, separating the Dullstroom volcanic rocks from the remainder of the Rooiberg felsites. Accordingly we redefine the Rooiberg Group to include the Dullstroom volcanic rocks as its lowermost formation (Schweitzer et al., 1994), (Fig. 2), resulting in a proposed new subdivision into four formations (Table 1).

The rocks comprising the Rooiberg Group, especially the upper Kwaggasnek and Schrikkloof Formations (Fig. 2), exhibit regionally persistent lithological and geochemical characteristics (Schweitzer et al., 1994). Specifically, these include a zone of prominent quartzite xenoliths towards the top of the Kwaggasnek Formation (e.g. Rhodes, 1975; Du Plessis, 1976; Rhodes and Du Plessis, 1976), overlain by an agglomerate and shale (Fig. 2). The latter zone, The Union Tin Member, is succeeded by strongly flow-banded rhyolites comprising the Schrikkloof Formation, which is terminated by a tuff at its top

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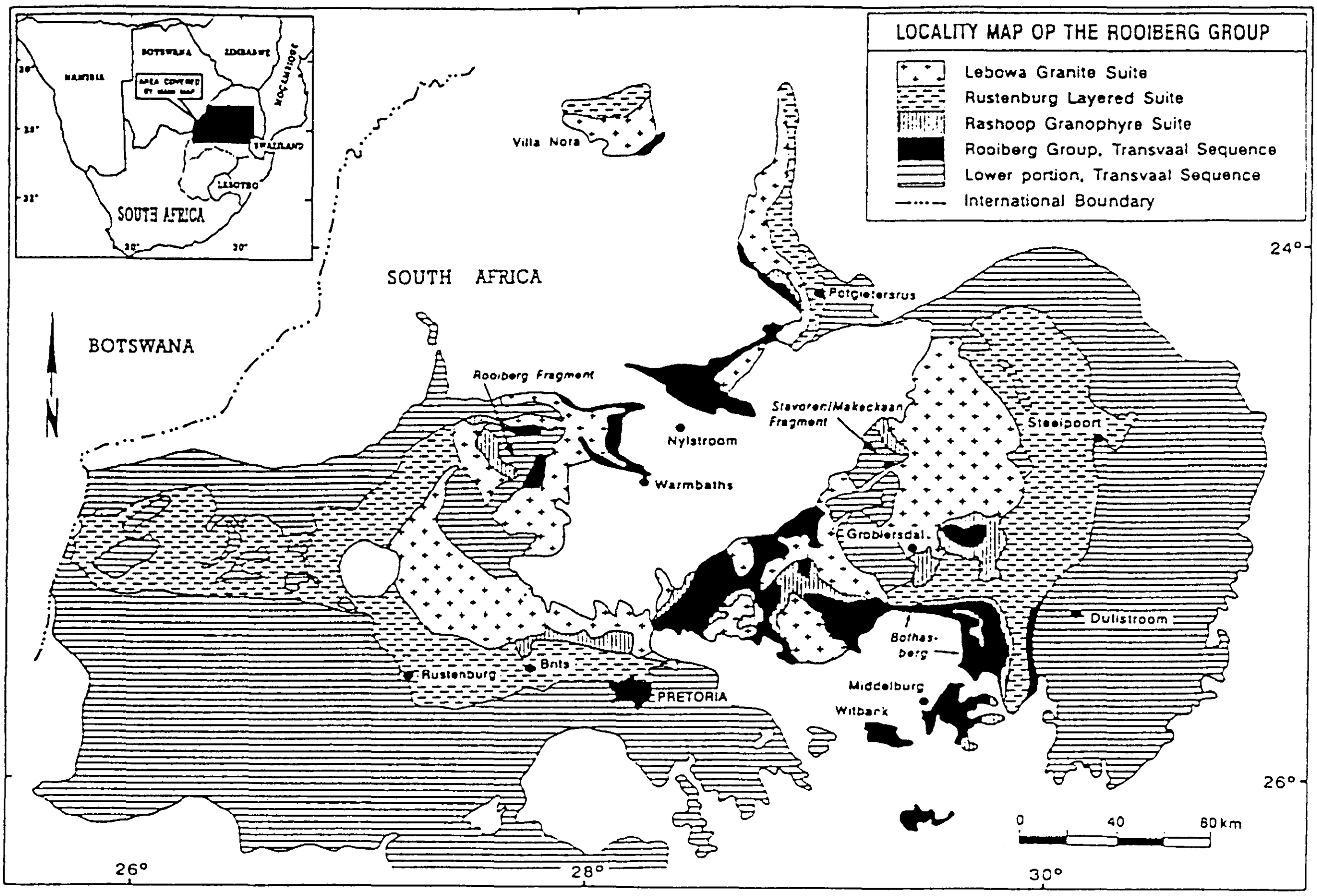

Fig. 1. Rooiberg Group occurrences related to rocks comprising the Bushveld Complex and those of the lower portion of the Transvaal Sequence (modified after Walraven, 1982)

Table 1. Newly proposed Rooiberg Group subdivision (after Schweitzer et al., 1994) compared to the one currently considered by SACS (1980)

SACS, 1980			Schweitzer et al., 1994		
Group	Formation	Member	Group	Formation	Member
Rooiberg	Selons River	Klipnek Doornkloof	Rooiberg	Schrikkloof Kwaggasnek	 Union Tin
	Damwal			Damwal Dullstroom	
Pretoria	Dullstroom				

(e.g. Clubley-Armstrong, 1977, 1980; Twist, 1985). The regional recognition of these features permits the stratigraphic correlation of previously mined Rooiberg deposits or mineral occurrences (Fig. 2) and the targeting of potential economic areas.

We have reviewed and examined occurrences of the Rooiberg Group over its extent and find that the complete Dullstroom Formation is present only in the eastern Transvaal (Fig. 3). The Dullstroom Formation therefore constitutes a localised phase of early volcanic activity, preceding the more widespread volcanism of the Kwaggasnek and Schrikkloof Formations (Figs. 2 and 3). A hiatus between the Damwal and Kwaggasnek Formations is defined by the appearance of sedimentary rocks showing a strong volcanic component (Eriksson, P.G., personal communication, 1994), and by the last extrusion of the Bothasberg low-Mg Felsite (LMF) magma type (Fig. 2).

According to the distribution of the formations comprising the Rooiberg Group (Fig. 3), four regions can be defined. The two major regions are, in present outcrop, the Bothasberg Package (where all Rooiberg formations are present) and the Nylstroom Package (where only the Kwaggasnek and Schrikkloof Formations are present, Fig. 3). Rooiberg felsite of the Bothasberg Package is, to a large extent, underlain by the RLS, whereas granite of the LGS (Walraven, 1985) intruded into the upper portion of the Rooiberg Group in the Nylstroom Package. Two further regions are defined by the felsite occurrences within the Stavoren and Rooiberg Fragments (Figs. 1 and 3). There, the basal succession of the Dullstroom Formation is preserved (Schweitzer et al., 1994). This succession is overlain by flows of the Kwaggasnek and Schrikkloof Formations within the Rooiberg Fragment. The Rooiberg succession within both fragments abuts against the LGS.

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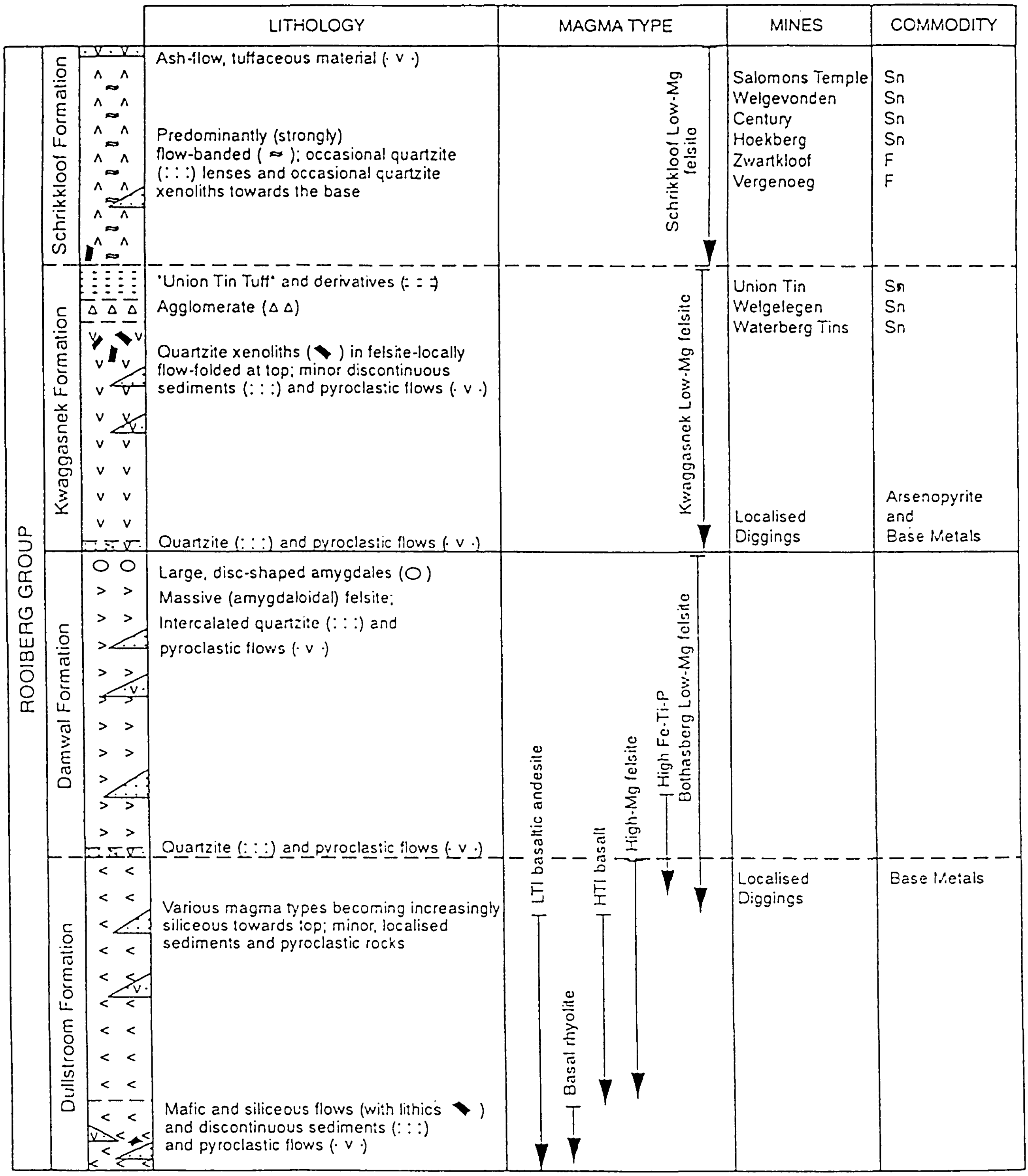

Fig. 2. Stratigraphic subdivision of the Rooiberg Group as deduced from regional lithological and chemical features (modified after Schweitzer et al., 1994). Mines and localised diggings are related to the commodity mined and are listed according to their stratigraphic position

Mineral deposits and occurrences in the Rooiberg Group

The stratigraphic and geographic position, and the type of mineralisation, of the major and minor deposits that have been mined within the Rooiberg Group, are shown in Figs. 2 and 3. Inspection of these figures reveals that no major deposits have been discovered within the area delineated by the Bothasberg Package. However, various mineral occurrences have been described within this package (Fig. 2; Twist 1983; Martini, 1988, 1990; Schweitzer and Hatton, 1994) and these will also be discussed in the following.

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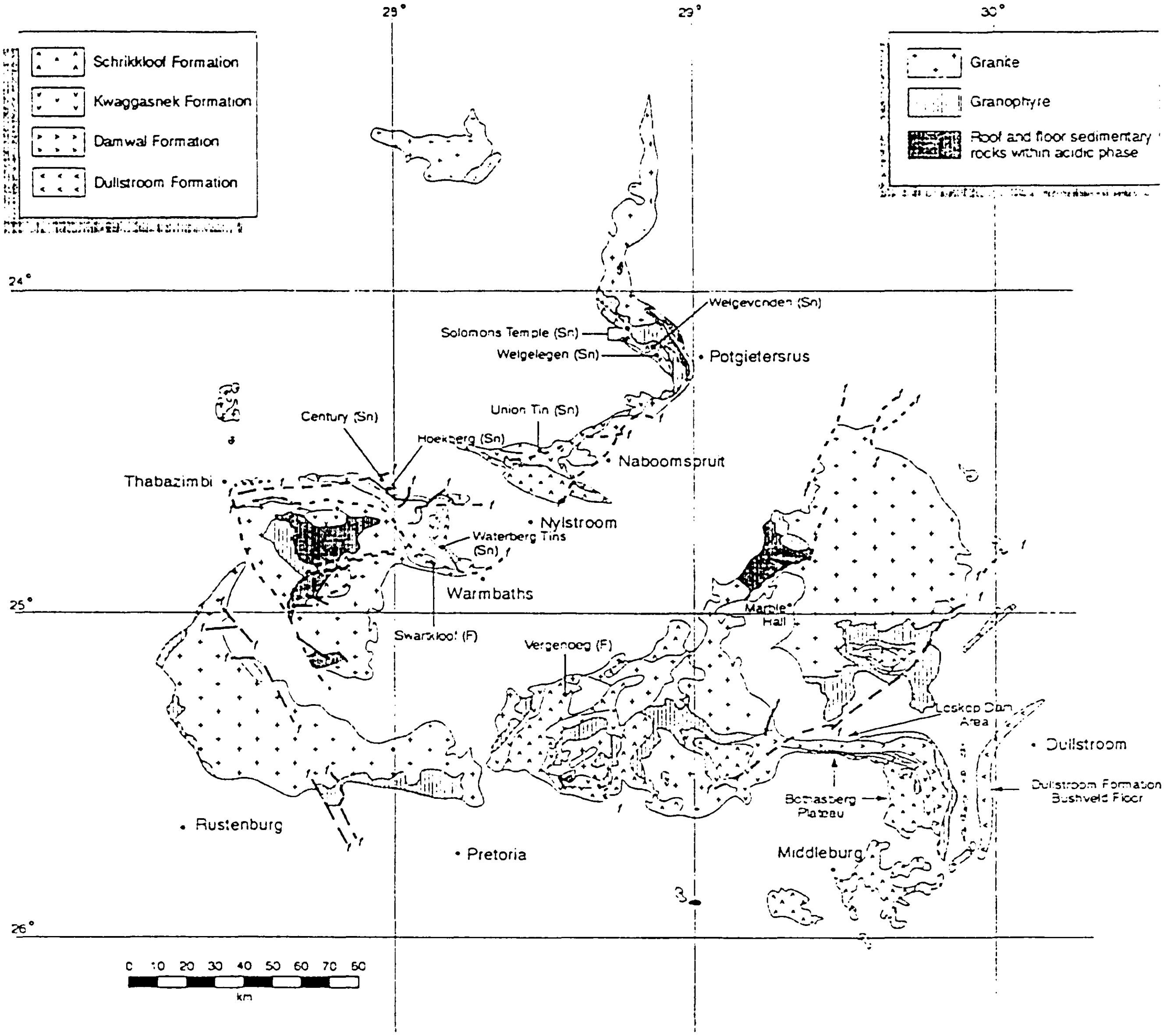

Fig. 3. Geographic distribution of the various Rooiberg Group formations. Also shown are the positions of defunct and operating mines within Rooiberg Group rocks. The Stavoren and Rooiberg Fragments are comprised of floor sedimentary rocks and Rooiberg Group volcanic rocks, and are situated within Bushveld Granite

Volcanogenic massive sulphide deposits are indigenous to felsic volcanic rocks throughout the world and their potential in the Rooiberg Group should not be neglected (Twist, 1983). However, massive sulphide deposits appear to be absent (or minor) in the Rooiberg Group, possibly due to the intracratonic character of Bushveld magmatism (Sawkins, 1984).

Tin and fluorspar are, to date, the only major commodities that have been mined within the sedimentary and volcanic rocks of the Rooiberg Group. In general, the granite intrusion resulted in updoming of Rooiberg felsite, creating favourable structural traps in which mineralisation resulted from volatile enrichment. In the absence of structural traps or fissures, pipe deposits formed within the granite or the adjacent rock(s). Deposit distances from the source rock vary between 2–10 km (Crocker and Callaghan, 1979).

Production statistics referring to individual mines or mines within a region (as only one producer may exist in a region) are only available in limited cases, due to confidentiality constraints. An accurate assessment of the quantity of the various deposits mined is therefore not possible. Only limited production figures are published (Lenthall, 1974; Crocker and Callaghan, 1979; Crocker, 1986; Pringle, 1986a and b) and these are summarised in Tables 2 to 4.

Rooiberg and Zaaiplaats tin mines were two major tin producers that mined in rocks not included in the Rooiberg Group, and are therefore excluded from the statistics presented in Table 2. The sedimentary rocks

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referred to in Table 2 most probably relate to deposits encountered in the sedimentary rocks intercalated within the Rooiberg Group, especially the Union Tin Member, mined at various localities (e.g. Union Tin Mines, the second largest tin producer in South Africa). Granophyres are genetically linked to the volcanic rocks of the Rooiberg Group (Walraven, 1982, 1985). However, they do not form part of the Rooiberg Group, are of minor economic significance (e.g. Table 2), and are not considered in this study.

Comparison of Tables 3 and 4 reveals that only about a tenth of South Africa's tin production, 99% of which is derived from the rocks associated with the Bushveld Complex (Crocker and Callaghan, 1971), was derived from deposits located within the Rooiberg Group.

Table 2. Tin production as derived from different host rocks (excluding Rooiberg and Zaaiplaats tin mines), modified after Lenthall, 1974

Host rock	Concentrates (Tons)	% of Total	Metallic Tin (Tons)	% of Total
Granite	11 442	30.12	7 585	34.89
Granophyre	229	0.86	167	0.77
Felsite	11 835	31.16	5 521	25.39
Sedimentary Rocks	14 380	37.86	8 467	38.95
	37 956	100.00	21 740	100.00

Table 3. Tin production from various geographic areas (Fig. 3), modified after Lenthall, 1974. The figures given for the metallic tin recovered consider the period between 1904 and 1971

Area	Concentrates (Tons)	% of Total	Metallic Tin (Tons)	% of Total
Rooiberg	62 366	56.43	39 150	56.06
Potgietersrus	31 288	28.32	21 948	31.56
Nylstroom	11 599	10.50	5 395	7.72
Marble Hall	4 862	4.40	3 034	4.34
Warmbaths	222	0.20	118	0.17
Pretoria	170	0.15	104	0.15
	110 507	100.00	69 749	100.00

Mineralising events

We distinguish four mineralising events which we link to the various intrusive phases comprising the Bushveld Complex. These events are described in inferred chronological order, simultaneously relating the mineral occurrences and deposits to their stratigraphic position within the Rooiberg Group.

First mineralising event: Dullstroom Formation beneath RLS

Dullstroom Formation volcanic flows as preserved in the RLS floor (Figs. 3 and 4) show, despite their proximity to the RLS, minor signs of element redistribution (Schweitzer and Hatton, 1994). The RLS apparently dehydrated these floor rocks and fluid flow was consequently minimal. Detailed field work, however, reveals that localised copper occurrences in epidotised zones along fault planes do occur. Copper could have originated from the volcanic rocks. Mafic intrusions are also likely to introduce copper into their host rocks and we relate the localised copper mineralisation in the Dullstroom Formation of the RLS floor to the initial intrusions of this suite.

The base of the Dullstroom Formation is marked by an unconformity (Cheney and Twist, 1991). Three palaeovalleys, initially described as eruption centres (Schweitzer, 1984), have been mapped. The establishment of the character of these depressions requires further attention but it is noted that chalcopyrite and pyrite (disseminated and/or as amygdale fillings) are encountered in these areas.

Second mineralising event: Kwaggasnek Formation

Mineralisation, mainly pyrite and arsenopyrite, is largely confined to a quartzite layer marking the base of the Kwaggasnek Formation (Fig. 2). The zone of mineralisation is also characterised by silicification and sericitisation, interpreted to have resulted from shallow intrusion of granophyre of the RGS (Martini, 1988). Martini observed that Pb and Zn were introduced at a later stage and he could not find any possible explanation for this change in mineralisation. We relate this phase of later

Table 4. Production statistics of defunct and operating mines within deposits of the Rooiberg Group. Period, where indicated, does not imply the period of operation but the period over which tonnages were recorded. Tin recovery from the Warmbaths area was mainly derived from deposits within felsite, where a total of 118 tons of metallic tin was recovered

Area	Mine	Commodity	Period	Tons treated	Tons recovered
Potgietersrus	Salomons Temple	Sn	–	–	48
Potgietersrus	Welgevonden	Sn	–	–	125
Potgietersrus	Welgelegen	Sn	–	–	–
Nylstroom	Union Tin	Sn	1953–1983	2 616 650	10 000
Warmbaths	Waterberg Tins	Sn	1909–1910	–	3
Warmbaths	Hoekberg	Sn	± 1912	–	–
Warmbaths	Century	Sn	± 1912	–	–
Warmbaths	Zwartkloof	F	1971–1973	509 117	99 149
Pretoria	Vergenoeg	F	–	–	–

– Production figures are not available. See Fig. 2 for stratigraphic position of various deposits

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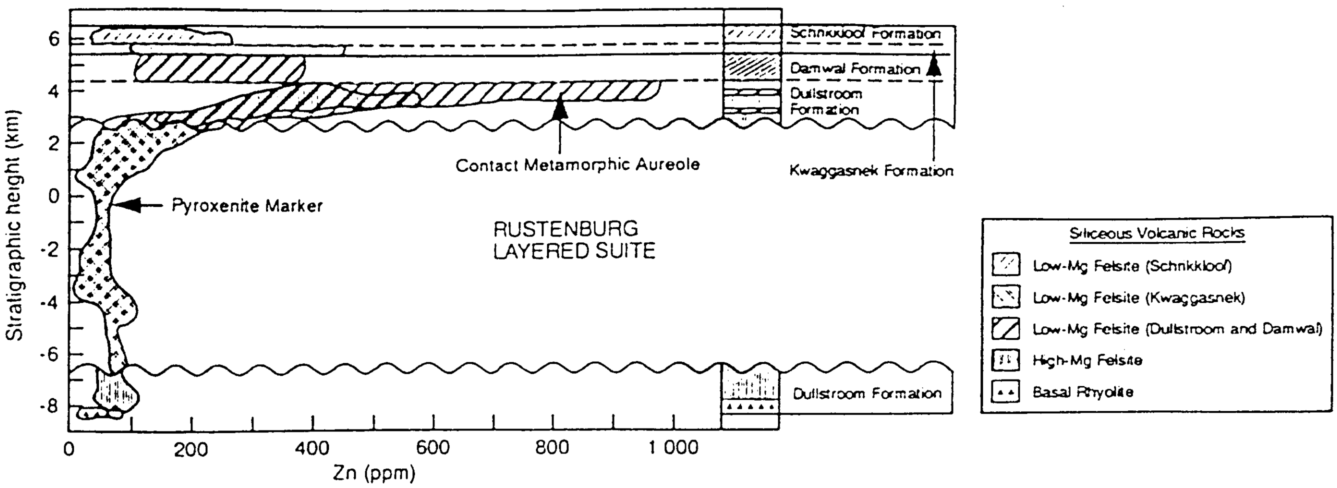

Fig. 4. Zn variations in the volcanic rocks of the Rooiberg Group, related to the Bushveld contact metamorphic aureole (modified after Schweitzer and Hatton, 1994). The Zn variations within the RLS are also shown. The stratigraphic level of the RLS-Rooiberg Group package is normalised to the position of the pyroxenite marker.

mineralisation to the system of magmatically driven circulation of base metal-rich fluids, being part of the third mineralising event (see below).

Third mineralising event: Dullstroom Formation above RLS

The only occurrence of Dullstroom Formation flows above the RLS is preserved in the Loskop Dam area (Figs. 3 and 4; units 1 and 2 of Twist, 1985). The top of the Dullstroom Formation is marked by the last extrusion of the high-Mg felsite (HMF) magma (Fig. 2) and the first sedimentary and pyroclastic rocks of the Damwal Formation. The primary composition of the flows comprising this Dullstroom succession has been severely altered due to Bushveld contact metamorphism (Fig. 4).

Base metal occurrences are encountered in this part of the Dullstroom Formation above the RLS (Mineral Map of the Republic of South Africa, 1976). However, no major deposits have been discovered. The base metal mineralisation is linked to the intrusions of the RLS. A detailed geochemical study of felsite overlying the RLS revealed that a zone of increasing hydration is developed away from the contact with the RLS (Schweitzer and Hatton, 1994). A zone of maximum Zn (Fig. 4), Pb and Mn concentration is encountered about 1.4 kilometers away from the contact with the RLS. Zn contents in the volcanic rocks exceed 900 ppm (Fig. 4), as opposed to average concentrations of about 50 ppm in unaltered siliceous volcanic rocks. The presented Zn values reflect concentrations of the interior, massive portion of the volcanic flows. Significantly higher Zn and Pb concentrations are to be expected in, for example, porous sedimentary rocks, intercalated with these volcanic rocks.

Evaluation of the enrichment and/or depletion of Pb and Zn considering volume and/or mass changes in the volcanic rocks within the contact metamorphic aureole, using Gresen's method (e.g. Grant, 1986) reveals that gains have been balanced by losses. Both Pb and Zn have been introduced. Zn is likely to have originated from the RLS, whereas Pb could have possibly been derived from within the volcanic flows of the Rooiberg Group.

Elevated Zn concentrations are also encountered in the Rooiberg volcanic rocks overlying the Dullstroom Formation (Fig. 4). We consider the hydrothermal system to have modified primary concentrations of the complete Rooiberg package. Base metal-rich fluids were driven away from the heat source, manifested in the contact metamorphic aureole, to ascend through the volcanic pile. Cooling near the surface resulted in the sinking of these fluids back towards the heat source. The resultant circulation produced the elevated base metal concentrations observed in the Rooiberg package overlying the Dullstroom Formation in the Bothasberg area.

Dullstroom Formation flows also occur in the Rooiberg and Stavoren Fragments (Fig. 3), but no economic mineral deposits have been described for the lowermost Rooiberg Group in these areas.

Fourth mineralising event: Kwaggasnek and Schrikkloof Formations

The fourth mineralising event affected the volcanic rocks comprising the top of the Rooiberg Group, the Kwaggasnek and Schrikkloof Formations (Fig. 2). This event is linked to the intrusive events comprising the LGS, resulting in tin and fluorspar mineralisation (Fig. 2, Tables 2 to 4).

Kwaggasnek Formation. Major mineral deposits within the Kwaggasnek Formation of the Bothasberg Package have not been described. In the Nylstroom Package this formation hosts Union Tin Mine Ltd., Welgelegen Mine, and Waterberg Tins (Fig. 3).

Welgelegen represents the southernmost, defunct tin mine west of Potgietersrus (Fig. 3). It is positioned towards the top of the Kwaggasnek Formation, close to the Union Tin Member. Crocker (1986) described this deposit in a breccia at a granite porphyry/Kwaggasnek

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lava contact. He further states that the granite intruded the highest levels in the southern portion of these Rooiberg Group occurrences, with the granite plunging towards the north. Therefore, he interprets the tin occurrences at Welgelegen to have formed in the ruptured roof zone of the granite intrusion.

Union Tin Mines Ltd., northwest of Naboomspruit (Fig. 3) was the major tin producing mine situated in Rooiberg Group deposits (Table 4). The cassiterite occurrences are similar to those in the Potgietersrus area and occur in agglomerate as odd blows or pockets, or in pipe-form replacements in the Union Tin Shale, along hair-like fractures or bedding partings (Crocker and Callaghan, 1979). A more detailed description of the cassiterite occurrences at and around Union Tin Mines is provided by Menge (1963), Crocker et al. (1976), and Pringle (1986a), and is summarised in the following paragraph.

The tin deposits at Union Tin Mines occur close to fractures within the 150 m thick Union Tin Member (Fig. 2). Three prominent fracture orientations are observed, which are 350°/35–45°E, 120°/65–70°NE, and 80°/65–70°N. Other minerals associated with cassiterite are magnetite, haematite, chalcopyrite, arsenopyrite and galena. The intensity of mineralisation varies with the fracture orientation. The cassiterite is microscopic in occurrence and mining directions were therefore decided upon by continuous panning. Alteration of the associated felsite is expressed by ferruginisation, sericitisation and silicification ($\pm$ tourmaline). The agglomerate underlying the shale of the Union Tin Member is interpreted as an ignimbrite deposit (Menge, 1963) and possesses a transitional upper contact. Low-grade cassiterite lodes occur within this ignimbrite and limited mining has been undertaken in this horizon towards the southeast of Union Tin Mines (Erasmus Workings). The deposit at Union Tin Mines has been interpreted to be of hydrothermal-pneumatolitic replacement type or of hydrothermal origin.

Waterberg Tin mine is situated towards the west of Warmbaths and little is known about this deposit. Cassiterite occurs as a lode in a well-defined fissure system and accompanied breccia zones in the volcanic flows (Crocker and Callaghan, 1979).

Schrikkloof Formation. Both tin and fluorspar deposits occur in the rocks comprising the Schrikkloof Formation. Tin was mined in the Potgietersrus (Salomons Temple, Welgevonden) and Warmbaths (Century, Hoekberg) areas and fluorspar at Zwartkloof and is still mined at Vergenoeg (Fig. 3).

Smaller, defunct, tin mining operations within the Schrikkloof deposits are Salomons Temple and Welgevonden (Fig. 3). The mineralisation has been described in detail by Strauss (1954). Welgevonden is a breccia-type deposit, similar to the one previously described for Welgelegen. However, Crocker (1986) grouped the tin occurrences in the Potgietersrus area into three major types which are contact breccia, bedded breccia and fracture stockwork. The bedded, tourmaline breccia in the Union Tin Shale, which is sandwiched between competent felsite, is generally of low grade. The fracture stockwork type of mineralisation, which is best known from Salomons Temple, is most payable at two horizons, i.e. immediately above the contact with the intrusion and close to the breccia in the Union Tin Member.

Limited information is available from the tin producers towards the west of Warmbaths, such as Hoekberg and Century mines. Tin was mined along the contact of LGS and felsite and within a pyroclastic layer of the Union Tin Member (Crocker and Callaghan, 1979).

Zwartkloof fluorspar mine, towards the west of Warmbaths (Fig. 3) was first described by Kynaston and Mellor (1909), and a detailed description is given by Pringle (1986b). Fluorite is associated with (in decreasing order) siderite, quartz, chlorite, sphalerite, fayalite, pyrite, chalcopyrite, galena, magnetite, ilmenite and accessory molybdenite. The fluorspar is in fractured and brecciated felsite and the fracture pattern conforms with the joint pattern observed in anticlinal structures (Zwartkloof anticline; Pringle, 1986b).

The fluorite-hematite deposits at Vergenoeg are situated in a uniquely preserved area. Stratigraphically the rocks at Vergenoeg have been incorporated into the Rust De Winter Formation (SACS, 1980), conformably overlying the Rooiberg Group, or the Vergenoeg volcanogenic province (Crocker, 1985), encompassing the Vergenoeg mine breccia pipe ore body and the Vergenoeg pyroclastic rock suite. However, mineralisation in the Rooiberg Group is exogranitic, similar to the tin deposits described above. Vergenoeg represents the only deposit currently being mined in Rooiberg Group rocks. The Fe-rich lithologies and mineralisation at Vergenoeg appear to be a product of a combination of plutonic, volcanic exhalative and metasomatic activities, whose nature is not clearly understood (Pirajno, 1992).

Exsolution and degassing of HF represented the driving force behind the Fe-F-alteration, and HF could have passed through Fe-rich lithologies of the RLS to leach Ca and Fe to form fluorite, chlorite, Fe-actinolite and hematite (Pirajno, 1992). The mushroom-shaped ore body extends to a depth exceeding 600 m. The Vergenoeg pyroclastic suite is bimodal in character, comprised of felsic and iron-rich pyroclastic rocks. High grade specularite-hematite iron ore contains about 60% CaF_2. Crocker (1985) proposed that two immiscible liquids were present in the late stage granite magma fraction, a silica-sodium-rich melt and an actinolite-rich mafic melt. These melts migrated upward and collected in a chamber, possibly beneath the Rooiberg Group rocks, to finally result in violent eruption. The siliceous melt erupted first followed by the mafic melt. Pressure release at constant temperatures resulted in the conversion of ferroactinolite to magnetite-siderite-fluorite + residue.

Schrikkloof Formation flows are terminated by a deposit previously described as an ash-flow or tuff (von Gruenewaldt, 1968, 1971; Clubley-Armstrong, 1977, 1980; Twist, 1985; Fig. 2). Within and beneath this stratigraphic horizon, the flows are prominently silicified, with silica contents exceeding magmatic values (> 80 wt%). Devitrification is associated with secondary calcite, quartz, epidote and hornblende. The total disappearance of the original minerals and a strong depletion in, for example, MgO, CaO and Na_2O (Fig. 5) is similar to chemical

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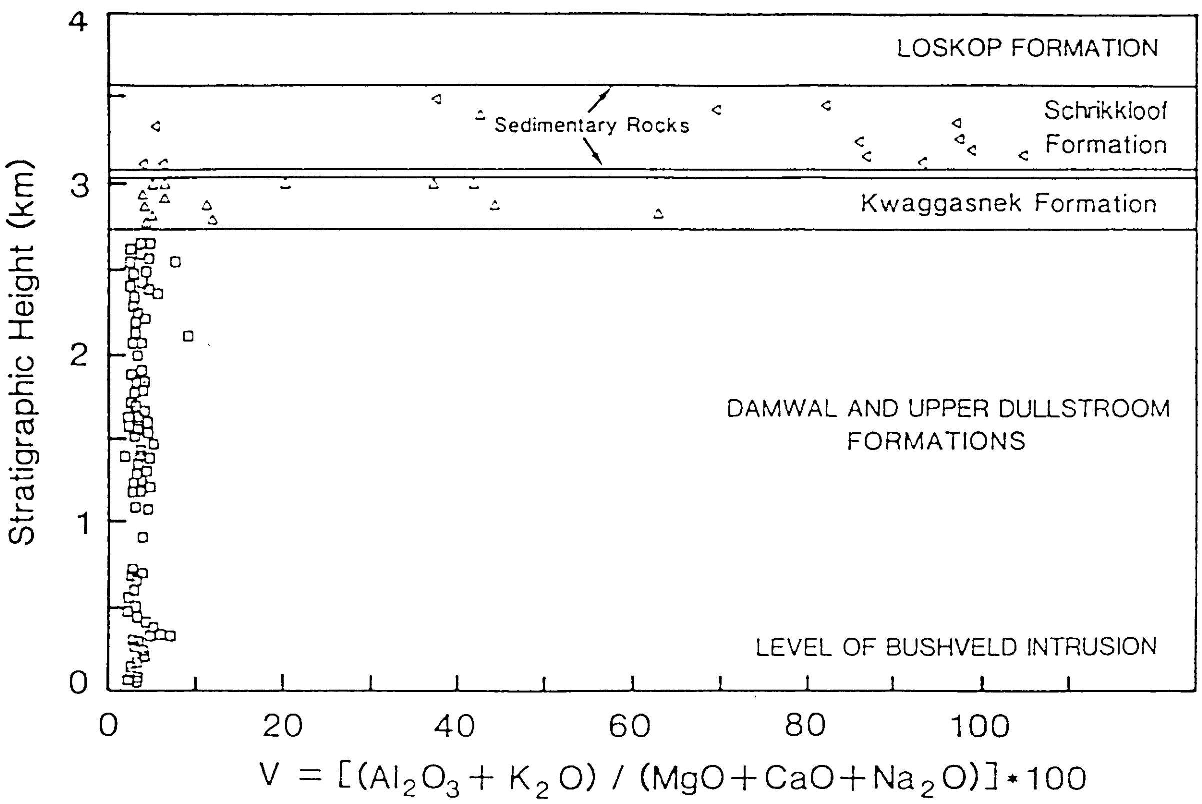

Fig. 5. Palaeoweathering index (Vogt index, Harnois, 1988), versus stratigraphic height for the Rooiberg Group as preserved in the roof of the RLS (Loskop Dam area)

characteristics observed in palaeosol horizons (e.g. Barrientos and Silverston, 1987). Palaeoweathering and ground water circulation producing silcrete horizons may therefore be accountable for the alteration pattern observed towards the top of the Rooiberg Group (Martini, 1990; Schweitzer and Hatton, 1994). These horizons have been described as having economic potential for gold mineralisation (e.g. Sawkins, 1984).

Mineral potential of the Rooiberg Group

The mineral potential of the rocks comprising the Rooiberg Group may also be viewed in the light of comparable deposits that occur elsewhere. The comparison to similar mineral deposits and occurrences is hampered, possibly due to the uniqueness of the events that comprise the Bushveld Complex.

Mineralisation within the lowermost Rooiberg Group is controlled by the intrusive events comprising the RLS. The layered mafic rocks of the Stillwater and Sudbury intrusions have been, similarly to the RLS, emplaced in anorogenic environments (Sawkins, 1984). However, we are not aware of any contact metamorphic mineralisation or deposits that have been documented for these intrusions.

The Bushveld tin deposits are among the oldest known and may be similar to those formed during vertical graben tectonics in stable platform areas (Crocker and Callaghan, (1979). Rifting resulted in fracturing and depression of crust with subsequent anatexis. Crocker and Callaghan (op. cit.) compare the South African tin deposits to those located on a failed limb of a triple junction such as in Nigeria, Zimbabwe, Brazil, Namibia and the various tin deposits described in Europe.

Union Tin, representing open systems, may belong to the sub-volcanic class of tin deposits. Differences in these deposits appear to be related more to the competency of the roof rocks than to the depth of intrusion of the granite source rock (Crocker and Callaghan, 1979). Tourmaline, as observed in the tourmaline breccia in the Union Tin Shale, is interpreted to have formed after *in situ* replacement of pre-existing aluminous lithologies, similar to the Permian tourmalinites described by Zhang et al. (1994).

The exogranitic tin deposits in the Rooiberg Group may also be related to the distal and proximal deposits of the Xinlu ore field in southern China, where proximal deposits developed at relatively high intrusion levels, whereas distal deposits were developed where the intrusion was emplaced relatively deeply (Chi et al. 1993).

Conclusions

Re-examination of the mineral potential of the rocks comprising the Rooiberg Group results in the identification of four phases of mineralisation. Three of these are possibly related to the emplacement of the RLS and the fourth mineralising phase originated from the LGS. An exploration model, therefore, has to collectively consider the

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various characteristics of the Rooiberg Group, RLS, LGS and RGS.

Base metals are the major mineral occurrences in felsite over- and underlying RLS. Only sub-economic deposits have been described. The rocks comprising the RLS intruded the Rooiberg package at various stratigraphic levels. The lowest level of intrusion is the Stoffberg area where the mafic suite discordantly underlies flows of the Dullstroom and Damwal Formations. Base metal mineralisation is therefore largely confined to the two basal Rooiberg formations (Fig. 2). Sedimentary intercalations are encountered towards the base of the Dullstroom Formation and within the Damwal Formation. These horizons may represent suitable host rocks for base metal mineralisation.

Of special importance is the zone of Zn and Pb enrichment in the Rooiberg Group approximately 1.4 km above the roof contact of the RLS. X-ray diffraction studies (Verryn et al., 1994), show that Zn-enrichment is positively correlated with pervasive alteration and hydration of the primary minerals.

Deposits hosting Sn and F formed in the uppermost portion of the Rooiberg Group, and are associated with the LGS in the Nylstroom Facies. These deposits are exogranitic and their characteristics reflect the intrusion level and nature of the granites. The uppermost portion of the Kwaggasnek Formation (Fig. 2 and 3), the Union Tin Member, comprised of agglomerate and shale, acted as an impermeable barrier. This horizon appears to be the most prominent host of this type of mineralisation.

In summary, it is concluded that exploration models have to consider the complex inter-relationship of the various extrusive and intrusive events of the Bushveld Complex. It is unlikely that large, near-surface deposits, will be discovered within rocks of the Rooiberg Group. There is, however, potential for small gold deposits in the silcrete of the Schrikkloof Formation. These and other, shallow deposits, suitable for small scale mining, are likely to exist and have to be explored through drilling and the application of geophysical techniques.

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References

Barrientos, X., Silverstone, J. (1987) Metamorphosed soils as stratigraphic indicators in deformed terrains: an example from the eastern Alps. Geol. 15:841–844

Cheney, E., Twist, D. (1991) The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa Precambrian Res. 52:115–132

Chi, G., Guha, J., Lu, H-Z. (1993) Separation mechanisms in the formation of proximal and distal tin polymetallic deposits. Xinlu Ore Field, Southern China-evidence from fluid inclusion data. Econ. Geol. 88:916–933

Clubley-Armstrong, A.R. (1977) The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome. M.Sc. thesis, Univ. Pretoria, South Africa, 107pp

Clubley-Armstrong, A.F. (1980) Petrochemistry of the Rooiberg Felsite Group and overlying Loskop Formation, north of Middelburg, southeastern Transvaal. Ann. Geol. Surv. S. Afr. 14-2:11–28

Crocker, I.T. (1985) Volcanogenic fluorite-hematite deposits and associated pyroclastic rock suite at Vergenoeg, Bushveld Complex. Econ. Geol. 80:1181–1200

Crocker, I.T. (1986) The Zaaiplaats Tinfield, Potgietersrus District. In: Anhaeusser, C.R., Maske, S. (eds.) Mineral deposits of Southern Africa. Geol. Soc. S. Afr., pp. 1287–1299

Crocker, I.T., Coetzee, G.L., Mehliss, A.T.M. (1976) Tin. In: Coetzee, C.B. (ed.) The Mineral Resources of the Republic of South Africa. Handbook Geol. Surv. S. Afr. 7:213–220

Crocker, I.T., Callaghan, C.C. (1979) Tin resources of South Africa: classification and inventory. Geol. Surv. S. Afr. Bull. 66:28pp

De Bruiyn, H. (1980) The geology of the acid phase of the Bushveld Complex, north of Pretoria-a geochemical statistical approach. Ph.D. thesis, Univ. Orange Free State, South Africa, 171pp

Du Plessis, M.D. (1976) The Bushveld granites and associated rocks in the area north-west of Warmbaths, Transvaal. M.Sc. thesis, Univ. Pretoria, South Africa, 85pp

Elston, W.E. (1992) Does the Bushveld-Vredefort system (South Africa) record the largest known terrestrial impact catastrophy? In: Pap. Int. Conf. large Meteor. Impacts Planet. Evolut., Sudbury, Ontario. Lunar and Planet. Inst. Contr. No. 790:23–24

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., Deventer, J.L. van, Hatton, C.J. (1993) The Transvaal Sequence: an overview. J. Afr. Earth Sci. 16:25–51

Grant, J.A. (1986) The isocon diagram – a simple solution to Gresens' equation for metasomatic alteration. Econ. Geol. 81:1976–1982

Hamilton, W. (1970) Bushveld Complex – product of impacts? Geol. Soc. S. Afr. Spec. Publ. 1:367–379

Harnois, L. (1988) The CIW Index: a new chemical index of weathering. Sediment. Geol. 55:319–322

Hatton, C.J., Sharpe, M.R. (1988) Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: Crawford, A.J. (ed.) Boninites and related rocks. Unwin Hyman, London, pp. 299–311

Kleemann, G.J. (1985) The geochemistry and petrology of the roof rocks of the Bushveld Complex, east of Groblersdal. M.Sc. thesis, Univ. Pretoria, South Africa, 178pp

Kynaston, H., Mellor, E.T. (1909) The geology of the Waterberg tin fields. Mem. Geol. Surv. S. Afr. 4:124pp

Lenthall, D.H. (1974) Tin production from the Bushveld Complex. Econ. Geol. Res. Unit. Inf. Circ. No. 93. Univ. Witwatersrand, Johannesburg, 25pp

Martini, J.E.J. (1988) As-Zn mineralization associated with a Proterozoic geothermal system in the Rooiberg Group. S. Afr. J. Geol. 91/3:337–345

Martini, J.E.J. (1990) Hydrothermal veins and pre-Waterberg palaeogossens in the Bushveld granite above Blackwood Camp, Transvaal. S. Afr. J. Geol. 93 (5/6):754–760

Menge, G.F. (1963) The cassiterite deposits on Doornhook 342 KR and vicinity, west of Naboomspruit, Transvaal. M.Sc. thesis, Univ. Pretoria, South Africa, 56pp

Mineral Map of the Republic of South Africa (1976) In: Coetzee, C.B. (ed.) Mineral resources of the Republic of South Africa. Geol. Surv., Dept. of Mines, Handbook 7:478pp

Pirajno, F. (1992) Hydrothermal mineral deposits – principles and fundamental concepts for the exploration geologist. Springer, Berlin Heidelberg New York, 799pp

Pringle, I.C. (1986a) The Union Tin Mine, Naboomspruit District. In: Anhaeusser, C.R., Maske, S. (eds) Mineral deposits of Southern Africa. Geol. Soc. S. Afr., pp. 1301–1305

Pringle, I.C. (1986b) The Zwartkloof fluorite deposits, Warmbaths District. In: Anhaeusser, C.R., Maske, S. (eds.) Mineral deposits of Southern Africa. Geol. Soc. S. Afr. pp. 1343–1349

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Reimold, W.U. (1993) Further debate on the Sudbury structure: is it relevant to the Vredefort Dome and the Bushveld Complex? S. Afr. J. Sci. 89: 546–552

Rhodes, R.C. (1975) New evidence for impact origin of the Bushveld Complex, South Africa. Geol. 3: 549–554.

Rhodes, R.C., Du Plessis, M.D. (1976) Notes on some stratigraphic relations in the Rooiberg Felsite. Trans. Geol. Soc. S. Afr. 79: 183–185

Rozendaal, A., Toros, M.S., Anderson, J.R. (1986) The Rooiberg tin deposits, West-Central Transvaal. In: Anhaeusser, C.R., Maske, S. (eds.) Mineral deposits of Southern Africa. Geol. Soc. S. Afr., pp. 1307–1327

Sawkins, F.J. (1984) Metal deposits in relation to plate tectonics. P.J. Willie (ed.) Springer, Berlin Heidelberg New York, 325pp

Schiffries, C.M., Skinner, B.J. (1987) The Bushveld hydrothermal system: field and petrologic evidence. Am. J. Sci. 287: 566–595

Schweitzer, J.K. (1984) The Dullstroom volcanics and their relation to the Rooiberg felsite. Inst. Geol. Res. Bushveld Complex, Univ. Pretoria, Ann. Rep. 1984: 49–56

Schweitzer, J.K. (1986) Field and geochemical investigations of the Dullstroom and Rooiberg volcanic rocks (abstract). Geocongress'86, Geol. Soc. S. Afr., Johannesburg, pp. 873–876

Schweitzer, J.K. (1987) The transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group, Transvaal sequence: a volcanological, geochemical and petrological investigation. Ph.D. thesis, Univ. Pretoria (under revision)

Schweitzer, J.K., Hatton, C.J. (1994a) Alteration processes within the floor and roof rocks of the Bushveld Complex. Econ. Geol. (submitted for publication)

Schweitzer, J.K., Hatton, C.J. (1994b) Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex (abstract). Geocongress'95, Geol. Soc. S. Afr., Johannesburg (in press)

Schweitzer, J.K., Hatton, C.J., Waal, S.A. de (1994) Regional lithochemical stratigraphy of the Rooiberg Group, Upper Transvaal Supergroup: a proposed new subdivision. S. Afr. J. Geol. (in press)

South African Committee for Stratigraphy (SACS) (1980) Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. Handbook Geol. Surv. S. Afr. No. 8: 633pp

Stear, W.M. (1977) The stratigraphy and sedimentation of the Pretoria Group at Rooiberg, Transvaal. Trans. Geol. Soc. S. Afr. 80: 53–65

Strauss, C.A. (1954) The geology and mineral resources of the Potgietersrus tin-fields. Geol. Surv. S. Afr. Memoir 46: 241pp

Twist, D. (1983) An economic evaluation of the Rooiberg Felsite. Res. Rep. Inst. Geol. Res. Bushveld Complex: 25pp

Twist, D. (1985) Geochemical evolution of the Rooiberg siliceous lavas in the Loskop Dam area, southeastern Bushveld. Econ. Geol. 80: 1153–1165

Verryn, S.M.C., Waal, S.A. de, Schweitzer, J.K., Hatton, C.J. (1994) Contact metamorphic aureole above the Rustenburg Layered Suite of the Bushveld Complex: Zn mineralization as characterized by an X-ray diffraction study (abstract). Geocongress'95, Geol. Soc. S. Afr., Johannesburg, (in press)

Von Gruenewaldt, G. (1968) The Rooiberg Felsite north of Middelburg and its relation to the layered sequence of the Bushveld Complex. Trans. Geol. Soc. S. Afr. 71: 153–172

Von Gruenewaldt, G. (1971) Petrographical and mineralogical investigation of the Bushveld Igneous Complex in the Tauteshoogte – Rossenekal area of the Eastern Transvaal. Unpubl. D.Sc. thesis, Univ. Pretoria, 228pp

Walraven, F. (1982) Textural, geochemical and genetical aspects of the granophyric rocks of the Bushveld Complex. Ph.D. thesis, Univ. Witwatersrand, Johannesburg, South Africa, 251pp

Walraven, F. (1985) Genetic aspects of the granophyric rocks of the Bushveld Complex. Econ. Geol. 80: 1166–1180

Zhang, J.S., Passchier, C.W., Slack, J.F. (1994) Cryptocrystalline Permian tourmalinites of possible metasomatic origin in the Oribic Alps, northern Italy. Econ. Geol. 89: 391–396

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Evidence for synchronous extrusive and intrusive Bushveld magmatism

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Abstract - The intracratonic, 2.06 Ga volcanic rocks of the Rooiberg Group of southern Africa consist of nine magma types, varying in composition from basalt to rhyolite. Basalts and andesites, intercalated with dacites and rhyolites, are found towards the base; rhyolite is the chief magma composition in the upper succession. The absence of compositions intermediate to the magma types and variations in major and trace element concentrations suggest that fractional crystallization was not prominent in controlling magma compositions. REE patterns are comparable for all magma types and concentrations increase for successively younger magmas; LREE show enriched patterns and HREE are flat. Elevated Sr_i-ratios and high concentrations of elements characteristically enriched in the crust suggest that the Rooiberg magmas were crustally contaminated or derived from crustal material. Some Rooiberg features are related to the intrusive events of the Bushveld complex.

Petrogenesis of both the Rooiberg Group and the mafic intrusives of the Bushveld complex is linked to a mantle plume, melting at progressively higher crustal levels. The basal Rooiberg magmas have undergone a complex history of partial melting, magma mixing and crustal contamination. Crustal melts extruded as siliceous volcanic flows to form the Upper Rooiberg Group, simultaneously intruding at shallow levels as granophyres. Crustally contaminated plume magma synchronously intruded beneath the Rooiberg Group to produce the mafic rocks of the Rustenburg Layered Suite. Granite intrusions terminated the Bushveld event. The Bushveld plume was short-lived, which conforms, together with other features, with younger, voluminous plume environments.

Résumé - Les roches volcaniques intracratoniques à 2,06 Ga du Groupe de Rooiberg en Afrique du Sud, constituent neuf types de magmas, variant en composition du basalte à la rhyolite. Les basaltes et les andésites, intercalées avec des dacites et des rhyolites, se situent à la base, les rhyolites étant majoritaires dans la partie supérieure de la succession. L'absence de compositions intermédiaires ainsi que les variations des éléments majeurs et en traces suggèrent que la cristallisation fractionnée n'ait pas contrôlé d'une manière prépondérante la composition des magmas. Les spectres de terres rares sont semblables dans tous les magmas, la concentration totale augmentant avec la jeunesse des magmas. Les terres rares légères définissent des spectres enrichis et les terres rares lourdes des spectres plats. Les rapports initiaux du strontium élevés et les fortes teneurs en éléments classiquement enrichis dans la croûte suggèrent que les magmas de Rooiberg soient contaminés par la croûte ou proviennent de la croûte. Certains caractères de Rooiberg sont liés aux événements intrusifs du complexe de Bushveld.

La pétrogenèse du Groupe de Rooiberg et des roches intrusives mafiques du Bushveld est liée à une plume mantellique provoquant une fusion à des niveaux crustaux de plus en plus élevés. Les magmas de la base de Rooiberg ont subi une histoire complexe de fusion partielle, de mélange de magmas et de contamination crustale. Les magmas crustaux se sont épanchés comme coulées volcaniques riches en silice pour former la partie supérieure du Groupe de Rooiberg et en même temps se sont intrudés à faible profondeur en tant que granophyres. Les magmas dérivant de la plume et contaminés par la croûte se sont intrudés simultanément sous le Groupe de Rooiberg pour former les roches mafiques de la Suite Litée de Rustenburg. Les intrusions granitiques closent l'événement Bushveld. La plume du Bushveld fut de courte durée, ce qui est comparable, ainsi que d'autres caractéristiques, aux environnements volumineux, plus jeunes, de type plume.

INTRODUCTION

The Rooiberg Group of South Africa is one of the largest accumulations of siliceous volcanic rocks (Figs 1 and 2; see Schweitzer *et al.*, 1995a, b; Schweitzer and Hatton, *in press* for general geological setting). Descriptions of the Rooiberg Group as unique (Harmer and von Gruenewaldt, 1991), catastrophic (Rhodes, 1975), problematical (de Bruiyn, 1980) and enigmatic (Sharpe *et al.*, 1983) indicates that its genesis is poorly understood. Similarly, the genetic relationship between the Rooiberg Group and the various intrusive events of the Bushveld complex is far from clear (e.g. Twist and French, 1983).

Poor understanding of the Rooiberg Group has resulted from an ill-defined, regionally applicable stratigraphy and the mistaken perception that these rocks are significantly older than the intrusive phases of the Bushveld complex [currently defined by SACS (1980) to consist of the Rustenburg Layered Suite (RLS), the Rashoop Granophyre Suite (RGS) and the Lebowa Granite Suite (LGS)]. Some evidence, such as

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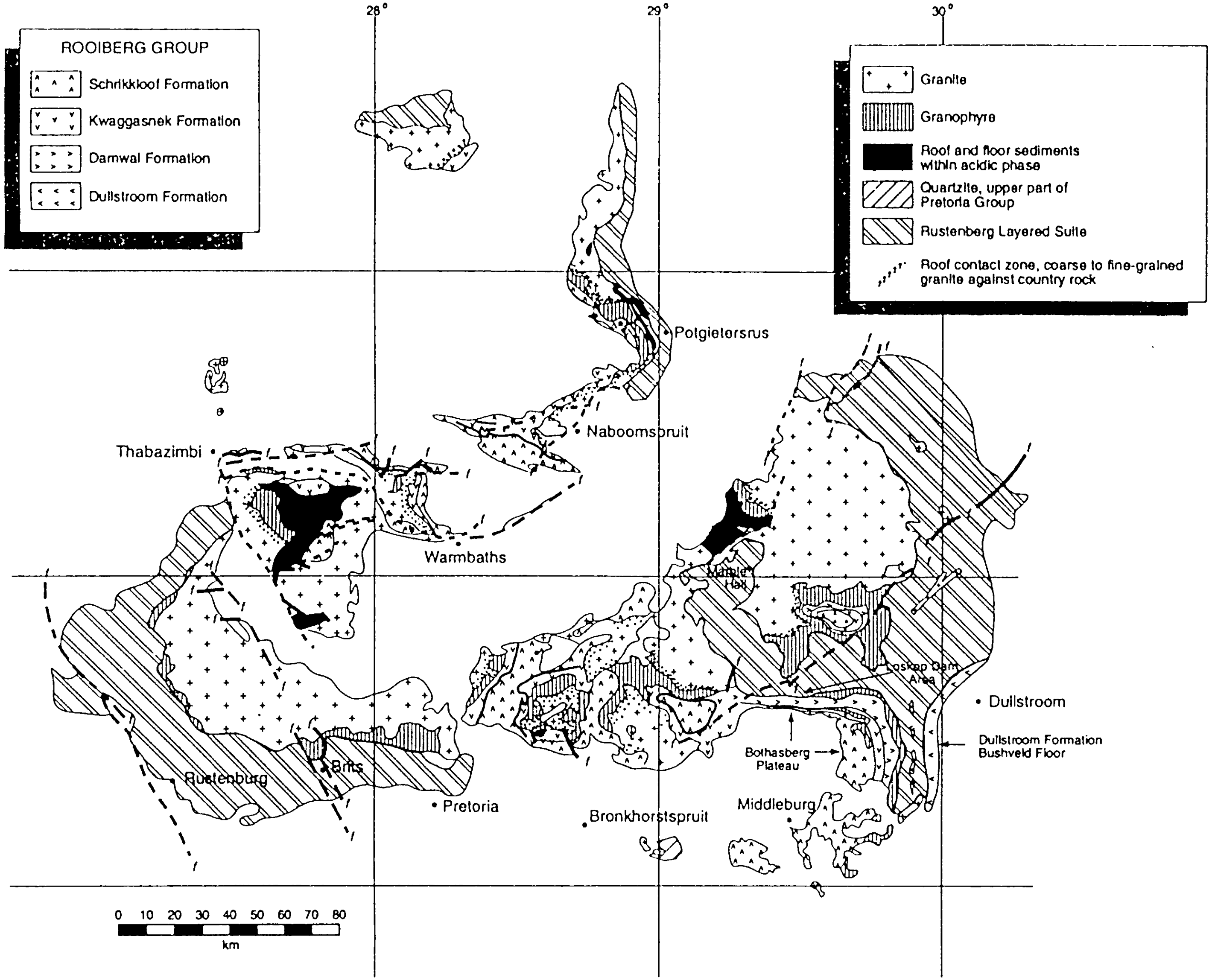

Figure 1. Geographical distribution of the Rustenburg Layered Suite, granites and granophyres and the formations of the Rooiberg Group (modified after Schweitzer *et al.*, 1995b).

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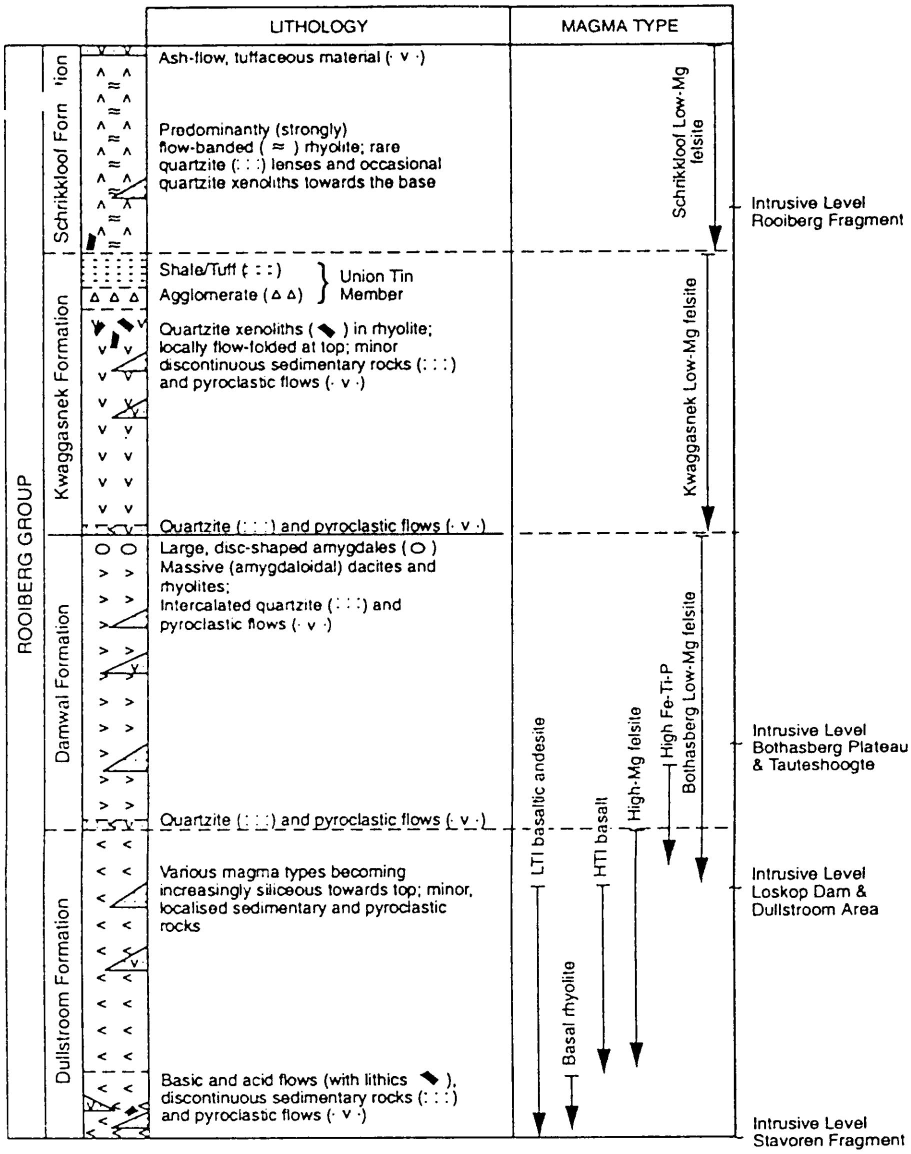

Figure 2. Stratigraphical column of the Rooiberg Group. Also shown are the stratigraphical levels at which the various magma types occur (modified after Schweitzer *et al.*, 1995b).

the intrusion level of Bushveld sills and dykes (e.g. Sharpe, 1985), suggests that at least portions of the volcanic pile are pre-RLS in age.

In this paper the authors present evidence indicating that the Rooiberg volcanic event was synchronous with the events of the Bushveld complex, suggesting that the volcanic suite should be incorporated into the Bushveld complex. The Bushveld magmatic event is interpreted to be a result of mantle diapirism, as was initially suggested by Sharpe *et al.* (1981) and Sawkins (1984).

THE ROOIBERG GROUP

General geology

The intracratonic Rooiberg Group is largely confined to the roof of the Bushveld complex, except for parts of the Dullstroom Formation preserved in the southeastern Bushveld floor (Fig. 1). The Rooiberg Group predominantly roofs the RLS in the east, whereas granite of the LGS underlies the volcanic rocks in the west.

The Rooiberg Group consists of nine magma types (Figs 2 and 3). The largest variety of magma types is encountered in the basal Dullstroom Formation (listed in order of first appearance): low-Ti (LTI) basaltic andesite, basal rhyolite, high-Mg felsite (HMF), high-Ti (HTI) basalt, high Fe-Ti-P lavas and low-Mg felsite (LMF) (Fig. 2). LTI basaltic andesites, basal rhyolites, HMF and HTI basalt are interspersed towards the base of the Dullstroom Formation. The formation becomes increasingly more siliceous towards the top, where LMF (rhyolites) and HMF (dacites) predominate over high Fe-Ti-P basaltic andesites. Discontinuous sedimentary intercalations are only prominent towards the base of the Dullstroom

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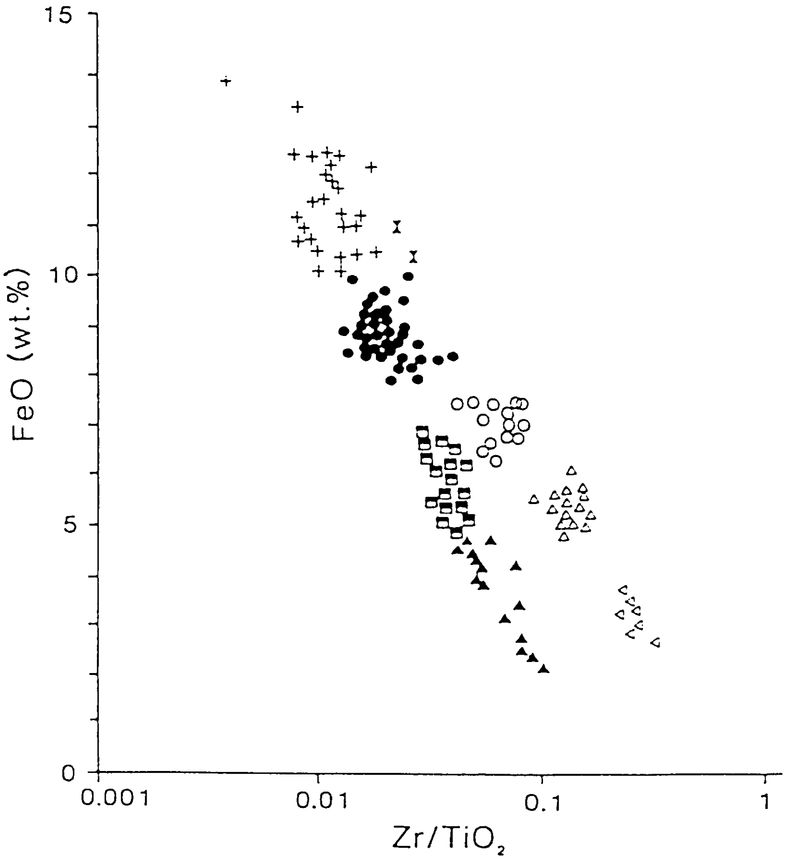

Symbol	Magma Type	Formation
◁	Low Magnesium Felsite	Schrikkloof
△	Low Magnesium Felsite	Kwaggasnek
○	Low Magnesium Felsite	Damwal
⧗	High Fe-Ti-P Lava	Dullstroom
+	High Titanium Basalt	
▭	High Magnesium Felsite	
▲	Basal Rhyolite	
•	Low Titanium Basaltic Andesite	

Figure 3. Total FeO versus Zr/TiO_2 delineating the discrete geochemical composition of the various Rooiberg magma types. The LMF's of the Dullstroom Formation are not shown but fall within the compositional field defined by the LMF's of the Damwal Formation (see Table 1).

Formation, where the volcanic flows also contain abundant sedimentary xenoliths. The average flow thickness of the mafic flows is about 5 m with rhyolite sheets being less than 250 m thick.

The HMF of the Dullstroom Formation has been identified as a magma type common to the volcanic rocks preserved in the floor and roof of the RLS. This led to the proposal that the volcanic rocks of the Dullstroom package should be included into the Rooiberg Group and the new stratigraphical subdivision (Schweitzer, 1987; Eriksson *et al.*, 1993; Schweitzer *et al.*, 1995b; Figs 1 and 2) is applied in this paper. The inclusion of the volcanic floor succession into the Rooiberg Group is supported by the presence of a major unconformity beneath the Dullstroom Formation (Cheney and Twist, 1991). This unconformity therefore marks the top of the predominantly sedimentary Transvaal Supergroup.

Compositionally distinct LMF magmas constitute the majority of the Damwal Formation and the entire Kwaggasnek and Schrikkloof Formations (Fig. 2). Compositional variations within individual LMF magma types are minor (Fig. 3). Flow thicknesses may reach up to 400 m and thicknesses increase towards the top. Flow banding is most pronounced in the upper succession. Sedimentary intercalations are present throughout. Sedimentary xenoliths are abundant at some stratigraphical levels (Fig. 2). The Kwaggasnek and Schrikkloof Formations are nowhere in contact with the RLS.

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Table 1. Average major (wt.%), trace (ppm) and REE (ppm) compositions of the nine Rooiberg Group magma types

	Dullstroom Formation												Damwal Formation		Kwaggasnek Formation		Schrikkloof Formation		Lower continental crust	Upper continental crust
	LTI		Basal Rhyolite		HMF		HTI		High Fe-Ti-P		LMF		LMF		LMF		LMF			
	n=77	Std	n=24	Std	n=26	Std	n=35	Std	n=5	Std	n=29	Std	n=11	Std	n=24	Std	n=6	Std		
SiO_2	57.30	2.30	74.00	2.70	66.60	1.70	53.90	2.20	61.30	1.60	67.90	1.10	68.30	0.80	72.30	1.00	74.40	0.70	54.4	66.0
TiO_2	0.62	0.09	0.31	0.06	0.60	0.05	1.87	0.22	1.02	0.06	0.63	0.07	0.60	0.06	0.35	0.02	0.24	0.01	1.0	0.5
Al_2O_3	14.7	0.60	11.30	0.60	13.30	0.60	13.60	0.70	12.00	0.20	12.00	0.30	12.20	0.30	11.60	0.40	11.60	0.40	16.1	15.2
FeO	8.87	0.44	3.28	0.81	5.87	0.65	11.50	1.22	10.69	1.20	7.16	0.65	7.18	0.34	5.24	0.51	3.20	0.33	10.6	4.5
MnO	0.16	0.02	0.08	0.02	0.11	0.03	0.17	0.02	0.28	0.05	0.21	0.27	0.14	0.03	0.14	0.08	0.03	0.01	-	-
MgO	5.06	1.14	1.66	0.57	1.96	0.49	4.62	0.54	0.81	0.21	0.53	0.20	1.09	0.32	0.66	0.21	0.61	0.08	6.3	2.2
CaO	7.92	0.84	2.94	0.72	4.31	0.76	8.37	1.21	3.56	0.25	2.04	0.80	2.31	0.53	0.69	0.51	0.24	0.28	8.5	4.2
Na_2O	2.28	0.41	1.64	0.20	3.01	0.30	3.00	0.45	2.86	0.41	2.81	0.63	2.84	0.34	2.69	0.53	2.62	0.52	2.8	3.9
K_2O	1.43	0.40	3.75	0.64	2.77	0.29	1.38	0.38	3.25	0.26	4.43	0.86	4.17	0.46	5.07	0.89	5.82	0.71	0.34	3.4
P_2O_5	0.12	0.03	0.08	0.01	0.13	0.02	0.23	0.05	0.35	0.04	0.16	0.03	0.15	0.02	0.05	0.01	0.02	0.01	-	-
LOI	1.38	0.56	0.89	0.33	1.13	0.33	0.95	0.39	1.95	0.49	1.19	0.50	1.27	0.49	1.52	0.36	1.26	0.07	-	-
Total	99.90	-	99.90	-	99.80	-	99.50	-	98.10	-	99.10	-	100.10	-	100.30	-	100.00	-	100.00	99.90
Nb	3	3	6	1	8	2	13	3	14	2	16	1	18	3	23	3	30	2	6	25
Zr	130	42	228	33	229	25	206	51	282	19	328	20	376	47	475	49	601	56	70	190
Y	21	5	25	5	29	3	30	6	49	2	49	7	56	9	69	7	81	8	19	22
Sr	252	47	223	22	292	36	389	58	159	16	136	60	145	32	101	62	34	10	230	350
Rb	58	22	142	36	103	12	50	20	126	11	169	36	163	27	215	30	232	32	5.3	112
Zn	79	17	32	13	68	18	94	22	407	131	246	168	150	53	152	61	46	22	83	71
Cu	60	199	3	10	21	19	55	49	52	38	46	36	38	48	13	9	4	6	90	25
Ni	81	32	22	11	18	10	90	28	13	4	14	9	6	9	4	7	1	2	135	20
Co	68	10	89	21	74	12	68	7	-	-	-	-	77	18	79	258	120	27	35	10
Cr	134	93	181	45	76	62	67	109	-	-	-	-	8	1	5	2	2	2	235	35
V	170	25	55	18	104	27	212	65	-	-	-	-	3	5	0	0	0	0	285	60
Ba	394	109	1055	184	740	119	336	125	431	26	659	226	862	78	1012	297	1349	128	150	550
Sc	30	3	9	3	18	2	24	3	20	3	12	2	13	1	7	1	1	0	36	11
Ga	14	1	11	1	15	1	19	1	19	1	16	2	17	1	17	2	18	2	18	17
Hf	1	3	0	2	1	3	1	4	-	-	7	3	4	6	8	6	16	2	2.1	5.8
U	0	2	0	0	0	0	0	1	4	0	8	12	1	2	1	2	1	1	0.28	2.8
Th	12	8	17	8	16	2	10	3	15	3	18	2	23	2	26	2	28	1	1.06	10.7
Pb	7	13	6	3	6	2	4	2	98	68	48	48	10	3	11	3	9	2	4	20
	n=3		n=1		n=7		n=5		n=2		n=3		n=8		n=2		n=2		-	-
La	23.9	3.7	35.1	-	35.3	3.1	30.9	6.9	53.2	4.0	61.0	0.9	60.1	1.9	70.4	0.3	81.2	2.2	11	30
Ce	48.4	9.0	70.0	-	69.9	6.4	70.9	7.8	133	5	117	3	114	4	132	1	158	1	23	64
Nd	19.6	1.1	22.1	-	25.9	2.3	34.0	4.3	44.9	2.6	49.3	0.8	48.8	2.0	56.0	0.1	60.3	0.3	12.7	26
Sm	4.3	0.4	5.0	-	5.5	0.5	7.3	1.0	9.7	0.4	10.2	0.3	10.1	0.5	11.6	0.1	12.5	0.1	3.2	4.5
Eu	1.0	0.1	1.0	-	1.2	0.1	1.9	0.1	2.1	0.1	2.0	0.1	2.0	0.2	2.2	0.1	1.9	0.1	1.2	0.9
Gd	-	-	-	-	4.3	0.3	-	-	8.7	0.3	8.6	0.3	8.6	0.5	9.8	0.1	9.6	0.1	3.1	3.8
Dy	-	-	-	-	3.9	0.3	-	-	8.4	0.1	8.5	0.4	8.2	0.6	10.0	0.2	10.0	0.1	3.6	3.5
Er	-	-	-	-	2.0	0.2	-	-	4.3	0	4.4	0.2	4.4	0.6	5.4	0.1	5.4	0.1	2.2	2.3
Yb	1.9	0.1	1.9	-	2.3	0.2	3.0	0.4	4.5	0.1	4.8	0.2	4.7	0.4	5.9	0.1	6.5	0.1	2.2	2.2
Lu	0.25	0.02	0.25	-	0.34	0.02	0.44	0.04	0.67	0	0.67	0.07	0.70	0.06	0.89	0	0.92	0.1	0.29	0.32

Analyses are compared to the chemical composition of the lower and upper continental crusts (after Taylor and McLennan, 1985). Only analyses of samples from least altered localities (see Schweitzer and Hatton, *in press* for detail) are considered. n=number of samples; Std=standard deviation.

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Initial Rooiberg volcanism was localized in occurrence with the upper formations becoming increasingly more widespread. Phenocrysts are absent, or minor, in all the magma types of the Rooiberg Group; quench-textures are abundant throughout. These textures have, in conjunction with flow distances and thicknesses, been taken as evidence for high magma temperatures (<1100°C), resulting in the interpretation that the upper Rooiberg erupted as 'flood rhyolites' (Twist *et al.*, *in prep.*). Mantle xenoliths are not encountered in the Rooiberg volcanic rocks.

Previous petrogenetic studies

A detailed petrogenetic study considering the nine magma types of the Rooiberg Group has not been carried out. Some workers considered individual Rooiberg magma types (Twist, 1985; Harmer and von Gruenewaldt, 1991), whereas others regarded the volcanic succession, or portions thereof, as a homogeneous volcanic pile (e.g. Sharpe *et al.*, 1983; Myers *et al.*, 1987; Crow and Condie, 1990).

Sharpe *et al.* (1983) deduced that the volcanic rocks of the Dullstroom Formation underwent 10%, shallow level, fractional crystallization of equal proportions of olivine and orthopyroxene. Modelled and observed concentrations show a poor match. Up to 75% of shallow level, fractional crystallization of olivine (40%), clinopyroxene (50%), plagioclase (10%)± magnetite was proposed for the same rocks by Crow and Condie (1990). The LMF magma types were interpreted as exhibiting smooth differentiation trends with breaks suggesting cyclicity in evolution (Clubley-Armstrong, 1977, 1980).

Sharpe *et al.* (1983) regarded the Dullstroom magma types, using a limited number of analyses (<10 samples), as the product of 2-3% of partial melting of a previously depleted mantle source, followed by minimal contamination (about 5%). Myers *et al.* (1987) deduced that the Dullstroom volcanic rocks, like the older volcanic successions of the Kaapvaal craton, originated by the melting of a modally metasomatized, LREE enriched and Fe and Ti depleted subcontinental lithosphere. Crow and Condie (1990) suggested that the Dullstroom tholeiitic to calc-alkaline rocks were derived by 15-20% melting of an undepleted garnet lherzolite. The mantle source was interpreted as having been enriched in LILE relative to the HFSE and HREE, similar to the source of young continental-margin arc basalts. High concentrations in Th, Rb and Ba were related by Crow and Condie (1990) to a subduction component that was acquired by the subcontinental lithosphere during earlier subduction regimes. A subduction component within the andesitic units and a volcanic arc component of the acidic components of the Dullstroom Formation was also recognized by Harmer and von Gruenewaldt (1991). These authors proposed magmatic underplating at the time of crustal formation, similar to the suggestion of Crow and Condie (1990).

Twist (1985) proposed that the HMF and LMF magma types were derived from separate, normally and reversely zoned magma chambers, respectively. Both have a related origin due to their interstratified nature. The high Fe-Ti-P magma type was interpreted as having originated from the LMF magma chamber on the basis of comparable geochemical trends and the inclusions of high Fe-Ti-P magma into LMF flows (Twist, 1985). The variations within the HMF and LMF have been ascribed to the fractionation of similar mineral assemblages during partial melting from chemically distinct sources (Twist and Harmer, 1987).

SOME GEOCHEMICAL CHARACTERISTICS OF ROOIBERG VOLCANIC ROCKS

Primary element concentrations of the Rooiberg Group have been modified during alteration processes with varying degrees of alteration at different localities (Schweitzer and Hatton, *in press*). After the effects of alteration have been taken into account, none of the Rooiberg magma types can be regarded as a primitive mantle melt (Table 1). In contrast to primitive mantle melts, mafic Rooiberg magmas have MgO generally <5 wt.%, SiO_2 >53 wt.%, and Ni and Cr concentrations varying between 16-158 ppm, and <367 ppm, respectively. Sr_i ratios of 0.705 (LTI basaltic andesite) and 0.709 (LMF, Dullstroom and Damwal Formations) have been recorded (Harmer and Farrow, 1995). The youngest rhyolites have MgO of <1 wt.%, Ni <35 ppm, and Cr <10 ppm (Table 1). Some magma types have major, trace and REE concentrations that compare remarkably well with upper crustal compositions (compare, e.g. basal rhyolite, but especially HMF concentrations with upper continental crust in Table 1). Some LMF flows of the Dullstroom Formation that have been affected by metamorphism due to the RLS, have Pb concentrations of up to 900 ppm. Geochemical studies suggest that these volcanic rocks were originally rich in Pb with this element being subsequently redistributed due to RLS metamorphism (Schweitzer and Hatton, *in press*).

Elements that have been identified as having been regionally immobile are employed in Fig. 4. The incompatible elements Zr, Nb and Y generally increase towards the top of the succession, whereas the reverse is commonly observed for P_2O_5, TiO_2 and Sc. This is especially well exhibited by the LMF magma types (Fig. 4b). Al_2O_3 forms clusters, implying that the fractionation of plagioclase was subordinate. FeO and Sc exhibit limited variations within individual magma types, suggesting that fractional crystallization of mafic mineral phases was not pronounced. The increase in incompatible element concentrations

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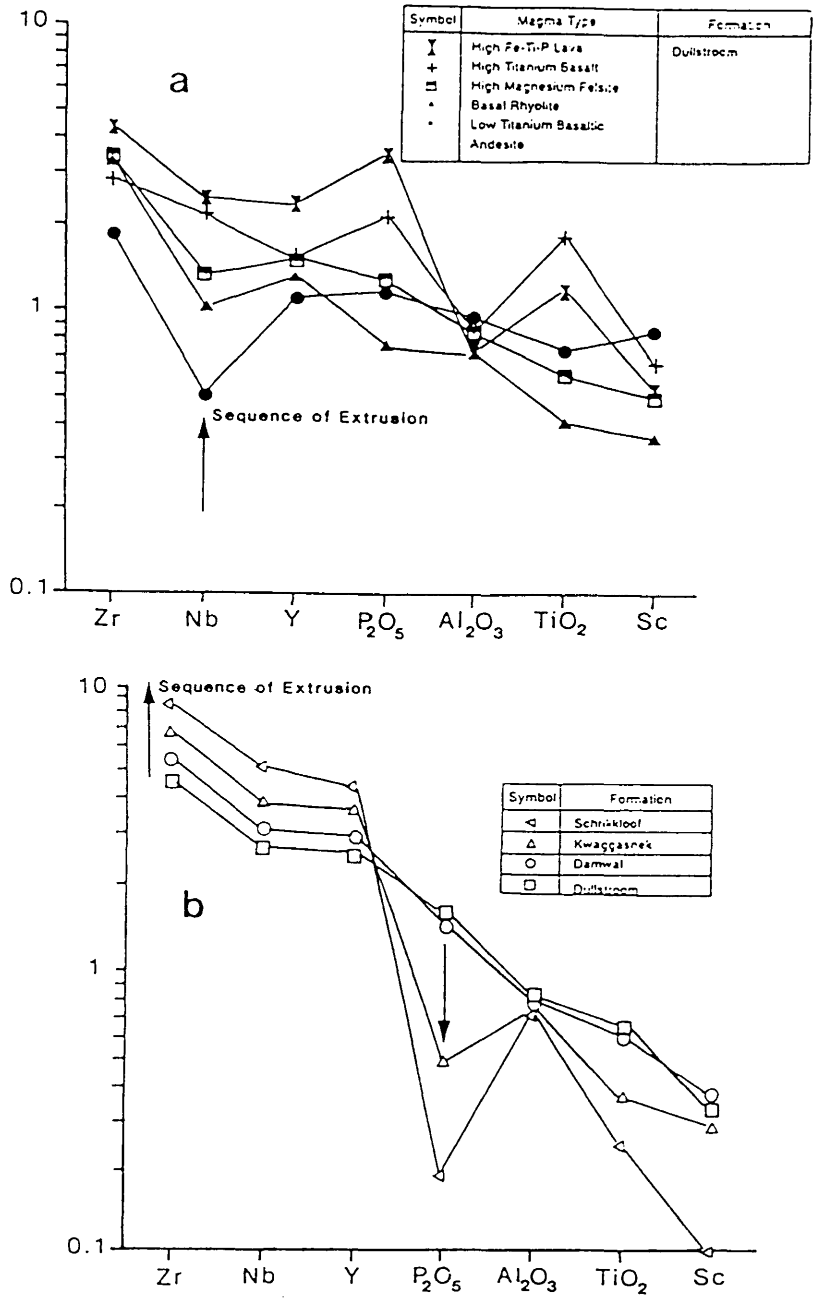

Figure 4. Spidergrams considering the average concentrations of immobile elements, as defined by Schweitzer and Hatton (*in press*), normalized to lower crustal compositions (normalizing values after Taylor and McLennan, 1985, except for P_2O_5 - taken from Taylor, 1964, crustal average page 1280). (a) LTI basaltic andesite (n=77); basal rhyolite (n=24); HMF (n=26); HTI basalt (n=35). (b) LMF - Dullstroom Formation (n=29); LMF - Damwal Formation (n=75); LMF - Kwaggasnek Formation (n=15); LMF - Schrikkloof Formation (n=14).

is accompanied by an increase in the light and heavy REE's (Fig. 5). The flat, heavy REE pattern shows that residual garnet was absent in the source region.

The magma types of the Rooiberg Group are also identified using their Na_2O+K_2O, FeO^* and MgO concentrations (Fig. 6). Some scatter is introduced due to the mobility of the alkaline elements. Most mafic Dullstroom magmas (HTI and LTI) plot to the left of the line separating the calc-alkaline and tholeiitic fields (Fig. 6). These magma types, together with the HMF's and the basal rhyolites, show broad variations in Cr (Fig. 7) and Ni (Table 1). The LMF magma types plot along the Na_2O+K_2O/FeO^* edge of an AFM diagram (Fig. 6) and have low Cr (Fig. 7), V and Ni (Table 1) concentrations.

EVIDENCE FOR SYNCHRONOUS ROOIBERG AND BUSHVELD MAGMATISM

Geochemical characteristics of the Rooiberg Group have previously been related to those of Bushveld

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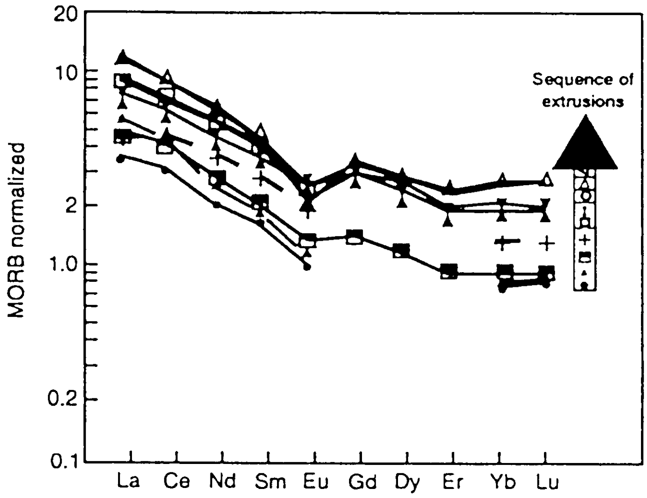

Symbol	Magma Type	Formation
◁	Low Magnesium Felsite	Schrikkloof
△	Low Magnesium Felsite	Kwaggasnek
○	Low Magnesium Felsite	Damwal
□	Low Magnesium Felsite	Dullstroom
⧗	High Fe-Ti-P Lava	
+	High Titanium Basalt	
■	High Magnesium Felsite	
▲	Basal Rhyolite	
•	Low Titanium Basaltic Andesite	

Figure 5. MORB normalized (normalizing factors after Sun and McDonough, 1989) REE concentrations for the Rooiberg magma types.

intrusive events. Geochemical similarities between the Lebowa Granite Suite (LGS) and the volcanic rocks were proposed by several authors (e.g. Hall, 1932; Lombaard, 1932; de Bruiyn, 1980; Kleemann, 1985). The majority of the 2053±12 Ma (Pb evaporation technique, Walraven, *in prep.*) Rashoop Granophyre Suite (RGS) was interpreted as representing intrusive Rooiberg magmas (Walraven, 1979, 1982, 1985), although this has been debated (von Gruenewaldt, 1971, 1972). Links have also been proposed between the mafic cumulates of the Rustenburg Layered Suite (RLS) and the volcanic rocks. Geochemical similarities between the HMF and initial RLS magma were noted (Hatton and Sharpe, 1989). Metamorphic and alteration signatures of the Rooiberg volcanic rocks have also been linked to the various intrusions of the RLS (Schweitzer *et al.*, 1995b).

Some characteristics of the Rooiberg Group are listed below as additional support for synchronous Rooiberg and Bushveld magmatism. Firstly, there is the close spatial association of the Rooiberg Group with the mafic and siliceous intrusions (Fig. 1). The Lower Dullstroom Formation is localized in occurrence, the Damwal, Kwaggasnek and Schrikkloof Formations cover increasingly larger areas (Fig. 1) and the volcanic rocks exhibit remarkable regional, lithological and geochemical uniformity. Second is the close temporal relationship. An age of 2061±2 Ma from zircons extracted from the Kwaggasnek LMF flows is indistinguishable from the RLS age (2061±27 Ma; Pb evaporation technique, Walraven, *in prep.*).

Finally, the geochemical stratigraphy established for the Rooiberg volcanic rocks (Schweitzer *et al.*, 1995b) provides unambiguous evidence that the vast majority of granophyres are not remelted felsites, providing additional support for the synchronous nature of the Rooiberg volcanism and the Bushveld magmatism. A co-magmatic origin of the Stavoren granophyre, comprising the vast majority of the RGS and the Rooiberg volcanic rocks, was previously proposed by Walraven (1979, 1985). The authors of this paper employed more than 140 granophyre analyses from various geographical regions and from different geological settings and compared these compositions to those of the associated Rooiberg magma types (Table 2, Fig. 8). Except for the Potgietersrus area (Granophyre[7], Table 2), granophyre compositions differ from the compositions of the abutting felsite, but correspond to compositions of younger felsite magmas (Fig. 8). Damwal-type granophyre intruded beneath the LMF of the

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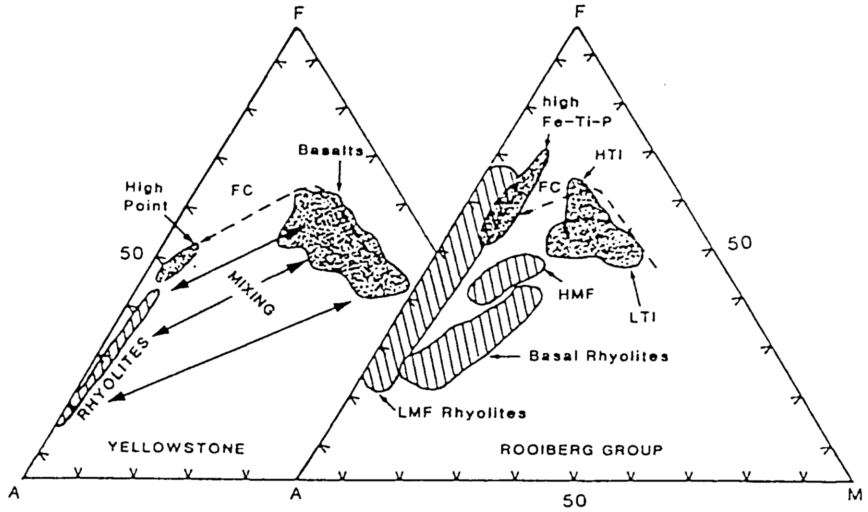

Figure 6. AFM plot for the Rooiberg Group magma types and the basalts and rhyolites from the Yellowstone area (after Hildreth *et al.*, 1991). A=Na_2O+K_2O; F=FeO^*; M=MgO. Compositions of LMF's of the Dullstroom, Damwal, Kwaggasnek and Schrikkloof Formations are summarized as one field. Basalt and andesite fields are shaded; dacite and rhyolite fields are hatched. The High Point lavas are highly fractionated (and contaminated), Fe-rich, intermediate lavas and occupy a field similar to the high Fe-Ti-P lavas.

Dullstroom Formation (Granophyre[1], Table 2) in the eastern Transvaal, whereas Schrikkloof-type granophyre intruded beneath the Kwaggasnek Formation towards the north of Pretoria and east of Groblersdal (Granophyres[4, 5, 8], Table 2, Figs 8 and 9). This implies that granophyres corresponding to progressively younger LMF magma compositions intruded continuously younger volcanic rocks of the Rooiberg Group. Felsites and granophyres are therefore co-magmatic. However, the RGS is currently included in the Bushveld complex and the Rooiberg Group is the uppermost part of the Transvaal Supergroup (SACS, 1980).

Granophyres compositionally corresponding to the Kwaggasnek and Schrikkloof LMF are in contact with sedimentary rocks beneath the volcanic pile (Granophyres[3, 6], Table 2, Fig. 9) in the Rooiberg and Stavoren fragments (isolated occurrences of floor rocks surrounded by Bushveld intrusions).

DISCUSSION

Proposed sequence of events

Certain aspects of the relative timing of events during the Bushveld magmatism are not in doubt. Granites of the LGS intrude granophyre (Walraven, 1982; Granophyre[2], Table 2), the Rooiberg Group and also mafic rocks of the RLS (Hammerbeck, 1969), suggesting that the LGS represents the terminal phase of the Bushveld magmatic event. The relation between the granophyres and the felsites has been disputed, but the relations presented here clearly support the view that the granophyres are, by and large, intrusive equivalents of the felsites (Walraven, 1979, 1985) rather than remelted felsites (von Gruenewaldt, 1971, 1972).

The relation between the mafic intrusives of the RLS and the Rooiberg volcanic rocks is rather more complex. In general terms, the RLS consists of the sequence: Lower Zone, Critical Zone, Main Zone and Upper Zone (e.g. von Gruenewaldt *et al.*, 1985). Field relations show that the Dullstroom Formation was intruded by the Main and Upper Zones (Visser, 1984), but this allows the possibility that the Dullstroom Formation preceded the Lower and perhaps even Critical Zone. The Kwaggasnek and Schrikkloof Formations are nowhere in contact with the RLS (Fig. 2) and their relation to RLS events is unconstrained. The sequence of events proposed here is that the Dullstroom Formation extruded first and the Lower Zone of the RLS intruded below this volcanic cap. The low overburden pressures (0.15 GPa, Wallmach *et al.*, 1989) recorded by calc-silicate xenoliths in the Lower Zone support this. The Damwal Formation extruded in late Lower Zone to early Critical Zone times. Lavas of the Kwaggasnek extruded prior to and during emplacement of the Critical Zone and the Schrikkloof Formation extruded prior to and during emplacement of the Main Zone.

Nature of magmatism

Suggestions that the Rooiberg volcanic rocks are melts that were derived from subduction-modified mantle (Hatton and Sharpe, 1989; Crow and Condie, 1990; Harmer and von Gruenewaldt, 1991) and then evolved by fractional crystallization (Sharpe *et al.*, 1983; Crow and Condie, 1990) are not supported by the detailed geochemical data presented here (Table 1).

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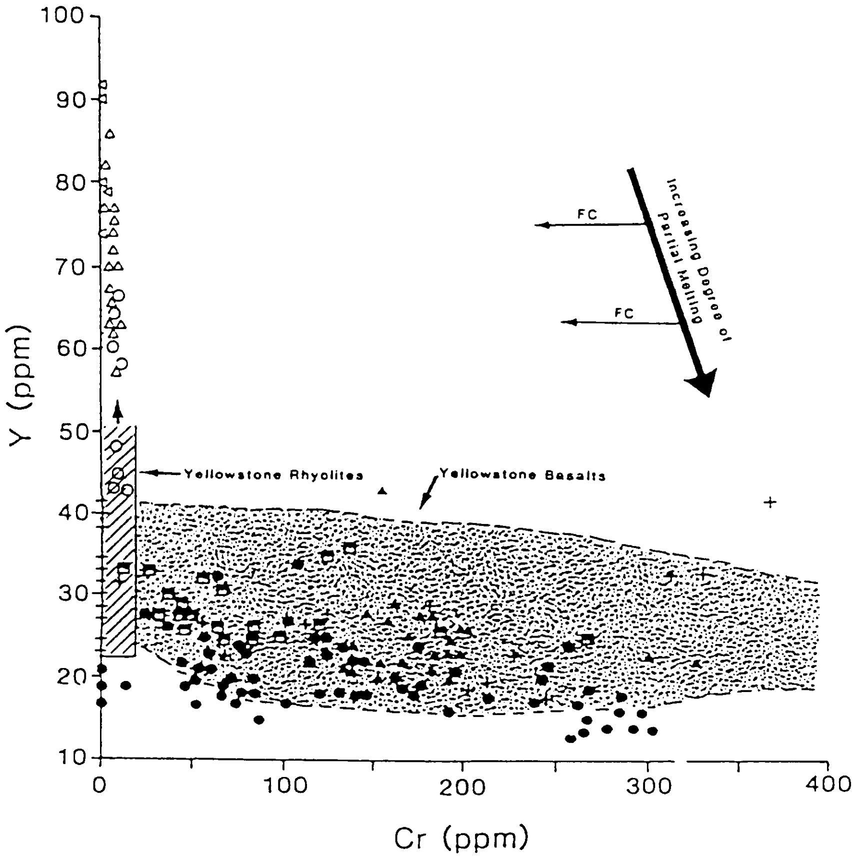

Symbol	Magma Type	Formation
◁	Low Magnesium Felsite	Schrikkloof
△	Low Magnesium Felsite	Kwaggasnek
○	Low Magnesium Felsite	Damwal
+	High Titanium Basalt	Dullstroom
▭	High Magnesium Felsite	
▲	Basal Rhyolite	
•	Low Titanium Basaltic Andesite	

Figure 7. Yttrium and Cr concentrations of the Rooiberg magma types. Vectors are after Hildreth *et al.* (1991) and represent partial melting of spinel-lherzolite mantle and fractional crystallization (FC) of assemblages containing olivine and Cr-rich spinel. Also shown are the compositional fields of the Yellowstone basalts and rhyolites (after Hildreth *et al.*, 1991).

None of the magmas are close to primary mantle melts (e.g. relatively high SiO_2 contents, Table 1) and the limited variation of Fe and Sc within, and of Al (Fig. 4) between, magma types, does not support the idea of fractional crystallization. Instead the pattern of Rooiberg magmatism shows similarities to acid magmatism above an intracratonic plume (e.g. Yellowstone, Figs 6 and 7; Hildreth *et al.*, 1991). A characteristic observed at Yellowstone is an initial phase of bimodal basaltic and rhyolitic magmatism. This is matched by the initial pairing of the LTI basaltic andesite and the basal rhyolite, followed by the HTI basalt - HMF pair, accompanied by LTI eruptions (Figs 2 and 6). The main stage is marked by extensive rhyolite magmatism with an intermediate stage of Fe-rich lavas (Rooiberg high Fe-Ti-P, Yellowstone High Point; Figs 2 and 6). The similarities with Yellowstone are striking, but so are the differences. At Yellowstone, mixing between basaltic and rhyolitic magmas is inferred by some stretching of the basalt field toward rhyolites (Fig.6). In the Rooiberg, the mixing lines inferred at Yellowstone are largely filled by the data points from the HMF and basal rhyolites (Fig. 6).

The composition of the HMF is very similar to that of upper continental crust, as estimated by Taylor and McLennan (1985) (Table 1; Hatton and Sharpe, 1989). Two alternatives can be considered: either the HMF are very high degree melts of upper continental crust, or the process which generated the upper continental crust is similar to the process which generated the HMF. Figure 6 suggests that the HMF could have been generated by mixing between a broadly basaltic

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Table 2. Average concentrations and standard deviations of TiO_2, P_2O_5, Nb, Zr and Y for the low-Mg felsite (LMF) flows and compositionally corresponding granophyres from various regions

	Damwal Formation				Kwaggasnek Formation					
	LMF		Granophyre[1]		LMF		Granophyre[2]		Granophyre[3]	
	n=86	Std	n=2	Std	n=39	Std	n=10	Std	n=26	Std
TiO_2	0.57	0.06	0.46	0.02	0.34	0.07	0.32	0.03	0.33	0.04
P_2O_5	0.15	0.03	0.13	0.01	0.05	0.01	0.04	0.01	na	
Nb	15	2	15	1	22	3	na		21	2
Zr	330	32	327	26	447	53	467	63	400	38
Y	51	13	46	1	67	7	na		68	11

	Schrikkloof Formation											
	LMF		Granophyre[4]		Granophyre[5]		Granophyre[6]		Granophyre[7]		Granophyre[8]	
	n=20	Std	n=15	Std	n=41	Std	n=23	Std	n=24	Std	n=34	Std
TiO_2	0.25	0.01	0.28	0.03	0.26	0.02	0.28	0.04	0.24	0.04	0.24	0.04
P_2O_5	0.03	0.01	0.04	0.03	na		na		na		0.02	0.01
Nb	24	4	na		26	2	22	2	26	3	26	6
Zr	486	93	420	90	498	24	440	32	466	47	507	48
Y	71	9	na		84	6	78	6	94	17	78	12

n: number of analyses; na: not analysed; Std: standard deviation.

Source of granophyre analyses and geographical locations are as follows:

1: Twist (1985); Loskop Dam area; between RLS and Dullstroom Formation.

2: De Bruiyn (1980); Blinkwater granophyre, northeast of Pretoria; between RLS and granite.

3: Walraven (1982); Stavoren area; between granite/sediments.

4: De Bruiyn (9180); Sterk river granophyre, northeast of Pretoria; between granite/Kwaggasnek Formation.

5: Walraven (1982); Groblersdal area; between RLS-granite/Kwaggasnek Formation.

6: Walraven (1982); Rooiberg area; between granite/sediment.

7: Walraven (1982); Potgietersrus area; between granite/Schrikkloof Formation.

8: Kleeman (1985); Groblersdal area; between RLS-granite/Kwaggasnek Formation.

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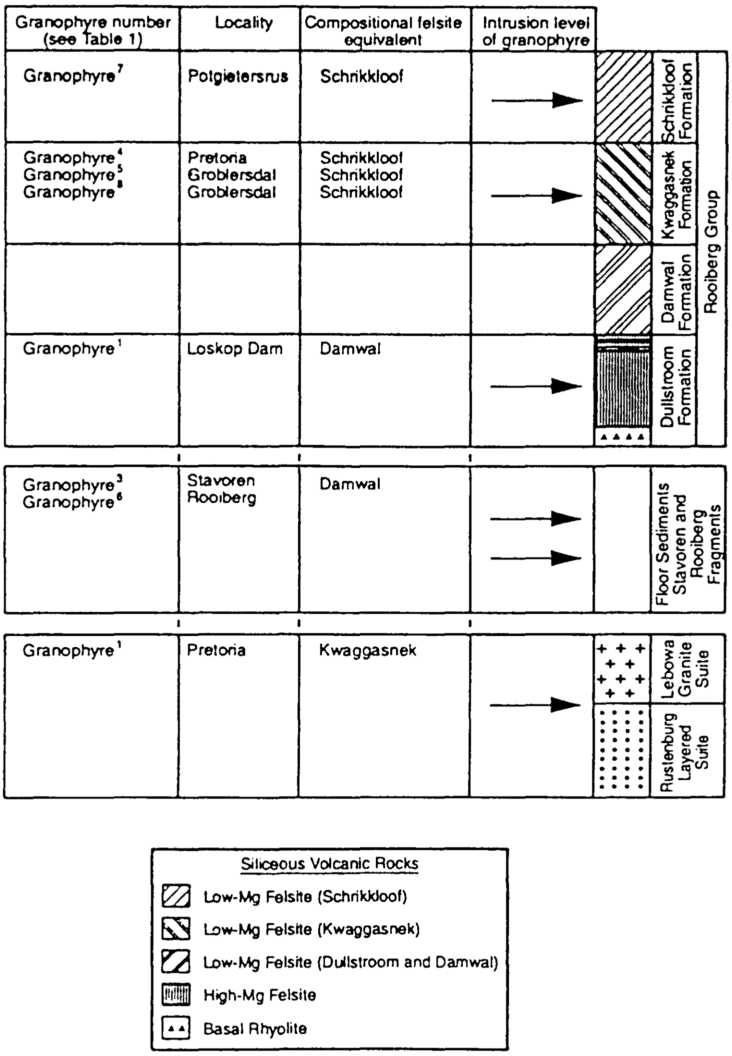

Figure 8. Intrusion levels and other details of the granophyres listed in Table 2.

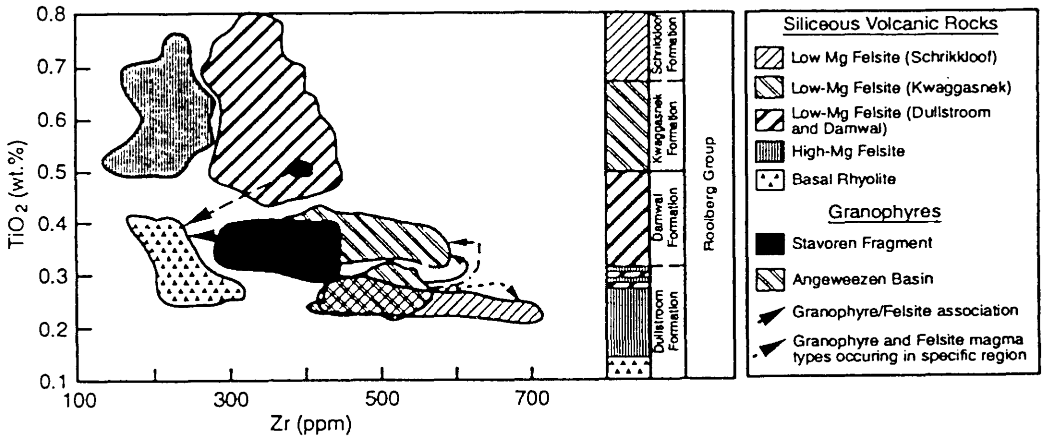

Figure 9. Chemostratigraphical subdivision of the siliceous volcanic rocks of the Rooiberg Group using TiO_2 and Zr concentrations. Also shown are, as examples, the compositional fields of the granophyres as preserved in the Stavoren fragment and the Angeweezen basin (modified after Schweitzer and Hatton, 1995).

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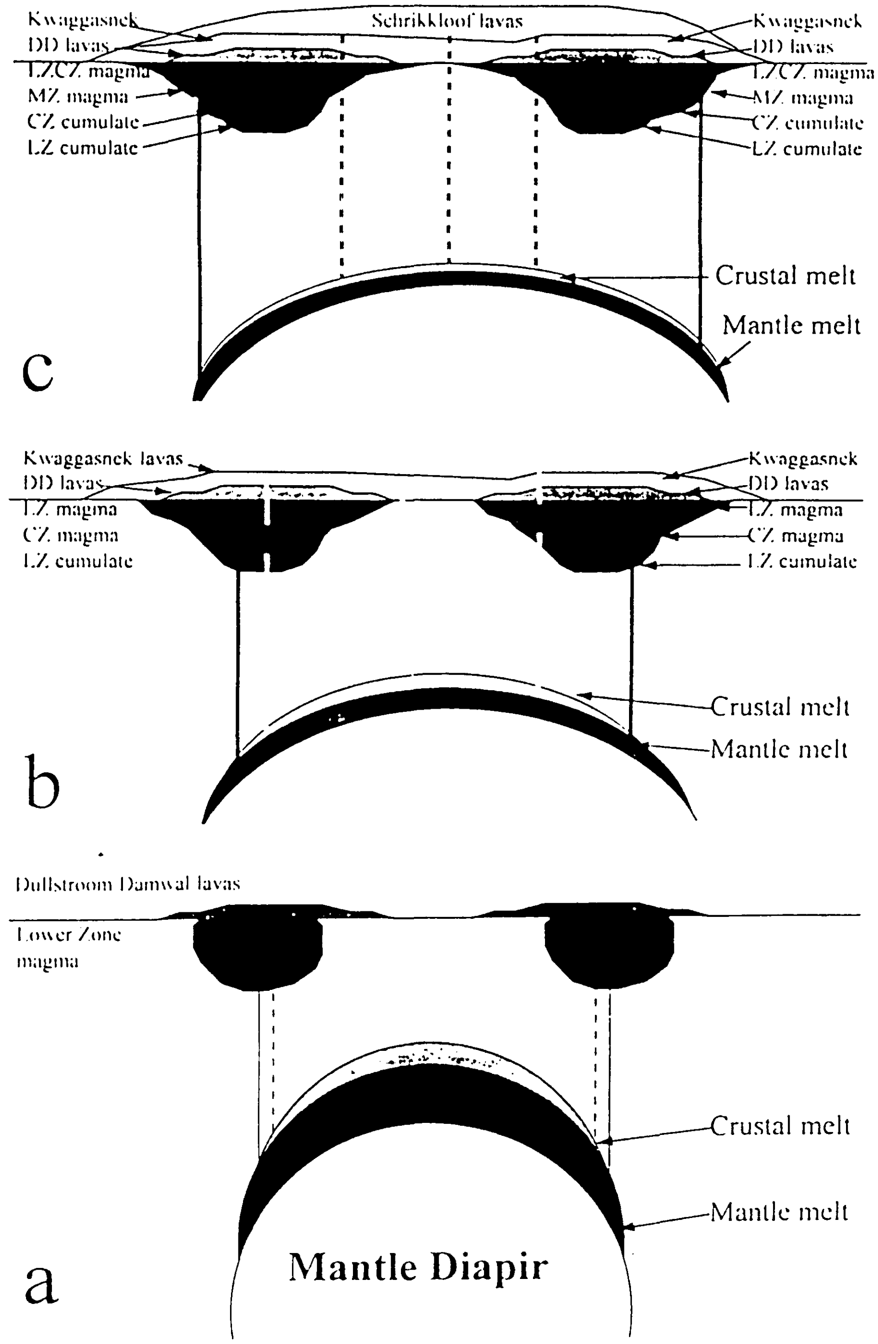

Figure 10. Sketch outlining the proposed sequence of events for the Rooiberg/Rustenburg Layered Suite system.

component and a broadly rhyolitic component derived by the melting of some component of the Proterozoic crust. The nature of these components is explored further later. Before this, the implications of the geographical arrangement of Bushveld magmatism for the source of these components are set down.

Distribution of magmatism

The predominant feature of the Bushveld outcrop pattern is the central disposition of acid magmatism with the peripheral distribution of mafic intrusives (Fig. 1). This geometry is consistent with that expected above a mantle plume (Hatton, 1995). In more detail, the Dullstroom and Damwal Formations have a more localized distribution and are more closely associated with the mafic intrusives than the more widespread Kwaggasnek and Schrikkloof Formations. This geometry can also be accounted for by a mantle plume (Fig. 10; also see Hildreth *et al.*, 1991 for further details).

Unconformities beneath the Kwaggasnek and possibly also the Schrikkloof Formation have been described for the western portion of the Bushveld

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complex (Schweitzer *et al.*, 1995b). In this area, upper Rooiberg formations rest on the lower Dullstroom Formation. The Kheis orogeny, situated at the western margin of the Kaapvaal craton, was active between 2000 and 2200 Ma (Beukes and Smit, 1987). Compression from the west may have caused uplift of the western Bushveld complex during Rooiberg times. This resulted in unconformities being best developed in the west and the formation of north-south trending folds in the eastern Bushveld floor (Sharpe and Chadwick, 1982).

Plume origin

The predominant theme in the hypothesis depicted in Fig. 10 and outlined below is the interaction between dominantly crustal melts, produced by heating of the crust, and mantle melts, derived from the mantle diapir. The diapir penetrates the crust to levels which may be as shallow as 18 km (Hatton, 1995). A blanket of crustal melt is produced and this blocks the ascent of magma and stops it segregating from the diapir. Those crustal melts that are heavily contaminated by mantle melts (Fig. 7) are the first to ascend (Fig. 2) and leak out from the base of the blanket of crustal melt as the diapir flattens and expands. The degree of contamination is likely to have been variable and this may have produced bimodal compositions. Alternatively, variation in crustal composition may have been an important factor. The most mafic component ascends as the LTI basaltic andesite and the less mafic magma ascends as the basal rhyolite. As crustal melting and mixing continues, the nature of the magmas changes. The basal rhyolite melt ceases and the HMF and HTI lavas join the LTI.

Large compositional variations in Ni and Cr (Fig. 7) suggest that these elements were incompatible during melting. Vanadium behaved as a compatible element, implied by limited V variations in Rooiberg magma types. These features point towards a spinel-rich source, possibly in the lower to middle crust.

Continuing with the evolution of the plume, the Lower Zone magma escapes on the margins of the blanket and intrudes below the volcanic rocks (Fig. 10a). Selective diffusion (e.g. Watson, 1982) from the crust leads to high K and high initial Sr isotope ratios in the Lower Zone magma (Hatton, *in press*). After further flattening and expansion of the diapir, high volumes of crustal melt of more uniform composition (Fig. 7) ascend from the blanket to erupt as the Kwaggasnek lava. Contaminated mantle melt of tholeiitic composition intrudes the chamber to produce the Critical Zone (Fig. 10b). Finally, further expansion and flattening produces the widespread Schrikkloof lavas, while the corresponding crustally contaminated mantle melt intrudes the chamber to produce the Main Zone (Fig. 10c).

Details of the evolution of the RLS and the associated generation of economic mineralization can be found in Kruger and Marsh (1982), Sharpe (1985) and Hatton (*in press*), while the relation between mineralization and lava extrusion in the Rooiberg Group is described by Schweitzer *et al.* (1995a).

SUMMARY

Evidence suggests that the Rooiberg Group should be excluded from the predominantly sedimentary Transvaal Supergroup. The Rooiberg volcanism and Bushveld magmatism were co-magmatic, requiring the incorporation of the Rooiberg Group into the Bushveld complex. Similar relationships have been described for the Yellowstone area (Hildreth *et al.*, 1991) and the Kanye volcanic rocks of the Gaborone Granite Suite (Moore *et al.*, 1993).

The mechanism, which simultaneously generated intrusive and extrusive rocks, is considered to be the intrusion of a mantle plume into the middle crust. The alternative hypothesis, that a meteorite impact was responsible for these events (e.g. Rhodes, 1975), has been rejected by Twist and French (1983) because shock metamorphic features have not been found. The Bushveld complex is not a unique phenomenon, rather it is a larger and older example of processes currently operating at Yellowstone (Hildreth *et al.*, 1991) and recorded in various forms throughout the geological record (e.g. Anderson, 1994; Kerr, 1994).

Acknowledgements

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REFERENCES

Anderson, D. L. 1994. Superplumes or supercontinents? *Geology* 22, 39-42.

Beukes, N. J. and Smit, C. A. 1987. New evidence for the thrust faulting in Griqualand West, South Africa: implications for stratigraphy and the age of the red beds. *South African Journal Geology* 90(4), 378-394.

Cheney, E. S. and Twist, D. 1991. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. *Precambrian Research* 52, 115-132.

Clubley-Armstrong, A. R. 1977. The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome. *M. Sc. thesis* 107p. University Pretoria, Pretoria, South Africa.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Clubley-Armstrong, A. R. 1980. Petrochemistry of the Rooiberg Group and overlying Loskop Formation north of Middelburg, South-Eastern Transvaal. *Annals Geological Survey South Africa* **14-2**, 11-28.

Crow, C. and Condie, K. C. 1990. Geochemistry and origin of early Proterozoic volcanic rocks from the Transvaal and Soutpansberg successions, South Africa. *Precambrian Research* **47**, 17-26.

De Bruiyn, H. 1980. The geology of the acid phase of the Bushveld Complex, north of Pretoria - a geochemical statistical approach. *Ph. D. dissertation* 171p. Orange Free State University, Bloemfontein, South Africa.

Eriksson, P. G., Schweitzer, J. K., Bosch, P. J. A., Schreiber, U. M., van Devender, J. L. and Hatton, C. J. 1993. The Transvaal Sequence: an overview. *Journal African Earth Sciences* **16**, 25-51.

Hall, A. L. 1932. The Bushveld Igneous Complex in the central Transvaal. *Memoir Geological Survey South Africa* 28, 560p.

Hammerbeck, E. C. I. 1969. The Steelport Park granite, eastern part of the Bushveld Complex, and the magnetitites in the gabbroic country rock. In: *Symposium on the Bushveld Igneous Complex and other layered intrusions*. Geological Society South Africa, Special Publication **1**, 299-311.

Harmer, R. E. and Farrow, D. 1995. An isotopic study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. *Mineralium Deposita* 30, 188-195.

Harmer, R. E. and von Gruenewaldt, G. 1991. A review of magmatism associated with the Transvaal Basin - implications for its tectonic setting. *South African Journal Geology* **94**, 104-122.

Hatton, C. J. 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. *Journal African Earth Sceinces* **21**, 571-577.

Hatton, C. J. *In press*. The Bushveld Complex - Product of interaction among magmas derived from a mantle plume. *Communications Geological Survey Namibia*.

Hatton, C. J. and Sharpe, M. R. 1989. Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: *Boninites and related rocks* (Edited by Crawford, A. J.) pp174-208, Unwin Hyman, London.

Hildreth, W., Halliday, A. N. and Christiansen, R. L. 1991. Isotope and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellestowne Plateau volcanic field. *Journal Petrology* **32/1**, 63-138.

Kerr, A. C. 1994. Lithospheric thinning during the evolution of continental large igneous provinces: a case study from the North Atlantic Tertiary province. *Geology* **22**, 1027-1030.

Kleemann, G. J. 1985. The geochemistry and petrology of the roof rocks of the Bushveld Complex, east of Groblersdal. *M. Sc. thesis* 178p. University Pretoria, Pretoria, South Africa.

Kruger, F. J. and Marsh, J. S. 1982. Significance of $^{87}Sr/^{86}Sr$ ratios in the Merensky cyclic unit of the Bushveld Complex. *Nature* **298**, 53-55.

Lombaard, B. V. 1932. The felsites and their relations in the Bushveld Complex. *Transactions Geological Society South Africa* **37**, 5-52.

Moore, M., Davis, D. W., Robb, L. J., Jackson, M. C. and Grobler, D. F. 1993. Archean rapakivi granite-anorthosite-rhyolite complex in the Witwatersrand basin hinterland, southern Africa. *Geology* **21**, 1031-1034.

Myers, R. E., Cawthorn, R. G., McCarthy, T. S. and Anhaeusser, C. R. 1987. Fundamental uniformity in the trace element patterns of the volcanics of the Kaapvaal Craton from 3000 to 2100 Ma: evidence for the lithospheric origin of these continental tholeiites. In: *Geochemistry and mineralization of Proterozoic Volcanic Suites* (Edited by Pharaoh, T. L., Beckinsale, R. D. and Richard, G.), *Geological Society Publication* 33, 315-325.

Rhodes, A. C. 1975. New evidence for impact origin of the Bushveld Complex, South Africa. *Geology* 3, 549-554.

Sawkins, F. J. 1984. *Metal deposits in relation to plate tectonics* (Edited by Wyllie, P. J.) pp158-176. Springer-Verlag, Berlin.

Schweitzer, J. K. 1987. The transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group, Transvaal Supergroup: a volcanological, geochemical and petrological investigation. *Ph. D. thesis* University Pretoria, Pretoria, South Africa, under revision.

Schweitzer, J. K. and Hatton, C. J. 1995. Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex. In: *Extended Abstracts of the Centennial Geocongress* (Edited by Barton, J. M. and Copperwaite, Y. E.) pp532-535. *Geological Society South Africa*, Johannesburg.

Schweitzer, J. K. and Hatton, C. J. *In press*. Chemical alteration in the roof rocks of the Bushveld Complex. *Economic Geology*.

Schweitzer, J. K., Hatton, C. J. and de Waal, S. A. 1995a. Economic potential of the Rooiberg Group: volcanic rocks in the floor and roof of the Bushveld Complex. *Mineralium Deposita* 30, 168-177.

Schweitzer, J. K., Hatton, C. J. and de Waal, S. A. 1995b. Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Supergroup: a proposed new subdivision. *South African Journal Geology* 98, 245-255.

Sharpe, M. R. 1985. Strontium isotope evidence for preserved density stratification in the main zone of the Bushveld Complex, South Africa. *Nature* 316, 119-126.

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Sharpe, M. R. and Chadwick, B. 1982. Structures in Transvaal Sequence rocks within and adjacent to the eastern Bushveld Complex. *Transactions Geological Society South Africa* 85, 29-41.

Sharpe, M. R., Bahat, D. and von Gruenewaldt, G. 1981. The concentric elliptical structure of feeder sites to the Bushveld Complex and possible economic implications. *Transactions Geological Society South Africa* 84, 239-244.

Sharpe, M. R., Brits, R. and Engelbrecht, J. P. 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3 Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. *Research Report* 40, 63p. *Institute Geological Research Bushveld Complex*, University Pretoria, Pretoria, South Africa.

SACS (South African Committee for Stratigraphy) 1980. Stratigraphy of South Africa Part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the Republics of Bophuthatswana, Transkei and Venda. *Handbook Geological Survey South Africa* 8, 690p. Pretoria, South Africa.

Sun, S.-S. and McDonough, W. F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: *Magmatism in the ocean basins* (Edited by Saunders, A. D. and Norry, M. J.) *Geological Society Special Publication* 42, 313-345.

Taylor, S. R. 1964. Abundance of chemical elements in the continental crust: a new table. *Geochemica Cosmochemica Acta* 28, 1273-1285.

Taylor, S. R. and McLennan, S. M. 1985. *The continental crust: its composition and evolution*. 312p. Geoscience Texts, Blackwell Scientific Publications, Oxford, London, Edinburgh.

Twist, D. 1985. Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, Southeastern Bushveld. *Economic Geology* 80, 1153-1165.

Twist, D. and French, B. M. 1983. Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite. *Bulletin Volcanology* 46-3, 225-242.

Twist, D. and Harmer, R. E. J. 1987. Geochemistry of contrasting siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for tectonic setting diagrams. *Journal Volcanological Geothermal Research* 32, 83-98.

Von Gruenewaldt, G. 1971. Petrographical and mineralogical investigation of the Bushveld Igneous Complex in the Tauteshoogte - Rossenekal area of the Eastern Transvaal. *D. Sc. thesis* 228p. University Pretoria, Pretoria, South Africa.

Von Gruenewaldt, G. 1972. The origin of the roof-rocks of the Bushveld Complex between Tauteshoogte and Paardekop in the eastern Transvaal. *Transactions Geological Society South Africa* 75, 121-134.

Von Gruenewaldt, G., Sharpe, M. R. and Hatton, C. J. 1985. The Bushveld Complex: Introduction and review. *Economic Geology* 80, 803-812.

Wallmach, T., Hatton, C. J. and Droop, G. T. R. 1989. The petrogenesis of high-grade contact metamorphic mineral assemblages in calc-silicate xenoliths, eastern Bushveld Complex, South Africa. *Canadian Mineralogist* 27, 509-523.

Walraven, F. 1979. Granophyre - lava relations in the Bushveld Complex. *Annals Geological Survey South Africa* 13, 59-80.

Walraven, F. 1982. Textural, geochemical and genetical aspects of the granophyric rocks of the Bushveld Complex. *Ph. D. thesis* 251p. University Witwatersrand, Johannesburg, South Africa.

Walraven, F. 1985. Genetic aspects of the granophyric rocks of the Bushveld Complex. *Economic Geology* 80, 1166-1180.

Watson, E. B. 1982. Basalt contamination by continental crust: some experiments and models. *Contributions Mineralogy Petrology* 80, 73-87.

Geological map

Geological map of the Republics of South Africa, Transkei, Bophuthatswana, Venda and Ciskei and the Kingdoms of Lesotho and Swaziland, NE Sheet; 1:1 000 000. 1984. Compiled by Visser, D. J. L. *Geological Survey South Africa*, Pretoria.

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Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa

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Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa

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Abstract—Until recently, it was proposed that the Bushveld Complex, consisting of the extrusive Rooiberg Group and the intrusive Rashoop Granophyre, Rustenburg Layered and Lebowa Granite Suites, evolved over a long period of time, possibly exceeding 100 Ma. Most workers therefore considered that the various intrusive and extrusive episodes were unrelated.
Recent findings suggest that the intrusive, mafic Rustenburg Layered Suite, siliceous Rashoop Granophyre Suite and the volcanic Rooiberg Group were synchronous, implying that the Bushveld igneous event was short-lived. Accepting the short-lived nature of the complex, the hypothesis that the granites are genetically unrelated to the other events of the Bushveld Complex can be reconsidered.
Re-examination of the potential Rooiberg Group/Lebowa Granite Suite relationship suggests that the granites form part of the Bushveld event. Rhyolite lava, granite and granophyre melts originated from a source similar in composition to upper crustal rocks. This source is interpreted to have been melted by a thermal input associated with a mantle plume. Granite intruded after extrusion of the last Rooiberg rhyolite, or possibly overlapped in time with the formation of the youngest volcanic flows. © *1997 Elsevier Science Limited.*

Résumé—Jusque récemment, il était proposé que le Complexe du Bushveld, comprenant le Groupe de Rooiberg extrusif ainsi que les Suites intrusives du Granophyre de Rashoop, du Complexe Lité de Rustenburg et du Granite de Lebowa, s'est formé au cours d'une longue période de temps ayant pu durer plus de 100 Ma. Pour cette raison, la plupart des chercheurs considéraient que les épisodes intrusifs divers et extrusif ne présentaient pas de relation entre eux.
Des données récentes suggèrent que la Suite Litée de Rustenburg, intrusive et mafique, est synchrone de la Suite saturée du Granophyre de Rashoop et du Groupe volcanique de Rooiberg, impliquant que la mise en place de l'ensemble du Complexe du Bushveld s'est opérée en un bref laps de temps. Sur cette base, l'hypothèse des granites ne présentant pas de relation génétique avec les autres termes du Complexe du Bushveld doit être revue.
La ré-examination des relations potentielles entre le Groupe de Rooiberg et la Suite des Granites de Lebowa suggère que ceux-ci appartiennent au Complexe du Bushveld. Pour les liquides des laves rhyolitiques, granites et granophyres, une source de composition similaire à celle de la croûte supérieure peut être envisagée. La fusion de celle-ci résulte du réchauffement attribué à un panache du manteau. Les granites se sont intrudés après l'extrusion des dernières rhyolites de Rooiberg ou éventuellement sont contemporains des coulées volcaniques terminales. © *1997 Elsevier Science Limited.*

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Table 1. Summary of Bushveld components and subdivisions

	Subdivisions	Magma Types	
Rooiberg Group	Schrikkloof Formation	LMF_S	(Low-Mg Felsite)
	Kwaggasnek Formation	LMF_K	(Low-Mg Felsite)
	Damwal Formation	LMF_D	(Low-Mg Felsite)
		High-Fe-Ti-P	(High Fe-Ti-P andesite)
	Dullstroom Formation	High-Fe-Ti-P	(High Fe-Ti-P andesite)
		LMF_D	(Low-Mg Felsite)
		HMF	(High-Mg Felsite)
		HTI	(High-Ti basalt)
		Basal Rhyolite	
		LTI	(Low-Ti basaltic andesite)
Rashoop Granophyre Suite	Rooikop Porphyry	LMF_S	
	Stavoren	LMF_S	
		LMF_K	
		LMF_D	
	Zwartbank		
Lebowa Granite Suite	Klipkloof		
	Makhutso		
	Nebo	LMF_S	
Rustenburg Layered Suite	Upper Zone		
	Main Zone		
	Critical Zone		
	Lower Zone		

The Rooiberg Group is included as part of the Bushveld Complex, adapting the proposal of Hatton and Schweitzer (1995). Magma types of the Rooiberg Group are listed in order of extrusion and are, where possible, related to the Rashoop Granophyre and Lebowa Granite Suites. Low-Mg Felsite compositions of the Damwal (LMF_D), Kwaggasnek (LMF_K) and Schrikkloof (LMF_S) Formations are distinct. See Kleeman and Twist (1989), and SACS (1980) for more detail on granite subdivision, and Harmer and Sharpe (1985) and Hatton (1989) for definition of the mafic Rustenburg Layered Suite magma types.

INTRODUCTION

The Bushveld Complex contains the largest known example of A-type granite plutonism (the Lebowa Granite Suite; Kleeman, 1985; Kleeman and Twist, 1989), the largest known accumulation of siliceous volcanism (the Rooiberg Group; Twist and French, 1983) and the largest intrusions of layered mafic rocks (the Rustenburg Layered Suite; von Gruenewaldt and Harmer, 1992; Table 1). Exceptionally large intrusive and extrusive volumes are accompanied by high temperatures (Rooiberg Group >1000°C, Elston, 1995; Lebowa Granite Suite >900°C, Kleeman and Twist 1989; Rustenburg Layered Suite >1200°C; Sharpe, 1985).

Emplacement of these enormous volumes of magma was accompanied by the intrusion of granophyres (Rashoop Granophyre Suite; Walraven, 1985). Previous age determinations implied that the complex evolved over a period in excess of 100 Ma (e.g. Burger and Coertze, 1975; Coertze *et al.*, 1978; see also Walraven and Hattingh, 1993 for a review of ages), influencing the debate on the petrogenetic relationship of the various components of the Bushveld Complex. This also led to the proposition that the Rooiberg Group and the Lebowa Granite Suite are older and younger, respectively, than the mafic rocks of the Rustenburg Layered Suite, consequently excluding their derivation from a common parental magma (e.g. Twist and Harmer, 1987). A petrogenetic relationship was excluded despite the close geographical association of the rocks under consideration and the existence of common geochemical traits between the Rooiberg volcanic rocks and those of the Rustenburg Layered Suite (Hatton and Sharpe, 1989), the Lebowa Granite Suite (Hartzer, 1994) and the Rashoop Granophyre Suite (Walraven, 1985; Hatton and Schweitzer, 1995). The relationship between the granites and the volcanic rocks of the Rooiberg Group is re-examined in this study.

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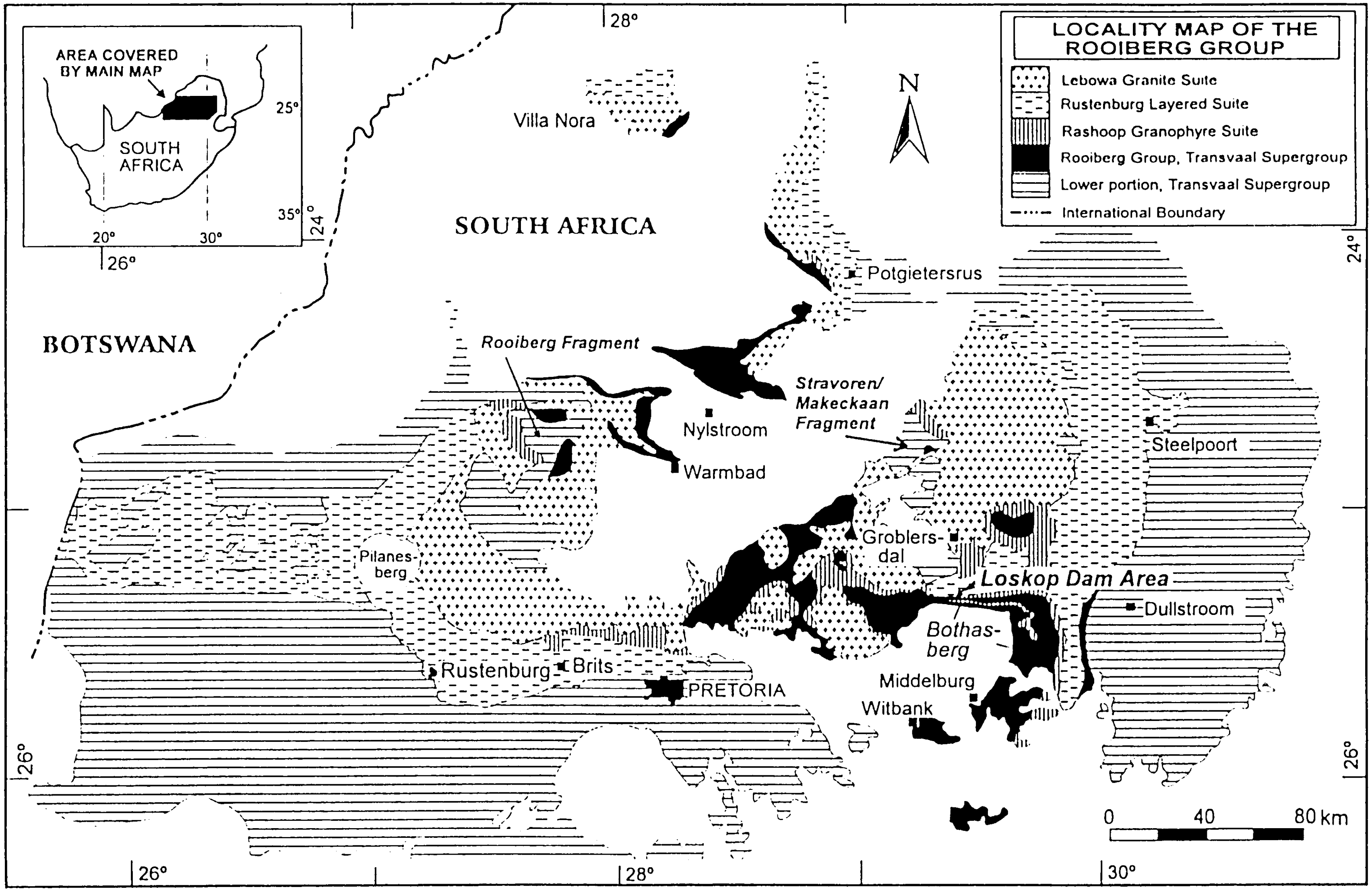

Figure 1. Geological map of the Bushveld Complex showing the distribution of the Rustenburg Layered Suite, Rooiberg Group, some Rashoop Granophyre occurrences and the Lebowa Granite Suite (modified after Walraven, 1982).

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Table 2. Average compositions of the youngest Rooiberg Group rhyolites, the Rooikop Granophyre (intrusive into the youngest Rooiberg rhyolites), the bottom and top compositions of the Nebo Granite as preserved towards the north of Groblersdal (after Kleeman and Twist, 1989) and the upper continental crust (after Taylor and McLennan, 1985, except for P_2O_5, which represent bulk crustal compositions after Taylor, 1964)

	ROOIBERG GROUP			RASHOOP GRANOPHYRE	LEBOWA GRANITE		UPPER CONTINENTAL CRUST
	Damwal Formation	Kwaggasnek Formation	Schrikkloof Formation	Rooikop Porphyry	Nebo Granite (b)	Nebo Granite (t)	
SiO_2	68.30	72.30	74.40	73.91	69.45	76.01	66
TiO_2	0.60	0.35	0.24	0.25	0.42	0.13	0.5
Al_2O_3	12.20	11.60	11.60	11.97	12.56	11.48	15.2
FeO*	7.18	5.24	3.20	3.45	6.00	1.92	4.5
MnO	0.14	0.14	0.03	0.08	0.09	0.03	
MgO	1.09	0.66	0.61	0.53	0.00*	0.00*	2.2
CaO	2.31	0.69	0.24	0.30	1.69	0.41	4.2
Na_2O	2.84	2.69	2.26	3.12	3.71	3.60	3.9
K_2O	4.17	5.07	5.82	5.48	4.64	5.70	3.4
P_2O_5	0.15	0.05	0.02	0.03	0.04	0.01	-0.105
LOI	1.27	1.52	1.62	1.21	0.71	0.56	
Total:	100.10	100.30	100.00	100.33	99.31	99.85	99.9
Nb	18	23	30	38	27	19	25
Zr	376	475	601	628	607	180	190
Y	56	69	81	109	71	40	22
Sr	145	101	34	82	144	26	350
Rb	163	215	232	289	147	225	112
Zn	150	152	46	188	109	53	71
Cu	38	13	4	0	5	3	25
Ni	6	4	1	0	6	7	20
Co	77	79	120	105			10
Cr	8	5	2	3			35
V	3	0	0	0			60
Ba	862	1012	1349	846	2294	449	550
Sc	13	7	1	3	2	<1	11
Ga	17	17	18	20	21	20	17
Hf	4	8	16	14	11	7	5.8
U	1	1	1	4	5	8	2.8
Th	23	26	28	31	19	34	10.7
Pb	10	11	9	11	14	18	20
La	60.1	70.4	81.2		59	74	30
Ce	114	132	158		118	149	64
Nd	48.8	56	60.3		73	80	26
Sm	10.1	11.6	12.5			11•	4.5
Eu	2	2.2	1.9			0.8•	0.9
Gd	8.6	9.8	9.6				3.8
Dy	8.2	10	10				3.5
Er	4.4	5.4	5.4				2.3
Yb	4.7	5.9	6.5			6.9•	2.2
Lu	0.7	0.89	0.92			1.05•	0.32

*Note that the granites towards the north of Warmbath have MgO contents of up to 0.28 wt% (Du Plessis, 1976). • = data from Robb *et al.* (1994).

BACKGROUND

Several features suggest that the Bushveld Complex owes its existence to a short-lived event (<7 Ma; Walraven, *in press*), interpreted to be triggered by a mantle plume (Sharpe *et al.*, 1981; Walraven, 1982; Sawkins, 1984; Hatton, 1995a, b; Hatton and Schweitzer, 1995; Schweitzer and Hatton, 1995a):

i) An unconformity beneath the Rooiberg Group (Cheney and Twist, 1991) shows that the volcanic rocks are unrelated to the Transvaal Supergroup.

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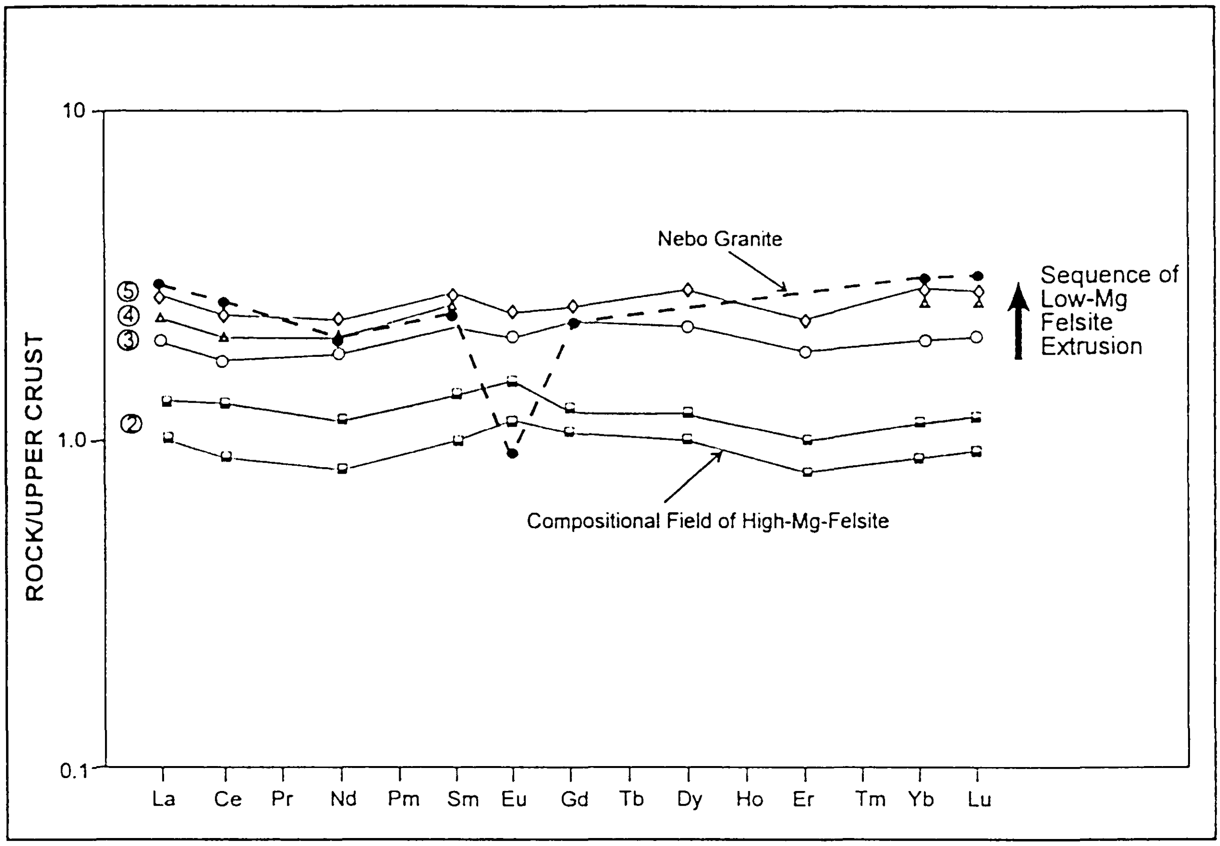

Figure 2. Rare earth element pattern of the youngest Rooiberg rhyolite normalised to the upper crust, compared to those of the unaltered, average Nebo Granite north of Pretoria (after Robb et al., *1994) and those of the older High-Mg Felsite (Rooiberg Group). See Hatton and Schweitzer (1995) for the average composition of the High-Mg Felsite. Circled numbers refer to the sequence of extrusions.*

ii) A magma type common to the volcanic floor and roof succession of the Rustenburg Layered Suite (Schweitzer *et al.*, 1995a; Schweitzer and Hatton, 1995b) testifies that the volcanic pile was continuous before the intrusion of the Rustenburg Layered Suite.

iii) Employing field and geochemical evidence, the extrusion of the Rooiberg Group is suggested to have been synchronous with the intrusions of the Rustenburg Layered Suite and Rashoop Granophyre Suite (Walraven, 1985; Hatton and Schweitzer, 1995). Several workers also proposed that the rhyolite and granite are genetically linked, considering their geochemical similarities and close geographical association (e.g. Hall, 1932; Lombaard, 1932; Lenthall and Hunter, 1977). Hartzer (1994) suggests that the Rooiberg rhyolite could be the less fractionated equivalent of the granite. Geochemical similarities were also detected between the granite and granophyres towards the north of Warmbath, leading to the proposal that the granophyre represents earlier granite intrusions (du Plessis, 1976).

iv) The geographical distribution of the various Bushveld rock types is in accord with a short-lived, mantle plume event (Hatton and Schweitzer, 1995). Siliceous rocks are centrally placed within the outcrop pattern of the Bushveld Complex, with mafic intrusive and extrusive rocks emplaced at the periphery (Fig. 1).

v) The short-lived nature of the Bushveld event is confirmed by recent age determinations, implying a duration of less than 7 Ma for the emplacement of the entire Bushveld Complex (Walraven, *in press*). The Rustenburg Layered Suite, the Rashoop Granophyre Suite, and the Rooiberg Group were all emplaced penecontemporaneously at 2061 Ma, with the youngest age obtained for the Lebowa Granite Suite (2054 Ma; Walraven, *in press*).

The currently favoured hypothesis is that the Lebowa Granite Suite and other siliceous components of the Bushveld Complex are unrelated (e.g. Fourie, 1969; Rhodes, 1974; Rhodes and Bornhost, 1975; Twist and Harmer, 1987; Kleeman and Twist, 1989). However, considering recent findings, the relationship of the Lebowa Granite Suite to the other components of the complex is still open to debate.

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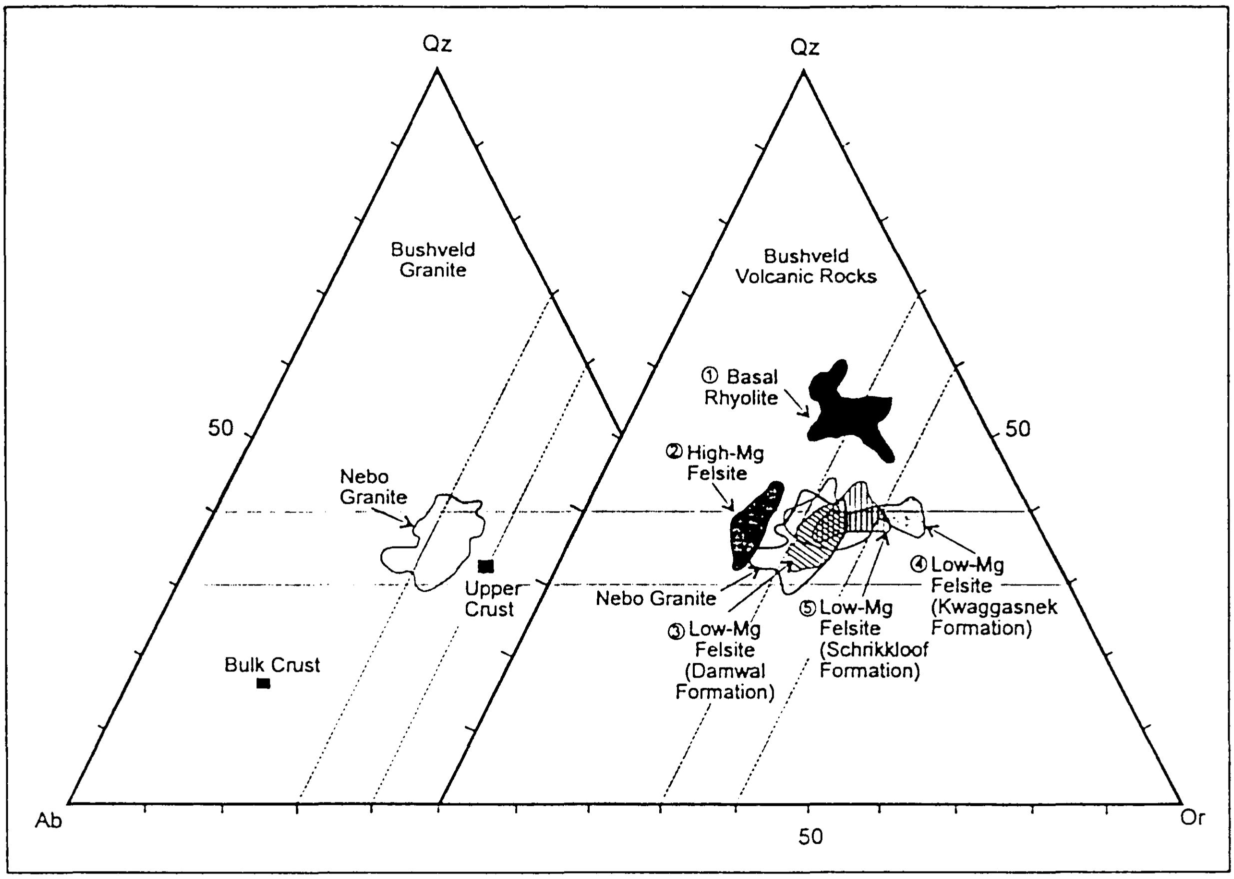

Figure 3. Ternary quartz, orthoclase, albite diagram considering the distributional fields of the Lebowa Granite Suite (after du Plessis, 1976; de Bruyn, 1980; Kleeman and Twist, 1989) and the dacite and rhyolite of the Rooiberg Group. Circled numbers refer to the sequence of extrusions. Bulk and upper crustal compositions after Taylor and McLennan (1985).

SILICEOUS ROOIBERG VOLCANIC ROCKS AND THEIR RELATIONSHIP TO THE LEBOWA GRANITE SUITE

Smooth element patterns are observed when the siliceous Bushveld magma types are normalised to upper crustal compositions (Table 2, Fig. 2). Compositional similarities between the High-Mg Felsite and the upper crust are striking (Fig. 2). The youngest Rooiberg Group rhyolites of the Low-Mg Felsite group have REE patterns comparable to those of the High-Mg Felsite, with Low-Mg Felsite concentrations 2-3 times higher than those of the upper crust. REE concentrations of the Nebo Granite are similar to those of the Low-Mg Felsite, except for a pronounced, negative Eu anomaly. However, a positive Eu anomaly has been observed at the base of the Nebo Granite sheet (J. Harmer, *pers. comm.*, in Kleeman and Twist, 1989) and the negative Eu anomaly as shown in Fig. 2 cannot therefore be used to geochemically distinguish the Bushveld granite from the rhyolite. With the exclusion of Eu, the REE concentrations of Low-Mg Felsites and those of the Nebo Granite are essentially indistinguishable.

The compositional fields of the youngest Low-Mg Rooiberg rhyolite and the Nebo Granite also compare favourably on a ternary quartz/orthoclase/albite diagram (Fig. 3). Compositions are again shown to be close to those of the upper crust. Early Rooiberg Group High-Mg Felsite and Basal Rhyolite are compositionally distinct from the granite.

The compositions of the Low-Mg Felsite are also indistinguishable from the Nebo Granite on a multi-element spidergram plot (Fig. 4a). Both are characterised by Sr, P_2O_5, TiO_2 and, to a lesser degree, Nb depletions when normalised against the upper crust. The remaining elements are about 2-3 times enriched when compared to upper crustal concentrations. Except for lower Nb concentrations, the high-Mg Felsite closely reflects upper crustal compositions (Fig. 4b). Element concentrations of a granite porphyry (Rooikop Granophyre; SACS, 1980; Tables 1 and 2) intruded into the upper Low-Mg Felsite succession, are also indistinguishable from those of the Nebo Granite and the youngest Low-Mg Felsite (Fig. 4b).

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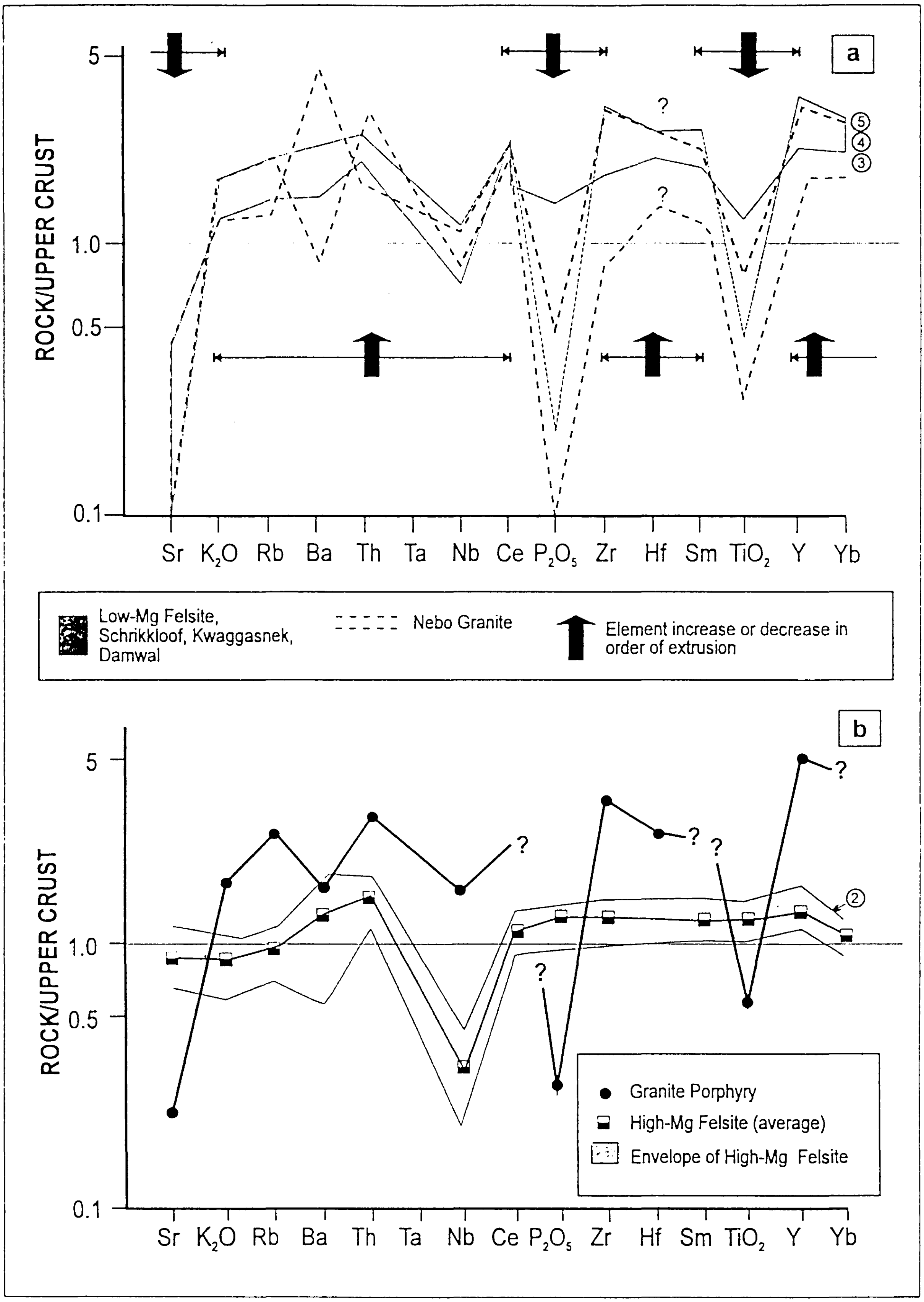

Figure 4. *Spiderdiagrams of (a) Low-Mg Felsite and (b) High-Mg Felsite normalised to upper crustal compositions. The composition of rocks of the Lebowa Granite Suite and the youngest Rooiberg rhyolites are similar. The envelope for the Nebo Granite has been deduced from Kleeman and Twist (1989) taking the analyses from the bottom and top of the compositionally zoned granite. One of the youngest rocks of the Rashoop Granophyre Suite has compositions comparable to those of the Rooiberg Group and the Lebowa Granite Suite (compare a and b). Circled numbers refer to the sequence of rhyolite extrusions.*

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In summary it is concluded that the chemical composition of the Low-Mg Felsites, the Nebo Granite and the youngest Rashoop granophyre are closely matched, suggesting that the Rooiberg Group and the Lebowa Granite Suite, as well as the Rashoop granophyres, are derived from a similar source.

DISCUSSION

Granite/rhyolite comparison is hampered by element redistribution. Concentrations of mobile elements vary substantially within otherwise comparable (using immobile elements) rhyolite flows from different localities (Schweitzer and Hatton, 1995b; Schweitzer *et al.*, 1995b). The extent and degree of alteration is therefore geographically variable within the Rooiberg rhyolite. In addition, it has been recorded that the Rooiberg magma type compositions are eruption centre specific (Schweitzer *et al.*, *in prep.*). Accepting that granite formation immediately succeeded the last rhyolite extrusions, or even overlapped in time with the Upper Rooiberg Group, lateral variations, reflecting alteration processes (Crocker and Callaghan, 1979) and compositional inhomogeneities of the source, may also be present in the Bushveld granite.

The incorporation of crustal material into the mafic rocks of the Bushveld Complex has been frequently proposed (e.g. von Gruenewaldt and Harmer, 1992; Kruger, 1994). The findings of this study suggest that the granitic and rhyolitic magmas broadly resemble upper crustal composition. Derivation of these melts from the subcontinental lithosphere appears to be unlikely considering the huge amounts of silicic Bushveld magmas. Large volumes of silicic magma may be generated by a plume positioned at the lower lithosphere, with magma being emitted to shallow crustal chambers. There, crustal contamination and melting can occur. Alternatively, the mantle plume may have intruded into crustal levels, as proposed by Hatton and Schweitzer (1995). Lithospheric, or even crustal thinning may be expected, especially beneath major basins such as the Transvaal Basin, into which the Bushveld Complex intruded. The association of thinspots and depositional basins has previously been suggested (Thompson and Gibson, 1991).

Distinct element concentrations and variations exhibited by the rhyolite and granite led Twist and Harmer (1987) to propose that these rocks are genetically unrelated. Twist and Harmer (1987) compare the average composition of 182 Low-Mg Felsite with an average of 170 Bushveld granite analyses. Their average Low-Mg Felsite is biased towards the Low-Mg Felsite magma type of the Damwal Formation (Table 2), which is from the Lower Rooiberg succession. When the Low-Mg Felsite magma types are subdivided (Schweitzer *et al.*, 1995a) it becomes clear that the rhyolites of the Schrikkloof Formation are very similar in composition to the Nebo Granite (Table 2), or the average Bushveld granite (Twist and Harmer, 1987). Further inspection of the Twist and Harmer (1987) data (their Fig. 4) also reveals that altered, silicified rhyolite samples (Schweitzer and Hatton, 1995b), with SiO_2 concentrations exceeding 78 wt% were employed during the rhyolite/granite comparison.

After emplacement, the granitic magma has undergone crystal fractionation, making it difficult to recognise the original magma. Twist and Harmer (1987) propose that the different trends observed in the granites and rhyolites showed that these magmas were unrelated, and possibly originated from different sources. However, it is clear that extensive fractional crystallisation has occurred in the granites (McCarthy and Hasty, 1976; Groves and McCarthy, 1978; McCarthy and Fripp, 1980; Walraven *et al.*, 1985; Kleeman and Twist, 1989) while the extrusives have undergone very little modification after emplacement. The different trends cannot therefore be taken as evidence for different sources. It is proposed that the geochemical similarities between the rhyolites and granites show that they are genetically related and derived from similar crustal source rocks.

CONCLUSIONS

Field and geochemical evidence suggest that the Bushveld event was short-lived. Extrusion of the volcanic rocks was synchronous with the intrusions of the Rustenburg Layered Suite and the Rashoop Granophyre Suite. In addition, evidence presented here indicates that the most evolved granophyre and the youngest rhyolite of the Rooiberg Group are geochemically comparable to the intrusions of the Lebowa Granite Suite. These rocks are suggested to have been derived from similar sources of upper crustal composition. The source rocks are interpreted to have been melted by a heat source that is related to a mantle plume. The data support the hypothesis that the Rooiberg Group/Rustenburg Layered Suite/ Rashoop Granophyre Suite event was immediately followed by granite intrusion.

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REFERENCES

Burger, A. J. and Coertze, F. J. 1975. Age determinations - April 1972 to March 1974. *Annals Geological Survey South Africa* 10, 15-141.

Cheney, E. and Twist, D. 1991. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. *Precambrian Research* V52, 115-132.

Coertze, F. J., Burger, A. J., Walraven, F., Marlow, A. G. and MacCaskie, D. R. 1978. Field relations and age determinations in the Bushveld Complex. *Transactions Geological Society South Africa* 81, 1-12.

Crocker, I. T. and Callaghan, C. C. 1979. Tin resources of South Africa: classification and inventory. *Geological Survey South Africa Bulletin* 66, 28p.

De Bruiyn, H. 1980. The geology of the acid phase of the Bushveld Complex, north of Pretoria - a geochemical statistical approach. *Unpub. Ph. D. thesis* 171p. Orange Free State University, Potchefstroom, South Africa.

Du Plessis, M. D. 1976. The Bushveld granites and associated rocks in the area north-west of Warmbaths, Transvaal. *M. Sc. thesis* 85p. University of Pretoria, Pretoria, South Africa.

Elston, W. E. 1995. Bushveld Complex and Vredefort Dome: Case for multiple impact origin. *Extended Abstracts of the Centennial Geocongress* (Edited by Barton, J. M. and Copperwaite, Y. E.) pp504-507. *Geological Society South Africa*, Johannesburg.

Fourie, P. J. 1969. Die Geochemie van granitiese Gesteentes van die Bosveldstollingskompleks. *D. Sc. dissertation* 290p. University of Pretoria, Pretoria, South Africa.

Groves, D. and McCarthy, T. S. 1978. Fractional crystallization and the origin of tin deposits in granitoids. *Mineralium Deposita* 13, 11-26.

Hall, A. L. 1932. The Bushveld Igneous Complex in the central Transvaal. *Memoir Geological Survey South Africa* 28, 560p.

Harmer, R. E. and Sharpe, M. R. 1985. Field relations and strontium isotope systematics of the marginal rocks of the eastern Bushveld Complex. *Economic Geology* 80, 813-837.

Hartzer, F. J. 1994. Geology of Transvaal inliers in the Bushveld Complex. *Ph. D. thesis* 363p. Rand Afrikaans University, Johannesburg, South Africa.

Hatton, C. J. 1989. Densities and liquidus temperatures of the Bushveld parental magmas as constraints on the formation of the Merensky Reef in the Bushveld Complex, South Africa. In: *Magmatic Sulphides - the Zimbabwe Volume* (Edited by Prendergast, M. D. and Jones, M. J.) pp87-94. Institute for Mining and Metallurgy, London.

Hatton, C. J. 1995a. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. *Journal African Earth Sciences* 21, 571-577.

Hatton, C. J. 1995b. The Bushveld Complex - Product of interaction among magmas derived from a mantle plume. *Communications Geological Survey Namibia* 10, 93-98.

Hatton, C. J. and Schweitzer, J. K. 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. *Journal African Earth Sciences* 21, 579-594.

Hatton, C. J. and Sharpe, M. R. 1989. Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: *Boninites and related rocks* (Edited by Crawford, A. J.) pp299-311. Unwin Hyman, London.

Kleeman, G. J. 1985. The geochemistry and petrology of the roof rocks of the Bushveld Complex, east of Groblersdal. *M. Sc. thesis* 178p. University of Pretoria, Pretoria, South Africa.

Kleeman, G. J. and Twist, D. 1989. The compositionally zoned sheet-like granite pluton of the Bushveld Complex: Evidence bearing on the nature of A-type magmatism. *Journal Petrology* 30, 1383-1414.

Kruger, F. J. 1994. The Sr-isotope stratigraphy of the western Bushveld Complex. *South African Journal Geology* **97**, 393-398.

Lenthall, D. H. and Hunter, D. R. 1977. The geology, petrology, and geochemistry of the Bushveld granites and felsites in the Potgietersrus tin-field. Economic Geology Research Unit (EGRU), University of the Witwatersrand, *Information Circular* 110, 91p.

Lombaard, B. V. 1932. The felsites and their relations in the Bushveld Complex. *Transactions Geological Society South Africa* 37, 5-52.

McCarthy, T. S. and Fripp, R. E. P. 1980. The crystallization history of a granitic magma as revealed by trace element abundances. *Journal Geology* 88, 211-224.

McCarthy, T. S. and Hasty, R. A. 1976. Trace element distribution patterns and their relationship to the crystallization of granite melts. *Geochemica Cosmochemica Acta* 40, 151-158.

Rhodes, R. C. 1974. Petrochemical characteristics of the Bushveld granite and Rooiberg felsite. *Transactions Geological Society South Africa* 77, 93-98.

Rhodes, R. C. and Bornhost, T. J. 1975. Application of discriminant function analyses to the felsic rocks of the Bushveld Complex, South Africa. *Lithos* 8, 19-198.

Robb, L. J., Robb, V. M. and Walraven, F. 1994. The Albert Silver Mine revisited: towards a model for polymetallic mineralization in granites of the Bushveld Complex, South Africa. Economic Geology Research Unit (EGRU), University of the Witwatersrand. *Information Circular* 277, 25p.

Sawkins, F. J. 1984. *Metal deposits in relation to plate tectonics* (Edited by Wyllie, P. J.) pp158-176. Springer-Verlag, Berlin.

Schweitzer, J. K. and Hatton, C. J. 1995a. Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex. *Extended Abstract of the Centennial Geocongress* (Edited by Barton, J. M. and Copperwaite, Y.E.) pp532-535. *Geological Society South Africa*, Johannesburg.

Schweitzer, J. K. and Hatton, C. J. 1995b. Chemical alteration in the roof rocks of the Bushveld Complex. *Economic Geology* 90, 2218-2231.

Schweitzer, J. K., Hatton, C. J. and de Waal, S. A. 1995a. Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Supergroup: a proposed new subdivision. *South African Journal Geology* 98, 245-255.

Schweitzer, J. K., Hatton, C. J. and de Waal, S. A. 1995b. Economic potential of the Rooiberg Group - volcanic rocks in the floor and roof of the Bushveld Complex. *Mineralium Deposita* 30, 168-177.

Sharpe, M. R. 1985. Strontium Isotope evidence for preserved density stratification in the main zone of the Bushveld Complex, South Africa. *Nature* **316/11**, 119-126.

Sharpe, M. R., Bahat, D. and von Gruenewaldt, G. 1981. The concentric elliptical structure of feeder sites to the Bushveld Complex and possible economic implications. *Transactions Geological Society South Africa* 84, 239-244.

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South African Committee for Stratigraphy (SACS) 1980. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. *Geological Survey South Africa, Handbook* **8**, 633p.

Taylor, S. R. 1964. Abundance of chemical elements in the continental crust: a new table. *Geochemica Cosmochemica Acta* **28**, 1273-1285.

Taylor, S. R. and McLennan, S. M. 1985. *The continental crust: its composition and evolution*. 312p. Geoscience Texts, Blackwell Scientific Publications, Oxford, London, Edinburgh.

Thompson, R. N. and Gibson, S. A. 1991. Subcontinental mantle plumes, hotspots and pre-existing thinspots. *Journal Geological Society, London* **148**, 973-977.

Twist, D. and French, B. M. 1983. Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite. *Bulletin Volcanology* **46**, 225-242.

Twist, D. and Harmer, R. E. 1987. Geochemistry of contrasting siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for tectonic setting diagrams. *Journal Volcanology Geothermal Research* 32, 83-98.

Von Gruenewaldt, G. and Harmer, R. E. 1992. Tectonic setting of Proterozoic layered intrusions with special reference to the Bushveld Complex. In: *Proterozoic Crustal Evolution* (Edited by Condie, K. C.) pp181-213. Elsevier Scientific Publishers, Amsterdam.

Walraven, F. 1982. Textural, geochemical and genetic aspects of the granophyric rocks of the Bushveld Complex. *Ph. D. thesis* 251p. University of the Witwatersrand, Johannesburg, South Africa.

Walraven, F. 1985. Genetic aspects of the granophyric rocks of the Bushveld Complex. *Economic Geology* 80, 1166-1180.

Walraven, F. *In press*. Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. *Chemical Geology Isotope Geosciences*.

Walraven, F. and Hattingh, E. 1993. Geochronology of the Nebo Granite, Bushveld Complex. *South African Journal Geology* **96**, 31-41.

Walraven, F., Kleeman, G. J. and Allsopp, H. L. 1985. Disturbance of trace element or isotope systems and its bearing on mineralization in acid rocks of the Bushveld Complex, South Africa. *Conference on High Heat Production Granites (HHP), Hydrothermal Circulation and Ore Genesis, Institute Mineralogy Metallurgy*, St. Austell, Cornwell, pp393-408.

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The basal portion of the Rooiberg Group, South Africa: the onset of Bushveld magmatism

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The basal portion of the Rooiberg Group, South Africa: The onset of Bushveld magmatism

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Abstract

The 2.05 Ga Bushveld Complex is a short-lived event (< 7Ma) containing volcanic rocks, granites, granophyres and layered intrusives. The short-lived nature is compatible with a meteorite impact or a mantle plume. Features at the base of the volcanic pile, the Rooiberg Group, place strong constraints on these possible origins.

The Rooiberg Group is a predominantly siliceous volcanic sequence that covers an area of at least 40 000 km^2, with extrusive volumes in excess of 100 000 km^3. The Dullstroom Formation, the lowermost unit of the Rooiberg Group, is the first surface expression of Bushveld magmatism, and the Formation is best exposed along the southeastern perimeter of the Complex. This Formation overlies unconformably the predominantly sedimentary rocks of the Transvaal Supergroup (>2.2 Ga). Erosional remnants of distal Dullstroom deposits are preserved in floor-originated fragments in the central Bushveld Complex. Dullstroom volcanic rocks are also associated with the Molopo Farms Complex, Botswana, more than 200 kilometers towards the west of the Bushveld Complex.

A mature sand sheet, which was unconsolidated at the onset of Dullstroom volcanism, developed along the relatively flat unconformity above the Transvaal sediments. Localised depressions are superimposed on the unconformity, and are inferred to have formed in the vicinity of eruption centres.

Volcanism started abruptly with the widespread emplacement of Low-Ti basaltic andesites (average TiO_2 = 0.62wt.%), accompanied by debris flow deposition. Much of the debris

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originated from the underlying unconformity sand sheet. Within the Low-Ti basaltic andesites two compositionally distinct magmas are encountered, and these are linked to different eruption centres. Initial Low-Ti basaltic andesite eruption was followed by local extrusion of rhyolite lava flows, close to the inferred eruption centres. These rhyolites are up to 200m thick, are strongly flow-folded, and have large eruptive volumes (>20 km^3). Initial rhyolite eruptions are the least siliceous and flowed furthest, up to 7 km. Minor, discontinuous sedimentary intercalations and pyroclastic flows are preserved in the basal Low-Ti basaltic andesite/rhyolite/debris flow association.

Sedimentary intercalations are almost completely absent above the stratigraphic level of the basal rhyolites. There, two new magma types, the High-Ti basalts (average TiO_2 = 1.87wt.%) and the dacitic High-Mg Felsites (average MgO = 1.96wt.%), are intercalated with Low-Ti basaltic andesites.

Features of the initial Bushveld manifestation also include relatively undisturbed sedimentary rocks, interstratified, distinct magma types and sedimentary layers, and lateral compositional and textural variations of initial lava flows, related to distinct eruptive centres. Evaluation of these features suggests that the origin of the Rooiberg Group, and the associated Bushveld components, is best explained by a mantle plume. Findings, taken together with evidence from beyond the present-day exposure of the Bushveld Complex, indicate that the Bushveld plume was positioned towards the north of the present-day Complex. Intraplating of the Kaapvaal Craton from north to south resulted in regional Bushveld magmatism, expressed by several satellite intrusions, and a regional metamorphic event at 2.05Ga.

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1. Introduction

The intracratonic, predominantly volcanic, Rooiberg Group is geographically associated with the mafic Rustenburg Layered Suite (RLS) and siliceous (Rashoop Granophyre and Lebowa Granite Suites) plutonic rocks of the Bushveld Complex (e.g. Twist, 1985; Fig. 1). The Group overlies unconformably sedimentary rocks of the Transvaal Supergroup (Cheney and Twist, 1992), which contain volcanic rocks dated at 2.2 Ga (Cornell et al., 1996). The Rooiberg Group forms an integral part of the Bushveld magmatic event (Hatton and Schweitzer, 1995; Schweitzer et al., 1997). Radiometric ages show that the volcanic, granitic, granophyric and mafic intrusive rocks of the Complex had a life-span of less than 7 Ma, from 2061 to 2054 Ma (Walraven, 1998; Table 1).

Several previous workers have related the Rooiberg Group to a major astrobleme impact event (see Elston, 1995, for review of previous work). For example, Dietz (1961, 1963) suggested that the Rooiberg Group may represent a fallback breccia, which was deposited after crater excavation by a meteorite. Large quartzite xenoliths are often present in the Rooiberg Group at distinct stratigraphic levels (Schweitzer et al., 1995a and b), and these have been interpreted as relict fragments of almost completely melted crater-floor rocks (Rhodes, 1975). The absence of volcanic detritus in sedimentary rocks of the lower Rooiberg Group, above the RLS, was proposed as additional evidence for an impact origin of these rocks by Eriksson et al. (1994).

Other studies have failed to identify any unequivocal shock-metamorphic features (such as shatter cones, pseudotachylites, megabreccias or high pressure minerals) in rocks associated with the Bushveld Complex (French and Hargraves, 1971; Twist and French, 1983).

The Transvaal Supergroup/Rooiberg Group contact was identified as a potential target for tracing impact features (Elston, 1995). The best exposure of this contact is preserved in the southeastern portion of the Bushveld Complex, although its presence has been documented at other localities, even beyond the perimeters of the Complex (Fig. 2). This study concentrates on the previously undocumented basal portion of the Rooiberg Group in the Dullstroom area (Fig. 1), and evaluates its significance for the genesis of the Bushveld Complex.

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2. Geological background

The Bushveld igneous event consists of the intrusive Rustenburg Layered Suite (RLS), the Rashoop Granophyre Suite, the Lebowa Granite Suite (SACS, 1980), and the extrusive Rooiberg Group (Hatton and Schweitzer, 1995). Intrusion of the RLS began with the emplacement of a relatively hot, primitive and siliceous high-Mg basaltic magma that gave rise to the Lower Zone of the RLS. Subsequent crustally contaminated, tholeiitic magmas of the Lower Critical, Upper Critical, and Main Zones were cooler and more dense (Irvine and Sharpe, 1986; Sharpe, 1985; Hatton, 1989; Hatton and Sharpe, 1989; Kruger, 1994; Hatton, 1995, 1996) and were, at the time, sequentially emplaced between the cumulate pile and current residual Lower Zone magma. The intrusive volume of the RLS increases towards the top, in a manner similar to that of the Rooiberg Group (Table 1).

The Rashoop Granophyre Suite was geochemically subdivided and related to three Rooiberg magma types (Hatton and Schweitzer, 1995). The granophyre sheets therefore represent shallow intrusive equivalents of the youngest Rooiberg magmas. Granites of the Lebowa Granite Suite intrude all the other components of the Complex, terminating the Bushveld event. The oldest granites of the Lebowa Granite Suite are comparable geochemically to the youngest rhyolites of the Rooiberg Group, indicating that these are genetically related and derived from a common source (Schweitzer et al., 1997). The huge amounts of intrusive and extrusive rhyolitic magmas of the Complex imply substantial melting of crustal material.

Four magma types are confined to the Dullstroom Formation (Tables 1 and 2) the basal portion of the Rooiberg Group, occurring below the RLS. These are the Low-Ti (LTI) basaltic andesite (Table 3), first rhyolite extrusions (termed Basal Rhyolite, Table 4), High-Mg Felsite (HMF, dacitic in composition; average MgO = 1.96wt.%) and High-Ti (HTI) basalt (average TiO_2 = 1.87wt.%). The three Rooiberg formations overlying the RLS exhibit less textural and compositional diversity, with compositionally-distinct Low-Mg Felsite (LMF) making up the bulk of the Damwal (average MgO = 1.09wt.%), Kwaggasnek (average MgO = 0.66wt.%), and Schrikkloof (average MgO = 0.61wt.%) Formations (Tables 1 and 2, Fig. 1).

Towards the top of the Rooiberg Group an increase in areal

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extent and eruptive volume of the magma types is apparent (Fig. 1, Table 1). Eruptive volumes of 300 000 km^3 over an area of 50 000 km^2 were proposed for the Rooiberg Group by Twist and French (1983), who extrapolated the Rooiberg Group thickness of the Loskop Dam area (Fig. 1, southeastern Bushveld Complex) across the areal extent of the Bushveld Complex. The Rooiberg Group is, however, thickest in the southeastern portion of the Complex, with internal, onlapping unconformities towards the north and northwest (Schweitzer et al., 1995b). We therefore recalculate the eruptive volumes and areal extents of the Rooiberg formations employing average thicknesses of the individual formations, and derive a minimum cumulative eruptive volume of about 110 000 km^3 (Table 1). Nonetheless, the Rooiberg Group still remains one of the largest known accumulation of siliceous volcanic rocks.

3. The Dullstroom Formation: General field description

Dullstroom occurrences associated with the Bushveld Complex have been documented in the Rooiberg- and Makeckaan Fragments, the area north of Pretoria, the Dennilton Dome, and along the southeastern extent of the Complex (Figs. 1 and 2). Sedimentary intercalations are least prominent with the latter, with the volcanic pile being thickest. Dullstroom equivalents are also present beyond the perimeter of the Bushveld Complex, in the Lobatse and Molopo Farms Complex areas (Figs. 1 and 2; Crockett, 1972; Key, 1983; Reichhardt, 1994; Hartzer, 1995). The Molopo Farms Complex intruded into strata equivalent to the Transvaal Supergroup. Uplift and faulting predated the intrusion (2044$\pm$24Ma; Kruger, 1989), potentially synchronous with the Bushveld Complex. Although Dullstroom occurrences associated with the Molopo Farms Complex (Reichhardt, 1994) are not well documented, it is suggested that Dullstroom volcanism extended over an area exceeding 600 kilometers.

The Dullstroom Formation is best exposed in the southeastern portion of the Bushveld Complex (Fig. 1). This occurrence is therefore considered in detail. The described features could well be of regional significance, and this is highlighted where recognised.

In the southeastern Bushveld Complex the Dullstroom Formation is a basalt to rhyolite association (Fig. 3; Tables 1 and 2). Limited field investigations were carried out by Hall

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(1913) and Groeneveld (1968). Together with acidic flows, which were first documented by Groeneveld (1968), highly vesicular lavas with pronounced scoriaceous flow tops (now termed HTI basalts) are a characteristic magma type of the Dullstroom Formation (Sharpe et al., 1983). Some flows of this Formation are recorded to reach thicknesses of 60m (Tankard et al., 1982).

The Dullstroom Formation overlies unconformably the sedimentary rocks of the Steenkampsberg Quartzite and Houtenbek Formations, both part of the upper Pretoria Group, Transvaal Supergroup (Figs. 2 and 3; SACS, 1980). Rocks of the Pretoria Group are preserved in fault-bounded basins that may have developed due to reactivation of Ventersdorp (<2700 Ma, Armstrong et al., 1991) rift zones (Eriksson and Clendenin, 1990). The upper Pretoria Group also contains arkosic sediments (Schreiber et al., 1991), that were deposited under unstable tectonic conditions (Schreiber and Eriksson, 1992). The source areas were positioned to the northeast and east of the present-day exposure (Schreiber et al., 1991) with the most proximal deposits in the north (Schreiber and Eriksson, 1992). Carbonate chert with algal laminations and stromatolitic domes is a prominent rock type in the southern Houtenbek exposures. The Houtenbek Formation has been interpreted as sediment deposited in a supratidal marginal platform environment (Button, 1973, 1976), or in a shallow-lake and wind-tidal flat setting (Schreiber and Eriksson, 1992).

The outcrop of the Dullstroom Formation is sandwiched between the broadly north-south striking gabbroic rocks of the Main Zone of the RLS and the underlying Transvaal Supergroup (Figs. 1 and 3). The northernmost outcrop of the volcanic rocks occurs as a small north-south striking strip and the succession exceeds 2.5km in thickness some 25km to the south, adjacent to the Laersdrif fault (Fig. 3). A primary thickening of the Dullstroom Formation from north to south is suggested by the increasing thickness of individual flow-units and an increase in the number of flows (Fig. 4). To the south, the preserved formation thins gradually, due to its unconformable relationships at the base and top, thinning to 500m near Belfast, some 50km south of the Laersdrif fault. The southernmost exposures of the Dullstroom Formation are covered by sedimentary rocks of the Karoo Supergroup (about 300Ma old).

The N145^{O}E-trending Laersdrif fault divides the volcanic rocks into two sectors. Displacements of 2310m at the base and

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2750m at the top of the Dullstroom volcanic rocks result from rotation along the fault plane. South of the fault, the units dip more steeply (±35° towards the west) than in the northern sector (±15° towards the west), but dips flatten out towards the southernmost outcrop area. Minor faults are developed parallel to the major Laersdrif structure.

The bulk of the Dullstroom succession consists of lava flows. These are intercalated, especially towards the base of the succession, with pyroclastic flows and minor sedimentary and volcaniclastic rocks. The upper portion of the Dullstroom Formation, in contrast, represents a succession of rapidly erupted lava flows, and sedimentary intercalations are almost completely absent.

The different Dullstroom magma types, all lava flows, are interstratified (Figs. 3 and 4). LTI basaltic andesite lavas are present throughout the Dullstroom Formation but decrease in abundance upwards. Towards the base, Basal Rhyolites are intercalated with the LTI basaltic andesites, with HTI basalts and HMF's being absent (Figs. 3 and 4). The Dullstroom succession becomes increasingly siliceous towards the top (Table 2).

An account of metamorphic effects on the primary petrographic and geochemical features of the Dullstroom magma types was provided by Schweitzer and Hatton (1995a and b). Metamorphic grades vary from lower greenschist facies, generally at the base of the succession, to amphibolite/granulite facies at the contact with the mafic rocks of the RLS. Metamorphism had little effect on primary element concentrations but altered primary textures, especially pronounced towards the contact with the RLS.

A description of the basal Dullstroom rock types (Figs. 4 and 5) is provided in the Appendix. Certain field characteristics are photographically documented in Figures 14 a-i, and these are also referred to throughout the text.

4. Nature of basal contact

4.1 Dullstroom Area

A sand sheet situated on the basal unconformity (Fig. 5) contaminated the earliest Dullstroom lavas and pyroclastic flows. A variety of lava and pyroclastic flows are preserved

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above the sand sheet, within the approximately 300m thick basal Dullstroom succession. Pillow structures are absent. Incorporation of the sand sheet into overlying deposits is especially pronounced in three areas (Fig. 3, arrows), on the farms Messchunfontein, Kwaggaskop, and Rietvallei. These areas are associated with debris flows, LTI basaltic andesites, discontinuous volcaniclastic sediments and sedimentary rocks, and Basal Rhyolites. Contamination of initial Dullstroom flows by the underlying sand sheet is evidenced by xenocrystic sand grains in initial flows, sand-filled cracks (Messchunfontein area), and peperites (Kwaggaskop area). Pipe amygdales (e.g. du Toit, 1907; Petrov, 1984) in earliest LTI basaltic andesites suggest that the sand sheet was wet at the time of first magma extrusion. Inspection of the regional map (Fig. 3) indicates that the depressions are spaced at intervals of about 17km.

The lithologies typically associated with Messchunfontein, Kwaggaskop, and Rietvallei, the three areas characterised by depressions (Fig. 3), are generally comparable. Extensive debris flows, which contain volcanic clasts exceeding 1m in length were deposited in close proximity to the depressions. Areal extents of these deposits decrease towards the south (Fig. 5), from Messchunfontein, over Kwaggaskop, to Rietvallei. The unconformity sand sheet is overlain by two to four lava flows of LTI basaltic andesites, intercalated with debris flow deposits beyond the depositional range of the Basal Rhyolites. There a succession of interstratified LTI, HTI and HMF lavas is superimposed (Fig. 5).

4.1.1. Messchunfontein depression

Deposits at Messchunfontein (Figs. 3 and 5) show pronounced changes in strike and dip relative to the surrounding areas. Several faults locally disrupt the strike of the basal layers (Fig. 6a). Units confined to the depression are LTI basaltic andesites, volcaniclastic sediments and shales (Fig. 14a), and an overlying debris flow (Figs. 14b and c).

The floor of the Messchunfontein depression is formed by coarse-grained quartzite (Fig. 5), representing the basal unconformity sand sheet. The 100m thick sequence that lies above the sand sheet consists of volcaniclastic quartzite, in which randomly-oriented planar cross-beds have wavelengths of about meter-size and angles of up to 30^{o}. These cross-beds suggest a north to south flow direction (G. Germs, pers.

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communication, 1996). Discontinuous LTI basaltic andesite and volcaniclastic shale are intercalated with volcaniclastic quartzite. The latter is overlain by a sequence that commences with LTI basaltic andesite, followed by thick debris flow deposits containing three distinct layers of volcaniclastic shale. LTI basaltic andesites contain quartzite and shale fragments, derived from the underlying Transvaal Supergroup (Figs. 14d and e).

Outside the bounds of the depression, two lava flows of LTI basaltic andesite underlie the debris flow and one rests on top. Pipe amygdales, consisting of tubular concentrations of gas bubbles, are common in basal LTI basaltic andesites where they are bent towards the south. The pipe amygdales formed when the lava transgressed over the wet sand sheet and gas or steam bubbles penetrated upwards through the flowing lava (Waters, 1960; MacDonald, 1967; Wyatt, 1976). The orientation of these pipe amygdales, observed over many kilometres, together with the southward thinning of the lava flows, suggests a north to south flow direction.

Twenty readings of the longest axes of volcanic fragments (Fig. 14c) were taken at individual outcrops approximately every 200m along strike of the debris flow (Fig. 6), to determine any size variations relative with distance to the depression. The clasts appear to increase in size towards Messchunfontein from an average of 0.7cm to about 10cm at a point immediately south of the depression. There the largest clasts exceed 0.5m in size. The proportion of blocky fragments increases in accordance with average clast sizes. At the southernmost outcrops of the debris flow, quenched rhyolite fragments are more common than basaltic andesite material, but the latter increase in frequency towards the north. In common with the underlying LTI basaltic andesite lavas, a north to south flow direction is indicated for the debris flow deposit.

Well laminated volcaniclastic shales (Fig. 14a), interbedded with the volcaniclastic sediments, the debris flow and discontinuous LTI basaltic andesites are restricted within the bounds of the depression.

The Basal Rhyolite - Messchunfontein Area: The Basal Rhyolite is on average 110m thick, but it attains a maximum thickness of 140m some 1.5km south of Messchunfontein and then decreases in thickness to pinch out some 5.5 km further towards the south (Fig. 6a). Taking an average thickness of 100m and considering

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that the rhyolite covered an area of 200km^2, the estimated extrusive volume is 20 km^3. The lowest portion of the rhyolite is pale grey, and becomes even paler upwards whilst simultaneously becoming enriched in amygdales (Fig. 14f). The central part of the flow is strongly spherulitic. Amygdales become increasingly more common in the uppermost portion of the lava, until at the contact with the overlying LTI basaltic andesite, the Basal Rhyolite is strongly quartz-amygdaloidal. The flow-top of the Basal Rhyolite becomes increasingly brecciated and irregular southwards; simultaneously, the extent of autobrecciation in the interior of the flow becomes greater. These observations are compatible with increasing degrees of cooling away from Messchunfontein, i.e. from north to south.

A thin section traverse through the Basal Rhyolite considers the average length and width of quenched quartz plates (Fig. 7). This, in combination with the field and geochemical evidence enables the identification of cooling units. Thinnest quartz plates (average width < 0.17mm) occur at the base of the rhyolite and in areas of autobrecciation. Relatively wider plates are present in the interior and in the upper portion. The Basal Rhyolite may be geochemically subdivided into a bottom and a top portion (see 5. Geochemical characteristics of the basal volcanic succession). The weight of evidence suggests that the bottom portion extruded as one sheet. A horizon of autobrecciation, associated with thin quartz plates is intercalated in the geochemically distinct top portion (Table 4) of the Basal Rhyolite, implying that this portion extruded as two, geochemically homogeneous sheets (Fig. 7). Wide quartz plates (average = 0.4mm) at the upper Basal Rhyolite/LTI basaltic andesite contact could have resulted from LTI basaltic andesite extrusion shortly after the formation of the Basal Rhyolite. This is supported by comparable compositions of LTI basaltic andesites beneath and above the Basal Rhyolite (data not shown here but are available on request), and the incorporation of brecciated rhyolite material into the lower portion of the LTI lava.

Cracks filled with coarse, quartzo-feldspathic detrital material are widespread within the Basal Rhyolite close to the depression (Fig. 14g), but not elsewhere. Beyond the depression, detrital material also occurs as dismembered and rotated fragments, generally 10cm in diameter, surrounded by concentrically arranged, flattened amygdales. These structures formed by fragmentation and rotation of the sand-filled cracks

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during flow of the rhyolite.

Within the body of the Basal Rhyolite, elongated, stretched amygdales, alternating layers of spherulites and microlites, and rotated sand fragments are taken as indicators of the flow direction. In the vicinity of Messchunfontein, the rhyolite is deformed on a micro (cm) and macro (tens of metres) scale (Figs. 8 and 14h). Although most of the flow was from north to south, as indicated by stretched amygdales, and thinning of the lava flow towards the south of Messchunfontein, a local change in direction is suggested west of the depression (Fig. 6a). Orientation of fold axes parallel to the north-south strike of the rhyolite suggests that an east-west pressure constraint was applied to the viscous lava (Fig. 8b). The minor folds present within the contorted flow increase progressively in both amplitude and frequency when traced westwards. This is also considered to be diagnostic of flow direction. The resultant overall flow close to the depression was therefore from the northeast to the southwest.

One lobe of the Basal Rhyolite is exposed 7 km south of the depression (Figs. 6a and 9). The surface of the lobe is irregular, and flow-top breccia, debris and crust that formed on top of the flow are preserved, similar to the lava flow-front described by Borgia et al. (1983). Four cross sections through lava toes, referred to as folds in the following, are identified; these folds are marked by crusts of debris and zones of stretched and oriented lithophysae and amygdales beneath these crusts. Folds are interpreted to have formed due to relatively low and high viscosities in the central and marginal areas of the rhyolite, respectively. The main fold (Fig. 9, fold I) is exposed in the northeastern part of the front and stretched lithophysae and amygdales formed for approximately 28m at the bottom of the flow. Blocks of debris and parts of the crust were apparently dragged along the base during high viscosity flowage. Two minor folds developed near the edge of the lobe (Fig. 9, folds II and III), each accompanied by debris and fragments of the crust in the centres of the folds. The main fold (Fig. 9, fold I) draped over a large area of the floor; then, as magma broke through it, the second and third folds formed with a small volume of magma breaking through the third fold to the southern limit of the lobe. Continued flow of magma allowed escape of magma through the top surface and formation of the fourth fold (Fig. 9, fold IV).

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The rhyolite and debris flows interfinger, in the vicinity of the Laersdrif fault (Figs. 3 and 6a), with LTI basaltic andesite lavas. Pipe amygdales, up to 1.60m long and 7cm wide, indicate a flow direction of these andesites from south to north.

4.1.2. Kwaggaskop depression

As in the Messchunfontein area, volcaniclastic sediments, debris flows and a Basal Rhyolite are preserved in the Kwaggaskop area (Figs. 3, 5 and 10). Algal stromatolites of the Houtenbek Formation unconformably underlie the sand sheet (Fig. 10). The sand sheet, in turn, is overlain by a massive debris flow and/or a LTI basaltic andesite. The Basal Rhyolite, locally under- and overlain by a debris flow, attains a maximum thickness of 210m and its lobe is observed some 5km towards the north of Kwaggaskop (Fig. 10). This Basal Rhyolite exhibits macroscopic and microscopic features comparable to the Messchunfontein Basal Rhyolite. The pocket-surfaced debris flow (Fig. 14b) overlying the Kwaggaskop Basal Rhyolite terminates some 100m towards the north of the rhyolite lobe. This debris flow is overlain by LTI basaltic andesite which, in turn is overlain by HTI basalt (Fig. 10).

Pipe amygdales in initial LTI basaltic andesites are inclined towards the north, indicative of northward flowage. Flow direction indicators in the Basal Rhyolite, similarly, suggest lava propagation towards the north. Clasts of basement rocks and LTI basaltic andesite in the debris flow are largest close to the Kwaggaskop depression. Spectacular peperites, resulting from interaction between initial LTI basaltic andesite and the unconformity sand sheet are developed close to, and in the vicinity of Kwaggaskop (Figs. 5 and 14i). They formed due to shallow invasion of the initial lava flow into the, probably water saturated, sand sheet. This resulted in the brecciation of the flow, with blocks of lava being surrounded by baked sand. The baked sand intruded the initial lava flow as multiple dykelets (see Walton Jr. and O'Sullivan, 1950, for mechanics of intrusion). The lava blocks are concentrically jointed, similar to the blocks in the Pomona peperites described by Schmincke (1967; see also MacDonald, 1967; Ladnorg, 1976; Boulter, 1993).

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5. Geochemical characteristics of the basal volcanic succession

Some geochemical characteristics of the Rooiberg magma types have been described and summarised by Twist (1985), Hatton and Schweitzer (1995), Schweitzer and Hatton (1995b), and Schweitzer et al. (1995a and b). Palaeoenvironmental reconstruction in an environment as old as the Bushveld Complex is hampered, mainly due to limited, two-dimensional exposures, and metamorphism. We therefore employ immobile element concentrations (Schweitzer and Hatton, 1995b), to provide additional clues for palaeoenvironmental reconstruction. Identification of the petrogenetic processes, such as partial melting, crustal contamination, or fractional crystallisation, causing the observed element variations, will be considered by Schweitzer and Hatton (in prep.).

Although an individual magma type predominates over a stratigraphic interval of some 300m, interstratification of compositionally distinct magmas is apparent (Fig. 11). HMF lava flows predominate in the upper portion of the Dullstroom Formation, where they are intercalated with LTI and HTI lavas. No systematic variations in element concentrations are observed for the individual magma types, implying that fractional crystallisation was not a major process. Towards the base, pyroclastic flow compositions are similar to those of the Basal Rhyolite. Total FeO concentrations are distinct for the magma types so is, to a lesser extent, V. HTI basalts and HMF lavas have high TiO_2 (1.44 to 2.13 wt.%) and SiO_2 (62.93 to 68.73 wt.%), respectively. The magma types have overlapping Zr concentrations.

Comparison of Al_2O_3, MgO and TiO_2 concentrations of initial LTI basaltic andesite lavas from the Kwaggaskop and Messchunfontein regions (Tables 3 and 4) reveals that the Messchunfontein lavas generally have higher TiO_2 and Al_2O_3 (Fig. 12a). MgO contents tend to be higher in initial Kwaggaskop LTI basaltic andesites (Fig. 12b). LTI basaltic andesites from the Makeckaan and Rooiberg Fragments (Fig. 1) exhibit compositional affinities to the stratigraphically corresponding lavas from the Messchunfontein and Kwaggaskop areas, respectively (Figs. 12a and b, Table 3). The geochemical characteristics confirm the field evidence; the distinctly different compositions of the Kwaggaskop and Messchunfontein LTI basaltic andesites support the notion that these lavas originated from separate eruption centres.

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The Messchunfontein Basal Rhyolite may be compositionally subdivided into a bottom and top portion (Figs. 13a and b; Table 4). When considered in conjunction with the petrographic evidence (Fig. 7) it can be deduced that the Messchunfontein Basal Rhyolite erupted as two compositionally distinct flow units. The bottom, least siliceous portion of the rhyolite flowed furthest and its lobe is exposed some 7 km towards the south of Messchunfontein (Figs. 6a and 9). The Kwaggaskop Basal Rhyolite is equivalent in composition to the lowermost Basal Rhyolite from Messchunfontein. The Basal Rhyolite from the Makeckaan Fragment is similar in composition to the top portion of the Messchunfontein Basal Rhyolite (Figs. 13a and b), suggesting that Basal Rhyolite compositions are more evolved towards the north.

6 Discussion

The Bushveld igneous event commenced with the deposition of the basal Dullstroom succession (Hatton and Schweitzer, 1995). Field and geochemical characteristics of this succession are utilised to better understand Bushveld genesis. The relatively short time interval (<7Ma) during which the Bushveld Complex evolved suggests that a meteorite impact or a mantle plume were the triggering mechanism. Proposals in favour of an impact origin for the Bushveld Complex obviously considered the Rooiberg Group as an integral part of the Bushveld event. Opponents of this origin argue that the Rooiberg Group is older than the intrusive mafic and siliceous rocks of the Complex (e.g. Harmer and Farrow, 1995). We are in agreement with the proposal that the volcanic rocks and the Bushveld event are synchronous (Hatton and Schweitzer, 1995; Schweitzer et al., 1997).

Elston (1995) presents the most recent view on the impact origin of the Bushveld Complex, also proposing that the Vredefort Dome is a time equivalent (i.e. multiple impact). The meteorite impact genesis for the Bushveld (Elston, 1995), is summarised as follows: Only the periphery of the Bushveld basins is exposed and shock phenomena should not be expected in autochthonous rocks, with heat phenomena taking precedence over shock phenomena. The Crocodile River and Marble Hall Fragments (south of the Rooiberg and Makeckaan Fragments, respectively; Fig. 1) are interpreted as autochthonous segm ıts of the walls

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of transient impact cavities. Overturned strata, megabreccias and folding are present in these fragments. The Rooiberg and Makeckaan Fragments (Fig. 1) are interpreted as allochthonous blocks that slid into the transient cavities as their unstable walls collapsed. Makeckaan quartzite is found in various stages of melting. Rooiberg rhyolites are suggested to have formed at temperatures of at least 1 200 ^{O}C. Element concentrations of HMF's, and to a lesser degree those of the Basal Rhyolites, are similar to Proterozoic, upper crustal sediments (Hatton and Schweitzer, 1995), as defined by Taylor and McLennan (1985). This led Elston (1995) to suggest that these lavas are impact melts.

The regionally developed, mature unconformity sand sheet overlies a relatively undisturbed unconformity surface. The sand sheet would have been severely disturbed due to a meteorite impact. However, we observe an abrupt onset of volcanism, interacting with a previously undisturbed sand sheet. The rock assemblage at the base of the Rooiberg Group is diverse and complex. Individual lava flows, in addition, exhibit proximal/distal relationships. A relatively homogeneous impact melt is absent. HMF's possess upper crustal compositions but this magma type extruded only in the upper portion of the Dullstroom Formation, and not at the base. Siliceous magma types exhibit textures attributed to supercooling throughout lavas up to 200m in thickness. Considering an impact event, supercooling is likely to only have occurred close to the crater floor. Sedimentary intercalations, present in the lower Dullstroom and overlying Damwal, Kwaggasnek and Schrikkloof Formations are, in addition, not in accord with a rapid impact origin of the Rooiberg Group. We have inferred localised eruption centres, only some 20 km apart (e.g. Figs. 12 and 13). This is difficult to reconcile with a meteorite impact. Quartzite fragments in rhyolite flows have been interpreted as crater floor remnants or debris avalanche fragments (Elston, 1995). The two most prominent stratigraphic horizons containing quartzite fragments are defined by the Basal Rhyolites and the rhyolites towards the top of the Kwaggasnek Formation (Schweitzer et al., 1995b). Sedimentary fragments of basement rocks are, in addition, present in the initial eruptions of each new magma type. This evidence suggests that the origin of the quartzite fragments is related to volcanic processes.

The regional occurrence of Bushveld-related rocks would necessitate that the Kaapvaal craton was hit by a meteorite

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swarm at about 2054Ma. Current age dating results suggest that the Vredefort structure is about 30Ma younger than the Bushveld Complex (2024Ma; U/Pb zircon age from pseudotachylites interpreted to date the time of impact, Kamo et al., 1995). This is in accord with the findings by Gibson and Wallmach (1995), i.e. the Bushveld magmatic event metamorphosed the Vredefort area before the formation of the Vredefort structure.

The depressions are interpreted to have formed in the vicinity of inferred eruption centres, representing laterally extensive topographic features that may have formed due to collapse in the vicinity of vent areas e.g. (Aramaki and Ui, 1996), or due to gravity sliding (Roobol et al., 1983). From the two-dimensional view afforded by present-day outcrop it is possible to make some inferences about the original disposition of extrusive centres. The spacing of about 20 kilometres between centres, when extrapolated, suggests that each centre could have fed an area of some 300 km^2. On this basis the 66 000 km^2 surface area of the Bushveld Complex (von Gruenewaldt et al., 1985) could have been covered by lava emanating from approximately 200 extrusive centres. Comparable eruption centre densities are encountered in present-day environments (Houghton et al., 1995). Multiplicity of extrusive centres also resulted in compositional, lateral variations (providing scope to even further subdivide individual magma types, Figs. 12 and 13) and varying lava flow features due to distal/proximal relationships.

There is considerable debate on the nature of extensive, voluminous rhyolite flows, such as the Basal Rhyolite. Fluidal, siliceous lava flows are thought to be characterised by limited areal extents (flow-lengths of about 1 km; Henry et al., 1988; Nakada et al., 1995). However, large volume rhyolite lava flows covering great areal extents have also been described (e.g. Manley, 1995). High eruption rates of rhyolititc lava flows could reflect high temperatures, high alkali or volatile contents, and enhanced fluor (e.g. Creaser and White, 1991). Ash flows, alternatively can, through viscous laminar flow just before halt, destroy all evidence of shards and pumice, so that they resemble lava flows (e.g. Schmincke and Swanson, 1967; Elston and Smith, 1970).

It has been suggested that high temperature and large-volume rhyolites may be common in plume related settings (e.g. Parson et al., 1994; Manley, 1995), such as the Yellowstone area (e.g. Ekren et al., 1984; Bonnichsen and Kauffman, 1987; Honjo et

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al., 1992). Field and geochemical features of the upper Rooiberg rhyolites also compare favourably to other high volume flows, such as those of the Karoo Supergroup (Twist and Bristow, 1990). Irregular flow tops, increasing degrees of autobrecciation away from the depressions, flow-banding and folding, elongated amygdales, and the absence of shards and pumice fragments and shattered crystals in the Basal Rhyolites suggest that they erupted as fluidal lava flows with eruptive volumes of about $20km^3$. The Basal Rhyolites are therefore taken as another example of extensive, high volume rhyolite lavas genetically linked to plume activity.

Taking all evidence, we prefer to view Bushveld genesis in the light of a mantle plume. The plume or initiation model predicts that uplift occurs 10-20 Ma before the onset of volcanism (e.g. Campbell and Griffiths, 1990; Griffiths and Campbell, 1990; Parson et al., 1994; Rainbird, 1993). The relatively undisturbed, uniform nature of the unconformity sand sheet and the absence of a hotspot track argue against a plume head being positioned beneath, or in close proximity to, the Complex. Features observed in the uppermost Pretoria Group sediments (Eriksson and Clendenin, 1990) are therefore unrelated to mantle plume uplift. The time-gap between the Transvaal Supergroup and the onset of Bushveld magmatism is implied to be significant. North to south flow direction in the sand sheet and unconformities in the overlying Rooiberg Group that onlap towards the north and northwest (Schweitzer et al., 1995a), suggest that crustal uplift in response to an ascending mantle plume occurred towards the north of the present day outcrop of the Bushveld Complex. Uplift along the Thabazimbi Murchison Lineament, north of the Complex, is also proposed by Uken and Watkeys (1995). It is suggested that the plume magma intraplated the Kaapvaal Craton from north to south, also melting the huge amounts of crustal material. The intraplating event coincides with the magmatic event that metamorphosed the Vredefort structure (Gibson and Wallmach, 1995; Merkle and Wallmach, 1977), and was also responsible for the formation of the Molopo Farms Complex and several other Bushveld satellite intrusions (Coetzee and Kruger, 1989; Stettler et al., 1998).

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7. Summary

No detailed studies were previously performed on the Dullstroom Formation, the basal portion of the Rooiberg Group. The field evidence presented here, viewed in conjunction with recently published geochemical studies (Hatton and Schweitzer, 1995; Schweitzer et al., 1995a and b; Schweitzer and Hatton, 1995a and b; Walraven, 1998) reveals that the basal Rooiberg succession provides clues towards an improved understanding of the genetic processes involved in Bushveld magmatism.

The basal Rooiberg unconformity formed during an extended period of erosion that was succeeded by the regional development of the mature sand sheet during a prolonged period of quiescence (Fig. 5). Eruption of the initial LTI basaltic andesites was preceded by local subsidence, expressed by three depressions at the base of the Dullstroom succession. The depressions are characterised by increasing subsidence from south to north, and are interpreted to have developed close to eruption centres. Field and geochemical evidence reveal that early magmas of distinct compositions flowed away from the depressions.

The onset of Bushveld magmatism is manifested by a complex succession of lavas, pyroclastic flows, and associated minor sedimentary intercalations. Interaction of the initial, aphyric lavas and pyroclastic flows, with the sand sheet was important. Rhyolites possess large extrusive volumes and a maximum flow distance of 7 km is recorded.

Volcanic activity succeeding the basal Dullstroom event was short-lived, with areal extents and extrusive volumes increasing towards the top of the Rooiberg Group (Table 1). The extrusive rocks are proposed to be contemporaneous with the intrusions of the mafic Rustenburg Layered Suite (Hatton and Schweitzer, 1995), with the Bushveld igneous event being concluded by the intrusion of granites belonging to the Lebowa Granite Suite (Schweitzer et al., 1997).

Considering all evidence, we prefer to relate the Rooiberg Group, and the remainder of the Bushveld Complex, to a mantle plume. Field evidence suggests that the plume was positioned towards the north of the present-day outcrop of the Complex, and that the Bushveld magmatic event affected a large portion of the Kaapvaal craton. This points towards a regional intraplating event at about 2054Ma.

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APPENDIX

Description of rock types and similar stratigraphic successions in other areas of the Bushveld Complex

The following describes the rock-types under consideration, in ascending stratigraphic order, together with some petrographic (as observed in the area of lower greenschist facies metamorphism) and depositional features.

The Sand sheet

A mature quartzite forms the base of the Dullstroom Formation. This quartzite represents a laterally-extensive sheet that formed over a long period of time and covered large areas of the unconformity/land surface. Accidental sand grains and sand breccias in the initial lavas and pyroclastic flows leave little doubt that the quartzite was unconsolidated at the time of first magma extrusion.

Volcaniclastic sediments

Volcaniclastic quartzites, exhibiting a variety of sedimentary structures are confined to three depressions at the base of the Dullstroom Formation (Fig. 3, arrows). These quartzites consist predominantly of rounded to subrounded quartz grains with minor volcanic material contained in the matrix, and occasional LTI basaltic andesite fragments.

Volcaniclastic shales are restricted to the northernmost depression (Figs. 3, 5 and 6b). They exhibit a variety of sedimentary structures, such as cross-bedding, microripples, folds and dunes (Fig. 14a), locally displaced by microfaults. These faults may be the result of low-frequency earthquakes that have been observed to precede volcanism in other areas (e.g. Rainbird, 1993; Nakada et al., 1995). Volcaniclastic shale thicknesses vary along strike, from less then tens of centimetres to a maximum of four metres. In thin section, these rocks possess variable ratios of volcanic to sedimentary material. Accidental quartz fragments are similar to those in the debris flow (see below). The volcanic matrix consists predominantly of plagioclase, amphibole and quartz. Plagioclase

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and amphibole needles are in places broken. Opaque minerals may locally cluster into stringlets. These rocks are interpreted to have been generated by reworking of volcanic material. Further studies may consider their formation as pyroclastic flows, for example as base surges (e.g. Fisher and Waters, 1970). It is noted that sedimentary rocks have been reinterpreted as pyroclastic surge deposits in younger, and less complex environments (e.g. McDonough et al., 1984) than the setting considered here.

Debris flows

Pyroclastic flows are widespread, but confined to the basal Dullstroom succession. They are predominantly debris flow deposits (>90%) that range from clast- to matrix-supported. Angular fragments of the sedimentary basement rocks (quartzite, shale, and limestone; Fig. 14b) and Dullstroom volcanic rock (mainly of LTI basaltic andesite; Fig. 14c), range from a few millimetres to sizes exceeding 1 metre. The debris flows are unsorted, completely free of sedimentary structures, and exhibit varying clast/matrix ratios along strike. Subrounded to rounded quartz grains, similar to those forming the sand sheet, are set in a microlitic, volcanic matrix. The proportion of quartz grains to matrix is highly variable. Zoned zircon grains are occasionally observed.

Low-Ti (LTI) basaltic andesites

LTI basaltic andesites are typically quartz amygdaloidal. Lower lavas frequently contain xenoliths of basement rocks (quartzite, shale and limestone; Figs. 14d and e) and accidental quartz grains. There is a distinction between basal and upper lava flows of this magma type. The basal lavas are aphyric with original textures generally well preserved (Schweitzer and Hatton, 1995b). Subophitic textures of twinned plagioclase and needle-like, swallow-tailed actinolite/tremolite crystals (both generally <0.3mm), are set in a microlitic matrix. Opaque minerals do not exceed 2%. The equigranular groundmass consists predominantly of micrographic intergrowths of plagioclase, amphibole and interstitial quartz.

In contrast to the basal flows upper lava flows are typically porphyritic (phenocryst contents generally less than 10%) and commonly contain apatite and magnetite as inclusions

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within other phenocryst phases. Plagioclase (labradorite/bytownite, generally 0.5mm in size), and amphibole (<0.6mm) phenocrysts also form glomerocrysts.

Basal Rhyolites

Quartz- and amphibole-amygdaloidal (Fig. 14f), flow-banded (Fig. 14h), and spherulitic rhyolites are found locally at the base of the Dullstroom Formation. In outcrop, these flows do not exceed 7 km in strike length. Fragments of sedimentary basement rocks and sand sheet material (Fig. 14g) are found throughout these rhyolites.

In thin section, quenched, polycrystalline quartz plates from microlites (<0.1mm) to 1mm plates are common; phenocrysts are absent. The quartz plates are usually straight but can sometimes be broken or bent and may represent pseudomorphs after tridymite (Green, 1970; Rhodes, 1975; Twist and French, 1983). Small, randomly oriented quartz plates are abundant in the spherulites, which are spherical to subspherical. Long, apparently quenched, quartz plates transect these spherulites. Plagioclase forms radiating fans in the strongly devitrified matrices. Opaque minerals occur as accessory phases.

Sedimentary rocks

Minor, lensoid and thin beds of pure to impure quartzite, feldspathic quartzite, arkose and shale are occasionally intercalated within the basal Dullstroom succession. These beds are also deposited on the irregular surfaces of Basal Rhyolites.

High-Ti (HTI) basalts

HTI basalts are characteristically quartz-amygdaloidal and have brecciated (strongly amygdaloidal, angular fragments) flow-tops. Sedimentary and volcanic fragments are found within the lowermost lavas. This magma type extends for significant strike lengths. HTI lavas are more porphyritic (phenocryst contents up to 20 Vol.%) than LTI basaltic andesites. Plagioclase (<1mm) and amphibole (<0.4mm) occur in glomeroporphyritic clusters. Magnetite phenocrysts, generally less than 0.2mm in size, are abundant.

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High-Mg Felsite (HMF)

HMF's are predominantly aphyric, amphibole-amygdaloidal lavas with granophyric textures. Like the Basal Rhyolite they contain oriented, swallow-tailed and polycrystalline quartz plates as the main constituent. In plane polarised light the plates are seen to be surrounded by rims of granophyric material. The quartz plates are sometimes broken or bent. Apatite is a common mineral phase in the devitrified groundmass, which consists of micrographic intergrowths of plagioclase and quartz. Quartz forms an intimate intergrowth with plagioclase in spherulites. Opaque minerals are found as accessory phases.

Rock types in the Makeckaan and Rooiberg Fragments

The fragments consider sedimentary and volcanic rocks of the Bushveld floor and roof succession, entirely imbedded by granite. Andesitic lava flows are intercalated with sediments of both the Rooiberg and Makeckaan Fragments (Fig. 1). These lavas correspond stratigraphically and chemically with the LTI basaltic andesites of the lower Dullstroom Formation (Truter, 1949; Visser, 1969; Eriksson et al., 1993; Hartzer, 1995; Schweitzer et al., 1995b; Fig. 12). Both fragments are characterised by an abrupt transition from the basal sediment/lava association into the overlying rhyolite sequence (Rhodes, 1972; Stear, 1977; Fig. 2).

Elston (1995) considered the Rooiberg and Makeckaan Fragments as allochthonous blocks that slid into the craters as the unstable impact crater wall collapsed. Alternatively, these fragments have been suggested to represent palaeohighs, preserved in eastern and western sub-basins separated by a central palaeohigh (Eriksson and Clendenin, 1990; Hartzer, 1995).

Makeckaan Fragment

The highly faulted rocks of the Makeckaan Fragment (Fig. 1) are part of the roof of the Bushveld Complex (Wagner, 1921, 1927). Mellor (1905) first recognised the felsite occurrences within the fragment, which form part of the Makeckaan Formation (Rhodes, 1972), a correlative of the lower Rooiberg Group (Eriksson et al., 1993; Schweitzer et al., 1995b; Hartzer, 1995). The Makeckaan Formation consists of a variety of

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sedimentary rocks intercalated with mafic and siliceous volcanic rocks (Rhodes, 1972; Hartzer, 1995). Unconformable relationships between these rocks and the underlying Transvaal Supergroup are observed (Hartzer, 1995).

Peperites, similar to those observed at Kwaggasnek, are developed in the initial LTI basaltic andesite lavas of the Makeckaan Fragment (F. Hartzer, personal communication), implying that the unconformity sand sheet was regionally developed. The LTI basaltic andesite lava of the Makeckaan Formation (Fig. 12) contains phenocrysts of clinopyroxene (<0.3mm), amphibole ($\pm$0.4mm) and minor plagioclase (<0.1mm), intergrown in an ophitic texture, with a matrix of clinopyroxene, amphibole and plagioclase.

The rhyolites of the Makeckaan Fragment correspond, petrographically and geochemically, to the Basal Rhyolites (Schweitzer et al., 1995b; Fig. 13; Table 4). Flow-banding is, in contrast, absent in the Makeckaan Basal Rhyolites. Spherulites weather out as round, pea-sized nodules. Vesicles filled with quartz, calcite and chlorite are common. Lithic, recrystallised quartzite fragments are confined to discrete zones within the Basal Rhyolite. They show all gradations from angular to rounded and range from a couple of centimetres to metres in size. Some quartzite blocks show preserved stratification, such as cross-bedding and ripple marks. The contacts of the quartzite zones with the neighbouring rhyolites are gradational, as are the contacts between lithic fragments and rhyolite.

Rooiberg Fragment

The succession at Rooiberg Hill within the Rooiberg Fragment (Fig. 1) consists of the lower Dullstroom Formation, formerly termed Smelterskop Formation (Stear, 1977; Fig. 2), overlain by the 340m-thick Schrikkloof Formation, both of which have been gently folded into a syncline (Schweitzer et al., 1995b; Hartzer, 1995). Several authors have proposed a conformable relationship of the felsites and the underlying sediments and intercalated andesitic lava flows (Humphrey, 1909; Boardman, 1946; Coertze et al., 1977). In contrast, Schweitzer et al. (1995b) and Hartzer (1995) suggested that the upper Rooiberg Group overlies unconformably the lower Dullstroom succession in the Rooiberg Fragment.

The lower Dullstroom Formation in the Rooiberg Fragment is

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280m thick. It consists of a basal quartzite member, four or five discontinuous feldspathic quartzite units, and occasional tuffaceous shales. The sedimentary rocks were deposited in a fluviatile environment (Stear 1977). LTI basaltic andesite lavas are intercalated with these sedimentary rocks (Fig. 12). The lavas are strongly vesicular, with the vesicles partly filled by quartz, calcite, chlorite and sulphides (pyrite and minor chalcopyrite). Numerous plagioclase phenocrysts (<0.6mm) make up to 30 Vol.% of the rock, and are almost completely replaced by chlorite, calcite and sericite. The groundmass consists of plagioclase, chlorite, calcite, interstitial quartz and opaque minerals.

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References

Aramaki, S. and Ui, T., 1966. The Aira and Ata pyroclastic flows and related caldera and depressions in southern Kyushu, Japan. Bull. Volcanol., 29: 29-47.

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S. and Welke, H.J., 1991. Zircon ion-microprobe studies bearing on the age and evolution of the Witwatersrand triad. Prec. Res., 53: 243-266.

Boardman, L.G., 1946. The geology of a portion of the Rooiberg Tinfields. Trans. Geol. Soc. S. Afr., 49: 103-133.

Bonnichsen, B. and Kauffman, D.F., 1987. Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho. In: J.H. Fink (Editor). The emplacement of silicic domes and lava flows. Geol. Soc. Am. Spec. Pap., 212: 119-145.

Borgia, A., Linneman, S., Spencer, D., Morales, L.D. and Andre, J.B., 1983. Dynamics of lava flow fronts, Arenal volcano, Costa Rica. J. Volcanol. Geotherm. Res., 19: 303-329.

Boulter, C.A., 1993. Comparison of Rio Tinto, Spain, and Guaymas Basin, Gulf of California: An example of a supergiant massive sulfide deposit in an ancient sill-sediment complex. Geol., 21: 801-804.

Button, A., 1973. A regional study of the stratigraphy and development of the Transvaal basin in the eastern and northeastern Transvaal. Ph.D. Thesis, Univ. Witwatersrand, Johannesburg, South Africa, 352pp.

Button, A., 1976. Stratigraphy and relations of the Bushveld floor in the Eastern Transvaal. Trans. Geol. Soc. S. Afr., 97: 3-12.

Campbell, T.H. and Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth Planet. Sci. Lett., 99: 79-93.

Cheney, E.S. and Twist, D., 1992. The conformable emplacement

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. Prec. Res., 52: 115-132.

Coertze, F.J., Jansen, H. and Walraven, F., 1977. The transition from the Transvaal Sequence to the Waterberg Group. Trans. Geol. Soc. S. Afr., 80: 145-156.

Coetzee, H. and Kruger, F.J., 1989. The geochronology, Sr- and Pb-isotope geochemistry of the Losberg Complex, and the southern limit of Bushveld Complex magmatism. S. Afr. J. Geol., 92: 37-41.

Cornell, D.H., Schutte, S.S. and Eglington, B.L., 1996. The Ongeluk Basaltic Andesite Formation in Griqualand West, South Africa: Submarine alteration in a 2222Ma Proterozoic sea. Prec. Res., 79: 101-123.

Creaser, R.A. and White, A.J.R., 1991. Yardea Dacite - Large-volume, high-temperature felsic volcanism from the middle Proterozoic of South Australia. Geol., 19: 48-51.

Crockett, R.N., 1972. The Transvaal system in Botswana: its geotectonic and depositional environment and special problems. Trans. Geol. Soc. S. Afr., 75, 275-291.

Dietz, R.S., 1961. Astroblemes: Scient. Am., 205: 51-58.

Dietz, R.S., 1963. Cryptoexplosion sructures: A discussion. Am. J. Sci., 261: 650-664.

Du Toit, A.L., 1907. Pipe amygdaloids. Geol. Mag., 44: 13-17.

Ekren, E.B., McIntyre, D.H. and Bennett, E.H., 1984. High temperature, large volume, lava-like ash-flow tuffs without calderas in southwestern Idaho. Geol. Soc. Am. Prof. Pap., 1272: 73pp.

Elston, W.E., 1995. Bushveld Complex and Vredefort Dome: Case for multiple impact origin (abstract). Geocongress '95, Centennial, Geological Society of South Africa, April 3-7, Johannesburg, 504-507.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Elston, W.E. and Smith, E.I., 1970. Determination of flow direction of rhyolitic ash-flow tuffs from fluidal textures. Geol. Soc. Am. Bull., 81: 3393-3406.

Eriksson, P.G. and Clendenin, C.W., 1990. A review of the Transvaal Sequence, South Africa. J. Afr. Earth Sci., 10: 101-116.

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., van Deventer, J.L. and Hatton, C.J., 1993. The Transvaal Sequence: an overview. J. Afr. Earth Sci., 16: 25-51.

Eriksson, P.G., Schreiber, U.M., Reczko, B.F.F. and Snyman, C.P., 1994. Petrography and geochemistry of sandstones interbedded with the Rooiberg Felsite Group (Transvaal Sequence, South Africa): implications for provenance and tectonic setting. J. Sed. Res., A64:, 836-846.

Fisher, R. and Waters, A., 1970. Base surge bed forms in maar volcanoes. Am. J. Sci., 268: 157-180.

French, B.M. and Hargraves, R.B., 1971. Bushveld Igneous Complex, South Africa: Absence of shock-metamorphic affects in a preliminary search. J. Geol., 79/5: 616-620.

Gibson, R.L. and Wallmach, T., 1995. Low pressur - high temperature metamorphism in the Vredefort Dome, South Africa: anticlockwise pressure-temperature path followed by rapid decompression. Geol. J., 30: 319-331.

Green, J.C., 1970. Snowflake texture not diagnostic of devitrified ash-flow tuffs: and. Geol. Soc. Am. Bull., 81: 2527-2528.

Griffiths, R.W. and Campbell, I.H., 1990. Stirring and structure in mantle plumes. Earth Planet. Sci. Lett., 99: 66-78.

Groeneveld, D., 1968. The Bushveld Igneous Complex in the Stoffberg area, eastern Transvaal, with special reference to the magnetite seams. D.Sc. Thesis, Univ. Pretoria, South Africa, 165pp.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Hall, A.L., 1913. The geology of the country south-west of Lydenburg. Explanation of Sheet 11 (Lydenburg). Geol. Surv. S. Afr., 38pp.

Harmer, R.E. and Farrow, D., 1995. An isotopic study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. Mineral. Dep., 30: 188-195.

Hartzer, F.J., 1995. Geology of Transvaal inliers in the Bushveld Complex. Ph.D. Thesis, Rand Afrikaans Univ., Johannesburg, South Africa, 363pp.

Hatton, C.J., 1989. Densities and liquidus temperatures of the Bushveld parental magmas as constraint on the formation of the Merensky Reef in the Bushveld Complex. In: M.D. Prendergast and M.J. Jones M.J. (Editors). Magmatic Sulphides - the Zimbabwe Volume, Institute of Mining and Metallurgy, London, pp. 87-93.

Hatton, C.J., 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. J. Afr. Earth Sci., 21: 571-577.

Hatton, C.J., 1996. The Bushveld Complex - Product of interaction among magmas derived from a mantle plume. Communications Geological Survey Namibia: 10, 93-98.

Hatton, C.J. and Sharpe, M.R., 1989. Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: A.J. Crawford (Editor). Boninites and related rocks. London, Unwin Hyman, pp. 299-311.

Hatton, C.J. and Schweitzer, J.K., 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. J. Afr. Earth Sci., 21: 579-594.

Henry, C.D., Price, J.G., Rubin, J.N., Parker, D.F., Wolff, J.A., Self, S., Franklin, R. and Barker, D.S., 1988. Widespread lavalike silicic volcanic rocks of Trans-Pecos Texas. Geol., 16: 509-512.

Honjo, H., Bonnichsen, B., Leehman, W.P. and Stormer, J.C., 1992. Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain. Bull.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Volcanol., 54: 220-237.

Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. and Pringle, M.S., 1995. Chronology and dynamics of a large silicic magmatic system: Central Taupo Zone, New Zealand. Geol., 23: 13-16.

Humphrey, W.A., 1909. On a portion of the Bushveld bordering the Crocodile River and including the Rooiberg tin-field. Geol. Surv., 1908: 102-122.

Irvine, T.N. and Sharpe, M.R., 1986. Magma mixing and the origin of stratiform oxide ore zones in the Bushveld and Stillwater Complexes. In: M.J. Gallagher, R.A. Ixer, C.R. Neary, H.M. Pritchard (Editors). Metallogeny of Basic and Ultrabasic Rocks, Institute of Mining and Metallurgy, London, pp. 183-198.

Kamo, S.L., Reimold, W.U., Krogh, T.E. and Colliston, W.P., 1995. Shocked zircons in Vredefort pseudotachylite and the U-Pb zircon age of the Vredefort impact event (abstract). Geocongress '95, Centennial, Geological Society of South Africa, Johannesburg, April 3-7, 566-569.

Key, R.M., 1983. The geology of the area around Gaborone and Lobatse, Kweneng, Kgatleng, Southern and South East Districts. Dist. Mem. Geol. Surv. Botswana, 5: 230pp

Kruger, F.J., 1989. The geochronology and Sr-isotope geochemistry of the Molopo Farms Complex, Bushveld magmatic province: a preliminary report. Molopo Botswana (Pty) Ltd., Final report for prospecting licenses 14/85 and 38/90, open file report, Geol. Surv. Botswana.

Kruger, F.J., 1994. The Sr-isotope stratigraphy of the western Bushveld Complex. S. Afr. J. Geol., 97: 393-398.

Ladnorg, U., 1976. Zur Genese einiger Basaltvorkommen des Westerwaldes. Ph.D. Thesis, Johannes Gutenberg Univ., Mainz, Germany, 179pp.

Merkle, R.K.W. and Wallmach, T., 1997. Ultramafic rocks in the centre of the Vredefort structure (South Africa): geochemical

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

affinity to Bushveld rocks. Chem. Geol., 143: 43-64.

MacDonald, G.A., 1967. Forms and structures of extrusive basaltic rocks. In: H.H. Hess and A. Poldervaart (Editors). Basalts. New York, John Wiley and Sons, pp. 1-61.

McDonough, W.F., Waibel, A. F., and Gannet, M. W., 1984. The reinterpretation of Leone Lake sediments as a pyroclastic surge deposit and its tectonic significance. J. Volcanol. Geotherm. Res., 20: 101-115.

Manley, C.R., 1995. How voluminous rhyolite lavas mimic rheoignimbrites: Eruptive style, emplacement conditions, and formation of tuff-like textures. Geol., 23: 349-352.

Mellor, E.T., 1905. The geology of a portion of the Springbok Flats and the adjacent areas. Rep. S. Afr. Geol. Surv., 1904: 26-36.

Nakada, S., Miyaka, I., Sato, H., Oshima, O. and Fujinawa, A., 1995. Endogeneous growth of dacite dome at Unzen volcano (Japan), 1993-1994. Geol., 23: 157-160.

Parson, T., Thompson, G.A. and Sleep, N.H., 1994. Mantle plume influence on the Neogene uplift and extension of the U.S. western Cordillera? Geol., 22: 83-86.

Petrov, V.P., 1984. Tubular cavities and porous cylinders in lavas and their petrogenetic significance. Intern. Geol. Rev., 26: 857-864.

Rainbird, R.H., 1993. The sedimentary record of mantle plume uplift preceding eruption of the Neoproterozoic Natkusiak flood basalts. J. Geol., 101: 305-318.

Reichhardt, F.J., 1994. The Molopo Farms Complex, Botswana: History, stratigraphy, petrography, petrochemistry and Ni-Cu-PGE mineralization. Explor. Mining Geol., 3: 263-284.

Rhodes, R.C., 1972. Palaeocurrents in the Pretoria Group north of Marble Hall, Transvaal. An. Geol. Surv. S. Afr., 9: 119-120.

Rhodes, R.C., 1975. New evidence for impact origin of the

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Bushveld Complex, South Africa. Geol., 3: 549-554.

Roobol, M.J., Wright, J.V. and Smith, A.L., 1983. Calderas or gravity-slide structures in the Lesser Antilles island arc. J. Volcanol. Geotherm. Res., 19: 121-134.

Schmincke, H.-U., 1967. Fused tuff and peperites in south-central Washington. Geol. Soc. Am. Bull., 78: 319-330.

Schmincke, H.-U. and Swanson, D.A., 1967. Laminar viscous flowage structures in ash-flow tuffs from Gran Canaria, Canary Islands. J. Geol., 75/6: 641-664.

Schreiber, U.M., Eriksson, P.G. and Snyman, C.P., 1991. A provenance study of the sandstones of the Pretoria Group, Transvaal Sequence (South Africa): petrography, geochemistry, and palaeocurrent directions. S. Afr. J. Geol., 94: 288-298.

Schreiber, U.M. and Eriksson, P.G., 1992. The sedimentology of the post-Magaliesberg formations of the Pretoria Group, Transvaal Sequence, in the eastern Transvaal. S. Afr. J. Geol., 95: 1-16.

Schweitzer, J.K. and Hatton, C.J., 1995a. Synchronous emplacement of the felsites, granophyres, granites and mafic intrusives of the Bushveld Complex (abstract). Geocongress '95, Centennial, Geological Society of South Africa, Johannesburg, April 3-7, 1995, 532-535.

Schweitzer, J.K. and Hatton, C.J., 1995b. Chemical alteration within the volcanic roof rocks of the Bushveld Complex. Econ. Geol., 90: 2218-2231.

Schweitzer, J.K., Hatton, C.J. and de Waal, S. A., 1995a. Economic potential of the Rooiberg Group - volcanic rocks in the floor and roof of the Bushveld Complex. Mineral. Dep., 30: 168-177.

Schweitzer, J.K., Hatton, C.J. and de Waal, S. A., 1995b. Regional lithochemical stratigraphy of the Rooiberg Group: a proposed new subdivision. S. Afr. J. Geol., 98/3: 245-255.

Schweitzer, J.K., Hatton, C.J. and de Waal, S. A., 1997. Link

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

between the granitic and volcanic rocks of the Bushveld Complex, South Africa. J. Afr. Earth Sci., 24: 95-104.

Sharpe, M.R., 1985. Strontium isotope evidence for preserved density stratification in the main zone of the Bushveld Complex, South Africa. Nature, 316/11: 119-126.

Sharpe, M.R., Brits, R. and Engelbrecht, J.P., 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. Institute Geological Research Bushveld Complex, University Pretoria Research Report, 40: 63pp.

South African Committee for Stratigraphy (SACS), 1980. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. Handb. Geol. Surv. S. Afr., 8: 633pp.

Stear, W.M., 1977. The stratigraphy and sedimentation of the Pretoria Group at Rooiberg, Transvaal. Trans. Geol. Soc. S. Afr., 80: 53-65.

Stettler, E.H., Tinnion, M.P., du Plessis, A., Weder, E.E. and du Plessis, S.J., 1998. Geophysical signatures of Bushveld Complex satellites. S. Afr. Geoph. Rev., 2: in press.

Tankard, A.J., Eriksson, K.A., Hunter, D.R., Jackson, M.P.A., Hobday, D.K. and Minter, W.E.L., 1982. Crustal evolution of southern Africa: 3.8 billion years of earth history. New York, Springer Verlag, 525pp.

Taylor, S.R. and McLennan, S.M., 1985. The continental crust: its composition and evolution. Geoscience Texts, Blackwell Scientific Publications, Oxford, London, Edinburgh, 312pp.

Truter, F.C., 1949. A review of volcanism in the geological history of South Africa. Trans. Geol. Soc. S. Afr., 52: 39-89.

Twist, D., 1985. Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, southeastern Bushveld. Econ. Geol., 80: 1153-1165.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Twist, D. and French, B.M., 1983. Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite. Bull. Volcanol., 46/3: 225-242.

Twist, D. and Bristow, J.W., 1990. Extensive lava-like siliceous flows in southern Africa: a review of occurrences. Univ. Pretoria, Inst. Geol. Res. Bushveld Complex, Res. Rept., 82: 35pp.

Uken, R. and Watkeys, M.K., 1995. The Bushveld Complex aureole: structural processes in a low pressure, high temperature contact metamorphic terrane (abstract). Geocongress '95, Centennial, Geological Society of South Africa, April 3-7, Johannesburg, 688-690.

Visser, J.N.J., 1969. 'n Sedimentologies studie van die serie Pretoria in Transvaal. D.Sc. Thesis, Univ. Bloemfontein, South Africa, 263pp.

Von Gruenewaldt, G., Sharpe, M.R. and Hatton, C.J., 1985. The Bushveld Complex: Introduction and review. Econ. Geol., 80: 803-812.

Wagner, P.A., 1921. The Mutue Fides - Stavoren Tinfields. Department of Mines and Industries South Africa, 16: 160pp.

Wagner, P.A., 1927. The geology of the north-eastern part of the Springbok Flats and surrounding country (Explanation of sheet 17 Springbok Flats). Geological Survey - Department of Mines and Industries, South Africa, 104pp.

Walton, Jr., M.S. and O'Sullivan, R.B., 1950. The intrusive mechanics of a clastic dike. Am. J. Sci., 248: 1-21.

Walraven, F., 1998. Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. Chem. Geol. (Isotope Geosciences Section), in press.

Waters, A. C., 1960. Determining direction of flow in basalts. American Journal of Science - Bradley Volume, 258-A: 350-366.

Wyatt, B.A., 1976. The geology and geochemistry of the Klipriviersberg volcanics, Ventersdorp Supergroup, south of

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Johannesburg. M.Sc. Thesis, Univ. Witwatersrand, Johannesburg, South Africa, 178pp.

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Table Captions

Table 1: Estimated erupted volumes and areas covered by individual Rooiberg Group formations. The figures for the Dullstroom Formation were constructed by considering evidence from the Dullstroom area and the Makeckaan and Rooiberg Fragments. Thicknesses were adjusted for the occurrence of sills and Rooiberg internal unconformities. Average thicknesses for the Damwal (1.5km), Kwaggasnek (1.4km), and Schrikkloof (1.2km) Formations were deduced considering various localities (Schweitzer et al., 1995b). See Walraven (1998) for source of radiometric ages. ZE = single-grain zircon Pb evaporation technique; ZB = U-Pb bulk zircon chemistry technique. The Rooikop Granite Porphyry intrudes the upper levels of the Rooiberg Group and its compositions compare favourably to the lava compositions of the Schrikkloof Formation and those of the Lebowa Granite Suite (Schweitzer et al., 1997).

Table 2: Approximate percentages of Dullstroom magma types as preserved in the floor and roof of the Rustenburg Layered Suite. About 65% of the about 5km thick Dullstroom Formation is made up of dacites and rhyolites.

Table 3: Average compositions of the first LTI basaltic andesite eruptions from various areas. Total iron is given as FeO, major elements in weight percent, normalised to 100% water free, and trace elements in parts per million. Standard deviation is given in brackets; n = number of analyses; na = not analysed. The average of the Rooiberg LTI flow is deduced from five analyses originating from samples along strike of one, individual flow.

Table 4: Average compositions of the Basal Rhyolite (BR) magma type as determined for Messchunfontein, bottom and top portion, Kwaggaskop, and the Makeckaan Fragment. Total iron is given as FeO, major elements, normalised to 100% water free, in weight percent and trace elements in parts per million. Standard deviations are given in brackets, n = number of analyses.

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Figure Captions

Figure 1: Distribution of the four formations of the Rooiberg Group relative to the other components of the Bushveld Complex. Also identified are the Makeckaan and Rooiberg Fragments, and the Dullstroom Formation in the floor of the Rustenburg Layered Suite. A thin package of Dullstroom Formation is also preserved in the basal portion of the Rooiberg succession at Loskop Dam (Schweitzer et al., 1995b), but can not be shown on the scale considered. Insert schematically identifies the mafic intrusives of the Bushveld and Molopo Farms Complexes (Simplified after Reichhardt, 1994).

Figure 2: Regional correlation of the basal Dullstroom succession and underlying unconformity. The distance between the Dullstroom occurrences in the eastern Bushveld and at the Molopo Farms Complex is about 600 kilometer. See Figure 1 for approximate location of profiles.

Figure 3: Simplified map of the Dullstroom Formation (floor of Rustenburg Layered Suite), outlining the distribution of magma types. Individual horizons were mapped; magma type distribution was also determined employing the composition of 157 samples taken throughout this occurrence of the Dullstroom Formation. Pyroclastic horizons, individual lava flows, and some intrusions can not be shown.

Figure 4: Sections through the Dullstroom Formation identifying the stratigraphic position of the four Dullstroom magma types, and associated pyroclastic rocks. See insert for position of section lines.

Figure 5: Schematic north/south section through the basal Dullstroom succession. The occurrence of the Rooiberg Group in the roof of the Rustenburg Layered Suite is also sketched.

Figures 6 a and b: a) Geological map of the Messchunfontein depression and associated rocks. Positions of Figures 7, 8, and 9 are given in squares. Averages and variations of clast sizes in the debris flow consider 20 measurements at each station (Fig. 6b). The unconformity sand sheet is omitted.

Figure 7: Cross section through the basal Dullstroom succession

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in the vicinity of Messchunfontein (see Figure 6a for approximate location of section line). Also shown are the width variations of quenched quartz plates (20 measurements per thin section) throughout the Basal Rhyolite.

Figures 8 a and b: Plan view and cross sections of flow lineations in the Basal Rhyolite west of Messchunfontein. The fragments consist of dismembered quartz detritus. See Figure 6a for locality.

Figure 9: Section through the lobe of the Messchunfontein Basal Rhyolite. Numbers refer to the different toe (fold) structures. See text for explanation and Figure 6a for locality.

Figure 10: Geological map of the Kwaggaskop area. See Figure 3 for locality.

Figure 11: Selected element concentrations of the four Dullstroom magma types and a basal debris flow deposit related to the three stratigraphic profiles presented in Figure 4. Matrix material was analysed to derive the composition of the debris flow/pyroclastic flow deposit.

Figures 12 a and b: TiO_2 vs Al_2O_3 (a) and MgO (b) for initial LTI eruptions of flows sourcing from the Messchunfontein and Kwaggaskop regions. The compositions of these flows are compared to the equivalent magma type from the Rooiberg and Makeckaan Fragments (see also Table 3).

Figures 13 a and b: TiO_2 vs Al_2O_3 (a) and Sc (b) for the bottom and top portion of the Messchunfontein Basal Rhyolite compared to the compositions of the Kwaggaskop and Makeckaan Fragment Basal Rhyolites. The average compositions of these flows are given in Table 4.

Figures 14 a-i: Fine-grained volcaniclastic shale deposit on Messchunfontein (a). Note cross-beds and disturbed layering. Kwaggaskop debris flow deposit (b). The pock-marked surface appearance is due to the preferential weathering of stromatolitic limestone clasts. Other clasts are LTI basaltic andesites. The Messchunfontein debris flow contains prominent LTI basaltic andesite fragments (c). LTI basaltic andesite containing quartzite {d} and shale {e} fragments from the

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underlying Transvaal Supergroup. Stretched amphibole-filled amygdales (f), sand-filled cracks (g), and prominent flow-banding (h) in the Messchunfontein Basal Rhyolite. Peperites in the basal LTI basaltic andesite at Kwaggaskop (i).

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ROOIBERG GROUP					
Formation	Estimated volume (km^3)	Estimated area covered (km^2)	First occurrence of magma type	Age	First definition of magma type
Schrikkloof	47 000	40 000	Low-Mg Felsite		Schweitzer et al. (1995b)
Kwaggasnek	48 000	40 000	Low-Mg Felsite	2061 ±2 (ZE)	Twist (1985); Schweitzer et al. (1995b)
Damwal	15 000	11 000	Low-Mg Felsite		Schweitzer et al. (1995b)
Dullstroom	2 000	3 000	Low-Mg Felsite High-Fe-Ti-P andesite → High-Mg Felsite High-Ti basalt Basal Rhyolite Low-Ti basaltic andesite		 Twist (1985) Twist (1985) Schweitzer et al. (1995b) Schweitzer et al. (1995b) Schweitzer et al. (1995b)
Total	112 000				

Other Bushveld Complex Ages	
Lebowa Granite Suite	2054 ±2 (ZE)
Rustenburg Layered Suite (Upper Zone)	2061 ±27 (Rb - Sr)
Rashoop Granophyre Suite	2053 ±12 (ZB)
Rooikop Granite Porhyry	2060 ±2 (ZE)

→ Intrusive level of Rustenburg Layered Suite

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<table>
<tr><th></th><th colspan="3">Approximate volume percentage of magma types
Dullstroom Formation</th></tr>
<tr><th></th><th>Dullstroom Formation
(Floor to RLS)
(Thickness: 2.5 km)</th><th>Dullstroom Formation
(Roof to RLS)
(Thickness: 2.41 km)</th><th>Dullstroom Formation
(Total)</th></tr>
<tr><td>Low-Mg Felsite</td><td></td><td>89</td><td>45.0</td></tr>
<tr><td>High Fe-Ti-P andesite</td><td></td><td>1</td><td>0.5</td></tr>
<tr><td>High-Mg Felsite (roof)</td><td></td><td>10</td><td rowspan="3">19.0</td></tr>
<tr><td colspan="3">→</td></tr>
<tr><td>High-Mg Felsite (floor)</td><td>28</td><td></td></tr>
<tr><td>High-Ti basalt</td><td>41</td><td></td><td>20.0</td></tr>
<tr><td>Basal Rhyolite</td><td>1</td><td></td><td>0.5</td></tr>
<tr><td>Low-Ti basaltic andesite</td><td>30</td><td></td><td>15.0</td></tr>
</table>

→ Intrusive level of Rustenburg Layered Suite

Table 2:

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	LTI Messchunfontein (n=6)		LTI Kwaggaskop (n=11)		LTI Rooiberg (n=5)		LTI Makeckaan (n=1)
SiO_2	56.78	(0.61)	57.88	(0.84)	58.41	(0.43)	55.96
TiO_2	0.67	(0.10)	0.46	(0.02)	0.40	(0.01)	0.71
Al_2O_3	15.35	(0.30)	14.57	(0.31)	14.19	(0.12)	15.27
FeO	9.15	(0.48)	8.85	(0.34)	11.89	(0.31)	9.76
MnO	0.18	(0.03)	0.16	(0.02)	0.08	(0.01)	0.18
MgO	5.58	(0.35)	6.55	(0.31)	7.60	(0.55)	5.45
CaO	8.88	(0.58)	7.91	(0.46)	2.61	(0.51)	7.73
Na_2O	2.13	(0.24)	2.21	(0.32)	2.46	(0.32)	4.14
K_2O	1.18	(0.53)	1.34	(0.24)	2.27	(0.36)	0.72
P_2O_5	0.10	(0.00)	0.07	(0.01)	0.09	(0.02)	0.08
Nb	4	(2)	1	(2)	0	(0)	na
Zr	127	(14)	91	(17)	97	(9)	na
Y	22	(2)	15	(2)	12	(4)	na
Sr	291	(28)	208	(29)	80	(4)	456
Rb	44	(16)	61	(15)	200	(47)	19
Zn	81	(20)	79	(26)	35	(7)	na
Cu	46	(44)	21	(27)	135	(166)	na
Ni	82	(6)	129	(12)	139	(2)	na
Co	81	(15)	68	(5)	47	(4)	na
Cr	112	(90)	274	(18)	427	(51)	na
V	159	(20)	165	(8)	141	(3)	na
Ba	293	(112)	324	(61)	125	(41)	na
Sc	30	(1)	32	(2)	28	(1)	na
Ga	15	(1)	13	(1)	12	(1)	na
Hf	0	(0)	0	(0)	0	(0)	na
U	0	(0)	0	(0)	0	(0)	na
Th	11	(1)	15	(16)	12	(1)	na
Pb	6	(2)	11	(22)	5	(1)	na

Table 3:

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	BR - Bottom Messchunfontein (n=4)		BR - Top Messchunfontein (n=7)		BR Kwaggaskop (n=4)		BR Makeckaan (n=7)	
SiO_2	70.22	(0.18)	76.26	(1.35)	73.42	(0.52)	76.87	(1.20)
TiO_2	0.40	(0.01)	0.27	(0.02)	0.39	(0.01)	0.26	(0.05)
Al_2O_3	12.56	(0.10)	10.99	(0.35)	11.93	(0.15)	10.75	(0.64)
FeO	4.69	(0.13)	2.76	(0.40)	4.13	(0.21)	3.17	(0.89)
MnO	0.11	(0.02)	0.07	(0.02)	0.07	(0.02)	0.10	(0.03)
MgO	2.72	(0.05)	1.37	(0.43)	1.71	(0.27)	1.72	(0.46)
CaO	4.24	(0.25)	2.35	(0.41)	3.43	(0.37)	0.96	(0.42)
Na_2O	1.72	(0.25)	1.72	(0.17)	1.67	(0.05)	1.29	(0.95)
K_2O	3.25	(0.39)	4.13	(0.59)	3.16	(0.44)	4.79	(0.72)
P_2O_5	0.09	(0.00)	0.08	(0.01)	0.09	(0.01)	0.09	(0.01)
Nb	6	(1)	7	(1)	7	(1)	5	(2)
Zr	194	(20)	237	(20)	210	(5)	231	(35)
Y	21	(3)	27	(7)	24	(2)	21	(5)
Sr	222	(19)	235	(9)	222	(11)	111	(135)
Rb	110	(23)	165	(43)	124	(19)	194	(70)
Zn	55	(13)	27	(5)	29	(10)	135	(152)
Cu	1	(2)	2	(5)	14	(20)	1	(2)
Ni	36	(10)	21	(9)	22	(2)	16	(9)
Co	65	(12)	104	(18)	68	(13)	93	(15)
Cr	139	(4)	164	(17)	256	(59)	508	(274)
V	80	(5)	42	(8)	77	(4)	39	(13)
Ba	885	(121)	1190	(168)	903	(92)	1433	(277)
Sc	14	(1)	8	(1)	12	(1)	6	(2)
Ga	12	(1)	10	(1)	12	(1)	9	(1)
Hf	0	(0)	1	(3)	0	(0)	2	(4)
U	0	(0)	0	(0)	0	(0)	0	(0)
Th	14	(1)	16	(2)	15	(1)	16	(1)
Pb	7	(2)	5	(1)	7	(4)	7	(3)

Table 4:

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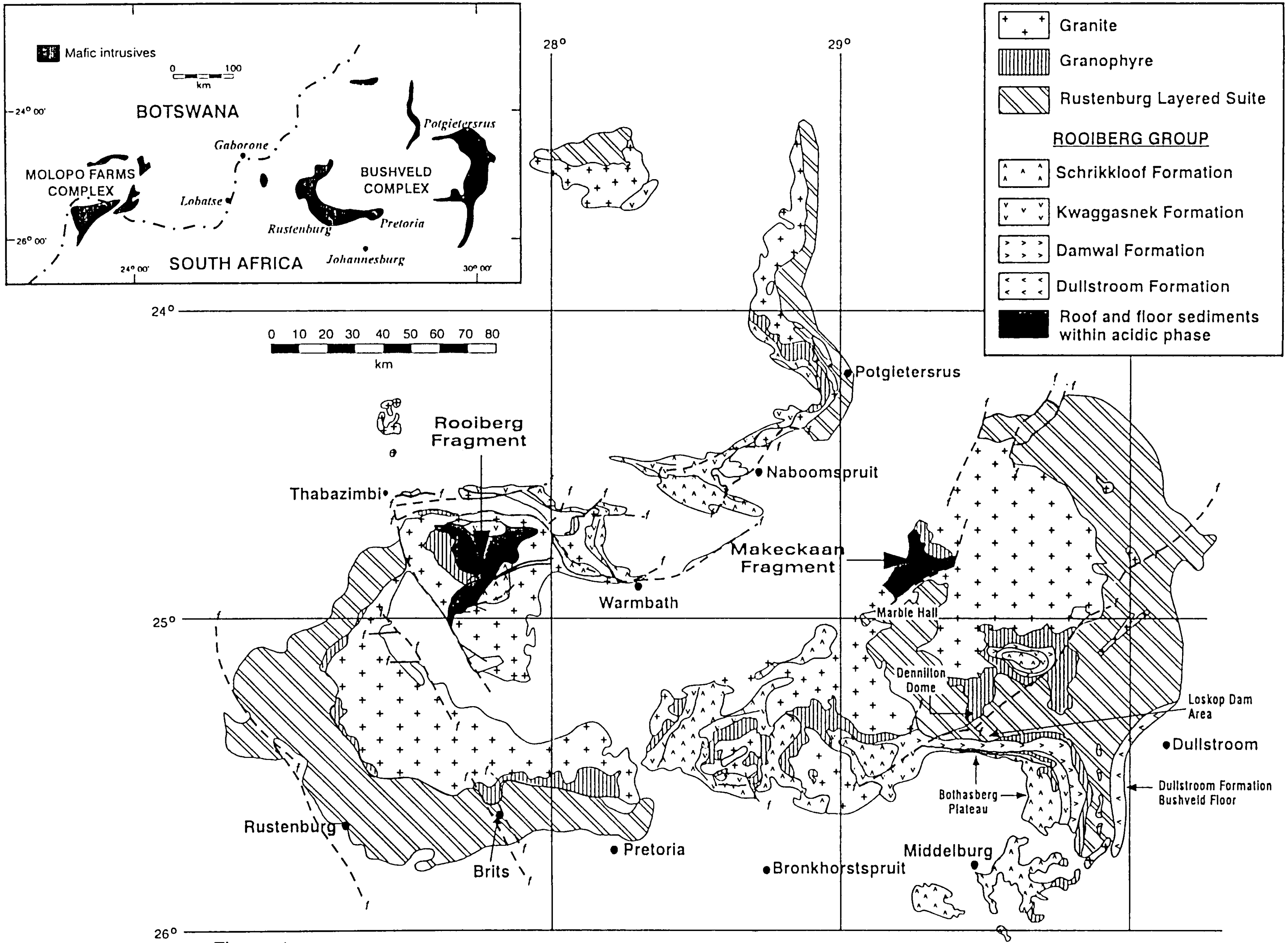

Figure 1:

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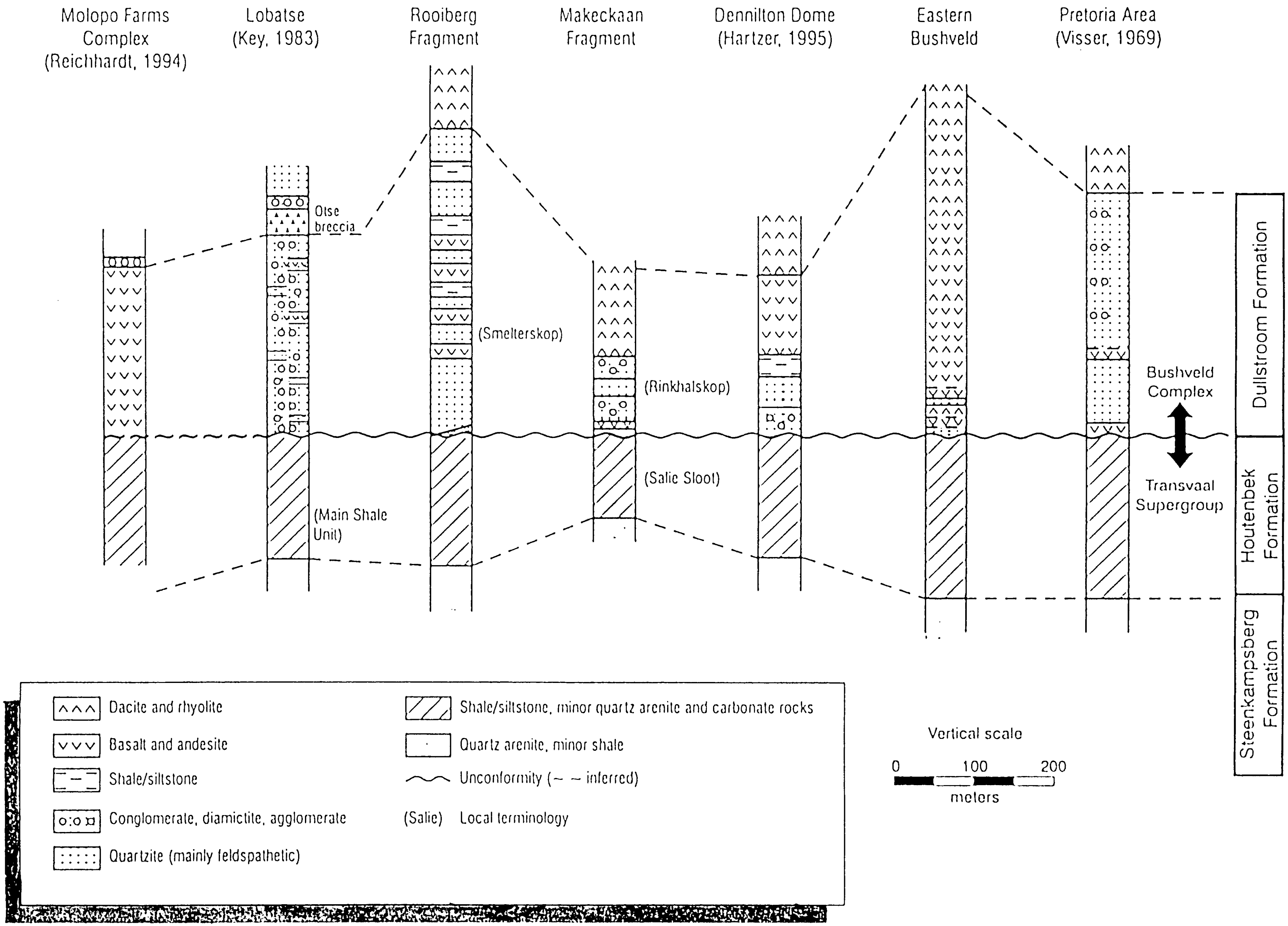

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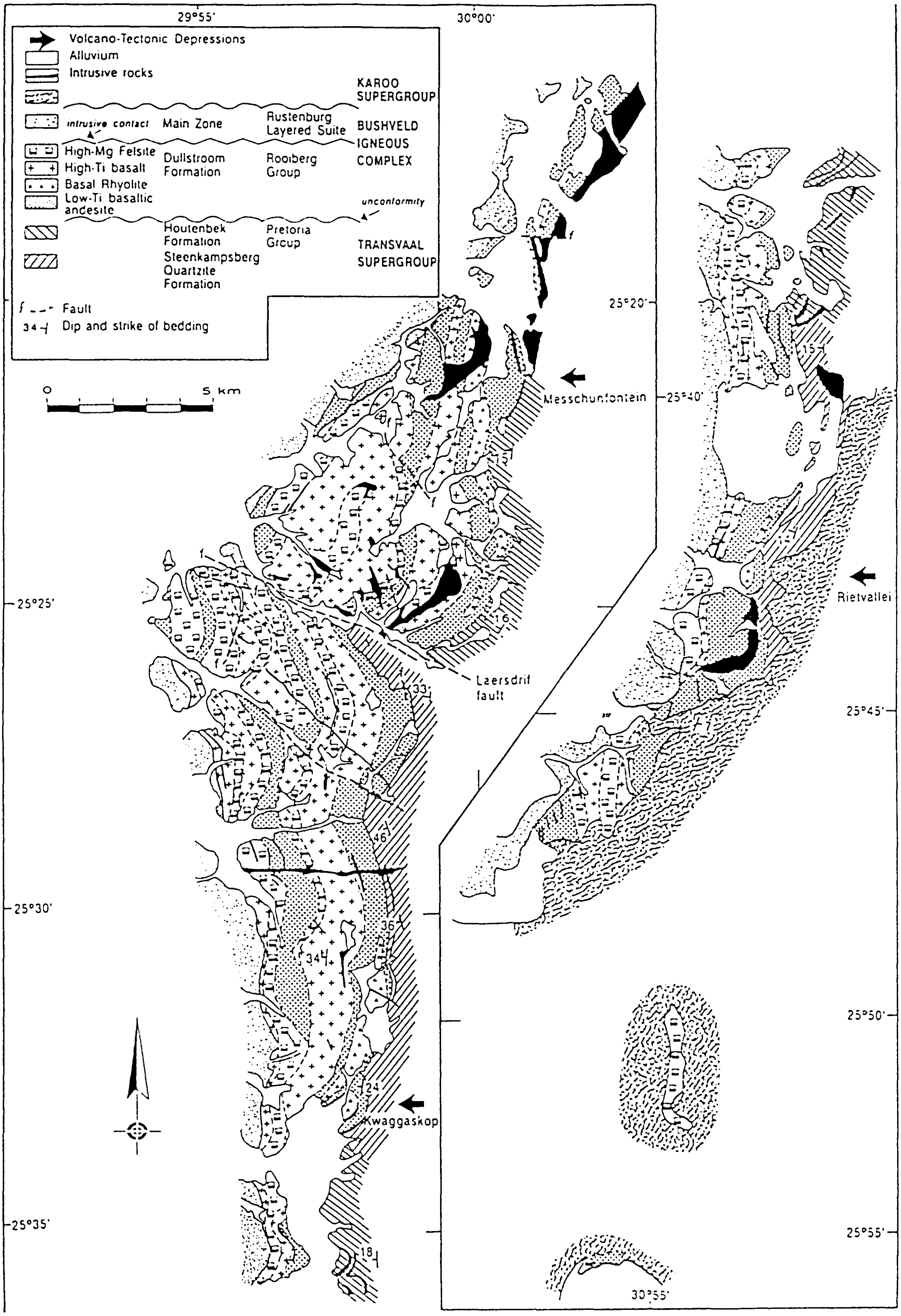

Figure 3:

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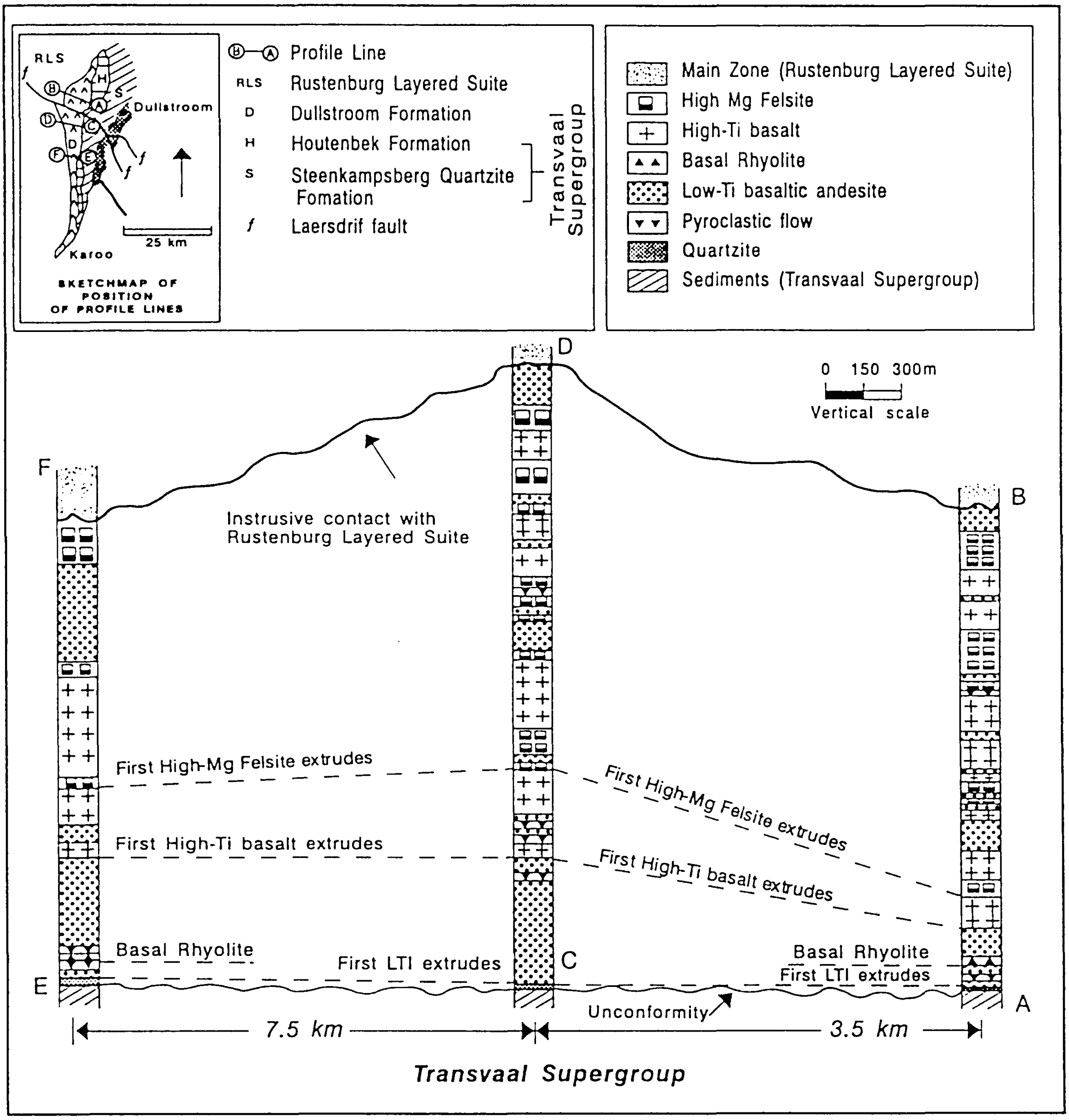

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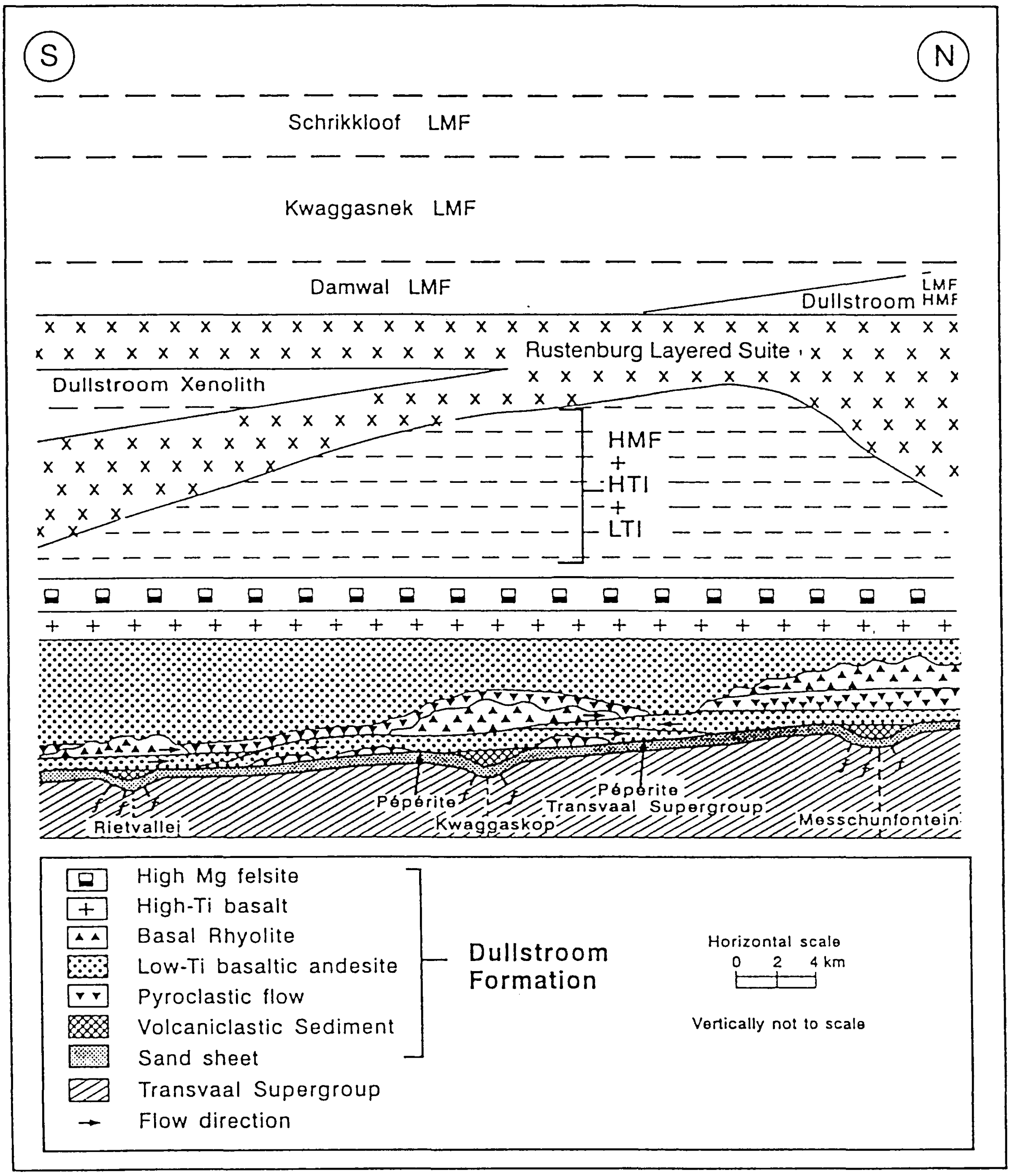

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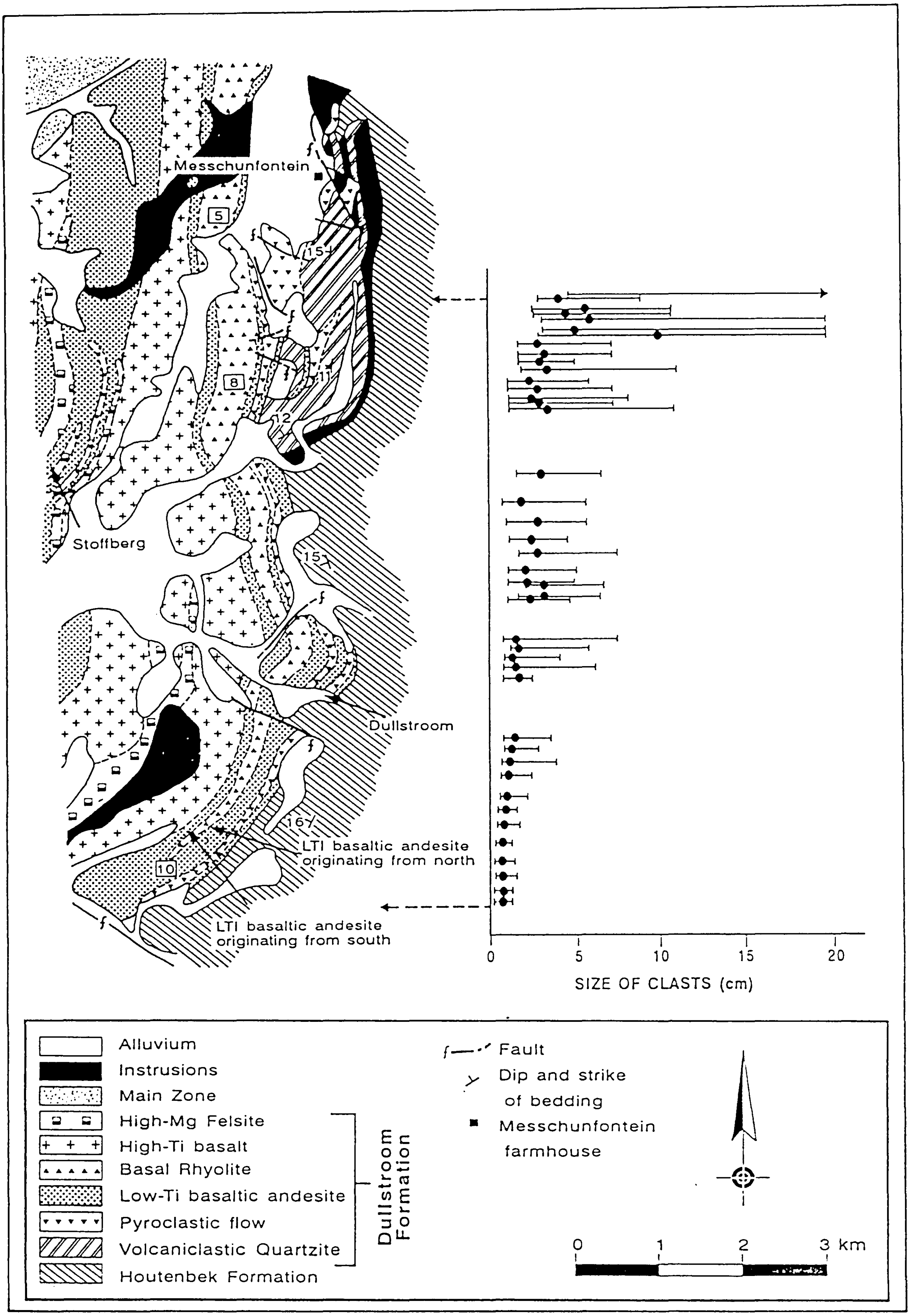

Figures 6a and b:

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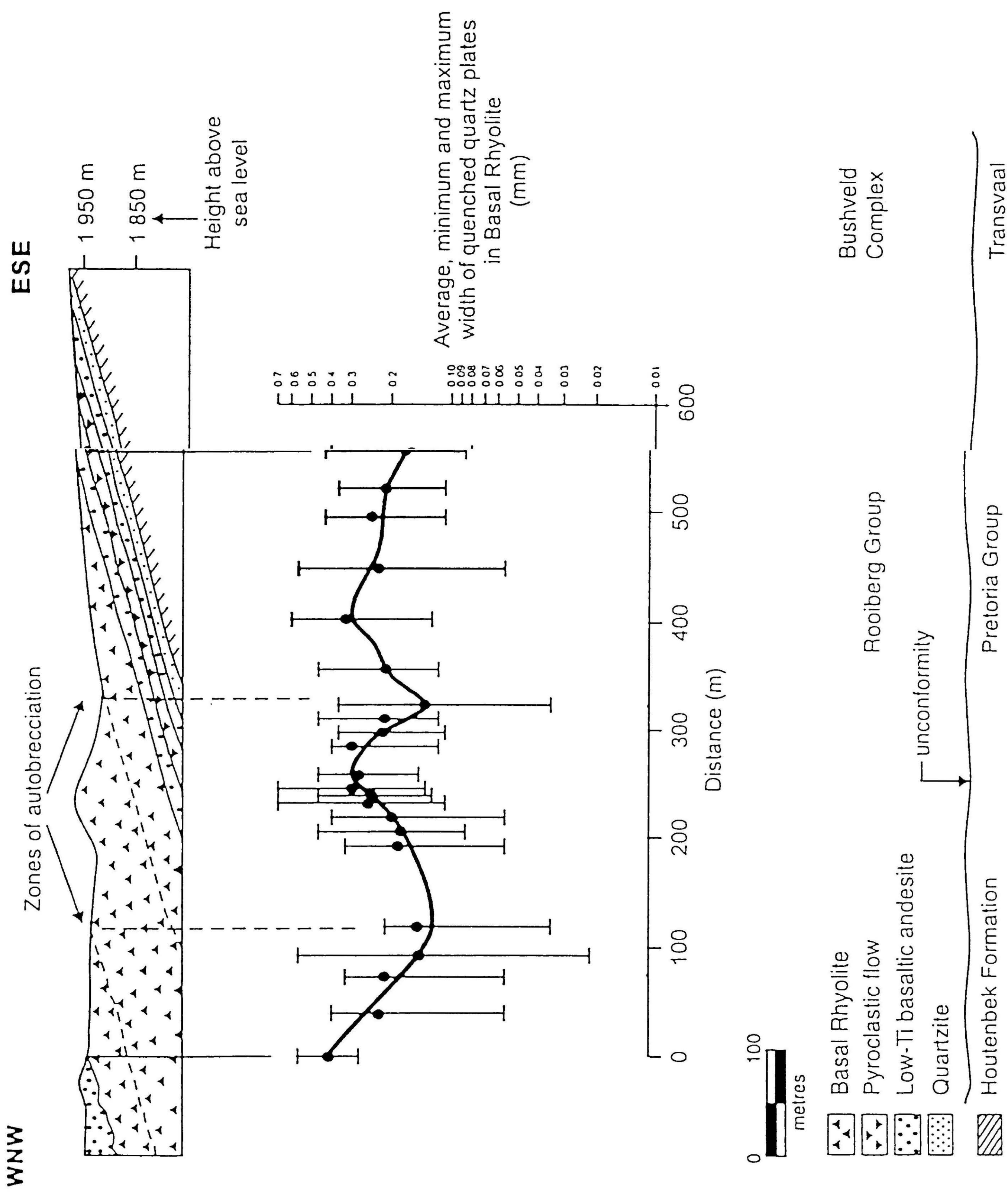

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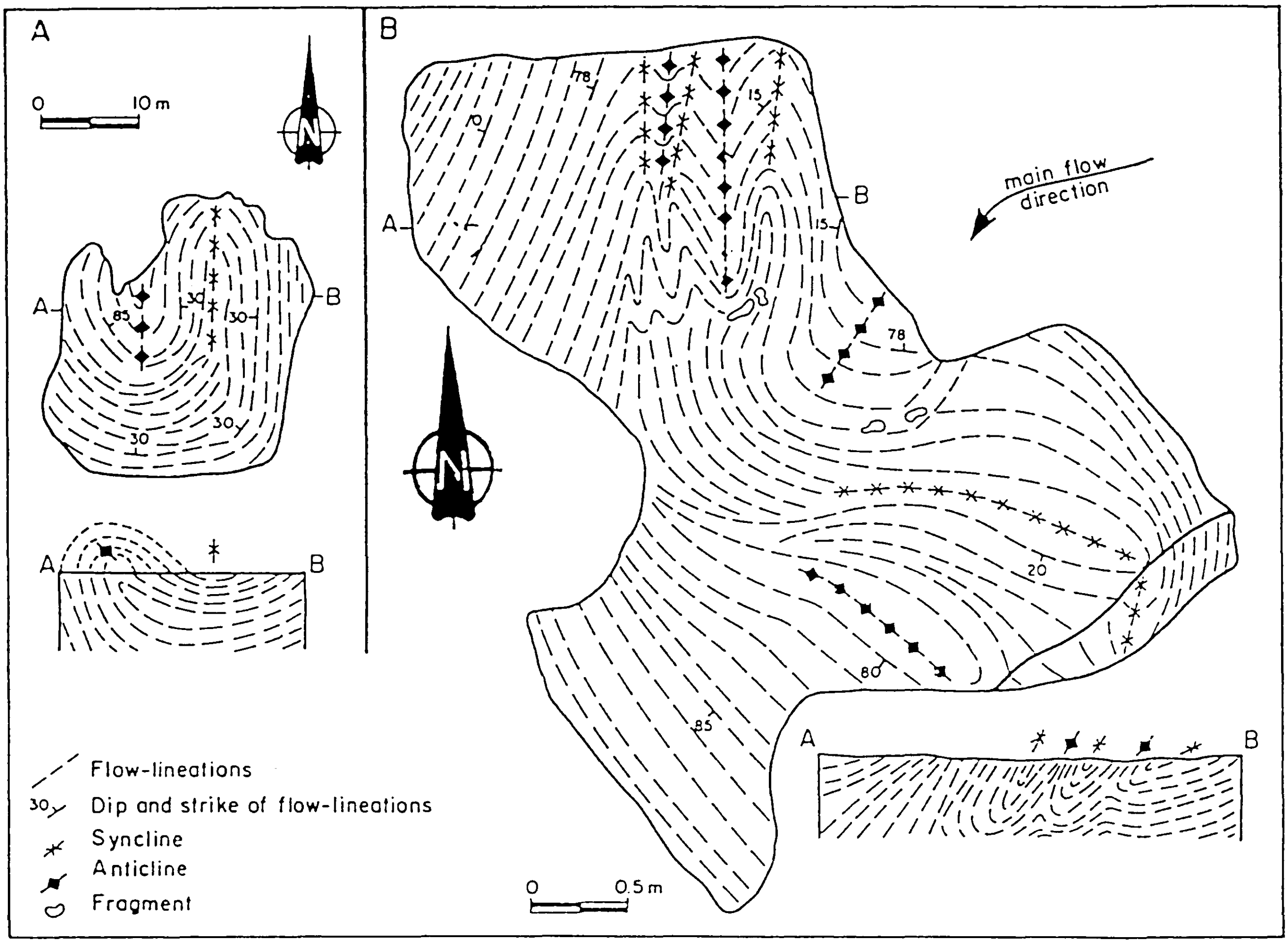

Figures 8a and b:

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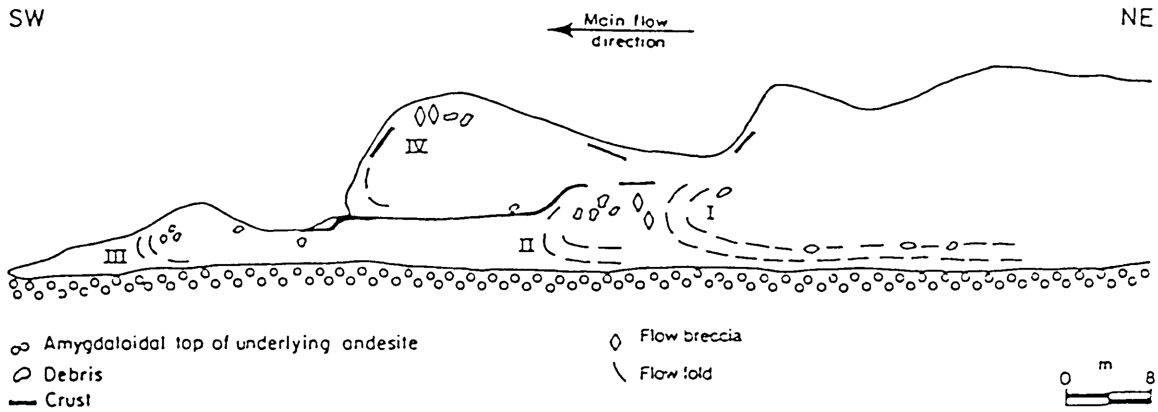

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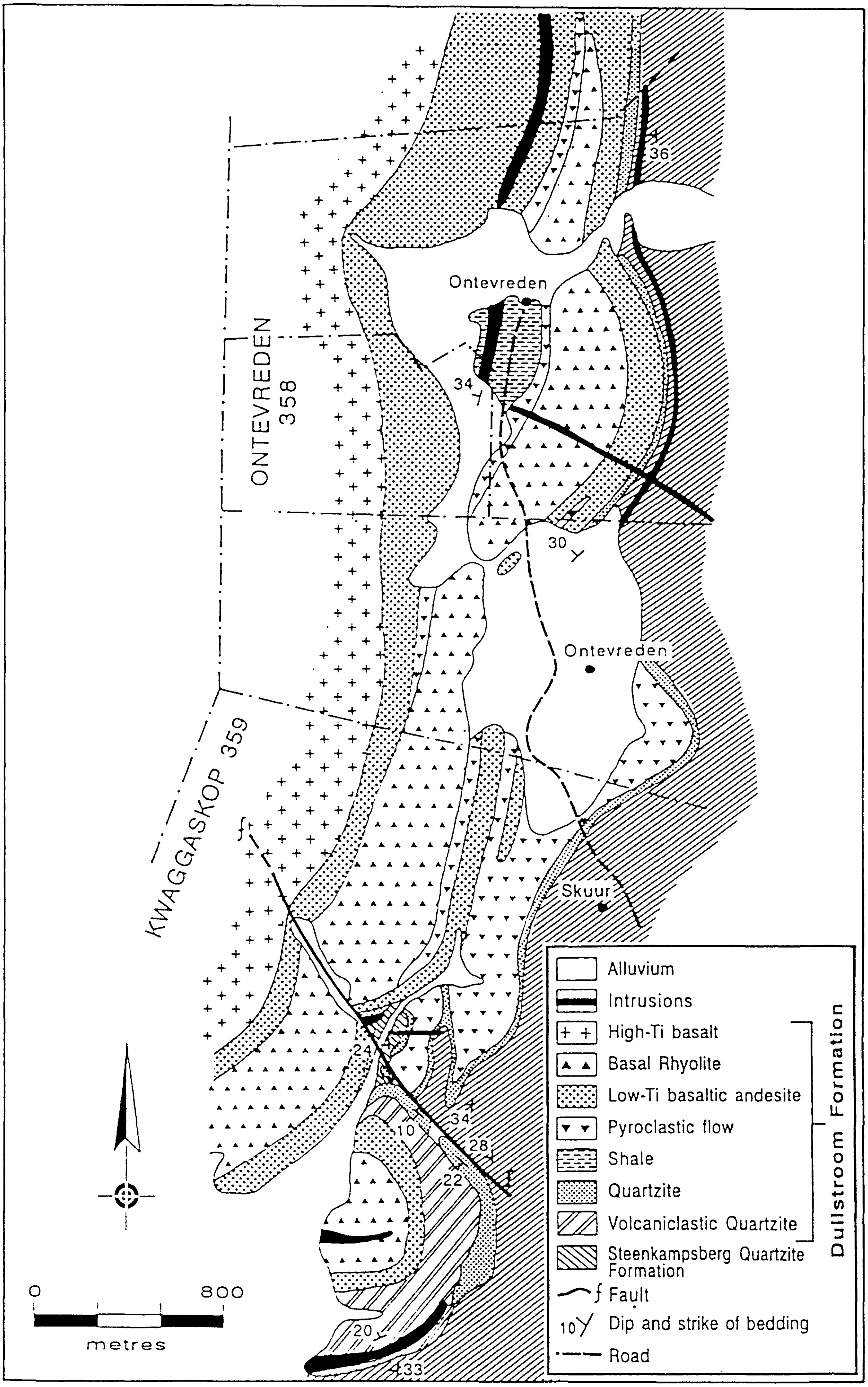

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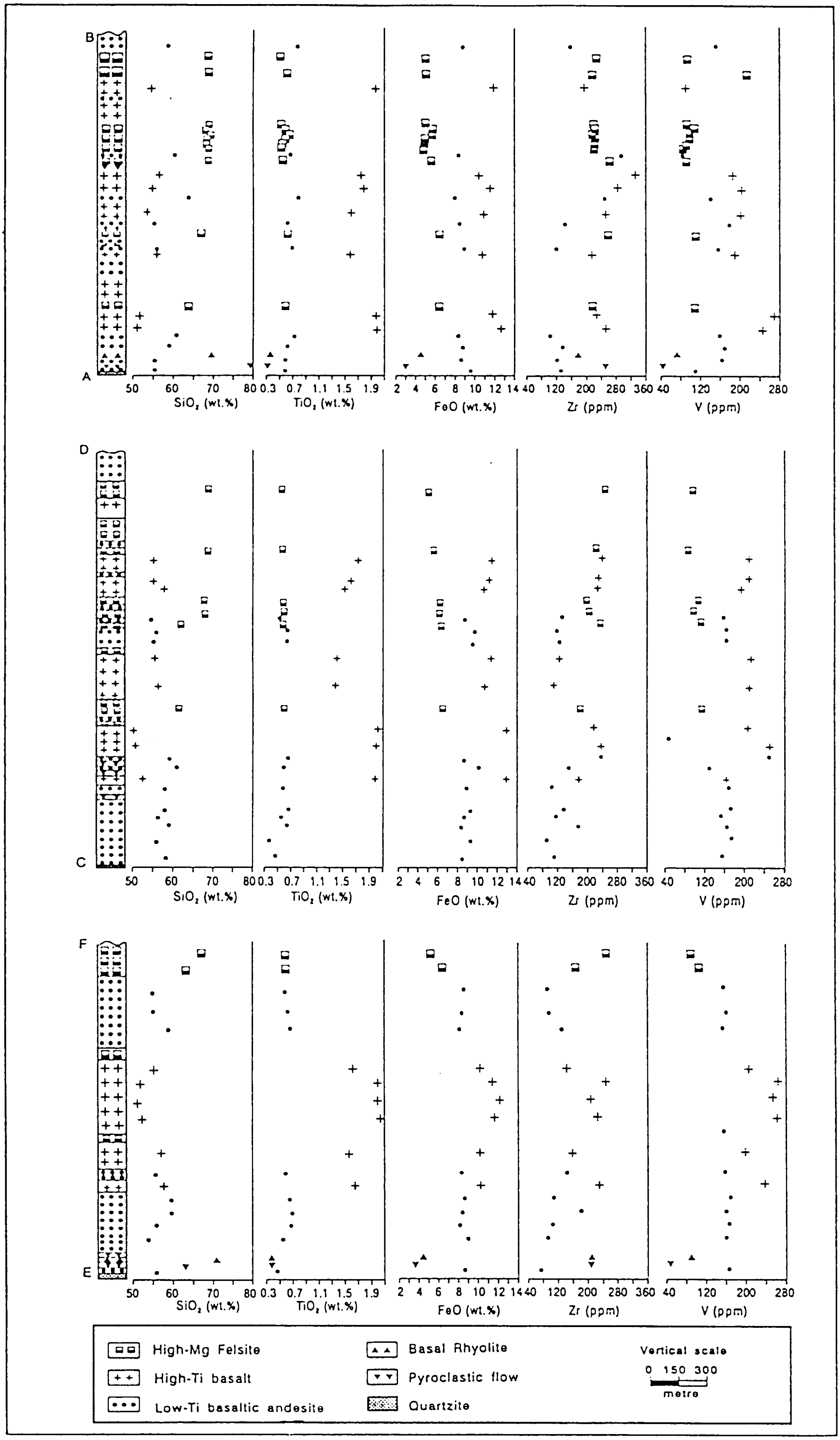

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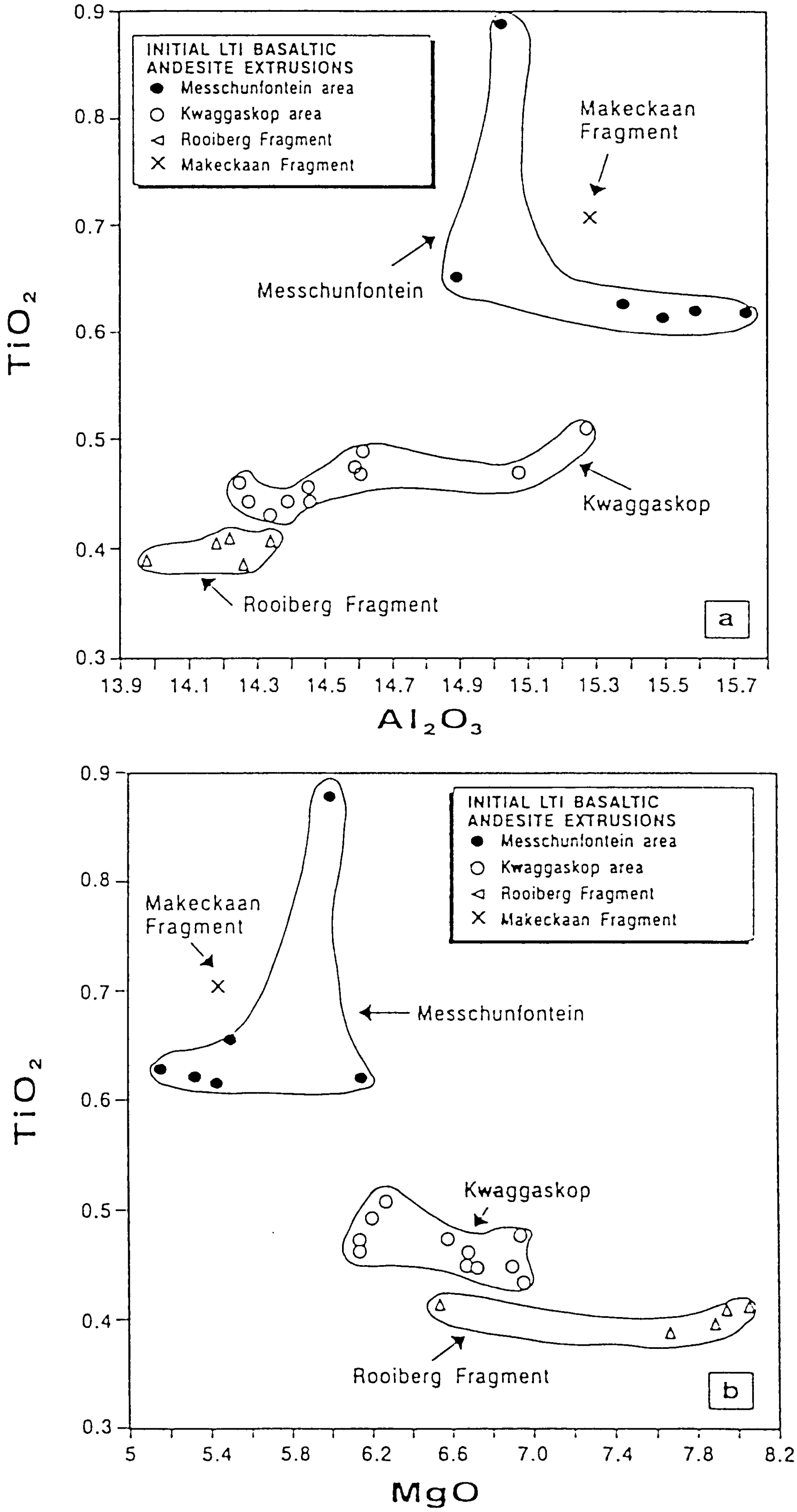

Figures 12a and b:

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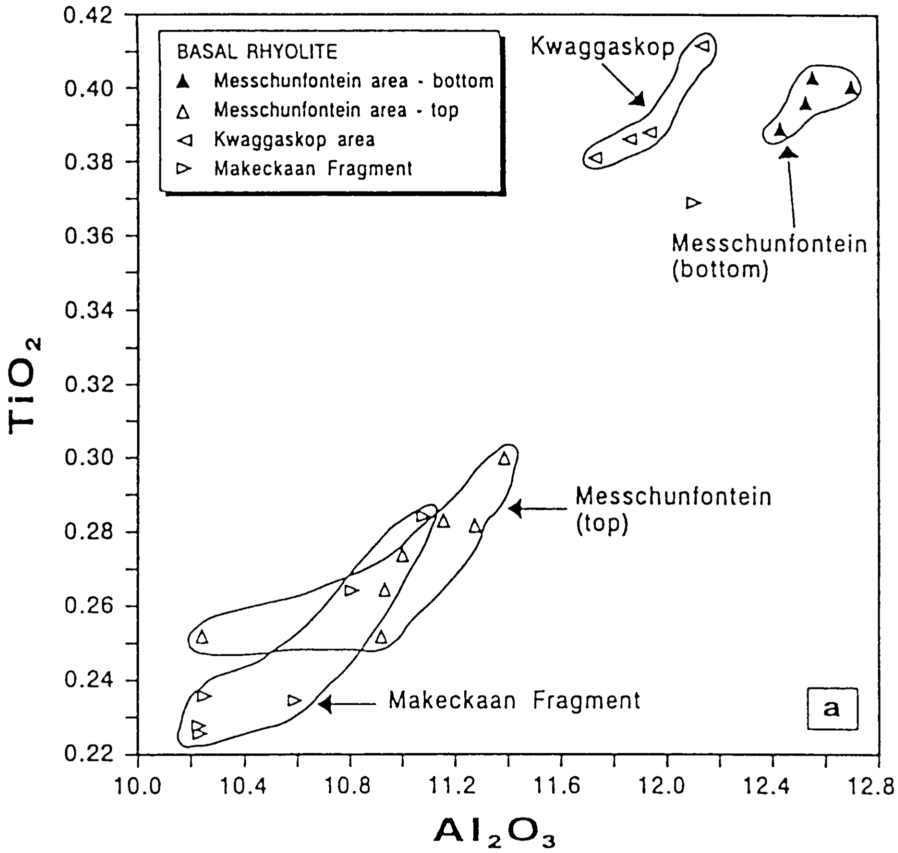

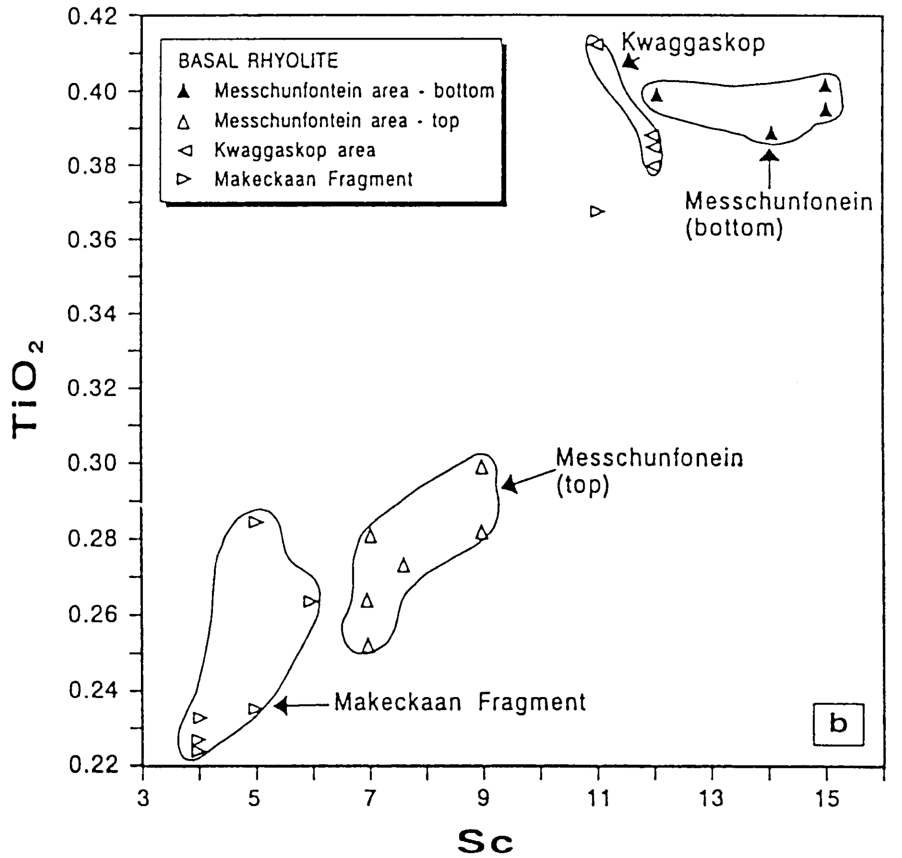

Figures 13a and b:

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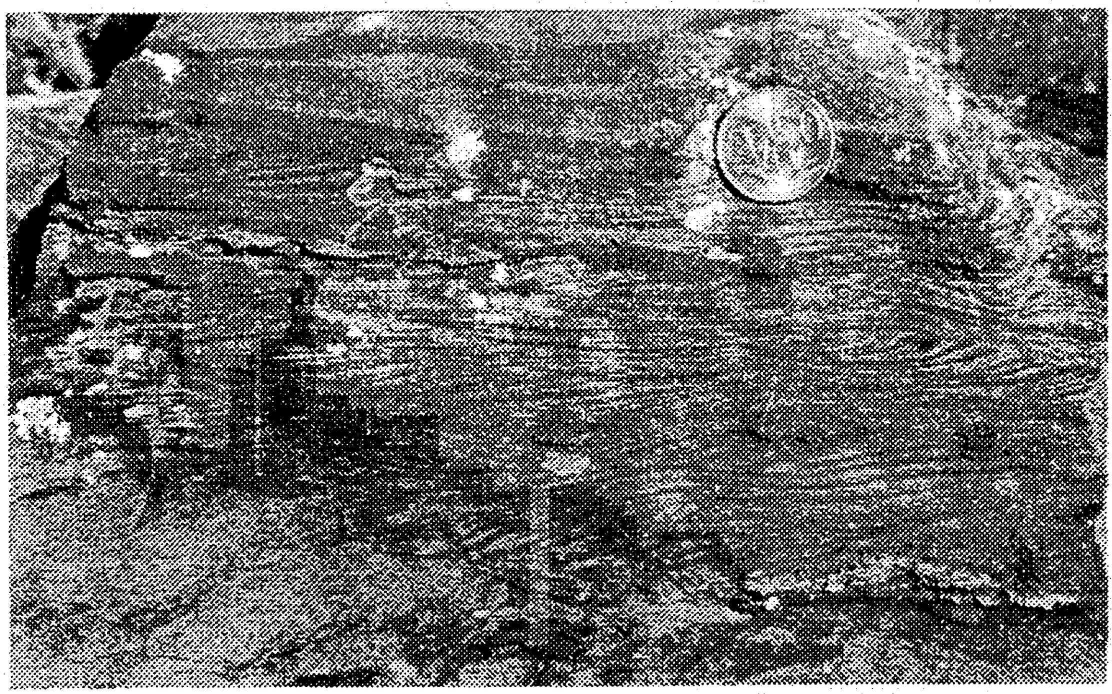

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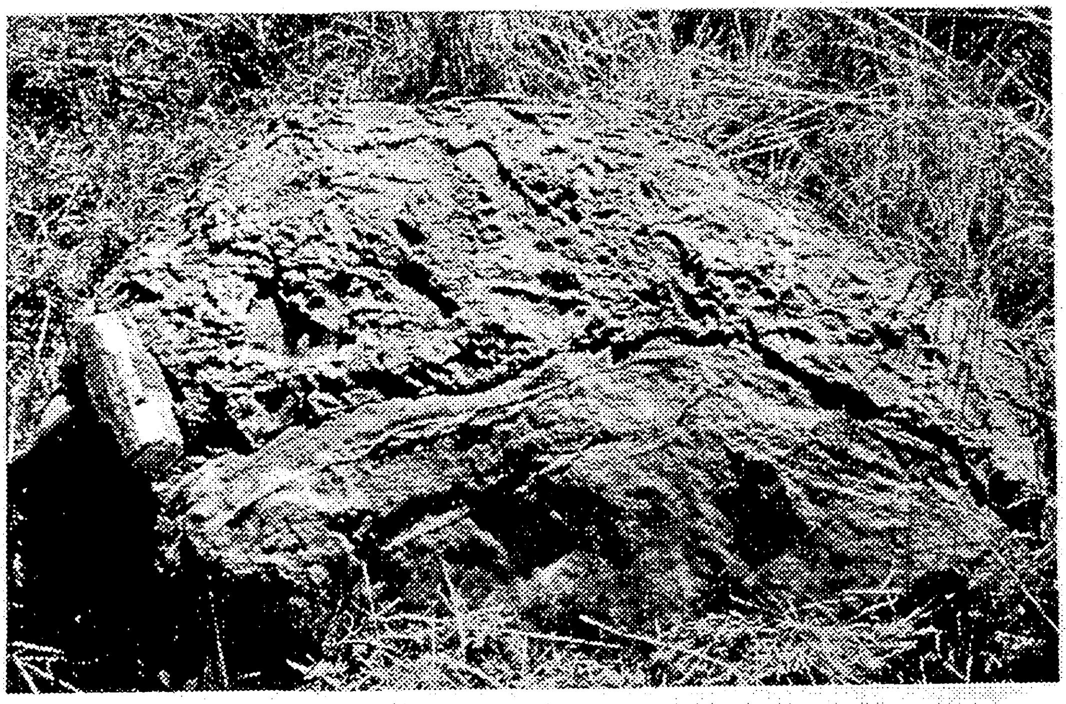

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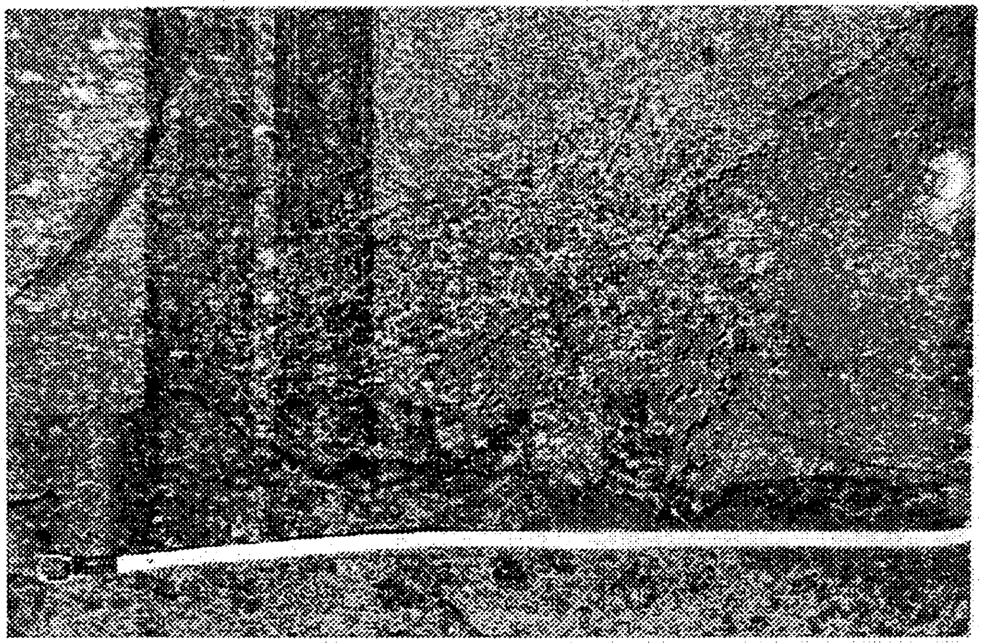

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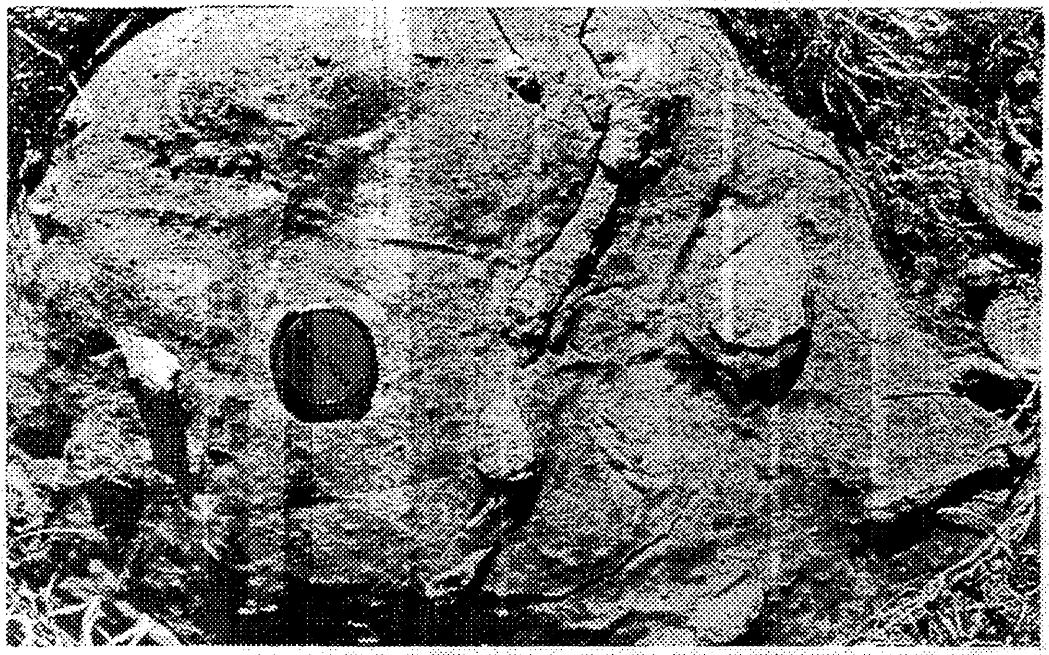

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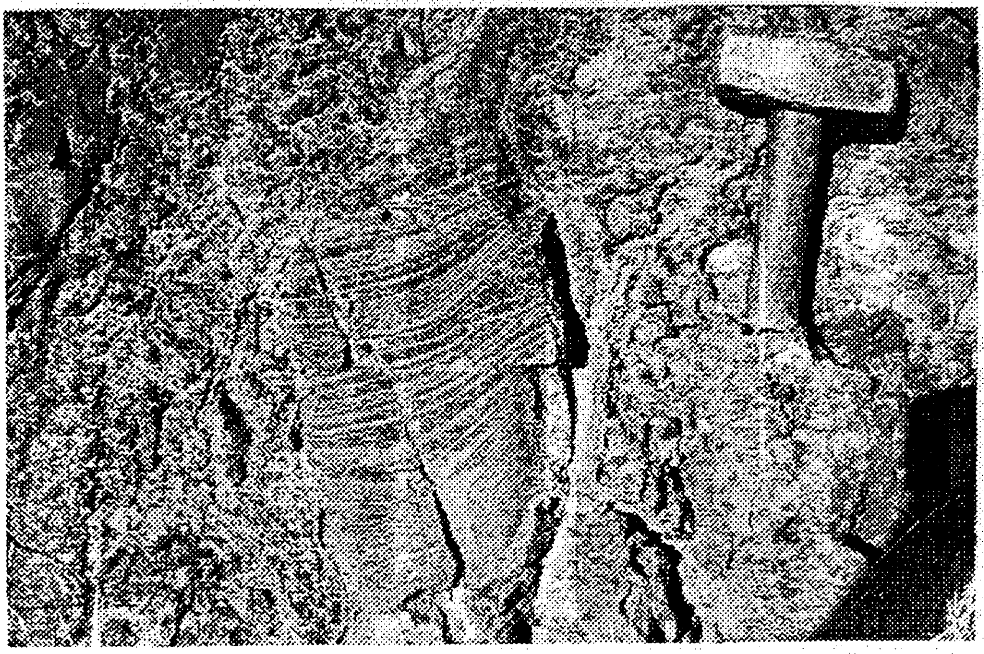
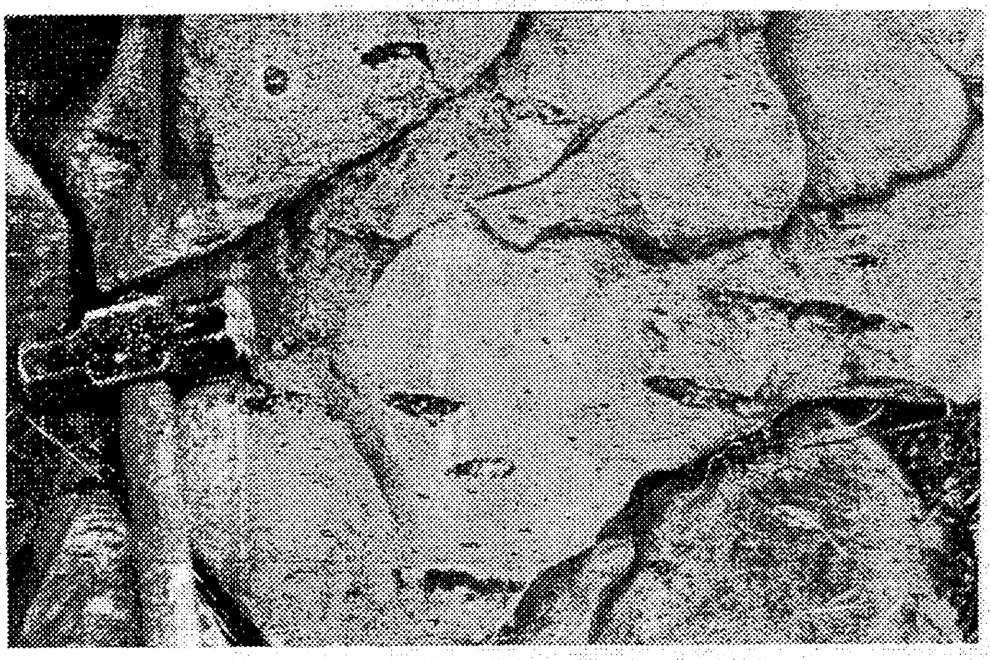


14e



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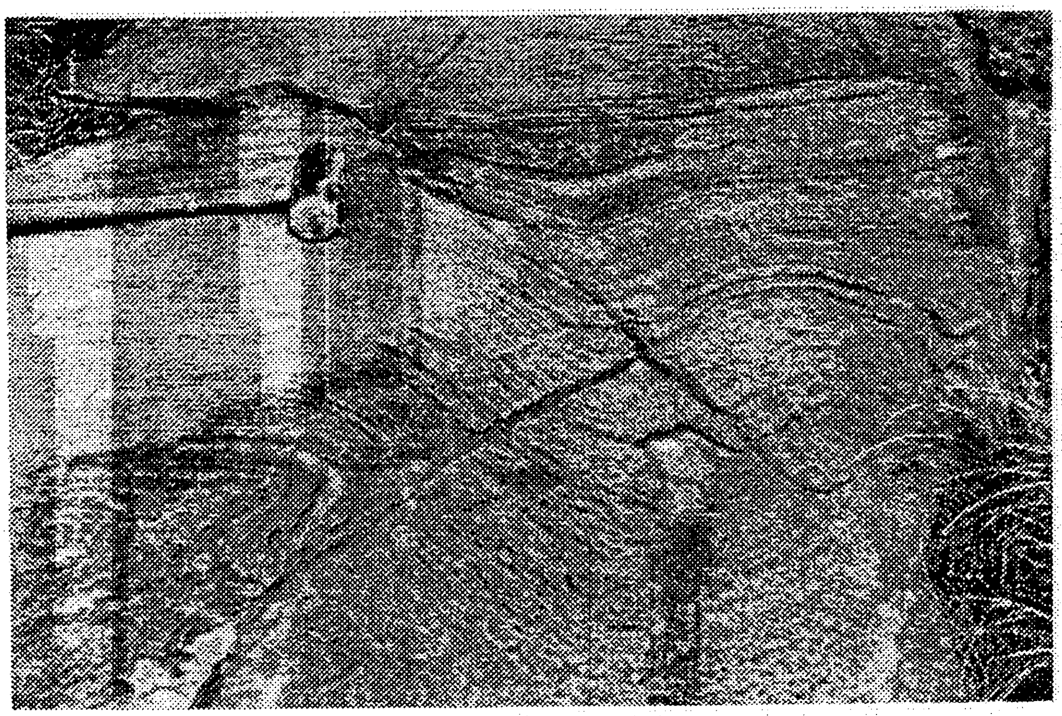

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Appendix B: Abstracts

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SYNCHRONOUS EMPLACEMENT OF THE FELSITES, GRANOPHYRES, GRANITES AND MAFIC INTRUSIVES OF THE BUSHVELD COMPLEX

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BACKGROUND

As currently defined by SACS (1980), the Bushveld Complex is comprised of the Rustenburg Layered Suite (RLS), the Rashoop Granophyre Suite (RGS), and the Lebowa Granite Suite (LGS). Volcanic rocks of the Rooiberg Group are in spatial association with the rocks of the Bushveld Complex (e.g. Twist, 1985). The correlation and continuity of stratigraphic horizons comprising the RLS and the Rooiberg Group has been described as remarkable (Hatton and Sharpe, 1988; Schweitzer et al., 1994).

In a new subdivision proposed to SACS (1980; SACS does not yet consider the Dullstroom to be part of the Rooiberg volcanic event) the Rooiberg Group is comprised of the Dullstroom, Damwal, Kwaggasnek and Schrikkloof Formations (Schweitzer et al., 1994; Figs. 1 and 2). Some evidence suggests that at least portions of the volcanic pile are pre-RLS in age, such as the intrusion level of Bushveld sills and dykes (e.g. Sharpe, 1985) or the existence of a contact metamorphic aureole within the volcanic rocks above the RLS (Schweitzer and Hatton, 1994). In this abstract we present evidence indicating that the Rooiberg volcanic event was synchronous with the events comprising the Bushveld Complex, suggesting that this volcanic suite could be incorporated into the Bushveld Complex.

EVIDENCE FOR SYNCHRONOUS INTRUSIVE AND EXTRUSIVE BUSHVELD MAGMATISM

The high Mg-Felsite (HMF) was identified as a magma type common to the volcanic rocks preserved in the floor and roof of the RLS. This led to the proposal that the volcanic rocks comprising the Dullstroom package should be included into the Rooiberg Group (Schweitzer, 1987; Eriksson et al., 1993; Schweitzer et al., 1994; Figs. 1 and 2). The inclusion of the floor volcanics into the Rooiberg Group is supported by the presence of an unconformity beneath the volcanic pile, in the floor of the intrusion (Cheney and Twist, 1991). This suggests that the Rooiberg Group should not form part of the Transvaal Supergroup, as is currently proposed (SACS, 1980).

The granophyres and their relationship to the other rocks of the Bushveld Complex, and those comprising the Rooiberg Group, provide evidence for the synchronous nature of Rooiberg volcanism and Bushveld magmatism. A co-magmatic origin of the Stavoren granophyre, comprising the vast majority of the RGS, and the Rooiberg volcanic rocks was already proposed by Walraven (1979, 1985). We employ more than 140 granophyre analyses from various geographic regions and from different geological settings and compare these compositions to those of the associated felsite (Table 1, Fig. 1), employing a geochemical subdivision of Rooiberg volcanic rocks using immobile elements (Schweitzer et al., 1994). Except for the Potgietersrus area (Granophyre[7], Table 1), granophyre compositions do not compare to the compositions of the abutting felsite but correspond to compositions of felsite further up in the succession (Fig. 1). Damwal-type granophyre intruded beneath low-Mg Felsite (LMF) of the Dullstroom Formation (Granophyre[1], Table 1) in the eastern Transvaal, whereas Schrikkloof-type granophyre intruded beneath the Kwaggasnek Formation towards the north of Pretoria and east of Groblersdal (Granophyres[4,5,8], Table 1, Figs. 1 and 2). This implies that granophyres corresponding to progressively younger felsite compositions are associated with continuously younger volcanic rocks of the Rooiberg Group and suggests that younger felsite magma intruded beneath older felsite roof rocks. Granites of the LGS intrude granophyre (Walraven, 1982; and Granophyre[2], Table 1), the Rooiberg Group, and also mafic rocks of the RLS (Hammerbeck, 1969), suggesting that the LGS represents the terminal phase of the Bushveld magmatic event.

Granophyre compositionally corresponding to Kwaggasnek and Schrikkloof LMF are in contact with sediments beneath the volcanic pile (Granophyres[3,6], Table 1, Fig. 1) in the Rooiberg and Stavoren Fragments. Kwaggasnek and Schrikkloof LMF flows are not preserved in the Stavoren Fragment, implying that this succession was eroded in this area.

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Bushveld magmatism has been related to mantle plume, hot-spot activity (Sawkins, 1984; Hatton, 1994). This suggests that one heat source was responsible for the Bushveld magmatic event. The Rooiberg volcanic rocks and those of the RGS are co-magmatic (e.g. Walraven, 1979, 1982), with the former being currently included in the Transvaal Supergroup and the latter into the rocks comprising the Bushveld Complex (SACS, 1980). If the events involved in Bushveld and Rooiberg magmatism are a result of hot-spot activity it is most unlikely that the Rooiberg Group and the RGS, both comprised of several, but comparable magma types (Table 1; Figs. 1 and 2), were produced in the same geographic region, but at different times. The volcanic rocks of the Rooiberg Group are, therefore, closely linked, in time and space, to the events currently included in the Bushveld Complex, similar to the relationship exhibited by the Gaborone Granite Suite and the Kanye Formation (Moore et al., 1993). This suggests that the Rooiberg Group could be included into the events comprising the Bushveld Complex.

The volcanic rocks comprising the Rooiberg Group could have erupted in response to processes involved in the formation of the RLS, and this is considered in the following hypothesis: We propose that eruption of the HMF magma, confined to the Dullstroom Formation, is linked to the formation of the lower zone. A genetic link between the lower zone source magma and the HMF was already suggested by Hatton and Sharpe (1988). LMF magma of the upper Dullstroom and the Damwal Formations erupted in response to the processes involved in the formation of the critical zone. Both Dullstroom and Damwal Formations and lower and critical zone are localized in occurrence. Events resulting in the intrusion of the widespread main zone magmas could possibly be linked to the regional eruption of LMF magmas of the Kwaggasnek and Schrikkloof Formations.

Table 1: Average (Avg) concentrations and standard deviations (Std) of TiO_2, P_2O_5, Nb, Zr and Y for the low-Mg felsite (LMF) flows and compositionally corresponding granophyres from various regions. N refers to number of analyses. na = not analysed. Sources of granophyre analyses are as follows: Granophyre[1]: Twist (1985); Granophyre[2]: De Bruiyn (1980); Granophyre[3]: Walraven (1982); Granophyre[4]: De Bruiyn (1980); Granophyre[5]: Walraven (1982); Granophyre[6]: Walraven (1982); Granophyre[7]: Walraven (1982); Granophyre[8]: Kleemann (1985); see Figure 1 for further detail.

CONCLUSIONS

A magma type common to the volcanic rocks in the floor and roof of the RLS and an unconformity beneath the volcanic pile suggests that the volcanic Rooiberg Group should be excluded from the predominantly sedimentary Transvaal Supergroup. The granophyre/felsite relationship and the discordant behaviour of the LGS to the associated rocks of the Bushveld Complex suggest that Rooiberg volcanism and Bushveld magmatism were contemporaneous.

Damwal Formation	TiO_2		P_2O_5		Nb		Zr		Y		N
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std	
LMF	0.57	(0.06)	0.15	(0.03)	15	(2)	330	(32)	51	(13)	86
Granophyre[1]	0.46	(0.02)	0.13	(0.01)	15	(1)	327	(26)	46	(1)	2
Kwaggasnek Formation											
LMF	0.34	(0.07)	0.05	(0.01)	22	(3)	447	(53)	67	(7)	39
Granophyre[2]	0.32	(0.03)	0.04	(0.01)	na		467	(63)	na		10
Granophyre[3]	0.33	(0.04)	na		21	(2)	400	(38)	68	(11)	26
Schrikkloof Formation											
LMF	0.25	(0.01)	0.03	(0.01)	24	(4)	486	(93)	71	(9)	20
Granophyre[4]	0.28	(0.03)	0.04	(0.03)	na		420	(90)	na		15
Granophyre[5]	0.26	(0.02)	na		26	(2)	498	(24)	84	(6)	41
Granophyre[6]	0.28	(0.04)	na		22	(2)	440	(32)	78	(6)	23
Granophyre[7]	0.24	(0.04)	na		26	(3)	466	(47)	94	(17)	24
Granophyre[8]	0.24	(0.04)	0.02	(0.01)	26	(6)	507	(48)	78	(12)	34

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REFERENCES

Cheney, E. and Twist, D., 1991. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. Prec. Res., V52, 115-132.

De Bruiyn, H., 1980. The geology of the acid phase of the Bushveld Complex, north of Pretoria - a geochemical statistical approach. Unpubl. Ph.D. thesis, Univ. Orange Free State, 171pp.

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., van Deventer, J.L. and Hatton, C.J., 1993. The Transvaal Sequence: An overview. J. African Earth Sci., V16 (1/2), 25-51.

Hammerbeck, E.C.I., 1969. The Steelport Park granite, eastern part of the Bushveld Complex, and the magnetitites in the gabbroic country rock. In: Symposium on the Bushveld Igneous Complex and other layered intrusions, Geol. Soc. S. Afr., Spec. Publ. No. 1, 299-311.

Hatton, C.J., 1994. PGE and Cr mineralization in the Bushveld Complex - product of interaction among magmas derived from a mantle plume. Commun. Geol. Surv. Namibia, submitted.

Hatton, C.J. and Sharpe, M.R., 1988. Significance and origin of boninite-like rocks associated with the Bushveld Complex. In: Boninites and related rocks (Ed.: Crawford, A.J.), 174-207.

Kleemann, G.J., 1985. The geochemistry and petrology of the roof rocks of the Bushveld Complex, east of Groblersdal, Unpubl. M.Sc. thesis, Univ. Pretoria, 178pp.

Moore, M., Davis, D.W., Robb, L.J., Jackson, M.C. and Grobler, D.F., 1993. Archean rapakivi granite-anorthosite-rhyolite complex in the Witwatersrand basin hinterland, southern Africa. Geology, V21, 1031-1034.

Sawkins, F.J., 1984. Metal deposits in relation to plate tectonics. P.J. Willie (Ed.), Springer Verlag, 325pp.

Schweitzer, J.K., 1987. The transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group, Transvaal Supergroup: A volcanological, geochemical and petrological investigation. Ph.D. thesis, Univ. Pretoria, in revision.

Schweitzer, J.K. and Hatton, C.J., 1994. Alteration processes within the floor and roof rocks of the Bushveld Complex. Econ. Geol., in revision.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1994. Regional lithochemical stratigraphy of the Rooiberg Group, Upper Transvaal Supergroup: a proposed new subdivision. S. Afr. J. Geol., in revision.

Sharpe, M.R., 1985. Strontium isotope evidence for preserved density stratification in the main zone of the Bushveld Complex, South Africa, Nature, V316, 119-126.

South African Committee for Stratigraphy (SACS), 1980. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. Handbook Geol. Surv. S. Afr., No 8, 633pp.

Twist, D., 1985. Geochemical evolution of the Rooiberg siliceous lavas in the Loskop Dam area, southeastern Bushveld. Econ. Geol., V80, 1153-1165.

Walraven, F., 1979. Granophyre-lava relations in the Bushveld Complex: Ann. Geol. Surv. S. Afr., V13, 59-80

Walraven, F., 1982. Textural, geochemical and genetical aspects of the granophyric rocks of the Bushveld Complex. Unpubl. Ph.D. thesis, Univ. Witwatersrand, Johannesburg, 251pp.

Walraven, F., 1985. Genetic aspects of the granophyric rocks of the Bushveld Complex. Econ. Geol., V80, 1166-1180.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

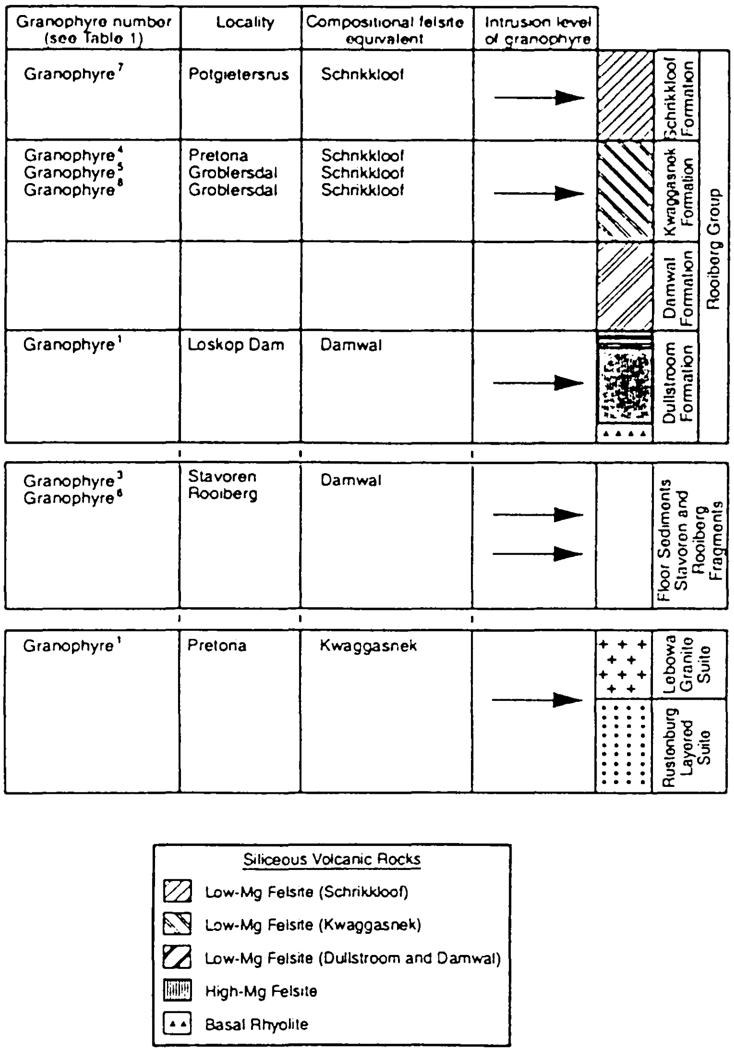

Figure 1. Intrusion levels and other details of the granophyres listed in Table 1.

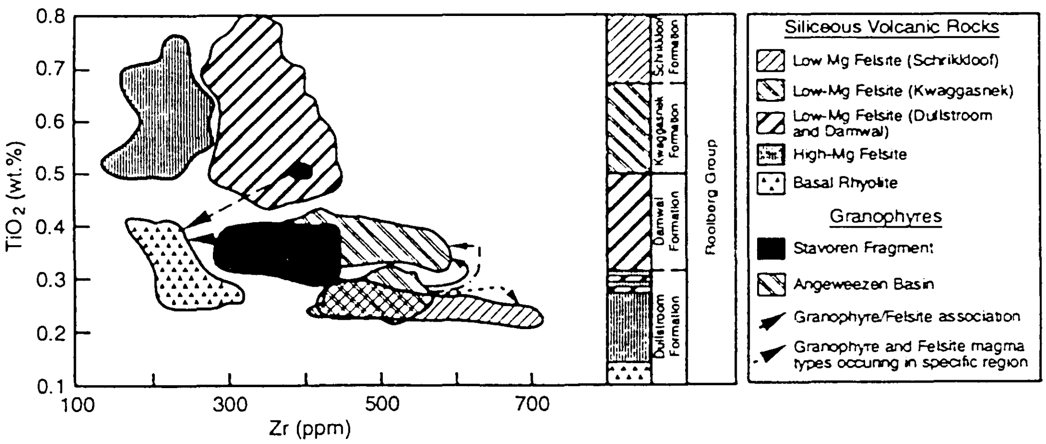

Figure 2: Chemostratigraphic subdivision of the siliceous volcanic rocks comprising the Rooiberg Group using TiO_2 and Zr concentrations. Also shown are the compositional fields of the granophyres as preserved in the Stavoren Fragment and the Angeweezen Basin.

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The World's Largest Platinum, Chromitite, and Gold Deposits, South Africa: Mantle Plume in Origin?

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The link between the Bushveld Complex, the world's largest repository of platinum and chrome, and the Witwatersrand Supergroup, the world's largest repository of gold, is established via lavas of the Ventersdorp Supergroup. The magma parental to the lower zone of the Bushveld Complex is high in magnesium, suggestive of a mantle source. In the Ventersdorp Supergroup are certain lavas with compositions similar to the lower zone magma, but without the high potassium contents. These lavas are thought to be the products of a mantle plume which melted at very shallow levels, at approximately 15-20 km depth. For this to happen the plume must have penetrated the crust. The lower zone magma is thus regarded as a mantle melt similar to the Ventersdorp lavas, but more extensively contaminated by the crust.

The acid lavas of the Bushveld Complex can be modelled as very high degree melts of the shallow crust and can also be linked to a shallow mantle plume which generated secondary melting in the middle crust.

The possible relevance of the mantle plume hypothesis to gold in the Witwatersrand arises from a number of possibilities. It is clear that gold was mobilised in the early stages of the Ventersdorp magmatic event. Sediments associated with the Westonaria Group, the lowermost of the Ventersdorp groups, are rich in gold. These sediments are the products of tectonism associated with the 2.78 Ga Westonaria plume. One possibility is that gold in the Westonaria sediments was remobilised from detrital gold in the underlying 2.93-2.87 Ga Witwatersrand sediments. The upper Witwatersrand sediments of the Central Rand Group are markedly coarser than the lower Witwatersrand sediments of the West Rand Group. This points to increasing tectonism in the later stages of Witwatersrand sedimentation, and we relate this tectonism to the accretion of the Kimberley and Pietersburg terranes to the Wits terrane at 2.88 Ga. Gold mineralisation is frequently associated with terrane accretion, so these accretionary events may have generated source areas for detrital gold in the Central Rand Group.

Another possibility is that gold was not detrital but was introduced by the Westonaria plume in one of two ways. The plume may have dehydrated the crust and so flushed gold into

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the shallow crustal sediments. Alternatively the plume itself could have been the source of the gold. Early Archean plumes are likely to have been unusually rich in gold and platinum group elements, because earth accretion models show that all the gold and PGE in the mantle was added by a late accreting component which constituted only about one percent of the mass of the earth. Mixing of this component into the mantle was probably not instantaneous so many early Archean plumes could contain unusually high proportions of the gold-rich, late accreting component.

Whatever the ultimate source of the gold, we suggest that a mantle plume played a major role in localising gold in the Witwatersrand basin and that the link between plumes and gold be given serious consideration in designing strategies to locate major gold ore-bodies.

The similarities in the composition of some of the Bushveld and Ventersdorp magmas suggests that only a small portion of the gold associated with the Bushveld plume has been economically concentrated, or that major gold deposits are still to be found in the Bushveld aureole.

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The Rooiberg Group: Missing link to the understanding of the Bushveld Igneous Complex?

J.K. Schweitzer, C.J. Hatton and S.A. de Waal

Initial work on the Dullstroom Formation (eastern Transvaal, Makeckaan and Rooiberg Fragments), and some occurrences of the acidic Rooiberg volcanic rocks (Bothasberg Plateau and Tauteshoogte) aimed to establish a link between the Dullstroom and Rooiberg successions, now prized apart by the mafic rocks of the Rustenburg Layered Suite. Field, geochemical and petrographic investigations (Schweitzer et al., 1997a) resulted in: compilation of the first map of the Dullstroom Formation (eastern Transvaal); identification of four magma types (and their vol.%, extrusive mechanisms, and petrographic characteristics) in the Dullstroom floor succession; identification of three potential eruption centers superimposed on the basal unconformity; and the exclusion of an impact origin for the Bushveld Igneous Complex.

Further studies were aimed at the identification of primary and secondary element concentrations within the Rooiberg volcanic rocks (Schweitzer and Hatton, 1995; Schweitzer et al., 1995a). A geochemical database of available Rooiberg, major, trace and rare earth element analyses was compiled. Primary and secondary element concentrations were, as a result, identified by region, facilitating petrogenetic modelling and the correlation of magma types. Nine Rooiberg magma types were defined; the high-Mg Felsite (HMF) magma type is common to the volcanic floor and roof successions, unequivocally establishing that the volcanic sequence was continuous before separation by the mafic rocks occurred. Furthermore, the Rooiberg Group underwent four mineralizing events based on which a regional exploration model could be established. Mafic and siliceous volcanic rocks and associated sedimentary layers of the Makeckaan and Rooiberg Fragments can be related to the basal Dullstroom succession.

The potential of establishing a regionally applicable stratigraphy of the Rooiberg Group was investigated by regionally reviewing previous field work on the Rooiberg Group and combining these findings with the geochemical database (Schweitzer et al., 1995b). Major findings are the establishment of a regionally applicable stratigraphy, the classification of previously undefined Rooiberg occurrences according to their stratigraphic position, the compilation of the first regional Rooiberg Group map detailing the distribution of the four formations, and the identification of intra-Rooiberg unconformities, which are onlapping towards the north and northwest (i.e. uplift in these areas).

The potential link between the Rooiberg volcanic rocks and the other components of the Bushveld Complex was also considered (Hatton and Schweitzer, 1995). Firstly a database comprising the compositions of granophyres of the Rashoop Granophyre Suite was compiled and compositions were compared to those of the Rooiberg volcanic rocks. It was deduced that the vast majority of granophyres are shallow intrusive Rooiberg magmas,

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with more evolved granophyres encountered in the upper Rooiberg succession. The Rooikop Granite Porphyry is the shallow intrusive equivalent of most evolved, youngest Rooiberg magma. Findings suggest that the Rooiberg Group should form part of the Bushveld Complex, with extrusive and intrusive Bushveld magmatism probably having been synchronous. A mantle plume was identified as the most likely source, triggering the Bushveld magmatic event.

In addition, a granite database was established which especially aimed at the comparison of the Nebo Granite and Rooiberg volcanic rocks (Schweitzer et al., 1997a). Nebo compositions compare favorably with youngest Rooiberg magma types, supporting that the Bushveld event was short-lived (<7Ma).

Current and future studies consider two major aspects, i.e. the potential petrogenetic link between the Rustenburg Layered Suite and the Rooiberg magmas, and petrogenetic modelling to investigate the potential interrelationship of the nine Rooiberg magma types.

References

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1995a. Economic potential of the Rooiberg Group - Volcanic rocks in the floor and roof of the Bushveld Complex. Mineralium Deposita, vol. 30, 168-177.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1995b. Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Sequence: a proposed new subdivision. South African Journal of Geology, vol. 98/3, 245-255.

Schweitzer, J.K. and Hatton, C.J., 1995. Chemical alteration within the volcanic roof rocks of the Bushveld Complex. Economic Geology, vol. 90, 2218-2231.

Hatton, C.J. and Schweitzer, J.K., 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. Journal of African Earth Sciences, vol. 21, 579-594.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1997a. The basal portion of the Rooiberg Group, South Africa: the onset of Bushveld magmatism. Journal of Volcanology and Geothermal Research, submitted.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A., 1997b. Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa. Journal of African Earth Science, vol. 24, 95-104.

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Sedimentary Rocks at the Base of the Ventersdorp and Bushveld Plume Events

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Volcanic rocks of the Ventersdorp Supergroup (2714 Ma, Armstrong et al., 1991) and the intrusive and extrusive rocks of the Bushveld Complex (2054 to 2061 Ma, Armstrong, 1997), are related to mantle plumes (Hatton, 1995). Sedimentary rocks at the base of these two major magmatic events are the Ventersdorp Contact reef (VCR), part of the Venterspost Conglomerate Formation (SACS, 1980), and the Sand Sheet (Schweitzer et al., 1997), respectively.

The VCR contributes some 6% to the world's gold production and unconformably overlies the sedimentary rocks of the Witwatersrand Supergroup. A hiatus of about 100Ma has been proposed for the unconformity separating the VCR from the underlying rocks (see Hall, 1997 for review of ages). The VCR is interstratified with komatiitic flows and, taken together with the pronounced basal unconformity, should be considered as the basal formation of the Ventersdorp Supergroup (Germs and Schweitzer, 1994). VCR characteristics are strongly controlled by topographic variations exhibited by the basal unconformity (Schweitzer et al., 1994; McWha, 1994; Henning et al., 1994), and elevation differences of up to 200m are observed where the Booysens Shale is the footwall to the orebody (Schweitzer et al., 1992, 1993). Various topographic elevations exhibit distinct gold concentrations. Individual levels are connected by thin (generally < 25cm) slope conglomerates that posses a low gold tenor. The VCR landscape was continuously uplifted with the oldest VCR deposits occupying topographic highest elevations. Topographic lows are associated with prominently trough cross bedded to planar bedded quartzites, and variable amounts of conglomerate. These are interpreted to represent channel deposits that were active prior to the eruption of initial Ventersdorp flows. The initial komatiitic flows are interstratified with the VCR in the low-lying areas. The VCR is over most of its occurrence capped by a thin (generally less than 30cm) oligomictic conglomerate, which is interpreted as a desert pavement (Germs and Schweitzer, 1994). The VCR was at least partly unconsolidated at the time of lava outpouring, witnessed by the incorporation of detritus into initial volcanic flows, and the loading of magma into the soft sediment.

The top of the Transvaal Supergroup is marked by a widespread unconformity (Cheney and Twist, 1992; Hartzer, 1995). This unconformity marks the onset of the Bushveld igneous event (Hatton and Schweitzer, 1995). Depressions are locally superimposed onto this unconformity, and these could have formed close to eruption centres (Schweitzer et al., 1997). The Sand Sheet covering the unconformity, attains thicknesses of less than 7m and 3m within and beyond the depressions, respectively. However, the sand sheet is generally undisturbed, with pronounced topographic variations

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being absent. The Sand Sheet was, similar to the VCR, unconsolidated at the time of initial outpouring of volcanic flows. The sheet is represented by a very mature, fine- to medium-grained quartzite, Within the depressions it is ubiquitously ripple marked and cross bedded, indicative of a flow direction from north to south. Sedimentary rocks beneath the basal unconformity were, in contrast, sourced towards the northeast and east (Schreiber, 1991).

Both, the VCR and the Sand Sheet, overly an unconformity, are intimately associated with volcanic rocks, and exhibit features distinct from the underlying sedimentary rocks of the Witwatersrand and Transvaal Supergroups. The VCR, in contrast to the Sand Sheet, has deposited on a land surface characterised by major topographic variations and is associated with komatiitic lavas, not found in the Bushveld Complex. Komatiitic lavas and major crustal uplift are located close to and above plume heads (e.g. Campbell and Griffiths, 1990; Rainbird, 1992). Plume uplift influenced VCR deposition, with highest elevation differences encountered above the plume head and the outpouring of komatiitic lavas in the associated lower-lying areas.

The relatively undisturbed, uniform nature of the Bushveld Sand Sheet argues against a plume head being positioned immediately beneath the complex. North to south flow direction of the Sand Sheet and unconformities in the overlying, volcanic Rooiberg Group which onlap towards the north (Schweitzer et al., 1995) suggest crustal uplift in response to an ascending mantle plume occurred towards the north of the present-day outcrop of the Bushveld complex. It is therefore suggested that the Bushveld plume was situated towards the north and that the complex may owe its origin to an intraplating event. The Bushveld mafic rocks emanated from the intraplated magma, intruding as a sill above the Transvaal Supergroup. The intraplating event could coincide with the magmatic event that metamorphosed the Vredefort Dome at the same time (Gibson and Stevens, 1997).

References

Armstrong, R.A., Compston, W., Retief, E.A., Williams, I.S. and Welke, H.J., 1991. Zircon ion-microprobe studies bearing on the age and evolution of the Witwatersrand triad. Prec. Res., 53, 243-266.

Armstrong, R.A. and McCourt, S., 1997. The circa 2.0 Ga "Bushveld Event" - a chronology of events leading to a mineralisation bonanza. Ext. Abstr., Plumes, Plates and Mineralisation Symposium, Pretoria University, 1-2.

Campbell, I.H. and Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth Planet. Sci. Lett., 99, 79-93.

Cheney, E.S. and Twist, D., 1992. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. Prec. Res., 52, 115-132.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Germs, G.J.B. and Schweitzer, J.K., 1994. A provisional model for the regional morphostratigraphy of the Venterspost Conglomerate Formation in the West Rand and Carletonville Goldfields. S. Afr. J. Geol., 3, 279-287.

Gibson, R.L. and Stevens, G., 1997. Regional metamorphism due to anorogenic intracratonic magmatism. Econ. Geol. Res. Unit, Univ. Witwatersrand, Circ. No. 311, 23pp.

Hall, R.C.B., Els, B.G. and Mayer, J.J., 1997. The Ventersdorp Contact Reef: Final phase of the Witwatersrand Basin, independent formation, or precursor to the Ventersdorp Supergroup? S. Afr. J. Geol., 100, 213-222.

Hartzer, F.J., 1995. Geology of Transvaal inliers in the Bushveld Complex. Ph.D. Thesis, Rand Afrikaans Univ., Johannesburg, South Africa, 363pp.

Hatton, C.J., 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. J. Afr. Earth Sci., 21, 571-577.

Hatton, C.J. and Schweitzer, J.K., 1995. Evidence for synchronous extrusive and intrusive Bushveld magmatism. J. Afr. Earth Sci., 21, 579-594.

Henning, L.T., Els, B.G. and Mayer, J.J., 1994. The Ventersdorp Contact Reef placer at Western Deep Levels South Gold Mine - an ancient terraced fluvial system. S. Afr. J. Geol., 3, 308-318.

McWha, M., 1994. The influence of landscape on the Ventersdorp Contact Reef at Western Deep Levels South Mine. S. Afr. J. Geol., 3, 319-331.

Rainbird, R.H., 1993. The sedimentary record of mantle plume uplift preceding eruption of the Neoproterozoic Natkusiak flood basalts. J. Geol., 101, 305-318.

Schreiber, U.M., Eriksson, P.G. and Snyman, C.P., 1991. A provenance study of the sandstones of the Pretoria Group, Transvaal Sequence (South Africa): petrography, geochemistry, and palaeocurrent directions. S. Afr. J. Geol., 94, 288-298.

Schweitzer, J.K., Petschnigg, J.J. and Ashworth, S.G.E., 1992. Topographic variation of the unconformity underlying the VCR at Kloof Gold Mining Co Limited. Ext. Abstr., Geocongress '92., Geol. Soc. S. Afr., Bloemfontein.

Schweitzer, J.K., Demmer, T., Lambert, P.E., McWha, M., Murray, C., Petschnigg, J. and Pilay, V., 1993. The pre-VCR landscape above Jeppestown and Booysens Shale. Ext. Abstr., VCR Mini Symposium - The VCR Revisited, Geol. Soc. S. Afr., Carletonville, 29-32.

Schweitzer, J.K., van Niekerk, A.W., Ashworth, S.G.E. and Henckel, J., 1994. Interrelationship between geomorphology, stratigraphy, and gold grade in the Ventersdorp Contact Reef, eastern portion of Elandsrand Gold Mine. S. Afr. J. Geol., 3, 339-347.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Schweitzer, J.K., Hatton, C.J. and de Waal, S. A., 1995. Regional lithochemical stratigraphy of the Rooiberg Group: a proposed new subdivision. S. Afr. J. Geol., 98/3, 245-255.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A. 1998. Volcanic flows at the base of the Rooiberg Group - the onset of Bushveld magmatism. J. Volcanol. Geotherm. Res., submitted.

South African Committee for Stratigraphy (SACS), 1980. Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Bophuthatswana, Transkei and Venda. Handb. Geol. Surv. S. Afr., 8, 633pp.

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THE CONTACT METAMORPHIC AUREOLE OF THE RUSTENBURG LAYERED SUITE OF THE BUSHVELD COMPLEX: ZN CONCENTRATION AS CHARACTERIZED BY AN X-RAY DIFFRACTION STUDY

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Schweitzer and Hatton (1994) identified two different alteration processes in the volcanic Rooiberg Group, forming the floor and roof rocks of the Rustenburg Layered Suite (RLS) of the Bushveld Complex. The dissipation of heat related to cooling of the Rooiberg volcanics, represented by pyrite and arsenopyrite mineralization, resulted in the first alteration event. This alteration is restricted to specific stratigraphic horizons. The second alteration process is related to the intrusion of the Rustenburg Layered Suite which effected the hydrothermal migration of Pb, Zn, Mn and H_2O away from the contact of the RLS into the Rooiberg volcanics. This paper investigates the correlation of the Zn contents and the mineralogy of the Rooiberg volcanics in the Loskop Dam area. Figure 1 shows the concentration of Zn in the RLS and its floor and roof rocks. The Zn concentration reaches a maximum in the upper Dullstroom Member and then falls abruptly to lower values. This pronounced enrichment of Zn in the Rooiberg felsites is regarded in this study to be the result of metamorphic and metasomatic processes due to the RLS.

A total of 58 samples from the Dullstroom- and Damwal Members of the Bothasberg Formation, and the Kwaggasnek- and Schrikkloof Members of the Selons River Formation were analyzed. Stratigraphically the samples range from the roof contact of the RLS with the Rooiberg felsite to a level 3500m above this contact (Figure 1). The rock samples were powdered to -200 mesh and mixed with Si powder, as internal standard, in a sample : Si ratio of 4 : 1. The mixtures were analyzed, at the University of Pretoria, by X-ray diffractometry (XRD). After background corrections, the peak intensities of selected lines were normalized through division by the count rate of the Si(111) line. The mineral names quoted in the following refer to these normalized XRD intensities of the quartz(101), plagioclase(202), chlorite(002), mica(001), amphibole(110) and calcite(104) lines measured in this study.
Quartz, plagioclase, chlorite, mica (in the form of sericite), amphibole, calcite and, in a few samples, epidote were detected through XRD. The normalized ratios for quartz indicate positive Pearson correlation (r = 0.62) with the distance above the roof contact of the RLS, those of plagioclase show a negative correlation with the same distance (r = -0.73). This results in a negative correlation between quartz and plagioclase (r = -0.60) The other minerals display only weak insignificant correlations with the distance from the RLS/Rooiberg contact.

The Zn concentrations, of the 58 samples follow a log-normal distribution and the logarithm to the base of 10 of the Zn concentration in ppm (logZn) is used in the calculations. LogZn

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shows a significant positive correlation with chlorite (r = 0.45) and a significant negative correlation with quartz (r = -0.49). The correlations between logZn, and plagioclase, mica, amphibole and calcite are very weak.

In order to determine if any relation exists between the Zn concentration and the mineralogy of the felsite, logZn was calculated in terms of the normalized XRD intensities using a multiple regression analysis. The highest correlation between the observed and predicted logZn values is achieved by the following relation:

$$\log Zn = 2.81 - 0.54 \cdot quartz - 1.10 \cdot plagioclase + 2.64 \cdot chlorite \quad (1)$$

The correlation coefficient between logZn and the predicted values is estimated to be 0.61. Variation in the mica, amphibole and calcite concentrations do not appear to significantly affect the amount of Zn present.
Classification of the samples into two groups, i.e. samples, which originate from the upper Dullstroom Member and samples taken above the upper Dullstroom Member, i.e. the Damwal-, Kwaggasnek- and Schrikkloof Members, yields quite different results than described above.
Within the 22 samples from the upper Dullstroom Member, correlations between logZn and the various minerals are generally stronger. The correlation between plagioclase and logZn increases from r = 0.06 to r = 0.46. A multiple regression analysis yields the following relation:

$$\log Zn = 3.06 - 0.98 \cdot quartz - 0.87 \cdot plagioclase + 2.59 \cdot chlorite + 3.48 \cdot calcite - 2.99 \cdot amphibole + 6.99 \cdot mica \quad (2)$$

The logZn estimates for the upper Dullstroom Member, based on Equation 2 are plotted against the observed logZn values in Figure 2. The correlation coefficient between the predicted and the observed logZn values is estimated to be 0.89. All six minerals under discussion seem to influence the Zn content. The primary minerals quartz, plagioclase and probably amphibole all have negative coefficients in Equation 2, whereas the secondary chlorite, calcite and mica give positive coefficients. The coefficients for amphibole and mica, however, show low significance levels of 0.1785 and 0.2263 respectively. These results indicate, that the alteration of plagioclase to secondary chlorite and mica (sericite) is the dominating process associated with the Zn enrichment, which confirms the findings of Schweitzer and Hatton (1994).

Using the remaining 36 samples, taken from levels above the Dullstroom Member, in a multiple regression analysis, the following relation becomes evident:

$$\log Zn = 2.58 - 0.33 \cdot quartz - 0.93 \cdot plagioclase + 1.78 \cdot chlorite \quad (3)$$

The correlation coefficient between logZn and the predicted values for this equation is estimated to be 0.41.

The above shows that, taking all 58 samples as one population, the correlation between the observed and predicted Zn content seems fairly high. Separation of the samples in two groups, i.e. samples from the Dullstroom Member and samples taken stratigraphically above that shows, however, that within the upper Dullstroom Member, the Zn concentration is well described by Equation 2, whereas above that, the Zn content cannot be as well

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shows a significant positive correlation with chlorite (r = 0.45) and a significant negative correlation with quartz (r = -0.49). The correlations between logZn, and plagioclase, mica, amphibole and calcite are very weak.

In order to determine if any relation exists between the Zn concentration and the mineralogy of the felsite, logZn was calculated in terms of the normalized XRD intensities using a multiple regression analysis. The highest correlation between the observed and predicted logZn values is achieved by the following relation:

$$\log Zn = 2.81 - 0.54 \cdot quartz - 1.10 \cdot plagioclase + 2.64 \cdot chlorite \quad (1)$$

The correlation coefficient between logZn and the predicted values is estimated to be 0.61. Variation in the mica, amphibole and calcite concentrations do not appear to significantly affect the amount of Zn present.
Classification of the samples into two groups, i.e. samples, which originate from the upper Dullstroom Member and samples taken above the upper Dullstroom Member, i.e. the Damwal-, Kwaggasnek- and Schrikkloof Members, yields quite different results than described above.
Within the 22 samples from the upper Dullstroom Member, correlations between logZn and the various minerals are generally stronger. The correlation between plagioclase and logZn increases from r = 0.06 to r = 0.46. A multiple regression analysis yields the following relation:

$$\log Zn = 3.06 - 0.98 \cdot quartz - 0.87 \cdot plagioclase + 2.59 \cdot chlorite + 3.48 \cdot calcite - 2.99 \cdot amphibole + 6.99 \cdot mica \quad (2)$$

The logZn estimates for the upper Dullstroom Member, based on Equation 2 are plotted against the observed logZn values in Figure 2. The correlation coefficient between the predicted and the observed logZn values is estimated to be 0.89. All six minerals under discussion seem to influence the Zn content. The primary minerals quartz, plagioclase and probably amphibole all have negative coefficients in Equation 2, whereas the secondary chlorite, calcite and mica give positive coefficients. The coefficients for amphibole and mica, however, show low significance levels of 0.1785 and 0.2263 respectively. These results indicate, that the alteration of plagioclase to secondary chlorite and mica (sericite) is the dominating process associated with the Zn enrichment, which confirms the findings of Schweitzer and Hatton (1994).

Using the remaining 36 samples, taken from levels above the Dullstroom Member, in a multiple regression analysis, the following relation becomes evident:

$$\log Zn = 2.58 - 0.33 \cdot quartz - 0.93 \cdot plagioclase + 1.78 \cdot chlorite \quad (3)$$

The correlation coefficient between logZn and the predicted values for this equation is estimated to be 0.41.

The above shows that, taking all 58 samples as one population, the correlation between the observed and predicted Zn content seems fairly high. Separation of the samples in two groups, i.e. samples from the Dullstroom Member and samples taken stratigraphically above that shows, however, that within the upper Dullstroom Member, the Zn concentration is well described by Equation 2, whereas above that, the Zn content cannot be as well

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predicted by this XRD method.
It is evident that the Zn concentration is a function of the activity of H_2O, as reflected in the alteration mineralogy, as well as temperature and distance from the RLS. Above the Dullstroom Member the alteration effects were apparently much more erratic than within the upper Dullstroom Member. Such effects could be expected where fluid channelling occurred.

The XRD method reported on here represents a first tentative step in the development of a relatively inexpensive method to explore for possible Zn and related mineralization in the Rooiberg volcanics.

REFERENCES

Schweitzer, J.K. and Hatton, C.J. (1994) Alteration Processes within the Volcanic Floor and Roof Rocks of the Bushveld Complex. (submitted for publication)

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A. (1994) Regional Lithochemical Stratigraphy of the Rooiberg Group, Upper Transvaal Sequence: A proposed new Subdivision. (submitted for publication)

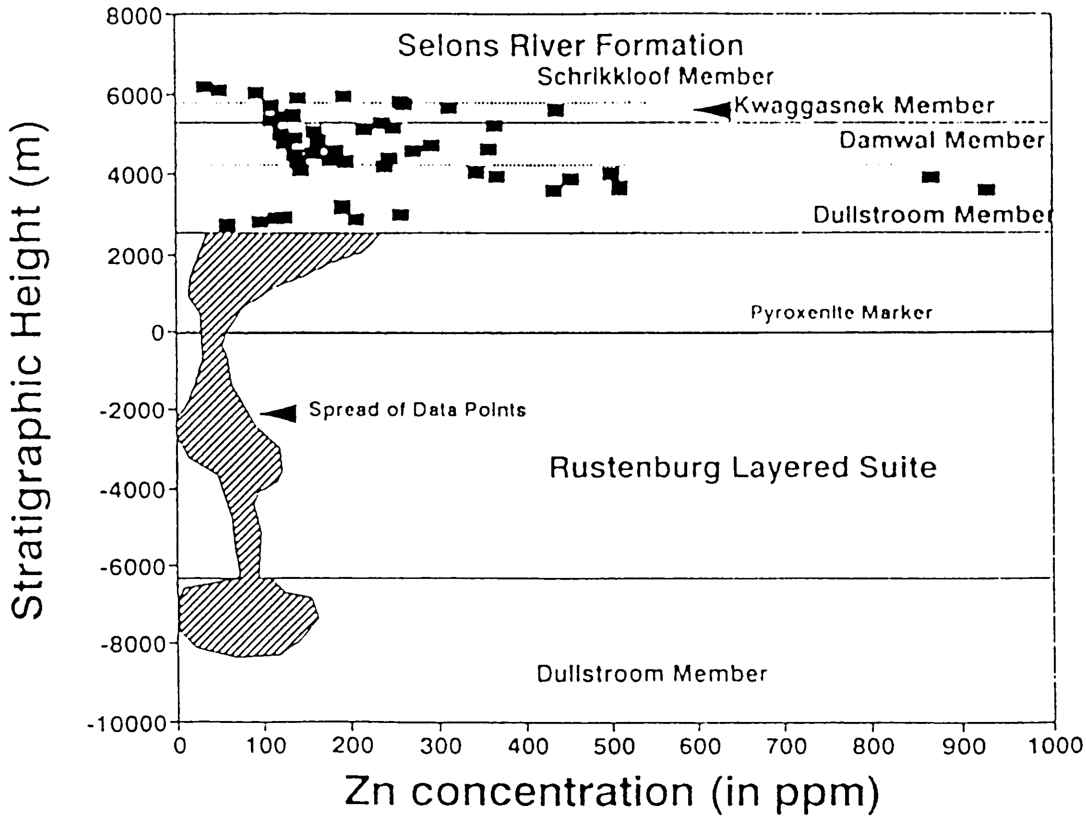

Fig. 1 Zn variation within the volcanic rocks of the Rooiberg Group in the Loskop Dam area related to the distance from the roof of the Rustenburg Layered Suite of the Bushveld Complex (modified after Schweitzer and Hatton, 1994). Nomenclature after Schweitzer et al., (1994)

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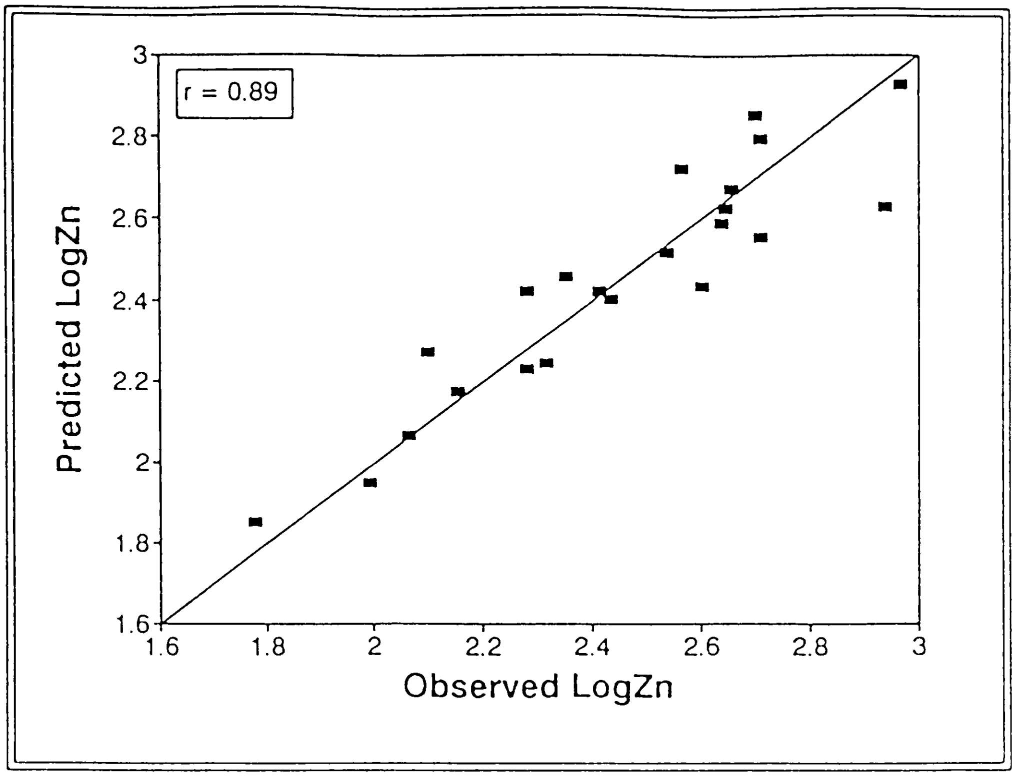

Fig. 2 Plot of observed logZn values versus predicted logZn values (Equation (2) in text) of 22 samples of the Rooiberg volcanics from the upper Dullstroom Member at the Loskop Dam area.

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Appendix C: Co-authored Manuscripts

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The Transvaal Sequence: an overview

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Abstract - The 15 000 m of relatively unmetamorphosed clastic and chemical sedimentary and volcanic rocks of the 2550-2050 Ma Transvaal Sequence as preserved within the Transvaal and correlated Griqualand West basins of South Africa, and in the Kanye basin of Botswana are described. Immature clastic sedimentary and largely andesitic volcanic rocks of the Wolkberg, Godwan and Buffelsfontein Groups and the Bloempoort and Wachteenbeetje Formations probably represent rift-related sequences of Ventersdorp age. The thin sandstones of the Black Reef Formation, developed at the base of both the Kanye and Transvaal basin successions and correlated with the basal Vryburg siltstones of the Griqualand West Sequence, are considered here to be the basal unit of the Transvaal Sequence. The Black Reef fluvial deposits grade up into the epeiric marine carbonates of the Malmani Subgroup. These stromatolitic dolomites and interbedded cherts were laid down within a steepened carbonate ramp setting; transgressions from an initial Griqualand West compartment towards the northeast covered both the Kanye and Transvaal basins. Iron formations of the succeeding Penge Formation and Griqualand West correlates are envisaged as relatively shallow water shelf deposits within the carbonate platform model; siliceous breccias of the Kanye basin are interpreted as reflecting subaerial brecciation of exposed silica gels. The Duitschland Formation overlying the Penge iron formations is seen as a final, regressive clastic and chemical sedimentary deposit, as the Malmani-Penge sea retreated from the Transvaal basin.

The interbedded sandstones and mudstones of the unconformity-bounded Pretoria Group probably represent a combination of alluvial fan and fluviodeltaic complexes debouching into the largely lacustrine Transvaal and Kanye basins. A strong glacial influence in the lower Pretoria Group is reflected in the correlated Makganyene diamictites of the Griqualand West Sequence. Sedimentation across all three basins was interrupted by the extrusion of the Hekpoort-Ongeluk andesites. Upper Pretoria Group sediments of the Silverton and Magaliesberg Formations probably reflect a marine transgression. These rocks are not present in the Griqualand West basin, and were affected by Bushveld Complex-related thermal doming in the Transvaal basin; post-Magaliesberg sedimentation continued thereafter in separate eastern and western fluviodeltaic-lacustrine sub-basins.

The largely volcanic Rooiberg Group (sensu lato) began with catastrophic basin floor collapse and Leeuwpoort Formation fluvial sedimentation in the western sub-basin. The succeeding Smelterskop and Makeckaan Formations reflect a transition from fluvial deposition to volcanism, and are succeeded by the widespread and voluminous, predominantly felsitic lavas of the Dullstroom, Damwal and Selonsrivier Formations. The correlated Loskop, Glentig and Rust de Winter Formations which overlie the felsites conformably, represent the final sedimentary phase of the Transvaal basin.

INTRODUCTION

The Late Archaean-Early Proterozoic Transvaal Sequence provides one of the largest and best preserved examples of rocks from this geological time period in the world. In addition, researchers working on these rocks postulate that early plate tectonic processes may have played a role in their deposition, as did magmatic events leading up to the intrusion of the Bushveld Complex. The Transvaal Sequence also encompasses a time period when significant changes may have taken place in the composition of the terrestrial atmosphere.

The Transvaal Sequence is preserved within a main Transvaal or Bushveld basin within South Africa and southeastern Botswana and within the much smaller Kanye basin (Crockett, 1972) of Botswana (Fig. 1). Both basins show a degree of correlation with the Griqualand West Sequence of South Africa (Table 1), particularly in the case of

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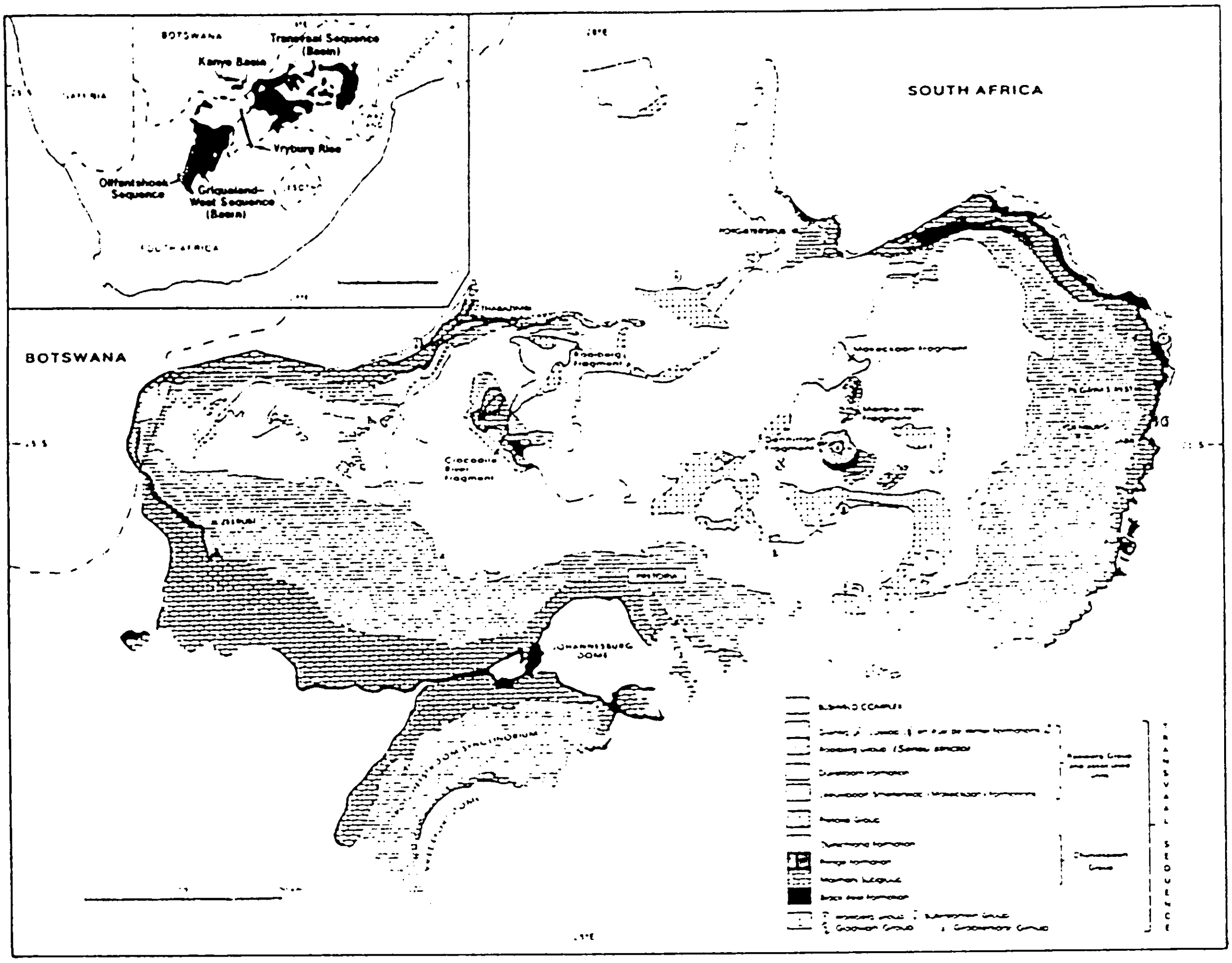

Fig. 1. Geological map of the Transvaal Sequence of the Transvaal-Bushveld basin, showing the distribution of the principal stratigraphic units. Inset map illustrates the location of the Transvaal-Bushveld, Kanye and Griqualand West basins. Also shown are the Bushveld Complex which intrudes the Transvaal rocks, the Vryburg rise between the Transvaal and Griqualand West basins, and isolated occurrences of Transvaal rocks surrounded by Bushveld intrusives at the so-called Rooiberg, Crocodile River, Dennilton, Marble Hall and Makeckaan

the chemical sedimentary rocks in the lower portions of the two sequences. This has led certain reseachers to use the term Transvaal Supergroup to include both sequences (for example, Beukes, 1986), an erroneous usage, as the lack of any contact between the Transvaal and Griqualand West basins precludes the use of an overall term according to normal stratigraphic terminology (SACS, 1980). The stratigraphic subdivision of the Transvaal Sequence adopted by the South African Committee for Stratigraphy (SACS) in 1980 is modified in this paper (Table 2), reflecting research carried out within the last decade. This review will concentrate on the succession within the Transvaal-Bushveld basin, and compare these rocks to those in the Griqualand West and Kanye basins.

The Transvaal Sequence in the Bushveld basin comprises up to 15 000 m (Button, 1986) of relatively undeformed and low grade metamorphosed mudrocks, sandstones, volcanics, dolomites and iron formations (Table 2). A basal clastic sedimentary and volcanic unit (Wolkberg Group and correlates) is found only within parts of the Bushveld basin, and is succeeded by a very widespread development of the Black Reef Formation clastic sedimentary rocks and the overlying chemical sedimentary unit, found in both Bushveld and Kanye basins as well as in the Griqualand West Sequence (Table 1). The overlying clastic sedimentary/volcanic unit (Pretoria Group of the Bushveld basin) is poorly represented in the Griqualand West Sequence and incompletely preserved within the Kanye basin (Table 1). The uppermost, largely volcanic unit is restricted to the Bushveld basin.

Modern research (Clendenin *et al.*, 1988b; Cheney *et al.*, 1990) has suggested that the pre-Black Reef Formation clastic sedimentary/volcanic rocks (Table 2) are correlates of the Late Archaean Ventersdorp Supergroup (Fig. 2), which has an age of approximately 2700 Ma (Armstrong *et al.*, 1991).

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Table 1 Correlation of Griqualand West, Kanye & Transvaal/Bushveld Basins

Overall lithology	Griqualand West Sequence (Basin)			Kanye Basin (Transvaal Sequence) (Botswana)		TRANSVAAL SEQUENCE (Transvaal or Bushveld Basin): S.E. Botswana (Bushveld basin)	TRANSVAAL SEQUENCE (Transvaal or Bushveld Basin): South Africa (Transvaal basin)	
Volcanic & clastic sedimentary unit							Loskop clastics & volcanics Damwal/Selonsrivier Dullstroom lavas/Smelterskop & Makeckaan clastics (lavas) Leeuwpoort sandstones	Rooiberg Group (sensu lato)
Clastic sediments & volcanics						Woodlands volcanics/clastics	Rayton sandstones & shales & volcanics	Pretoria Group
	Postmasburg Group		Mooiwater dolomites & Manganiferous Hotazel ironstones			Sengoma sandstones	Magaliesbeg sandstones	Pretoria Group
	Postmasburg Group		Mooiwater dolomites & Manganiferous Hotazel ironstones			Sengoma shales	Silverton shales	Pretoria Group
	Postmasburg Group		(absent)	Segwagwa Group	Mogapinyana & Gatsepane chert, sandstone & shale	Ditlhojana sandstones/conglomerates	Daspoort sandstones	Pretoria Group
	Postmasburg Group		(absent)	Segwagwa Group	Mogapinyana & Gatsepane chert, sandstone & shale	(absent)	Strubenkop shales	Pretoria Group
	Postmasburg Group		(absent)	Segwagwa Group	(absent)	(absent)	Dwaalheuwel/Droogedal sandstones	Pretoria Group
	Postmasburg Group		Ongeluk andesites	Segwagwa Group	Tsatsu andesites	Ditlhojana volcanics	Hekpoort andesite	Pretoria Group
	Postmasburg Group		Makganyene diamictites	Segwagwa Group	Ditlhojana & Tlaameng shales, sandstones & conglomerates	Ditlhojana shales: conglomerates / shales	Boshoek conglomerates/sandstones shales (Timeball Hill)	Pretoria Group
	Postmasburg Group		Makganyene diamictites	Segwagwa Group	Ditlhojana & Tlaameng shales, sandstones & conglomerates	Tsokwane sandstones	sandstone (Timeball Hill)	Pretoria Group
	Postmasburg Group		Makganyene diamictites	Segwagwa Group	Ditlhojana & Tlaameng shales, sandstones & conglomerates	Lephala: shales / conglomerates/sandstones	shales (Timeball Hill) Rooihoogte conglomerates/ sandstones	Pretoria Group
Regional unconformity								
Chemical sedimentary unit	Ghaap Group	Koegas Subgroup Asbesheuwels Subgroup	Griquatown & Kuruman iron formations	Taupone Group	Masoke ironstone/ferruginous chert	Ramotswa shale	Duitschland carbonates, clastics Penge iron formations	Chuniespoort Group
	Ghaap Group	Koegas Subgroup Asbesheuwels Subgroup	Griquatown & Kuruman iron formations	Taupone Group	Kgwakgwe chert breccia			Chuniespoort Group
	Ghaap Group	Campbellrand Subgrp	Campbellrand dolomites	Taupone Group	Ramonnedi dolomites	Magopane / Maholobota / Ramotswa dolomites	Malmani dolomites	Chuniespoort Group
	Ghaap Group	Schmidtsdrif Subgrp	Lokamonna Formation (shale) Boomplaas Form. (dolomite)	Taupone Group	Ramonnedi dolomites	Magopane / Maholobota / Ramotswa dolomites	Malmani dolomites	Chuniespoort Group
Clastic sediments	Ghaap Group	Schmidtsdrif Subgrp	Vryburg Formation	Black Reef Formation		Black Reef Formation	Black Reef Formation	
Clastic sediments & volcanics (Ventersdorp age)							Pre-Black Reef units - Wolkberg Group & correlates	

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Table 2. Lithostratigraphy and geochronology of the Transvaal/Bushveld Basin

Sequence & Groups		Formation	Age (Ma)	Lithology	Stratigraphic correlation
TRANSVAAL SEQUENCE	Rooiberg (sensu lato)	Loskop/Glentig/Rust de Winter	2060 (U-Pb)	Mudrocks/sandstones/lavas	
		Selonsrivier Damwal	<2090	Felsites (minor sandstones & mudrocks)	
		Dullstroom / Smelterskop Leeuwpoort / (Makeckaan)	<2089 ± 15 (Rb-Sr)	Mafic & felsic lavas/ clastic sediments / Sandstones/mudrocks/ lavas	Dullstroom thought to be basal part of Rooiberg Group
	Pretoria	Rayton/Woodlands: Houtenbek, Steenkampsberg, Nederhorst, Lakenvlei, Vermont		Mudrocks/sandstones/lavas/pyroclastic rocks/carbonate rocks	Pyroclastic Woodlands Formation of Botswana correlated with Rayton Formation of central Transvaal and five formations of eastern Transvaal
		Magaliesberg		Sandstones	
		Silverton		Mudrocks/volcanic rocks/carbonate rocks	
		Daspoort		Sandstones	
		Strubenkop		Mudrocks/sandstones	
		Dwaalheuwel/Droogedal		Sandstones/conglomerates	
		Hekpoort	2224 ± 21 (Rb-Sr)	Basaltic andesites	
		Boshoek		Conglomerates/sandstones	
		Timeball Hill	2263 (Rb-Sr)	Mudrocks/sandstones/minor tilloids	
		Rooihoogte		Breccias/conglomerates/sandstones/ mudrock	Major unconformity and time gap of ± 150Ma
	Chuniespoort	Duitschland		Mudrocks/carbonate rocks/minor volcanic rocks	
		Penge	2432 ± 31 (U-Pb SHRIMP)	Iron formations	
	Chuniespoort – Malmani Subgroup	Frisco		Dolomites/chert/minor shales & sandstones	
		Eccles			
		Lyttelton			
		Monte Christo			
		Oaktree	2557 ± 49 (U-Pb)		
		Black Reef	——	Sandstones/conglomerate	Probable base of Transvaal Sequence
Pre-Transvaal	Pre-Black Reef units	Buffelsfontein Group	Ages are unreliable due to weathered lavas & metamorphic resetting. Wolkberg probably about 2700 Ma.	Sandstones/mafic & felsic lavas/mudrocks	Provisionally considered to be equivalents of Ventersdorp Supergroup
		Godwan Group		Sandstones/lavas	
		Wachteenbeetje Fm.		Mudrocks/carbonate rocks/sandstones	
		Wolkberg Group		Mudrocks/sandstones/basalts	
		Upper Groblersal Group		Sandstones/lavas	
		Lower Groblersdal Group		Metamorphic rocks	Most likely pre-Wolkberg basement material

Age data from Burger and Walraven (1980), Beukes (1987), Jahn *et al.* (1990), Trendall *et al.* (1990) and Harmer and Von Gruenewaldt (1991).

This view is supported by the present authors and we thus consider the basal unit of the Transvaal Sequence to be the Black Reef Formation (Table 2). The Black Reef sandstones grade up into the basal carbonate rocks of the Oaktree Formation (Table 2); rocks at the equivalent stratigraphic level in the Griqualand West basin are dated at 2557 ±49 Ma (U-Pb) (Jahn *et al.*, 1990). Ages determined at various stratigraphic levels within the Transvaal Sequence (Table 2) culminate in an age of 2060 Ma (U-Pb) for lavas in the uppermost Rust de Winter Formation (Burger and Walraven, 1980). Walraven *et al.* (1990) have dated the intrusion of the mafic phase of the Bushveld Complex, which truncated the uppermost formations of the Pretoria Group and the Dullstroom lavas (Button, 1973, 1976), at 2061 ±27 Ma. An age constraint of approximately 2600/2500 - 2050 Ma may thus be placed on the Transvaal Sequence.

The intrusion of the Bushveld Complex detached the Rooiberg Group lavas and overlying Loskop Formation sedimentary rocks from the underlying Pretoria Group. Metamorphism of the Rooiberg felsites, which now form the roof of the complex, led to partial melting of the lavas and to the formation of leptites (French and Twist, 1983). Contact metamorphic effects on the Pretoria Group floor rocks included recrystallisation of sandstones to form quartzites, the formation of hornfelses or even partial melting and plastic flow of mudrocks (Button, 1986). The metamorphic aureole of the Bushveld Complex in the western outcrops of the Pretoria Group includes rocks belonging to the albite-epidote-hornfels, horn-

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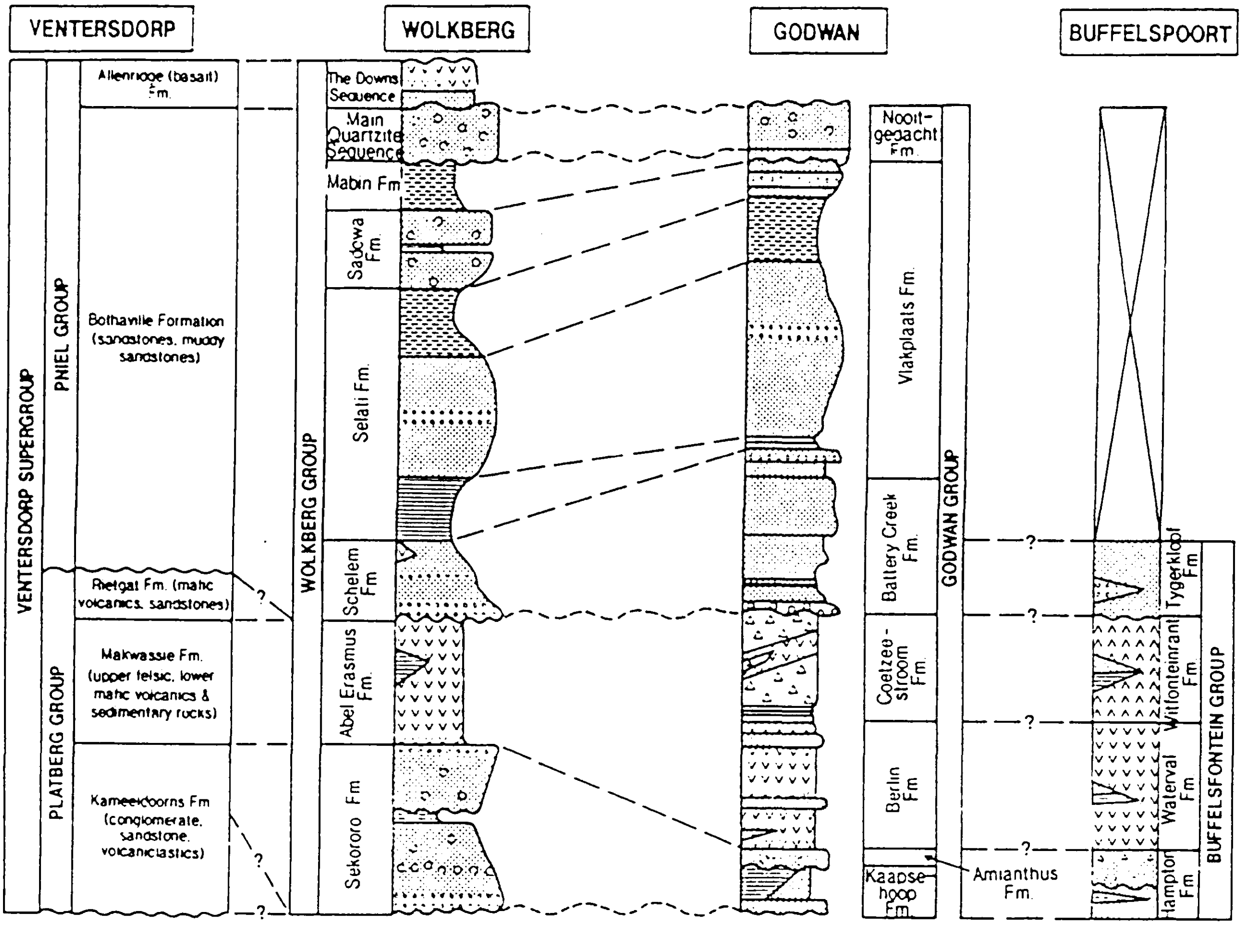

Fig. 2. Lithostratigraphy and correlation of the pre-Black Reef Formation units of the Transvaal Sequence. Note the proposed correlation of these units with the Ventersdorp Supergroup. Modified after Tyler (1979), Cheney *et al.* (1990), Myers (1990) and Bosch (1992).

blende-hornfels and pyroxene-hornfels facies (Engelbrecht, 1986). Cross-cutting Bushveld intrusives in the northeastern Transvaal basin formed metamorphic minerals in the Chuniespoort Group chemical sediments (Button, 1976, 1986). Bushveld related diabase sills commonly intrude the Pretoria Group strata, particularly the Silverton and succeeding formations (Table 2) (Button, 1976; Sharpe, 1981).

The Transvaal strata dip at angles up to 20° towards the centrally placed Bushveld intrusives (Fig. 1). Locally, diapiric structures are found within Transvaal sediments along the contact zone (Button, 1978, 1986) and complex deformation of the sequence occurred along the northern margin of the preserved basin, and in the south around the Vredefort Dome (Button, 1986). Isolated occurrences of Transvaal rocks surrounded by Bushveld intrusives, known as "fragments", are found at Rooiberg, Crocodile River, Dennilton, Marble Hall and Makeckaan (Fig. 1). These are ascribed either to pre-Bushveld updoming of the basin floor (Button, 1986; Hartzer, 1987), or may be related to a late Pretoria Group synsedimentary thermally induced palaeohigh (Eriksson *et al.*, 1990).

PRE-BLACK REEF FORMATION UNITS

Highly metamorphosed gneisses, schists and metavolcanics of the lower Dennilton Formation of the Groblersdal Group (Fig. 1) are inferred by the present authors to represent basement material to the pre-Black Reef units discussed here. The U-Pb age of 2460 Ma (Coertze *et al.*, 1978) obtained on rocks of this group is interpreted to be a reset metamorphic age. The overlying sedimentary and volcanic rocks of the Bloempoort formation are most likely correlates of the pre-Black Reef units (Hartzer, 1987). Both the 2600 m thick Wolkberg and 1700 m thick Buffelsfontein Groups are thickest over palaeovalleys in the earlier Archaean floor rocks and wedge out against basement highs (Button, 1973; Tyler, 1978; SACS, 1980). These successions and the correlated Godwan Group (Myers, 1990) most likely represent Ventersdorp-age, largely rift-controlled sedimentation and volcanism (Clendenin *et al.*, 1991) (Fig. 2), preserved around the present day northern and eastern margins of the succeeding Transvaal basin (Fig. 1). The 800 m of calcareous mudrocks, sand-

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stones and dolomites of the Wachteenbeetje Formation underlying the Crocodile River fragment in the west-centre of the Transvaal basin (Fig. 1) are ascribed to deeper basinal conditions (Hartzer, 1987), possibly related to thermal subsidence.

The Wolkberg Group comprises basal immature sandstones and conglomerates of the Sekororo Formation (Fig. 2), laid down by braided stream and subordinate alluvial fan processes (Button, 1973; Bosch, 1992). These are overlain by andesitic lavas of the Abel Erasmus Formation; eruption was largely subaerial, with periodic pillow lavas and aqueous sedimentation indicating intermittent, localised lacustrine environments (Button, 1973; Bosch, 1992). The succeeding Schelem Formation (Fig. 2) is analogous to the Sekororo braided stream deposits; these lower three formations of the Wolkberg Group most likely represent a rifting environment, with the succeeding Selati, Mabin and Sadowa Formations probably being related to thermal subsidence. The latter three units comprise predominant mudrocks, immature and mature sandstones (Fig. 2), which are ascribed to deltaic and marginal marine sedimentation (Button, 1973); the basin may alternatively have been intracratonic (Bosch, 1992). The Wolkberg Group (*sensu stricto*, SACS, 1980) is thickest in the Selati trough of the northeastern Transvaal, where the Sadowa Formation is overlain by a "main quartzite sequence" and the succeeding "The Downs sequence" (Fig. 3), both informal stratigraphic units not yet recognised by SACS (Schwellnus *et al.*, 1962; Clendenin *et al.*, 1991). Fluvially deposited siliciclastics of the "main quartzite sequence" are unconformably overlain by pebbly fluvial sandstones and the Serala Basalt Member of "The Downs sequence" (Fig. 3) (Clendenin *et al.*, 1991). Both of these informal, unconformity-bounded units are considered here to be part of the Wolkberg Group (*sensu lato*) (Schwellnus *et al.*, 1962; Clendenin *et al.*, 1991) (Fig. 2) and formation status is recommended. Clendenin *et al.* (1991) related "The Downs sequence" to thermal subsidence following the rifting which initiated lower Wolkberg deposition.

The Buffelsfontein Group comprises basal immature fluvial sandstones, overlain by up to 1050 m of mafic to rhyolitic volcanics, and uppermost immature pebbly sandstones (Fig. 2) (Tyler, 1978). A similar rift environment to that inferred for the lower Wolkberg Group is thought to have controlled Buffelsfontein deposition. Palaeocurrents for the Wolkberg and Buffelsfontein Groups indicate sediment transport from the northeastern and northwestern Transvaal towards the central Transvaal, where the deeper water basinal deposits of the Wachteenbeetje Formation occur (Tankard *et al.*, 1982; Hartzer, 1987). The Godwan Group, a correlate of the Wolkberg Group in the eastern Transvaal (Fig. 2), consists of analogous immature arenites and medial pyroclastic rocks (Myers, 1990), with a maximum thickness of about 1500 m (SACS, 1980); a similar fluvial-subaerial volcanic palaeoenvironment is envisaged.

BLACK REEF FORMATION

The Black Reef Formation, here regarded as the basal unit of the Transvaal Sequence, comprises a thin veneer of arenaceous rocks, which unconformably overlie earlier lithologies, including the Wolkberg Group (Fig. 3) (Button, 1973; Clendenin *et al.*, 1991). The formation is preserved around the present day margins of the Transvaal basin (Fig. 1). Thicknesses are mostly between a few metres and 30 m, with a maximum of 60 m being recorded in eastern Botswana (SACS, 1980; Key,

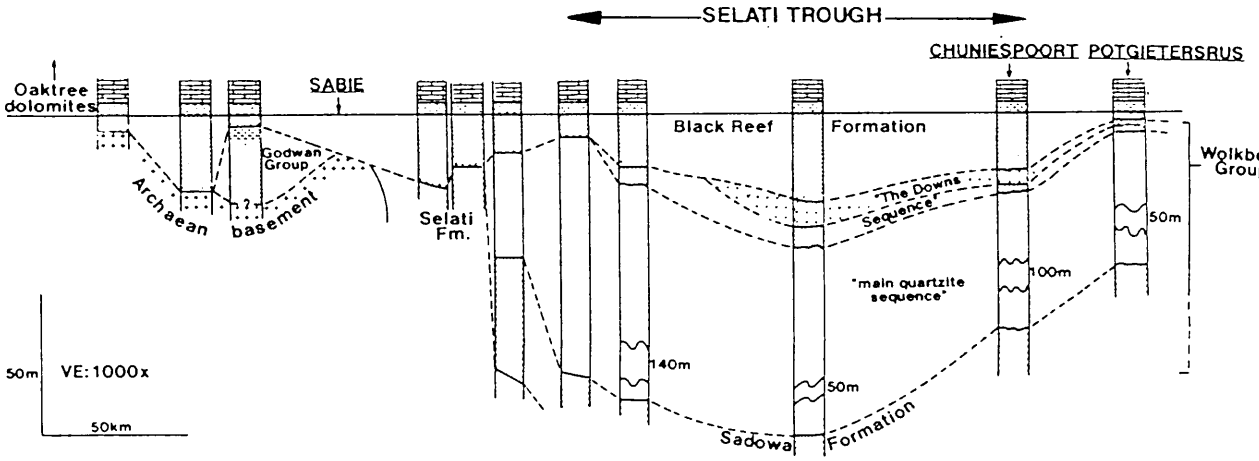

Fig. 3. Detailed lithostratigraphy of the upper part of the Wolkberg Group (sensu lato) illustrating the relationship of the Black Reef Formation with the underlying units. Modified after Clendenin *et al.* (1991).

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1986; Henry *et al.*, 1990). In the eastern Transvaal the maximum thickness of 30 m is attained over the pre-existing Selati trough (Fig. 3) (Clendenin *et al.*, 1991). The Black Reef Formation is correlated with the basal Vryburg Formation of the Griqualand West Sequence (Table 1), composed of predominant siltstone, with subordinate mudstone, quartzose sandstone and lava (SACS, 1980).

Recent research on the Black Reef Formation has concentrated on the eastern Transvaal, where Henry *et al.* (1990) identified six lithologies: poorly sorted lenticular clast- and matrix-supported conglomerates, trough and planar cross-bedded sandstones, plane laminated arenites and laminated carbonaceous mudrocks. These facies are stacked in a basal, locally developed, upward-fining sequence, overlain by a sheet-like upward-coarsening facies sequence (Fig. 4). The uppermost mudrocks generally grade into the overlying dolomites of the Malamani Subgroup (Fig. 4) (Button, 1973, 1986). A similar basal conglomerate-predominant arenite-interbedded mudrock association is found in the west of the basin, with the arenites or mudrocks grading up into the overlying dolomites (Key, 1983, 1986).

Button (1973) interpreted the basal Black Reef conglomerates as fluvial deposits, with the succeeding mature quartz arenites being envisaged as a subtidal sheet sand, laid down as an epeiric protobasin developed over the Kaapvaal craton. A similar marginal marine-fluvial model is proposed by Key (1983, 1986). Henry *et al.* (1990) interpreted the lower upward-fining sequence (Fig. 4) as having been deposited in a sandy braided fluvial setting, locally channelised, analogous to Button's (1973) view. However, the upper upward-coarsening sequence (Fig. 4) is ascribed to a prograding braid-delta or braid-plain environment (Henry *et al.*, 1990). The transgressive mudrock (Clendenin, 1989) at the top of the formation (Fig. 4) reflects a tidal flat setting, marking the establishment of the epeiric marine carbonate platform of the Chuniespoort sea. Henry *et al.* (1991) ascribed the subtle unconformity at the base of the Black Reef Formation to northward tectonic tilting, related to thermal subsidence over the Kaapvaal craton following the Ventersdorp rifting; they saw these events as reflecting the closing stages of Ventersdorp age sedimentation, rather than being the protobasin deposits to the Chuniespoort sea, as envisaged by Button (1973) and Key (1983).

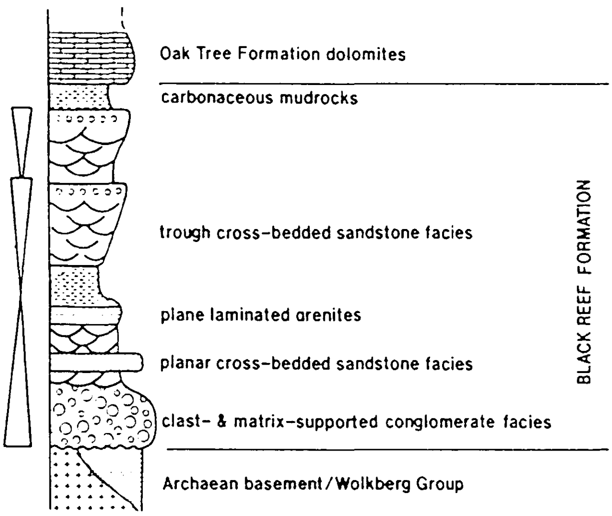

Fig. 4. Facies sequence of the Black Reef Formation in the eastern Transvaal basin. Modified after Henry *et al.* (1990).

MALMANI SUBGROUP

The dolomites and interbedded cherts and mudrocks making up the Malmani Subgroup represent epeiric marine deposits which were deposited over a very large portion of the Kaapvaal craton, stretching well beyong the preserved outcrops within the Transvaal, Griqualand West and Kanye basins (Fig. 1). The widespread nature of the Chuniespoort Group epeiric rocks contrasts with the succeeding Pretoria, Postmasburg and Segwagwa Groups, which appear to have been largely restricted to these three basins. The Malmani Subgroup is correlated with the upper portion of the Schmidtsdrif Subgroup and the overlying Campbellrand Subgroup of the Griqualand West Sequence and with the Ramonnedi dolomites of the Kanye basin (Table 1). Button (1973) and SACS (1980) subdivided the Malmani Subgroup into five formations (Fig. 5), based largely on chert contents and the nature of the stromatolites in the rocks. Interbedded chert-in-shale breccias, mudrocks and sandstones are thin and commonly mark the location of marginal unconformities (Clendenin and Maske, 1986). On the basis of these unconformity-bounded sequences, Clendenin (1989) has subdivided the Malmani epeiric sea succession and overlying Penge and Duitschland Formations into five "packages"; the lowermost package is found only in the Griqualand West basin and the uppermost package includes the Penge Formation and correlated Griqualand West iron formations which gradationally overlie the dolomites (Fig. 5). The modified stratigraphic subdivision of Clendenin (1989) makes use of the stratigraphic terminology originally devised by Button (1973) and is supported by the present authors (Fig. 5). The packages are generally thickest in the Griqualand West basin and thin towards both the Transvaal and Kanye basins (Aldiss *et al.*, 1989; SACS, 1980; Clendenin and Maske, 1986). Stromatolites characterise the carbonate-chert sequence of the Malmani Subgroup, with forms varying from crinkly laminations, domical

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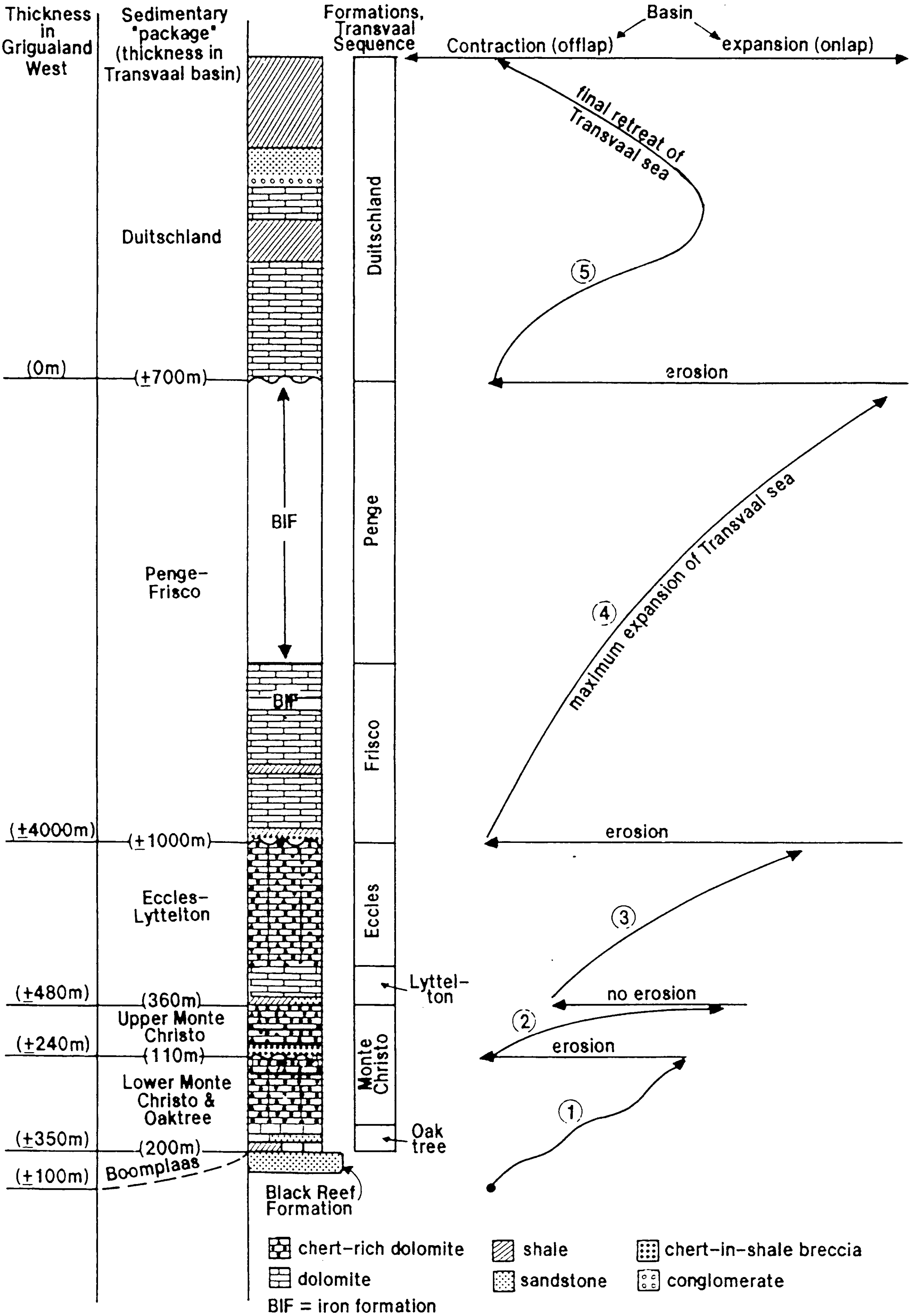

Fig. 5. Lithostratigraphy of the Malmani Subgroup, Penge and Duitschland Formations, Chuniespoort Group, Transvaal Sequence. Also shown are the "sedimentary packages" of Clendenin (1989), their thicknesses in the Transvaal and Griqualand West basins, and the transgressive expansion and regressive contraction of the proposed epeiric sea palaeoenvironment.

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and columnar stromatolites to enormous, elongated algal mounds, up to 100 m long and 2 m high (Eriksson and Truswell, 1973). MacGregor *et al.* (1974), Nagy (1984) and Klein *et al.* (1987) successfully isolated algal microstructures in Malmani samples. Mechanically-formed sedimentary structures are common in the dolomites, including numerous ripple marks, oolites, intraclastic breccias and lesser cross-laminations (Button, 1973).

The basic, tidally-influenced palaeoenvironmental model supported by most researchers for the Malmani Subgroup was first suggested by Truswell and Eriksson (1973), Eriksson and Truswell (1974) and Eriksson *et al.* (1975), for a number of isolated localities. These workers proposed a modified version of the limestone shelf model, encompassing supratidal deposits, columnar stromatolites in an intertidal zone, a high energy zone above wave base with oolites and mechanically-formed sedimentary structures, and shallow and deep subtidal zones characterised by large stromatolitic domes and mounds (Fig. 6a). Limestones and dolomites characterise the intertidal, high energy and shallow subtidal zones, with dolomites being found in the deep subtidal facies (Fig. 6a) (Eriksson *et al.*, 1975).

Following upon the earlier work of Eriksson and co-authors, Beukes (1978, 1980, 1986, 1987) applied this basic tidally-influenced model to the carbonate rocks throughout the Transvaal and Griqualand West Sequences. Beukes (1987) differentiated between an initial carbonate ramp setting characterised by giant stromatolitic mounds, and which deepened towards a deep shelf environment in the west of the Kaapvaal craton, and a succeeding mature rimmed carbonate shelf model for the upper portion of the carbonate sequence (Fig. 6c). The latter encompassed eastern supratidal mudflats, passing westwards into broad zones of intertidal mudflats and shelf lagoonal settings, with a deeper euxinic basin in the far west (Fig. 6c) which exhibited turbiditic deposits as well (Beukes, 1987). Geophysical investigations of the western part of the Kaapvaal craton support Beukes' concept of a carbonate basin which was shallower in the east and deeper towards the west (Geerthsen *et al.*, 1991). However, the southwestern portion of the Griqualand West carbonate succession has been subjected to multiple folding and thrusting (Altermann and Hälbich, 1990), and the resultant thickening of sediments may be partly responsible for the observed geophysical trends. Altermann and Herbig (1991) and Hälbich *et al.* (1992) dispute the postulate that the carbonate basin became deeper towards the western margin of the Kaapvaal craton; they provide evidence of supratidal to intertidal flats in the southwestern region, analogous to the shallow water carbonate platform of Beukes (1987) to the east. The deepest portion of the basin is envisaged to have lain between these two shallow tidal platforms, co-incident with the Griquatown fault zone (Altermann and Herbig, 1991). Water depths within the carbonate platform/shelf model are estimated to have been up to 80 m in the euxinic deep basin (Klein *et al.*, 1987); REE chemistry of the carbonates also supports generally shallow water marine conditions, with the possibility of some freshwater mixing having taken place (Danielson, 1990).

Clendenin (1989) and co-workers (Clendenin and Maske, 1986; Clendenin *et al.*, 1988b) refined the early shelf model of Eriksson *et al.* (1975) to include Beukes' (1987) distal shallow basin (Fig. 6b); in addition, Clendenin (1989) related his carbonate ramp/steepened carbonate ramp model to syndepositional tectonics, which formed part of a successor basin sequence within the Kaapvaal craton during the late Archaean (Clendenin *et al.*, 1988a and b). Clendenin's broad facies belt model (Fig. 6b) inferred an arid and/or tropical palaeoclimate, supported by palaeomagnetic data (Windley, 1979), and tides whose height may have increased as open ocean tides encroached onto the wide, shallow carbonate platform (Klein, 1982; Pratt and James, 1986); facies distribution was determined largely by water depth and regressions and transgressions of the vast Transvaal-Griqualand West epeiric sea led to vertical stacking of deposits from the different facies within the carbonate ramp model shown in Figure 6b. Transgressions were predominantly towards the north-northeast, as the depository expanded from an initial Griqualand West compartment (Figs 5 and 6d). At the end of lower Monte Christo times, the sea retreated off the Kaapvaal craton, forming the erosional unconformity developed within this formation (Fig. 5). The north-northeastward transgressions were re-initiated three more times during Malmani deposition (Figs 5 and 6d), developing the sedimentary packages preserved in the rock record (Fig. 5). It should be noted that the final Malmani transgression had the greatest extent and continued on into the period of deposition of the succeeding Penge iron formations (Fig. 5); a final, fifth transgression-regression cycle was responsible for the deposition of the Duitschland Formation, the uppermost unit of the Chuniespoort Group (Fig. 5, Table 2). Dolomitization of primary limestones appears to have taken place shortly after deposition (Eriksson *et al.*, 1975); dolomitization was probably also related to meteoric waters which lowered the pH (Eriksson *et al.*, 1976).

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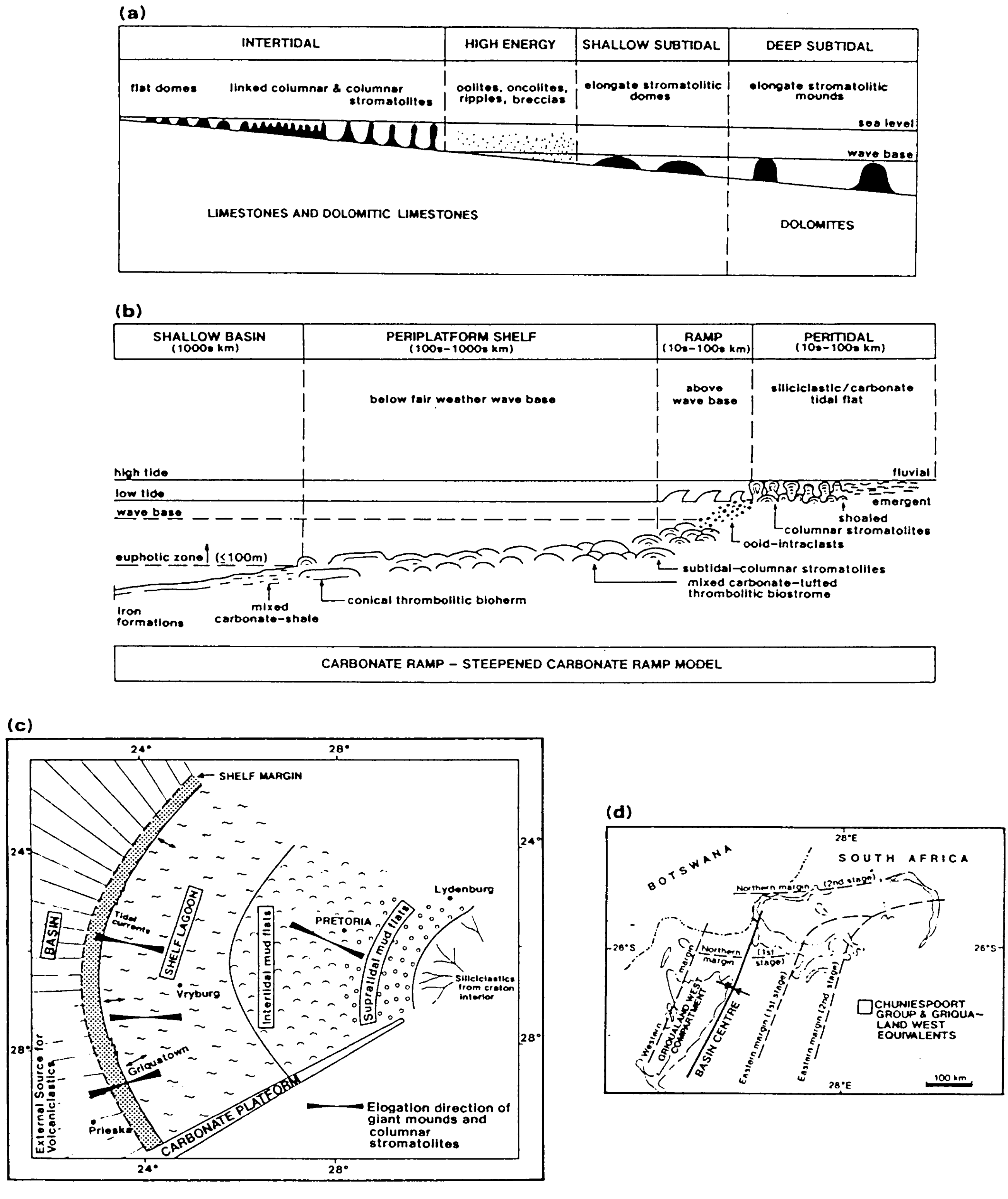

Fig. 6. Depositional models proposed for the Malmani Subgroup dolomites. (a) Limestone shelf model of Eriksson *et al.* (1975). (b) Carbonate ramp-steepened ramp model of Clendenin (1989). (c) Carbonate ramp - deep shelf model of Beukes (1987). d) Clendenin's (1989) proposed expansion of the Malmani epeiric sea from an initial Griqualand West compartment towards the north and northeast.

PENGE AND DUITSCHLAND FORMATIONS

The Penge and correlated iron formations of the Asbesheuwels Subgroup of Griqualand West (Table 1) overlie the Malmani dolomite sequence gradationally. As with the underlying dolomites, these iron formations formed part of a depositional system that covered a large portion of the Kaapvaal craton, including outcrops preserved in the Griqualand West, Transvaal and Kanye basins (Fig. 1).

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The Penge Formation is composed predominantly of micro- to macro-banded iron formations with laterally persistent monomineralic or mixed mineral laminae of quartz, magnetite, hematite, stilpnomelane, riebeckite, minnesotaite, grunerite and ferruginous carbonate minerals (Beukes, 1973; Button, 1986; Van Deventer *et al.*, 1986). Stacked cycles of alternating ferruginous minerals are common (Beukes, 1978), with subordinate interbeds of carbonaceous mudrock and intraclastic iron formation breccias (Button, 1986). Shard structures, mostly in the basal Penge Formation (La Berge, 1966) suggest volcanic influences in the formation of these ferruginous lithologies. Bushveld Complex related contact metamorphism of the Penge iron formations has resulted in large scale recrystallisation and gruneritisation (Beukes, 1973, 1978). In the west of the Transvaal basin, there is a gradation into the Ramotswa Shale Formation of Botswana (Table 1), where ferruginous and siliceous mudrocks overlie the dolomites gradationally (Key, 1983). Their ferruginous nature appears to be due to diagenetic weathering of disseminated pyrite (Key, 1983). In the Kanye basin (Fig. 1), chert breccias are found at the stratigraphic level of the Penge Formation (Crockett, 1972) (Table 1); these rocks comprise equidimensional, angular chert and jaspilite fragments in a ferruginous matrix (Crockett, 1972; Aldiss *et al.*, 1989).

Beukes (1978, 1983) postulates that the Griqualand West-Transvaal iron formations were laid down within a clear water epeiric sea, covering much of the Kaapvaal craton, and bounded to the west and north by a deep basinal setting (Fig. 7). An external source of siliciclastic and volcanoclastic material is inferred, with authochthonous iron formations being deposited in the deep basinal areas and orthochemical and allochemical iron formations on the central shallow platform region (Beukes, 1978, 1983) (Fig. 7). This basin may have been fault-controlled (Button, 1973; Beukes, 1977, 1978, 1980). Mechanical reworking of iron formations was widespread on the platform, and the clastic sediments in the Koegas Subgroup (Table 1) may have been laid down within a fresh water lacustrine setting (Beukes, 1986).

The stratigraphic continuity on which Beukes' model relies, is challenged by Altermann and Hälbich (1990), who present clear evidence for early tectonic displacement and karstification of both iron formations and underlying carbonate rocks in the southwest of the craton. Hälbich *et al.* (1992) also demonstrate convincingly that shallow water and fresh water contamination conditions prevailed during genesis of the iron formations in this same southwestern region; in addition they dispute the importance of a volcanic influence in iron formation genesis. The shallow water setting proposed by Hälbich *et al.* (1992) is in agreement with REE patterns determined by Danielson (1990) and with Clendenin's (1989) carbonate ramp model in which iron formations are seen as a deeper water facies equivalent of the platform carbonates (Fig. 6b). Water depths of Clendenin's (1989) euphotic zone (Fig. 6b) were equivalent to those of a shelf setting rather than the deep basin envisaged by Beukes (1983). The gradational basal contact of the Penge Formation with the underlying Malmani dolomites supports a similar depositional setting for these chemical sediments (Eriksson and Clendenin, 1990). Shallow water conditions are also postulated for the ferruginous mudrocks and cherts found in the Bushveld and Kanye basins in Botswana (Table 1). The Ramotswa Formation mudrocks are ascribed to a regressive nearshore back-reef palaeoenvironmental setting and to mudflat deposition (Key, 1983). The Kgwakgwe breccias may reflect either tectonic formation along thrust soles (Rabie, 1958), karstification of chert-rich dolomite (Cullen, 1958), or dehydration of silica gels related to tectonic instability in the northwestern margin of the Penge basin (Crockett, 1972). Tectonic studies do not support the first hypothesis and the petrology of the breccias cannot be explained adequately by the second theory. The most plausible explanation is that tectonic instability of the basin margin led to uplift and subaerial exposure, thereby promoting brecciation of exposed silica gels and the non-deposition of iron formation (Crockett, 1972; Aldiss *et al.*, 1989).

The Penge Formation (and correlates) is seen by Clendenin (1989) as part of a Frisco-Penge "package", laid down as the Transvaal-Griqualand West sea underwent maximum expansion, thereby depositing deeper water iron formations over the Malmani carbonate platform (Fig. 5). This primitive early Proterozoic ocean is inferred to have been the source of both iron and silica, with possible subordinate contributions from external volcanic and terrestrial weathering sources (Beukes, 1983). The carbonaceous mudrocks, limestones and dolomites, with subordinate conglomerates, diamictites and lavas of the Duitschland Formation, which overlies the Penge Formation unconformably (Taussig and Maiden, 1986), are interpreted as a final, shallow, regressive facies of the Malmani-Penge epeiric sea (Fig. 5) (Clendenin, 1989).

THE PRETORIA GROUP

The Pretoria Group overlies the chemical sedimentary rocks of the Chuniespoort Group unconformably; the unconformity is commonly both

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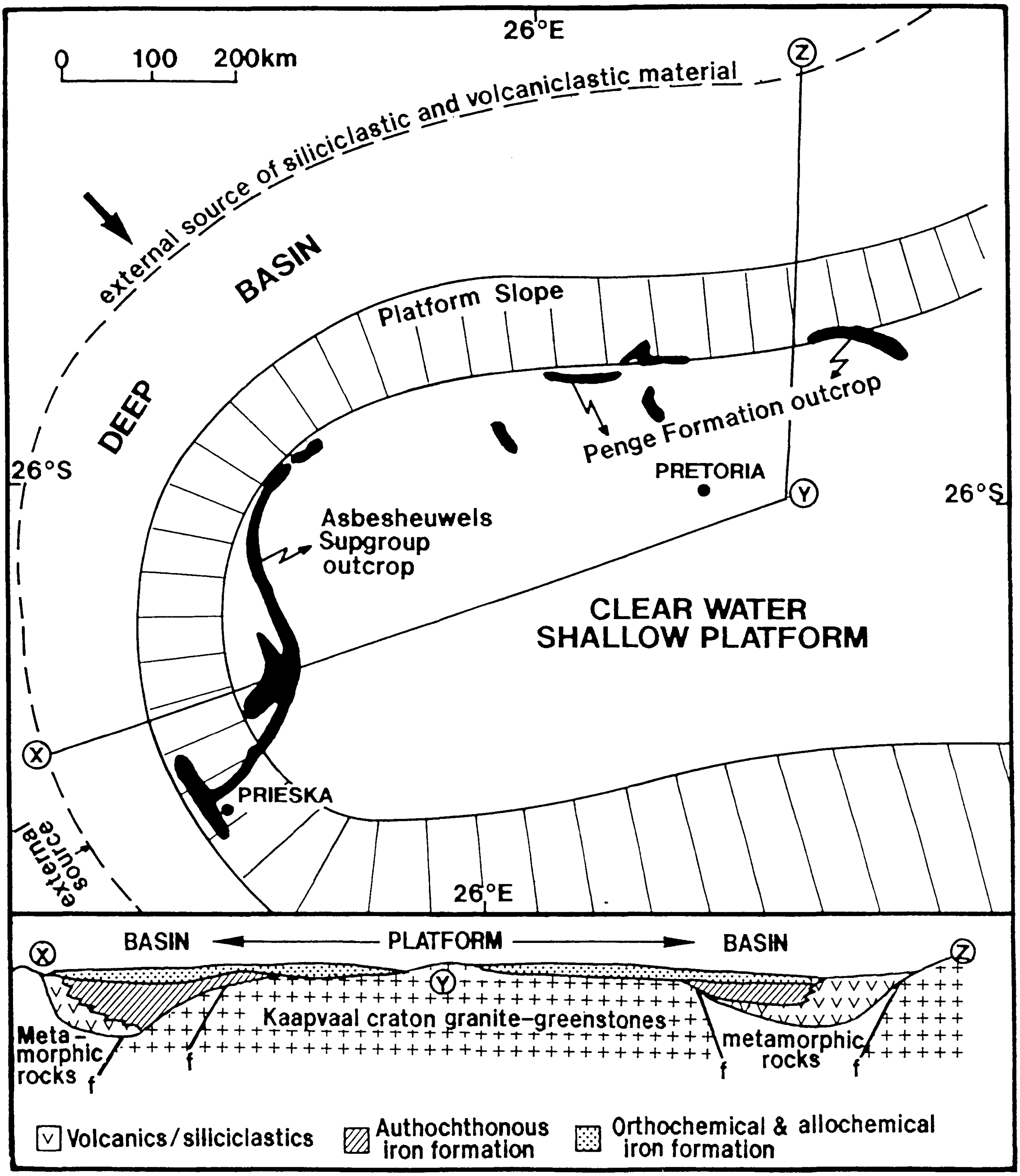

Fig. 7. Clear water epeiric platform - platform slope - deep basin model proposed for the Penge and correlated iron formations of the Transvaal and Griqualand West Sequences, after Beukes (1978, 1983).

angular and karstic (Button, 1973) and radiometric ages (Table 2) suggest a significant hiatus in Transvaal deposition. The lithostratigraphy of the Pretoria Group (Fig. 8) comprises a predominant alternation of mudrocks and sandstones, with less important volcanic horizons and subordinate diamictites and conglomerates. There are significant lithological differences across the basin, particularly in the upper part of the stratigraphy, and thicknesses are also variable (Fig. 8). Correlation of these rocks with the upper portion of the Griqualand West Sequence and with sedimentary rocks of the Kanye basin is poor (Table 1), with only the Hekpoort-Ditlhojana-Tsatsu-Ongeluk andesites

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Formations		TRANSVAAL BASIN WEST	CENTRE	EAST
HOUTENBEK	Mudrocks, sandstones, limestones			150-200m
STEENKAMPSBERG	Sandstones	Woodlands Formation in far west - interbedded mudrocks & sandstones, some conglomerates, significant andesitic pyroclastics & lavas, 800-1200m	Rayton Formation-interbedded mudrocks & sandstones, minor andesites & dolomites ±1200m	450-600m, erosive base in north
NEDERHORST	Sandstones Mudrocks			200-800m, sandstones are arkosic
LAKENVLEI	Sandstones			200-350m. Some arkosic sandstones
VERMONT	Mudrocks			500-700m
MAGALIESBERG	Sandstones (mudrock lenses & interbeds)	120-300m, significant mudrocks. Sandstones thicken to west & to east, wedge out into Silverton mudrocks	±300n Subordinate mudrocks thicken to west	±500m, subordinate mudrocks
SILVERTON	Sandstone lens Mudrocks Machadodorp Volcanic Member Mudrocks	13km x 150m sandstone lens present, ≤100m dolomites in west at top of formation. Minor reworked tuffs. Total thickness : 400-800m & thins to west.	No significant sandstones Thin pyroclastic & dolomitic /chert member Total thickness ± 600m	Upper mudrocks ±1700m & thin to north Machadodorp Member ± 500m Lower mudrocks ±250m
DASPOORT	Sandstones	130-200m, pebbly sandstones & mudrocks in far west, thickens to west, locally △	±80m , pebbly sandstones common, locally ▽	0-±100m, pebbly sandstones, mudrocks & thicker in north. Ironstones & Fe-mudrocks in N.E.
STRUBENKOP	Mudrocks, lesser sandstones	100-135m, minor sandstones	±110m, significant sandstones, locally ▽	± 30-100m, thickens to south
DWAALHEUWEL or DROOGEDAL	Diamictite, conglomerate, sandstone	Droogedal - 10-50m	Absent or very thin	Dwaalheuwel - 50-100m, thins to south
HEKPOORT	Basaltic andesite	510-600ı	±400m. Air fall & reworked pyroclastics locally	±25-500m, pyroclastics common, thins to north
BOSHOEK	Diamictite, conglomerate, sandstone	0--10m	0-50m	≤100m Large channels
TIMEBALL HILL	Upper mudrocks Diamictite\conglomerate lens Klapperkop Quartzite Member Lower mudrocks	Upper mudrocks 200-500m, thicken westwards, no diamictite lens Quartzites 5-500m, thicken westwards Lower mudrocks 300-500m, thicken westwards	Upper mudrocks, ±100-200m, thick lens of diamictite/conglomerate Quartzites ±30-70m Lower mudrocks ±230-400m	Upper mudrocks ±400-600m, arkose wedge in north, thin diamicites, deformed mudrocks Quartzite 0-15-100m, thins to South Lower mudrocks 400-700m, thin southwards
ROOIHOOGTE	Polo Ground Quartzite Member Mudrock Bevets Conglomerates (breccia) Member	Polo Ground 0-1 Mudrocks 0-150m Bevets 0-150m	0-10m 0-18-250m 0-150m	Only Bevets Member, 0-30m, locally quartzite
CHUNIESPOORT GROUP	Iron Formation & dolomite	PALAEOKARST TOPOGRAPHY		

Fig. 8. Lithostratigraphy of the Pretoria Group, illustrating thicknesses and lithological variation across the basin.

providing a convincing marker unit. It is probable thus that the Pretoria Group of the Transvaal/Bushveld basin, the Segwagwa Group of the Kanye basin and the Postmasburg Group of the Griqualand West basin (Table 1) developed to a large extent in separate basins, a concept first developed by Crockett (1972) and supported more recently by Eriksson *et al.* (1988, 1991) and Eriksson and Clendenin (1990).

The basal Rooihoogte Formation of the Pretoria Group comprises a lowermost chert breccia-reworked conglomerate member, overlain by

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mudrocks and an uppermost arenaceous member (Visser, 1969; Button, 1973; Engelbrecht, 1986) (Fig. 8). The breccias are mostly *in situ* residual deposits overlying the palaeokarst landscape developed on the Malmani carbonates (Button, 1973), with some of them possibly representing fault scarp talus deposits (Eriksson, 1988). Both matrix-supported and clast-supported conglomerates are found, supporting the alluvial fan and fan-delta complexes proposed by Eriksson (1988). This postulate is in sharp contrast to the transgressive marine/basinal environment inferred by previous workers (Visser, 1969; Button, 1973, 1986; Beukes,1983), but is supported by recent detailed facies anlayses around the basin (Van der Neut, 1990; Schreiber, 1991); these workers were able to delineate a number of fan complexes and interpret the succeeding mudrock and sandstone members to be distal fan-delta and lacustrine sediments. Eriksson *et al.* (1991) suggest that a relatively steep northerly palaeoslope is indicated by the depth of karstic weathering in the underlying dolomites. They also consider that this may have bounded a half-graben system, whose low angle hanging wall lay to the north (Fig. 9a), and which provided the major source of detritus. This postulated half-graben appears to have controlled Pretoria Group sedimentation through to the deposition of the Daspoort Formation, with a northern basin boundary which was reactivated a number of times.

The Timeball Hill Formation consists of basal carbonaceous mudrocks, with micro-algal fossils (Nixon *et al.*, 1988), which grade upwards into rhythmically interbedded ferruginous mudrocks and fine-grained sandstones, in turn passing up into the Klapperkop Sandstone Member (Fig. 8); uppermost carbonaceous and ferruginous mudrocks complete the stratigraphy of this formation (Visser, 1969; Button, 1973; Eriksson 1973). The locally pyritic carbonaceous mudrocks indicate deep water anoxic suspension sedimentation (Eriksson, 1973), with the overlying mudrock-sandstone facies possessing sedimentary structures compatible with turbidity current re-sedimentation of distal delta deposits (Rust, 1961; Kuenen, 1963; Visser, 1969, 1972; Button, 1973). The upward-coarsening sandstones of the Klapperkop Member support tidal reworking of delta front sands (Visser, 1969; Button, 1973; Eriksson and Clendenin, 1990), with localised oolitic ironstones having developed in a shallow offshore setting. The Timeball Hill palaeoenvironment is thus thought to have comprised a relatively deep basin, filled by fluviodeltaic complexes advancing from the north, northwest and east; with the exception of the arkoses preserved in the northeast of the basin (Fig. 8), only the more distal deltaic and basinal sediments appear to have been preserved. This postulate is compatible with the suggestion of a half-graben deriving sediment largely from northerly sources, or characterised by sedimentation parallel to the bounding faults (Fig. 9a).

The diamictites within the upper Timeball Hill mudrocks and the conglomerates/diamictites of the succeeding Boshoek Formation in the western and central portions of the Transvaal basin (Fig. 8), are correlated by Visser (1971) with the Makganyene diamictites of Griqualand West; we suggest a broader correlation of the latter formation with the full thickness of both Timeball Hill and Boshoek Formations (Table 1). The diamictite-immature sandstone-conglomerate lithologies correlated by Visser are interpreted as being glacial, glaciofluvial and glaciomarine deposits (Visser, 1971). Schreiber *et al.* (1990) interpreted the Boshoek Formation, including the immature sandstones found in the northeast of the basin, as alluvial sediments. It is thus possible, particularly in view of palaeomagnetic data (Fig. 9b), that both the Timeball Hill and Boshoek Formations had an important glacial influence in their genesis. It is postulated here that the Timeball Hill lithologies compare closely with deep glacial lake deposits such as those in Lakes Constance and Geneva (Reineck and Singh, 1975), and that the coarse-grained diamictite-conglomerate-sandy assemblages discussed by Visser (1971) represent more proximal glacial ablation deposits. The centre of glaciation probably lay on the Vryburg rise, an intra-basinal high lying to the south of the Kanye basin and separating the Griqualand West and Transvaal basins (Visser, 1971) (Fig. 1).

The thick lavas of the Hekpoort Formation, with correlates extending across both the Kanye and Griqualand West regions (Table 1), have a basaltic to intracratonic andesitic chemistry (Sharpe *et al.*, 1983; Engelbrecht, 1986); interbedded pyroclastics and resedimented volcaniclastic rocks appear to be widespread, with subordinate thin beds of mudrock and chert (Button, 1973; Engelbrecht, 1986; Eriksson and Twist, 1986). The scarcity of pillow lavas and mudrock interbeds points to subaerial extrusion, with an uppermost basin-wide aluminous mudrock layer, mostly 1 - 2 m thick, being interpreted as either a palaeosol (Button 1973) or due to chemical leaching of the lavas (Engelbrecht, 1986). Martini (1990) identified a semi-arid cool climate playa lake deposit within this aluminous mudrock horizon. The lavas in the Transvaal basin thicken southwards, possibly reflecting a half-graben basin setting (Fig. 9a). The lavas are overlain with a sharp contact by the conglomerates, immature sandstones and minor mudrocks of the Droogedal/Dwaalheuwel Forma-

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the centre of the depository, thought by Eriksson *et al.* (1988, 1990) to be a synsedimentary palaeohigh; the doming may have been thermal in nature, related to a rising plume of Bushveld magmas through the crust (Eriksson *et al.*, 1991). The sandstone isolith plot (Fig. 9c) indicates that sands may have been shed off the proposed dome, a postulate also supported by palaeocurrent data in the Magaliesberg Formation (Van der Neut, 1990; Schreiber, 1991). If such doming did occur, it may have led to a retreat of the Silverton epeiric sea, leaving the Magaliesberg shoreline sands subject to fluvial reworking. Such a postulate would be compatible with the beach-fluvial, delta-beach-shallow marine and tidal models proposed for the Magaliesberg Formation (Visser, 1969; Button, 1973; Eriksson *et al.*, 1987). Grain size patterns for the Magaliesberg Formation strongly support a fluvial influence in the deposition of these sandstones (Reczko *et al.*, 1992).

Continued doming in the centre of the Transvaal basin may have been responsible for the development of separate eastern and western intracratonic sub-basins in post-Magaliesberg times; a separate western lacustrine basin was first proposed by Crockett (1972) and more recently supported by Eriksson *et al.* (1988, 1991) and by Schreiber (1991). Lithostratigraphic differences between the far west and the east of the basin are also marked (Fig. 8). The five formations in the east of the

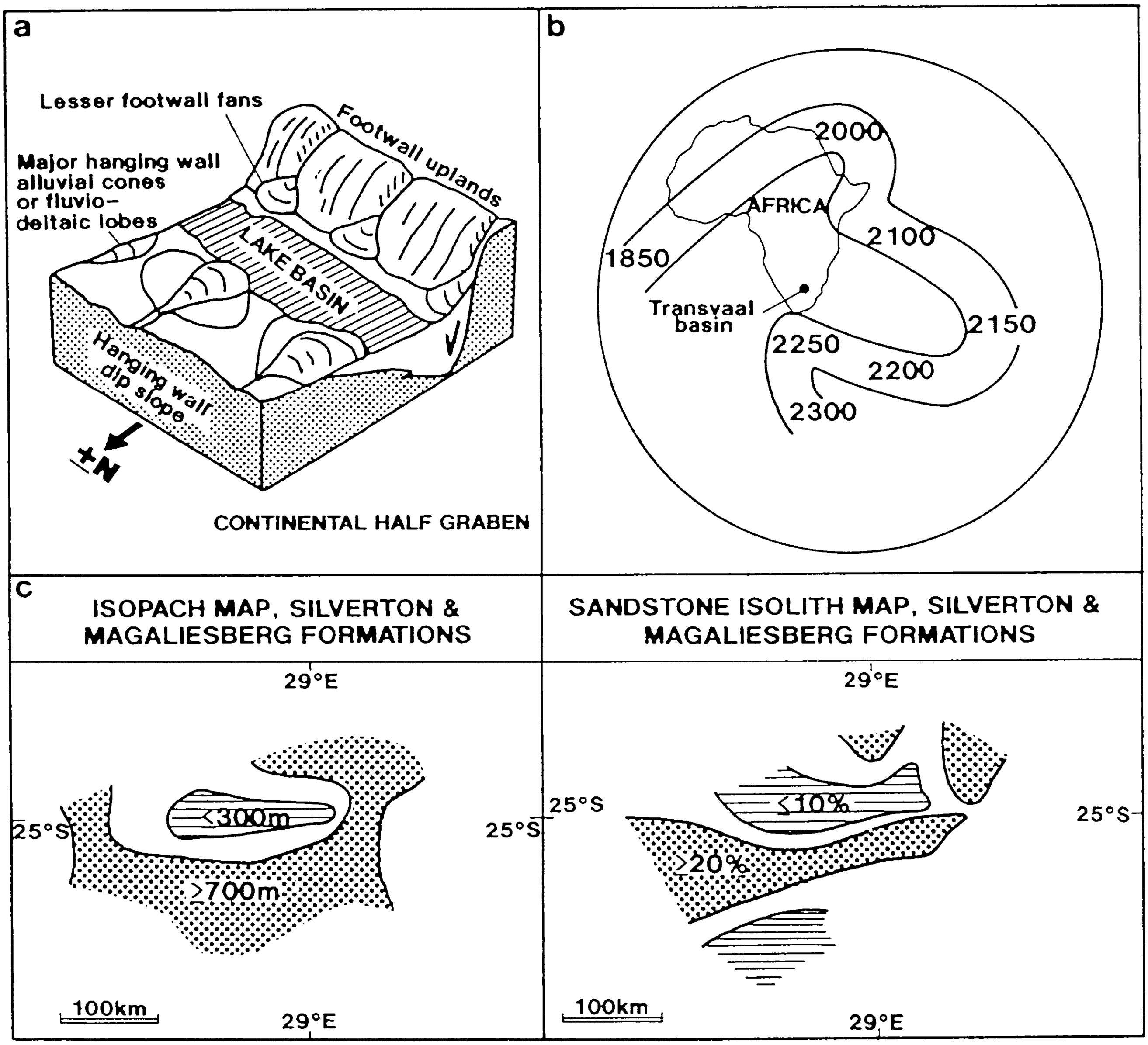

Fig. 9. Postulated controls on the Pretoria Group palaeoenvironment. (a) Half-graben tectono-sedimentary setting proposed by Eriksson et al. (1991). (b) Polar wandering curve for Africa for the Early Proterozoic; note location of Transvaal basin in cold latitudes at 2250 ma (Hekpoort Formation age) and movement away from polar latitudes in upper Pretoria Group times (Modified after Condie, 1989). (c) Thickness patterns of the Silverton and Magaliesberg Formations; note possible central basin palaeohigh indicated by thinner total sediment cover and surrounding zone of thicker sandstones.

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tions; the former represents a sheet of sediment entering the Transvaal basin from the northwest and the latter formation two lobes which entered from the north and east (Eriksson *et al.*, 1991). All three sheets thin and fine towards the Pretoria region, where these formations are absent and the Hekpoort lavas are succeeded by the mudrocks and subordinate sandstones of the Strubenkop Formation (Eriksson *et al.*, 1991). The shallow marine model proposed for the Dwaalheuwel Formation (Button, 1973) is disputed by Eriksson *et al.* (1989, 1991) who suggest alluvial fan and distal fan-delta deposition for both Droogedal and Dwaalheuwel Formations. The Strubenkop mudrocks overlie these sandstone sheets and are thickest where the Droogedal/Dwaalheuwel arenites wedge out, becoming thinner as the sandstones thicken towards the northwest, northeast and east of the basin (Eriksson *et al.*, 1991). This led Eriksson *et al.* (1991) to propose that the Strubenkop Formation represents a more distal lacustrine basin into which the Dwaalheuwel/ Droogedal fan-deltas debouched. Oolitic ironstone lenses, mudcracks, ripple marks, graded bedding, flute casts, flaser bedding and minor channel-fills (Visser, 1969; Button, 1973; Engelbrecht, 1986) are compatible with the shallow marine (Visser, 1969), tidal flat (Button, 1973) and lacustrine (Eriksson and Clendenin, 1990) models proposed for the Strubenkop Formation. As suggested for the Rooihoogte and Timeball Hill Formations, the predominant northerly source of the Droogedal and Dwaalheuwel Formations may reflect a half-graben setting (Fig. 9a).

The recrystallised, cross-bedded and planar stratified sandstones of the Daspoort Formation overlie the Strubenkop mudrocks sharply, except in eastern Botswana, where the Ditlhojana Formation (as the Daspoort is known in the far west of the Transvaal basin) (Table 1) lies on thin mudrocks developed above the Hekpoort lavas (Key, 1983), indicating erosion of the preceding Droogedal arenites and most of the Strubenkop mudrocks (Eriksson *et al.* under review). Planar stratified mature sandstones and very thin ironstones/ferruginous mudrocks in the east of the basin led Button (1973) to propose a shallow marine beach-barrier palaeoenvironment. A locally erosive base and pebbly sandstones in the Pretoria region were taken by Visser (1969) to support a fluvial-beach model. The immature nature of the Pretoria region sandstones (Van der Neut, 1990) and the occurrence of significant pebbly sandstones and mudrocks in the north and far west of the basin (Key, 1983; G. Potgieter, 1992 pers. comm.) support the distal fan-fluvial braidplain model of Eriksson *et al.* (under review). The latter is based largely on lateral and vertical facies relationships, palaeocurrents and thickness trends observed across the entire preserved Transvaal-Bushveld basin, rather than relying on the localised data used by Visser (1969) and Button (1973). Source areas were largely to the north of the Transvaal basin, possibly supporting the half-graben model. The Daspoort Formation also indicates a period of tectonic reorganisation within the Transvaal depository, as isopach maps of the preceding and succeeding Pretoria Group formations are quite different (Eriksson *et al.*, 1991).

The thick, monotonous laminated mudrocks of the Silverton Formation encompass significant volcanic lithologies (Button, 1973). Carbonaceous mudrocks are relatively common, with subordinate chert, sandstone and dolomite lenses; carbonate rocks become important in the north of the basin (Button 1973; Engelbrecht, 1986). In the eastern Transvaal, a medial Machadodorp Member includes lower agglomerates and tuffs and upper pillowed basalts, with bomb sizes decreasing towards the north (Button, 1973); some agglomerates are found at the equivalent stratigraphic position in the Pretoria region (Visser, 1969) and reworked tuffs are found in the west of the basin (Eriksson *et al.*, 1990). An upward-coarsening, 13 km long and 150 m thick, sandstone lens in the west of the basin, with planar and cross-bedding and ripple marks (Engelbrecht, 1986; Eriksson *et al.*, 1991), supports the prodeltaic palaeoenvironment suggested by Button (1973). Eriksson and Clendenin (1990) and Eriksson *et al.* (1991) proposed lacustrine deltas and fan-deltas as an alternative model. In addition, the latter workers suggested that the Magaliesberg sandstones which overlie the Silverton Formation gradationally, may represent the shoreline of the Silverton basin; this postulate is supported by the essentially similar thickness distribution of both formations across the Transvaal basin (Eriksson *et al.*, 1991). The Magaliesberg sandstones also wedge laterally into Silverton mudrocks in the west of the basin (Crockett, 1972; Engelbrecht, 1986; Key, 1986; Eriksson and Clendenin, 1990). Herringbone cross-beds, carbonate rocks, flaser bedding and interference ripple marks point to a marine influence in the Silverton-Magaliesberg basin, which is also evident from the palaeosalinity data of Eriksson (1992). It is thus possible that the intracratonic half-graben setting envisaged for the lower Pretoria Group (Eriksson *et al.*, 1991) (Fig. 9a) may have given way to a transgressive epeiric sea in Silverton-Magaliesberg times. Palaeomagnetism (Fig. 9b) indicates movement away from polar latitudes in late Pretoria Group time, thereby supporting the possibility of a marine transgression. The thickness patterns of these two formations (Fig. 9c) point to doming in

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eastern sub-basin are correlated with the Rayton Formation of the Pretoria region (SACS, 1980). The alternating mudrocks, arkosic and quartzitic sandstones, with subordinate carbonate and chert lithologies, which make up the five easternmost formations (Schreiber, 1991) include interbedded tuffaceous mudrock layers (Schreiber and Eriksson, in press). The beach-intertidal mudflat-shallow marine model of Button (1973) and Button and Vos (1977) does not explain adequately the common mudcracks, arkosic sandstones and overall upward-coarsening successions in these rocks. The latter are, perhaps, explained better by shallow lacustrine and wind-tidal flat deposition for the argillaceous units and by fan-delta and deltaic sedimentation for the interbedded arenites (Schreiber, 1991; Schreiber and Eriksson, in press). Source areas were located to the south, east and north of this steadily shrinking sub-basin (Schreiber, 1991). The analogous Rayton Formation succession of feldspathic arenites, quartzose sandstones and mudrocks, with subordinate dolomites and lavas, is ascribed to fluvial (Visser, 1969) or a combination of fan, fan-delta and fluvial sedimentation (Van der Neut, 1990). In the proposed western sub-basin, post-Magaliesberg rocks in the western Transvaal are obscured largely by Bushveld intrusives (Engelbrecht, 1986); further to the west in Botswana, the Woodlands Formation comprises interbedded sandstones and mudrocks, with significant andesitic pyroclastic rocks and lavas and some conglomerates (Key, 1983). Major tectonic disturbance of the Woodlands rocks has made palaeoenvironmental interpretation difficult; an intimate association between sedimentation, volcanism and tectonic instability is indicated (Crockett, 1969, 1972; Key, 1983). Crockett (1969, 1972) proposed catastrophic syn- to post-sedimentary collapse of the western sub-basin floor, resulting in gravity sliding of large blocks of sedimentary rocks towards the basin centre. Key (1983) relates this tectonism to the late-Transvaal intrusion of the Gaborone Granite to the west of the Bushveld basin; this postulate can perhaps be considered as related to the extrusion of the massive felsic lava province of the Rooiberg Group which succeeded Pretoria Group deposition in the east and centre of the Transvaal basin. No analogous late Pretoria sedimentary and volcanic rocks are preserved in either the Griqualand West or Kanye basins (Table 1).

There is a long-standing debate whether the sedimentary rocks of the Pretoria Group represent epeiric marine deposits or an intracratonic lacustrine basin (Du Toit, 1954; Visser, 1957; Willemse 1959; Visser, 1969; Crockett, 1972; Button, 1973; Button and Vos, 1977; Button, 1986; Eriksson and Clendenin, 1990). The epeiric postulate is supported by preserved tidal sedimentary structures, oolites, stromatolites and hummocky cross-bedding; however, these characteristics are equally compatible with the lacustrine alternative. The latter suggestion is in turn supported by common varves, the presence of palaeosols, predominantly arkosic to lithic sandstone petrography, inferred microtidal conditions typical of lakes (Schopf, 1980) and an absence of swash-formed ripple marks. The debate is discussed in some detail by Eriksson *et al.* (1991). Perhaps the best evidence in favour of an intracratonic basin is the Boron palaeosalinity data discussed by Eriksson (1992) (Fig. 10). Boron values determined by Böhmer (1977) from four widely spaced boreholes in the south of the Transvaal basin, when plotted against stratigraphic height, exhibit a very similar, in-phase variation, summed up in the palaeosalinity curve of Eriksson (1992) (Fig. 10). This in-phase variation from different localities supports a closed basin setting, and the rapid increases and decreases in Boron values further support inhomogeneous lacustrine basin chemistry rather than the far more uniform conditions typical of the marine environment (Schopf, 1980). The possible role of glacial and interglacial periods in the deposition of the Pretoria Group and the postulated marine incursion during Silverton times are supported by the palaeosalinity curve for the lower Pretoria Group (Fig. 10).

ROOIBERG GROUP

In this review we present a modified stratigraphy for the upper portion of the Transvaal Sequence (Tables 1 and 2) which is not in accord with SACS (1980), who consider the Rooiberg Group (sensu stricto) to comprise only the Damwal and Selonsrivier Formations; our stratigraphy reflects research carried out within the last five years on the Dullstroom Formation, Rooiberg Group (*sensu stricto*, SACS, 1980) and sedimentary units associated with these rocks, by Schweitzer and Hatton (in prep.). SACS (1980) considers the largely sedimentary Leeuwpoort, Smelterskop and Makeckaan Formations to belong to the upper Pretoria Group and various correlations with post-Magaliesberg units have been proposed, (e.g., Button, 1973; Schreiber, 1991). We consider the Leeuwpoort Formation, the basal unit outcropping within the Rooiberg "fragment" (Fig. 1), as the youngest post-Pretoria Group unit and assign it, tentatively, to the Rooiberg Group (*sensu lato*, as used here) (Table 2) as its basal unit; there do not appear to be any correlates elsewhere in the Transvaal basin, and no rocks equivalent to the Rooiberg Group (*sensu lato*) are found in either the Kanye or Griqualand West basins.

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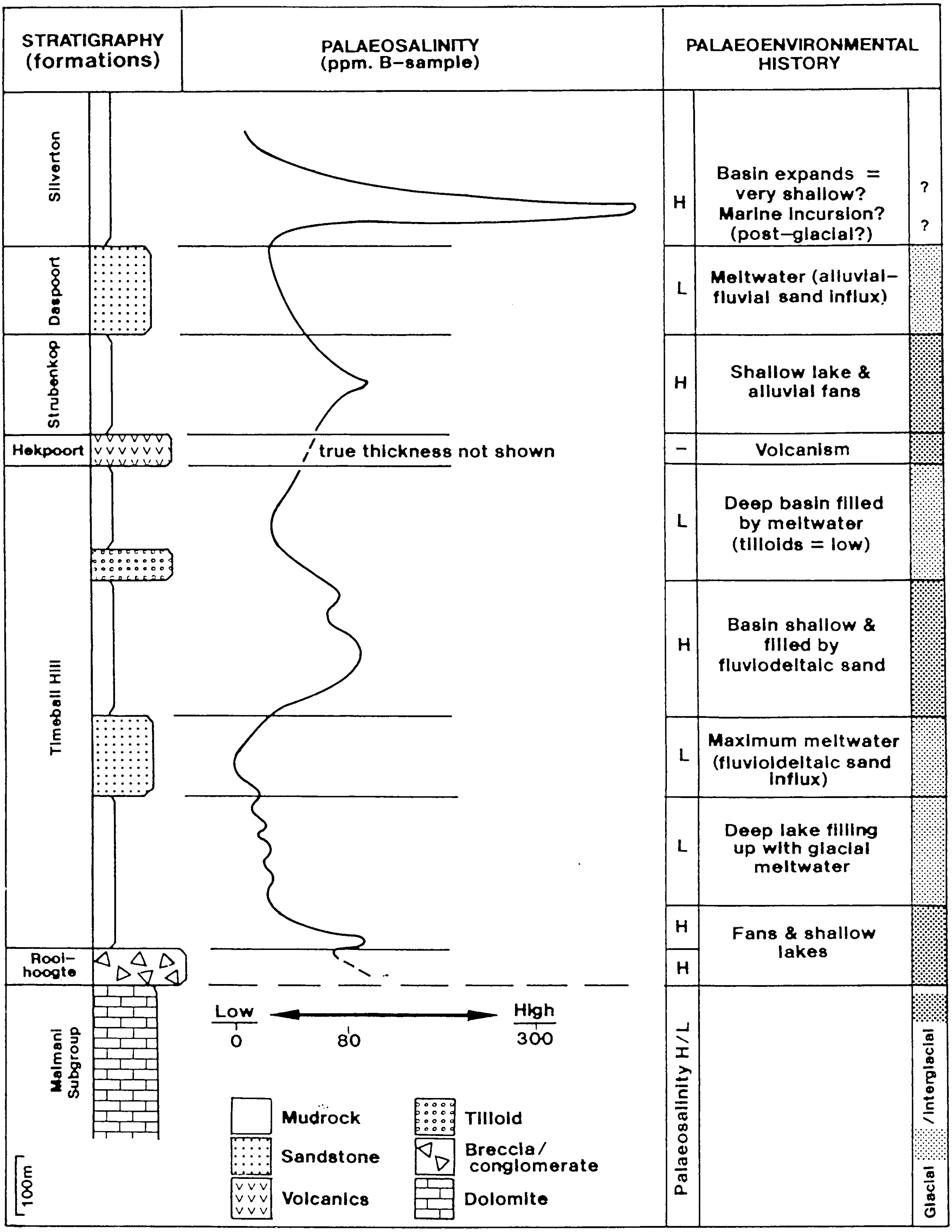

Fig. 10. Palaeosalinity curve for the lower Pretoria Group, based on Boron values determined in widely spaced boreholes by Böhmer (1977). Also shown is the possible role of glacial and interglacial periods on the Pretoria Group palaeoenvironment. Modified after Eriksson (1992).

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The approximately 1500 m of conglomerates, pebbly and arkosic sandstones and uppermost mudrocks which make up the Leeuwpoort Formation (Fig. 11) (Stear, 1976; Richards, 1987), are generally interpreted to represent lower braided and upper meandering river deposits (Stear, 1977a and b; Phillips, 1982; Rozendaal *et al.*, 1986; Richards and Eriksson, 1988). The coarse immature fluvial sandstones which characterise the Leeuwpoort Formation (Fig. 11) do not compare well lithologically with the alternating sandstones and mudrocks of the post-Magaliesberg units in either the east or west of the Pretoria Group basin. We thus suggest that the Leeuwpoort Formation is part of the Rooiberg Group (*sensu lato*) and postulate that these coarse, immature fluvial deposits are probably related to the catastrophic collapse proposed by Crockett (1969, 1972) for the western Pretoria Group sub-basin floor, during and after deposition of the Woodlands Formation. The gravity sliding of large blocks of sedimentary rocks in Botswana (Crockett, 1972) may have been accompanied by more subdued immature fluvial deposition on the eastern margin of the collapsing sub-basin, today preserved at the base of the Rooiberg "fragment". Predominantly southwesterly palaeocurrent directions in the Leeuwpoort sandstones (Stear, 1977a; Richards, 1987) are compatible with this postulate.

The Smelterskop Formation conformably overlies the Leeuwpoort Formation (Richards and Eriksson, 1988) (Fig. 11) and comprises a thickness of about 280 m, with a basal quartzose sandstone member, four to five lenticular arkosic sandstone units and subordinate tuffaceous mudrocks, conglomerates and wackes (Stear,

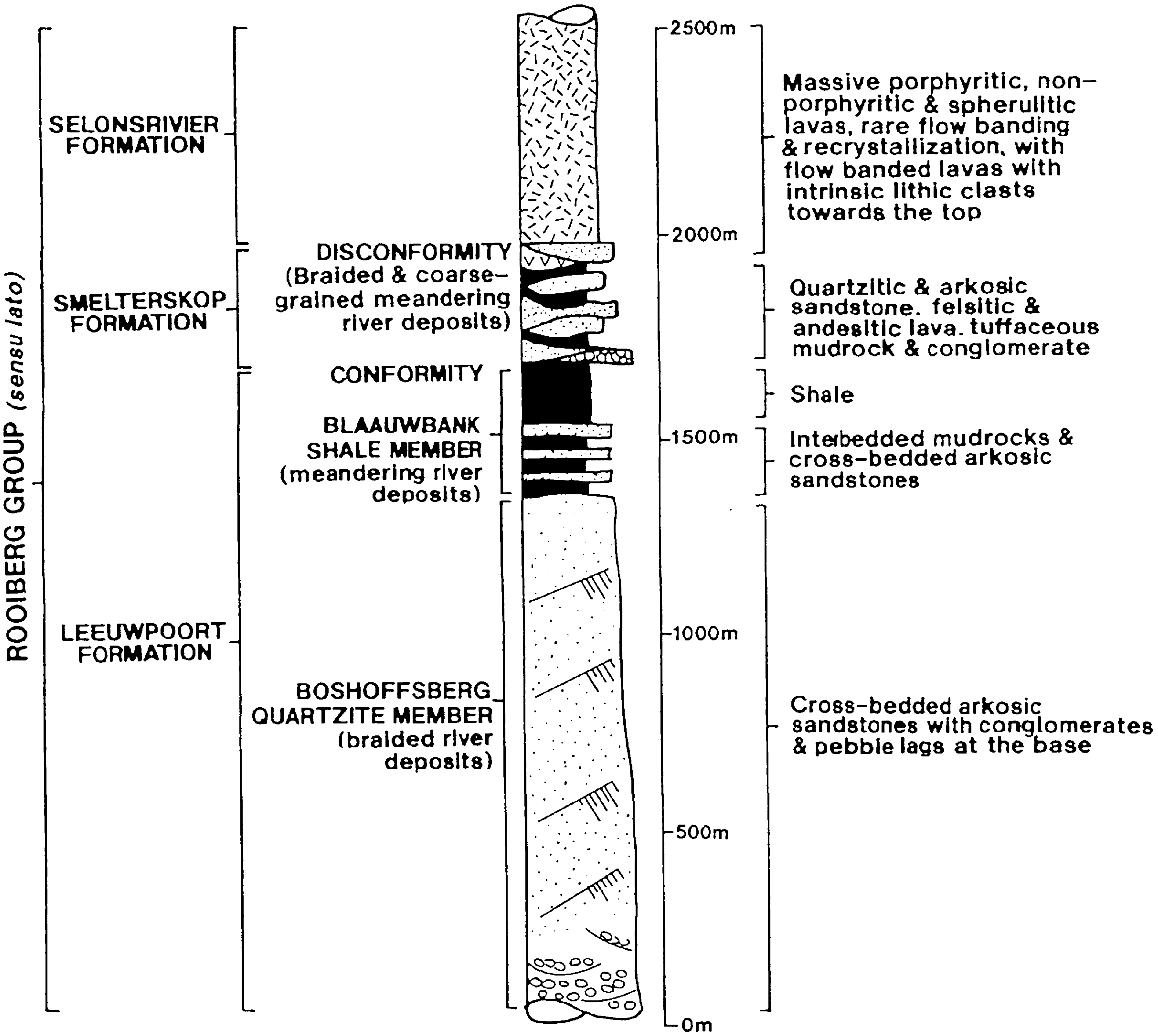

Fig. 11. Lithostratigraphy of the Leeuwpoort, Smelterskop and Selonsrivier Formations in the Rooiberg "fragment" (see Fig. 1 for location). Modified after Stear (1977a) and Richards (1987).

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1977a, Richards, 1987). Braided fluvial and coarse-grained meandering river systems are thought to have laid these sediments down (Stear, 1977a; Richards and Eriksson, 1988). Impersistent felsitic and andesitic lava flows are intercalated with the sedimentary rocks of the Smelterskop Formation; the andesites are flow-banded and strongly vesicular, and the uppermost felsite is flow-banded and petrographically similar to the basal flows of the overlying Rooiberg (*sensu stricto*) lavas.

The Makeckaan Formation, preserved in the Makeckaan (or Stavoren) "fragment" comprises lower and upper feldspathic sandstone members with large scale cross-beds and ripple marks, separated by mature, recrystallised quartzitic sandstones and micaceous wackes (Fig. 12) (Rhodes, 1972). Andesites and felsites are intercalated in the upper arkosic member (Fig. 12), and the sedimentary succession of the Makeckaan Formation is succeeded concordantly by felsitic lavas (Mellor, 1905; Wagner, 1921, 1927; Schweitzer and Hatton in prep.), here assigned to the Dullstroom Formation. The felsites are spherulitic, vesicular and abundant matrix-supported lithic fragments suggest emplacement as ignimbrites. The Makeckaan sediments are interpreted as fluvial to neritic (Rhodes, 1972) or fluviodeltaic

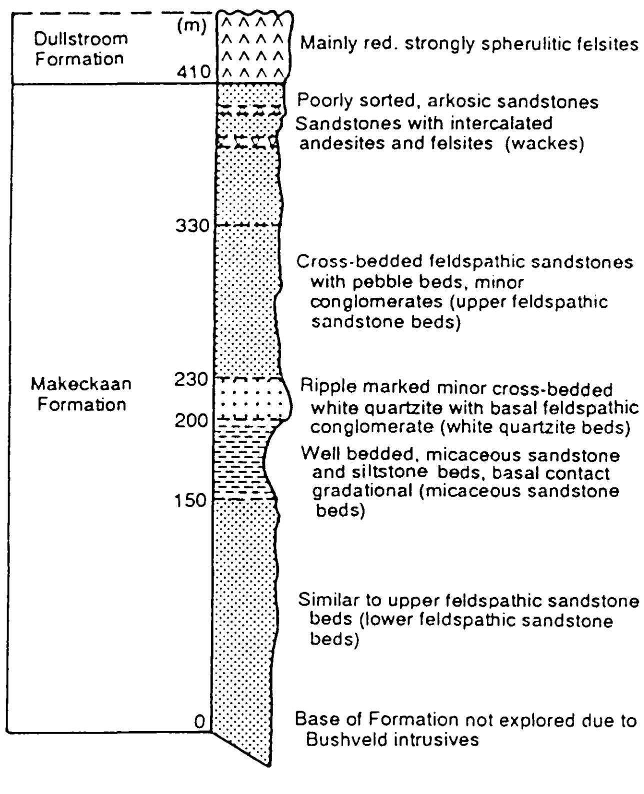

Fig. 12. Lithology of the Makeckaan Formation. Note the similarity to the rocks of the Smelterskop Formation (Fig. 11), and the overlying Dullstroom felsites. Modified after Rhodes (1972).

(Schreiber, 1991) deposits. The similarity between the apparently fluvially-deposited Smelterskop and Makeckaan feldspathic to quartzitic sandstones and their intercalated andesitic-felsitic lavas, leads us to suggest that these two formations may be correlated with each other, representing the transition from lower Rooiberg Group (*sensu lato*) fluvial sedimentation (Leeuwpoort Formation) to the vast outpourings of the main Rooiberg felsitic lavas. These two largely sedimentary formations are thus also, tentatively, correlated with the basal stage of the Dullstroom Formation (Figs 13 and 14) (Truter, 1949; Visser, 1969).

Lavas assigned to the Dullstroom Formation outcrop along a narrow strip in the eastern Transvaal basin and also overlie the Makeckaan Formation sediments in the Makeckaan "fragment" (Figs 13 and 14). The former is the type locality of the Dullstroom Formation, which unconformably (Cheney and Twist, 1991) succeeds the Houtenbek Formation of the Pretoria Group (Table 2). A maximum thickness of 1,4 km of this basalt-rhyolite association (Schweitzer, 1986) is preserved and the lavas are truncated in the north by Bushveld Complex intrusives (Fig. 13). Schweitzer (in prep.) and Schweitzer and Hatton (in prep.) distinguish a basal stage and an upper stage in the Dullstroom succession (Fig. 14). The former comprises about 300 m of fluidal and pyroclastic flows, with thin interbedded lenticular quartzitic and arkosic sandstones and mudrocks; the absence of pillow structures, and the presence of pipe amygdales and peperites suggests subaerial extrusion with localised shallow water conditions. Amygdaloidal low titanium andesites predominate, with flow-banded, amygdaloidal and spherulitic rhyolites referred to as the basal rhyolites (Fig. 14), occurring locally at the base. Volcaniclastic sediments and debris flow deposits are also found locally. The upper Dullstroom stage comprises more uniform lavas with almost no intercalated sedimentary rocks. Three major flow types are distinguished: porphyritic high titanium basalts with amygdaloidal and brecciated flow tops; high magnesium amygdaloidal and sparsely porphyritic flow-banded felsites; and low titanium andesites similar to those in the basal stage (Fig. 14). These different flow types are closely associated and interlayered, with a general upward increase in high magnesium felsites at the expense of the high titanium and low titanium flows.

A large xenolith within Bushveld mafic intrusives to the north of the Dullstroom outcrops (locality 2, Fig. 13) appears to comprise altered equivalents of the uppermost low magnesium felsites of the Dullstroom Formation and succeeding high Fe-Ti-P lavas at the base of the Damwal Formation

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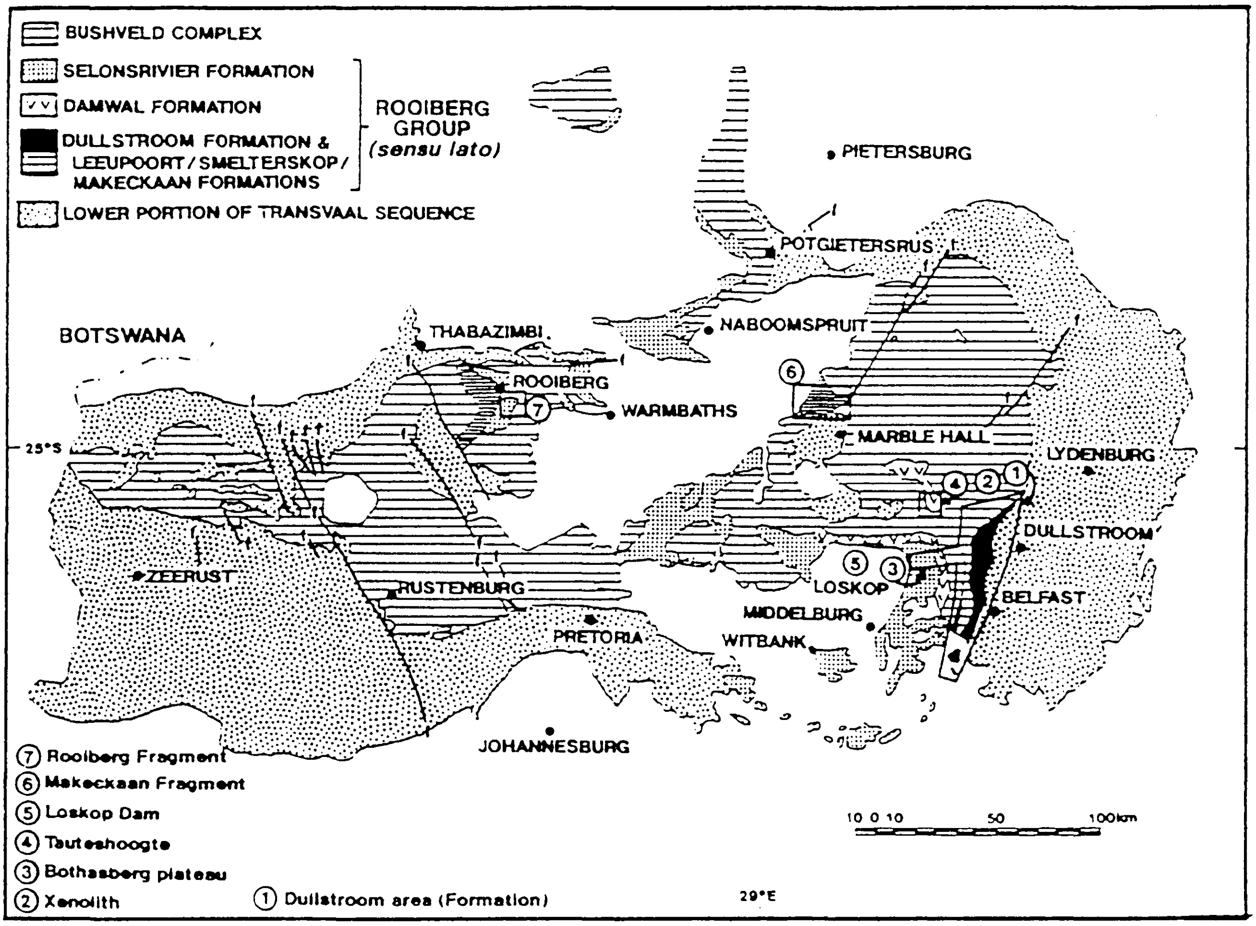

Fig. 13. Map of the Transvaal basin, South Africa, illustrating the distribution of rocks belonging to the Rooiberg Group (sensu lato, as used here). Note localities 1 to 7, as used also in Fig. 14.

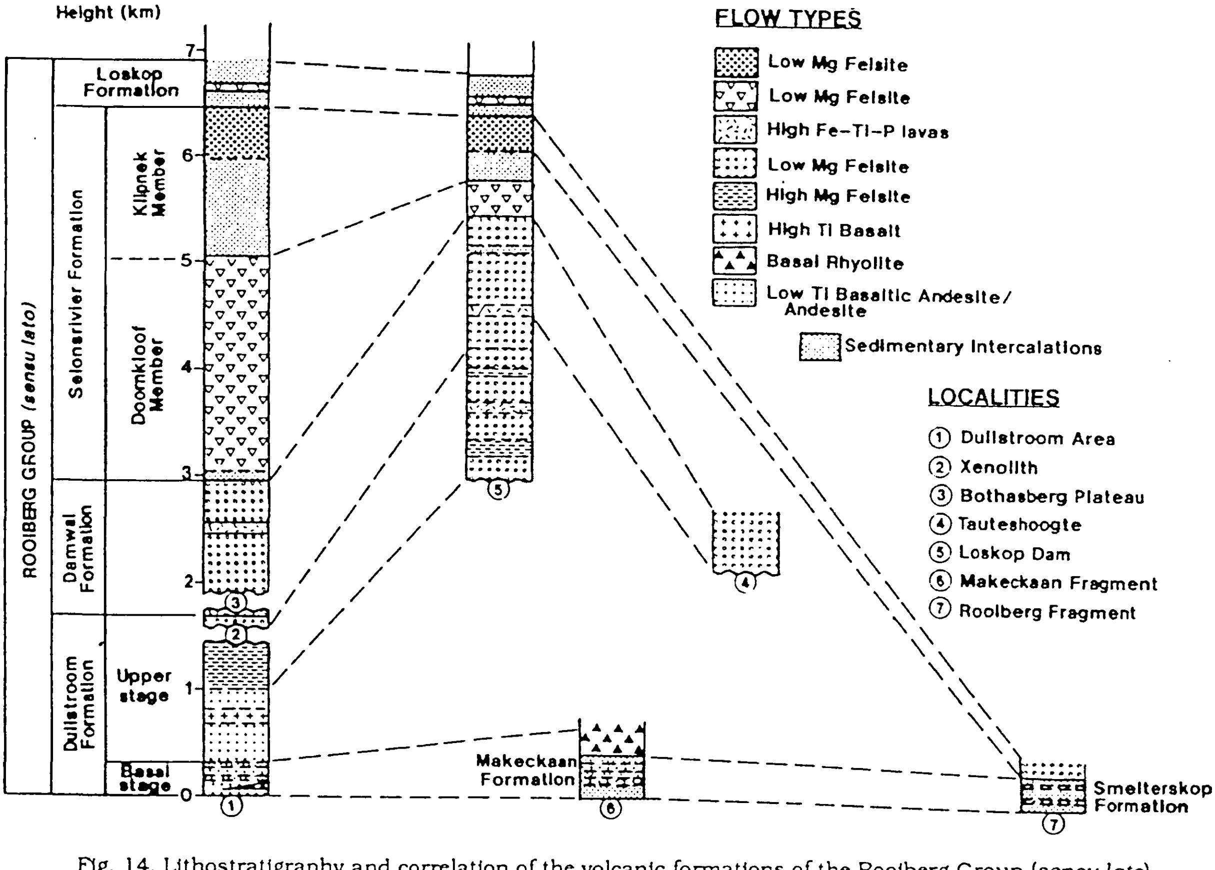

Fig. 14. Lithostratigraphy and correlation of the volcanic formations of the Rooiberg Group (*sensu lato*). See Fig. 13. for locations 1 to 7. Also note the different flow types identified within the volcanic formations.

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(Fig. 14). The Damwal Formation is found within the Bothasberg, Tauteshoogte and Loskop Dam areas (respectively, localities 3, 4 and 5 in Fig. 13) (Fig. 14). The succeeding Selonsrivier Formation, which is subdivided into a lower Doornkloof and upper Klipnek Member, is found at Bothasberg, Loskop Dam and overlying the Smelterskop Formation in the Rooiberg "fragment" (Figs 13 and 14). These two felsitic formations were first defined by Clubley-Armstrong (1977, 1980), and together comprise a succession of very extensive siliceous eruptives within the central and eastern parts of the Transvaal basin (Fig. 13); the original volume of these eruptives is estimated to have reached up to 300 000 km^3 (Twist and French, 1983), although this is probably an overestimate. The Damwal Formation comprises largely dark flows of low magnesium felsite, with subordinate high Fe-Ti-P lavas, whereas the Selonsrivier Formation is characterised by red-coloured, flow-banded flows of low magnesium felsite in the Doornkloof Member and intercalated sedimentary rocks and low-Mg felsites in the Klipnek Member (Fig. 14). Twist (1985) distinguished nine major units separated by sedimentary intercalations within the felsite succession at Loskop Dam, placing the Damwal-Selonsrivier contact at the boundary of units 5 and 6; the same stratigraphic level was inferred to mark the transition to an oxygen-rich atmosphere in the upper Transvaal Sequence (Twist and Cheney, 1986). However, Eriksson and Cheney (1992) showed that the colouration of the felsites in the Selonsrivier Formation was formed diagenetically, and proposed that the transition to an atmosphere rich in free oxygen lay rather at the Loskop Formation-Waterberg Group unconformity. The lavas of the Damwal and Selonsrivier Formations are predominantly rhyolitic to dacitic in composition, with both high- and low-Mg types occurring (Twist and French, 1983; Twist and Harmer, 1987). Extrusion was subaerial and feldspathic sandstone interbeds with some preserved sedimentary structures such as cross-bedding, channel-fills, ripple marks and mudcracks (Clubley-Armstrong, 1977), point to intermittent periods of deposition between volcanic eruptions, possibly by a combination of fluvial channels, small lakes and gravity flows.

Many authors (Button, 1976; Coertze *et al.*, 1977; Sharpe *et al.*, 1983; Twist and French, 1983) support the view expressed here, that the Dullstroom and Damwal-Selonsrivier volcanic events originally formed one continuous eruptive succession, implying that the latter two formations are also older than the intrusive mafic suite of the Bushveld Complex (Von Gruenewaldt, 1971, 1972); this view is confirmed by geochemical data (Schweitzer, 1986, Schweitzer and Hatton in prep.) (Fig. 15). The sedimentary rocks of the correlated Loskop, Glentig and Rust de Winter Formations (Fig. 1) overlie the Selonsrivier felsites conformably (SACS, 1980; Cheney and Twist, 1991); they represent the final sedimentary phase of the Transvaal basin. Minor interbedded volcanic flow deposits range in composition from basic to siliceous and probably represent continued eruptions of magmas related to the Damwal-Selonsrivier lavas (Clubley-Armstrong, 1977; Coertze *et al.*, 1977). This leads us to suggest here, tentatively, that these uppermost sedimentary formations also be considered part of the Rooiberg Group (*sensu lato*) (Tables 1 and 2).

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REFERENCES

Aldiss, D.T., Tombale, A. R., Mapeo, R. M. B. and Chiepe, M. 1989. The geology of the Kanye area. *Bull. Geol. Surv. Botswana* **33**.

Altermann, W., and Hälbich, I. W. 1990. Thrusting, folding and stratigraphy of the Ghaap Group along the south-western margin of the Kaapvaal Craton. *S. Afr. J. Geol.* **93**, 553-556.

Altermann, W. and Herbig, H.-G. 1991. Tidal flat deposits of the Lower Proterozoic Campbell Group along the southwestern margin of the Kaapvaal Craton, Northern Cape Province, South Africa. *J. Afr. Earth Sci.* **13**, 415-435.

Armstrong, R. A., Compston, W., Retief, E. A., Williams, I. S. and Welke, H. J. 1991. Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand Triad. *Precambrian Res.* **53**, 243-266.

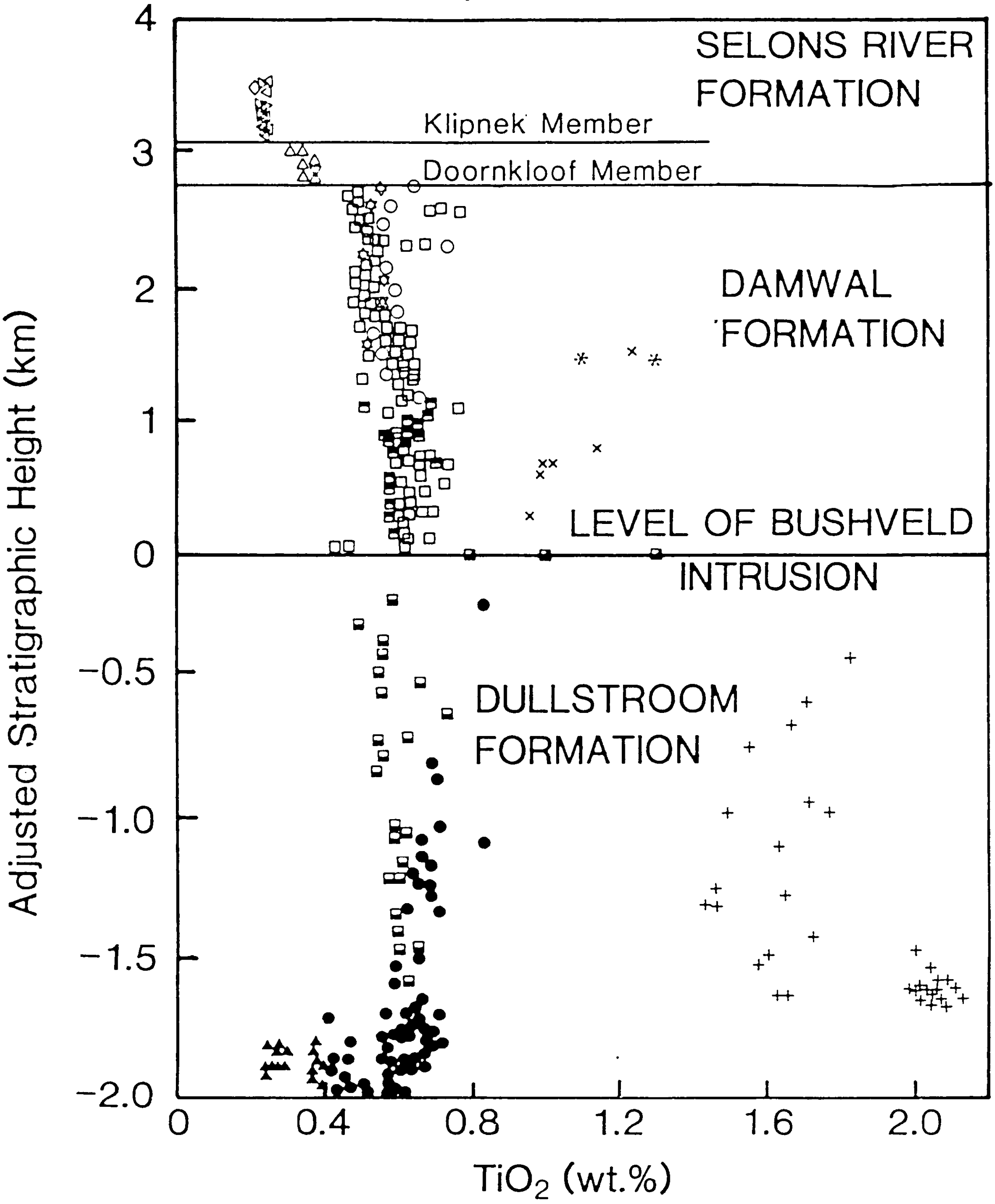
Beukes, N. J. 1973. Precambrian iron-formations of southern Africa. *Econ. Geol.* **68**, 960-1004.

Beukes, N. J. 1977. Transition from siliciclastic to carbonate sedimentation near the base of the Transvaal Supergroup at Bothithong in the northern Cape province, South Africa. *Sediment. Geol.* **18**, 201-222.

Beukes, N. J. 1978. Die Karbonaatgesteentes en ysterformasies van die Ghaap-Groep van die Transvaal-Supergroep in Noord-Kaapland. Ph.D. thesis (unpubl.), Rand Afrikaans University, Johannesburg, South Africa.

Beukes, N. J. 1980. Stratigrafie en litofasies van die CampbellrandSubgroep van die Proterofitiese Ghaap-Groep, Noord-Kaapland. *Trans. Geol. Soc. S. Afr.* **83**, 141-170.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021



◁	Low Mg Felsite (LMF_{Klip}) - Loskop Dam	○	Low Mg Felsite (LMF_{Dam}) - Bothasberg Plateau
◇	Low Mg Felsite (LMF_{Klip}) - Bothasberg Plateau	✡	Low Mg Felsite (LMF_{Dam}) - Tauteshoogte
▷	Low Mg Felsite (LMF_{Klip}) - Rooiberg Fragment	▭	High Mg Felsite (HMF) - Loskop Dam
△	Low MG Felsite (LMF_{Doorn}) - Loskop Dam	◪	Xenolith
▽	Low Mg Felsite (LMF_{Doorn}) - Bothasberg Plateau	▭	High Mg Felsite (HMF) - Dullstroom Area
×	High Fe-Ti-P lavas - Loskop Dam	+	High Ti Basalt (HTI) - Dullstroom Area
⁕	High Fe-Ti-P lavas - Bothasberg Plateau	▲	Basal Rhyolite - Dullstroom Area
□	Low Mg Felsite (LMF_{Dam}) - Loskop Dam	●	Low Ti Basaltic Andesite/Andesite ($LTI_{ba/a}$)

Fig. 15. Plot of TiO_2 content of Rooiberg lavas against stratigraphic height to illustrate continuity of the Dullstroom-Damwal-Selonsrivier volcanic event. Modified from Schweitzer (in prep.).

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Beukes, N. J. 1983. Palaeoenvironmental setting of iron-formations in the depositional basin of the Transvaal Supergroup, South Africa. In: *Iron Formations: Facts and Problems* (edited by Trendall, A. F. and Morris, R. C.), 131-209. Elsevier, Amsterdam, Holland.

Beukes, N. J. 1986. The Transvaal Sequence in Griqualand West. In: *Mineral Deposits of Southern Africa* (edited by Anhaeusser, C.R. and Maske, S.), 819-828. Geological Society of South Africa, Johannesburg, South Africa.

Beukes, N. J. 1987. Facies relations, depositional environments and diagenesis in a major Early Proterozoic stromatolitic carbonate platform to basinal sequence, Campbellrand Subgroup, Transvaal Supergroup, Southern Africa. *Sediment. Geol.* **54**, 1-46.

Böhmer, R. G. 1977. Die bepaling en verspreiding van spoorelemente in afsettingsgesteentes van die Groep Pretoria. Ph.D. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Bosch, P. J. A. 1992. Die geologie van die Wolkberg Groep tussen die Abel Erasmuspas en Graskop, Oos-Transvaal. M.Sc. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Burger, A. J. and Walraven, F. 1980. Summary of age determinations carried out during the period April 1978 to March 1979. *Ann. Geol. Surv. S. Afr.* **14**, 109-118.

Button, A. 1973. A regional study of the stratigraphy and development of the Transvaal Basin in the eastern and northeastern Transvaal. Ph.D. thesis (unpubl.), University of the Witwatersrand, Johannesburg, South Africa.

Button, A. 1976. Stratigraphy and relations of the Bushveld floor in the eastern Transvaal. *Trans. Geol. Soc. S. Afr.* **79**, 3-12.

Button, A. and Vos, R. G. 1977. Subtidal and intertidal clastic and carbonate sedimentation in a macrotidal environment: an example from the lower Proterozoic of South Africa. *Sediment. Geol.* **18**, 175-200.

Button, A. 1978. Diapiric structures in the Bushveld, northeastern Transvaal. *Inform. Circ. Econ. Geol. Res. Unit, Univ. Witwatersrand, Johannesburg* **123**.

Button, A. 1986. The Transvaal sub-basin of the Transvaal Sequence. In: *Mineral Deposits of Southern Africa* (edited by Anhaeusser, C. R. and Maske, S.), 811-817. Geological Society of South Africa, Johannesburg, South Africa.

Cheney, E. S., Roering, C. and Winter, H. de la R. 1990. The Archean-Proterozoic boundary in the Kaapvaal province of Southern Africa. *Precambrian Res.* **46**, 329-340.

Cheney, E. S. and Twist, D. 1991. The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. *Precambrian Res.* **52**, 115-132.

Clendenin, C. W. and Maske, S. 1986. Identification of syndepositional tectonics within the Transvaal sedimentary basin. *Geocongress '86 (Johannesburg, South Africa): Abstracts*, 501-504.

Clendenin, C. W., Charlesworth, E. G. and Maske, S. 1988a. Early Proterozoic successor basin development, southern Africa. *Geocongress '88 (Durban, South Africa), Abstracts*, 101-104.

Clendenin, C. W., Maske, S. and Charlesworth, E. G. 1988b. Resurgent basin development within an early Proterozoic successor basin sequence, southern Africa. *Geocongress '88 (Durban, South Africa), Abstracts*, 105-108.

Clendenin, C. W. 1989. Tectonic influence on the evolution of the early Proterozoic Transvaal Sea, southern Africa. Ph.D. thesis (unpubl.), University of the Witwatersrand, Johannesburg, South Africa.

Clendenin, C. W., Henry, G. and Charlesworth, E. G. 1991. Characteristics of and influences on the Black Reef depositional sequence in the eastern Transvaal. *S. Afr. J. Geol.* **94**, 321-327.

Clubley-Armstrong, A. R. 1977. The geology of the Selonsrivier area north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome. M.Sc. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Clubley-Armstrong, A. R. 1980. Petrochemistry of the Rooiberg Group and overlying Loskop Formation north of Middelburg, South-Eastern Transvaal. *Ann. Geol. Surv. S. Afr.* **14**, 11-28.

Coertze, F. J., Jansen, H. and Walraven, F. 1977. The transition from the Transvaal Sequence to the Waterberg Group. *Trans. Geol. Soc. S. Afr.* **80**, 145-156.

Coertze, F. J., Burger, A. J., Walraven, F., Marlow, A. G. and MacCaskie, D. R. 1978. Field relations and age determinations in the Bushveld Complex. *Trans. Geol. Soc. S. Afr.* **81**, 1-12.

Condie, K. C. 1989. *Plate Tectonics and Crustal Evolution*. Pergamon Press, Oxford, U.K.

Crockett, R. N. 1969. The geological significance of the margin of the Bushveld Basin in Botswana. Ph.D. thesis (unpubl.), University of London, London, U.K.

Crockett, R. N. 1972. The Transvaal System in Botswana: its geotectonic and depositional environment and special problems. *Trans. Geol. Soc. S. Afr.* **75**, 275-292.

Cullen, D. J. 1958. Geology of the Dikgomo-di-kae area. *Records of the Geological Survey of Bechuanaland Protectorate* 1956, 5-11.

Danielson, A. 1990. REE in the Griqualand West carbonates - evidence for seawater/fresh water mixing? *Geocongress '90 (Cape Town, South Africa): Abstracts*, 116-118.

Du Toit, A. L. 1954. *The geology of South Africa*. Oliver and Boyd, Edinburgh, U.K.

Engelbrecht, J. P. 1986. Die Bosveldkompleks en sy vloergesteentes in die omgewing van Nietverdiend, Wes-Transvaal. Ph.D. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Eriksson, K. A. 1973. The Timeball Hill Formation - a fossil delta. *J. Sedim. Petrol.* **43**, 1046-1053.

Eriksson, K. A. and Truswell, J. F. 1973. High inheritance elongate stromatolitic mounds from the Transvaal Dolomite. *Palaeont. afr.* **15**, 23-28.

Eriksson, K. A. and Truswell, J. F. 1974. Stratotypes from the Malmani Subgroup northwest of Johannesburg, South Africa. *Trans. Geol. Soc. S. Afr.* **77**, 211-222.

Eriksson, K. A., McCarthy, T. S. and Truswell, J. F. 1975. Limestone formation and dolomitization in a lower Proterozoic succession from South Africa. *J. Sedim. Petrol.* **45**, 604-614.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Eriksson, K. A., Truswell, J. F. and Button, A. 1976. Palaeoenvironmental and geochemical models from a lower Proterozoic carbonate succession in South Africa. In: *Stromatolites* (edited by Walter, M. R.), 635-643. Elsevier, Amsterdam, Holland.

Eriksson, P. G. and Twist, D. 1986. A note on a lahar deposit in the Hekpoort Formation, Transvaal Sequence, near Pretoria. *Trans. Geol. Soc. S. Afr.* **89**, 415-418.

Eriksson, P. G., Nixon, N. and Snyman, C. P. 1987. A study of upper Pretoria Group sedimentary rocks in contact with the Rustenburg Suite in the Buffelspoort Dam area, near Rustenburg. *S. Afr. J. Geol.* **90**, 124-136.

Eriksson, P. G. 1988. The sedimentology of the Rooihoogte Formation Transvaal Sequence. *S. Afr. J. Geol.* **91**, 477-489.

Eriksson, P. G., Meyer, R. and Botha, W. J. 1988. A hypothesis on the nature of the Pretoria Group basin. *S. Afr. J. Geol.* **81**, 490-497.

Eriksson, P. G., Labuschagne, H. and Engelbrecht, J. P. 1989. Stratigraphy, lithology and sedimentology of the Droogedal Formation, Transvaal Sequence, western Transvaal. *S. Afr. J. Geol.* **92**, 102-109.

Eriksson, P. G. and Clendenin, C. W. 1990. A review of the Transvaal Sequence, South Africa. *J. Afr. Earth Sci.* **10**, 101-116.

Eriksson, P. G., Twist, D., Snyman, C. P. and Burger, L. 1990. The geochemistry of the Silverton Shale Formation, Transvaal Sequence. *S. Afr. J. Geol.* **93**, 454-462.

Eriksson, P. G., Schreiber, U.M. and Van der Neut, M. 1991. A review of the sedimentology of the Early Proterozoic Pretoria Group, Transvaal Sequence, South Africa: implications for tectonic setting. *J. Afr. Earth Sci.* **13**, 107-119.

Eriksson, P. G. 1992. On discriminating Precambrian marine and lacustrine basins: an example from the Early Proterozoic Pretoria Group. *Geocongress '92 (Bloemfontein, South Africa): Abstracts*, 113-115.

Eriksson, P. G. and Cheney, E. S. 1992. Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the Lower Proterozoic sequences of southern Africa. *Precambrian Res.* **54**, 257-269.

Eriksson, P. G., Schreiber, U. M., Van der Neut, M., Labuschagne, H. Van der Schyff, W. and Potgieter, G. Under review. Problems in the palaeoenivronmental interpretation of non-fossiliferous Precambrian quartzitic sandstones: an example from the Early Proterozoic Transvaal Sequence, South Africa. Submitted to *J. Sedim. Petrol.*

French, B. M. and Twist, D. 1983. Status of the Rooiberg felsite in the Bushveld Complex: a review. *Res. Rep. Inst. geol. Research Bushveld Complex, Univ. Pretoria.* **39**.

Geerthsen, K., Maher, M. J. and Meyer, R. 1991. The western edge of the Griqualand West Basin - A geophysical perspective. *S. Afr. J. Geol.* **94**, 96-103.

Hälbich, I. W., Lamprecht, D., Altermann, W. and Horstmann, U. E. 1992. A carbonate-banded iron formation transition in the Early Proterozoicum of South Africa. *J. Afr. Earth Sci.* **15**, 217-236.

Harmer, R. E. and Von Gruenewaldt, G. 1991. A review of magmatism associated with the Transvaal Basin - implications for its tectonic setting. *S. Afr. J. Geol.* **94**, 104-122.

Hartzer, F. J. 1987. Die geologie van die Krokodilriviefragment, Transvaal. M. Sc. thesis (unpubl.), Rand Afrikaans University, Johannesburg, South Africa.

Henry, G., Clendenin, C. W. and Charlesworth, E. G. 1990. Depositional facies of the Black Reef Quartzite Formation in the eastern Transvaal. *Geocongress '90 (Cape Town, South Africa): Abstracts*, 230-233.

Jahn, B. M., Bertrand-Sarfati, J., Morin, J. and Mace', J. 1990. Direct dating of stromatolitic carbonates from the Schmidtsdrif Formation (Transvaal Dolomite), South Africa, with implications on the age of the Ventersdorp Supergroup. *Geology* **18**, 1211-1214.

Key, R. M. 1983. The geology of the area around Gaborone and Lobatse, Kweneng, Kgatleng, Southern and South East Districts. *District Memoir Geol. Surv. Botswana* 5.

Key, R. M. 1986. Sedimentation along the eastern margin of the Bushveld Basin, SE Botswana. *Geocongress '86 (Johannesburg, South Africa): Abstracts*, 527-530.

Klein, C., Beukes, N. J. and Schopf, J. W. 1987. Filamentous microfossils in the Early Proterozoic Transvaal Supergroup: their morphology, significance and palaeoenvironmental setting. *Precambrian Res.* **36**, 81-94.

Klein, G. de V. 1982. Probable sequential arrangement of depositional systems on cratons. *Geology* **14**, 167-170.

Kuenen, P. H. 1963. Turbidites in South Africa. *Trans. Geol. Soc. S. Afr.* **66**, 191-195.

La Berge, G. L. 1966. Altered pyroclastic rocks in South African iron formation. *Econ. Geol.* **61**, 572-581.

MacGregor, I. M., Truswell, J. F. and Eriksson, K. A. 1974. Filamentous algae from the 2300 m.y. old Transvaal Dolomite. *Nature* **247**, 538-540.

Martini, J. E. J. 1990. An Early Proterozoic Playa in the Pretoria Group, Transvaal, South Africa. *Precambrian Res.* **46**, 341-351.

Mellor, E.T. 1905. The geology of a portion of the Springbok Flats and the adjacent areas. *Rept. S. Afr. Geol. Survey* 1904, 26-36.

Myers, R. E. 1990. The geology of the Godwan Basin, Eastern Transvaal. M.Sc. thesis (unpubl.), University of the Witwatersrand, Johannesburg, South Africa.

Nagy, L.A. 1984. Transvaal stromatolite: first evidence for the diversification of cells about 2.2×10^9 years ago. *Science* **183**, 514-516.

Nixon, N., Eriksson, P. G., Jacobs, R. and Snyman, C. P. 1988. Early Proterozoic micro-algal structures in carbonaceous shales of the Pretoria Group, southwest of Potchefstroom. *S. Afr. J. Science* **84**, 592-595.

Phillips, A. H. 1982. The geology of the Leeuwpoort tin deposit and selected aspects of its environs. M. Sc. thesis (unpubl.), University of the Witwatersrand, Johannesburg, South Africa.

Pratt, B. R. and James, N. P. 1986. The St. George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas. *Sedimentology* **33**, 313-343.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Rable, L. 1958. Geological field report on the first investigation into the manganese ore possibilities in the Bangwaketse native reserve, Bechuanaland Protectorate. Unpublished report to Johannesburg Consolidated Investment Company.

Reczko, B. F. F., Eriksson, P. G. and Snyman, C. P. 1992. Geochemistry of shales interbedded in the Magaliesberg Formation, Pretoria Group, near Pretoria: palaeoenvironmental and diagenetic implications. *Geocongress '92 (Bloemfontein, South Africa): Abstracts*, 305-307.

Reineck, H.-E. and Singh, I. B. 1975. *Depositional Sedimentary Environments*. Springer, Berlin, Germany.

Rhodes, R. C. 1972. Palaeocurrents in the Pretoria Group north of Marble Hall, Transvaal. *Ann. Geol. Surv. S. Afr.* **9**, 119-120.

Richards, R. J. 1987. A geological investigation of the Upper Transvaal Sequence in the northern portion of the Rooiberg Fragment. M.Sc. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Richards, R. J. and Eriksson, P.G. 1988. The sedimentology of the Pretoria Group in selected areas of the northern portion of the Rooiberg Fragment. *S. Afr. J. Geol.* **91**, 498-508.

Rozendaal, A. R., Toros, M. S. and Anderson, J. R. 1986. The Rooiberg tin deposits, west-central Transvaal. In: *Mineral Deposits of Southern Africa* (edited by Anhaeusser, C. R. and Maske, S.), 1307-1328. Geological Society of South Africa, Johannesburg, South Africa.

Rust, I. C. 1961. Note on turbidite structures in the Pretoria Series. *Trans. Geol. Soc. S. Afr.* **64**, 99.

Schopf, T. J. M. 1980. *Oceanography*. Harvard University Press, Cambridge, Massachusetts, U. S. A.

Schreiber, U. M., Eriksson, P. G., Meyer, P. C. and Van der Neut, M. 1990. The sedimentology of the Boshoek Formation, Transvaal Sequence. *S. Afr. J. Geol.* **93**, 567-573.

Schreiber, U. M. 1991. A palaeoenvironmental study of the Pretoria Group in the eastern Transvaal. Ph. D. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Schreiber, U. M. and Eriksson, P. G. In press. The sedimentology of the post-Magaliesberg formations of the Pretoria Group, Transvaal Sequence, in the eastern Transvaal. *S. Afr. J. Geol.* **95**.

Schweitzer J. K. 1986. Field and geochemical investigations of the Dullstroom and Rooiberg volcanic rocks. *Geocongress '86 (Johannesburg, South Africa): Abstracts*, 873-876.

Schweitzer, J. K. In preparation. Petrogenesis, evolution and relationships of Dullstroom and Rooiberg volcanics. Ph. D. thesis (unpubl.) University of Pretoria, Pretoria, South Africa.

Schweitzer, J. K. and Hatton, C. J. In preparation. Chemostratigraphy of the volcanic Dullstroom and Rooiberg successions, South Africa.

Schwellnus, J. S. I., Engelbrecht, L. N. J., Coetzee, F. J., Russell, H. D., Malherbe, S. J., Van Rooyen, D. P. and Cooke, R. 1962. The geology of the Olifants River area, Transvaal. Explanation Sheets 2429B (Chuniespoort) and 2430A (Wolkberg), Geol. Surv. S. Afr., 87 pp.

Sharpe, M. R. 1981. Petrology and geochemistry of pre-Bushveld and Waterberg mafic sills. *Trans. geol. Soc. S. Afr.* **84**, 75-83.

Sharpe, M. R., Brits, R. and Engelbrecht, J. P. 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3 Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. *Res. Rep. Inst. geol. Res. Bushveld Complex, Univ. Pretoria* **40**.

South African Committee for Stratigraphy (SACS). 1980. Stratigraphy of South Africa, part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the Republics of Bophuthatswana, Transkei and Venda. *Handbook Geol. Surv. S. Afr.* **8**.

Stear, W. M. 1976. The geology and ore controls of the northern Rooiberg tin-fields, Transvaal. M.Sc. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Stear, W.M. 1977a. The stratigraphy and sedimentation of the Pretoria Group at Rooiberg, Transvaal. *Trans. Geol. Soc. S. Afr.* **80**, 53-65.

Stear, W. M. 1977b. The stratabound tin-deposits and structure of the Rooiberg Fragment. *Trans. Geol. Soc. S. Afr.* **80**, 67-78.

Tankard, A. J., Jackson, M. P. A., Eriksson, K. A., Hobday, D. K., Hunter, D. R. and Minter, W. E. L. 1982. *Crustal Evolution of Southern Africa*. Springer Verlag, New York, U. S. A.

Taussig, D. and Maiden, K. 1986. Stratabound copper mineralization in the Duitschland Formation, Transvaal Basin. *Geocongress '86 (Johannesburg, South Africa): Abstracts*, 545-547.

Trendall, A. F., Compston, W., Williams, I. S., Armstrong, R. A., Arndt, N.T., McNaughton, N. J., Nelson, D. R., Barley, M. E., Beukes, N. J., de Laeter, J. R., Retief, E. A. and Thorne, A. M. 1990. Precise zircon U-Pb chronological comparison of the volcano-sedimentary sequences of the Kaapvaal and Pilbara cratons between about 3.1 and 2.4 Ga. *Third Archaean Symposium (Perth, Australia): Abstracts*, 81-83.

Truswell, J. F. and Eriksson, K. A. 1973. Stromatolitic associations and their palaeoenvironmental significance: a re-appraisal of a Lower Proterozoic locality from the northern Cape Province, South Africa. *Sediment. Geol.* **10**, 1-23.

Truter, F. C. 1949. A review of volcanism in the geological history of South Africa. *Trans. Geol. Soc. S. Afr.* **52**, 39-89.

Twist, D. and French, B. M. 1983. Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite. *Bull. Volcanol.* **46**, 225-242.

Twist, D. 1985. Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, Southeastern Bushveld. *Econ. Geol.* **80**, 1153-1165.

Twist, D. and Cheney, E. S. 1986. Evidence for the transition to an oxidising atmosphere in the Rooiberg Group, South Africa - A note. *Precambrian Res.* **33**, 255-264.

Twist, D. and Harmer, R. E. 1987. Geochemistry of contrasting siliceous magma suites in the Bushveld Complex: Genetic aspects and implications for tectonic discrimination diagrams. *J. Volcanol. Geotherm. Res.* **32**, 83-98.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Tyler, N. 1978. The stratigraphy of the early-Proterozoic Buffalo Springs Group in the Thabazimbi area, west-central Transvaal. *Inform. Circ. Econ. Geol. Res. Unit, Univ. Witwatersrand* **120**.

Tyler, N. 1979. The stratigraphy of the Early-Proterozoic Buffalo Springs Group in the Thabazimbi area, west-central Transvaal. *Trans. geol. Soc. S. Afr.* **82**, 215-226.

Van der Neut, M. 1990. Afsettingstoestande van die Pretoria Groep gesteentes in die Pretoria-Bronkhorstspruit-Delmas gebied. M. Sc. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Van Deventer, J. L., Eriksson, P. G. and Snyman, C. P. 1986. The Thabazimbi iron ore deposits, northwestern Transvaal. In: *Mineral Deposits of Southern Africa* (edited by Anhaeusser, C. R. and Maske, S.), 923-929. Geological Society of South Africa, Johannesburg, South Africa.

Visser, D. J. L. 1957. The structural evolution of the Union. *Trans. Geol. Soc. S. Afr.* **60**, 13-49.

Visser, J. N. J. 1969. "n Sedimentologiese studie van die Serie Pretoria in Transvaal. Ph. D. thesis (unpubl.), University of the Orange Free State, Bloemfontein, South Africa.

Visser, J. N. J. 1971. The deposition of the Griquatown Glacial Member in the Transvaal Supergroup. *Trans. geol. Soc. S. Afr.* **74**, 187-199.

Visser, J. N. J. 1972. The Timeball Hill Formation at Pretoria - a prograding shoreline deposit. *Ann. Geol. Surv. S. Afr.* **9**, 115-118.

Von Gruenewaldt, G. 1971. Petrographical and mineralogical investigation of the Bushveld Igneous Complex in the Tauteshoogte-Roossenekal area of the Eastern Transvaal. Ph.D. thesis (unpubl.), University of Pretoria, Pretoria, South Africa.

Von Gruenewaldt, G. 1972. The origin of the roof-rocks of the Bushveld Complex between Tauteshoogte and Paardekop in the eastern Transvaal. *Trans. Geol. Soc. S. Afr.* **75**, 121-134.

Wagner, P. A. 1921. The Mutue Fides-Stavoren Tinfields. *Publ. Dept. Mines and Industries, South Africa* **16**, 160 pp.

Wagner, P. A. 1927. The geology of the north-eastern part of the Springbok Flats and surrounding country. Explanation Sheet 17 (Springbok Flats), Geol. Surv. S. Afr., 104 pp.

Walraven, F., Armstrong, R. A. and Kruger, F. J. 1990. A chronostratigraphic framework for the north-central Kaapvaal Craton, the Bushveld Complex and the Vredefort structure. *Tectonophysics* **171**, 23-48.

Willemse, J. 1959. The floor of the Bushveld Igneous Complex and its relationships with special reference to the eastern Transvaal. *Trans. Geol. Soc. S. Afr.* **62**, 21-80.

Windley, B. F. 1979. Tectonic evolution of continents in the Precambrian. *Episodes* **4**, 12-16.

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FLOOD RHYOLITES IN THE ROOIBERG GROUP OF SOUTH AFRICA

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Abstract

Voluminous, sheet-like flows of dacitic to rhyolitic composition occur in the Rooiberg Group of South Africa. The conventional classification of lava versus pyroclastic flow is difficult to apply because these units show features common to both. This applies in particular to dacitic and rhyolitic flows that extend for kilometres, but have the fluidal textures of lavas. These rocks probably erupted like flood basalts and may be termed flood rhyolites.

Flow units in the upper Rooiberg Group have flow-banded lower zones, thick, massive interior zones and much thinner, commonly brecciated upper zones. Individual flows are mineralogically homogeneous, and typically a few hundred metres thick. Phenocrysts usually constitute less than 10% of the rock; some flows are essentially aphyric. The phenocrysts are generally anhydrous, with mineralogy and textures caused by supercooling, implying eruption at 1000 to 1100^{o}C. Eruption centres are uncommon. Compositions of associated rocks are typically basaltic, and the bimodality of many such provinces and other features suggests that mantle plumes may have been a factor in their genesis.

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Introduction

Rhyolitic, rhyodacitic, and dacitic rocks (here collectively referred to as rhyolites or felsic rocks) occur as lavas, pyroclastic flows, and air-fall deposits. Most felsic lavas are viscous and congeal as domes, or flows that rarely are more than a few kilometres long (e.g. Nakada et al., 1995). In contrast, pyroclastic flows are highly particulate and represent deposits of great lateral extent. Air-fall deposits may cover even larger areas than pyroclastic flows. Pyroclastic flows that contain flow-banding were first recognised in peralkaline rocks and were termed rheoignimbrites (Rutten and Van Everdingen, 1961; Rittman, 1962); they are relatively common in such peralkaline associations (Table 1).

In recent years a controversial type of rhyolitic extrusion, that shows the contrasting features of lavas and pyroclastic flows (Fig. 1, Table 2), has been recognised in southern Africa (e.g. Bristow 1980, 1989; Bristow and Armstrong, 1989; Twist, 1985; Milner and Duncan, 1989; Twist and Bristow, 1990; Figs. 1 and 2) and elsewhere (Tables 1 and 2). This type typically forms extensive and voluminous flows, pyroclastic features are scarce or absent, and flow-banding tends to be concentrated in the lower and upper portions of flow units (Fig. 3). Terminologies that have been employed for this type of flow are rheoignimbrite, agglutinate, froth-flow, tuffolava, high-temperature ash-flow, ignimbrite, lava-like tuff, lava flow, flood silicic lava, and flood rhyolite (Fischer and Schminke, 1984; Ekren et al., 1984; Henry et al., 1988; Bristow, 1989; Petrini et al., 1989; Branney et al., 1992; Henry and Wolff, 1992). The nature of the structures or edifices from which the volcanic rocks were erupted is not always clear. A few are known to have erupted from fissures (Henry and Wolff, 1992; fig. 9). In the case of the Jozini rhyolites, Bristow et al. (1995) proposed eruption from elongate caldera-like structures. Milner and Ewart (1989) proposed the Messum Complex to be the site of some quartz latite eruptions.

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Some of the first "flood rhyolites" to be described were the Jozini rhyolites of the Lebombo monocline (Fig. 1). The felsic rocks of the Jozini Formation and those of the Nuanetsi and Etendeka provinces (Fig. 1) erupted in continental, extensional settings at different times during the break-up of Gondwana. The Etendeka rocks are contemporaneous with those of the Parana province of Brazil, where extensive lava-like felsic rocks also occur (Whittingham, 1989). Urie and Hunter (1963) concluded that the Jozini rhyolite units were ignimbrites. However, Wachendorf (1973) regarded similar rocks in the Mozambiquan portion of the province to be lava flows. Bristow and Cleverly (1979) argued that these rocks were high-temperature ash-flows. Similar conflicting opinions have been expressed in many other regions (Ekren et al., 1984; Bonnichsen and Kauffman, 1987; Henry et al., 1988; Whittingham, 1989; Petrini et al., 1989; Branney et al., 1992; Henry and Wolf, 1992).

This paper describes relevant field and textural features of the 2.06 Ga (Walraven, 1997) Rooiberg Group of South Africa. These features, and their comparison with other high-volume and large extent rhyolite occurrences may provide clues towards the mode of eruption of these volcanic rocks.

The Rooiberg Group

General

The tectonic setting of the Bushveld Complex and the Rooiberg Group has been discussed by several authors. Twist (1983) suggested intra-cratonic rifting. Hatton (1996), and Hatton and Schweitzer (1995) suggested that a mantle diapir (see also Sharpe et al., 1981; Sawkins, 1984) triggered

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Bushveld formation. Rhodes (1975) and Elston (1995) advocate an impact origin for the Bushveld Complex, with some of the Rooiberg flows representing impact melts.

Field and geochemical features of the Rooiberg volcanic rocks were documented and reviewed by Twist and French (1983), Twist (1985), Twist and Harmer (1987), Cheney and Twist (1991), Cheney and Winter (1995), Schweitzer et al. (1995a and b), Schweitzer and Hatton (1995), Hatton and Schweitzer (1997), Walraven (1997), and Schweitzer et al. (1998). The Rooiberg Group (Fig. 2) is mainly rhyolite and dacite, typically 3 to 5 km thick. To date, no eruption centres of the felsites have been described. The felsites were intruded by, but are virtually synchronous with, the 2.05 - 2.06 Ga Bushveld Complex (Walraven, 1997; Hatton and Schweitzer, 1995).

The estimated extrusive volume of the Rooiberg Group is about 100 000km^3 (Schweitzer et al., 1998). Eruptive volumes per formation increase from the base to the top, i.e. from the Dullstroom to the Damwal, Kwaggasnek and finally Schrikkloof Formation (Fig. 2). The diversity of magma types decreases upward with a total of nine geochemically distinct magma types documented (Schweitzer et al., 1995a). Four magma types (Low-Ti basaltic andesite, Basal Rhyolite, High-Ti basalt, and High-Mg Felsite) are present in the basal Dullstroom Formation; in the Damwal, Kwaggasnek and Schrikkloof Formations compositionally distinct Low-Mg Felsites are the predominant magma type. The Low-Mg Felsites are the major concern of this study. One magma type (the High-Mg Felsite) is common to the Dullstroom Formation, in the floor and roof of the Rustenburg Layered Suite (Schweitzer et al., 1995a). This and the existence of an unconformity beneath the Dullstroom Formation (Cheney and Twist, 1991), establishes that the volcanic rocks were a continuous succession separated by intrusion of the Rustenburg Layered Suite.

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Basalts and basaltic andesites towards the base of the Dullstroom Formation (Fig. 2), and the Rustenburg Layered Suite contrast with the siliceous components of the Complex, i.e. the Rashoop Granophyre and Lebowa Granite Suites, and the remainder of the Rooiberg Group. Bimodal magmatism is also documented in other areas of extensive felsic flow occurrences (Branney et al., 1992; Henry and Wolff, 1992; Milner et al., 1992).

Field Relations, Textural Features and Whole Rock Geochemistry

Field Relations

The southeastern portion of the Rooiberg province has distinctly mappable units (Clubley-Armstrong, 1977; Twist, 1985); individual flows range in thickness from a few meters to 390 m. Siliceous flows are extensive, and some extent for more than 40 km.

The Rooiberg rhyolites have thick, massive interior zones (Fig. 3). Flow-banding and breccias typically occur only in the basal and upper portions of the units, respectively. Flow-banded bases are more consistent with lava than pyroclastic flow (Henry and Wolff, 1992). Spherulites, rarely 10 centimetres in diameter, are common throughout. Amygdales and lithophysae are irregularly distributed but locally occur in great abundance. Intensely amygdaloidal flow-tops about a metre thick are developed locally (Fig. 4).

Flows in units 6 and 7 (Twist, 1985), the transition from the Damwal to the Kwaggasnek Formation as exposed at Loskop Dam (Figs. 2 and 5) exhibit comparable characteristics. Significantly, flows 2 and 3 do not have

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basal breccias, which are characteristic of the "tractor tread" advancement of conventional (viscous) felsic lava flows (Henry and Wolff, 1992). Furthermore, none of the other flow units in the Rooiberg Group seem to have basal breccias (Twist and Elston, 1989), and none have unwelded bases or tops that are so characteristic of pyroclastic flows. Each flow is capped by a zone of irregularly oriented, flow-banded blocks separated by dykelet-like bodies of siliceous, fine-grained material. We interpret these as flow-top breccias that were cut by hydrothermal chalcedonic veins as the underlying part of the flow cooled.

Flow 3 is capped by a tuffaceous-looking, weakly limonitic rock containing accretionary lapilli $\leq$ 13mm in diameter (Fig. 6). X-ray diffraction and petrographic investigations show that this lapilli-bearing unit consists largely of quartz and secondary mica. Opaques commonly form the nuclei of individual lapilli. The lapilli, together with extensive limonite at the contact with the underlying flow-top breccia of flow 3 suggest supergene weathering of a pyritic tuff.

Textural Features

In outcrop and thin section, the upper Rooiberg felsites contain rare shards, fiamme, and broken crystals are extremely rare; flow-banding, breccias, and euhedral phenocrysts are widespread.

Insights into the emplacement history of the uppermost part of unit 9 of Twist (1985), the Schrikkloof Formation (Schweitzer et al., 1995a), comes from an outcrop normally submerged by Loskop Dam. Three lithotypes occur in the outcrop. Lithotype 1 exhibits strongly flattened, devitrified inclusions that resemble densely welded fiamme (Fig. 7a): In thin section, despite pervasive devitrification, highly compacted shards are

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visible. Over about 5 m, lithotype 1 grades into a more densely welded variety, containing more elongate, flattened fiamme (Fig. 7b), which passes into lithotype 2, a flow-contorted rock that resembles ordinary rhyolitic lava (Fig. 7c). Lithotype 2 contains no obvious shards. Lensoid breccias describe lithotype 3. These breccias are interpreted as flow-breccias, with angular fragments of welded and flow-banded felsite set in a fine-grained, fragmented matrix. Thin sections show that some fragments in lithotype 3 contain unequivocal, welded shards (Fig. 7d), some with evidence of post-welding and secondary vesiculation (Fig. 7e). The delicate walls of the post-welding vesicles splintered into fragments, producing a second generation of shards in the matrix of the breccia (Fig. 7f).

It is noted that these pyroclastic textures are atypical. They only occur in unit 9. Unit 9 is also distinguished from the other flows by higher Nb and Zr and lower TiO_2 and Sc contents (Twist, 1985; Schweitzer and Hatton, 1995), as well as the widespread development of flow-banding, even in the central portion of the flow.

The rhyolitic rocks of the Rooiberg, Lebombo, and Etendeka provinces have strong mineralogical similarities (Table 3). The major phenocrysts in each province are plagioclase, augite (or ferroaugite), and titanomagnetite; primary hydrous phases are absent. Other similarities are resorbed crystals, commonly glomeroporphyritic phenocrysts, and a low (<10 vol.%) percentage of phenocrysts. Zircons are uncommon in the rhyolitic rocks of the Rooiberg, and Zr increases progressively through the succession (Twist, 1985; Twist and Harmer, 1987), indicating that crystallisation of zircon was suppressed, presumably because of elevated eruption temperatures (Harmer and Farrow, 1995). However, zircons have recently been separated for geochronological studies from rhyolites of the upper Rooiberg Group (Walraven, 1997; M. Barley, pers. communication,

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1997).

Swallow-tailed and hopper crystals (Fig. 8) occur in lavas (mainly in basalts). These are absent from unit 9. Experimental investigations of such textures show that they form during crystallisation of super-cooled magma but not during devitrification of glass (Lofgren, 1993). The lack of suitable geothermometers precludes precise estimates of eruption temperatures of the Rooiberg felsites. However, the complex supercooled textures (Fig. 8) in otherwise aphyric rocks implies that some units erupted at super-liquidus ($\geq$ 1100^{o}C) temperatures (Twist and Elston, 1989). For supercooled textures to form, the magma first must be heated well above its liquidus temperature to destroy sites of nucleation (Lofgren, 1983). Swallow-tailed microlites and hopper crystals (Fig. 8b) also occur in the Etendeka (Milner, 1988, plate 3.1g). Two-pyroxene geothermometry suggests equilibration temperatures of 1000-1100^{o}C in the flows of the Jozini rhyolites and Etendeka quartz latites (Milner et al., 1992),(Table 3). The same geothermometer indicates comparable temperatures for similar flows in Texas and the Yellowstone area (Henry and Wolff, 1992; Honjo et al., 1992; Table 2).

Randomly-oriented quartz needles or plates, probably pseudomorphs of tridymite, occur in the rhyolites of the Nuanetsi (Zimbabwe, Cox et al., 1965, p 95), the Rooiberg (Twist and French, 1983; fig. 2a), and the Keweenawan (USA, Green and Fritz, 1989) provinces. In the Keweenawan the tridymite is interpreted as a primary magmatic phase, which is indicative of high eruption temperatures (Green and Fitz, 1989). In all three provinces the tridymite occurs in the matrix of some but not all flows. The tridymite does not resemble the open-space, vapour-phase crystallisation, common in ash-flow tuffs (Ross and Smith, 1961).

Whole-Rock Geochemistry

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The geochemical data of Figures 5 and 9 demonstrate the chemical uniformity of the flows with respect to some elements. The flow-top breccias were, because of their argillic alteration, not analysed. However, parts of the flows adjacent to these breccias are geochemically the most variable (Fig. 5), even considering elements that were relatively immobile during alteration (Schweitzer and Hatton, 1995). It is indicated that elements which behave inert in the massive interior of flows were redistributed in the vicinity of high porosity zones (i.e. the flow-top breccias).

Despite differences in age and location, the compositions of rhyolite units in the Rooiberg, Nuanetsi, Jozini, and Etendeka occurrences are similar (Table 4). Compared to average rhyodacites these flows have high Fe and low Al. Another notable feature is the geochemical homogeneity of individual flows with respect to some elements, other than Zr (Figs. 5 and 10). This is in sharp contrast to the pronounced zonations in some large ash-flow sheets (Smith, 1979).

Trace elemental abundances show few common features and are not particularly distinctive. Compared to average trace element abundances cited in Wedepohl (1969) for comparable rocks, Y contents are relatively high in all but the Etendeka province; whereas, Zr, Nb, Ce, and Yb are enriched in the Nuanetsi and Jozini rhyolites. Chondrite-normalised spidergrams indicate moderate degrees of light rare earth element (LREE) enrichment and small-to-moderate negative Eu anomalies in all four provinces. Initial Sr isotopic ratios of rhyolites are variable and range from low to high in all four provinces.

Discussion

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The felsic flows of the Rooiberg are similar in setting, appearance, mineralogy, and geochemistry to those in younger provinces (Tables 1 and 2). Similar flows occur in Idaho, USA (Ekren et al., 1984; Bonnichsen and Kaufmann, 1987). Ekren et al. (1984) related the flow features to an unusually deep-seated source with an exceptionally thick wedge of solid crust overlying the magma chamber; thus, evacuation of the magma did not cause calderas. For the Rooiberg felsites, the lack of intra-flow geochemical zonations and the absence of crystal fractionation (Hatton and Schweitzer, 1995) or other high-level magmatic processes are compatible with minimal periods of residence in shallow magma chambers. Intraplating (Schweitzer et al., 1998), for example, could produce felsic melts that have relatively little time to cool during ascent.

The wide extents, large volumes, and high temperature of eruption of the Rooiberg felsites and other flows suggest high rates of eruption. Wilson and Head (1981) pointed out that rates of magma ascent, and ultimately of eruption, are influenced by the density contrast between the magma and its more solid envelope. Because the density contrast usually increases with depth, a deep magma may rise to higher crustal levels.

Relatively low Al and high Fe contents of extensive felsic flows reflect mild alkalic tendencies. This alkalic nature is confirmed by the high Zr and Y concentrations in some of the provinces. In Figure 11 most of these rocks fall in the field of A-type granites (Collins et al., 1982), which also is compatible with their mildly alkalic chemistry.

The cause of the A-type signature is conjectural. Initial Sr isotopic ratios (Table 4) are high enough to indicate a significant crustal component. The A-type signature may follow the model of Barker et al. (1975): crustal materials are melted and contaminated by limited volumes of mantle-derived liquids, eventually forming homogeneous reservoirs.

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The economic geology and exploration strategies in flood rhyolite environments may be significantly different from those in conventional rhyolites that erupted as lava domes and short flows. The presence of significant amounts of limonite derived from pyrite in lapilli tuffs implies that permeable units within otherwise lithified flows could be favourable sites for bulk-mineable, hydrothermal mineral deposits (cf. Hetherington and Cheney, 1985). In contrast, vein-type deposits of Sn and F (Schweitzer et al., 1995b) would be expected to occur in the competent devitrified interior parts of flows.

Conclusions

We suggest that an analogy with flood basalts is instructive. Like flood basalts, these extensive felsic rocks may have erupted so rapidly and at such high temperatures that they could flow long distances. Indeed, Henry and Wolff (1992) suggested the term "flood rhyolites" for these unusual rocks. The world-wide occurrence of flood rhyolites since at least 3 Ga (Table 2) implies that the process generating the Rooiberg felsites is not unique.

It is noted that transitions from lava- to pyroclastic flows have been documented, in space and time (Branney et al., 1992). Similar to the Bad Step Tuff (Branney et al., 1992), the uppermost Schrikkloof Formation exhibits pyroclastic features at its base, with lava-like characteristics being more pronounced towards the top. Care must therefore be taken to not pigeonhole by proposing one extrusive mechanism for, for example, all the rhyolites of the Rooiberg Group. A spectrum of flow types could be present by the rhyolites of the Rooiberg Group, ranging from lava flows, lava-like ignimbrites, rheomorphic ignimbrites, to non-rheomorphic -

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welded ignimbrites. This aspect deserves future attention.

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References

Barker, O.B. (1978). *A contribution to the geology of the Soutpansberg Group, Waterberg Supergroup, Northern Transvaal*. M.Sc. thesis (unpubl), Univ. Witwatersrand, 116 pp.

Barker, F., Wones, D.R., Sharp, W.N. & Desborough, G.A. (1975). The Pikes Peak batholith, Colorado Front Range, and a model for the origin of the gabbro - anorthosite - syenite - potassic granite suite. *Precambrian Research*, 2, 97-160.

Bonnichsen, B. & Kaufmann, D.F. (1987). Physical features of rhyolite lava flows in the Snake River Plain Volcanic Province, southwestern Idaho. **In**: Fink J.H. (Ed.), The emplacement of silicic domes and lava flows. *Geol. Soc. Am. Spec. Pap.*, **212**, 119-145.

Borsi, S., Marinelli, G. Mozzoni, F., Mittempergher, M. & Tedesco, C. (1963). Reconnaissance of some ignimbrites at Pantelleria and Eolian Islands. *Bull. Volcanol.*, **25**, 359-363.

Branney, M.J., Kokelaar, B.P. & McConnell, B.T. (1992). The Bed Step Tuff: A lava-like rheomorphic ignimbrite in a calc-alkaline Piecemeal Caldera, English Lake District. *Bull. Volcanol.*, **54**, 187-199.

Bristow, J.W. (1980). *The geochronology and geochemistry of Karoo volcanics in the Lebombo and adjacent areas*. Ph.D. thesis (unpubl.), Univ. Cape Town, 257 pp.

Bristow, J.W. (1989). Retracing Vulcan's fiery footsteps. *Nuclear Active*, **41**, 30-37.

Bristow, J.W. & Cleverly, R.W. (1979). Volcanology of the Lebombo

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

rhyolites. *Ext. Abstr., Geocongress '79*, Geol. Soc. S. Afr., Univ. Port Elizabeth, 60-63.

Bristow, J.W. & Armstrong, R.A. (1989). An emplacement and petrogenetic model for the high-temperature ash flows of the Jozini Formation, South Africa. *Abstr., New Mexico Bureau of Mines and Mineral Resources Bull.*, **131**, p 31.

Bristow, J.W., Duncan, A.R., van der Westhuizen, W. & Venter, F., 1995. Subcircular caldera-type structures in the Lebombo Monocline: feeder centres to the Lebombo rhyolites. *Ext. Abstr., Geocongress '95*, Johannesburg, p 1093.

Brown, P.E., Parsons, I. & Becker, S.M. (1987). Peralkaline volcanicity in the Arctic Basin - the Kap Washington Volcanics, petrology and palaeotectonics. *J. Geol. Soc. Lond.*, **44**, 707-715.

Cas, R.A.F. (1978). Silicic lavas in Palaeozoic flyschlike deposits in New South Wales, Australia: Behaviour of deep subaqueous silicic flows. *Geol. Soc. Am. Bull.*, 89, 1708-1714.

Chapin, C.E. & Lowell, G.R. (1979). Primary and secondary flow structures in ash-flows of the Gribbles Run paleovalley, Central Colorado. *Geol. Soc. Am. Spec. Pap.*, **180**, 137-153.

Cheney, E.S. & Twist, D. (1991). The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. *Precamb. Res.*, **52**, 115-132.

Cheney, E.S. & Winter. H. de la R. (1995). The late Archean and Proterozoic major unconformity-bounded units of the Kaapvaal Province of

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Southern Africa. *Precambrian Res.*, **74**, 203-223.

Cleverly, R.W., Betton, P.J. & Bristow, J.W. (1984). Geochemistry and petrogenesis of the Lebombo rhyolites. *Spec. Publ. Geol. Soc. S. Afr.*, 13, 171-194.

Clubley-Armstrong, A.R. (1977). *The geology of the Selonsrivier area, north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome.* M.Sc. thesis (unpubl.), Univ. Pretoria, 107pp.

Collins, W.J., Beams, S.D., White, A.J.R. & Chappell, B.W. (1982). Nature and origin of A-type granites with particular reference to southeastern Australia. *Contrib. Mineral. Petrol.*, **80**, 189-200.

Cox, K.G., Johnson, R.L., Monkman, L.J., Stillman, C.J. & Vail, J.R. (1965). The geology of the Nuanetsi igneous province. *Phil. Trans. Royal. Soc. Lond.*, **257**, 72-218.

Ekren, E.B., McIntyre, D.H. & Bennett, E.H. (1984). High temperature, large volume, lava-like ash-flow tuffs without calderas in southwestern Idaho. *U.S.G.S. Prof. Paper*, **1272**, 73 pp.

Elston, W.E. (1995). Bushveld Complex and Vredefort Dome: The case for multiple-impact origin. *Ext. Abstr., Geocongress '95*, Johannesburg, 504-507.

Fischer, V. & Schminke, H.U. (1984). *Pyroclastic rocks.* Springer-Verlag, Berlin, 472 pp.

Giles, C.W. (1982). The geology and geochemistry of the Archaean Spring Wells felsic volcanic complex, Western Australia. *J. Geol. Soc. Austr.*,

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

29, 205-220.

Green, J.C. & Fitz, T.J. (1989). Large rhyolites in the Keweenawan midcontinent rift plateau volcanics of Minnesota - lavas or rheoignimbrites? Abstract, *New Mexico Bureau of Mines and Mineral Resources*, Bull. **131**, p 113.

Harmer, R.E. & Farrow, D. (1995). An isotope study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. *Mineral. Deposita*, **30**, 188-195.

Hatton. C.J., (1995). Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces. *Jour. Afr. Earth Sciences*, **21**, 571-577.

Hatton, C.J. & Sharpe, M.R. (1988). *Significance and origin of boninite-like rocks associated with the Bushveld Complex*. In: Crawford A.J. (ed), Boninites and related rocks. Unwin Hyman, London, 299-311.

Hatton, C.J. & Schweitzer, J.K. (1995). Evidence for synchronous extrusive and intrusive Bushveld magmatism. *Jour. Afr. Earth Sciences*, 21, 579-594.

Hausback, B.P. (1987). An extensive, hot, vapour charged rhyodacite flow, Baja California, Mexico. In: Fink, J.H. (Ed.), The emplacement of silicic domes and lava flows. *Geol. Soc. Am. Spec. Pap.*, **212**, 111-118.

Henry, C.D. & Wolff, J.A. (1992). Distinguishing strongly rheomorphic tuffs from extensive silicic lavas. *Bull. Volcanol.*, **54**, 171-186.

Henry, C.D., Price, J.G., Rubin, J.N., Parker, D.F., Wolff, J.A., Self, S., Franklin, R. & Barker, D.S. (1988). Widespread, lava-like silicic

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

volcanic rocks of Trans-Pecos, Texas. *Geology*, **16**, 509-512.

Hetherington, M.J. & Cheney, E.S. (1985). Origin of the opalite breccia at the McDermitt mercury mine, Nevada. *Econ. Geol.*, **80**, 1981-1987.

Honjo, H., Bonnichson, B., Leehman, W.P. & Stormer, J.C. (1992). Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain. *Bull. Volcanol.*, **54**, 220-237.

Johnson, C.M. and Lipman, P.W. (1988). Origin of metaluminous and alkaline volcanic rocks of the Latir volcanic field, northern Rio Grande rift, New Mexico. Contrib. Mineral. Petrol., **100**, 107-128.

Le Maitre, R.W. (1976). The chemical variability of some common igneous rocks. *Jour. Petrol.*, **17**, 589-598.

Lock, B.E. (1972). A lower Palaeozoic rheoignimbrite from White Bay, new Foundland. Can. J. Earth Sci., **9**, 1495-1503.

Lofgren, G.E. (1983) Effect of heterogeneous nucleation on basaltic texture: a dynamic crystallization study. *Jour. Petrol.*, **24**, 229-255.

Milner, S.C. (1988). *The geology and geochemistry of the Etendeka Formation quartz latites, Namibia*. Ph.D. thesis (unpubl.), Univ. Cape Town, 263 pp.

Milner, S.C. & Duncan, A.R. (1989). Quartz latites of the Etendeka Formation, Namibia - the products of major high-temperature rheoignimbrite eruptions. Abstract, *New Mexico Bureau of Mines and Mineral Resources*, Bull. **131**, p 191.

Milner, S.C. & Ewart, A. (1989). The geology of the Goboboseb Mountain

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

volcanics and their relationship to the Messum Complex. *Communc. Geol. Surv. Namibia*, 5, 31-40.

Milner, S.C., Duncan, A.R. & Ewart, A. (1992). Quartz latite rheoignimbrite flows of the Etendeka Formation, north-central Namibia. *Bull. Volcanol.*, 54, 220-237.

Monkman, L.J. (1961). *The geology of the Moase-Malibangwe River Basins with special reference to the Stormberg vulcanicity of Southern Rhodesia*. Ph.D. thesis (unpubl.), Univ. Leeds, 320 pp.

Nakada, S., Miyaka, I., Sato, H., Oshima, O. & Fujinawa, A. (1995). Endogeneous growth of dacite dome at Unzen volcano (Japan), 1993-1994. *Geology*, 22, 83-86.

Noble, D.C. (1968). Laminar viscous flowage structures in ash-flow tuffs from Gran Canaria, Canary Islands: a discussion. *Jour. Geology*, 76, 721-723.

Noble, D.C., Anderson, R.E., Ekren, E.B. & O'Connor, J.T. (1964). Thirsty Canyon Tuff of Nye and Esmeralda Counties, Nevada. *U.S.G.S. Prof. Pap., 475-D*, 24-27.

Orkild, P. (1965). Paintbrush and Timber Mountain Tuff of Nye County, Nevada. *U.S.G.S. Bull.*, 1224-A, 44-51.

Petrini, R., Civette, L., Iacumin, P., Longinelli, A., Bellini, G., Comin-Chiaramonte, P., Erneston, N., Marques, L.S., Melfi, A., Pacca, I. & Piccirillo, E.M. (1989). High-temperature flood silicic lavas (?) from the Parana Basin (Brazil). *Abstract, New Mexico Bureau of Mines and Mineral Resources*, Bull. 131, p 213.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Pirajno, F. (1988). A preliminary assessment of the geology and mineralisation of the Erongo volcanic complex, Namibia. *Ext. Abstr., Geocongress '88*, Geol. Soc. S. Afr., 461-464.

Potgieter, G.J.A. & Lock, B.E. (1978). Correlation and lithology of the Ritchie Quartz porphyry formation along the Riet River, near Kimberley. *Trans. Geol. Soc. S. Afr.*, 81, 41-46.

Preston, V.A. (1987). *The geology and geochemistry of the Mpongaza Inlier, Northern Natal*. M.Sc. thesis (unpubl.), Univ. Natal, Pietermaritzburg, 282 pp.

Rankin, D.W. (1960). Palaeogeographic implications of deposits of hot ash flows (Maine). 21st Internat. *Geol. Cong. Copenhagen, 1960*, Rept. pt. 12, 19-34.

Rhodes, R.C. (1975). New evidence for impact origin of the Bushveld Complex, South Africa. *Geology*, 3, 549-554.

Rittman, A. (1962). *Volcanoes and their activity*. Intersci., N.Y., 305 pp.

Ross, C.S. & Smith, R.L. (1961). Ash-flow tuffs: their origin, geologic relations and identification. *U.S.G.S. Prof. Paper*, 366, 81 pp.

Rutten, M.G. & Van Everdingen, R.O. (1961). Rheo-ignimbrites of the Rammes volcano. *Geol. Mijnbou*, 40, 49-57.

Sawkins, F.J. (1984). *Metal deposits in relation to plate tectonics* (Ed.: P/J. Willie), Springer Verlag, Berlin, 326pp.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Schminke, H.U. & Swanson, D.A. (1967). Laminar viscous flowage structures in ash-flow tuffs from Gran Canaria, Canary Island. *Jour. Geology*, 7, 641-664.

Schweitzer, J.K., Hatton, C.J. & de Waal, S. A. (1995a). Regional lithochemical stratigraphy of the Rooiberg Group, upper Transvaal Supergroup: a proposed new subdivision. *South African Jour. Geology*, 98/3, 245-255.

Schweitzer, J.K., Hatton, C.J. & de Waal, S. A. (1995b). Economic potential of the Rooiberg Group - volcanic rocks in the floor and roof of the Bushveld Complex. *Mineral. Deposita*, 30, 168-177.

Schweitzer, J.K. & Hatton, C.J. (1995). Chemical alteration within the volcanic roof rocks of the Bushveld Complex. *Econ. Geol.*, 90, 2218-2231.

Schweitzer, J.K., Hatton, C.J. and de Waal, S.A. (1997). Link between the granitic and volcanic rocks of the Bushveld Complex, South Africa. Jour. Afr. Earth Sciences, 24, 95-104.

Schweitzer, J.K., Hatton, C.J. & de Waal, S. A. (1996). The basal portion of the Rooiberg Group, South Africa: the onset of Bushveld magmatism. *Jour. Volcanol. Geotherm. Res.*, submitted.

Sharpe, M.R., Bahat. D. and von Gruenewaldt, G. (1981). The concentric elliptical structure of feeder sites to the Bushveld Complex and possible economic implications. *Trans. Geol. Soc. S. Afr.*, 84, 239-244.

Smith, R.L. (1979). Ash-flow magmatism. In: Chapin, C.E. and Elston, W.E. (Eds.), Ash-flow tuffs. *Geol. Soc. Am. Spec. Pap.*, 180, 43-75.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Twist, D. (1983). An economic evaluation of the Rooiberg Felsites. Univ. Pretoria, *Inst. Geol. Res. Bushveld Complex, Res. Rept.*, 41, 25 pp.

Twist, D. (1985). Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, Southeastern Bushveld. *Econ. Geol.*, 80, 1153-1165.

Twist, D. & Elston, W.E. (1989). The Rooiberg Felsite (Bushveld Complex): textural evidence pertaining to emplacement mechanisms for high-temperature siliceous flows. Abstract, *New Mexico Bureau of Mines and Mineral Resources*, Bull. 131, p 274.

Twist, D. and French, B.M. (1983). Voluminous acid volcanism in the Bushveld Complex: A review of the Rooiberg Felsite. *Bull. Volcanol.*, 46/3, 225-242.

Twist, D. & Harmer, R.E. (1987). Geochemistry of contrasting siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for tectonic discrimination diagrams. *J. Volcanol. Geotherm. Res.*, 32, 83-98.

Twist, D. and Bristow, J.W. (1990). Extensive lava-like siliceous flows in southern Africa: a review of occurrences. Univ. Pretoria, *Inst. Geol. Res. Bushveld Complex, Res. Rept.*, 82, 35 pp.

Urie, J.G. & Hunter, D.R. (1963). The geology of the Stormberg volcanics. *Bull. Geol. Surv. Swaziland*, 3, 28-44.

Van der Westhuizen, W.A., Grobler, N.J., Bristow, J.W. & Tordiffe, E.A.W. (1988). High temperature ash-flows in the Ventersdorp Supergroup. *Ext. Abstr., Geocongress '88*, Geol. Soc. S. Afr., 661-662.

Wachendorf, H. (1973). The rhyolitic lavas of the Lebombo (SE Africa).

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Bull. Volcanol., 37, 515-529.

Walker, G.W. & Swanson, D.A. (1968). Laminar flowage in a Pliocene soda rhyolite ash-flow tuff, Lake and Harney Counties, Oregon. *U.S.G.S. Prof. Paper*, 600-B, B37-B47.

Walraven, F. (1997). Geochronology of the Rooiberg Group, Transvaal Supergroup, South Africa. Econ. Geol. Res. Unit, Inf. Circ. 316, 21pp.

Watters, B.R. (1974). Stratigraphy, igneous petrology and evolution of the Sinclair Group in southern South West Africa. Univ. Cape Town, *Chamber of Mines Precambrian Res. Unit*, Bull. 16, 220 pp.

Wedepohl, K.H. (1969). *Handbook of geochemistry*. Springer Verlag, Berlin, five volumes.

Whittingham, A.M. (1989). Geological features and geochemistry of the acidic units of the Serra Geval volcanic formation, south Brazil. Abstract, *New Mexico Bureau of Mines and Mineral Resources*, Bull. 131, p 293.

Wilson, L. & Head, J.W. (1981). Ascent and eruption of basaltic magma on the earth and moon. *Jour. Geophys. Res.*, 86, 2971-3001.

Wolff, J.A. (1989). Origin of widespread silicic lavas and lava-like tuffs. *Abstract, New Mexico Bureau of Mines and Mineral Resources*, Bull. 131, p 297.

Wolmarans, L.G. (1988) The Bumbeni Complex: a post-Karoo ash-flow tuff cauldron in the southern Lebombo Mountains. *Ext. Abstr., Geocongress '88*, Geol. Soc. S. Afr., 745-748.

Digitised by the Department of Library Services in support of open access to information, University of Pretoria, 2021

Wright, J.V. (1980). Stratigraphy and geology of the welded air-fall tuffs of Pantelleria, Italy. *Geol. Rundsch.*, 69, 263-291.

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Figure 1: Volcanic successions in southern Africa that contain extensive rhyolitic units with fluidal textures.

Figure 2: Geographic distribution of formations of the Rooiberg Group (modified after Schweitzer et al., 1995a).

Figure 3: Comparisons of typical sections through the extensive rhyolitic units of the Rooiberg, Jozini, Nuanetsi, and Etendeka successions.

Figure 4: Strongly amygdaloidal flow-top zone in one of the Rooiberg rhyodacites.

Figure 5: Columnar section of the transition from the Damwal to the Kwaggasnek Formations, Rooiberg Group, as exposed in a road cut north of the Loskop Damwal. The units strike east-west and dip 55 to 75^{o} S.

Figure 6: Accretionary lapilli from tuff above flow 3 (see Figure 5 for locality).

Figures 7a - f: Unusual features in Rooiberg unit 9 in the Loskop Dam Holiday Resort. Figures 7a - c are outcrop photographs, and Figures 7d - f photomicrographs. (7a) Densely welded fiamme-like features, (7b) very densely welded fiamme-like features, (7c) flow contortions, (7d) photomicrograph of welded shards in vesiculated fragment in auto-breccia associated with the same outcrop shown in Figures 7a to c; width of view is 0.9mm, (7e) wider photomicrograph view of the auto-breccia illustrated in Figure 7d; the welded fragment shown top left is the same fragment illustrated in Figure 7d; it shows secondary vesiculation and disintegration to form second generation

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(unwelded) shards. Width of view is 3.5mm, (7f) a closer view of 7e process. Width of view is 2.5mm.

Figures 8a and b: Photomicrographs of supercooled textures in Rooiberg felsite.

Figures 9a and b: TiO_2 versus P_2O_5 and Zr for the three Rooiberg flows as depicted in Figure 5.

Figure 10: TiO_2 variations against stratigraphic height in extensive rhyolitic flows from the Rooiberg, Jozini, and Etendeka provinces.

Figure 11: Ga vs Al_2O_3 for extensive rhyolitic flows of southern Africa.

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Table 1: Examples of flow-banded and flow-folded flows of peralkaline affinity.

Locality	Characteristics/Comments	Age (Ma)	Reference
Pantelleria, Italy	Extensive welding and compaction of air-fall deposits to form rheoignimbrites	Active	Borsi et al. (1963); Wright (1980)
Monte Amiate, Italy	Flow-banded rheoignimbrites	Recent	Rittman (1962)
Nye County, Nevada, USA	Flow-banded ash-flow tuff	Tertiary	Noble (1968)
Unnamed ash-flow NW Nevada	Flow structures in welded tuff	Tertiary	Noble (1968); Noble et al., (1964)
Kane Springs Wash Caldera, SE Nevada	Flow structures in welded tuff	Tertiary	Noble (1968)
Gran Canaria, Canary Islands	Intense stretching of pumice fragments, flow-folding	Tertiary	Schminke & Swanson (1967)
Wagontire Mountain Tuff, Lake and Harney Counties, Oregon, USA	Flow structures in welded tuff	Miocene	Noble (1968);
Belted Range Tuff, Nevada	Flow structures in ash-flow tuff	Pliocene	Walker & Swanson (1968)
Latir Volcanics, New Mexico	Ash-flows, lavas and rheoignimbrites. Associated with alkaline basaltic rocks	29 - 22	Johnson & Lipman (1988)
Kap Washington, Greenland	Pyroclastics, rhyolitic lavas and rheoignimbrites. Assoc. with alkaline basaltic rocks	Early Tertiary	Brown et al. (1987)
Bumbeni Complex, South Africa	Flow-banded/folded felsic units	$\pm$133	Wolmarans (1988)
Rammes Volcano, Oslo Graben Norway	Rheoignimbrites	Permian	Rutten & Van Everdingen (1961)

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Table 2: Examples of possible and probable high-temperature rhyolitic flows, excluding peralkaline associations.

Locality	Characteristics/Comments	Age (Ma)	Reference
Thirsty Canyon Tuff, Nevada. USA	Post-compaction flow in tuffs	Tertiary	Noble et al. (1964)
Timber Mountain Tuff, Nevada, USA	Post-compaction flow in tuffs	Tertiary	Orkild (1965)
Paroc Sequence, Maine, USA	Post-compaction flow in Tuffs	Devonian	Rankin (1960)
Baja California, Mexico	Extensive, hot rhyolitic flows	Tertiary	Hausback (1987)
Gribbles Run, Colorado, USA	Flow features and folding in ash-flow units	Tertiary	Chapin & Lowell (1979)
Bruneau-Jarbidge Snake River Plain, USA	Extensive flow-banded, contorted rhyolite flows, bimodal province	±16 - 10	Ekren et al. (1984); Bonnichsen & Kauffman (1987)
Trans Pecos, Texas, USA	Flow-banded and folded silicic units	48 - 17	Henry et al. (1988), Henry & Wolff (1992)
Parana, Brazil	Extensive flow-banded, contorted rhyolitic flows, bimodal province	±123	Wittingham (1989)
Etendeka Namibia	Extensive flow-banded, contorted latites, quartz-latites, bimodal province	±132	Milner (1988) Milner et al. (1992)
Erongo Complex, Namibia	Pyroclastic flows and rheomorphic rhyolitic rocks, bimodal association	±123	Pirajno (1988)
Lebombo, South Africa and Mozambique	Massive, extensive, flow-banded, contorted dacites, rhyodacites, rhyolites, bimodal province	±178	Bristow & Cleverly (1979)
Nuanetsi, Zimbabwe	Flow-banding and contortions in extensive rhyodacitic flows, bimodal province	±199	Monkman (1961); Cox et al. (1965)
Nathins Cove Formation, White Bay, Newfoundland	Tuffs, ignimbrites and thick rheoignimbrites	Lower Palaeozoic	Lock (1972)

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Table 2: contd.

Locality	Characteristics/Comments	Age (Ma)	Reference
Australia	Extensive silicic flows	Palaeozoic	Cas (1978)
Sinclair Formation, Namibia	Flow-banded and contorted rhyolites, bimodal province	±1300	Watters (1974)
Soutpansberg, South Africa	Unusual flow-banding and folding in felsic flows, bimodal province	±1800	Barker (1978); Bristow (1980)
Rooiberg Group, South Africa	Massive felsic units with flow-banding and folding, bimodal province	±2060	Twist (1985)
Ventersdorp Supergroup, South Africa	Massive felsic units with flow-banding and folding, bimodal province	±2714	Van der Westhuizen et al. (1988); Potgieter & Lock (1978)
Springs Well Tuff, Western Australia	Flow-folding noted in felsic units. Basalt - andesite-rhyolite association	Archaean	Giles (1982)
Nsuze Group, Mpongoza Inlier, South Africa	Sheet-like units with rheomorphic flow-banding, bimodal association	±3000	Preston (1987)

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Table 3: Phenocryst assemblages from the extensive fluidal rhyolitic units of the Rooiberg, Jozini, and Etendeka successions.

	Rooiberg	Jozini	Etendeka
Modal %	0 - ±10	7.3 - 22.1	0 - 11.6
Resorption	Yes	Yes	Yes
Major Phases	Plagioclase (secondary albite)	Plagioclase (oligoclase)	Plagioclase (labradorite)
	Clinopyroxene (ferroaugite & ferrosalite)	Clinopyroxene (ferroaugite and rare Fe-pigeonite)	Pyroxene (augite, pigeonite, hypersthene)
	Titanomagnetite	Titanomagnetite	Titanomagnetite
Other Features	Commonly glomero-porphyritic	Commonly glomero-porphyritic	Commonly glomero-porphyritic
	No primary hydrous phases	No primary hydrous phases	No primary hydrous phases
	Common micro-phenocrysts and microlites		Common micro-phenocrysts and microlites
Temperatures	> 1100°C	1030-1100°C (2 pyroxenes) 804-990°C (olivine-clinopyroxene) 830-1241°C (plagioclase)	1015-1070°C (2 pyroxenes) 970-1140°C (pigeonite) ±1200°C (plagioclase)

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Table 4: Average whole-rock data for the extensive, fluidal rhyolitic units of southern Africa compared with average rhyolite and rhyodacite.

	Average Rhyodacite	Average Rhyolite	Rooiberg (Unit 6) (n=29)	Nuanetsi (n=19)	Jozini (n=49)	Etendeka (n=14)
SiO_2	66.98	74.06	70.00	71.60	70.70	68.20
TiO_2	0.61	0.28	0.58	0.44	0.50	0.95
Al_2O_3	15.37	13.50	12.01	12.89	12.65	13.02
FeO	4.04	2.48	7.42	4.71	5.70	5.78
MnO	0.09	0.06	0.17	0.09	0.10	0.11
MgO	2.14	0.40	0.55	0.40	0.35	1.32
CaO	3.70	1.16	2.97	1.39	1.47	3.06
Na_2O	3.75	3.61	2.00	2.89	3.16	3.03
K_2O	3.07	4.37	4.14	5.03	4.61	4.27
P_2O_5	0.25	0.07	0.18	0.08	0.14	0.28
Rb			159	157	130	167
Sr			86	85	153	132
Nb			14	102	84	23
Zr			317	763	1085	259
Y			54	83	129	39
Ce			105	284	257	84
Yb			4.8	9.9	12.3	3.4
Sr_i			<0.710?	0.708	0.704	0.715-0.727

Major element concentrations recalculated volatile-free, with total Fe expressed as FeO. Average rhyolite and rhyodacite contents from Le Maitre (1976). Rooiberg data are Unit 6 of Twist (1985). Nuanetsi and Jozini data are from Cleverly et al. (1984). Etendeka data are the Upper Tafelberg flow of Milner (1988).

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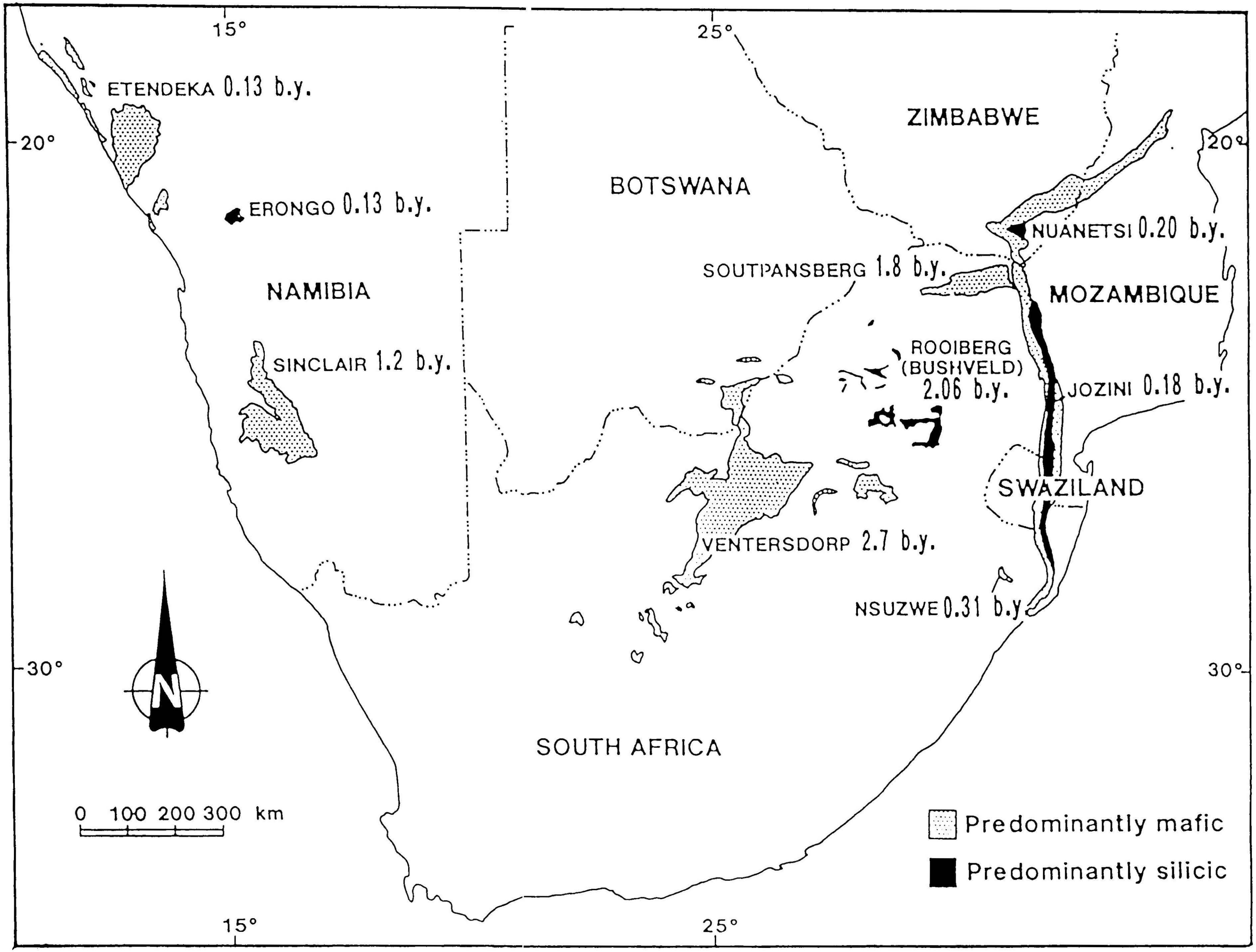

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Fig.1

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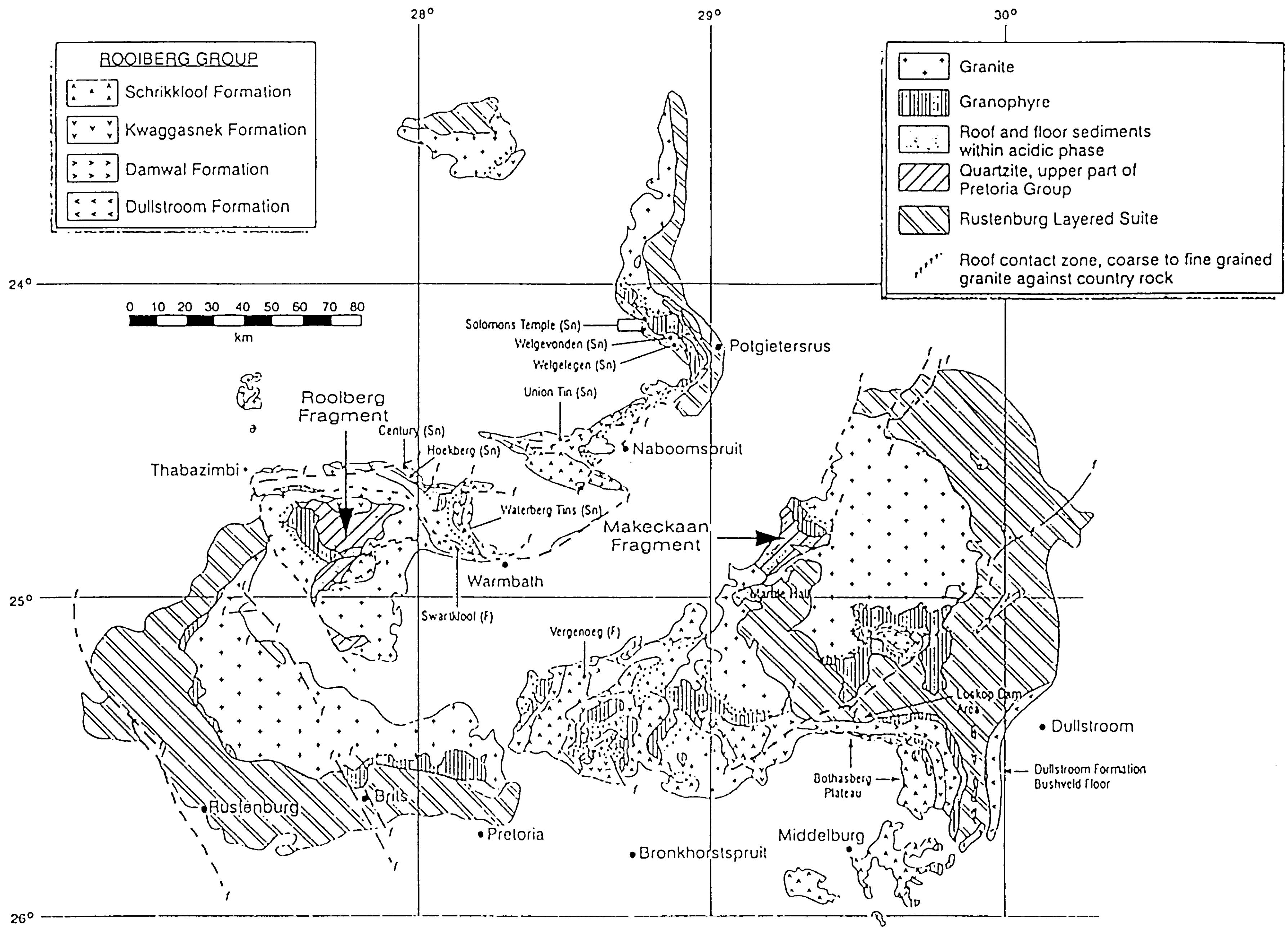

Fig.2

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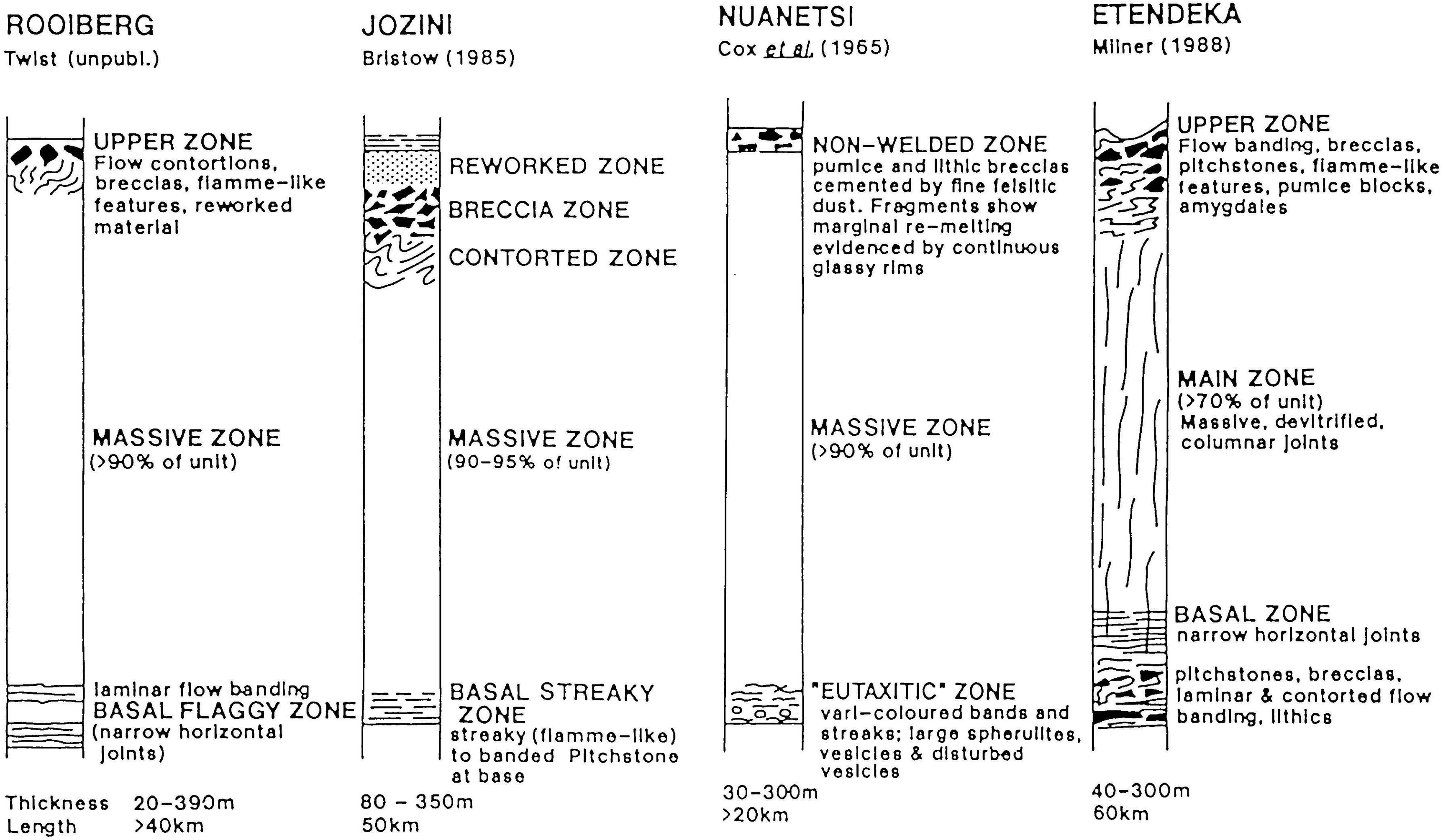

Fig.3

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Fig. 4

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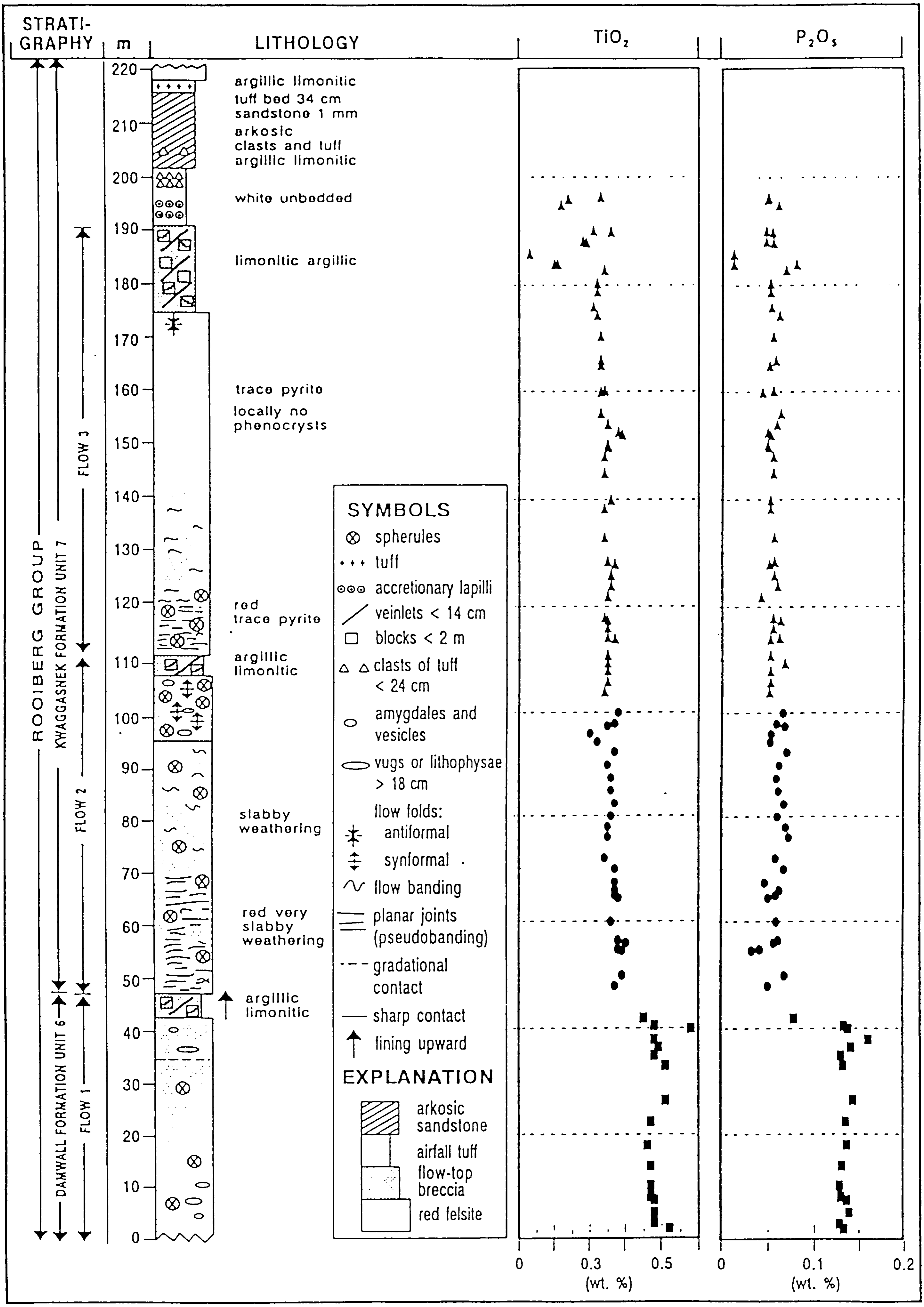

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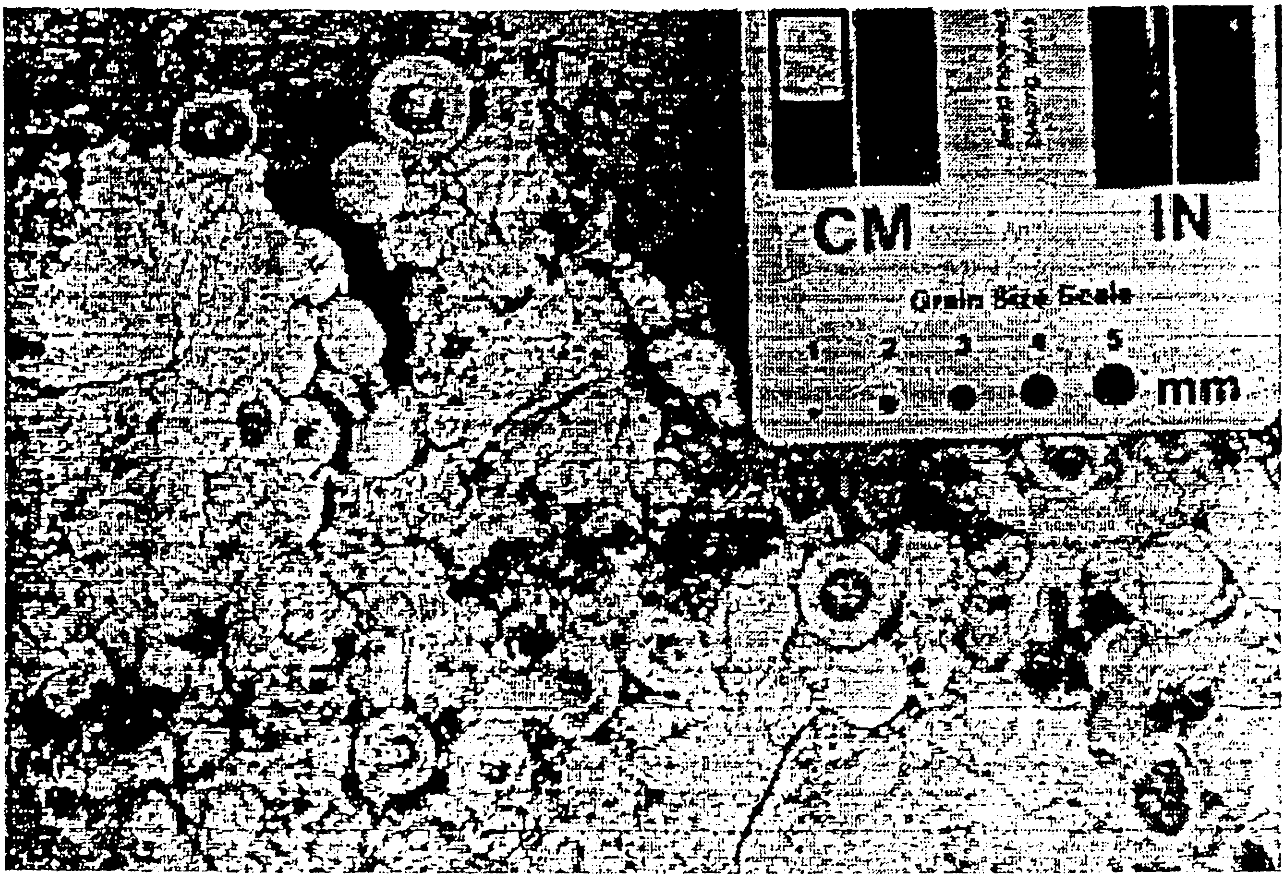

Fig. 6

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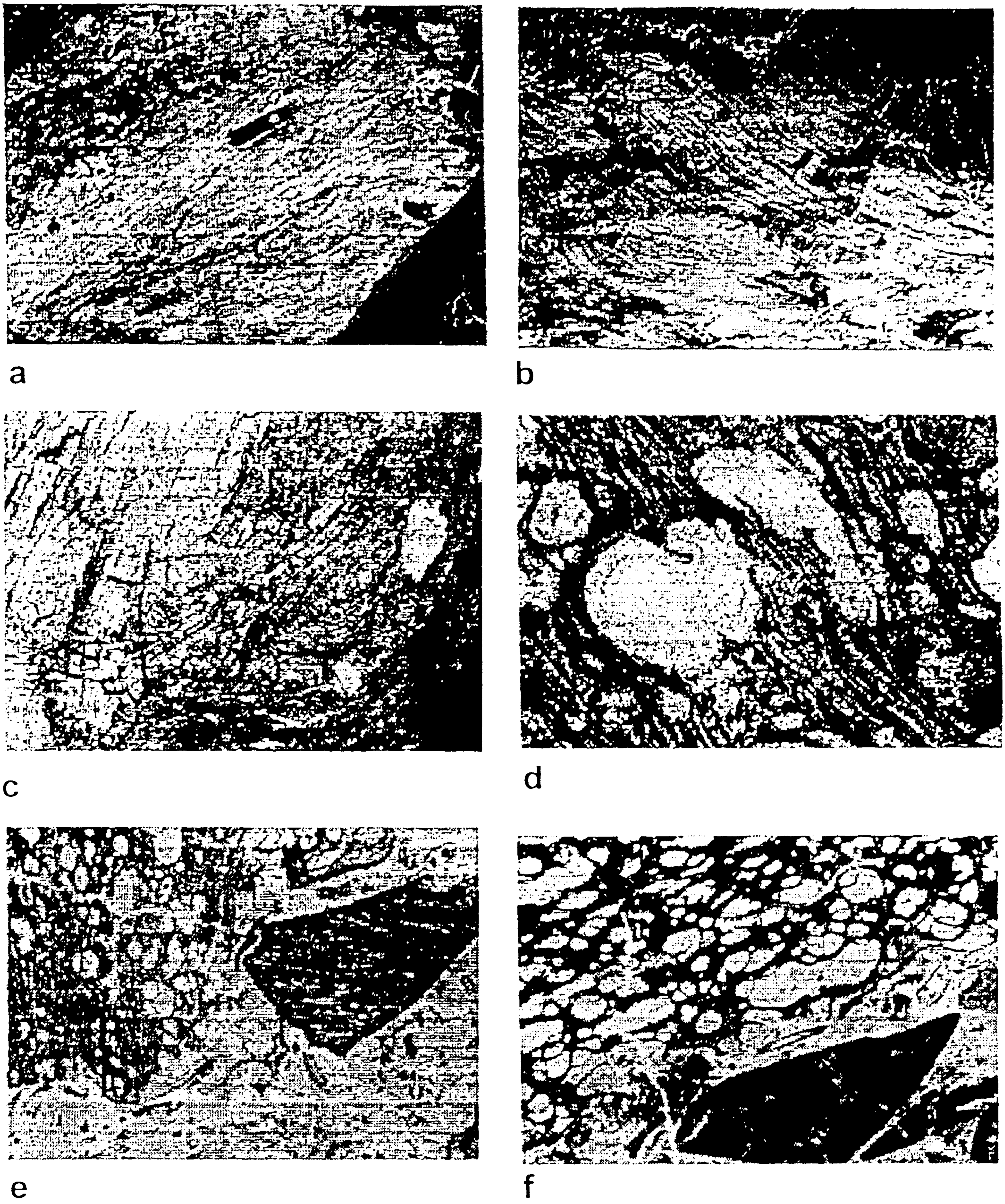

Figs. 7a to f

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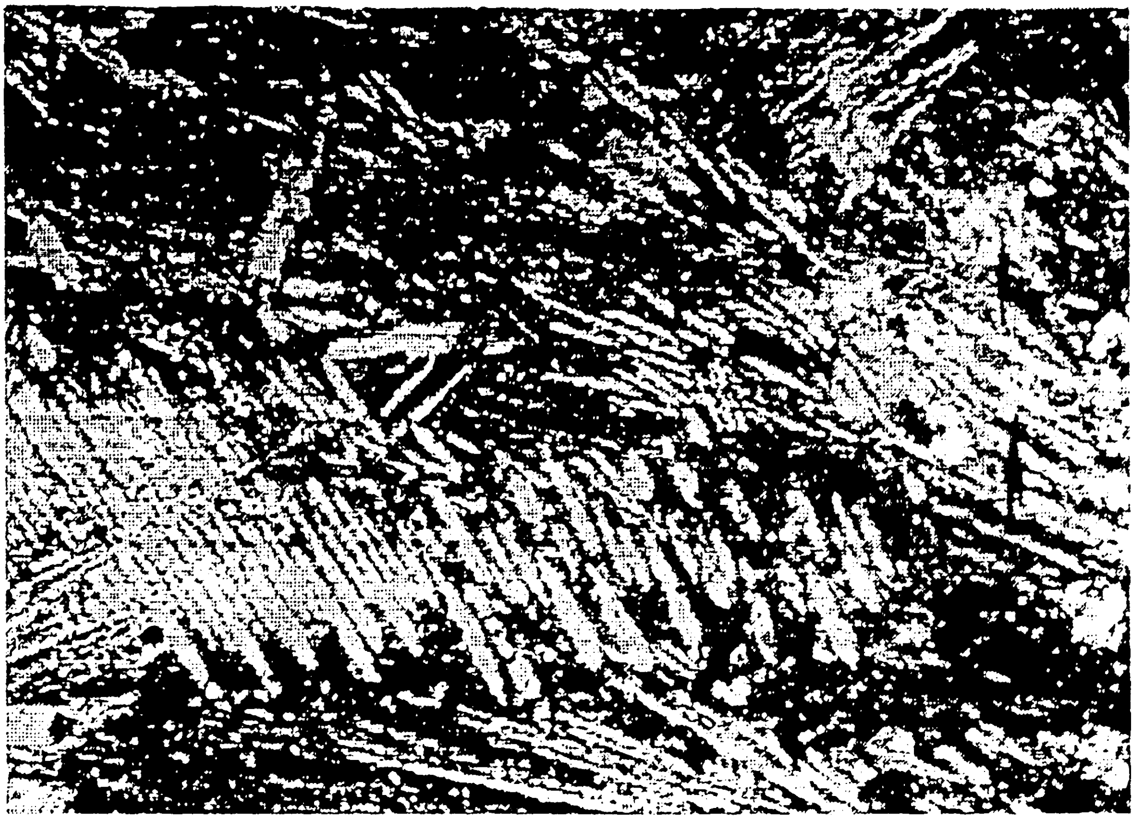

a

b

Figs. 8a and b

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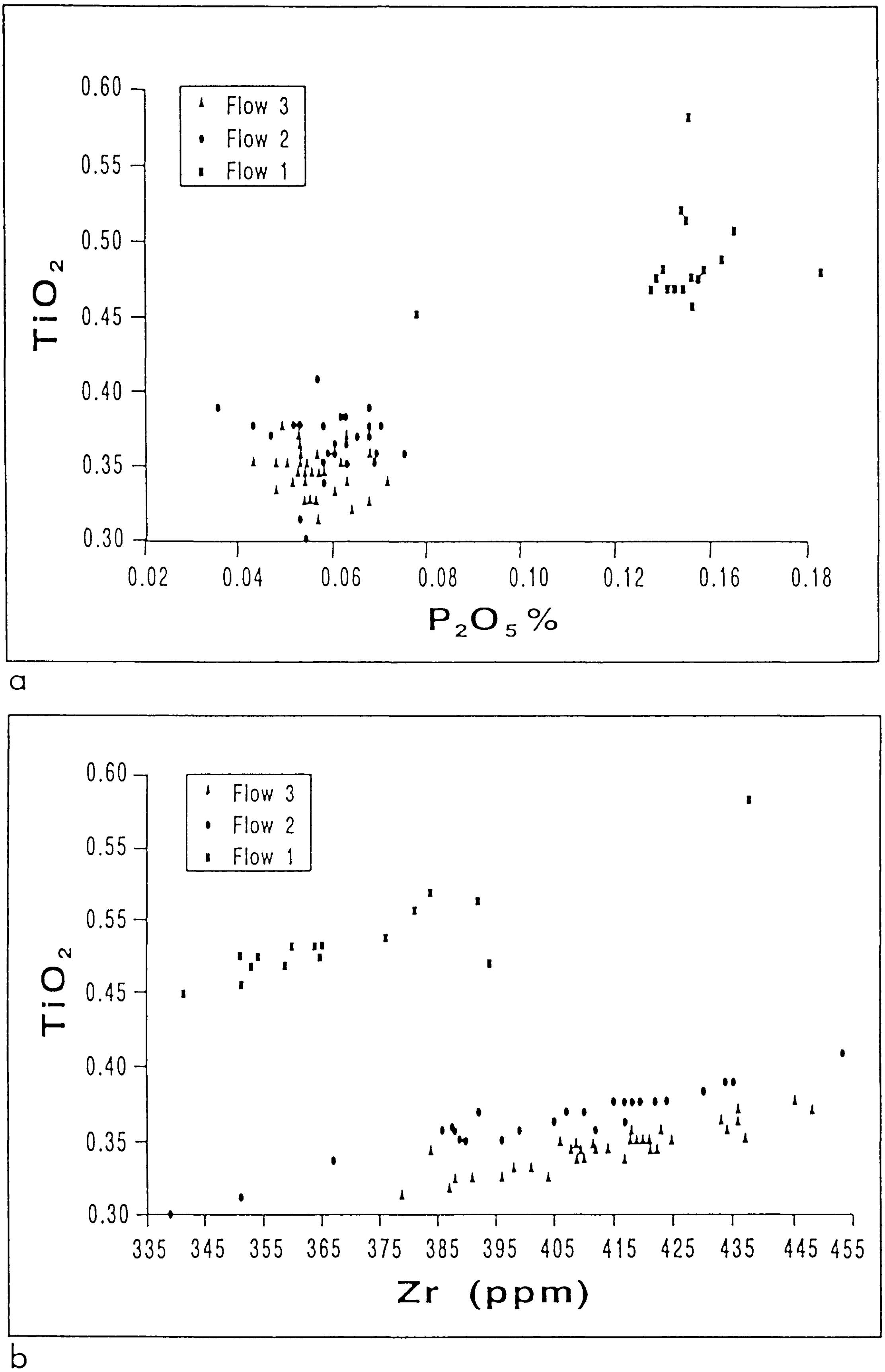

Figs.9a and b

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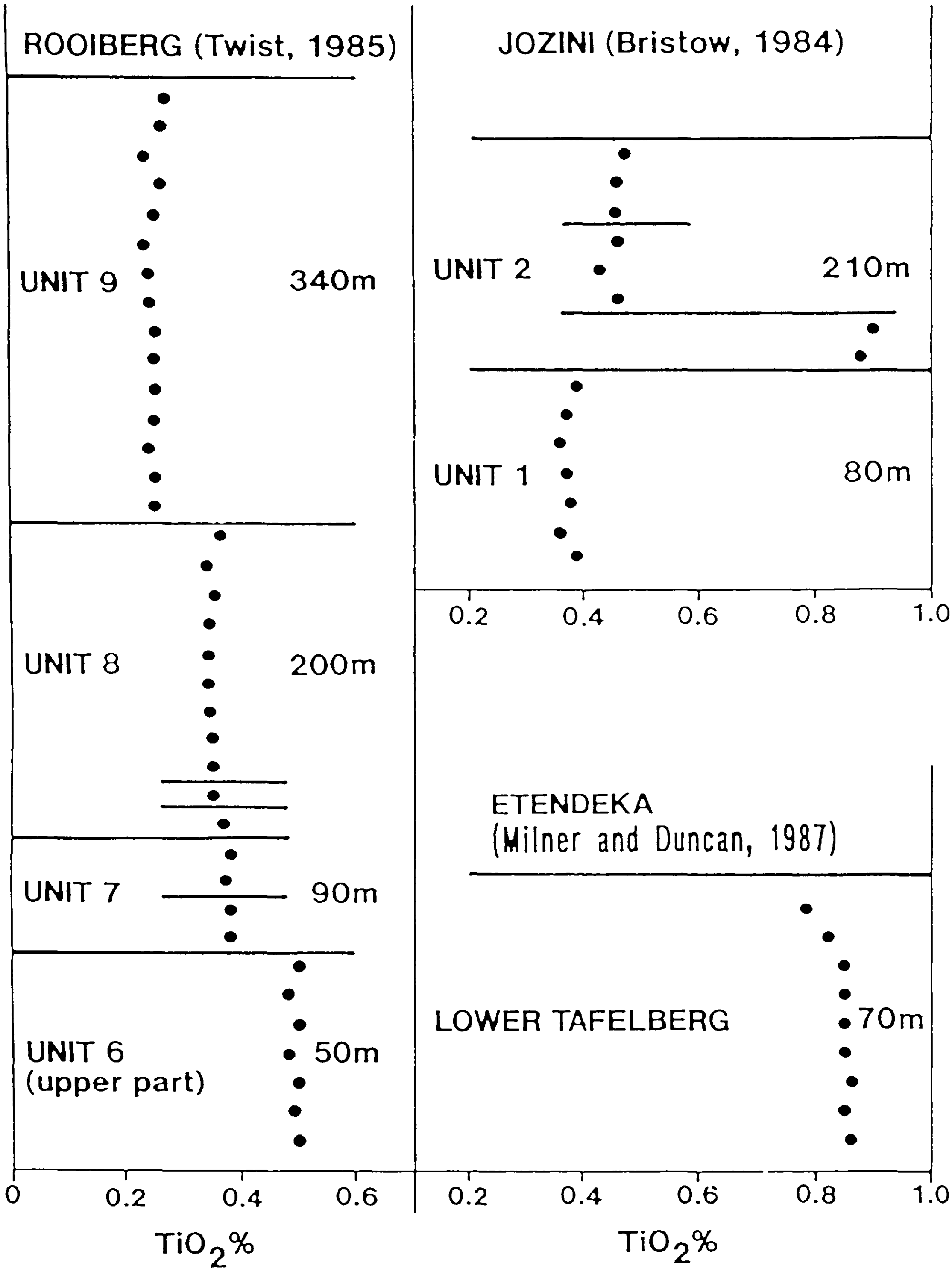

Fig.10

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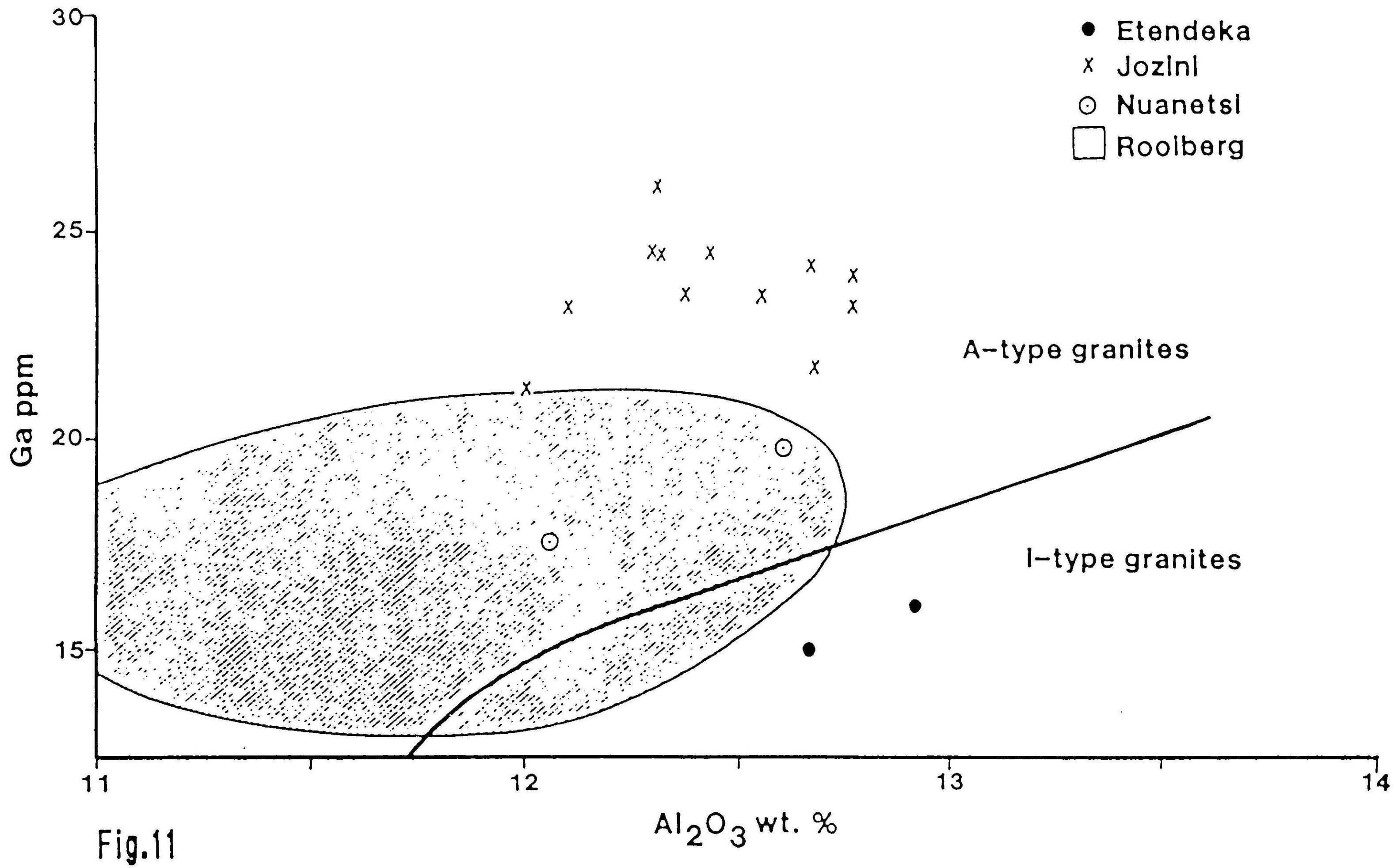

Fig.11

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Appendix D: Isotope Data

Harmer, R.E. and Farrow, D., 1995. An isotope study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. Mineralium Deposita, 30, 188-195.

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Mineral. Deposita 30, 188-195 (1995)

D1

MINERALIUM DEPOSITA
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An isotopic study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool

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Abstract. Many geochronological studies on silicic magmatic rocks associated with the Bushveld Complex (rhyolitic lavas of the Rooiberg Group and granites of the Lebowa Granite Suite) have shown evidence of open-system behaviour of the Rb–Sr and Pb–Pb isotopic systems until 1600-1000 Ma, many hundreds of million years after crystallisation of these rocks. This pervasive open-system behaviour has been attributed to sustained hydrothermal circulation driven by the high heat productivity of the Bushveld granites. New Sr and Pb isotopic data are presented for basaltic to rhyolitic volcanics from the Rooiberg Group of the Transvaal Sequence in the Dullstroom-Loskop Dam area of the eastern Transvaal. These data show little evidence of open-system behaviour after about 1950 Ma and many sample suites retain ages which could reflect the formation of the Rooiberg Group i.e. older than 2070 Ma. It is argued that this preservation is due to the absence of fractionated, fluid/vapour-rich Bushveld granites in the immediate vicinity of the volcanic occurrences. Rooiberg Group volcanics with extensively perturbed Rb–Sr and particularly Pb–Pb isotopic systems reflect the action of granite-derived hydrothermal fluids. As a consequence, the isotope systematics in these volcanics could prove a useful exploration tool for sites of granite-derived metal deposits.

Deposition of the Transvaal Sequence terminated with the eruption of large volumes of volcanic and volcaniclastic rocks of basaltic andesite to rhyolitic composition which make up the Dullstroom Formation of the Pretoria Group and the Rooiberg Group stratigraphic units (terminology of SACS, 1980). These volcanics were intruded by components of the Bushveld Complex: mafic magmas which gave rise to the Rustenburg Layered Suite (RLS) and subsequently by granitic magmas which formed the sheeted granite of the Lebowa Granite Suite (LGS).

Several isotopic studies on the Rooiberg rhyolites and the LGS granites have yielded anomalously young dates. Low ages in the LGS rocks have been variously ascribed to post-crystallisation metasomatism by heated groundwaters producing selective loss of radiogenic ^{87}Sr (Walraven et al., 1985) or the maintenance of long-lived hydrothermal systems in the granites because of elevated K, U and Th concentrations (McNaughton et al., 1993). These post-solidification modifications are thought to have had an important influence in the mineralisation of the LGS granites (e.g. Walraven et al., 1990b; Robb et al., 1994).

This contribution presents new Sr and Pb isotope data on representative units of the Dullstroom-Rooiberg volcanic succession in the Dullstroom-Loskop Dam area of the eastern Transvaal (Fig. 1). This sample set provides several useful constraints on the post-solidification history of the volcanics which form both the roof and floor of the LGS in this region and has significance in the formulation of exploration models for ore concentrations deposited from granite-sourced hydrothermal fluids.

Stratigraphy of Rooiberg Group

Stratigraphic relationships between the Rooiberg Group and Dullstroom Formation

Until relatively recently, the Dullstroom Formation volcanics were regarded as the uppermost preserved unit of the Pretoria Group of the Transvaal Sequence (terminology and classification following SACS, 1980). Evidence collected during systematic studies of the volcanology and petrology of the Rooiberg felsites (Twist, 1985; Twist and Harmer, 1987) and Dullstroom eruptives (Schweitzer, 1985, 1986) in the Dullstroom-Loskop Dam area of the eastern Transvaal have indicated that the volcanics comprising these two stratigraphic units form part of a continuous eruptive sequence (Schweitzer, 1986; Harmer and Von Gruenewaldt, 1990; Eriksson et al., 1993).

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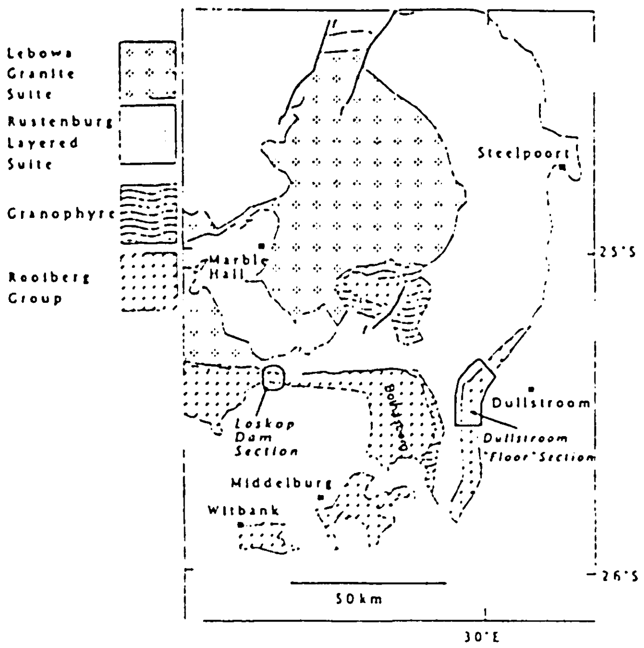

Fig. 1. Geological sketch map showing the Rooiberg Group occurrences discussed in the text

Table 1. Comparison between SACS (1980) stratigraphic terminology and revised lithostratigraphy of the Dullstroom and Rooiberg volcanics (Schweitzer et al., in press)

SACS (1980)		Schweitzer et al. (in press)	
Rooiberg Group	Selons River Formation Damwal Formation	Rooiberg Group	Klipnek Formation Schrikkloof Formation Damwal Formation Dullstroom Formation
Pretoria Group	Dullstroom Formation		

As a result, the stratigraphy of the Rooiberg Group has been re-evaluated by Schweitzer et al. (in press) who argue that the Dullstroom Formation should be considered part of the Rooiberg Group rather than the Pretoria Group. The recognition of an erosive base to the Dullstroom volcanics (Cheney and Twist, 1988) lends further support to this interpretation. Based on a regional correlation of the lithogeochemistry of the Rooiberg volcanics, a new stratigraphic subdivision of the Dullstroom-Rooiberg volcanics has been proposed (Schweitzer et al., in press) and this re-classification, presented in Table 1, will be adopted in this paper.

Volcanic stratigraphy of the Rooiberg Group

In the current (SACS, 1980) classification the Dullstroom Formation eruptives occur only below the level of intrusion of the RLS components and comprise about 80 flows of predominantly basaltic andesite composition with minor basalt, dacite and rhyolitic units. Two chemical sub-classes are distinguishable in the intermediate components: a high iron-titanium group ($Fe_2O_3^{Total}$ 11–15%; TiO_2 1.2–2.2%) and a more common low-titanium group having TiO_2 and $Fe_2O_3^{Total}$ below 1% and 11% respectively. The Rooiberg acid eruptives form the roof of the RLS in the Loskop Dam area where Twist (1985) subdivided the ca. 3.5 km thick volcanic succession into 9 units on the basis of colour, texture, phenocryst content and internal structure. Two contrasted compositional types of volcanic are recognised: a high magnesian variety (HMF = high magnesian felsite; MgO > 1.7%) and a low magnesian type (LMF = low magnesian felsite; MgO < 1.0%). LMF flows are found throughout the succession at Loskop Dam whereas HMF flows are found interbedded with LMF flows only in the lowest two volcanic units (i.e. Units # 1 and # 2).

Schweitzer (1985) demonstrated that the HMF flows in the Loskop Dam succession are the compositional equivalents of the low-TiO_2 of the Dullstroom Formation (terminology of SACS, 1980) whereas Harmer and Von Gruenewaldt (1991) highlighted the compositional similarity between the rhyolites erupted at the base of the Dullstroom and the HMF type. The persistence of the low iron-titanium magma type into the lower units of the Rooiberg Group has led to two important stratigraphic changes: firstly, the Dullstroom Formation is now considered a component of the Rooiberg Group and secondly, the Dullstroom Formation is extended to include the volcanics in Units # 1 and # 2 in the Loskop Dam area (Schweitzer et al., in press).

The age of the Rooiberg Group

Components of the RLS cut across the stratigraphic layering of the Pretoria Group and in the stratigraphically highest (southern) part of the eastern compartment of the Bushveld Complex, units of the RLS split the Dullstroom Formation of the Rooiberg Group. It is therefore apparent that the eruption of the lowest formations of the Rooiberg Group must have occurred prior to ca. 2050–2060 Ma, the currently accepted age of the RLS (Walraven et al., 1990a). Granites of the LGS were emplaced after the RLS mafic magmas and are thus younger than the Rooiberg volcanics. The Nebo Granite component of the LGS has been precisely dated by the zircon evaporation technique at 2054.4 ± 1.8 Ma by Walraven and Hattingh (1993). The Rooiberg volcanics must therefore be older than 2054 Ma. From field relationships, then, it is not possible that the Rooiberg Group can represent the volcanic equivalent of the Lebowa Granites. Significant compositional differences exist between the volcanics and granites (see discussion in Twist and Harmer, 1987) providing additional evidence against such a relationship.

In the Loskop Dam area, the uppermost Rooiberg Group and the overlying Loskop Formation sediments are intruded by a sheet of quartz porphyry (Clubley-Armstrong, 1977; Faurie, 1977) termed the Rooikop "Granophyre Porphyry" by SACS (1980). Zircons from this porphyry were analysed by Faurie (1977) and provide a date of $2072^{+23}/_{-22}$ Ma (errors are 95% confidence limits) when these data are recalculated following Eglington and Harmer (1993) by weighing the data for upper intercept. The data points show scatter in excess of the analytical uncertainty ("errorchron") and so the uncertainties are sensitive to the approach adopted to allow for this scatter. The age error limits quoted here were derived by augmenting the statistical uncertainties on the regression line by $(MSWD/F)^{1/2}$. This result constrains the age of the Rooiberg Group formations to be greater than 2050 Ma and possibly older than 2072 Ma.

Determining the absolute age of the Rooiberg Group is complicated by the fact that zircons are not found in the rhyolitic components: Zr increases progressively through the volcanic sequence at Loskop Dam (Twist, 1985; Twist and Harmer, 1987) indicating that, presumably because of elevated eruption temperatures, zircon crystallisation was suppressed in these lavas.

A Rb-Sr study of 12 Rooiberg Group rhyolites from the Witbank and Bothasberg areas by Walraven et al. (1985) yielded a date of 1604 ± 28 Ma and extremely high initial $^{87}Sr/^{86}Sr$ of 0.732 ± 2 (re-calculation as quoted in Walraven et al., 1990a; MSWD = 3.75). This date is too young to represent the time of crystallisation of the rhyolites. The same samples yielded a highly imprecise Pb–Pb age estimate of $2003^{+289}/_{-360}$ (Walraven et al., 1990; MSWD = 9.43).

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Isotope data

Sampling

Dullstroom Formation volcanics from the "floor" of the RLS. Rhyolitic samples were collected from the zone of basal rhyolites of the Dullstroom Formation which tend to form individual flows less than 8 km in strike length. The rhyolites are sparsely porphyritic with feldspar and augite phenocrysts variably replaced by sericite and chlorite, respectively. Lath-like augite phenocrysts are more abundant than the coarser-grained feldspar crystals. Swallow-tailed, polycrystalline quartz needles are common and presumably represent pseudomorphs after tridymite (Twist and French, 1983). The groundmass is wholly devitrified to a granular intergrowth of albite and quartz. Sericite and chlorite alteration is widespread throughout the groundmass and epidote is conspicuous. Basaltic andesite samples show ophitic textures with plagioclase and swallow-tailed amphibole crystals set in a fine, microlitic groundmass. Basalts tend to be porphyritic (phenocryst contents up to 20%) with plagioclase, clinopyroxene and amphibole grains frequently clustering in glomeroporphyritic textures. Magnetite phenocrysts are ubiquitous.

Rooiberg Group volcanics from the Loskop Dam area. Where possible, samples were taken from identifiable individual flows in the succession. Samples from the Loskop Dam section spanned most of the volcanic units delineated by Twist (1985) and include both high-MgO lava and low-MgO (LMF) types.

High-MgO samples were collected from flows in Unit # 2 and are generally holocrystalline, consisting of a fine intergrowth of sheaf-like albite and augite grains. "Swallow-tailed" albite grains are present. Chlorite and hornblende pseudomorphs, presumably after augite, are evident in some sections. Titanomagnetite is ubiquitous and comprises up to 1% of the samples. Patchy chlorite and sericite alteration is common.

Low-MgO rhyolites from Unit # 1 (RDW-1 to 10; Rb-11) have large lath-like albite phenocrysts in a devitrified groundmass of very fine quartz and feldspar. Unlike the previous sample set, no fresh pyroxene is found. Fine titanomagnetite is present throughout the groundmass constituting up to 1 modal percent. Some phenocrysts are sericitised and sericite and chlorite patches are evident in the groundmass. While still remarkably preserved for ancient fine-grained volcanics, these volcanics are more altered than those from the Unit # 4 flow.

Samples from Unit # 4 (DF-1 to 9 and 285/81, 313/81, 314/81) are dark grey low-MgO rhyolites containing 3–5% phenocrysts of augite, albite and titanomagnetite set in a groundmass of fine albite and augite laths with cryptocrystalline potash feldspar and quartz. Relict patches of volcanic glass are preserved in the groundmass of some samples. Excellent supercooling textures are noted including "swallow-tailed" albite crystals, sheaf-like aggregates of augite and elongate, skeletal titanomagnetite growths. Some albite phenocrysts exhibit minor sericitisation and epidote pseudomorphs are rarely seen. Preservation of augite and the barely devitrified glassy matrix testify to the essentially unaltered nature of the samples from this flow.

The remaining low-MgO volcanics are from Units 3,6,8 and 9 and most have a marked red colour in hand specimen. Phenocryst phases are extensively sericitised feldspar and, less commonly, quartz. The original glassy groundmass is wholly devitrified to a granophyric intergrowth of quartz and feldspar. Matrix quartz is coarser-grained than in the previously discussed sample groups and can be clearly distinguished microscopically. Sericite and chlorite alteration is widespread and epidote is also present; all mafic constituents are secondary. Red iron-oxide staining is pervasive throughout most samples and is presumably due to hematite exsolution during extensive devitrification.

Analytical methods

Samples were digested in full strength HF-HNO_3 mixtures in screw-top FEP Teflon vials and slowly taken to dryness with extra HNO_3. The dried sample was then dissolved in 6 M HCl and dried. Sr and Rb were separated on 10 mm internal diameter columns packed with 6 ml of AG50 W-x 12, 200–400 # cation exchange resin using 2.5 M HCl as the eluant. For Pb analyses, the samples were converted to bromide with 1 M HBr and loaded onto quartz glass micro-columns packed with ca. 40 µl of purified AG1 x 8 200–400 # mesh resin in 0.5 M HBr. Other elements were removed by washing with 0.5 M HBr and the Pb stripped using H_2O. A second pass through the columns was used to further purify the Pb. All reagents were repeatedly distilled and, in the case of H_2O and HBr, additionally cleaned through ion exchange resins. Total method blanks never exceeded 1 ng for Sr and Rb, and 0.5 ng for Pb.

Sr and Pb analyses were performed on a VG354 multi-collector mass spectrometer whereas Rb concentrations, and some Sr concentration and isotopic analyses were performed on a single-collector VG MM30 spectrometer. $^{87}Sr/^{86}Sr$ ratios were corrected for instrumental fractionation by normalising to $^{86}Sr/^{88}Sr$ of 0.1194. Fractionation of Pb isotopes was corrected by factors determined empirically from analyses of the NBS Pb standard SRM981 analysed in the same sample batch as the unknowns: at least two Pb standards were analysed per eight unknowns. Analytical uncertainties were assessed using duplicate analyses of rock standards and unknowns and are: 0.8% for $^{87}Rb/^{86}Sr$; 0.02% and 0.01% for $^{87}Sr/^{86}Sr$ determined on the MM30 and VG354 spectrometers respectively; 0.09% for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and 0.15% for $^{208}Pb/^{204}Pb$. The correlation between the errors in $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ was assessed as 0.95. Rb and Sr concentration measurements determined by X-ray fluorescence spectrometry have an uncertainty in $^{87}Rb/^{86}Sr$ of 1.5%. Repeated analyses of $^{87}Sr/^{86}Sr$ in the NBS Sr standard SRM 987 during the period of this study yielded 0.710271 ± 30 (1σ).

All regression calculations were performed following the recommendations described in Harmer and Eglington (1990). Uncertainties calculated for regression parameters where "geological scatter" is identified (i.e. "errorchrons" – tested using an F static based on errors determined on 60 replicates) are augmented by $(MSWD/F)^{1/2}$. All uncertainties are given as 95% confidence intervals.

Data

Results are presented in Table 2 and summaries of the various regression calculations discussed below are provided in Table 3.

1. Dullstroom Formation. Of the three sample suites analysed from the Dullstroom Formation volcanics cropping out below the RLS, only the basal rhyolites have sufficient range in Rb/Sr ratios to provide reasonably precise dates. All three suites yield Rb-Sr dates that are within error (admittedly extremely large) of 2080 Ma. Regressed on their own, the 10 basal rhyolite samples yield a date of 2037 ± 92 Ma and initial $^{87}Sr/^{86}Sr$ of 0.7071 ± 21. The Pb isotope data on 8 rhyolites yield an identical date of $2044^{+127}/_{-139}$. Considering the data sets together, it is clear that the high TiO_2 basalts have initial $^{87}Sr/^{86}Sr$ that are lower than the other groups (Fig. 2). Combining the low TiO_2 basaltic andesite with the rhyolite data yields a reasonably constrained (MSWD = 2.2) regression line date for 17 points of 2110 ± 31 Ma and initial $^{87}Sr/^{86}Sr$ of 0.7053 ± 5 (see Fig. 2).

The isotopic data for the sampled units from the Dullstroom Formation below the RLS, while providing only imprecise estimates of the possible primary age, show no evidence either of protracted cooling of the volcanics nor of pervasive isotopic/elemental disturbance at times

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Table 2. Isotopic data for the Rooiberg Group Volcanics from the Dullstroom-Loskop Dam area

Sample	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Precision	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Dullstroom Formation (Basalt: High-Ti Group)							
D-139a[b]	44.5	383	0.3363	0.71322 ± 5			
D-139c[b]	47.9	374	0.3711	0.71468 ± 7			
D-139d[b]	47.6	397	0.3477	0.71396 ± 7			
D-139f[b]	53.9	410	0.3802	0.71474 ± 6			
D-139g[b]	47.0	397	0.3432	0.71426 ± 5			
D-139h[b]	55.2	413	0.3872	0.71513 ± 6			
D-139i[b]	38.6	439	0.2541	0.71154 ± 5			
D-139k[b]	46.9	412	0.3297	0.71340 ± 6			
Dullstroom Formation (Basaltic andesite: Low-Ti Group)							
D-143a[b]	56.3	264	0.6173	0.72404 ± 5			
D-143b[b]	61.6	261	0.6850	0.72548 ± 7			
D-143d[b]	49.7	253	0.5701	0.72231 ± 6			
D-143e[b]	52.4	278	0.5470	0.72197 ± 5			
D-143g[b]	80.4	263	0.8872	0.73218 ± 5			
D-143h[b]	66.2	273	0.7038	0.72704 ± 8			
D-143i[b]	40.1	267	0.4361	0.73018 ± 8			
D-143k[b]	79.0	264	0.8667	0.72109 ± 6			
Dullstroom Formation (Basal rhyolites)							
D-14[b]	80.8	205	1.146	0.74235 ± 5			
D-53	104.4	227.4	1.333	0.745351 ± 13[a]	18.358	15.592	38.340
D-92a	112.5	202.9	1.612	0.754231 ± 14[a]	19.305	15.742	39.531
D-92d[a]	145	186	2.265	0.773961 ± 13[a]	19.690	15.785	39.933
D-92g	132.7	200.9	1.921	0.762721 ± 17[a]	17.639	15.505	37.615
D-92h	116.9	195.7	1.737	0.758131 ± 14[a]	17.497	15.503	37.554
D-92i[b]	133	194	1.993	0.768421 ± 13[a]			
D-92k	135.5	207.9	1.896	0.76295 ± 2	16.706	15.420	36.675
D-161	96.6	230.0	1.219	0.74297 ± 7	18.180	15.573	38.795
D-163[b]	144	208	2.008	0.76474 ± 4	17.517	15.503	37.544
D-4[b]	79.4	271	0.8496	0.73152 ± 9			
D-23[b]	86.7	237	1.060	0.73875 ± 5			
Dullstroom Formation (Loskop Dam: Unit # 1): Low-MgO type							
RDW-1	166.6	120.1	4.058	0.82407 ± 6	19.213	15.765	39.817
RDW-2A	176.1	118.4	4.355	0.83114 ± 4	18.458	15.696	38.860
RDW-3[b]	182	91.0	5.889	0.87002 ± 9	17.980	15.612	38.148
RDW-4	189.9	115.5	4.822	0.84289 ± 5	18.920	15.733	39.332
RDW-5	183.2	84.13	6.409	0.88266 ± 16	19.753	15.808	40.387
RDW-6	188.6	110.5	5.008	0.85044 ± 3	19.983	15.851	40.669
RDW-7A	189.0	112.4	4.932	0.85096 ± 10	17.786	15.654	37.811
RDW-8	192.6	137.5	4.096	0.81856 ± 3	17.374	15.576	37.366
RDW-9[b]	164	105	4.554	0.83072 ± 4	18.462	15.683	38.738
RDW-10	152.5	189.6	2.344	0.77668 ± 3			
RB-11	188.9	129.2	4.280	0.83049 ± 1	17.738	15.586	38.031
Dullstroom Formation (Loskop Dam: Unit # 2): High-MgO type							
RB-46					16.554	15.439	36.401
RB-52					15.740	15.361	35.493
RB-56					15.647	15.348	35.416
RB-68					16.232	15.386	35.434
RB-69[b]	137	267	1.4930	0.752460 ± 10[a]	15.696	15.363	35.505
Damwal Formation (Loskop Dam: Unit # 3)							
RB-95	156.4	213.9	2.1287	0.77277 ± 2	17.089	15.576	37.037
301/81	169.5	139.9	3.5394	0.80685 ± 1			
318/81	49.72	154.6	0.9329	0.73525 ± 1			
Damwal Formation (Loskop Dam: Unit # 4)							
DF-1	97.0	159	1.774	0.758273 ± 12[a]	20.390	16.044	40.981
DF-2	85.0	166	1.488	0.751528 ± 12[a]	20.990	16.047	41.590
DF-3	111	113	2.865	0.790917 ± 15[a]	18.879	15.793	39.091
DF-4	168	176	2.783	0.787900 ± 12[a]	20.068	15.918	40.688
DF-5	129	149	2.523	0.780283 ± 16[a]	19.960	15.906	40.431
DF-6	134	142	2.752	0.787470 ± 9[a]	18.962	15.793	39.346

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D5

Table 2. Continued

Sample	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ Precision	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
285/81	148	141	3.063	0.794043 ± 11*	18.454	15.727	38.533
313/81	41.0	172	0.6911	0.728994 ± 11*	24.758	16.503	46.686
314/81	-	-	-	-	23.264	16.342	44.378
Damwal Formation (Loskop Dam: Unit # 6)							
RB-152					19.396	15.883	39.724
L-140					16.766	15.487	36.658
L-144					16.282	15.408	35.992
L-153					18.963	15.753	38.939
Kwaggasnek Formation (Loskop Dam: Unit # 8)							
RB-181					17.078	15.542	36.823
RB-178					16.539	15.426	36.290
Schrikkloof Formation (Loskop Dam: Unit #9)							
RB-193					20.827	15.879	40.251
RB-196					17.571	15.614	37.235
RB-201					20.826	15.914	41.543

* $^{87}Sr/^{86}Sr$ determined on multi-collector VG354 spectrometer; unflagged values measured on single-collector MM30 spectrometer (see text)
[h] Rb, Sr determined by XRF

Table 3. Summary of regressions and age calculations

Sample	Age (Ma) ± 95%	$^{87}Sr/^{86}Sr_i$ or μ	MSWD/n (F)	Comment
Dullstroom Fm				
Low-Ti (bas. andesites & rhyolites)	2110 ± 31	Sr 0.7053 ± 5	2.2/17 (1.84)	Exclude D-14, D-143i, D-143K
Rhyolites	2037 ± 92	Sr 0.7071 ± 21	4.0/10 (2.10)	
	$2044^{+127}/_{-139}$	Pb 9.88 ± 0.17	1.4/8 (2.25)	
	$2137^{+143}/_{-158}$	Pb 9.88 ± 0.24	0.83/7 (2.39)	Exclude D92K
Loskop Dam: Unit # 1	1933 ± 32	Sr 0.7095 ± 12	8.5/13 (1.95)	
	$1677^{+170}/_{-192}$	Pb 10.17 ± 0.14	2.4/10 (2.1)	
Damwal Fm				
Unit # 4	1946 ± 23	Sr 0.7096 ± 5	2.5/8 (2.25)	
	$2007^{+90}/_{-96}$	Pb 10.5 ± 0.2	5.3/9 (2.17)	
	$2018^{+58}/_{-60}$	Pb 10.4 ± 0.1	0.77/8 (2.25)	Exclude DF-1
All Rhyolites from Loskop Dam	$2075^{+49}/_{-51}$	Pb 10.4 ± 0.2	4.7/29 (1.67)	Exclude DF-1, L193, L201, RB-152, RB-95

Notes: All uncertainties are given as 95% confidence intervals; where MSWD of regression exceeds the relevant F statistic, uncertainties have been augmented by $(MSWD/F)^{1/2}$
μ values are calculated for reservoirs of the second stage of the Stacey and Kramers (1975) model; i.e. reservoirs generated at 3700 Ma with ratios of $^{206}Pb/^{204}Pb$ = 11.152 and $^{207}Pb/^{204}Pb$ = 12.998

substantially younger than the time of emplacement of the RLS magmas.

2. *Rooiberg Group rhyolites from Loskop Dam.* Both Rb-Sr and Pb isotopic data are available for these samples.

A date of 1946 ± 23 Ma is reflected by the Rb-Sr data (8 points) for the petrographically freshest low-MgO rhyolites from Unit #4 whereas the Pb analyses for the same samples (9 data points) yield a statistically equivalent date of $2007^{+90}/_{-96}$ Ma. Excluding sample DF-1 from the calculation improves the goodness of fit (see Table 3) and provides an identical, but more precise, isochron date of $2018^{+58}/_{-60}$ Ma. The rather imprecise Pb–Pb estimate is within-error of 2080 Ma whereas the

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more precise Rb-Sr date is not. Data for the less fresh rhyolites from Unit #1 give a Rb-Sr date of 1933 ± 32 Ma which is comparable to the Unit #4 rhyolites while the Pb isotopic data for the same samples indicate a significantly younger date of $1677^{+170}/_{-192}$.

If the data sets are combined, the Rb-Sr data yield a date of 1946 ± 22 (on 21 samples) whereas a date of $2075^{+49}/_{-51}$ Ma may be recovered from 29 of the 34 Pb isotope analyses (see Fig. 3a and 3b). Interestingly, the samples excluded from this regression calculation are not from the data set giving the younger date: i.e. the "younger" data set are accomodated within the average spread of the data. Samples DF-1, Rb-95 and Rb-152 fall significantly above the best fit line whereas the two samples from Unit #9 (L-193, L201) fall below.

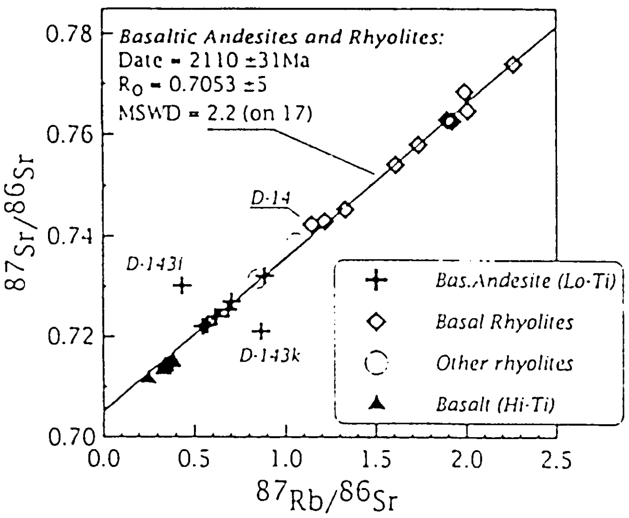

Fig. 2. Rb-Sr isochron plot of data for the Dullstroom Formation of the Rooiberg Group. Labelled samples and the basalt data were excluded from the regression

On average, then, the rhyolite succession at Loskop Dam remained closed systems to Rb and Sr at temperatures below the blocking temperature for the Rb-Sr isotopic system at least since 1950 Ma. The U-Pb isotopic system was possibly perturbed in those rhyolites from the lowermost volcanic unit at Loskop Dam. Considered as a group, however, the Pb isotopic data for the Rooiberg rhyolites from Loskop Dam largely preserve evidence of the assumed crystallisation age of the Rooiberg Group.

Discussion

Ages calculated from isotopic decay systems (e.g. Rb-Sr, U-Pb) reflect the times at which diffusion of parent and daughter nuclides ceased in the mineral or rock system under study i.e. the time at which the system last passed below the blocking temperature and "closed" (e.g. York, 1978). Isotope decay schemes offer the possibility, then, of detecting, and evaluating the scale of, post-crystallisation hydrothermal circulation and/or re-heating of igneous bodies.

Sr and Pb isotopic systems have been used to demonstrate that the LGS granites in the Zaaiplaats area were subjected to protracted periods of fluid circulation at temperatures in excess of about 300 °C (Walraven et al., 1990; McNaughton et al., 1993). McNaughton et al., 1993) demonstrated that the U-Pb isotopic system in the Zaaiplaats granites was last disturbed as recently as ca. 1000 Ma, i.e. over 1 Ga after crystallisation of the LGS granites. These authors argue that the protracted circulation of hydrothermal fluids, driven by heat generated by radioactivity of the high U, Th and K contents in the granites, was responsible for maintaining the granites at temperatures above the blocking temperature for U-Pb over this time period. Walraven et al. (1990b) also demonstrated substantial post-crystallisation open-system behaviour in the Rb-Sr system in the Zaaiplaats granites in close proximity to zones of Sn mineralisation.

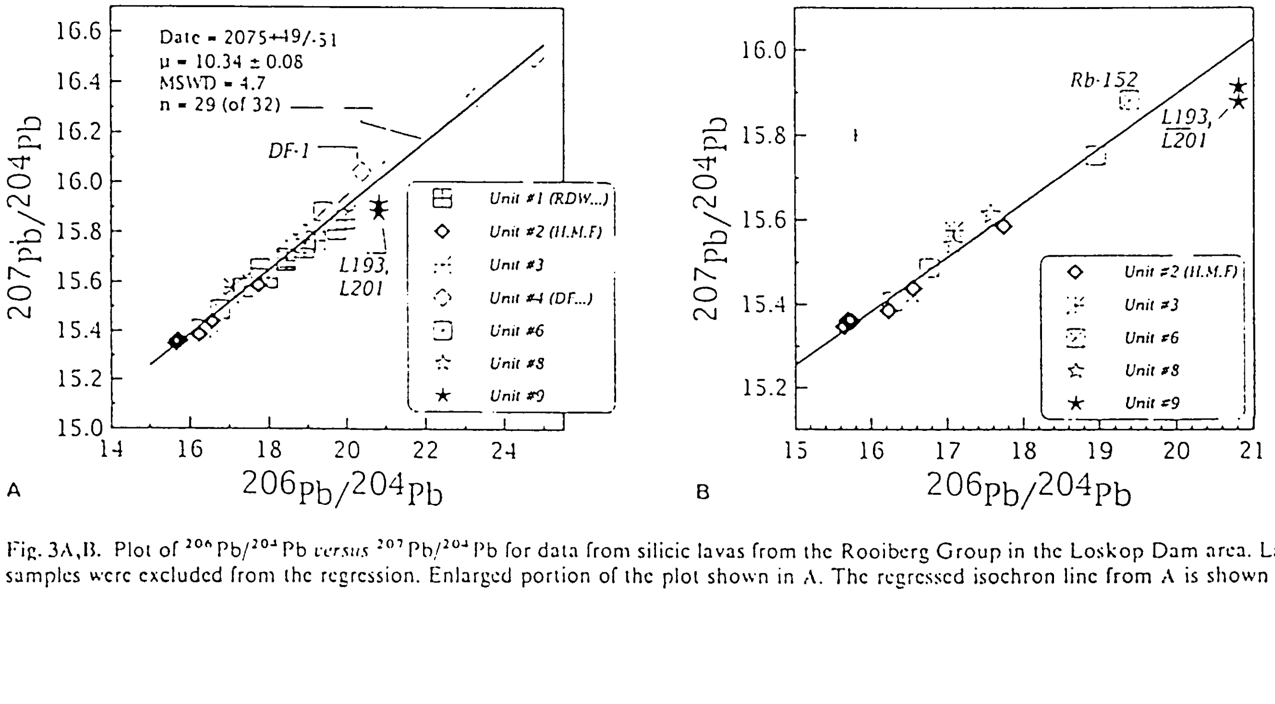

Fig. 3A,B. Plot of $^{206}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ for data from silicic lavas from the Rooiberg Group in the Loskop Dam area. Labelled samples were excluded from the regression. Enlarged portion of the plot shown in A. The regressed isochron line from A is shown

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Circulation of hydrothermal fluids, both within the crystallized RLS granites and into their enclosing rocks, is of obvious importance in mineralisation. Robb et al. (1994) regard both endo-granitic and exo-granitic polymetallic mineralisation related to the Bushveld Granites as the result of evolving hydrothermal systems which persisted for "several hundred million years" after the granites solidified.

The isotopic data for the Rooiberg Group presented in this communication can be usefully applied to investigate whether the Rooiberg volcanics, particularly those of rhyolitic composition, were also subjected to protracted post-solidification open system behaviour and, if present, whether the isotopic disturbance can be attributed to sustained hydrothermal circulation (either within the volcanics or from the granites) or to the thermal effects (possibly with associated fluid circulation) induced by the intrusion of the Rustenburg Layered Suite mafic magmas.

As detailed in previous sections, the isotopic data for volcanics from the Rooiberg Group from several areas suggest some post-crystallisation disturbance. However, the pervasive "re-setting" of the Rb-Sr systematics apparent in Rooiberg rhyolites sampled from Witbank and Bothasberg to give *isochron* ages of ca 1600 Ma (Walraven et al., 1985) is not noted in the sample sets from the Loskop Dam-Dullstroom area.

Results from the rhyolites from Unit # 1 suggest that the Rb-Sr and U-Pb decay systems responded in a different way to the post-crystallisation "disturbance": the younger Pb-Pb age indicating that the U-Pb system remained open (i.e. above the relevant blocking temperature) longer (i.e. to lower temperatures?) than the Rb-Sr. It is of interest to note that comparable differences in the response of Rb-Sr and U-Pb systems are also reflected in the data from the Zaaiplaats granites. Model dates calculated from the Rb-Sr data by Walraven et al. (1990b) indicate dates of final closure predominantly in the range 1.3–1.7 Ga (summarised in Fig. 4), several hundred million years prior to the 1.0 Ga closure times for the U-Pb system deduced by McNaughton et al. (1993).

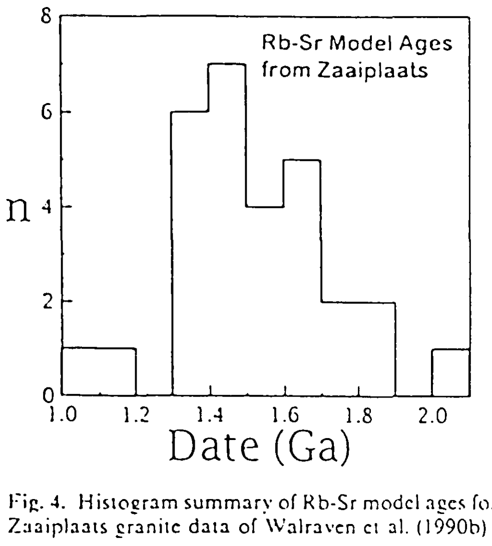

Fig. 4. Histogram summary of Rb-Sr model ages for the mineralised Zaaiplaats granite data of Walraven et al. (1990b)

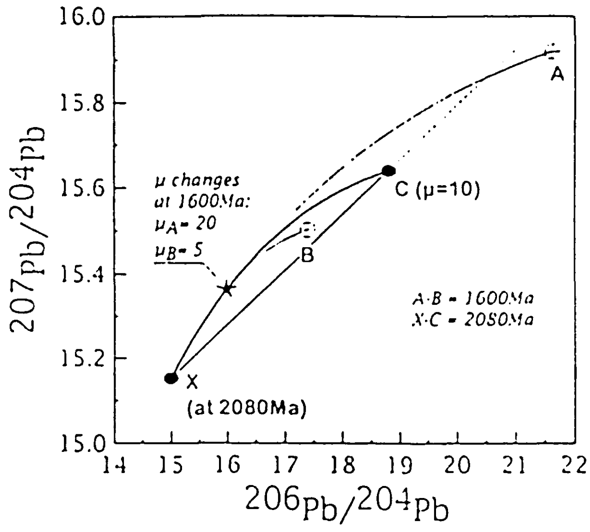

Fig. 5. $^{206}Pb/^{204}Pb$ *versus* $^{207}Pb/^{204}Pb$ plot to show the effect of changing μ at 1600 Ma on a sample formed at 2080 Ma (see text for discussion)

"Re-setting" of the Rb-Sr dates in certain Rooiberg volcanics and the Zaaiplaats granites has been attributed to selective loss of radiogenic ^{87}Sr. Anomalously young Pb–Pb ages are produced through changes in sample $^{238}U/^{204}Pb$ (= μ). This is demonstrated in Fig. 5 which depicts a sample formed at 2080 Ma which is subsequently altered (at 1600 Ma). Sub-sample B has the μ ratio halved whereas A has μ increased (doubled). The present day Pb ratios (A–C–B) fall on an array of age 1600 Ma: the sample with U/Pb increased by alteration plotting *below* the 2080 Ma isochron whereas the sample which suffered reduced U/Pb plots *above* the primary age isochron. Twist (1985) argued that alteration of the rhyolites at Loskop Dam tended to increase with stratigraphic height (i.e. to higher unit numbers) and that the uppermost units had suffered silicification and substantial U loss. It is apparent from Figs. 3a and 3b, however, that samples L193 and L201 from Unit #9 plot below the regressed isochron which suggests that, if these samples were erupted with the same initial Pb ratios as the other rhyolites, U was *enriched* relative to Pb subsequent to formation! The apparently systematic chemical variations in the LMF volcanics with height through the Loskop Dam succession, and limited initial Nd isotopic data (Twist and Harmer, 1987; unpublished data), provides no evidence of a change in source for the Unit # 9 eruptives.

The lack of pervasive re-setting of the isotopic systems in the Loskop Dam section is in marked contrast to the near-isochron 1600 Ma systematics noted for the Witbank and Bothasberg sample sets (Walraven et al., 1985). It is noteworthy that Bushveld granites do not occur in the Dullstroom-Loskop Dam region sampled for this study whereas granites are closely associated with the Rooiberg volcanics in the Witbank area. These observations possibly suggest that hydrothermal fluid circulation sustained by the high heat productivity of the LGS granites, particularly in the highly fractionated fractions of the sheet, may be responsible for any observed disturbance of

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isotopic systematics in the Rooiberg lavas. Radioactive elements were apparently not sufficiently concentrated in the rhyolites to sustain hydrothermal activity long after the cooling of the rhyolites and/or the mafic magmas of the RLS.

Anomalously young isotopic ages encountered in Rooiberg Group volcanics may therefore be utilised to identify the influence of granite-driven hydrothermal activity. In view of the importance of such hydrothermal activity in the generation of polymetallic ore concentrations (e.g. Robb et al., 1994), Pb isotope studies should prove useful as an exploration tool in locating regions of higher mineralisation potential in exposures of Rooiberg Group volcanics underlain by LGS granites.

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References

Cheney, E.S., Twist, D. (1988) The conformable emplacement of the Bushveld mafic rocks along a regional unconformity in the Transvaal succession of South Africa. Precambrian Res. 52: 115–132

Clubley-Armstrong, A.R. (1977) The geology of the Selons River area, north of Middelburg, Transvaal, with special reference to the structure of the regions southeast of the Dennilton Dome. MSc Thesis. Univ. Pretoria, South Africa, 107 pp

Eriksson, P.G., Schweitzer, J.K., Bosch, P.J.A., Schreiber, U.M., Deventer, J.L. van, Hatton, C.J. (1993) The Transvaal Sequence: an overview. J. Afr. Earth Sci. 16: 25–51

Eglington, B.M., Harmer, R.E. (1989) GEODATE: a program for the processing and regression of isotope data using IBM-compatible microcomputers. CSIR Manual EMAH 8901. CSIR, P.O. Box 395, Pretoria 0001, 57 pp

Eglington, B.M., Harmer, R.E. (1993) A review of the statistical principles of geochronometry II. Additional concepts pertinent to radiogenic U-Pb studies. S. Afr. J. Geol. 96: 9–21

Faurie, J.N. (1977) Uraan-lood ouderdomsbepalings op granitiese gesteentes van die oostelike Bosveldstollingskompleks. (Uranium-lead age determinations on granitic rocks of the eastern Bushveld Complex). MSc Thesis. Univ. Pretoria, South Africa, 72 pp

Harmer, R.E., Eglington, B.M. (1990) A review of the statistical principles of geochronometry: towards a more consistent approach for reporting geochronological data. S. Afr. J. Geol. 93: 845–856

Harmer, R.E., Von Gruenewaldt, G. (1990) A review of magmatism associated with the Transvaal Basin-implications for its tectonic setting. S. Afr. J. Geol. 94: 104–121

McNaughton, N.J., Pollard, P.J., Groves, D.I., Taylor, R.G. (1993) A long-lived hydrothermal system in the Bushveld Granites at the Zaaiplaats Tin Mine: lead isotope evidence. Econ. Geol. 88: 27–43

Robb, L.J., Robb, V.M., Walraven, F. (1994) The Albert Silver Mine revisited: towards a model for polymetallic mineralisation in granites of the Bushveld Complex, South Africa. Expl. Mining Geol. 3: 219–230

Schweitzer, J.K. (1985) The Dullstroom volcanics and their relation to the Rooiberg Felsite. Inst. Geol. Res. Bushveld Complex, University of Pretoria, Annual Report 1984: 49–55

Schweitzer, J.K. (1986) The geochemical transition from the Dullstroom Basalt Formation to the Rooiberg Felsite Group. Inst. Geol. Res. Bushveld Complex, University of Pretoria, Annual Report 1985: 72–81

Schweitzer, J.K., Hatton, C.J., Waal, S.A. (1994) Regional lithochemical stratigraphy of the Rooiberg Group, Upper Transvaal Sequence: a proposed new subdivision. S. Afr. J. Geol. 98 (in press)

South African Committee for Stratigraphy (SACS) (1980) Stratigraphy of South Africa, part 1. South Afr. Geol. Surv. Handbook 8: 690 pp

Stacey, J.S., Kramers, J.D. (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet. Sci. Lett. 26: 207–221

Twist, D. (1985) Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, Southeastern Bushveld. Econ. Geol. 80: 1153–1165

Twist, D., French, B.M. (1984) Voluminous acid volcanism in the Bushveld Complex: a review of the Rooiberg Felsite. Bull. Volcanol. 46: 225–242

Twist, D., Harmer, R.E. (1987) Geochemistry of contrasting siliceous magmatic suites in the Bushveld Complex: genetic aspects and implications for tectonic discrimination diagrams. J. Volcanol. Res. 32: 83–98

Walraven, F. (1988) Notes on the age and genetic relationships of the Makhutso Granite, Bushveld Complex, South Africa. Chem. Geol. 72: 17–28

Walraven, F., Kleeman, G.J., Allsopp, H.L. (1985) Disturbance of trace element or isotope systems and its bearing on mineralisation in acid rocks of the Bushveld Complex, South Africa (abstract). Conf. High Heat Production Granites (HHP), Hydrothermal Circulation and Ore Genesis. St. Austell, Cornwall, pp. 393–408

Walraven, F., Armstrong, R.A., Kruger, F.J. (1990a) A chrono-stratigraphic framework for the north-central Kaapvaal craton, the Bushveld Complex and the Vredefort structure. Tectonophysics 171: 23–48

Walraven, F., Strydom, J.H., Strydom, N. (1990b) Rb-Sr open system behaviour and its application as a pathfinder for Sn mineralisation in granites of the Bushveld Complex, South Africa. J. Geochem. Expl. 37: 333–350

Walraven, F., Hattingh, E. (1993) Geochronology of the Nebo Granite, Bushveld Complex. S. Afr. J. Geol. 96: 31–41

York, D. (1978) A formula describing both magnetic and isotopic blocking temperatures. Earth Planet. Sci. Lett. 39: 89–93

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Appendix E: Sampling and Sample Localities

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SAMPLING AND SAMPLE LOCALITIES

Sampling

The following abbreviations are used throughout Appendix E:

LMF_S:	Low-Mg Felsite, Schrikkloof Formation
LMF_K:	Low-Mg Felsite, Kwaggasnek Formation
LMF_{Da}:	Low-Mg Felsite, Damwal Formation
High Fe-Ti-P_{Da}:	High Fe-Ti-P Basaltic Andesite, Damwal Formation
High Fe-Ti-P_{Du}:	High Fe-Ti-P Basaltic Andesite, Dullstroom Formation
LMF_{Du}:	Low-Mg Felsite, Dullstroom Formation
(X):	Volcanic Xenolith
HMF_{Du}:	High-Mg Felsite, Dullstroom Formation
HTI:	High-Ti Basalt, Dullstroom Formation
BR:	Basal Rhyolite
LTI:	Low-Ti Basaltic Andesite, Dullstroom Formation

The number of samples by locality and magma type are summarised as follows:

Dullstroom Area: floor of Rustenburg Layered Suite

	No of samples
LTI	76
Basal Rhyolite	24
HTI	35
HMF	26
Volcanic Xenolith	3

Tauteshoogte Area

LMF_{Da}	8

Bothasberg Plateau

High Fe-Ti-P_{Da}	2
LMF_{Da}	11
LMF_K	23
LMF_S	6
Granophyre	1
Rooikop Granite Porphyry	2

Loskop Dam

High Fe-Ti-P_{Du}	5
High Fe-Ti-P_{Da}	1
HMF_{Du}	28
LMF_{Du}	29
LMF_{Da}	76
LMF_K	15
LMF_S	14

Satvoren Fragment

LTI	1
Basal Rhyolite	7

Rooiberg Fragment

LTI	5 (along strike of single flow)
LMF_S	43

A total of 438 volcanic rocks and 3 intrusive rocks are considered. The samples from Loskop Dam were obtained and analysed by Twist (1985). The previously undocumented compositions of these samples have been employed during this study. Their major, trace and rare earth element concentrations are therefore listed in Appendices G and I. The reader is referred to Twist (1985) where the sampling traverses and analytical methods are detailed.

Samples (weighing > 3kg) were taken from the centre of individual

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flows. Weathered crust, amygdales and joints were avoided during sampling. The three flows from the Dullstroom floor succession that were selected for isotopic investigation were sampled along strike (see Harmer and Farrow, 1995; Appendix D), and they are identified by the letters ranging from a to k.

References

Harmer, R.E. and Farrow, D., 1995. An isotopic study on the volcanics of the Rooiberg Group: age implications and a potential exploration tool. Mineral. Dep., 30: 188-195.

Twist, D., 1985. Geochemical evolution of the Rooiberg silicic lavas in the Loskop Dam area, southeastern Bushveld. Econ. Geol., 80: 1153-1165.

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Sample Localities

Dullstroom Area: floor of Rustenburg Layered Suite

Sample Number	Farm Name	Latitude	Longitude	Magma Type
143a	Windhoek 222JS	30.0021	25.2358	LTI
b	Windhoek 222JS	30.0029	25.2360	LTI
c	Windhoek 222JS	30.0033	25.2366	LTI
d	Windhoek 222JS	30.0036	25.2378	LTI
e	Windhoek 222JS	30.0041	25.2384	LTI
f	Windhoek 222JS	30.0021	25.2305	LTI
g	Windhoek 222JS	30.0022	25.2318	LTI
h	Windhoek 222JS	30.0019	25.2328	LTI
i	Windhoek 222JS	30.0039	25.2408	LTI
k	Windhoek 222JS	30.0038	25.2413	LTI
2	Witbooi 225JS	29.5830	25.2753	LTI
3	Konterdanskloof 223JS	29.5881	25.2679	LTI
6	Kwaggaskop 359JS	29.5804	25.3272	LTI
10	Windhoek 222JS	29.5998	25.2258	LTI
12	Windhoek 222JS	30.0056	25.2228	LTI
13	Windhoek 222JS	30.0048	25.2224	LTI
20	Windhoek 222JS	29.5901	25.2413	LTI
21	Konterdanskloof 223JS	29.5742	25.2672	LTI
26	Konterdanskloof 223JS	29.5686	25.2649	LTI
30	Konterdanskloof 223JS	29.5729	25.2676	LTI
31	Konterdanskloof 223JS	29.5742	25.2668	LTI
33	Konterdanskloof 223JS	29.5770	25.2419	LTI
43	Witpoort 216JS	29.5612	25.2378	LTI
44	Windhoek 222JS	29.5870	25.2252	LTI
47	Windhoek 222JS	29.5870	25.2312	LTI
52	Windhoek 222JS	30.0060	25.2423	LTI
54	Witbooi 225JS	29.5891	25.2739	LTI
55	Witbooi 225JS	29.5892	25.2728	LTI
56	Witbooi 225JS	29.5881	25.2717	LTI
57	Witbooi 225JS	29.5877	25.2703	LTI
58	Witbooi 225JS	29.5861	25.2703	LTI
59	Witbooi 225JS	29.5859	25.2709	LTI
60	Witbooi 225JS	29.5852	25.2709	LTI
62	Witbooi 225JS	29.5836	25.2696	LTI
63	Witbooi 225JS	29.5821	25.2699	LTI
67	Middelkraal 221JS	29.5822	25.2181	LTI
74	Witbooi 225JS	29.5870	25.2789	LTI
75	Witbooi 225JS	29.5853	25.2958	LTI
76	Witbooi 225JS	29.5843	25.2983	LTI
77	Kwaggaskop 359JS	29.5809	25.3258	LTI
79	Grootpan 456JS	29.5488	25.5421	LTI
86	Klipfontein 385JS	29.5792	25.3911	LTI
88	Klipfontein 385JS	29.5788	25.4082	LTI
91	Messchunfontein 98JS	30.0007	25.2128	LTI
93	Windhoek 222JS	30.0042	25.2208	LTI
98	Dornkoop 356JS	29.5669	25.2922	LTI
99	Dornkoop 356JS	29.5672	25.2922	LTI
100	Dornkoop 356JS	29.5691	25.2921	LTI
107	Witbooi 225JS	29.5800	25.2959	LTI
108	Witbooi 225JS	29.5813	25.2958	LTI
111	Witbooi 225JS	29.5804	25.2814	LTI
112	Onterverden 358JS	29.5862	25.3080	LTI
113	Onterverden 358JS	29.5868	25.3077	LTI
115	Onterverden 358JS	29.5882	25.3073	LTI
118	Onterverden 358JS	29.5858	25.3061	LTI
120	Onterverden 358JS	29.5848	25.3053	LTI
121	Onterverden 358JS	29.5843	25.3048	LTI
122	Onterverden 358JS	29.5840	25.3044	LTI
123	Onterverden 358JS	29.5827	25.3047	LTI
128	Zuikerboschkop 361JS	29.5717	25.3720	LTI
129	Witbooi 225JS	29.5853	25.2950	LTI
130	Witbooi 225JS	29.5842	25.2949	LTI
131	Witbooi 225JS	29.5831	25.2947	LTI
134	Witbooi 225JS	29.5815	25.2922	LTI
135	Witbooi 225JS	29.5804	25.2920	LTI

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Sample Number	Farm Name	Latitude	Longitude	Magma Type
140	Windhoek 222JS	30.0058	25.2357	LTI
144	Windhoek 222JS	30.0003	25.2359	LTI
164	Messchunfontein 98JS	30.0072	25.2097	LTI
165	Messchunfontein 98JS	30.0072	25.2103	LTI
166	Messchunfontein 98JS	29.5900	25.2122	LTI
167	Kwaggaskop 359JS	29.5818	25.3259	LTI
177	Rietvalley 387JS	29.5690	25.4278	LTI
178	Rietvalley 387JS	29.5683	25.4287	LTI
179	Rietvalley 387JS	29.5671	25.4293	LTI
180	Rietvalley 387JS	29.5638	25.4293	LTI
181	Rietvalley 387JS	29.5647	25.4309	LTI
184	Messchunfontein 98JS	30.0055	25.2148	LTI
92a	Windhoek 222JS	30.0022	25.2190	BR
b	Windhoek 222JS	30.0023	25.2218	BR
c	Windhoek 222JS	30.0023	25.2205	BR
d	Windhoek 222JS	30.0024	25.2214	BR
e	Windhoek 222JS	30.0024	25.2223	BR
f	Windhoek 222JS	30.0021	25.2242	BR
g	Windhoek 222JS	30.0018	25.2254	BR
h	Windhoek 222JS	30.0016	25.2267	BR
i	Windhoek 222JS	30.0022	25.2298	BR
k	Windhoek 222JS	30.0022	25.2305	BR
1	Windhoek 222JS	30.0027	25.2488	BR
7	Kwaggaskop 395JS	29.5800	25.3270	BR
11	Windhoek 222JS	30.0020	25.2214	BR
14	Windhoek 222JS	30.0037	25.2222	BR
53	Windhoek 222JS	30.0046	25.2410	BR
65	Onterverden 358JS	29.5868	25.3248	BR
66	Onterverden 358JS	29.5836	25.3249	BR
90	Windhoek 222JS	29.5998	25.2145	BR
95	Windhoek 222JS	30.0033	25.2308	BR
124	Onterverden 358JS	29.5855	25.3086	BR
161	Windhoek 222JS	30.0022	25.2231	BR
162	Windhoek 222JS	30.0022	25.2231	BR
163	Windhoek 222JS	30.0032	25.2238	BR
183	Windhoek 222JS	29.5998	25.2277	BR
139a	Witbooi 225JS	29.5832	25.2697	HTI
b	Witbooi 225JS	29.5832	25.2702	HTI
c	Witbooi 225JS	29.5831	25.2709	HTI
d	Witbooi 225JS	29.5830	25.2716	HTI
e	Witbooi 225JS	29.5828	25.2725	HTI
f	Witbooi 225JS	29.5825	25.2733	HTI
g	Witbooi 225JS	29.5818	25.2742	HTI
h	Witbooi 225JS	29.5814	25.2747	HTI
i	Witbooi 225JS	29.5813	25.2750	HTI
k	Witbooi 225JS	29.5811	25.2753	HTI
5	Witbooi 225JS	29.5751	25.2741	HTI
9	Windhoek 222JS	29.5918	25.2282	HTI
19	Windhoek 222JS	29.5907	25.2419	HTI
27	Konterdanskloof 223JS	29.5661	25.2639	HTI
28	Konterdanskloof 223JS	29.5631	25.2616	HTI
29	Konterdanskloof 223JS	29.5648	25.2633	HTI
41	Witpoort 216JS	29.5673	25.2399	HTI
45	Windhoek 222JS	29.5838	25.2304	HTI
46	Windhoek 222JS	29.5845	25.2307	HTI
48	Windhoek 222JS	29.5883	25.2315	HTI
50	Windhoek 222JS	29.5992	25.2409	HTT
51	Windhoek 222JS	29.5989	25.2407	HTI
61	Witbooi 225JS	29.5842	25.2704	HTI
64	Witbooi 225JS	29.5821	25.2706	HTI
72	Doornkop 356JS	29.5732	25.2772	HTI
101	Dornkoop 356JS	29.5712	25.2923	HTI
103	Dornkoop 356JS	29.5738	25.2923	HTI
104	Dornkoop 356JS	29.5752	25.2922	HTI
105	Dornkoop 356JS	29.5759	25.2922	HTI
109	Witbooi 225JS	29.5763	25.2697	HTI
110	Konterdanskloof 223JS	29.5761	25.2682	HTI
127	Zuikerboschkop 361JS	29.5702	25.3722	HTI
132	Witbboi 225JS	29.5848	25.2938	HTI
136	Witbooi 225JS	29.5819	25.2925	HTI

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Sample Number	Farm Name	Latitude	Longitude	Magma Type
173	Spitskop 383JS	29.5648	25.3762	HTI
4	Witbooi 225JS	29.5775	25.2742	HMF
8	Windhoek 222JS	29.5905	25.2280	HMF
15	Konterdanskloof 223JS	29.5636	25.2529	HMF
16	Witpoort 216 JS	29.5603	25.2582	HMF
17	Windhoek 222JS	29.5886	25.2422	HMF
18	Konterdanskloof 223JS	29.5906	25.2500	HMF
22	Konterdanskloof 223JS	29.5739	25.2681	HMF
23	Konterdanskloof 223JS	29.5722	25.2669	HMF
24	Konterdanskloof 223JS	29.5710	25.2678	HMF
25	Konterdanskloof 223JS	29.5691	25.2661	HMF
32	Konterdanskloof 223JS	29.5777	25.2420	HMF
34	Konterdanskloof 223JS	29.5768	25.2419	HMF
35	Konterdanskloof 223JS	29.5761	25.2418	HMF
36	Konterdanskloof 223JS	29.5757	25.2418	HMF
37	Witpoort 216JS	29.5749	25.2417	HMF
38	Witpoort 216JS	29.5742	25.2408	HMF
39	Witpoort 216JS	29.5710	25.2391	HMF
40	Witpoort 216JS	29.5688	25.2398	HMF
42	Witpoort 216JS	29.5650	25.2408	HMF
49	Windhoek 222JS	29.5892	25.2318	HMF
69	Middelkraal 221JS	29.5739	25.2279	HMF
70	Middelkraal 221JS	29.5721	25.2263	HMF
71	Doornkop 356JS	29.5723	25.2768	HMF
96	Doornkop 356JS	29.5620	25.2917	HMF
97	Doornkop 356JS	29.5638	25.2918	HMF
182	Generaalsdraai 423JS	29.5463	25.4643	HMF
4(X)	Zuikerboschkop 361JS	29.5441	25.3539	undefined
5(X)	Zuikerboschkop 361JS	29.5469	25.3508	undefined
137(X)	Doornkop 356JS	29.5439	25.3032	undefined

<u>Tauteshoogte Area</u>

Sample Number	Farm Name	Latitude	Longitude	Magma Type
1	Paardekloof 176JS	29.4675	25.1827	LMF_{Da}
2	Kafferskraal 181JS	29.4650	25.1816	LMF_{Da}
3	Paardekloof 176JS	29.4620	25.1603	LMF_{Da}
4	Paardekloof 176JS	29.4650	25.1604	LMF_{Da}
5	Paardekloof 176JS	29.4618	25.1602	LMF_{Da}
6	Uitkyk 172JS	29.4525	25.1601	LMF_{Da}
7	Uitkyk 172JS	29.4528	25.1586	LMF_{Da}
8	Uitkyk 172JS	29.4441	25.1596	LMF_{Da}

<u>Bothasberg Plateau</u>

Sample Number	Farm Name	Latitude	Longitude	Magma Type
2	Schietpad 212JS	29.4771	25.2557	Granophyre
30	Notuitgedacht 208JS	29.4275	25.2715	Granite Porphyry
38	Welverdiend 201JS	29.4117	25.2906	Granite Porphyry
4	Schietpad 212JS	29.4750	25.2563	High $Fe\text{-}Ti\text{-}P_{Da}$
4b	Schietpad 212JS	29.4750	25.2563	High $Fe\text{-}Ti\text{-}P_{Da}$
1	Schietpad 212JS	29.4822	25.2545	LMF_{Da}
3	Schietpad 212JS	29.4753	25.2562	LMF_{Da}
5	Schietpad 212JS	29.4744	25.2572	LMF_{Da}
6	Schietpad 212JS	29.4726	25.2566	LMF_{Da}
7	Schietpad 212JS	29.4703	25.2577	LMF_{Da}
8	Schietpad 212JS	29.4732	25.2580	LMF_{Da}
9	Schietpad 212JS	29.4720	25.2579	LMF_{Da}
10	Schietpad 212JS	29.4678	25.2588	LMF_{Da}
11	Schietpad 212JS	29.4633	25.2537	LMF_{Da}
12	Doornkloof 206JS	29.4552	25.2518	LMF_{Da}
14	Grootrietvley 210JS	29.4502	25.2560	LMF_{Da}
15	Doornkloof 206JS	29.4591	25.2543	LMF_{K}
16	Doornkloof 206JS	29.4480	25.2570	LMF_{K}
17	Doornkloof 206JS	29.4479	25.2572	LMF_{K}
18	Doornkloof 206JS	29.4472	25.2583	LMF_{K}
19	Grootrietvley 210JS	29.4467	25.2632	LMF_{K}
20	Grootrietvley 210JS	29.4448	25.2640	LMF_{K}
21	Grootrietvley 210JS	29.4432	25.2642	LMF_{K}
22	Grootrietvley 210JS	29.4428	25.2653	LMF_{K}
23	Grootrietvley 210JS	29.4420	25.2665	LMF_{K}
24	Grootrietvley 216JS	29.4400	25.2681	LMF_{K}

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Sample Number	Farm Name	Latitude	Longitude	Magma Type
26	Nootuitgedacht 208JS	29.4399	25.2690	LMF_K
27	Nootuitgedacht 208JS	29.4378	25.2689	LMF_K
28	Notuitgedacht 208JS	29.4353	25.2728	LMF_K
29	Notuitgedacht 208JS	29.4308	25.2715	LMF_K
31	Notuitgedacht 208JS	29.4112	25.2825	LMF_K
32	Notuitgedacht 208JS	29.4121	25.2775	LMF_K
33	Notuitgedacht 208JS	29.4129	25.2758	LMF_K
34	Doornkloof 202JS	29.4152	25.2735	LMF_K
35	Doornkloof 202JS	29.4178	25.2730	LMF_K
36	Doornkloof 202JS	29.4215	25.2724	LMF_K
37	Welverdiend 201JS	29.4230	25.2718	LMF_K
39	Welverdiend 201JS	29.4075	25.2915	LMF_K
40	Welverdiend 201JS	29.4038	25.2880	LMF_K
41	Naauwpoort 200JS	29.3816	25.2872	LMF_S
42	Naauwpoort 200JS	29.3825	25.2878	LMF_S
43	Naauwpoort 200JS	29.3845	25.2880	LMF_S
44	Schietpad 212JS	29.3872	25.2879	LMF_S
45	Nootuitgedacht 208JS	29.3880	25.2875	LMF_S
46	Welverdiend 201JS	29.3912	25.2870	LMF_S

Stavoren Fragment

80	Riffontein 709KS	29.1660	24.5105	LTI
81	Riffontein 709KS	29.1615	24.5123	BR
82	Rooibok 707KS	29.1970	24.4945	BR
145	Rooibok 707KS	29.1865	24.5021	BR
146	Salie Slogt 718KS	29.2020	24.4993	BR
147	Palmietfontein 708KS	29.1665	24.4963	BR
148	Palmietfontein 708KS	29.1718	24.4973	BR
149	Riffontein 709KS	29.1795	24.5022	BR

Rooiberg Fragment

82a	Vellefontein 517KQ	27.4653	24.5139	LTI
82b	Vellefontein 517KQ	27.4652	24.5141	LTI
82c	Vellefontein 517KQ	27.4651	24.5146	LTI
82d	Rietfontein 536KQ	27.4649	24.5148	LTI
82e	Rietfontein 536KQ	27.4648	24.5152	LTI
28	Vellefontein 517KQ	27.4752	24.5047	LMF_S
29	Boekenhoutplaat 519KQ	27.4763	24.5048	LMF_S
30	Boekenhoutplaat 519KQ	27.4771	24.5048	LMF_S
31	Boekenhoutplaat 519KQ	27.4787	24.5041	LMF_S
32	Boekenhoutplaat 519KQ	27.4798	24.5041	LMF_S
35	Vlakfontein 535KQ	27.4829	24.5068	LMF_S
36	Vlakfontein 535KQ	27.4838	24.5063	LMF_S
37	Vlakfontein 535KQ	27.4835	24.5066	LMF_S
38	Vlakfontein 535KQ	27.4849	24.5059	LMF_S
39	Vlakfontein 535KQ	27.4858	24.5068	LMF_S
40	Morgenzon 533KQ	27.4892	24.5113	LMF_S
41	Morgenzon 533KQ	27.4887	24.5108	LMF_S
42	Vlakfontein 535KQ	27.4880	24.5104	LMF_S
43	Vlakfontein 535KQ	27.4872	24.5100	LMF_S
44	Vlakfontein 535KQ	27.4868	24.5095	LMF_S
45	Vlakfontein 535KQ	27.4865	24.5090	LMF_S
46	Vlakfontein 535KQ	27.4862	24.5085	LMF_S
47	Vlakfontein 535KQ	27.4860	24.5097	LMF_S
48	Morgenzon 533KQ	27.4900	24.5135	LMF_S
49	Vlakfontein 535KQ	27.4888	24.5153	LMF_S
50	Vlakfontein 535KQ	27.4871	24.5159	LMF_S
51	Vlakfontein 535KQ	27.4868	24.5167	LMF_S
52	Vlakfontein 535KQ	27.4882	24.5172	LMF_S
53	Vlakfontein 535KQ	27.4890	24.5176	LMF_S
54	Vlakfontein 535KQ	27.4898	24.5180	LMF_S
55	Morgenzon 533KQ	27.4908	24.5190	LMF_S
56	Morgenzon 533KQ	27.4905	24.5193	LMF_S
57	Morgenzon 533KQ	27.4928	24.5198	LMF_S
58	Morgenzon 533KQ	27.4989	24.5209	LMF_S
60	Morgenzon 533KQ	27.4958	24.5219	LMF_S
61	Morgenzon 533KQ	27.4965	24.5219	LMF_S
62	Morgenzon 533KQ	27.4973	24.5221	LMF_S

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Sample Number	Farm Name	Latitude	Longitude	Magma Type
63	Morgenzon 533KQ	27.4978	24.5222	LMF_S
64	Morgenzon 533KQ	27.4982	24.5232	LMF_S
65	Morgenzon 533KQ	27.4989	24.5241	LMF_S
66	Morgenzon 533KQ	27.4998	24.5243	LMF_S
67	Morgenzon 533KQ	27.5002	24.5244	LMF_S
68	Morgenzon 533KQ	27.5007	24.5244	LMF_S
69	Morgenzon 533KQ	27.5011	24.5245	LMF_S
70	Morgenzon 533KQ	27.5025	24.5247	LMF_S
71	Vellefontein 517KQ	27.4742	24.5032	LMF_S
72	Vellefontein 517KQ	27.4732	24.5028	LMF_S
73	Vellefontein 517KQ	27.4723	24.5020	LMF_S

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Appendix F: Mineral Analyses

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Clinopyroxenes

Dullstroom Area: Dullstroom Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
HTI	48	53.30	0.07	0.37	11.91	0.00	0.42	12.13	22.79	0.26	0.03	0.12	101.40	1.992	0.002	0.016	0.372	0.000	0.013	0.676	0.913	0.019	0.002	0.004	4.009
HTI	48	52.59	0.07	0.53	13.06	0.00	0.42	12.15	21.79	0.27	0.03	0.01	100.92	1.981	0.002	0.023	0.412	0.000	0.013	0.682	0.880	0.020	0.001	0.000	4.014
HTI	48	52.22	0.10	0.51	14.54	0.00	0.37	12.10	20.41	0.36	0.06	0.01	100.68	1.980	0.003	0.023	0.461	0.000	0.012	0.684	0.829	0.027	0.003	0.000	4.022
HTI	48	51.96	0.10	0.40	11.40	1.12	0.37	11.72	22.99	0.34	0.02	0.07	100.49	1.973	0.003	0.018	0.362	0.032	0.012	0.663	0.936	0.025	0.001	0.002	4.027
HTI	48	52.88	0.05	0.36	12.23	0.00	0.41	11.84	22.83	0.26	0.03	0.00	100.89	1.990	0.002	0.016	0.385	0.000	0.013	0.665	0.921	0.019	0.001	0.000	4.012
HTI	48	52.55	0.08	0.34	11.56	0.00	0.41	12.14	23.29	0.18	0.04	0.05	100.64	1.981	0.002	0.015	0.364	0.000	0.013	0.682	0.941	0.013	0.002	0.002	4.015
HTI	45	53.30	0.20	0.91	7.45	0.00	0.51	14.24	23.50	0.43	0.03	0.03	100.60	1.974	0.006	0.040	0.231	0.000	0.016	0.786	0.932	0.031	0.001	0.001	4.018
HTI	45	53.73	0.12	0.63	6.26	1.45	0.54	14.68	23.20	0.48	0.07	0.02	101.18	1.968	0.003	0.028	0.195	0.041	0.017	0.817	0.928	0.034	0.003	0.000	4.034
HTI	45	53.30	0.15	0.66	7.33	0.00	0.51	14.70	23.24	0.41	0.02	0.00	100.32	1.977	0.004	0.029	0.228	0.000	0.016	0.813	0.923	0.030	0.001	0.000	4.021
HTI	45	53.13	0.13	0.60	7.19	0.00	0.52	14.46	22.96	0.36	0.10	0.00	99.45	1.986	0.004	0.026	0.225	0.000	0.017	0.806	0.920	0.026	0.005	0.000	4.015
Xenolith	X-137	51.49	0.02	0.18	13.08	1.10	0.42	10.06	23.99	0.16	0.02	0.00	100.52	1.976	0.001	0.008	0.420	0.032	0.014	0.576	0.987	0.012	0.001	0.000	4.027
Xenolith	X-137	52.04	0.02	0.12	13.93	0.00	0.41	10.19	24.06	0.11	0.01	0.03	100.92	1.983	0.001	0.005	0.444	0.000	0.013	0.579	0.982	0.008	0.000	0.001	4.016
Xenolith	X-137	51.49	0.03	0.15	10.14	1.21	0.40	11.67	24.31	0.15	0.02	0.01	99.58	1.973	0.001	0.007	0.325	0.035	0.013	0.666	0.998	0.011	0.001	0.000	4.030

Clinopyroxenes

Tauteshoogte Area: Damwal Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LMF	3	48.96	0.28	0.77	28.28	0.00	0.73	2.87	18.77	0.27	0.02	0.00	100.95	1.976	0.008	0.037	0.955	0.000	0.025	0.173	0.812	0.021	0.001	0.000	4.008
LMF	3	48.33	0.20	0.58	27.76	0.00	0.75	2.88	19.50	0.18	0.03	0.01	100.22	1.970	0.006	0.028	0.946	0.000	0.026	0.175	0.851	0.015	0.001	0.001	4.019
LMF	3	48.30	0.25	0.78	28.65	0.00	0.73	2.88	18.76	0.16	0.01	0.01	100.53	1.965	0.008	0.037	0.975	0.000	0.025	0.174	0.818	0.012	0.001	0.000	4.015
LMF	4	47.40	0.24	0.77	28.51	0.00	0.64	2.60	18.86	0.23	0.02	0.03	99.30	1.958	0.007	0.037	0.985	0.000	0.022	0.160	0.835	0.018	0.001	0.001	4.024
LMF	4	48.02	0.25	0.82	28.75	0.00	0.58	2.51	18.53	0.31	0.14	0.00	99.91	1.968	0.008	0.040	0.985	0.000	0.020	0.153	0.814	0.024	0.008	0.000	4.020
LMF	4	47.06	0.23	0.74	28.00	1.50	0.65	2.70	18.63	0.28	0.01	0.03	99.83	1.945	0.007	0.036	0.968	0.047	0.023	0.166	0.825	0.022	0.000	0.001	4.040
LMF	5	47.86	0.15	0.70	27.68	0.00	1.15	3.28	18.45	0.22	0.03	0.00	99.52	1.964	0.005	0.034	0.950	0.000	0.040	0.201	0.811	0.018	0.002	0.000	4.025
LMF	5	47.60	0.15	0.71	27.24	1.23	1.02	3.19	18.26	0.29	0.02	0.01	99.72	1.958	0.005	0.035	0.941	0.034	0.036	0.195	0.805	0.023	0.001	0.000	4.033
LMF	5	48.36	0.16	0.71	27.25	1.11	1.16	3.36	18.47	0.28	0.04	0.00	100.90	1.962	0.005	0.034	0.924	0.034	0.040	0.203	0.803	0.022	0.002	0.000	4.029
LMF	5	48.40	0.17	0.73	27.64	1.06	1.01	3.18	18.58	0.27	0.02	0.00	101.06	1.962	0.005	0.035	0.937	0.032	0.035	0.192	0.807	0.021	0.001	0.000	4.027
LMF	6	49.04	0.20	0.77	27.60	0.00	0.60	3.45	18.69	0.28	0.01	0.02	100.66	1.963	0.006	0.037	0.944	0.000	0.021	0.210	0.819	0.022	0.001	0.000	4.023
LMF	6	48.20	0.22	0.77	27.96	0.00	0.60	3.73	18.54	0.16	0.02	0.00	100.20	1.960	0.007	0.037	0.951	0.000	0.021	0.226	0.808	0.013	0.001	0.000	4.024
LMF	6	48.16	0.22	0.75	26.83	1.08	0.59	3.70	18.75	0.25	0.02	0.01	100.36	1.958	0.007	0.036	0.911	0.034	0.020	0.224	0.816	0.020	0.001	0.000	4.027
LMF	6	48.15	0.21	0.79	26.48	1.14	0.62	3.75	18.84	0.31	0.03	0.00	100.32	1.957	0.007	0.038	0.898	0.037	0.021	0.227	0.820	0.025	0.002	0.000	4.032
LMF	6	47.89	0.21	0.77	26.52	1.20	0.57	3.69	18.71	0.29	0.02	0.01	99.88	1.956	0.006	0.037	0.906	0.037	0.020	0.225	0.819	0.023	0.001	0.000	4.030
LMF	6	47.75	0.22	0.80	26.65	1.07	0.63	3.70	18.50	0.22	0.04	0.01	99.59	1.956	0.007	0.039	0.912	0.034	0.022	0.226	0.812	0.018	0.002	0.000	4.028

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Clinopyroxenes

Tauteshoogte Area: Damwal Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LMF	8	49.45	0.28	1.06	19.95	1.86	0.66	5.44	22.11	0.70	0.02	0.00	101.53	1.948	0.008	0.049	0.657	0.055	0.022	0.320	0.933	0.053	0.000	0.000	4.045
LMF	8	48.98	0.19	0.80	19.20	1.96	0.58	5.64	21.90	0.74	0.01	0.00	100.00	1.956	0.006	0.037	0.641	0.059	0.020	0.336	0.937	0.057	0.001	0.000	4.050
LMF	8	50.06	0.27	1.08	20.07	1.25	0.64	5.42	21.79	0.73	0.05	0.00	101.36	1.965	0.008	0.050	0.659	0.037	0.021	0.317	0.917	0.056	0.002	0.000	4.032
LMF	8	49.36	0.30	1.12	20.32	1.41	0.64	5.28	21.84	0.60	0.03	0.00	100.90	1.953	0.009	0.052	0.673	0.042	0.021	0.312	0.926	0.046	0.001	0.000	4.035
LMF	8	48.00	0.28	1.14	19.18	2.30	0.57	5.50	21.78	0.69	0.02	0.00	99.46	1.934	0.009	0.054	0.646	0.070	0.019	0.330	0.940	0.054	0.001	0.000	4.057
LMF	8	49.70	0.24	1.08	20.20	1.33	0.61	5.43	21.57	0.68	0.04	0.00	100.88	1.962	0.007	0.050	0.667	0.040	0.020	0.319	0.913	0.052	0.002	0.000	4.032
LMF	8	49.00	0.27	1.10	19.83	1.97	0.62	5.50	21.60	0.72	0.08	0.00	100.69	1.947	0.008	0.052	0.663	0.055	0.021	0.326	0.919	0.055	0.004	0.001	4.051
LMF	8	48.47	0.27	1.02	19.41	2.26	0.57	5.50	22.02	0.69	0.03	0.00	100.24	1.938	0.008	0.048	0.649	0.068	0.019	0.328	0.944	0.054	0.002	0.000	4.058

Clinopyroxene

Bothasberg Plateau: Damwal Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LMF	1	50.11	0.19	0.71	23.16	0.00	0.51	5.51	19.75	0.25	0.03	0.00	100.22	1.990	0.006	0.033	0.769	0.000	0.017	0.326	0.840	0.019	0.002	0.000	4.002

Clinopyroxenes

Bothasberg Plateau: Kwaggasnek Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LMF	24	48.70	0.51	0.79	29.25	0.00	0.69	2.41	18.88	0.15	0.02	0.01	101.41	1.966	0.016	0.038	0.988	0.000	0.024	0.145	0.817	0.012	0.001	0.000	4.007
LMF	24	48.73	0.53	0.95	29.09	0.00	0.66	2.58	18.75	0.20	0.01	0.00	101.50	1.962	0.016	0.045	0.980	0.000	0.023	0.158	0.809	0.015	0.001	0.000	4.009
LMF	24	48.48	0.51	0.72	29.13	0.00	0.67	2.50	18.73	0.13	0.02	0.00	100.89	1.967	0.016	0.035	0.989	0.000	0.023	0.151	0.814	0.010	0.001	0.000	4.006
LMF	40	50.36	0.23	0.45	22.30	0.00	0.94	5.56	20.50	0.20	0.04	0.01	100.59	1.991	0.007	0.021	0.737	0.000	0.032	0.327	0.868	0.015	0.002	0.000	4.000
LMF	40	49.79	0.09	0.57	25.02	0.00	1.03	3.89	20.10	0.19	0.07	0.02	100.77	1.990	0.003	0.027	0.836	0.000	0.035	0.232	0.861	0.015	0.004	0.001	4.004
LMF	40	48.42	0.18	0.58	22.34	1.01	1.01	4.59	20.63	0.29	0.03	0.00	99.08	1.967	0.006	0.028	0.759	0.031	0.035	0.278	0.898	0.023	0.002	0.000	4.027

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Clinopyroxenes and Olivine (40G)

Bothasberg Plateau: Kwaggasnek Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LMF	24(A)	48.73	0.53	0.95	29.09	0.00	0.66	2.63	18.75	0.20	0.01	0.00	101.55	1.962	0.016	0.045	0.980	0.000	0.023	0.158	0.809	0.015	0.001	0.000	4.009
LMF	24(B)	48.73	0.55	0.77	28.79	0.00	0.66	2.48	18.81	0.20	0.02	0.00	101.01	1.972	0.017	0.037	0.972	0.000	0.023	0.149	0.816	0.015	0.001	0.000	4.002
LMF	24(C)	48.18	0.49	0.78	29.20	0.00	0.70	2.28	18.82	0.19	0.01	0.00	100.65	1.964	0.015	0.038	0.995	0.000	0.024	0.139	0.822	0.015	0.002	0.000	4.014
LMF	40(D)	49.79	0.09	0.57	25.02	0.00	1.03	3.89	20.10	0.19	0.07	0.02	100.77	1.990	0.003	0.027	0.836	0.000	0.035	0.232	0.861	0.015	0.004	0.001	4.004
LMF	40(E)	48.70	0.20	1.37	25.23	0.00	0.95	3.85	19.16	0.30	0.21	0.00	99.97	1.965	0.006	0.065	0.851	0.000	0.032	0.231	0.828	0.024	0.011	0.000	4.013
LMF	40(F)	47.31	0.55	3.30	24.65	1.75	0.87	3.63	17.62	0.75	0.45	0.00	100.88	1.902	0.017	0.157	0.828	0.053	0.030	0.218	0.759	0.058	0.023	0.000	4.045
LMF	40(G)	26.92	5.08	2.82	54.56	0.00	0.58	3.04	7.78	0.52	0.29	0.00	101.59	0.854	0.121	0.105	1.447	0.000	0.016	0.144	0.264	0.032	0.012	0.001	2.996
LMF	40(H)	48.42	0.18	0.58	22.34	1.01	1.01	4.59	20.63	0.29	0.03	0.00	99.08	1.967	0.006	0.028	0.759	0.031	0.035	0.278	0.898	0.023	0.002	0.000	4.027
LMF	40(I)	46.61	0.91	1.73	20.61	2.13	0.91	5.85	20.41	0.26	0.04	0.02	99.48	1.888	0.028	0.082	0.698	0.065	0.031	0.353	0.886	0.020	0.002	0.001	4.054

24(A) to (C): Centre towards rim
40(D) to (F): Centre towards rim
40(G) to (I): Centre towards rim

40(G): Ion averages are calculated on the basis of 4 oxygen atoms.

Clinopyroxenes

Makeckaan Fragment: Dullstroom Formation

Ion averages on the basis of six oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	Fe2O3	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Fe+3	Mn	Mg	Ca	Na	K	Cr	Total
LTI	80	52.34	0.20	1.49	9.37	0.00	0.26	17.20	18.03	0.11	0.03	0.11	99.14	1.952	0.006	0.066	0.292	0.000	0.009	0.956	0.720	0.008	0.001	0.003	4.013
LTI	80	53.60	0.34	1.54	10.93	0.00	0.24	16.82	17.58	0.12	0.01	0.06	101.24	1.963	0.009	0.066	0.335	0.000	0.008	0.918	0.690	0.009	0.001	0.002	4.001

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Amphiboles

Dullstroom Area: Dullstroom Formation

Ion averages on the basis of 23 oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Mn	Mg	Ca	Na	K	Cr	Total
HTI	51	53.99	0.06	1.74	17.58	0.46	13.00	12.27	0.21	0.04	0.00	99.35	7.810	0.007	0.297	2.126	0.056	2.803	1.903	0.059	0.008	0.000	15.069
HTI	48	50.96	0.63	3.94	17.14	0.33	13.24	11.36	0.79	0.36	0.02	98.77	7.448	0.069	0.679	2.094	0.041	2.885	1.779	0.225	0.066	0.002	15.288
HTI	48	51.26	0.63	4.06	17.14	0.29	13.23	10.98	0.87	0.40	0.01	98.87	7.471	0.069	0.697	2.089	0.036	2.874	1.715	0.245	0.074	0.000	15.270
HTI	48	49.00	0.88	5.12	18.44	0.25	11.82	11.35	0.91	0.53	0.03	98.33	7.269	0.098	0.896	2.288	0.031	2.614	1.804	0.263	0.100	0.003	15.366
HTI	48	49.47	0.88	4.63	17.18	0.30	12.68	11.50	1.05	0.49	0.02	98.20	7.310	0.098	0.807	2.123	0.035	2.793	1.821	0.301	0.093	0.002	15.383
HTI	45	53.36	0.33	2.29	9.61	0.37	17.64	11.92	0.27	0.18	0.01	95.98	7.716	0.035	0.390	1.163	0.046	3.802	1.846	0.076	0.033	0.002	15.109

Amphiboles

Tauteshoogte Area: Damwal Formation

Ion averages on the basis of 23 oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Mn	Mg	Ca	Na	K	Cr	Total
LMF	3	49.69	0.00	1.30	37.94	0.59	0.88	9.41	0.29	0.28	0.00	100.38	7.841	0.000	0.242	5.006	0.079	0.207	1.591	0.088	0.056	0.000	15.110
LMF	4	48.17	0.11	1.35	34.46	0.81	0.98	10.78	0.24	0.30	0.00	97.20	7.813	0.013	0.257	4.673	0.111	0.236	1.872	0.075	0.062	0.000	15.112

Amphibole

Bothasberg Plateau: Kwaggasnek Formation

Ion averages on the basis of 23 oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Mn	Mg	Ca	Na	K	Cr	Total
LMF	40	45.98	1.02	5.21	28.77	0.67	4.54	10.66	1.15	0.72	0.01	98.73	7.184	0.121	0.960	3.766	0.088	1.059	1.788	0.350	0.144	0.002	15.462

Amphiboles

Bothasberg Plateau: Rashoop Granophyre Suite

Ion averages on the basis of 23 oxygen atoms

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	Cr2O3	Total	Si	Ti	Al	Fe+2	Mn	Mg	Ca	Na	K	Cr	Total
Granophyre	2	39.88	1.83	7.62	33.03	0.41	1.46	10.32	2.03	1.38	0.00	97.96	6.550	0.226	1.475	4.537	0.057	0.357	1.816	0.646	0.289	0.000	15.953
Granophyre	2	39.36	1.80	8.23	33.54	0.43	0.71	10.48	2.06	1.61	0.00	98.22	6.481	0.222	1.596	4.618	0.060	0.173	1.849	0.658	0.337	0.000	15.994

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Appendix G: Whole Rock Analyses

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	P2O5	LOI	Total
LTI	30	55.32	0.67	14.82	8.72	0.12	5.88	9.28	2.22	1.11	0.12	1.39	0.13	1.06	99.94
LTI	31	55.47	0.68	14.79	9.17	0.16	5.88	8.60	2.12	1.35	0.11	1.21	0.13	0.77	100.64
LTI	33	61.23	0.70	14.15	8.52	0.19	2.98	6.53	3.29	1.62	0.16	1.47	0.14	0.80	100.20
LTI	43	58.35	0.84	14.52	9.23	0.16	3.94	7.67	3.00	1.85	0.17	0.84	0.12	0.78	100.70
LTI	44	56.35	0.67	15.14	8.99	0.15	5.48	8.48	2.40	1.26	0.12	0.91	0.13	0.88	100.21
LTI	47	63.90	0.84	13.12	7.93	0.13	1.93	5.24	2.91	2.54	0.16	0.40	0.13	1.30	100.18
LTI	52	56.18	0.60	15.35	8.45	0.16	6.07	8.85	2.04	1.13	0.13	1.94	0.13	1.39	100.03
LTI	54	58.39	0.45	13.91	8.11	0.13	5.98	7.28	2.27	1.08	0.06	1.59	0.13	1.94	99.81
LTI	55	55.75	0.43	13.94	8.88	0.17	6.67	7.96	1.98	1.07	0.07	2.23	0.16	0.62	99.07
LTI	56	58.71	0.68	14.34	8.41	0.13	3.04	6.87	2.08	2.22	0.16	2.65	0.16	1.54	100.17
LTI	57	56.07	0.58	15.38	8.62	0.13	4.98	7.66	2.45	1.71	0.13	1.31	0.13	2.63	99.32
LTI	58	58.17	0.68	14.68	9.18	0.14	4.09	7.76	2.28	1.38	0.14	1.07	0.14	1.95	100.70
LTI	59	57.14	0.63	15.03	9.00	0.17	4.84	8.66	1.79	1.59	0.12	0.92	0.10	1.29	100.70
LTI	60	58.87	0.66	14.54	8.76	0.15	3.84	7.89	2.55	1.47	0.16	1.04	0.16	0.78	100.77
LTI	62	62.59	0.58	13.34	10.06	0.12	2.18	6.05	2.01	1.13	0.10	0.93	0.10	1.01	99.58
LTI	63	59.27	0.67	14.58	8.34	0.14	3.81	7.97	3.26	1.06	0.14	1.08	0.11	1.27	100.68
LTI	67	57.86	0.72	13.60	10.39	0.14	3.75	6.29	3.74	2.39	0.18	0.35	0.12	1.50	99.54
LTI	74	57.78	0.46	14.79	7.96	0.13	6.01	6.80	2.99	1.17	0.06	1.32	0.11	0.97	100.02
LTI	75	55.88	0.44	13.92	8.44	0.17	6.43	7.68	1.86	1.47	0.06	2.49	0.14	1.57	100.73

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LTI	30	4	129	22	266	46	63	3	92	64	246	177	0	258	415	32	14	0	0	11	6
LTI	31	0	134	24	278	50	66	18	93	59	258	175	0	261	371	31	14	0	0	12	4
LTI	33	8	291	34	305	131	78	22	22	89	108	91	0	256	362	31	14	0	0	11	4
LTI	43	6	170	28	320	71	79	80	41	71	24	156	142	164	362	32	15	0	0	10	9
LTI	44	4	140	23	298	46	80	41	90	64	228	176	133	165	451	31	15	0	0	10	9
LTI	47	11	242	33	285	102	89	36	16	72	0	143	176	158	453	30	14	0	0	12	5
LTI	52	0	121	19	251	50	42	147	86	58	45	171	166	154	334	29	14	0	0	11	5
LTI	54	0	118	17	244	85	61	0	110	67	239	151	164	158	440	30	14	0	0	18	7
LTI	55	4	90	17	216	65	68	35	128	59	262	167	123	158	493	29	16	9	0	15	5
LTI	56	7	167	25	242	88	53	52	35	45	57	161	121	157	445	28	14	0	0	18	7
LTI	57	4	117	18	231	49	56	56	68	54	131	156	78	170	502	31	14	0	0	12	3
LTI	58	4	130	21	213	47	62	30	46	56	59	170	174	148	371	30	14	0	0	10	4
LTI	59	4	105	18	210	47	65	24	94	53	83	167	120	154	471	28	14	0	0	11	3
LTI	60	5	142	23	246	36	60	0	53	54	79	156	169	166	334	30	12	0	0	10	3
LTI	62	4	150	25	342	49	73	1767	43	72	117	125	48	175	384	31	14	0	0	11	3
LTI	63	13	235	33	369	44	109	57	50	54	0	256	101	155	417	28	15	0	0	15	4
LTI	67	18	323	41	478	102	114	87	75	76	0	182	67	179	335	28	15	0	0	10	2
LTI	74	4	100	16	257	49	61	7	114	64	297	148	52	174	417	29	14	0	0	10	3
LTI	75	0	72	13	181	56	87	0	121	70	258	173	196	176	379	31	15	0	0	12	6

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LTI	30	55.32	0.67	14.82	8.72	0.12	5.88	9.28	2.22	1.11	0.12	1.39	99.65
LTI	31	55.47	0.68	14.79	9.17	0.16	5.88	8.60	2.12	1.35	0.11	1.21	99.54
LTI	33	61.23	0.70	14.15	8.52	0.19	2.98	6.53	3.29	1.62	0.16	1.47	100.84
LTI	43	58.35	0.84	14.52	9.23	0.16	3.94	7.67	3.00	1.85	0.17	0.84	100.57
LTI	44	56.35	0.67	15.14	8.99	0.15	5.48	8.48	2.40	1.26	0.12	0.91	99.95
LTI	47	63.90	0.84	13.12	7.93	0.13	1.93	5.24	2.91	2.54	0.16	0.40	99.10
LTI	52	56.18	0.60	15.35	8.45	0.16	6.07	8.85	2.04	1.13	0.13	1.94	100.90
LTI	54	58.39	0.45	13.91	8.11	0.13	5.98	7.28	2.27	1.08	0.06	1.59	99.25
LTI	55	55.75	0.43	13.94	8.88	0.17	6.67	7.96	1.98	1.07	0.07	2.23	99.15
LTI	56	58.71	0.68	14.34	8.41	0.13	3.04	6.87	2.08	2.22	0.16	2.65	99.29
LTI	57	56.07	0.58	15.38	8.62	0.13	4.98	7.66	2.45	1.71	0.13	1.31	99.02
LTI	58	58.17	0.68	14.68	9.18	0.14	4.09	7.76	2.28	1.38	0.14	1.07	99.57
LTI	59	57.14	0.63	15.03	9.00	0.17	4.84	8.66	1.79	1.59	0.12	0.92	99.89
LTI	60	58.87	0.66	14.54	8.76	0.15	3.84	7.89	2.55	1.47	0.16	1.04	99.93
LTI	62	62.59	0.58	13.34	10.06	0.12	2.18	6.05	2.01	1.13	0.10	0.93	99.09
LTI	63	59.27	0.67	14.58	8.34	0.14	3.81	7.97	3.26	1.06	0.14	1.08	100.32
LTI	67	57.86	0.72	13.60	10.39	0.14	3.75	6.29	3.74	2.39	0.18	0.35	99.41
LTI	74	57.78	0.46	14.79	7.96	0.13	6.01	6.80	2.99	1.17	0.06	1.32	99.47
LTI	75	55.88	0.44	13.92	8.44	0.17	6.43	7.68	1.86	1.47	0.06	2.49	98.84

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LTI	30	4	129	22	266	46	63	3	92	64	246	177	369	29	15	0	0	10	3
LTI	31	0	134	24	278	50	66	18	93	59	258	175	350	30	15	0	0	11	3
LTI	33	8	291	34	305	131	78	22	22	89	108	91	809	16	17	0	0	20	6
LTI	43	6	170	28	320	71	79	80	41	71	24	156	538	23	17	0	0	12	9
LTI	44	4	140	23	298	46	80	41	90	64	228	176	377	28	16	0	0	11	6
LTI	47	11	242	33	285	102	89	36	16	72	0	143	704	21	16	11	0	13	3
LTI	52	0	121	19	251	50	42	147	86	58	45	171	292	32	14	0	12	0	15
LTI	54	0	118	17	244	85	61	0	110	67	239	151	260	29	12	0	0	10	3
LTI	55	4	90	17	216	65	68	35	128	59	262	167	231	33	14	0	0	8	3
LTI	56	7	167	25	242	88	53	52	35	45	57	161	577	27	15	0	8	48	14
LTI	57	4	117	18	231	49	56	56	68	54	131	156	322	30	15	0	0	12	4
LTI	58	4	130	21	213	47	62	30	46	56	59	170	308	30	15	0	0	13	5
LTI	59	4	105	18	210	47	65	24	94	53	83	167	426	30	14	0	0	11	4
LTI	60	5	142	23	246	36	60	0	53	54	79	156	286	30	15	0	0	14	4
LTI	62	4	150	25	342	49	73	1767	43	72	117	125	312	27	15	12	0	12	7
LTI	63	13	235	33	369	44	109	57	50	54	0	256	287	21	17	12	0	9	4
LTI	67	18	323	41	478	102	114	87	75	76	0	182	381	20	21	14	0	12	3
LTI	74	4	100	16	257	49	61	7	114	64	297	148	314	31	13	0	0	10	3
LTI	75	0	72	13	181	56	87	0	121	70	258	173	350	33	13	0	0	11	4

G2

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LTI	122	60.06	0.69	14.47	9.01	0.15	3.28	6.80	1.71	2.33	0.15	1.33	99.98
LTI	123	55.44	0.58	14.46	8.91	0.20	6.42	8.92	1.58	1.18	0.09	0.91	98.69
LTI	128	53.82	0.68	15.23	10.18	0.19	5.59	9.15	2.19	1.11	0.13	0.73	99.00
LTI	129	55.88	0.50	14.99	8.97	0.18	6.14	7.86	2.47	1.14	0.07	1.11	99.31
LTI	130	55.25	0.59	15.00	9.06	0.22	5.13	7.28	2.44	1.56	0.09	2.92	99.54
LTI	131	55.52	0.59	15.11	9.05	0.17	5.12	7.44	2.31	1.46	0.10	2.06	98.93
LTI	134	57.62	0.48	14.34	8.70	0.16	6.08	7.14	2.24	1.39	0.06	1.11	99.32
LTI	135	55.56	0.59	15.31	8.68	0.18	5.03	7.41	2.38	1.80	0.10	2.73	99.77
LTI	140	56.05	0.62	15.20	9.72	0.15	5.11	9.33	2.19	0.40	0.10	1.55	100.42
LTI	144	57.66	0.66	14.53	8.70	0.16	4.61	7.69	1.97	1.42	0.14	1.94	99.48
LTI	164	56.48	0.64	14.61	8.69	0.23	5.39	8.39	1.99	1.63	0.10	1.17	99.32
LTI	165	54.61	0.87	14.75	9.51	0.16	5.86	8.35	2.13	1.84	0.10	1.17	99.35
LTI	166	57.98	0.66	14.90	8.42	0.20	4.82	8.53	2.06	1.36	0.11	1.45	100.49
LTI	167	55.22	0.72	15.26	8.84	0.14	5.56	9.39	1.70	1.22	0.12	1.11	99.28
LTI	177	57.92	0.65	14.24	8.76	0.13	5.14	7.92	2.01	1.86	0.11	1.67	100.41
LTI	178	56.55	0.60	14.47	8.66	0.16	6.52	8.51	2.13	1.16	0.11	1.36	100.23
LTI	179	56.89	0.62	14.86	8.56	0.14	5.15	7.92	2.60	1.37	0.11	1.52	99.74
LTI	180	59.02	0.65	14.98	8.65	0.17	4.10	6.87	2.38	1.96	0.17	1.84	100.79
LTI	181	56.34	0.59	14.90	8.85	0.14	6.66	8.94	1.93	1.26	0.11	1.21	100.93
LTI	184	56.72	0.62	15.77	8.44	0.21	6.16	9.93	1.69	0.57	0.11	0.82	101.04

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LTI	122	0	119	22	240	57	79	0	96	62	144	173	431	32	13	0	0	11	6
LTI	123	0	144	20	243	55	54	0	92	59	164	169	330	32	14	0	0	10	3
LTI	128	0	96	15	216	34	75	18	88	71	86	192	330	34	15	0	0	9	3
LTI	129	0	123	19	234	58	86	0	136	70	268	172	342	31	14	0	0	65	81
LTI	130	0	123	23	270	68	84	0	93	69	59	165	658	30	14	0	0	10	7
LTI	131	4	122	21	284	73	81	0	86	61	55	169	492	31	14	0	0	11	4
LTI	134	4	95	15	165	50	65	0	130	71	267	162	435	29	13	0	0	11	4
LTI	135	4	99	20	233	60	83	0	82	65	71	175	481	31	14	0	0	10	5
LTI	140	4	126	21	279	17	54	110	79	65	0	118	99	30	15	0	0	10	8
LTI	144	4	141	22	287	89	91	98	47	66	139	164	459	31	14	0	0	13	6
LTI	164	4	131	22	278	66	61	3	90	81	247	161	422	29	14	0	0	9	7
LTI	165	5	150	26	316	58	81	3	75	102	207	156	309	30	15	0	0	12	5
LTI	166	4	131	27	197	75	78	98	49	80	102	203	428	34	15	0	0	12	5
LTI	167	0	94	18	218	78	63	29	122	82	286	166	348	32	14	0	0	11	3
LTI	177	0	109	18	226	62	67	33	46	78	66	190	440	34	14	0	0	10	4
LTI	178	0	97	16	210	37	72	78	96	70	192	173	317	31	13	0	0	9	6
LTI	179	0	113	18	218	46	81	96	106	71	77	169	408	30	14	0	0	11	4
LTI	180	5	142	22	242	64	121	96	56	71	114	163	537	31	15	0	0	12	6
LTI	181	0	114	19	244	46	71	0	82	67	178	164	412	31	14	0	0	0	69
LTI	184	4	129	23	332	34	115	7	86	88	124	167	195	31	15	0	0	11	5

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
BR	92a	75.90	0.27	11.13	2.70	0.07	1.26	3.06	1.78	3.62	0.08	0.67	100.54
BR	92b	75.70	0.28	11.02	2.94	0.08	1.48	2.85	1.54	4.06	0.07	0.64	100.66
BR	92c	75.24	0.28	11.12	2.77	0.07	1.76	2.64	1.57	4.13	0.07	0.75	100.40
BR	92d	74.82	0.28	10.81	2.90	0.07	1.87	2.56	1.36	4.15	0.08	0.66	99.56
BR	92e	75.96	0.30	11.16	2.47	0.05	1.06	2.78	1.49	4.38	0.10	0.67	100.42
BR	92f	75.51	0.26	10.91	2.86	0.07	1.25	2.51	1.51	4.13	0.07	0.65	99.73
BR	92g	76.20	0.28	10.93	2.92	0.08	1.58	2.54	1.61	4.05	0.06	0.60	100.85
BR	92h	75.83	0.25	10.51	2.60	0.10	1.37	2.55	1.70	3.81	0.07	0.77	99.56
BR	92i	74.89	0.26	11.17	2.60	0.09	1.72	2.39	1.99	3.09	0.07	0.74	99.01
BR	92k	76.73	0.26	10.66	2.81	0.10	0.85	2.77	1.15	4.72	0.07	0.58	100.70
BR	1	68.87	0.39	12.41	4.49	0.10	2.71	3.75	1.93	2.90	0.09	2.05	99.69
BR	7	72.34	0.38	11.73	4.11	0.04	1.33	3.68	1.68	2.78	0.08	0.96	99.11
BR	11	74.53	0.28	11.03	3.41	0.06	1.50	2.42	1.61	4.11	0.07	0.78	99.80
BR	14	69.21	0.39	12.36	4.74	0.08	2.60	4.32	1.80	3.04	0.09	1.03	99.66
BR	53	68.61	0.38	12.17	4.72	0.11	2.68	4.42	1.74	2.95	0.09	1.39	99.26
BR	65	73.17	0.38	11.72	3.86	0.08	1.90	3.22	1.60	3.84	0.10	0.82	100.69
BR	66	72.85	0.38	11.69	3.97	0.08	1.54	2.88	1.71	3.23	0.09	1.13	99.55
BR	90	74.94	0.26	10.78	2.59	0.07	1.63	2.20	1.83	4.04	0.07	0.87	99.28
BR	95	78.12	0.25	10.13	2.15	0.04	0.50	1.54	1.95	4.21	0.07	0.48	99.44
BR	124	70.51	0.40	11.79	4.31	0.06	1.97	3.72	1.59	2.64	0.09	1.45	98.53

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
BR	92a	6	237	25	203	113	31	0	13	118	170	49	1022	7	10	0	0	14	0
BR	92b	5	216	21	238	154	33	0	14	97	184	47	1083	8	11	0	0	17	5
BR	92c	5	216	20	232	177	34	0	15	92	153	48	1067	8	10	0	0	16	6
BR	92d	6	211	20	186	148	31	1	39	84	194	46	1005	8	11	0	0	14	5
BR	92e	6	211	23	221	155	20	0	26	118	199	41	1402	8	9	0	0	15	5
BR	92f	6	269	26	282	190	24	0	9	89	199	40	1122	8	10	0	0	55	
BR	92g	7	287	29	201	133	26	0	18	85	162	46	1091	8	10	0	0	14	5
BR	92h	8	273	28	196	117	23	0	9	92	177	44	1113	7	10	0	0	14	6
BR	92i	7	309	28	195	133	37	0	16	101	182	44	858	7	11	0	0	16	7
BR	92k	5	228	23	202	127	21	0	13	97	186	37	1170	7	9	0	0	15	7
BR	1	7	194	21	254	112	76	5	53	51	138	72	804	12	11	0	0	14	7
BR	7	7	214	25	210	98	14	0	19	86	194	72	1008	12	12	0	0	14	4
BR	11	6	228	22	242	175	30	0	17	68	166	49	1170	9	11	0	0	16	4
BR	14	6	181	21	205	81	45	0	28	73	134	82	992	15	11	0	0	14	4
BR	53	6	225	28	221	104	57	0	33	56	146	86	730	14	12	0	0	15	8
BR	65	6	210	22	213	149	29	0	25	50	327	77	961	12	12	0	0	14	14
BR	66	5	201	23	228	118	41	47	21	63	301	75	877	12	12	0	0	15	5
BR	90	6	225	23	242	173	21	2	33	96	192	40	1098	7	10	9	0	12	4
BR	95	7	263	27	241	197	19	0	7	124	159	37	1425	7	8	0	0	15	7
BR	124	8	213	26	236	130	30	7	22	73	202	83	767	11	10	0	0	16	5

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
BR	161	76.65	0.25	10.83	2.75	0.06	1.08	2.49	1.53	3.41	0.09	0.92	100.06
BR	162	74.65	0.30	11.39	3.15	0.09	1.97	2.92	1.91	3.54	0.10	0.88	100.90
BR	163	69.70	0.40	12.49	4.51	0.14	2.72	4.20	1.30	3.90	0.09	0.92	100.37
BR	183	75.02	0.28	11.22	2.36	0.09	1.45	2.07	1.57	5.36	0.09	0.88	100.39
HTI	139a	52.34	2.13	13.93	12.89	0.17	4.26	8.61	2.75	1.10	0.29	1.32	99.79
HTI	139b	51.88	2.06	13.89	12.32	0.19	4.45	8.94	2.80	1.44	0.27	1.45	99.69
HTI	139c	52.68	2.07	14.07	12.00	0.18	4.49	8.78	2.81	1.40	0.27	1.72	100.47
HTI	139d	52.28	2.07	14.28	12.21	0.19	4.64	8.73	2.84	1.46	0.29	1.03	100.02
HTI	139e	52.36	2.08	14.00	12.30	0.18	4.46	8.91	2.92	1.34	0.27	1.13	99.95
HTI	139f	51.97	2.07	13.93	12.51	0.20	4.59	8.83	2.94	1.25	0.26	0.68	99.23
HTI	139g	51.05	2.01	13.80	12.27	0.19	4.64	9.10	2.56	1.21	0.26	1.77	98.86
HTI	139h	52.09	2.07	14.06	12.20	0.20	4.64	9.20	2.66	1.34	0.26	1.13	99.85
HTI	139i	51.93	2.03	14.10	12.60	0.20	4.45	9.50	2.94	0.97	0.26	0.63	99.61
HTI	139k	51.80	2.05	14.04	12.35	0.20	4.66	9.57	2.82	0.99	0.26	0.99	99.73
HTI	5	56.77	1.47	12.13	11.02	0.15	5.20	7.79	2.51	1.44	0.15	0.98	99.61
HTI	9	56.37	1.59	13.14	10.56	0.17	4.70	7.83	2.83	1.49	0.17	0.72	99.57
HTI	19	56.74	1.65	12.99	10.33	0.17	4.33	7.39	2.56	1.85	0.16	0.89	99.06
HTI	27	57.07	1.56	12.67	10.27	0.15	4.89	7.14	3.39	1.58	0.18	0.97	99.87
HTI	28	55.21	1.68	12.98	11.30	0.15	5.23	7.56	3.22	1.61	0.17	1.22	100.33
HTI	29	55.14	1.72	12.79	11.08	0.17	4.82	7.05	3.23	1.99	0.18	1.07	99.24

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
BR	161	7	222	24	234	90	27	13	31	108	138	31	1168	7	10	0	0	16	5
BR	162	6	211	22	232	142	36	0	27	117	154	57	939	9	10	0	0	15	6
BR	163	5	174	20	208	144	43	0	28	81	138	81	1012	15	12	0	0	14	10
BR	183	8	265	43	241	238	29	0	11	119	155	37	1436	7	10	0	0	16	7
HTI	139a	12	191	30	383	45	84	20	65	67	0	273	338	25	20	0	0	9	4
HTI	139b	11	118	29	309	37	83	20	72	70	0	266	455	24	19	0	0	9	5
HTI	139c	11	189	27	374	48	86	142	108	60	0	261	358	25	19	0	0	4	1
HTI	139d	10	190	27	397	48	87	4	91	64	0	265	448	26	20	0	0	11	4
HTI	139e	25	243	42	374	37	84	6	72	65	0	261	437	24	20	0	8	16	14
HTI	139f	14	239	33	410	54	92	18	87	62	330	47	316	26	20	0	0	0	0
HTI	139g	13	229	42	397	47	72	149	80	55	367	48	307	25	19	14	0	10	4
HTI	139h	12	230	33	413	55	98	84	78	59	313	39	358	25	19	0	0	7	4
HTI	139i	11	194	28	439	39	90	46	84	66	0	277	287	26	21	0	0	9	3
HTI	139k	12	222	29	412	47	93	34	82	64	0	268	316	26	20	0	0	9	4
HTI	5	9	128	20	311	64	84	119	72	77	213	206	239	25	17	0	0	12	3
HTI	9	10	164	27	364	49	105	137	92	62	55	192	322	24	19	0	0	9	2
HTI	19	11	212	29	472	100	128	109	74	68	182	194	351	22	19	0	0	12	4
HTI	27	11	201	28	371	40	116	37	154	73	124	192	345	24	18	0	0	9	3
HTI	28	11	219	29	380	33	68	4	136	69	0	205	299	25	19	0	0	11	4
HTI	29	13	229	29	387	52	82	120	134	74	0	204	345	24	21	0	0	8	2

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
HTI	41	54.65	1.83	13.52	11.55	0.14	4.24	7.38	3.64	1.48	0.18	0.89	99.50
HTI	45	57.34	1.72	13.60	10.39	0.14	3.75	6.29	3.74	2.39	0.18	0.35	99.89
HTI	46	55.02	1.78	13.26	11.19	0.13	4.70	7.12	3.96	1.59	0.18	0.93	99.86
HTI	48	54.15	1.64	12.95	11.01	0.18	5.53	7.64	2.85	2.09	0.17	0.96	99.17
HTI	50	51.55	2.01	14.40	12.48	0.21	4.03	8.63	3.82	0.94	0.27	0.49	98.83
HTI	51	51.95	2.05	14.16	11.90	0.21	4.75	8.49	2.49	1.86	0.28	1.17	99.31
HTI	61	52.48	2.09	14.49	12.47	0.19	4.33	8.55	2.31	1.41	0.30	1.80	100.42
HTI	64	52.18	2.03	14.17	12.25	0.18	4.46	9.02	2.62	1.40	0.28	0.73	99.31
HTI	72	54.20	1.73	14.21	12.22	0.14	3.39	8.01	3.14	0.90	0.20	0.40	98.54
HTI	101	56.18	1.62	12.77	10.68	0.17	4.77	7.67	3.01	1.49	0.18	0.44	98.98
HTI	103	52.18	2.06	14.08	11.80	0.15	4.64	9.94	3.19	0.45	0.26	0.50	99.25
HTI	104	51.55	2.02	13.74	12.37	0.18	4.74	8.95	3.15	1.18	0.25	0.67	98.80
HTI	105	52.72	2.11	14.25	11.95	0.18	4.35	9.69	3.03	1.22	0.27	0.53	100.30
HTI	109	57.18	1.44	12.06	10.81	0.17	5.66	7.84	2.54	1.54	0.14	0.90	100.28
HTI	110	56.10	1.47	11.74	11.13	0.18	5.87	8.15	2.52	1.19	0.17	0.90	99.42
HTI	127	50.13	2.07	13.65	13.35	0.19	5.08	8.59	3.07	1.42	0.26	0.37	98.18
HTI	132	57.41	1.67	14.07	10.37	0.14	3.41	6.41	2.62	1.33	0.18	1.35	98.96
HTI	136	57.50	1.65	13.76	10.10	0.14	4.07	6.84	3.06	1.46	0.16	1.51	100.25
HTI	173	53.19	2.01	13.91	6.39	0.17	5.41	12.91	4.34	0.57	0.34	0.54	99.78

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
HTI	41	12	196	29	412	41	112	56	100	76	0	83	824	15	14	0	0	16	4
HTI	45	18	323	41	478	102	114	87	75	76	0	182	381	20	21	14	0	12	3
HTI	46	16	288	39	470	62	88	96	132	82	0	218	200	23	19	0	0	10	4
HTI	48	14	243	32	428	77	154	135	158	79	10	212	369	26	17	0	0	12	5
HTI	50	15	248	34	431	20	116	12	84	75	0	249	280	24	20	0	0	10	3
HTI	51	15	239	34	378	58	133	4	85	66	0	272	450	26	20	0	0	9	3
HTI	61	7	163	27	270	56	70	0	39	54	113	160	415	29	18	0	0	16	10
HTI	64	13	233	32	374	51	84	51	81	61	0	257	456	26	20	0	0	8	2
HTI	72	18	299	40	436	48	69	0	73	75	0	212	194	22	20	11	0	11	4
HTI	101	9	154	23	337	48	123	82	90	74	68	206	314	25	19	0	0	10	4
HTI	103	15	245	35	431	13	93	0	79	64	0	260	173	25	20	0	0	10	8
HTI	104	13	224	31	385	41	117	102	80	68	0	254	259	25	20	0	0	9	3
HTI	105	14	237	34	404	25	100	0	77	66	0	262	308	26	20	0	0	8	4
HTI	109	8	119	19	283	87	88	109	110	58	203	214	165	25	17	0	0	12	4
HTI	110	9	123	18	291	53	92	15	92	81	246	220	134	25	17	0	0	9	3
HTI	127	9	171	25	313	32	83	66	129	74	0	267	522	24	19	12	0	11	5
HTI	132	13	253	33	466	75	70	45	20	61	0	238	362	19	21	0	0	13	5
HTI	136	9	170	24	325	48	72	9	89	69	0	199	232	23	19	0	0	9	4
HTI	173	16	101	27	513	18	46	14	67	68	110	273	185	31	19	0	0	7	7

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	LOI	Total
HMF	4	63.13	0.62	14.53	6.96	0.12	3.22	5.63	2.71	2.04	1.30	100.40
HMF	8	67.83	0.64	13.01	5.70	0.13	1.76	5.32	2.67	2.91	0.78	100.89
HMF	15	67.29	0.57	12.79	5.47	0.08	1.54	3.67	3.09	2.92	0.88	98.44
HMF	16	67.15	0.57	12.95	5.17	0.19	1.58	3.68	3.45	2.86	1.99	99.72
HMF	17	66.22	0.62	13.57	6.28	0.19	2.37	5.10	2.77	2.44	1.10	100.80
HMF	18	63.77	0.61	14.16	6.81	0.10	2.27	5.26	3.04	2.37	1.87	100.39
HMF	22	62.93	0.63	13.55	6.82	0.12	2.61	5.55	2.79	2.08	1.00	98.21
HMF	23	66.14	0.62	13.28	6.07	0.08	1.90	4.25	3.05	2.75	1.38	99.65
HMF	24	65.67	0.60	13.56	6.32	0.11	2.52	4.94	2.66	2.65	1.08	100.24
HMF	25	66.33	0.60	13.99	6.28	0.11	2.53	4.73	2.59	2.58	1.00	100.87
HMF	32	67.75	0.55	12.81	5.24	0.10	1.34	3.40	3.51	2.77	1.35	98.94
HMF	34	67.39	0.56	12.00	5.01	0.09	1.50	3.48	3.28	2.88	1.12	97.45
HMF	35	68.47	0.57	12.87	5.07	0.08	1.52	3.35	3.21	3.13	1.03	99.51
HMF	36	67.89	0.56	12.92	5.17	0.09	1.41	3.40	3.11	2.98	1.21	98.86
HMF	37	67.27	0.64	13.05	5.73	0.10	1.67	4.28	2.83	2.86	0.84	99.40
HMF	38	68.37	0.74	13.04	6.40	0.10	1.48	4.34	2.70	3.01	0.37	100.69
HMF	39	67.65	0.67	13.41	6.10	0.11	1.87	4.70	2.65	2.78	0.66	100.73
HMF	40	67.85	0.56	12.86	5.23	0.07	1.61	2.81	3.39	3.06	1.38	98.94
HMF	42	68.73	0.50	12.93	4.91	0.09	1.93	4.02	2.65	2.98	0.96	99.81
HMF	49	65.40	0.60	13.68	6.11	0.12	1.99	4.68	2.96	2.54	0.99	99.19

Magma Type	Sample Number	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	V	Ba	Sc	Ga	Hf	U	Th	Pb
HMF	4	6	177	26	271	79	63	0	25	63	115	555	22	16	0	0	14	3
HMF	8	8	222	30	289	84	68	24	26	83	102	848	18	13	0	0	18	8
HMF	15	9	219	26	275	103	43	5	19	71	91	744	16	16	11	0	19	5
HMF	16	11	262	30	274	106	37	0	4	84	90	708	17	15	0	0	16	8
HMF	17	10	273	33	367	110	76	84	25	69	106	683	21	15	0	0	16	6
HMF	18	6	218	26	342	102	45	39	18	47	104	703	20	15	0	0	14	4
HMF	22	5	214	25	313	78	67	3	27	67	119	951	21	16	11	0	15	4
HMF	23	6	205	25	237	87	33	16	40	67	97	656	19	16	0	0	17	4
HMF	24	6	210	25	299	98	81	16	37	60	117	672	19	15	0	0	15	4
HMF	25	8	199	25	283	96	71	0	20	60	113	628	19	15	0	0	15	8
HMF	32	9	272	32	304	112	84	49	30	77	85	789	16	14	0	0	17	5
HMF	34	8	224	28	264	101	74	12	3	90	84	777	15	15	0	0	18	9
HMF	35	8	228	27	272	112	69	12	10	83	90	804	16	15	0	0	18	7
HMF	36	9	232	29	266	113	57	9	6	87	89	841	16	14	0	0	16	4
HMF	37	9	232	28	262	112	68	46	7	64	100	751	17	15	0	0	16	6
HMF	38	9	235	30	238	103	75	36	7	62	100	816	18	14	0	0	17	5
HMF	39	8	222	29	264	97	71	30	9	62	110	718	18	15	0	0	19	6
HMF	40	8	232	26	261	117	65	8	7	95	80	826	14	14	0	0	16	5
HMF	42	9	221	25	258	112	57	27	26	72	79	930	13	14	0	0	17	5
HMF	49	8	240	31	356	103	99	36	15	70	104	703	18	15	0	0	16	5

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
HMF	69	68.40	0.57	13.20	5.08	0.08	1.62	3.81	3.19	3.11	0.14	1.10	100.30
HMF	70	67.86	0.60	13.21	5.45	0.05	1.47	3.65	3.49	3.26	0.13	1.25	100.42
HMF	71	65.03	0.61	14.41	6.82	0.11	2.62	5.09	2.74	2.54	0.12	0.91	101.00
HMF	96	66.54	0.62	13.56	5.69	0.10	1.73	3.96	3.52	2.82	0.13	1.25	99.92
HMF	97	63.89	0.64	13.94	6.86	0.11	2.51	4.98	3.21	2.70	0.13	1.37	100.34
HMF	182	66.18	0.61	13.52	5.81	0.13	2.43	4.08	2.91	2.89	0.14	1.31	100.01
XENOLITH	X-4	65.32	1.00	12.90	4.24	0.15	1.24	8.36	4.05	0.47	0.27	0.80	98.80
XENOLITH	X-5	60.69	1.30	12.57	10.42	0.22	1.71	4.99	3.13	3.40	0.25	0.36	99.04
XENOLITH	X-137	67.95	0.80	12.98	5.20	0.06	1.21	3.98	4.86	2.64	0.22	0.80	100.70

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
HMF	69	7	212	26	277	106	59	27	20	99	46	227	323	22	20	0	0	12	3
HMF	70	11	259	33	322	102	46	22	6	87	26	90	777	14	14	0	0	16	8
HMF	71	8	228	29	352	119	77	0	24	71	181	108	779	20	16	0	0	14	7
HMF	96	10	268	35	328	125	94	11	10	85	124	92	791	17	13	0	0	17	7
HMF	97	6	185	27	283	93	102	24	25	85	117	117	722	19	14	0	0	16	7
HMF	182	10	271	36	346	111	91	19	15	76	137	96	732	17	15	0	0	18	12
XENOLITH	X-4	16	302	56	372	12	38	3	7	160	7	15	97	17	18	0	0	17	7
XENOLITH	X-5	12	245	43	219	85	162	92	39	156	7	119	910	22	18	11	0	19	9
XENOLITH	X-137	13	207	53	198	57	29	5	11	125	45	57	846	16	16	0	0	17	5

Tauteshoogte Area: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	1	68.87	0.53	11.74	7.51	0.07	0.88	2.78	3.39	2.96	0.15	0.82	99.70
LMF	2	68.70	0.54	12.15	7.55	0.15	0.92	3.29	2.29	3.85	0.13	0.90	100.47
LMF	3	67.90	0.55	12.10	7.35	0.14	0.87	2.82	3.04	4.31	0.15	0.57	99.80
LMF	4	68.22	0.56	12.25	7.65	0.14	0.84	2.60	3.29	3.97	0.14	0.73	100.39
LMF	5	67.37	0.52	11.92	7.13	0.14	0.74	2.48	3.35	4.44	0.13	0.50	98.72
LMF	6	68.81	0.54	12.09	7.58	0.11	0.81	2.62	3.60	3.70	0.13	0.56	100.55
LMF	7	68.02	0.52	12.06	7.10	0.12	0.87	1.65	3.84	4.58	0.12	1.13	100.01
LMF	8	68.75	0.55	12.02	6.27	0.08	0.94	2.48	4.19	4.11	0.14	0.66	100.19

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	1	14	321	46	148	112	55	14	0	94	9	0	716	12	19	0	0	24	8
LMF	2	16	323	46	156	129	146	33	24	76	9	0	824	11	18	0	0	25	9
LMF	3	17	391	54	178	149	112	21	9	75	10	0	1069	13	19	14	0	18	7
LMF	4	19	417	59	195	145	116	0	0	85	10	0	1045	14	18	0	0	20	14
LMF	5	21	425	66	170	182	125	16	0	99	9	0	1122	12	19	17	0	26	12
LMF	6	22	431	64	180	171	140	16	0	106	6	0	840	10	19	18	0	24	10
LMF	7	19	375	57	93	156	109	5	0	126	7	0	1156	11	18	13	5	26	9
LMF	8	17	336	90	103	137	49	12	0	138	7	0	961	11	17	0	0	22	6

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Bothasberg Plateau: Granophyre and Rooikop Granite Porphyry

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
Granophyre	2	70.40	0.37	11.99	5.62	0.10	0.67	1.81	3.24	4.65	0.06	0.85	99.76
Gran. Porphyry	30	74.39	0.24	12.01	3.40	0.05	0.50	0.11	3.03	5.37	0.02	1.30	100.42
Gran. Porphyry	38	73.43	0.25	11.92	3.50	0.11	0.56	0.49	3.21	5.59	0.03	1.11	100.20

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
Granophyre	2	15	329	49	141	161	119	25	0	116	8	1	1073	7	19	10	0	28	9
Gran. Porphyry	30	38	632	117	76	3011	217	0	0	90	1	0	593	4	21	15	3	31	11
Gran. Porphyry	38	37	624	100	87	277	158	0	0	120	4	0	1099	1	19	12	4	30	10

Bothasberg Plateau: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
Fe-Ti-P	4	62.01	1.24	12.14	10.99	0.19	1.59	4.76	2.88	3.43	0.43	0.42	100.08
Fe-Ti-P	4B	64.03	1.09	12.02	10.31	0.22	1.24	3.99	2.53	4.66	0.33	0.32	100.74
LMF	1	68.67	0.65	12.28	6.69	0.07	1.09	3.03	3.20	4.18	0.18	0.70	100.74
LMF	3	69.21	0.57	12.17	6.95	0.12	0.82	1.95	3.20	4.38	0.14	0.97	100.48
LMF	5	68.82	0.55	11.95	7.23	0.18	1.17	1.42	3.12	4.12	0.12	1.21	99.89
LMF	6	68.82	0.54	12.01	6.90	0.12	0.77	2.45	2.87	4.05	0.13	0.75	99.41
LMF	7	68.86	0.57	12.04	7.61	0.20	0.95	1.74	2.93	4.45	0.13	1.30	100.78
LMF	8	68.52	0.60	11.90	7.29	0.13	1.01	1.94	3.19	4.30	0.16	0.99	100.03
LMF	9	67.72	0.60	11.86	7.25	0.14	1.02	2.31	2.79	4.60	0.15	0.96	99.40
LMF	10	67.38	0.74	12.18	7.53	0.11	0.93	2.64	2.31	4.61	0.18	1.45	100.06
LMF	11	68.18	0.57	11.84	7.45	0.15	0.75	2.35	2.98	4.16	0.12	1.21	99.76
LMF	12	68.06	0.59	12.56	6.56	0.13	1.62	2.21	2.32	4.20	0.16	2.00	100.41
LMF	14	66.52	0.65	12.86	7.51	0.15	1.81	3.32	2.33	2.84	0.19	2.39	100.57

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
Fe-Ti-P	4	13	281	46	198	110	123	28	18	84	11	15	859	19	17	12	0	19	8
Fe-Ti-P	4B	14	294	45	170	147	174	35	0	96	14	0	891	18	16	0	0	21	17
LMF	1	19	386	67	116	181	55	18	0	104	8	8	910	13	16	0	3	22	9
LMF	3	19	408	63	107	182	122	30	23	120	7	1	943	12	17	14	0	24	8
LMF	5	19	408	63	107	182	141	29	6	84	9	1	926	12	18	0	0	25	10
LMF	6	21	426	62	177	177	144	25	0	72	8	0	887	12	18	0	4	27	12
LMF	7	20	428	66	130	190	176	23	0	69	8	0	873	13	19	11	0	25	9
LMF	8	21	394	58	127	178	121	1	0	60	8	0	804	13	17	12	0	22	7
LMF	9	15	331	48	133	153	167	15	0	79	9	0	914	13	17	11	0	22	9
LMF	10	15	305	43	154	139	122	50	0	71	10	1	920	12	17	0	0	22	9
LMF	11	20	418	60	175	182	192	23	0	60	7	1	873	12	18	0	3	24	10
LMF	12	14	313	43	162	129	277	185	23	63	8	8	748	12	16	0	0	22	18
LMF	14	15	315	45	211	101	137	15	11	66	8	15	687	15	18	0	4	23	9

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Bothasberg Plateau: Kwaggasnek Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	15	72.53	0.38	12.08	4.85	0.02	0.46	0.09	2.71	5.45	0.05	1.88	100.50
LMF	16	72.85	0.37	11.63	4.16	0.03	0.62	0.12	1.69	7.19	0.05	1.52	100.23
LMF	17	70.88	0.37	11.59	5.38	0.11	0.47	1.51	2.59	5.22	0.06	1.28	99.46
LMF	18	72.79	0.38	11.79	3.80	0.03	0.63	0.11	1.61	7.19	0.04	1.86	100.23
LMF	19	71.85	0.37	11.64	5.36	0.10	0.46	0.93	2.49	5.75	0.05	1.55	100.55
LMF	20	73.97	0.36	10.74	5.44	0.06	0.50	0.14	2.92	4.78	0.05	0.88	99.84
LMF	21	71.35	0.36	11.58	5.20	0.11	0.44	1.51	2.93	4.74	0.04	1.34	99.60
LMF	22	71.05	0.36	12.60	5.78	0.15	0.56	0.62	3.26	4.24	0.05	1.47	100.14
LMF	23	72.80	0.37	11.63	5.69	0.11	0.62	0.13	3.29	4.12	0.07	1.36	100.19
LMF	24	72.73	0.35	11.61	5.10	0.11	0.78	0.94	3.08	4.44	0.05	1.38	100.57
LMF	26	72.26	0.36	11.46	5.59	0.15	0.56	0.78	2.79	4.97	0.04	1.73	100.69
LMF	27	71.82	0.35	11.56	5.27	0.16	0.88	0.62	2.80	4.84	0.05	1.56	99.91
LMF	28	73.16	0.35	11.84	4.89	0.39	0.49	0.19	3.19	4.44	0.04	1.92	100.90
LMF	29	71.63	0.36	11.41	5.67	0.21	0.94	0.11	1.43	6.45	0.06	2.16	100.43
LMF	31	75.22	0.32	10.67	4.69	0.06	0.41	1.38	2.60	4.67	0.04	0.83	100.89
LMF	32	73.27	0.35	11.41	5.03	0.05	0.58	1.17	2.75	5.03	0.05	0.88	100.57
LMF	33	72.52	0.34	11.62	5.27	0.06	0.54	1.10	2.97	4.84	0.06	0.96	100.28
LMF	34	71.29	0.35	11.65	5.71	0.21	0.96	0.26	1.60	6.59	0.05	1.95	100.62
LMF	35	72.63	0.35	11.74	5.11	0.20	0.44	1.14	3.11	4.66	0.04	1.37	100.79
LMF	36	72.16	0.34	11.67	5.50	0.24	0.87	0.25	3.02	4.33	0.04	1.79	100.21

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	15	22	466	74	40	227	93	0	0	88	4	0	1075	6	16	14	0	26	14
LMF	16	21	449	62	53	268	199	42	4	77	6	0	1546	7	16	0	3	26	13
LMF	17	20	418	58	100	206	157	14	0	69	9	0	1002	7	18	0	3	25	12
LMF	18	23	468	67	57	280	291	12	0	88	8	0	1200	7	18	0	0	27	15
LMF	19	20	426	63	86	216	147	14	0	72	7	0	1140	7	17	0	0	27	9
LMF	20	26	520	70	48	224	177	0	0	124	4	0	1011	5	12	11	0	26	13
LMF	21	26	548	76	137	252	115	13	0	78	6	0	1040	6	18	0	3	25	10
LMF	22	27	531	70	144	206	268	5	21	92	7	0	773	7	20	12	3	26	14
LMF	23	26	560	77	43	200	193	13	9	66	5	0	872	6	20	13	0	25	10
LMF	24	21	467	65	99	187	131	9	0	69	6	0	953	6	17	13	3	29	16
LMF	26	20	429	58	89	205	106	15	3	60	8	0	685	9	17	13	0	26	10
LMF	27	22	441	64	83	190	155	12	0	61	7	0	1038	6	18	0	5	28	12
LMF	28	20	455	67	63	170	202	10	0	52	5	0	321	8	18	14	0	26	9
LMF	29	22	417	57	59	251	236	31	0	60	7	0	1403	6	19	10	0	27	16
LMF	31	24	515	75	248	224	63	4	0	126	4	0	901	5	13	13	0	24	9
LMF	32	26	530	82	265	228	71	27	21	133	1	0	344	9	15	13	0	24	9
LMF	33	26	545	77	226	222	26	6	7	135	1	0	784	6	16	13	0	28	8
LMF	34	21	438	66	60	256	164	11	0	71	6	0	1352	6	19	13	0	26	16
LMF	35	23	436	70	90	177	124	13	1	69	5	0	839	6	17	0	3	27	10
LMF	36	21	431	63	56	178	110	10	0	50	5	0	1096	6	17	12	0	24	9

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Bothasberg Plateau: Kwaggasnek Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	37	72.30	0.35	11.68	5.41	0.19	0.87	0.15	2.87	4.70	0.04	1.81	100.37
LMF	39	71.76	0.31	11.24	5.01	0.16	0.90	1.06	2.97	4.49	0.02	1.78	99.70
LMF	40	70.81	0.35	11.54	6.23	0.14	1.21	1.52	2.89	4.05	0.07	1.48	100.29

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	37	23	442	63	62	182	156	13	0	71	4	0	1243	5	17	16	0	24	7
LMF	39	29	573	86	102	238	147	1	0	59	5	0	1473	6	18	0	3	26	10
LMF	40	22	464	72	98	176	132	19	21	55	6	1	1161	10	16	0	0	22	8

Bothasberg Plateau: Schrikkloof Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	41	74.80	0.22	11.03	2.73	0.05	0.71	0.69	2.24	5.48	0.04	1.30	99.29
LMF	42	74.63	0.23	11.44	3.09	0.01	0.64	0.10	3.17	5.15	0.02	1.22	99.70
LMF	43	73.06	0.23	11.25	3.33	0.03	0.62	0.57	3.30	5.24	0.00	1.18	98.81
LMF	44	75.23	0.23	11.84	2.98	0.02	0.65	0.05	2.39	5.87	0.02	1.37	100.65
LMF	45	74.68	0.25	11.92	3.31	0.03	0.49	0.02	1.84	7.27	0.02	1.30	101.13
LMF	46	73.94	0.25	12.13	3.79	0.03	0.52	0.02	2.78	5.88	0.02	1.18	100.54

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	41	35	714	90	54	240	55	6	5	80	1	0	1412	1	15	19	3	28	8
LMF	42	30	619	92	38	204	15	0	0	153	1	0	1365	0	18	18	0	28	13
LMF	43	28	569	79	34	194	20	15	1	124	4	0	1163	1	17	15	0	28	9
LMF	44	29	594	74	25	253	52	0	0	96	1	0	1262	1	20	17	0	28	8
LMF	45	28	544	70	27	288	62	0	0	150	6	0	1574	1	18	13	0	27	8
LMF	46	30	565	80	28	213	74	0	0	114	1	0	1317	1	21	16	0	29	7

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Loskop Dam: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
HMF	8	66.67	0.59	12.67	6.23	0.14	2.13	3.45	3.80	3.16	0.14	1.48	100.44
HMF	16	65.00	0.57	13.53	5.39	0.21	2.22	3.20	3.61	3.34	0.13	1.75	98.95
HMF	17	65.76	0.58	13.32	5.61	0.24	2.13	2.64	3.19	3.59	0.14	2.05	99.25
HMF	18	65.99	0.58	13.38	5.35	0.16	2.31	2.41	3.27	3.87	0.14	1.68	99.13
HMF	23	66.08	0.57	13.33	5.45	0.20	2.03	3.17	3.41	3.53	0.13	1.74	99.64
HMF	28	65.78	0.57	13.53	5.26	0.18	1.92	3.55	2.93	3.54	0.13	1.85	99.25
HMF	30	66.33	0.57	13.40	5.28	0.16	1.87	3.40	3.12	3.58	0.14	1.13	98.98
HMF	31	66.28	0.58	13.59	5.15	0.16	1.78	3.39	3.66	3.21	0.14	1.55	99.49
HMF	32	66.61	0.57	13.43	5.24	0.21	1.89	3.29	3.59	3.49	0.13	1.45	99.88
HMF	34	66.43	0.58	13.27	5.50	0.20	2.26	2.96	2.78	3.45	0.14	1.81	99.38
HMF	40.46	67.25	0.69	11.95	8.11	0.13	2.00	1.60	2.22	5.56	0.14	0.15	99.79
HMF	48.43	65.92	0.58	13.54	5.32	0.24	2.12	2.46	3.34	3.77	0.13	1.58	98.99
HMF	49.51	66.12	0.61	13.47	5.71	0.22	2.07	3.03	3.52	3.03	0.13	1.74	99.64
HMF	50.52	64.73	0.63	13.75	5.88	0.24	2.44	3.00	3.57	3.40	0.15	1.73	99.52
HMF	51.44	65.68	0.57	13.47	5.32	0.24	1.98	3.06	2.69	3.61	0.12	1.87	98.61
HMF	52.53	64.57	0.58	12.79	5.88	0.18	2.19	3.50	3.19	2.49	0.13	3.62	99.12
HMF	54	67.76	0.56	12.78	5.55	0.17	2.09	2.90	2.66	2.77	0.12	1.98	99.34
HMF	55	63.57	0.61	13.73	6.06	0.28	2.24	2.88	3.46	3.60	0.13	2.48	99.03
HMF	57	61.82	0.64	13.84	6.92	0.34	2.88	2.25	2.92	3.48	0.14	3.73	98.96
HMF	60	63.91	0.62	13.61	6.49	0.23	2.84	3.49	2.68	3.11	0.13	1.87	98.97

G13

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
HMF	8	10	210	28	169	136	208	42	23				413	15	15	0	3.3	12	49
HMF	16	9	201	27	147	129	242	31	22				487	15	15	6	2.9	10	53
HMF	17	8	204	28	144	139	263	21	19				574	15	15	5	13.2	12	39
HMF	18	8	206	28	137	147	259	10	15				644	15	14	6	3.6	13	30
HMF	23	8	208	28	166	132	245	10	17				595	15	15	5	3.6	13	13
HMF	28	9	207	28	224	133	272	22	22				545	14	15	6	3.4	11	72
HMF	30	9	212	28	216	142	192	18	16				493	15	15	8	3.1	13	44
HMF	31	9	212	28	226	130	197	17	14				400	14	16	6	3.7	11	78
HMF	32	9	212	30	180	135	226	21	15				458	14	15	5	3.2	11	44
HMF	34	9	209	28	203	133	251	21	39				636	14	15	5	3.8	12	30
HMF	40.46	16	350	54	52	192	210	128	9				842	13	14	7	4.8	20	74
HMF	48.43	9	209	30	141	141	339	13	30				629	16	14	5	3.4	13	44
HMF	49.51	8	203	27	173	104	418	45	41				519	16	15	5	3.3	10	139
HMF	50.52	8	202	28	187	113	445	31	34				571	17	16	5	3.1	12	110
HMF	51.44	9	211	29	162	147	445	56	27				564	14	15	0	3.4	14	86
HMF	52.53	9	192	30	104	125	424	14	29				353	15	14	8	2.6	11	20
HMF	54	7	182	22	194	93	434	15	24				563	14	12	5	2.9	9	14
HMF	55	9	198	30	186	129	511	17	29				669	17	15	5	2.9	12	52
HMF	57	7	186	28	181	135	511	35	28				664	19	16	0	2.6	9	202
HMF	60	6	186	26	316	133	343	59	61				721	18	15	5	2.8	9	41

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Loskop Dam: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
HMF	61	60.84	0.65	14.06	7.05	0.30	3.46	4.78	3.62	2.25	0.14	1.81	98.95
HMF	62	64.86	0.66	14.28	7.21	0.26	3.48	4.20	2.70	3.24	0.13	0.22	101.24
HMF	65	69.40	0.50	11.17	6.55	0.16	3.07	0.21	0.17	5.54	0.13	2.62	99.51
HMF	66	62.14	0.64	13.60	6.78	0.27	2.74	3.18	3.27	2.72	0.14	3.73	99.22
HMF	67	60.04	0.68	13.92	7.30	0.24	3.35	4.95	2.96	3.08	0.15	2.08	98.74
HMF	68	63.22	0.61	13.67	6.22	0.23	2.72	3.79	2.94	3.36	0.14	1.67	98.56
HMF	69	59.35	0.67	13.71	7.52	0.30	3.56	4.53	2.70	3.38	0.14	1.97	97.81
HMF	70	62.48	0.62	13.74	6.44	0.30	3.41	3.43	1.99	3.46	0.14	2.91	98.91
Fe-Ti-P	1150	61.52	0.96	11.87	10.53	0.32	0.87	3.69	2.87	2.87	0.37	1.61	97.48
Fe-Ti-P	1350	61.88	0.99	12.26	9.92	0.29	0.75	3.38	2.66	3.57	0.33	2.10	98.13
Fe-Ti-P	1360	62.44	0.99	11.92	10.10	0.20	0.63	3.26	3.59	3.20	0.31	1.23	97.87
Fe-Ti-P	1370	62.40	1.02	11.84	9.87	0.25	0.62	3.49	2.87	3.53	0.33	2.12	98.34
Fe-Ti-P	145.480	58.08	1.14	12.22	13.05	0.35	1.18	3.96	2.33	3.10	0.42	2.68	98.51
LMF	1	70.93	0.47	11.72	5.48	0.10	0.43	1.69	3.08	4.10	0.13	0.85	98.97
LMF	2	70.86	0.44	11.54	5.56	0.11	0.36	1.60	3.20	4.12	0.12	0.83	98.75
LMF	3	67.79	0.63	12.44	6.28	0.12	0.83	3.58	3.68	3.43	0.19	0.72	99.68
LMF	4	67.89	0.63	12.44	6.57	0.13	0.77	3.10	3.51	3.59	0.20	0.23	99.05
LMF	5	67.31	0.61	12.13	6.55	0.16	0.74	2.78	3.43	3.70	0.18	0.94	98.53
LMF	6	68.28	0.69	11.82	7.13	0.17	0.19	3.27	3.10	3.36	0.19	1.05	99.24
LMF	9	68.34	0.62	11.93	7.06	0.13	0.38	1.56	3.43	4.35	0.14	1.00	98.94

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
HMF	61	7	176	25	286	103	401	81	69				476	18	15	5	2.7	7	34
HMF	62	7	185	28	283	150	345	53	61				716	19	15	0	2.6	8	31
HMF	65	5	144	26	32	215	273	26	38				740	14	12	5	2.5	7	23
HMF	66	8	187	26	115	94	558	70	30				410	18	15	0	2.6	10	101
HMF	67	6	170	26	225	129	264	48	48				501	19	15	5	2.7	7	76
HMF	68	8	189	27	266	143	309	28	35				687	16	15	4	2.9	12	45
HMF	69	5	170	25	280	148	375	53	76				698	18	15	0	2.5	8	86
HMF	70	5	186	26	229	125	454	36	52				1306	18	15	0	2.8	9	51
Fe-Ti-P	1150	11	257	44	162	115	308	37	12				452	20	18		3.5	13	35
Fe-Ti-P	1350	14	288	50	140	146	446	78	20				447	21	19		4.1	19	80
Fe-Ti-P	1360	14	301	48	186	122	234	25	15				414	17	17		3.9	15	106
Fe-Ti-P	1370	16	302	51	163	129	432	7	10				453	17	18		3.9	17	44
Fe-Ti-P	145.480	13	263	50	146	116	616	112	7				388	24	21		3.7	12	225
LMF	1	14	301	46	123	156	60	51	33				602	11	15	7	5	19	20
LMF	2	16	352	45	126	160	116	35	23				634	10	15	6	5.9	19	30
LMF	3	17	313	51	182	126	68	11	15				512	12	17	6	5.4	18	23
LMF	4	16	304	37	167	132	98	25	11				529	13	17	8	4.6	19	24
LMF	5	14	308	42	161	146	202	6	11				490	11	16	8	4.7	13	22
LMF	6	15	298	43	235	128	143	18	9				529	12	17	7	4.9	15	13
LMF	9	17	351	54	90	165	123	24	5				522	11	17	8	5.3	19	14

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Loskop Dam: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	10	68.05	0.61	11.89	7.27	0.12	0.39	1.44	2.79	5.41	0.15	0.96	99.06
LMF	11	67.98	0.62	11.93	7.44	0.11	0.32	1.63	2.90	5.31	0.14	0.66	99.04
LMF	12	68.42	0.61	11.96	7.53	0.12	0.35	1.20	3.26	5.05	0.14	0.17	98.82
LMF	13	68.15	0.63	12.04	7.35	0.10	0.43	1.48	3.17	4.91	0.14	0.84	99.23
LMF	14	68.09	0.61	11.83	7.00	0.13	0.41	2.19	3.05	4.63	0.14	1.37	99.44
LMF	19	66.38	0.65	11.81	8.18	0.22	0.80	0.71	1.07	6.13	0.16	1.79	97.89
LMF	19.1	66.82	0.69	12.43	7.48	0.18	0.67	1.50	1.80	5.92	0.17	1.72	99.37
LMF	19.2	68.04	0.67	12.36	7.04	0.14	0.95	1.51	1.01	6.17	0.18	1.22	99.30
LMF	21	67.93	0.62	12.07	7.11	0.17	0.57	0.84	2.28	5.42	0.17	1.49	98.66
LMF	22	67.96	0.62	11.92	7.23	0.13	0.66	1.19	2.65	5.12	0.15	1.20	98.83
LMF	25	67.36	0.68	11.69	8.27	0.14	0.64	1.74	2.83	4.78	0.18	1.16	99.46
LMF	27	68.29	0.62	12.47	6.67	0.16	0.84	2.43	3.04	3.59	0.19	0.88	99.17
LMF	29	66.57	0.73	12.36	7.73	0.24	0.80	3.08	3.10	3.49	0.22	1.06	99.38
LMF	33	68.00	0.67	11.81	7.38	1.61	0.46	3.34	2.39	3.92	0.18	1.20	100.95
LMF	38	66.49	0.74	12.16	7.33	0.20	0.28	2.90	2.97	4.01	0.21	1.50	98.77
LMF	39	66.61	0.67	11.88	7.41	0.22	0.60	2.57	3.18	4.00	0.17	1.45	98.75
LMF	39.1	67.59	0.63	11.75	7.02	0.23	0.51	2.89	2.94	3.70	0.16	1.69	99.11
LMF	41.4	69.55	0.60	11.62	6.93	0.23	0.40	1.66	2.73	4.31	0.13	1.14	99.29
LMF	44.42	67.86	0.66	11.61	7.42	0.22	0.58	1.99	3.23	3.60	0.17	1.05	98.38
LMF	53.45	68.09	0.65	11.51	7.60	0.22	0.20	0.94	2.97	3.33	0.13	1.85	97.48
LMF	63	68.84	0.57	12.05	6.94	0.15	0.33	1.63	2.14	5.15	0.15	1.73	99.67
LMF	64	65.74	0.78	12.05	8.37	0.20	0.60	2.59	2.66	3.76	0.21	2.63	99.59

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	10	17	348	50	81	211	116	24	6				931	11	14	6	4.7	20	16
LMF	11	17	359	52	131	201	116	49	35				800	11	15	7	52	19	34
LMF	12	16	352	54	69	200	142	37	19				693	11	14	9	51	18	9
LMF	13	18	354	52	100	187	126	45	15				776	10	14	6	5	21	27
LMF	14	16	346	51	82	171	168	44	11				561	11	15	6	8.8	20	44
LMF	19	15	321	51	103	252	326	50	7				1307	12	15	0	6.1	18	21
LMF	19.1	14	334	54	166	221	245	74	33				1002	14	13	5	4.6	20	34
LMF	19.2	14	323	51	168	265	234	46	21				1279	13	15	7	6.9	17	31
LMF	21	15	324	48	48	207	335	29	7				752	11	15	9	4.7	19	13
LMF	22	15	320	49	75	179	197	120	7				825	11	13	6	5.2	16	29
LMF	25	15	323	48	93	182	192	56	28				559	13	15	8	4.9	18	25
LMF	27	13	292	41	172	148	167	31	19				550	12	16	0	4.7	18	33
LMF	29	13	294	43	190	140	226	30	15				481	14	18	8	4.4	14	47
LMF	33	16	331	48	350	142	225	187	5				360	11	17	11	5.4	17	36
LMF	38	15	306	45	169	145	401	19	11				438	12	15	0	5.1	19	102
LMF	39	16	319	46	125	148	395	13	8				505	13	15	9	5.1	19	40
LMF	39.1	16	319	46	170	140	379	74	6				436	12	17	8	5	19	57
LMF	41.4	18	344	51	105	163	389	36	7				591	11	16	7	5.7	19	51
LMF	44.42	15	325	47	152	134	325	32	28				514	13	18	7	4.8	17	82
LMF	53.45	17	356	76	64	133	929	31	7				647	12	15	8	5.4	18	111
LMF	63	17	345	55	134	189	263	52	8				697	12	18	9	5.1	19	159
LMF	64	16	350	59	112	136	442	80	9				584	18	19	8	4.5	16	234

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Loskop Dam: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
Fe-Ti-P	3930	57.25	1.25	11.64	11.10	0.17	0.92	5.33	2.17	0.84	0.40	6.28	97.35
LMF	78.79	64.62	0.62	11.37	6.62	0.37	0.28	3.61	1.54	4.12	0.14	5.61	98.90
LMF	79.75	69.34	0.62	11.89	7.03	0.18	0.35	0.90	2.46	3.72	0.14	1.82	98.45
LMF	80	65.70	0.61	11.33	6.12	0.33	0.16	3.45	1.26	4.25	0.14	4.90	98.27
LMF	81	65.30	0.61	11.35	6.68	0.45	0.18	3.47	1.75	4.01	0.14	5.01	98.94
LMF	82	64.49	0.51	11.36	6.40	0.38	0.25	3.61	1.55	3.99	0.15	5.57	98.26
LMF	83	66.39	0.64	11.69	6.97	0.27	0.17	2.32	1.93	5.14	0.16	2.72	98.41
LMF	84	66.29	0.64	11.63	7.00	0.34	0.19	2.44	2.51	4.57	0.15	2.84	98.59
LMF	85	66.40	0.65	11.78	6.45	0.23	0.30	2.39	1.30	2.41	0.16	3.50	95.57
LMF	86	64.05	0.62	11.31	7.18	0.26	0.11	2.29	2.69	4.22	0.15	3.67	96.57
LMF	87	66.77	0.64	11.61	5.84	0.22	0.13	2.26	1.46	5.00	0.15	4.61	98.67
LMF	88	63.38	0.58	10.41	5.10	0.19	0.07	6.75	3.08	1.37	0.13	7.12	98.17
LMF	89	64.29	0.63	11.40	7.01	0.18	0.13	2.64	2.48	4.08	0.16	4.89	97.88
LMF	90	65.83	0.63	11.62	6.78	0.15	0.12	2.09	1.47	6.04	0.15	5.21	100.09
LMF	91	69.30	0.53	10.60	5.75	0.13	0.06	3.45	2.12	2.90	0.13	4.53	99.50
LMF	94	65.85	0.61	11.47	6.77	0.15	0.25	3.21	2.59	3.57	0.15	3.62	98.24
LMF	95	65.81	0.63	11.56	7.15	0.09	0.15	2.02	1.94	4.99	0.16	2.61	97.09
LMF	96	63.75	0.57	11.38	6.55	0.13	0.83	3.88	0.57	5.13	0.16	6.60	99.55
LMF	98	66.22	0.63	11.79	6.46	0.17	0.87	3.04	2.76	3.78	0.17	3.35	99.23
LMF	99	66.15	0.63	11.91	7.07	0.13	0.90	2.86	2.18	3.61	0.17	3.27	98.87

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
Fe-Ti-P	3930	13	238	37	159	33	184	64	6				175	22	17		1.9	13	21
LMF	78.79	13	314	44	91	173	416	24	19				500	12	16	8	4.9	18	50
LMF	79.75	19	402	53	93	152	868	16	5				570	12	17	6	4.9	19	221
LMF	80	13	327	49	7	189	368	9	15				544	13	16	6	5	21	75
LMF	81	14	318	45	90	158	473	33	9				523	11	15	6	2.5	13	52
LMF	82	13	323	45	85	163	501	37	10				458	12	17	7	4.8	19	34
LMF	83	14	330	47	173	180	327	55	6				950	12	16	6	5.3	17	183
LMF	84	15	326	46	213	151	370	46	8				692	12	16	7	4.9	18	158
LMF	85	15	332	51	153	225	344	44	7				933	12	17	7	5.3	17	117
LMF	86	15	330	48	136	162	346	58	9				613	12	16	7	5.3	18	209
LMF	87	16	343	53	154	259	337	159	31				746	12	13	7	5.4	18	238
LMF	88	14	300	42	145	86	145	32	16				73	8	16	9	4.6	17	98
LMF	89	15	325	49	177	197	401	47	15				641	11	16	7	4.9	16	335
LMF	90	17	352	54	157	266	348	159	10				753	12	13	8	4.9	19	242
LMF	91	14	288	43	84	131	240	22	9				304	10	15	8	4.8	16	55
LMF	94	15	312	43	131	119	146	42	5				589	12	16	5	2.9	16	33
LMF	95	15	326	36	217	163	154	32	7				1330	12	15	6	3.7	17	53
LMF	96	13	312	47	179	232	141	38	29				1011	11	15	8	2.9	19	55
LMF	98	16	313	43	117	120	142	59	14				596	14	16	7	3.2	17	28
LMF	99	15	314	44	158	126	197	13	10				708	13	17	9	3	16	47

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Loskop Dam: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	100	64.79	0.61	11.51	6.71	0.16	0.56	2.54	1.51	5.31	0.18	5.00	98.88
LMF	101	63.38	0.61	11.47	6.73	0.15	0.44	4.17	2.42	2.78	0.18	7.15	99.47
LMF	102	64.37	0.65	11.99	6.83	0.13	0.37	2.67	1.31	4.91	0.20	5.35	98.77
LMF	103	64.30	0.62	12.72	7.13	0.16	0.13	3.57	3.96	2.04	0.18	4.65	99.44
LMF	104	62.27	0.63	11.93	6.54	0.15	0.11	3.95	1.09	5.89	0.19	5.09	97.85
LMF	105	65.13	0.61	12.79	6.61	0.13	0.50	3.24	2.57	2.81	0.17	4.67	99.23
LMF	106	65.42	0.60	11.17	6.61	0.14	0.64	2.90	2.13	3.61	0.18	5.21	98.60
LMF	110	65.27	0.57	11.03	6.34	0.19	0.81	3.70	1.22	3.68	0.17	6.40	99.39
LMF	111	65.74	0.51	11.34	6.96	0.19	0.49	4.14	2.40	3.42	0.13	4.52	99.82
LMF	112	66.62	0.54	11.54	6.85	0.16	0.33	2.70	2.62	4.55	0.12	3.10	99.13
LMF	113	68.25	0.56	11.80	6.77	0.13	0.35	1.56	2.78	4.78	0.14	1.90	99.02
LMF	114	67.25	0.56	11.71	6.84	0.12	0.14	2.38	2.45	4.26	0.13	2.91	98.75
LMF	115	68.07	0.52	11.31	6.53	0.15	0.45	3.50	0.94	3.64	0.12	4.67	99.90
LMF	116	65.53	0.53	11.42	6.87	0.14	0.49	3.72	1.60	4.25	0.12	4.18	98.84
LMF	117	68.20	0.51	10.39	4.72	0.20	0.35	4.99	0.17	4.44	0.13	5.83	99.92
LMF	118	64.02	0.50	10.51	6.78	0.17	0.46	5.92	0.17	3.57	0.13	6.75	98.96
LMF	119	67.51	0.51	10.01	7.04	0.19	0.54	4.56	0.18	3.34	0.13	6.07	100.06
LMF	120	65.29	0.49	10.20	7.31	0.24	0.56	3.96	0.16	4.33	0.13	6.92	99.58
LMF	121	67.20	0.51	10.85	7.54	0.19	0.54	2.33	1.32	3.11	0.12	5.24	98.94
LMF	122	69.14	0.55	10.60	6.92	0.19	0.44	1.30	2.71	1.90	0.11	4.66	98.51

Magma Type	Sample Number	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	100	15	303	46	173	211	252	38	12				829	13	16	6	2.9	15	104
LMF	101	16	302	42	161	118	143	24	5				376	13	14	10	2.9	16	53
LMF	102	16	327	50	138	209	197	103	6				1236	15	16	7	3.4	18	108
LMF	103	15	303	41	174	81	173	19	4				318	12	18	9	2.8	15	67
LMF	104	15	314	49	149	201	178	17	5				1010	15	15	7	31	14	55
LMF	105	16	321	44	167	116	166	33	31				417	14	18	7	3.1	19	41
LMF	106	15	300	44	131	143	119	11	21				620	13	17	6	2.5	15	36
LMF	110	15	290	44	101	208	246	15	5				525	12	16	6	2.6	17	34
LMF	111	16	340	51	95	125	224	10	4				665	12	15	7	3.4	19	19
LMF	112	17	344	52	144	157	137	33	5				752	12	17	9	6.6	18	47
LMF	113	17	348	49	149	165	143	28	5				1025	12	17	8	5.1	18	20
LMF	114	17	345	50	127	143	158	33	31				877	12	17	6	3.4	17	36
LMF	115	17	333	51	88	183	160	17	23				451	11	17	8	3.3	18	30
LMF	116	17	336	51	77	162	184	19	14				596	12	17	6	3.2	18	20
LMF	117	14	311	49	143	205	134	8	10				606	10	14	9	3	18	22
LMF	118	15	320	53	115	186	273	13	10				355	12	15	6	3.3	17	40
LMF	119	16	315	49	91	182	358	5	6				253	10	15	7	2.7	18	35
LMF	120	15	308	48	79	202	348	7	5				497	11	17	6	2.9	16	20
LMF	121	15	331	45	362	157	241	13	1				390	11	15	7	3.1	17	19
LMF	122	17	349	49	61	103	294	26	4				262	12	16	11	3.2	18	65

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Loskop Dam: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	124	68.18	0.50	11.57	6.20	0.12	0.54	2.55	2.57	4.04	0.11	3.21	99.58
LMF	125	69.79	0.50	11.81	6.06	0.11	0.47	2.00	2.60	4.54	0.11	2.34	100.31
LMF	128.13	68.24	0.49	11.52	6.02	0.13	0.52	2.62	2.44	4.38	0.11	3.16	99.63
LMF	129.13	67.83	0.51	11.94	6.85	0.45	0.65	0.52	0.65	4.08	0.11	3.58	97.15
LMF	130.13	66.20	0.52	11.52	6.93	0.15	0.39	2.97	2.62	3.83	0.13	3.45	98.71
LMF	131.13	66.35	0.52	11.69	6.92	0.13	0.33	2.94	2.48	4.07	0.13	3.60	99.16
LMF	132.13	66.68	0.52	11.51	6.78	0.13	0.33	2.88	3.02	3.08	0.12	3.54	98.59
LMF	134.13	68.77	0.54	11.61	6.77	0.13	0.71	2.98	2.56	3.49	0.19	2.97	100.71
LMF	135.13	68.60	0.54	11.42	6.53	0.10	0.63	2.52	1.33	4.44	0.17	3.70	99.97
LMF	136	66.90	0.55	11.83	7.09	0.18	0.55	1.78	2.97	3.54	0.17	2.63	98.17
LMF	137	65.54	0.55	11.64	6.84	0.13	0.51	3.19	2.90	3.34	0.18	3.83	98.63
LMF	138	65.58	0.63	11.51	7.18	0.16	0.59	2.79	2.61	3.81	0.23	3.38	98.47
LMF	140	67.35	0.68	11.51	7.77	0.17	0.80	1.63	2.81	2.52	0.26	2.83	98.34
LMF	141	66.33	0.57	11.42	6.76	0.15	0.69	3.38	2.37	3.59	0.21	3.75	99.21
LMF	142	56.57	0.55	11.07	6.67	0.15	0.78	3.20	2.12	3.48	0.18	3.93	98.69
LMF	143	66.30	0.53	11.36	6.32	0.19	0.59	3.22	2.26	3.63	0.15	3.77	98.31
LMF	144	69.01	0.54	11.49	6.70	0.11	0.69	2.24	0.17	4.25	0.17	3.95	99.31
LMF	145	69.32	0.54	11.46	6.57	0.11	0.63	1.24	2.24	3.81	0.16	2.36	98.45
LMF	146	67.34	0.53	11.17	6.68	0.17	0.60	2.74	2.29	3.95	0.15	3.24	98.85
LMF	147	67.54	0.50	10.55	6.67	0.13	0.52	3.83	0.16	3.77	0.16	5.11	98.93

Magma Type	Sample Number	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	124	16	339	47	125	136	126	33	24				768	11	17	9	3.6	20	25
LMF	125	16	343	48	106	160	164	27	14				781	10	16	8	3.6	19	28
LMF	128.13	17	336	46	108	154	198	26	10				702	10	16	8	3.4	20	10
LMF	129.13	17	346	48	18	175	275	71	12				407	10	19	7	3.1	20	145
LMF	130.13	17	344	51	130	133	164	35	28				682	12	18	9	3.4	19	37
LMF	131.13	17	346	49	101	139	142	34	34				699	12	18	7	3.2	22	22
LMF	132.13	17	343	51	120	109	138	34	15				551	12	17	8	3.3	17	31
LMF	134.13	15	314	45	73	129	172	20	7				624	13	16	7	2.9	18	11
LMF	135.13	14	307	46	71	190	157	10	10				660	13	16	7	2.9	16	15
LMF	136	15	322	47	140	122	157	34	13				765	13	18	5	2.9	20	28
LMF	137	14	313	46	91	134	122	33	7				472	13	18	9	3.1	18	14
LMF	138	14	300	43	108	142	225	22	9				726	14	15	10	2.4	16	15
LMF	140	13	276	40	77	98	262	36	10				577	15	17	5	2.3	11	50
LMF	141	13	304	44	120	132	160	28	8				684	14	17	7	2.7	15	16
LMF	142	11	284	39	96	110	321	42	31				776	13	16	6	2.7	14	87
LMF	143	13	307	44	118	130	305	41	38				660	13	15	7	2.7	15	26
LMF	144	13	311	68	53	152	365	72	18				1351	14	18	6	2.9	16	49
LMF	145	14	312	43	43	133	376	16	15				950	12	17	9	3.2	17	62
LMF	146	13	304	45	82	149	217	14	14				756	12	16	6	2.8	18	20
LMF	147	11	286	45	66	180	290	116	7				1045	12	16	0	2.2	15	439

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Loskop Dam: Damwal Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	148	65.74	0.51	10.77	6.49	0.20	0.62	3.79	1.89	3.72	0.14	4.31	98.18
LMF	149	66.38	0.53	11.36	6.27	0.16	0.65	2.85	2.23	3.81	0.17	3.58	97.99
LMF	150	67.25	0.51	11.35	6.11	0.17	0.49	2.42	2.63	3.76	0.17	3.12	97.97
LMF	150.1	66.38	0.50	11.11	6.29	0.19	0.10	4.47	0.19	5.36	0.17	5.25	100.00
LMF	151	68.36	0.54	11.44	6.55	0.16	0.65	1.65	2.50	3.81	0.17	2.60	98.41
LMF	152	65.23	0.52	11.40	6.24	0.16	0.64	3.49	2.26	3.76	0.17	4.24	98.10
LMF	153	66.01	0.77	12.23	9.55	0.27	0.27	0.23	1.76	3.97	0.21	2.64	97.89
LMF	154	64.35	0.71	11.70	8.64	0.15	0.49	2.93	2.00	4.17	0.22	3.81	99.17
LMF	155	63.85	0.72	11.72	8.83	0.19	0.56	3.39	2.52	3.59	0.22	3.78	99.37
LMF	160	67.54	0.50	11.68	6.92	0.09	0.24	2.51	1.97	4.70	0.14	3.27	99.55
LMF	161.16	65.75	0.49	11.22	7.16	0.18	0.28	3.20	2.29	4.42	0.12	4.24	99.35
LMF	162.17	65.75	0.50	11.37	7.02	0.17	0.36	3.52	1.97	3.16	0.13	4.51	98.46
LMF	163.17	64.12	0.48	11.19	7.77	0.20	0.36	4.47	1.77	3.56	0.12	6.27	100.31
LMF	164.16	65.96	0.50	11.43	7.01	0.23	0.44	3.12	1.09	4.76	0.13	5.14	99.80
LMF	165.17	65.57	0.48	11.20	7.40	0.11	0.39	3.43	1.02	4.18	0.12	4.97	98.87
LMF	166.17	65.66	0.50	11.65	8.26	0.15	0.38	2.36	0.19	5.15	0.14	4.09	98.52

Magma Type	Sample Number	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	148	14	296	43	107	146	250	24	8				800	12	15	7	2.8	17	49
LMF	149	15	349	43	97	135	286	42	7				947	12	16	9	2.8	16	24
LMF	150	13	321	42	84	143	275	53	7				709	12	15	8	2.4	14	24
LMF	150.1	12	277	43	41	214	243	34	30				1310	13	13	6	2.5	16	29
LMF	151	15	317	55	79	159	365	20	37				784	12	17	6	2.9	17	57
LMF	152	14	315	47	96	158	200	41	16				615	13	17	9	2.7	18	25
LMF	153	17	336	86	64	212	145	10	12				828	20	21	8	2.8	17	25
LMF	154	7	294	72	80	163	238	10	12				1219	18	19	6	2.8	16	86
LMF	155	17	318	54	143	138	202	31	4				678	17	18	7	3.1	15	39
LMF	160	16	359	67	70	210	112	13	16				712	12	17	8	3.5	19	18
LMF	161.16	17	349	57	87	185	111	8	4				581	11	17	9	3.1	20	17
LMF	162.17	17	350	55	95	160	111	17	31				414	13	18	8	3.3	19	13
LMF	163.17	17	347	54	115	163	120	10	13				424	12	17	6	3.1	18	19
LMF	164.16	15	350	59	85	225	139	13	5				722	12	18	9	3.2	19	24
LMF	165.17	16	334	53	68	177	121	9	12				444	12	18	8	3.3	18	14
LMF	166.17	18	351	54	53	226	124	17	11				651	14	17	9	3	18	13

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Loskop Dam: Kwaggasnek Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	170.16	71.58	0.04	11.44	5.00	0.14	0.27	1.07	0.22	5.94	0.07	2.82	98.60
LMF	171.17	69.04	0.38	11.13	5.45	0.10	0.46	3.49	0.18	5.27	0.07	4.52	100.07
LMF	172.17	67.95	0.37	11.43	5.88	0.10	0.26	4.08	0.16	5.20	0.06	4.91	100.40
LMF	173.17	67.84	0.04	10.87	5.73	0.19	0.35	3.43	0.15	4.70	0.06	5.77	99.11
LMF	178	77.21	0.37	11.86	2.11	0.01	0.10	0.03	0.16	5.94	0.04	2.46	100.28
LMF	179	71.05	0.35	11.54	6.79	0.16	0.28	1.13	0.14	4.84	0.07	3.35	99.67
LMF	180	71.01	0.35	11.81	8.72	0.02	0.17	0.06	0.14	4.73	0.05	3.49	100.55
LMF	181	68.20	0.35	11.37	6.36	0.25	0.28	4.25	0.15	4.86	0.04	5.15	101.26
LMF	182	70.93	0.34	11.00	3.94	0.14	0.24	4.73	0.15	5.01	0.04	5.16	101.68
LMF	183	71.80	0.34	11.37	6.75	0.24	0.26	2.24	0.14	4.23	0.04	4.31	101.74
LMF	184	71.12	0.34	11.75	7.84	0.13	0.35	2.17	0.14	3.66	0.04	3.95	101.49
LMF	185	70.32	0.34	11.43	7.20	0.11	0.35	3.14	0.13	3.59	0.03	4.58	101.20
LMF	186	75.05	0.35	11.26	4.74	0.07	0.14	0.61	0.17	6.86	0.06	2.25	101.54
LMF	187	78.67	0.34	10.99	3.62	0.01	0.18	0.06	0.15	5.58	0.05	1.96	101.61
LMF	188	74.06	0.32	13.40	5.21	0.01	0.29	0.07	0.13	4.70	0.06	3.14	101.38

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	170.16	18	409	78	39	274	280	7	10				1096	7	20	11	3.9	20	13
LMF	171.17	17	385	65	86	228	147	11	5				760	7	16	8	3.1	21	17
LMF	172.17	19	390	62	89	217	136	4	4				615	7	15	8	3.3	20	12
LMF	173.17	18	386	63	90	233	146	5	4				509	7	18	8	3.5	20	18
LMF	178	21	425	65	24	275	108	8	10				753	7	18	9	3.6	22	50
LMF	179	20	403	61	32	210	139	11	10				623	6	18	8	3.8	19	16
LMF	180	20	417	73	14	216	438	75	14				944	6	17	5	4.2	22	108
LMF	181	20	406	62	98	203	195	13	8				890	6	16	8	3.7	22	65
LMF	182	21	420	64	96	215	183	19	4				771	6	18	7	3.7	21	66
LMF	183	20	398	59	38	165	314	10	4				463	6	17	8	3.7	22	93
LMF	184	19	413	74	38	168	194	8	3				398	5	18	9	3.9	23	15
LMF	185	19	397	59	53	167	185	14	29				369	5	17	9	3.8	22	23
LMF	186	19	393	59	44	278	143	20	29				1031	6	16	8	3.7	21	37
LMF	187	17	385	57	17	230	111	7	13				774	5	15	7	2.7	21	21
LMF	188	19	408	56	12	221	263	12	16				862	6	21	7	3.8	25	60

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Loskop Dam: Schrikkloof Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	189	73.03	0.25	11.16	4.41	0.15	0.32	3.51	0.14	3.42	0.03	4.69	101.09
LMF	190	74.14	0.26	11.23	5.00	0.13	0.16	2.34	0.13	3.86	0.04	3.51	100.79
LMF	191	82.26	0.24	11.37	1.80	0.01	0.00	0.03	0.14	4.84	0.04	1.57	102.31
LMF	192	78.23	0.26	11.31	5.66	0.01	0.00	0.04	0.15	4.97	0.03	1.57	102.22
LMF	193	79.04	0.25	11.46	3.69	0.01	0.00	0.03	0.14	5.70	0.03	1.42	101.77
LMF	194	80.65	0.25	11.40	2.25	0.01	0.00	0.02	0.16	5.44	0.03	1.63	101.82
LMF	195	78.13	0.24	10.50	4.64	0.01	0.00	0.03	0.15	4.60	0.03	1.59	99.91
LMF	196	75.27	0.24	10.86	5.89	0.01	0.00	0.02	0.15	5.55	0.04	0.41	98.45
LMF	197	76.70	0.23	10.67	5.00	0.01	3.00	0.02	0.16	5.30	0.04	1.34	102.46
LMF	198	76.81	0.25	10.99	4.11	0.01	0.00	0.01	0.16	5.87	0.06	1.25	99.51
LMF	199	77.27	0.26	11.01	4.75	0.01	0.00	0.16	0.22	5.03	0.03	1.54	100.29
LMF	200	80.18	0.23	11.19	2.60	0.01	0.00	0.05	0.18	4.66	0.03	1.66	100.79
LMF	201	78.97	0.26	11.77	2.89	0.01	0.00	0.00	0.20	4.60	0.03	2.47	101.20
LMF	202	76.36	0.27	12.12	4.51	0.06	0.00	0.30	0.16	4.98	0.04	2.02	100.82

Magma Type	Sample Number	Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	189	24	439	61	72	165	232	6	8				230	2	18	10	4.2	24	21
LMF	190	23	443	62	42	205	259	3	4				339	8	18	11	3	25	26
LMF	191	20	445	62	7	237	163	12	4				316	2	17	10	3.5	24	30
LMF	192	23	444	64	8	230	141	8	4				361	2	17	10	4.1	23	16
LMF	193	21	453	66	11	246	132	16	5				419	2	18	10	3.9	25	14
LMF	194	22	458	68	12	264	193	12	23				459	2	18	12	3.9	24	67
LMF	195	21	445	69	13	249	178	12	27				320	2	18	12	3.3	23	32
LMF	196	20	430	64	18	258	108	8	14				457	2	17	8	3.8	22	43
LMF	197	20	428	63	26	244	94	6	12				406	2	17	11	3.2	23	23
LMF	198	24	463	71	31	261	51	3	11				446	2	17	9	3.2	24	16
LMF	199	19	437	68	28	254	68	7	10				331	2	19	10	2.9	23	49
LMF	200	20	454	65	24	231	35	5	8				263	2	18	12	3.1	24	12
LMF	201	22	478	71	27	271	36	4	5				210	2	20	10	3.8	26	15
LMF	202	27	494	77	30	224	136	25	4				505	2	19	10	3.3	26	30

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Stavoren Fragment: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LTI	80	53.80	0.68	14.68	9.38	0.17	5.24	7.43	3.98	0.69	0.08	3.21	99.34
BR	81	74.54	0.28	10.92	2.74	0.07	1.74	1.58	2.09	4.20	0.08	1.52	99.76
BR	82	76.12	0.22	9.90	2.07	0.05	1.51	0.75	1.98	4.44	0.08	1.55	98.67
BR	145	74.09	0.26	10.63	3.27	0.07	2.32	1.02	2.30	4.40	0.08	1.98	100.42
BR	146	73.72	0.36	11.81	5.01	0.13	2.33	0.19	0.18	3.78	0.10	2.93	100.54
BR	147	75.17	0.23	9.97	2.96	0.11	1.53	1.20	0.21	6.00	0.09	2.47	99.94
BR	148	76.18	0.22	9.97	3.14	0.13	1.27	1.18	0.21	5.38	0.09	2.66	100.43
BR	149	76.90	0.23	10.43	2.54	0.10	1.09	0.68	1.87	4.60	0.09	1.70	100.23

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LTI	80				456	19													
BR	81	0	191	12	27	65	26	5	13	91	905	43	1348	5	10	0	0	16	15
BR	82	7	304	30	437	176	46	0	5	123	460	31	1673	4	8	0	0	15	5
BR	145	7	237	22	68	172	81	0	12	102	905	43	1406	6	9	0	0	16	5
BR	146	6	206	20	16	175	500	0	22	69	535	68	849	11	11	0	0	16	6
BR	147	6	213	21	85	273	84	0	12	95	297	32	1778	5	8	0	0	15	6
BR	148	5	215	21	90	297	82	4	34	84	260	27	1438	4	9	0	0	17	6
BR	149	6	251	19	56	199	129	0	15	88	192	29	1538	4	9	11	0	16	5

Rooiberg Fragment: Dullstroom Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LTI	R82a	55.59	0.39	13.44	10.75	0.08	6.18	2.57	2.81	2.68	0.08	6.03	100.60
LTI	R82b	54.82	0.38	13.26	11.46	0.06	7.41	2.06	2.21	1.86	0.06	5.95	99.53
LTI	R82c	55.50	0.39	13.63	11.54	0.06	7.64	2.10	2.25	1.87	0.07	5.93	100.98
LTI	R82d	55.07	0.37	13.11	11.19	0.07	7.39	2.22	1.89	2.42	0.10	5.99	99.82
LTI	R82e	53.55	0.36	13.26	10.95	0.08	7.11	3.31	2.41	1.86	0.09	7.60	100.58

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LTI	R82a	0	104	12	73	243	22	120	141	41	330	140	146	27	12	0	0	14	7
LTI	R82b	0	104	11	80	166	41	9	139	43	457	145	74	29	12	0	0	11	5
LTI	R82c	0	99	11	80	265	35	92	136	50	427	137	191	28	11	0	0	12	5
LTI	R82d	0	100	20	82	191	35	0	141	50	474	143	96	28	12	0	0	11	3
LTI	R82e	0	80	8	86	137	42	453	137	49	445	139	120	29	13	0	0	11	4

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Rooiberg Fragment: Schrikkloof Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	28	74.55	0.24	11.47	4.38	0.11	0.00	0.90	2.66	4.88	0.02	1.64	100.85
LMF	29	74.78	0.24	11.47	4.14	0.07	0.00	0.37	1.89	6.57	0.03	1.42	100.98
LMF	30	72.33	0.24	11.18	4.45	0.10	0.00	1.39	1.83	6.08	0.02	1.95	99.57
LMF	31	73.85	0.24	10.66	3.72	0.10	0.00	1.74	3.01	4.77	0.02	2.08	100.19
LMF	32	76.76	0.24	6.26	4.80	0.09	0.00	0.76	2.61	5.14	0.08	1.31	98.05
LMF	35	73.77	0.24	11.40	5.95	0.05	0.38	0.10	2.43	4.44	0.04	1.10	99.90
LMF	36	73.22	0.25	11.31	3.70	0.09	0.33	1.02	2.16	6.09	0.05	1.64	99.86
LMF	37	72.97	0.24	11.18	5.14	0.21	0.26	0.19	2.73	4.40	0.03	1.17	98.52
LMF	38	74.37	0.24	11.45	3.44	0.15	0.28	1.44	3.13	4.54	0.03	1.78	100.85
LMF	39	73.43	0.24	11.24	4.19	0.11	0.22	1.57	2.56	5.02	0.02	1.99	100.59
LMF	40	72.88	0.23	11.13	5.58	0.07	0.38	0.42	1.33	6.48	0.03	1.30	99.83
LMF	41	76.14	0.23	11.06	2.88	0.05	0.29	0.67	1.87	5.65	0.03	1.31	100.18
LMF	42	74.12	0.24	11.18	5.10	0.03	0.29	0.76	2.03	5.21	0.03	1.54	100.53
LMF	43	72.69	0.23	11.05	3.42	0.04	0.36	1.58	0.69	8.37	0.02	1.99	100.44
LMF	44	73.09	0.24	11.22	7.26	0.03	0.24	0.11	2.28	4.21	0.03	1.14	99.85
LMF	45	73.12	0.24	11.41	4.46	0.04	0.27	0.75	1.15	7.10	0.05	1.41	100.00
LMF	46	73.94	0.25	11.30	3.78	0.04	0.22	1.11	2.21	5.79	0.03	1.60	100.27
LMF	47	75.58	0.25	11.63	3.15	0.18	0.37	0.12	2.16	6.52	0.03	1.01	101.00
LMF	48	74.52	0.25	11.67	3.31	0.01	0.16	0.00	0.29	8.56	0.02	1.45	100.24
LMF	49	73.27	0.24	11.22	5.45	0.10	0.27	0.20	1.97	5.75	0.03	1.35	99.85

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	28	22	484	65	32	184	184	0	0	95	4	0	1093	2	18	13	0	28	21
LMF	29	23	482	65	15	257	254	3	0	78	5	0	1121	3	18	13	3	27	10
LMF	30	23	483	66	32	2477	171	6	0	53	0	0	1183	2	18	18	3	29	11
LMF	31	22	472	64	31	183	80	8	0	80	0	0	855	3	17	12	0	27	9
LMF	32	24	492	66	22	197	162	17	0	68	5	0	803	2	19	15	0	27	7
LMF	35	22	482	63	12	200	80	37	21	71	0	0	871	2	18	15	3	26	7
LMF	36	24	483	65	32	252	306	0	7	77	4	0	1206	3	17	19	0	29	10
LMF	37	23	481	68	16	184	124	13	0	64	5	0	1052	2	17	13	0	27	15
LMF	38	24	491	68	41	182	163	46	0	60	0	0	963	4	18	14	4	30	23
LMF	39	23	484	69	40	1943	284	0	0	59	5	0	1002	3	19	22	0	29	14
LMF	40	23	481	65	10	298	45	41	0	81	6	0	1056	2	17	13	4	28	8
LMF	41	20	434	59	11	230	29	17	0	73	6	0	927	3	16	17	5	26	6
LMF	42	23	480	63	15	249	32	26	0	79	0	0	913	3	17	13	4	0	2
LMF	43	23	476	67	17	420	91	0	12	94	0	0	1096	3	13	16	3	29	9
LMF	44	25	464	67	14	222	48	41	23	77	8	0	731	2	20	16	3	27	7
LMF	45	23	482	68	16	320	32	15	9	85	0	0	1274	2	15	13	0	30	9
LMF	46	30	620	86	23	329	32	49	0	65	5	0	945	3	17	12	0	0	0
LMF	47	35	686	87	33	333	241	0	0	100	4	0	1245	2	16	0	0	30	17
LMF	48	33	633	89	18	625	9	22	0	121	0	0	1457	2	19	15	4	28	7
LMF	49	5	565	67	15	400	31	29	0	85	4	0	899	2	17	17	0	27	8

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Rooiberg Fragment: Schrikkloof Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	50	74.67	0.22	10.09	6.66	0.02	0.22	0.00	0.23	7.18	0.03	1.34	100.66
LMF	51	72.63	0.23	10.91	5.87	0.09	0.23	0.00	0.24	7.44	0.03	1.59	99.26
LMF	52	74.19	0.23	10.52	4.99	0.02	0.18	0.00	0.26	7.41	0.02	1.17	98.99
LMF	53	73.00	0.23	11.37	4.70	0.02	0.27	0.02	0.24	8.95	0.04	1.15	99.99
LMF	54	74.23	0.25	11.56	3.76	0.02	0.38	0.03	0.23	8.34	0.05	1.24	100.09
LMF	55	74.61	0.22	11.04	4.81	0.03	0.31	0.00	0.22	8.53	0.03	1.03	100.83
LMF	56	72.88	0.24	11.38	5.36	0.07	0.33	0.21	1.47	6.60	0.02	1.10	99.66
LMF	57	74.52	0.24	11.65	4.76	0.04	0.31	0.00	0.23	7.06	0.03	1.51	100.35
LMF	58	74.18	0.24	11.31	4.83	0.04	0.40	0.00	0.23	7.48	0.03	1.50	100.24
LMF	60	71.95	0.24	11.40	4.33	0.04	0.24	0.88	1.87	6.75	0.03	1.38	99.11
LMF	61	73.19	0.24	11.37	4.24	0.04	0.25	0.82	2.30	5.90	0.02	1.32	99.69
LMF	62	72.38	0.24	11.13	4.34	0.20	0.38	0.30	1.85	6.38	0.02	1.11	98.33
LMF	63	74.10	0.25	11.44	4.30	0.10	0.52	0.20	2.10	6.32	0.03	0.78	100.14
LMF	64	73.85	0.25	11.45	4.45	0.02	0.50	0.46	2.09	6.89	0.04	0.74	100.74
LMF	65	73.51	0.24	11.26	4.46	0.04	0.42	0.33	1.97	6.88	0.03	0.77	99.91
LMF	66	73.95	0.24	11.35	4.39	0.04	0.48	0.28	2.40	6.21	0.02	0.85	100.21
LMF	67	74.16	0.24	11.32	4.75	0.04	0.42	0.36	2.11	6.75	0.02	0.79	100.96
LMF	68	73.52	0.24	11.26	4.62	0.05	0.41	0.61	2.77	5.50	0.02	1.06	100.06

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	50	14	420	51	8	366	6	0	0	120	8	0	1132	2	10	13	0	27	6
LMF	51	21	440	61	11	427	21	13	0	99	6	0	1325	2	17	19	0	26	6
LMF	52	25	459	66	19	382	15	4	0	72	6	0	1340	2	19	13	0	26	7
LMF	53	19	437	53	9	417	14	8	24	113	6	0	1509	2	11	15	0	23	5
LMF	54	28	500	71	13	469	20	19	6	116	6	0	1334	2	17	14	0	28	7
LMF	55	24	519	74	10	481	20	0	0	108	6	0	1237	2	12	12	3	27	11
LMF	56	29	603	80	12	491	26	14	0	79	6	0	986	2	17	11	0	27	8
LMF	57	27	586	81	12	475	37	22	0	75	0	0	1029	0	18	13	0	26	6
LMF	58	28	583	69	12	426	37	8	0	84	6	0	1075	2	19	15	4	26	7
LMF	60	25	514	71	26	302	36	20	0	81	4	0	1161	4	18	19	4	29	7
LMF	61	24	498	66	24	277	19	25	0	92	0	0	1003	2	18	18	0	26	6
LMF	62	23	480	65	20	319	13	0	0	93	4	0	1125	0	16	13	4	26	7
LMF	63	23	494	66	19	311	20	7	21	83	5	0	1190	2	18	14	0	27	7
LMF	64	23	481	59	22	297	34	12	8	87	6	0	1270	2	18	19	3	27	8
LMF	65	28	587	81	22	388	46	3	0	86	6	0	1230	3	17	13	44	49	31
LMF	66	30	632	88	32	351	58	6	0	125	5	0	1200	2	18	12	4	30	11
LMF	67	27	585	77	21	366	35	4	0	108	0	0	1194	2	16	13	0	29	7
LMF	68	31	519	78	32	306	45	0	0	107	4	0	1065	2	17	12	0	31	9

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Rooiberg Fragment: Schrikkloof Formation

Magma Type	Sample Number	SiO2	TiO2	Al2O3	FeOt	MnO	MgO	CaO	Na2O	K2O	P2O5	LOI	Total
LMF	69	74.20	0.25	11.52	4.80	0.11	0.44	0.36	2.99	5.18	0.02	1.02	100.89
LMF	70	73.44	0.24	11.19	4.98	0.20	0.38	0.27	2.18	6.02	0.02	0.98	99.90
LMF	71	74.56	0.25	11.33	4.86	0.03	0.43	0.63	2.25	5.27	0.02	1.40	101.03
LMF	72	73.47	0.25	11.49	5.02	0.04	0.62	0.34	2.12	5.71	0.04	1.35	100.45
LMF	73	73.02	0.25	11.36	4.82	0.17	0.53	0.15	2.15	5.57	0.05	2.43	100.50

		Nb	Zr	Y	Sr	Rb	Zn	Cu	Ni	Co	Cr	V	Ba	Sc	Ga	Hf	U	Th	Pb
LMF	69	27	525	74	22	229	62	12	0	126	0	0	969	2	18	15	4	29	7
LMF	70	22	476	66	21	299	54	0	0	87	6	0	1007	2	17	15	4	29	7
LMF	71	25	487	68	22	277	27	8	0	70	5	0	1011	3	18	12	0	28	7
LMF	72	23	454	62	12	278	36	14	19	99	4	0	1006	2	18	18	3	29	7
LMF	73	24	465	66	14	277	16	0	9	95	0	0	811	2	19	16	0	28	8

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Appendix H: CIPW-Norm

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Abbreviations used in the CIPW-Norms:

Q = Quartz
C = Corundum
or = Orthoclase
ab = Albite
an = Anorthite
ac = Acmite
di = Diopside
he = Hedenbergite
en = Enstatite
fs = Ferrosilite
wo = Wollastonite
mt = Magnetite
il = Ilmenite
cr = Chromite
hm = Hematite
ap = Apatite
ns = Nosean

DI = Differentiation Index
CrI = Crystallisation Index
CI = Colour Index
MgI = Mg-Index (Mg/Mg+Fe^{2+})
NPc = Normative Plagioclase Composition (An/An+Ab) x 100

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LTI	143a	12.59	0.00	8.42	16.56	29.41	0.00	5.14	3.86	10.49	9.05	0.00	3.06	1.13	0.00	0.00	0.30	0.00	37.57	41.90	32.72	0.41	63.97
LTI	143b	13.30	0.00	7.27	17.41	28.68	0.00	6.16	4.27	10.20	8.10	0.00	3.10	1.21	0.00	0.00	0.30	0.00	37.98	41.99	33.05	0.42	62.22
LTI	143c	13.81	0.00	5.94	18.35	28.88	0.00	6.06	4.55	9.57	8.23	0.00	3.10	1.20	0.00	0.00	0.33	0.00	38.09	41.64	32.70	0.40	61.15
LTI	143d	13.17	0.00	6.91	17.57	28.45	0.00	6.48	4.89	9.60	8.31	0.00	3.10	1.21	0.30	0.00	0.28	0.00	37.65	41.66	33.60	0.40	61.82
LTI	143e	13.68	0.00	7.56	20.35	26.04	0.00	5.73	4.71	8.89	8.37	0.00	3.12	1.22	0.03	0.00	0.30	0.00	41.59	38.00	32.05	0.38	56.13
LTI	143f	10.52	0.00	7.94	18.01	30.14	0.00	5.44	3.70	11.09	8.66	0.00	3.04	1.11	0.05	0.00	0.30	0.00	36.46	43.35	33.05	0.43	62.60
LTI	143g	13.97	0.00	9.51	15.66	29.22	0.00	5.22	3.80	9.87	8.26	0.00	3.05	1.11	0.03	0.00	0.31	0.00	39.14	41.35	31.31	0.41	65.11
LTI	143h	13.19	0.00	8.56	17.51	28.68	0.00	5.09	3.80	10.03	8.58	0.00	3.09	1.14	0.03	0.00	0.31	0.00	39.26	40.80	31.73	0.41	62.10
LTI	143i	18.46	0.00	7.37	23.58	23.65	0.00	5.13	5.17	5.42	6.27	0.00	3.22	1.33	0.03	0.00	0.38	0.00	49.41	32.58	26.53	0.32	50.08
LTI	143k	19.08	0.00	10.41	22.16	22.92	0.00	3.43	3.69	5.97	7.37	0.00	3.23	1.35	0.03	0.00	0.38	0.00	51.55	30.53	25.02	0.31	50.84
LTI	2	14.51	0.00	10.62	17.89	25.60	0.00	4.98	4.64	8.17	8.73	0.00	3.23	1.29	0.00	0.00	0.31	0.00	43.03	36.31	31.05	0.35	58.86
LTI	3	10.28	0.00	8.84	21.62	28.71	0.00	4.56	3.25	10.01	8.19	0.00	3.05	1.11	0.05	0.00	0.33	0.00	40.75	40.28	30.18	0.41	57.04
LTI	6	11.75	0.00	8.67	22.00	17.69	0.00	9.94	7.08	8.39	6.86	0.00	4.35	2.84	0.04	0.00	0.37	0.00	42.43	33.51	39.47	0.38	44.57
LTI	10	25.59	0.00	9.80	13.08	27.72	0.00	1.93	2.07	6.64	8.17	0.00	3.23	1.38	0.03	0.00	0.37	0.00	48.47	34.29	23.41	0.31	67.93
LTI	12	9.86	0.00	7.66	20.81	27.55	0.00	6.43	4.59	10.23	8.37	0.00	3.08	1.17	0.02	0.00	0.24	0.00	38.33	41.15	33.87	0.42	56.97
LTI	13	4.32	0.00	13.06	23.27	20.18	0.00	11.03	5.56	11.52	6.68	0.00	3.03	1.11	0.02	0.00	0.25	0.00	40.64	39.26	38.90	0.50	46.45
LTI	20	9.59	0.00	8.41	17.27	27.90	0.00	7.18	4.87	11.19	8.70	0.00	3.24	1.35	0.02	0.00	0.28	0.00	35.27	42.93	36.53	0.43	61.76
LTI	21	8.71	0.00	8.26	19.14	26.18	0.00	7.23	5.00	11.54	9.16	0.00	3.19	1.32	0.02	0.00	0.26	0.00	36.11	41.49	37.44	0.43	57.77
LTI	26	11.75	0.00	9.22	16.42	28.48	0.00	6.17	3.97	10.94	8.07	0.00	3.24	1.38	0.04	0.00	0.33	0.00	37.39	42.31	33.76	0.43	63.42
LTI	30	9.45	0.00	6.66	19.06	27.60	0.00	9.47	5.49	10.47	6.96	0.00	3.19	1.29	0.06	0.00	0.28	0.00	35.18	44.41	36.88	0.46	59.15
LTI	31	9.65	0.00	8.10	18.19	27.23	0.00	7.69	4.85	11.29	8.17	0.00	3.21	1.31	0.06	0.00	0.26	0.00	35.94	42.83	36.61	0.44	59.95
LTI	33	16.36	0.00	9.62	27.94	19.13	0.00	4.90	5.40	5.18	6.54	0.00	3.20	1.34	0.03	0.00	0.37	0.00	53.92	27.66	26.55	0.31	40.64
LTI	43	10.91	0.00	10.95	25.39	20.69	0.00	7.11	6.36	6.52	6.69	0.00	3.39	1.60	0.00	0.00	0.39	0.00	47.25	32.67	31.67	0.35	44.90
LTI	44	10.07	0.00	7.51	20.45	27.00	0.00	7.21	4.74	10.40	7.85	0.00	3.17	1.28	0.04	0.00	0.28	0.00	38.02	41.50	34.65	0.43	56.91
LTI	47	22.46	0.00	15.19	24.89	15.40	0.00	3.47	4.79	3.25	5.15	0.00	3.43	1.61	0.00	0.00	0.38	0.00	62.54	21.14	21.69	0.24	38.22
LTI	52	11.00	0.00	6.74	17.40	29.63	0.00	7.22	4.01	11.89	7.57	0.00	3.07	1.15	0.02	0.00	0.30	0.00	35.14	45.19	34.92	0.47	63.00
LTI	54	15.07	0.00	6.53	19.62	25.10	0.00	5.96	3.33	12.45	7.99	0.00	2.89	0.87	0.05	0.00	0.14	0.00	41.22	39.78	33.49	0.48	56.13
LTI	55	11.07	0.00	6.51	17.57	26.75	0.00	6.92	4.04	13.89	9.30	0.00	2.88	0.84	0.06	0.00	0.17	0.00	35.16	43.40	37.87	0.48	60.80
LTI	57	9.89	0.00	10.33	21.16	26.46	0.00	5.54	3.88	10.09	8.11	0.00	3.08	1.13	0.03	0.00	0.31	0.00	41.38	39.07	31.82	0.42	55.56
LTI	58	15.21	0.00	8.27	19.54	26.07	0.00	5.21	4.73	7.90	8.23	0.00	3.20	1.31	0.02	0.00	0.33	0.00	43.01	36.82	30.57	0.36	57.17
LTI	59	13.52	0.00	9.48	15.27	28.51	0.00	6.55	4.99	9.11	7.96	0.00	3.11	1.21	0.02	0.00	0.28	0.00	38.27	41.45	32.93	0.40	65.12
LTI	60	14.90	0.00	8.77	21.76	24.09	0.00	6.23	5.65	6.76	7.02	0.00	3.16	1.26	0.02	0.00	0.37	0.00	45.44	35.06	30.08	0.35	52.54
LTI	62	26.48	0.00	6.79	17.28	24.43	0.00	1.52	3.08	4.81	11.16	0.00	3.07	1.12	0.03	0.00	0.24	0.00	50.55	29.32	24.75	0.21	58.57
LTI	63	13.38	0.00	6.30	27.73	22.14	0.00	7.50	6.30	6.06	5.84	0.00	3.15	1.28	0.00	0.00	0.33	0.00	47.41	33.88	30.18	0.37	44.39
LTI	67	28.20	0.00	16.41	22.61	16.68	0.00	2.86	2.33	3.38	3.16	0.00	3.01	1.04	0.08	0.00	0.26	0.00	67.22	21.91	15.77	0.33	42.45
LTI	74	10.64	0.00	7.03	25.71	23.86	0.00	5.31	2.86	12.75	7.86	0.00	2.89	0.89	0.06	0.00	0.14	0.00	43.86	38.11	32.55	0.49	48.14
LTI	75	11.65	0.00	9.03	16.35	26.27	0.00	6.75	3.78	13.51	8.67	0.00	2.92	0.87	0.06	0.00	0.15	0.00	37.03	42.49	36.49	0.48	61.64
LTI	76	9.43	0.00	6.25	20.38	28.31	0.00	6.69	4.70	10.91	8.78	0.00	3.14	1.19	0.02	0.00	0.21	0.00	36.06	42.65	35.41	0.42	58.14
LTI	77	10.80	0.00	10.17	15.90	26.20	0.00	7.11	4.14	13.02	8.69	0.00	2.86	0.89	0.06	0.00	0.16	0.00	36.87	42.43	36.70	0.47	62.23
LTI	79	15.31	0.00	4.05	25.40	24.32	0.00	5.57	4.30	8.71	7.72	0.00	3.15	1.22	0.00	0.00	0.26	0.00	44.75	35.98	30.67	0.39	48.91

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LTI	86	10.34	0.00	10.61	16.03	25.05	0.00	8.28	4.74	12.72	8.35	0.00	2.84	0.84	0.06	0.00	0.14	0.00	36.98	42.25	37.77	0.48	60.98
LTI	88	10.45	0.00	8.23	18.05	25.80	0.00	7.71	4.44	12.69	8.81	0.00	2.86	0.82	0.06	0.00	0.14	0.00	35.78	43.11	38.22	0.49	58.84
LTI	91	11.58	0.00	6.95	18.68	28.96	0.00	6.19	4.20	10.65	8.28	0.00	3.06	1.14	0.02	0.00	0.30	0.00	37.21	42.61	33.52	0.43	60.79
LTI	93	11.45	0.00	7.65	18.70	28.41	0.00	6.32	4.27	10.54	8.15	0.00	3.10	1.16	0.02	0.00	0.24	0.00	37.80	42.12	33.54	0.43	60.31
LTI	98	9.90	0.00	6.79	20.37	27.03	0.00	7.47	4.88	10.75	8.06	0.00	3.19	1.26	0.05	0.00	0.26	0.00	37.05	42.03	35.61	0.44	57.03
LTI	99	9.13	0.00	7.28	19.96	26.90	0.00	8.86	5.35	10.43	7.22	0.00	3.23	1.33	0.06	0.00	0.26	0.00	36.38	43.06	36.41	0.45	57.40
LTI	100	15.94	0.00	12.16	24.75	19.11	0.00	5.57	5.36	5.77	6.36	0.00	3.29	1.40	0.00	0.00	0.29	0.00	52.85	28.73	27.76	0.33	43.57
LTI	107	12.99	0.00	5.93	24.23	24.42	0.00	6.68	5.84	7.54	7.56	0.00	3.20	1.31	0.00	0.00	0.31	0.00	43.15	36.39	32.13	0.37	50.19
LTI	108	11.26	0.00	8.28	19.40	28.21	0.00	5.46	4.33	9.72	8.85	0.00	3.06	1.12	0.03	0.00	0.28	0.00	38.95	40.48	32.54	0.39	59.25
LTI	111	14.35	0.00	8.11	21.82	24.83	0.00	5.88	5.25	7.36	7.53	0.00	3.21	1.31	0.02	0.00	0.33	0.00	44.28	35.87	30.55	0.36	53.22
LTI	112	4.99	0.00	5.44	27.64	26.36	0.00	5.50	3.96	11.98	9.90	0.00	2.98	1.02	0.07	0.00	0.16	0.00	38.07	40.25	35.34	0.42	48.83
LTI	113	10.37	0.00	7.86	17.78	25.97	0.00	7.05	4.33	13.33	9.39	0.00	2.88	0.84	0.06	0.00	0.14	0.00	36.01	42.36	37.82	0.46	59.35
LTI	115	10.25	0.00	6.74	18.09	26.74	0.00	7.07	4.03	13.95	9.11	0.00	2.88	0.90	0.06	0.00	0.19	0.00	35.08	43.59	37.93	0.48	59.65
LTI	118	6.58	0.00	9.39	22.18	24.27	0.00	6.53	3.87	13.49	9.16	0.00	3.14	1.13	0.03	0.00	0.24	0.00	38.15	40.25	37.31	0.47	52.25
LTI	120	11.85	0.00	6.94	18.29	28.90	0.00	7.00	4.51	10.31	7.62	0.00	3.11	1.16	0.02	0.00	0.28	0.00	37.08	43.14	33.72	0.44	61.24
LTI	121	17.93	0.00	13.71	18.41	23.31	0.00	3.68	3.83	6.46	7.72	0.00	3.23	1.35	0.02	0.00	0.30	0.00	50.04	31.52	26.25	0.32	55.88
LTI	122	19.38	0.00	13.94	24.63	15.20	0.00	3.15	3.45	6.80	8.54	0.00	3.21	1.33	0.03	0.00	0.35	0.00	47.95	33.11	26.47	0.31	63.27
LTI	123	11.89	0.00	7.12	13.64	29.46	0.00	7.80	4.52	12.70	8.44	0.00	3.08	1.12	0.03	0.00	0.21	0.00	32.65	46.16	37.65	0.47	68.36
LTI	128	7.13	0.00	6.67	18.81	28.88	0.00	7.55	5.93	10.63	9.57	0.00	3.20	1.31	0.02	0.00	0.31	0.00	32.61	43.88	38.20	0.40	60.56
LTI	129	9.08	0.00	6.85	21.23	26.86	0.00	6.17	3.88	12.67	9.13	0.00	2.95	0.96	0.06	0.00	0.17	0.00	37.15	41.91	35.76	0.45	55.86
LTI	130	9.62	0.00	9.53	21.32	26.19	0.00	4.95	3.68	10.90	9.30	0.00	3.13	1.16	0.02	0.00	0.22	0.00	40.46	38.78	33.11	0.41	55.13
LTI	131	10.69	0.00	8.89	20.13	27.34	0.00	4.74	3.49	10.94	9.26	0.00	3.12	1.15	0.02	0.00	0.24	0.00	39.71	39.74	32.69	0.41	57.60
LTI	134	12.62	0.00	8.34	19.25	25.35	0.00	5.19	3.16	12.97	9.06	0.00	2.92	0.93	0.06	0.00	0.14	0.00	40.22	39.64	34.23	0.46	56.85
LTI	135	9.61	0.00	10.95	20.70	26.50	0.00	5.12	3.61	10.50	8.50	0.00	3.12	1.15	0.02	0.00	0.24	0.00	41.26	38.98	32.00	0.56	56.14
LTI	140	12.44	0.00	2.39	18.70	30.74	0.00	6.97	5.67	9.61	8.96	0.00	3.10	1.19	0.00	0.00	0.23	0.00	33.53	44.45	35.50	0.39	62.18
LTI	144	15.98	0.00	8.59	17.04	27.21	0.00	5.12	3.83	9.37	8.03	0.00	3.20	1.28	0.03	0.00	0.33	0.00	41.61	38.89	30.02	0.40	61.49
LTI	164	11.77	0.00	9.80	17.11	26.54	0.00	7.50	4.87	10.16	7.57	0.00	3.15	1.24	0.06	0.00	0.24	0.00	38.68	41.16	34.49	0.44	60.80
LTI	165	7.54	0.00	11.05	18.30	25.64	0.00	7.94	4.96	11.14	7.97	0.00	3.49	1.68	0.05	0.00	0.24	0.00	36.89	41.39	37.18	0.44	58.35
LTI	166	14.53	0.00	8.10	17.56	27.59	0.00	6.98	4.77	8.86	6.94	0.00	3.15	1.26	0.02	0.00	0.26	0.00	40.18	40.77	31.96	0.42	61.11
LTI	177	14.47	0.00	11.12	17.18	24.59	0.00	7.04	4.77	8.67	7.51	0.00	3.15	1.25	0.02	0.00	0.26	0.00	41.76	38.40	33.38	0.42	58.87
LTI	178	10.86	0.00	6.92	18.18	26.73	0.00	8.02	4.41	12.66	7.79	0.00	3.07	1.15	0.05	0.00	0.26	0.00	35.96	43.63	37.01	0.48	59.52
LTI	179	10.90	0.00	8.23	22.34	25.22	0.00	6.90	4.55	9.83	7.44	0.00	3.12	1.20	0.02	0.00	0.26	0.00	41.47	39.01	33.03	0.43	53.02
LTI	180	14.82	0.00	11.69	20.30	24.60	0.00	3.89	3.25	8.49	8.16	0.00	3.14	1.24	0.03	0.00	0.40	0.00	46.80	34.43	28.17	0.37	54.79
LTI	181	10.12	0.00	7.46	16.33	28.28	0.00	8.11	4.41	12.83	8.01	0.00	3.03	1.12	0.04	0.00	0.26	0.00	33.91	45.38	37.51	0.48	63.39
LTI	184	12.81	0.00	3.36	14.23	33.61	0.00	7.76	4.24	11.67	7.31	0.00	3.06	1.72	0.03	0.00	0.25	0.00	30.90	49.55	35.21	0.48	70.25
BR	92a	43.77	0.00	21.40	15.05	11.67	0.00	2.19	0.15	2.12	0.16	0.00	2.57	0.51	0.29	0.00	0.19	0.00	80.42	15.35	7.70	0.52	43.68
BR	92b	43.22	0.00	23.96	13.00	11.13	0.00	1.73	0.27	2.88	0.51	0.00	2.58	0.53	0.05	0.00	0.16	0.00	80.18	14.97	8.48	0.51	46.12
BR	92c	42.45	0.00	24.47	13.30	11.10	0.00	1.15	0.08	3.86	0.29	0.00	2.59	0.53	0.03	0.00	0.16	0.00	80.22	14.95	8.49	0.59	45.49
BR	92d	43.32	0.00	24.77	11.61	11.22	0.00	0.76	0.08	4.35	0.52	0.00	2.60	0.54	0.05	0.00	0.19	0.00	79.70	15.03	8.85	0.58	49.15
BR	92e	43.77	0.00	25.92	12.61	10.82	0.00	1.81	0.00	1.80	0.00	0.00	1.99	0.57	0.04	0.43	0.23	0.00	82.31	13.89	6.60	0.54	46.18

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
BR	92f	44.18	0.00	24.60	12.87	10.86	0.00	0.83	0.13	2.75	0.50	0.00	2.57	0.50	0.04	0.00	0.16	0.00	81.65	13.62	7.29	0.48	45.77
BR	92g	43.55	0.00	23.85	13.56	10.58	0.00	1.10	0.15	3.41	0.54	0.00	2.57	0.53	0.03	0.00	0.14	0.00	80.96	14.06	8.29	0.53	43.82
BR	92h	44.92	0.00	22.76	14.53	9.88	0.00	1.82	0.09	2.60	0.15	0.00	2.56	0.48	0.05	0.00	0.16	0.00	82.21	13.52	7.70	0.55	40.49
BR	92i	44.61	0.38	18.56	17.10	11.58	0.00	0.00	0.00	4.35	0.13	0.00	2.59	0.50	0.05	0.00	0.17	0.00	80.26	15.15	7.58	0.61	40.37
BR	92k	45.27	0.00	27.83	9.70	9.94	0.00	2.16	0.48	1.11	0.28	0.00	2.54	0.49	0.04	0.00	0.16	0.00	82.80	12.87	7.06	0.39	50.61
BR	1	34.33	0.00	17.53	16.69	16.99	0.00	0.82	0.33	6.52	3.00	0.00	2.80	0.76	0.03	0.00	0.21	0.00	68.55	22.38	14.22	0.48	50.45
BR	7	42.23	0.00	16.72	14.45	16.52	0.00	0.77	0.47	3.01	2.10	0.00	2.77	0.73	0.05	0.00	0.19	0.00	73.40	19.40	9.85	0.35	53.34
BR	11	42.03	0.00	24.40	13.73	10.80	0.00	0.50	0.17	3.64	1.41	0.00	2.60	0.54	0.03	0.00	0.16	0.00	80.26	13.78	8.75	0.45	44.04
BR	14	33.91	0.00	18.19	15.41	16.86	0.00	2.33	1.10	5.47	2.96	0.00	2.77	0.75	0.03	0.00	0.21	0.00	67.51	23.02	15.39	0.45	52.24
BR	53	34.01	0.00	17.79	15.01	17.00	0.00	2.63	1.23	5.59	2.99	0.00	2.78	0.74	0.03	0.00	0.21	0.00	66.81	23.55	15.95	0.46	53.11
BR	65	39.19	0.00	22.69	13.52	13.43	0.00	1.12	0.39	4.21	1.70	0.00	2.72	0.72	0.07	0.00	0.23	0.00	75.41	17.50	10.86	0.46	49.93
BR	66	41.92	0.36	19.37	14.67	13.89	0.00	0.00	0.00	3.89	2.15	0.00	2.76	0.73	0.06	0.00	0.21	0.00	75.95	17.12	9.53	0.39	48.63
BR	90	42.69	0.00	24.23	15.70	9.39	0.00	0.93	0.02	3.68	0.07	0.00	2.59	0.50	0.05	0.00	0.17	0.00	82.62	12.90	7.79	0.60	37.42
BR	95	47.36	0.00	25.11	16.64	6.50	0.00	0.58	0.00	0.99	0.00	0.00	1.26	0.48	0.03	0.90	0.16	0.00	89.11	7.77	4.20	0.45	28.08
BR	124	40.52	0.00	16.05	13.83	17.72	0.00	0.40	0.19	4.86	2.60	0.00	2.83	0.78	0.05	0.00	0.19	0.00	70.40	21.51	11.66	0.43	56.16
BR	161	48.13	0.31	20.30	13.03	11.84	0.00	0.00	0.00	2.71	0.41	0.00	2.55	0.48	0.03	0.00	0.21	0.00	81.46	14.17	6.15	0.47	47.61
BR	162	40.92	0.00	20.89	16.12	12.02	0.00	1.21	0.21	4.34	0.86	0.00	2.60	0.57	0.03	0.00	0.23	0.00	77.94	16.26	9.79	0.55	42.70
BR	163	33.84	0.00	23.15	11.04	16.77	0.00	2.04	0.83	5.85	2.73	0.00	2.76	0.76	0.03	0.00	0.21	0.00	68.02	22.91	14.97	0.48	60.31
BR	183	39.55	0.00	31.80	13.32	7.75	0.00	1.53	0.00	2.91	0.00	0.00	1.91	0.53	0.03	0.47	0.21	0.00	85.67	11.32	7.35	0.63	36.76
HTI	139a	6.98	0.00	6.58	23.54	22.68	0.00	7.95	7.50	7.05	7.63	0.00	5.33	4.09	0.00	0.00	0.68	0.00	37.10	35.57	39.54	0.30	49.07
HTI	139b	4.86	0.00	8.64	24.02	21.37	0.00	9.76	8.27	6.71	6.53	0.00	5.23	3.97	0.00	0.00	0.64	0.00	37.52	35.84	40.47	0.32	47.08
HTI	139c	6.02	0.00	8.35	23.99	21.83	0.00	9.37	7.40	6.94	6.28	0.00	5.22	3.97	0.00	0.00	0.63	0.00	38.63	36.60	39.17	0.33	47.65
HTI	139d	5.33	0.00	8.64	24.05	21.92	0.00	8.98	7.13	7.41	6.75	0.00	5.18	3.94	0.00	0.00	0.67	0.00	38.02	36.09	39.38	0.34	47.69
HTI	139e	5.06	0.00	7.99	24.91	21.31	0.00	9.67	8.07	6.71	6.43	0.00	5.23	3.98	0.00	0.00	0.63	0.00	37.96	35.68	40.10	0.32	46.11
HTI	139f	4.60	0.00	7.47	25.13	21.34	0.00	9.51	8.02	7.14	6.91	0.00	5.23	3.97	0.07	0.00	0.61	0.00	37.20	35.82	40.78	0.33	45.92
HTI	139g	5.55	0.00	7.34	22.21	23.17	0.00	9.72	7.95	7.35	6.89	0.00	5.22	3.92	0.08	0.00	0.62	0.00	35.11	38.03	41.03	0.33	51.05
HTI	139h	5.50	0.00	8.00	22.70	22.66	0.00	9.97	7.89	7.03	6.38	0.00	5.22	3.97	0.07	0.00	0.61	0.00	36.19	37.56	40.47	0.34	49.96
HTI	139i	4.66	0.00	5.78	25.04	22.56	0.00	10.11	9.08	6.47	6.67	0.00	5.15	3.88	0.00	0.00	0.61	0.00	35.47	37.20	41.36	0.32	47.40
HTI	139k	4.95	0.00	5.91	24.07	22.93	0.00	10.56	8.64	6.81	6.40	0.00	5.19	3.93	0.00	0.00	0.61	0.00	34.93	38.27	41.53	0.33	48.79
HTI	5	11.75	0.00	8.67	22.00	17.69	0.00	9.94	7.08	8.39	6.86	0.00	4.35	2.84	0.04	0.00	0.37	0.00	42.43	33.51	39.47	0.38	44.57
HTI	9	10.70	0.00	8.89	24.14	18.90	0.00	9.24	6.49	7.52	6.06	0.00	4.52	3.05	0.02	0.00	0.40	0.00	43.82	33.41	36.87	0.37	43.92
HTI	19	12.63	0.00	11.08	21.94	18.72	0.00	8.21	6.06	7.11	6.02	0.00	4.63	3.17	0.05	0.00	0.38	0.00	45.65	31.92	35.21	0.35	46.05
HTI	27	9.42	0.00	9.42	28.90	14.80	0.00	9.82	6.33	7.72	5.71	0.00	4.47	2.99	0.03	0.00	0.42	0.00	47.73	30.02	37.02	0.39	33.86
HTI	28	6.45	0.00	9.58	27.39	16.30	0.00	9.82	6.85	8.54	6.83	0.00	4.64	3.21	0.00	0.00	0.40	0.00	43.42	32.11	39.89	0.38	37.30
HTI	29	6.71	0.00	11.95	27.74	14.74	0.00	9.37	6.72	7.84	6.45	0.00	4.74	3.32	0.00	0.00	0.42	0.00	46.40	29.60	38.43	0.37	34.70
HTI	41	5.76	0.00	8.85	31.12	16.35	0.00	8.73	7.36	6.62	6.40	0.00	4.88	3.51	0.00	0.00	0.42	0.00	45.73	29.72	37.50	0.33	34.44
HTI	45	7.62	0.00	14.16	31.68	13.28	0.00	7.71	6.14	5.78	5.28	0.00	4.68	3.27	0.00	0.00	0.42	0.00	53.46	25.03	32.85	0.33	29.53
HTI	46	4.14	0.00	9.47	33.75	13.81	0.00	9.80	7.13	7.24	6.04	0.00	4.79	3.42	0.00	0.00	0.42	0.00	47.36	28.69	38.41	0.36	29.04
HTI	48	5.34	0.00	12.54	24.47	16.61	0.00	10.36	6.62	9.17	6.72	0.00	4.62	3.16	0.00	0.00	0.40	0.00	42.35	33.39	40.65	0.40	40.43
HTI	50	1.55	0.00	5.63	32.75	19.62	0.00	9.21	9.04	5.90	6.65	0.00	5.16	3.87	0.00	0.00	0.64	0.00	39.93	32.97	39.82	0.30	37.47

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
HTI	51	5.30	0.00	11.17	21.39	22.30	0.00	8.78	6.53	7.94	6.77	0.00	5.23	3.95	0.00	0.00	0.66	0:00	37.86	36.74	39.19	0.35	51.04
HTI	61	8.18	0.00	8.42	19.74	25.26	0.00	6.87	6.05	7.71	7.78	0.00	5.25	4.01	0.03	0.00	0.70	0.00	36.34	37.53	37.67	0.31	56.13
HTI	64	5.90	0.00	8.37	22.40	23.01	0.00	9.16	7.72	6.98	6.75	0.00	5.17	3.90	0.02	0.00	0.63	0.00	36.96	37.06	39.68	0.33	50.67
HTI	72	9.12	0.00	5.41	26.98	22.63	0.00	6.27	7.68	5.67	7.95	0.00	4.76	3.34	0.00	0.00	0.47	0.00	41.51	32.61	35.66	0.26	45.32
HTI	101	10.01	0.00	8.91	25.76	17.12	0.00	9.75	6.82	7.49	6.01	0.00	4.58	3.11	0.02	0.00	0.42	0.00	44.68	32.13	37.76	0.37	39.93
HTI	103	5.39	0.00	2.69	27.23	22.97	0.00	11.88	8.74	6.15	5.19	0.00	5.21	3.95	0.00	0.00	0.61	0.00	35.31	39.17	41.11	0.35	45.76
HTI	104	3.15	0.00	7.09	27.06	20.17	0.00	10.59	8.61	7.08	6.60	0.00	5.18	3.90	0.00	0.00	0.59	0.00	37.30	35.72	41.94	0.34	42.71
HTI	105	4.76	0.00	7.21	25.60	21.65	0.00	11.31	8.98	5.57	5.08	0.00	5.23	4.00	0.00	0.00	0.63	0.00	37.56	36.86	40.16	0.33	45.82
HTI	109	11.46	0.00	9.14	21.55	17.00	0.00	10.48	6.80	9.28	6.90	0.00	4.28	2.74	0.04	0.00	0.33	0.00	42.15	33.99	40.47	0.40	44.10
HTI	110	11.11	0.00	9.12	21.56	17.37	0.00	11.09	7.26	7.64	7.23	0.00	4.35	2.82	0.06	0.00	0.40	0.00	39.78	35.21	42.40	0.40	44.62
HTI	127	0.52	0.00	8.55	26.45	19.63	0.00	9.75	8.49	8.37	8.36	0.00	5.27	4.00	0.00	0.00	0.61	0.00	35.52	35.24	44.28	0.33	42.59
HTI	132	16.85	0.00	8.03	22.63	23.23	0.00	3.51	3.14	7.04	7.21	0.00	4.69	3.24	0.00	0.00	0.43	0.00	47.51	31.68	28.83	0.31	50.66
HTI	136	13.07	0.00	8.72	26.13	19.68	0.00	6.48	4.63	7.23	5.92	0.00	4.61	3.16	0.00	0.00	0.38	0.00	47.92	31.23	32.03	0.35	42.96
HTI	173	0.71	0.00	3.38	36.86	16.86	0.00	29.17	0.05	0.00	0.00	3.20	5.11	3.83	0.03	0.00	0.79	0.00	40.96	46.03	38.18	0.61	31.38
HMF	4	21.38	0.00	12.15	23.08	21.60	0.00	2.66	1.94	6.84	5.71	0.00	3.09	1.19	0.04	0.00	0.33	0.00	56.60	29.05	21.43	0.38	48.34
HMF	8	27.74	0.00	17.16	22.52	14.86	0.00	4.68	4.03	2.20	2.17	0.00	3.09	1.21	0.02	0.00	0.32	0.00	67.41	21.08	17.39	0.31	39.77
HMF	15	28.17	0.00	17.66	26.73	12.68	0.00	2.14	2.01	2.93	3.14	0.00	3.07	1.11	0.02	0.00	0.33	0.00	72.57	16.88	14.40	0.29	32.17
HMF	16	26.37	0.00	17.27	29.80	11.64	0.00	2.76	2.31	2.74	2.63	0.00	3.06	1.11	0.00	0.00	0.31	0.00	73.45	16.31	14.61	0.31	28.08
HMF	17	25.68	0.00	14.45	23.46	17.40	0.00	3.17	2.62	4.44	4.21	0.00	3.08	1.18	0.00	0.00	0.33	0.00	63.58	23.68	18.70	0.34	42.58
HMF	18	21.35	0.00	14.16	25.98	18.17	0.00	2.95	3.16	4.34	5.32	0.00	3.09	1.17	0.02	0.00	0.31	0.00	61.49	24.16	20.03	0.30	41.15
HMF	22	22.50	0.00	12.59	24.16	18.73	0.00	3.69	3.42	4.94	5.26	0.00	3.16	1.23	0.02	0.00	0.31	0.00	59.25	25.89	21.70	0.33	43.67
HMF	23	25.29	0.00	16.46	26.12	14.59	0.00	2.41	2.49	3.67	4.37	0.00	3.10	1.19	0.02	0.00	0.31	0.00	67.86	19.57	17.23	0.29	35.84
HMF	24	24.74	0.00	15.73	22.58	17.28	0.00	2.88	2.46	4.96	4.86	0.00	3.06	1.14	0.02	0.00	0.30	0.00	63.05	23.64	19.35	0.34	43.36
HMF	25	26.10	0.00	15.25	21.89	18.91	0.00	1.72	1.32	5.50	4.83	0.00	3.04	1.14	0.02	0.00	0.30	0.00	63.24	24.48	17.54	0.36	46.34
HMF	32	27.74	0.00	16.75	30.36	11.26	0.00	2.16	2.15	2.41	2.76	0.00	3.04	1.07	0.02	0.00	0.29	0.00	74.86	15.11	13.59	0.28	27.05
HMF	34	28.13	0.00	17.48	28.48	12.28	0.00	2.09	1.62	2.87	2.56	0.00	3.07	1.09	0.02	0.00	0.33	0.00	74.08	16.37	13.29	0.32	30.12
HMF	35	28.50	0.00	18.78	27.54	11.62	0.00	2.06	1.60	2.89	2.58	0.00	3.04	1.10	0.02	0.00	0.28	0.00	74.82	15.70	13.27	0.32	29.67
HMF	36	29.08	0.00	18.01	26.89	12.76	0.00	1.60	1.44	2.85	2.94	0.00	3.05	1.09	0.02	0.00	0.28	0.00	73.98	16.35	12.97	0.29	32.18
HMF	37	28.21	0.00	17.13	24.24	14.63	0.00	2.61	2.37	3.03	3.13	0.00	3.14	1.23	0.00	0.00	0.31	0.00	69.58	19.34	15.48	0.30	37.64
HMF	38	28.81	0.00	17.71	22.72	14.49	0.00	2.26	2.77	2.62	3.68	0.00	3.22	1.40	0.02	0.00	0.32	0.00	69.24	18.58	15.95	0.25	38.93
HMF	39	28.06	0.00	16.40	22.36	16.43	0.00	2.58	2.38	3.54	3.65	0.00	3.14	1.27	0.00	0.00	0.30	0.00	66.81	21.42	16.45	0.31	42.36
HMF	40	27.76	0.00	18.51	29.33	11.08	0.00	1.09	0.88	3.60	3.32	0.00	3.06	1.09	0.02	0.00	0.29	0.00	75.60	14.68	13.03	0.32	27.41
HMF	42	30.47	0.00	17.79	22.63	14.71	0.00	2.38	1.45	3.75	2.62	0.00	2.93	0.96	0.06	0.00	0.26	0.00	70.88	19.72	14.09	0.38	39.40
HMF	49	25.08	0.00	15.27	25.45	16.80	0.00	2.59	2.38	3.84	4.06	0.00	3.09	1.16	0.02	0.00	0.28	0.00	65.79	22.07	17.11	0.31	39.77
HMF	69	27.54	0.00	18.50	27.15	12.58	0.00	2.61	1.92	2.85	2.40	0.00	3.02	1.09	0.02	0.00	0.33	0.00	73.19	17.19	13.89	0.33	31.67
HMF	70	25.21	0.00	19.40	29.71	10.81	0.00	2.82	2.62	2.38	2.54	0.00	3.06	1.15	0.00	0.30	0.16	0.00	74.33	15.29	14.56	0.29	26.68
HMF	71	22.94	0.00	14.98	23.11	19.45	0.00	2.19	1.89	5.49	5.44	0.00	3.05	1.16	0.04	0.00	0.28	0.00	61.02	25.49	19.21	0.34	45.70
HMF	96	24.14	0.00	16.87	30.11	13.01	0.00	2.64	2.32	3.13	3.15	0.00	3.11	1.19	0.03	0.00	0.31	0.00	71.12	17.85	15.54	0.31	30.17
HMF	97	19.84	0.00	16.10	27.38	15.78	0.00	3.62	3.24	4.63	4.75	0.00	3.13	1.23	0.03	0.00	0.30	0.00	63.32	22.63	20.58	0.33	36.56
HMF	182	25.24	0.00	17.28	24.89	15.42	0.00	2.00	1.34	5.19	3.99	0.00	3.09	1.17	0.03	0.00	0.33	0.00	67.40	21.09	16.79	0.38	38.31

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
XENOLITH	X-4	26.16	0.00	2.82	34.76	15.86	0.00	6.76	1.59	0.00	0.00	5.83	3.66	1.93	0.00	0.00	0.64	0.00	63.74	22.62	13.93	0.33	31.33
XENOLITH	X-5	14.23	0.00	20.14	26.52	10.22	0.00	3.19	7.89	2.79	7.91	0.00	4.07	2.47	0.00	0.00	0.58	0.00	60.89	15.36	28.32	0.16	27.81
XENOLITH	X-137	20.97	0.00	15.45	40.92	5.77	0.00	5.30	5.02	0.54	0.59	0.00	3.32	1.51	0.02	0.00	0.51	0.00	77.42	11.45	16.28	0.25	12.36

Tauteshoogte Area: Damwal Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LMF	1	28.61	0.00	17.67	28.95	8.14	0.00	0.99	3.14	1.76	6.41	0.00	2.97	1.02	0.00	0.00	0.35	0.00	75.23	10.36	16.28	0.13	21.96
LMF	2	29.77	0.00	22.83	19.42	11.52	0.00	0.83	2.60	1.91	6.82	0.00	2.97	1.03	0.00	0.00	0.30	0.00	72.02	13.69	16.16	0.14	37.23
LMF	3	24.76	0.00	25.64	25.87	6.67	0.00	1.34	4.12	1.56	5.59	0.00	2.99	1.05	0.00	0.00	0.35	0.00	76.27	9.10	16.72	0.13	20.50
LMF	4	24.80	0.00	23.51	27.87	6.93	0.00	0.98	3.39	1.64	6.49	0.00	2.99	1.07	0.00	0.00	0.33	0.00	76.18	9.06	16.56	0.12	19.92
LMF	5	23.32	0.00	26.68	28.80	4.43	0.00	1.37	4.85	1.24	5.02	0.00	2.98	1.00	0.00	0.00	0.31	0.00	78.80	6.67	16.46	0.12	13.34
LMF	6	24.83	0.00	21.84	30.40	5.88	0.00	1.19	4.20	1.46	5.92	0.00	2.95	1.02	0.00	0.00	0.30	0.00	77.07	8.10	16.75	0.12	16.21
LMF	7	21.62	0.00	27.34	32.79	2.15	0.00	1.15	3.42	1.65	5.64	0.00	2.96	1.00	0.00	0.00	0.28	0.00	81.75	4.46	15.82	0.14	6.16
LMF	8	21.84	0.00	24.37	35.54	1.85	0.20	2.62	5.54	1.13	2.75	0.00	2.98	1.05	0.00	0.00	0.33	0.00	81.76	5.26	16.07	0.17	4.94

Bothasberg Plateau: Granophyre and Rooikop Granite Porphyry

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
Granophyre	2	27.78	0	27.75	27.66	4.47	0	0.96	2.64	1.24	3.91	0	2.74	0.71	0	0	0.14	0	83.2	6.3	12.2	0.14	13.91
Gran. Porphyry	30	34.78	1.06	31.99	25.82	0.42	0	0	0	1.25	1.63	0	2.54	0.46	0	0	0.05	0	92.59	2.78	5.89	0.21	1.59
Gran. Porphyry	38	32.53	0	27.07	25.62	4.14	0	0.33	0.58	2.13	4.27	0	2.68	0.6	0	0	0.05	0	85.21	5.97	10.6	0.2	13.93

Bothasberg Plateau: Damwal Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
Fe-Ti-P	4	17.77	0.00	20.30	24.38	10.07	0.00	2.58	6.63	2.77	8.17	0.00	3.98	2.36	0.00	0.00	1.00	0.00	62.46	14.58	26.48	0.15	29.22
Fe-Ti-P	4B	18.95	0.00	27.38	21.26	7.61	0.00	2.06	6.47	2.11	7.61	0.00	3.73	2.06	0.00	0.00	0.76	0.00	67.59	11.16	24.04	0.13	26.37
LMF	1	25.15	0.00	24.66	27.00	6.77	0.00	2.04	3.95	1.76	3.91	0.00	3.11	1.23	0.00	0.00	0.42	0.00	76.82	10.05	16.00	0.18	20.05
LMF	3	26.35	0.00	25.98	27.15	5.91	0.00	0.62	1.84	1.76	5.96	0.00	3.01	1.09	0.00	0.00	0.33	0.00	79.48	7.77	14.28	0.14	17.88
LMF	5	27.27	0.06	24.64	26.69	6.33	0.00	0.00	0.00	2.95	7.72	0.00	3.01	1.06	0.00	0.00	0.28	0.00	78.60	8.48	14.73	0.17	19.17
LMF	6	28.48	0.00	24.23	24.56	8.01	0.00	0.71	2.24	1.61	5.83	0.00	2.99	1.04	0.00	0.00	0.31	0.00	77.27	9.85	14.42	0.13	24.59
LMF	7	26.57	0.00	26.40	24.87	6.57	0.00	0.26	0.80	2.25	7.88	0.00	3.01	1.09	0.00	0.00	0.30	0.00	77.84	8.41	15.29	0.14	20.89

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Bothasberg Plateau: Damwal Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LMF	8	25.77	0.00	25.63	27.19	5.48	0.00	0.76	1.95	2.18	6.45	0.00	3.07	1.15	0.00	0.00	0.37	0.00	78.59	7.77	15.56	0.15	16.78
LMF	9	25.72	0.00	27.58	23.93	6.32	0.00	1.04	2.64	2.09	6.08	0.00	3.09	1.16	0.00	0.00	0.35	0.00	77.23	8.83	16.09	0.16	20.91
LMF	10	27.33	0.00	27.59	19.78	9.35	0.00	0.62	1.71	2.06	6.46	0.00	3.27	1.42	0.00	0.00	0.42	0.00	74.70	11.41	15.53	0.14	32.10
LMF	11	26.75	0.00	24.92	25.53	6.72	0.00	0.79	2.92	1.52	6.44	0.00	3.04	1.10	0.00	0.00	0.28	0.00	77.19	8.58	15.81	0.12	20.83
LMF	12	29.39	0.57	25.19	19.90	10.06	0.00	0.00	0.00	4.09	6.22	0.00	3.07	1.14	0.00	0.00	0.38	0.00	74.48	13.71	14.52	0.25	33.56
LMF	14	29.79	0.38	17.07	20.03	15.48	0.00	0.00	0.00	4.58	7.80	0.00	3.17	1.26	0.00	0.00	0.45	0.00	66.90	19.21	16.80	0.24	43.58

Bothasberg Plateau: Kwaggasnek Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LMF	15	33.89	1.69	32.63	23.21	0.12	0.00	0.00	0.00	1.16	3.70	0.00	2.76	0.73	0.00	0.00	0.12	0.00	89.72	3.30	8.35	0.13	0.52
LMF	16	33.69	0.97	43.00	14.46	0.27	0.00	0.00	0.00	1.56	2.48	0.00	2.74	0.71	0.00	0.00	0.12	0.00	91.15	2.72	7.49	0.20	1.84
LMF	17	30.89	0.00	31.39	22.28	4.64	0.00	0.48	1.74	0.97	4.00	0.00	2.76	0.71	0.00	0.00	0.14	0.00	84.56	5.80	10.66	0.11	17.25
LMF	18	34.52	1.27	43.15	13.82	0.29	0.00	0.00	0.00	1.59	1.78	0.00	2.77	0.73	0.00	0.00	0.09	0.00	91.49	3.17	6.87	0.23	2.04
LMF	19	31.02	0.00	34.29	21.24	3.62	0.00	0.13	0.48	1.09	4.57	0.00	2.73	0.71	0.00	0.00	0.12	0.00	86.55	4.51	9.72	0.11	14.55
LMF	20	35.84	0.63	28.52	24.92	0.37	0.00	0.00	0.00	1.27	4.95	0.00	2.72	0.69	0.00	0.00	0.12	0.00	89.27	2.13	9.61	0.12	1.46
LMF	21	31.38	0.00	28.48	25.18	4.50	0.00	0.53	1.92	0.87	3.60	0.00	2.74	0.69	0.00	0.00	0.09	0.00	85.04	5.64	10.36	0.11	15.17
LMF	22	31.59	1.66	25.37	27.90	2.78	0.00	0.00	0.00	1.41	5.76	0.00	2.73	0.69	0.00	0.00	0.12	0.00	84.86	6.08	10.59	0.12	9.06
LMF	23	34.75	1.70	24.61	28.11	0.19	0.00	0.00	0.00	1.56	5.47	0.00	2.74	0.71	0.00	0.00	0.16	0.00	87.47	3.66	10.47	0.13	0.67
LMF	24	32.96	0.15	26.43	26.22	4.36	0.00	0.00	0.00	1.96	4.44	0.00	2.70	0.67	0.00	0.00	0.12	0.00	85.61	5.94	9.77	0.18	14.27
LMF	26	32.43	0.17	29.65	23.81	3.64	0.00	0.00	0.00	1.41	5.42	0.00	2.71	0.69	0.00	0.00	0.09	0.00	85.88	4.86	10.22	0.12	13.26
LMF	27	32.79	0.66	29.07	24.05	2.79	0.00	0.00	0.00	2.23	4.89	0.00	2.72	0.68	0.00	0.00	0.12	0.00	85.91	5.28	10.52	0.19	10.40
LMF	28	34.79	1.55	26.48	27.21	0.69	0.00	0.00	0.00	1.23	4.59	0.00	2.71	0.67	0.00	0.00	0.09	0.00	88.48	3.71	9.19	0.12	2.46
LMF	29	35.12	2.05	38.75	12.29	0.16	0.00	0.00	0.00	2.38	5.69	0.00	2.74	0.69	0.00	0.00	0.14	0.00	86.16	4.68	11.50	0.18	1.25
LMF	31	37.69	0.00	27.58	21.96	3.44	0.00	0.65	2.05	0.72	2.59	0.00	2.63	0.61	0.00	0.00	0.00	0.00	87.22	4.60	9.24	0.12	13.55
LMF	32	33.25	0.00	29.79	23.30	3.93	0.00	0.38	0.96	1.27	3.67	0.00	2.69	0.67	0.00	0.00	0.12	0.00	86.33	5.20	9.63	0.15	14.42
LMF	33	31.96	0.00	28.77	25.26	4.09	0.00	0.21	0.65	1.25	4.34	0.00	2.58	0.65	0.00	0.00	0.14	0.00	85.99	5.18	9.78	0.13	13.93
LMF	34	32.65	1.54	39.43	13.69	0.97	0.00	0.00	0.00	2.42	5.79	0.00	2.71	0.67	0.00	0.00	0.12	0.00	85.78	4.82	11.59	0.18	6.64
LMF	35	33.11	0.43	26.98	25.50	3.76	0.00	0.00	0.00	1.48	5.24	0.00	2.71	0.69	0.00	0.00	0.12	0.00	85.58	5.39	10.12	0.13	12.84
LMF	36	33.45	1.45	27.12	25.86	0.99	0.00	0.00	0.00	2.19	5.48	0.00	2.70	0.65	0.00	0.00	0.09	0.00	86.43	4.56	11.03	0.18	3.69
LMF	37	34.18	1.72	28.15	24.59	0.49	0.00	0.00	0.00	2.19	5.20	0.00	2.72	0.67	0.00	0.00	0.09	0.00	86.93	4.41	10.78	0.18	1.95
LMF	39	31.05	0.00	33.31	27.36	1.60	0.00	0.25	0.29	1.29	1.75	0.00	2.56	0.48	0.00	0.00	0.07	0.00	91.72	2.76	6.61	0.22	5.54
LMF	40	31.07	0.00	24.20	24.70	6.61	0.00	0.16	0.30	2.97	6.45	0.00	2.71	0.67	0.00	0.00	0.16	0.00	79.96	8.85	13.26	0.20	21.11

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Bothasberg Plateau: Schrikkloof Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LMF	41	38.85	0.25	33.02	19.31	3.22	0.00	0.00	0.00	1.80	0.48	0.00	2.54	0.43	0.00	0.00	0.10	0.00	91.18	4.84	5.25	0.37	14.30
LMF	42	35.36	0.52	30.88	27.19	0.37	0.00	0.00	0.00	1.62	1.03	0.00	2.54	0.44	0.00	0.00	0.05	0.00	93.43	2.23	5.64	0.29	1.34
LMF	43	32.20	0.00	31.69	28.55	0.40	0.00	1.12	0.94	1.06	1.03	0.00	2.57	0.45	0.00	0.00	0.00	0.00	92.44	2.26	7.16	0.26	1.39
LMF	44	37.65	1.51	34.91	20.33	0.12	0.00	0.00	0.00	1.63	0.84	0.00	2.52	0.44	0.00	0.00	0.05	0.00	92.89	3.37	5.43	0.31	0.58
LMF	45	34.75	1.02	43.00	15.57	0.00	0.00	0.00	0.00	1.22	1.39	0.00	2.54	0.48	0.00	0.00	0.05	0.00	93.31	2.27	5.62	0.22	0.00
LMF	46	33.58	1.19	34.94	23.63	0.00	0.00	0.00	0.00	1.30	2.29	0.00	2.54	0.47	0.00	0.00	0.05	0.00	91.16	2.58	6.61	0.19	0.00

Stavoren Fragment: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LTI	80	2.42	0.00	4.24	34.96	20.93	0.00	7.57	6.30	10.04	9.58	0.00	2.39	1.34	0.02	0.00	0.22	0.00	41.62	35.53	37.22	0.39	37.44
BR	81	41.05	0.26	25.21	17.94	7.42	0.00	0.00	0.00	4.40	0.18	0.00	2.62	0.54	0.19	0.00	0.19	0.00	84.21	10.86	7.74	0.59	29.26
BR	82	43.40	0.23	29.28	17.14	3.27	0.00	0.00	0.00	3.85	0.00	0.00	1.12	0.43	0.11	0.99	0.19	0.00	89.82	6.29	6.38	0.73	16.03
BR	145	38.35	0.42	26.35	19.71	4.59	0.00	0.00	0.00	5.85	1.25	0.00	2.58	0.50	0.19	0.00	0.19	0.00	84.41	9.28	10.19	0.57	18.91
BR	146	53.62	7.51	22.95	1.56	0.30	0.00	0.00	0.00	5.96	4.29	0.00	2.77	0.70	0.12	0.00	0.24	0.00	78.13	14.94	13.71	0.40	15.90
BR	147	47.03	1.19	36.33	1.82	5.49	0.00	0.00	0.00	3.90	0.95	0.00	2.57	0.45	0.06	0.00	0.21	0.00	85.18	9.88	7.87	0.50	75.12
BR	148	50.59	1.90	32.48	1.81	5.37	0.00	0.00	0.00	3.23	1.37	0.00	2.55	0.43	0.06	0.00	0.21	0.00	84.88	10.29	7.57	0.42	74.77
BR	149	46.09	1.37	27.56	16.03	2.82	0.00	0.00	0.00	2.75	0.15	0.00	2.54	0.44	0.05	0.00	0.21	0.00	89.67	6.66	5.89	0.50	14.97

Rooiberg Fragment: Dullstroom Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LTI	82a	8.29	1.51	16.72	25.07	12.87	0.00	0.00	0.00	16.23	15.35	0.00	2.89	0.78	0.08	0.00	0.20	0.00	50.08	26.38	35.25	0.40	34.00
LTI	82b	13.14	4.27	11.72	19.92	10.47	0.00	0.00	0.00	19.66	16.88	0.00	2.90	0.77	0.11	0.00	0.15	0.00	44.79	30.21	40.22	0.43	34.45
LTI	82c	12.90	4.46	11.60	19.97	10.45	0.00	0.00	0.00	19.96	16.74	0.00	2.88	0.78	0.09	0.00	0.17	0.00	44.47	39.67	40.36	0.44	34.35
LTI	82d	13.06	3.81	15.21	16.99	11.01	0.00	0.00	0.00	19.56	16.41	0.00	2.87	0.75	0.11	0.00	0.25	0.00	45.26	30.03	39.57	0.43	39.31
LTI	82e	8.71	1.59	11.80	21.86	16.98	0.00	0.00	0.00	18.99	16.12	0.00	2.89	0.73	0.11	0.00	0.22	0.00	42.37	32.50	38.73	0.43	43.71

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Rooiberg Fragment: Schrikkloof Formation

Magma Type	Sample Number	Q	C	or	ab	an	ac	di	he	en	fs	wo	mt	il	cr	hm	ap	ns	DI	CrI	CI	MgI	NPC
LMF	28	37.13	0.22	29.05	22.65	4.36	0.00	0.00	0.00	0.00	3.55	0.00	2.54	0.46	0.00	0.00	0.05	0.00	88.82	4.67	6.55	0.00	16.15
LMF	29	36.63	0.64	38.97	16.03	1.64	0.00	0.00	0.00	0.00	3.02	0.00	2.53	0.46	0.00	0.00	0.07	0.00	91.63	2.54	6.01	0.00	9.30
LMF	30	35.12	0.00	36.78	15.83	4.42	0.00	0.00	2.23	0.00	2.54	0.00	2.58	0.47	0.00	0.00	0.05	0.00	87.72	4.41	7.81	0.00	21.80
LMF	31	35.48	0.00	28.71	25.91	1.50	0.00	0.00	4.40	0.00	0.00	0.92	2.57	0.46	0.00	0.00	0.05	0.00	90.10	1.50	7.43	0.00	5.48
LMF	32	48.75	0.00	31.37	3.67	0.00	5.20	0.00	2.99	0.00	4.30	0.00	0.00	0.47	0.00	0.00	0.19	3.07	83.78	0.00	12.95	0.00	0.00
LMF	35	39.49	2.53	26.54	20.77	0.24	0.00	0.00	0.00	0.96	6.37	0.00	2.55	0.46	0.00	0.00	0.09	0.00	86.80	4.44	10.33	0.08	1.13
LMF	36	34.67	0.00	36.61	18.57	3.21	0.00	0.41	0.96	0.65	1.75	0.00	2.58	0.49	0.00	0.00	0.12	0.00	89.85	4.07	6.82	0.13	14.75
LMF	37	38.14	1.69	26.69	23.69	0.77	0.00	0.00	0.00	0.66	5.24	0.00	2.59	0.47	0.00	0.00	0.07	0.00	88.51	3.59	8.96	0.06	3.13
LMF	38	35.45	0.00	27.06	26.68	3.80	0.00	0.82	1.92	0.32	0.87	0.00	2.54	0.46	0.00	0.00	0.07	0.00	89.20	4.85	6.93	0.12	12.47
LMF	39	35.37	0.00	30.06	21.93	4.39	0.00	0.48	2.44	0.33	1.92	0.00	2.55	0.46	0.00	0.00	0.05	0.00	87.37	5.11	8.20	0.07	16.69
LMF	40	36.82	1.25	38.83	11.40	1.91	0.00	0.00	0.00	0.96	5.78	0.00	2.54	0.44	0.00	0.00	0.07	0.00	87.05	4.32	9.72	0.09	14.36
LMF	41	41.91	0.73	33.74	15.98	3.16	0.00	0.00	0.00	0.73	0.72	0.00	2.53	0.44	0.00	0.00	0.07	0.00	91.63	4.68	4.42	0.17	16.51
LMF	42	38.56	0.89	31.08	17.32	3.60	0.00	0.00	0.00	0.73	4.74	0.00	2.54	0.46	0.00	0.00	0.07	0.00	86.96	5.36	8.48	0.08	17.22
LMF	43	33.61	0.00	50.20	5.92	2.34	0.00	1.76	2.87	0.10	0.18	0.00	2.54	0.44	0.00	0.00	0.05	0.00	89.73	4.16	7.89	0.16	28.34
LMF	44	39.69	2.81	25.18	19.51	0.35	0.00	0.00	0.00	0.60	8.77	0.00	2.55	0.46	0.00	0.00	0.07	0.00	84.38	4.70	12.39	0.04	1.78
LMF	45	36.19	0.59	42.52	9.85	3.44	0.00	0.00	0.00	0.68	3.59	0.00	2.55	0.46	0.00	0.00	0.12	0.00	88.57	4.74	7.29	0.08	25.86
LMF	46	35.90	0.00	34.62	18.90	4.09	0.00	0.24	0.87	0.44	1.84	0.00	2.57	0.48	0.00	0.00	0.07	0.00	89.41	4.64	6.43	0.09	17.78
LMF	47	36.62	0.87	38.50	18.24	0.40	0.00	0.00	0.00	0.92	1.38	0.00	2.53	0.47	0.00	0.00	0.07	0.00	93.37	2.25	5.30	0.17	2.14
LMF	48	39.58	1.94	51.15	2.48	0.00	0.00	0.00	0.00	0.40	1.37	0.00	2.56	0.48	0.00	0.00	0.05	0.00	93.20	2.99	4.81	0.08	0.00
LMF	49	37.03	1.47	34.47	16.89	0.81	0.00	0.00	0.00	0.68	5.55	0.00	2.56	0.46	0.00	0.00	0.07	0.00	88.40	3.35	9.25	0.06	4.56
LMF	50	42.23	1.94	42.66	1.96	0.00	0.00	0.00	0.00	0.55	7.67	0.00	2.51	0.42	0.00	0.00	0.07	0.00	86.84	3.09	11.15	0.04	0.00
LMF	51	40.38	2.51	44.96	2.08	0.00	0.00	0.00	0.00	0.59	6.41	0.00	2.56	0.45	0.00	0.00	0.07	0.00	87.42	3.91	10.00	0.05	0.00
LMF	52	42.81	2.11	44.72	2.24	0.00	0.00	0.00	0.00	0.46	4.62	0.00	2.56	0.45	0.00	0.00	0.05	0.00	89.77	3.26	8.08	0.05	0.00
LMF	53	35.43	1.29	53.45	2.05	0.00	0.00	0.00	0.00	0.68	4.03	0.00	2.53	0.44	0.00	0.00	0.09	0.00	90.93	2.28	7.69	0.08	0.00
LMF	54	39.74	2.17	49.80	1.96	0.00	0.00	0.00	0.00	0.96	2.22	0.00	2.56	0.48	0.00	0.00	0.12	0.00	91.50	3.69	6.22	0.15	0.00
LMF	55	38.24	1.44	50.45	1.86	0.00	0.00	0.00	0.00	0.77	4.26	0.00	2.49	0.42	0.00	0.00	0.07	0.00	90.55	2.54	7.94	0.09	0.00
LMF	56	36.22	1.50	39.54	12.60	0.92	0.00	0.00	0.00	0.83	5.32	0.00	2.56	0.46	0.00	0.00	0.05	0.00	88.36	3.59	9.17	0.00	6.82
LMF	57	44.38	3.32	42.31	1.97	0.00	0.00	0.00	0.00	0.78	4.15	0.00	2.56	0.46	0.00	0.00	0.07	0.00	88.66	5.17	7.95	0.09	0.00
LMF	58	42.10	2.86	44.71	1.97	0.00	0.00	0.00	0.00	1.01	4.27	0.00	2.55	0.46	0.00	0.00	0.07	0.00	88.78	4.69	8.29	0.11	0.11
LMF	60	32.53	0.00	40.78	16.16	2.82	0.00	0.22	1.04	0.51	2.83	0.00	2.58	0.47	0.00	0.00	0.07	0.00	89.48	3.39	7.64	0.08	14.84
LMF	61	34.35	0.00	35.42	19.75	3.31	0.00	0.11	0.49	0.58	2.93	0.00	2.56	0.46	0.00	0.00	0.05	0.00	89.51	3.82	7.13	0.08	14.34
LMF	62	35.28	0.70	38.75	16.07	1.39	0.00	0.00	0.00	0.97	3.75	0.00	2.58	0.47	0.00	0.00	0.05	0.00	90.10	3.04	7.76	0.11	7.98
LMF	63	35.19	0.85	37.56	17.85	0.80	0.00	0.00	0.00	1.30	3.36	0.00	2.55	0.48	0.00	0.00	0.07	0.00	90.60	2.90	7.68	0.16	4.29
LMF	64	32.16	0.00	40.68	17.65	1.49	0.00	0.13	0.32	1.18	3.29	0.00	2.53	0.47	0.00	0.00	0.09	0.00	90.49	2.45	7.93	0.15	7.78
LMF	65	33.06	0.04	40.98	16.78	1.45	0.00	0.00	0.00	1.05	3.57	0.00	2.54	0.46	0.00	0.00	0.07	0.00	90.82	2.24	7.63	0.13	7.96
LMF	66	33.54	0.21	36.91	20.40	1.26	0.00	0.00	0.00	1.20	3.44	0.00	2.54	0.46	0.00	0.00	0.05	0.00	90.85	2.40	7.63	0.14	5.83
LMF	67	32.76	0.00	39.79	17.79	1.46	0.00	0.04	0.13	1.03	4.00	0.00	2.51	0.45	0.00	0.00	0.05	0.00	90.34	2.21	8.16	0.12	7.57
LMF	68	33.18	0.00	32.81	23.63	2.05	0.00	0.18	0.58	0.95	3.59	0.00	2.54	0.46	0.00	0.00	0.05	0.00	89.62	2.89	8.29	0.12	7.98
LMF	69	33.63	0.38	30.63	25.29	1.65	0.00	0.00	0.00	1.10	4.28	0.00	2.52	0.48	0.00	0.00	0.05	0.00	89.54	2.96	8.38	0.12	6.14
LMF	70	34.74	0.64	35.94	18.61	1.22	0.00	0.00	0.00	0.96	4.84	0.00	2.55	0.46	0.00	0.00	0.05	0.00	89.28	2.79	8.81	0.10	6.15
LMF	71	37.49	0.82	31.23	19.07	3.00	0.00	0.00	0.00	1.07	4.25	0.00	2.54	0.48	0.00	0.00	0.05	0.00	87.79	4.90	8.34	0.11	13.59
LMF	72	35.91	1.30	34.02	18.07	1.44	0.00	0.00	0.00	1.56	4.58	0.00	2.56	0.48	0.00	0.00	0.09	0.00	88.00	4.34	9.17	0.15	7.36
LMF	73	36.83	1.67	33.54	18.52	0.42	0.00	0.00	0.00	1.34	4.51	0.00	2.57	0.48	0.00	0.00	0.12	0.00	88.89	3.69	8.91	0.13	2.24

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Appendix I: Rare Earth Element Analyses

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Dullstroom Area: Dullstroom Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LTI	12	22.48	44.00	19.44	3.95	0.99				1.71	0.27
LTI	31	20.28	40.24	18.24	4.08	0.93				1.81	0.29
LTI	58	28.94	60.90	21.02	4.93	1.05				2.05	0.31
BR	162	35.06	70.44	22.08	4.95	1.01				1.85	0.25
HTI	29	33.61	74.95	35.74	7.58	1.90				2.92	0.40
HTI	41	30.01	65.96	33.61	7.59	2.03				2.66	0.45
HTI	45	39.74	84.04	40.66	8.49	1.97				3.67	0.51
HTI	48	32.21	67.80	32.89	7.18	1.75				2.90	0.43
HTI	51	18.68	61.76	27.27	5.41	1.92				2.80	0.43
HMF	4	34.30	66.99	26.34	5.46	1.16				2.31	0.34
HMF	16	41.01	85.68	26.49	5.91	1.30				2.26	0.35
HMF	18	33.09	67.31	21.26	5.39	1.22				2.27	0.35
HMF	23	41.08	81.56	30.61	6.33	1.21				2.55	0.38

Bothasberg Plateau: Damwal Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
Fe-Ti-P	4	53.07	197.66	42.07	9.48	1.81				4.39	0.68

Bothasberg Plateau: Schrikkloof Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LMF	41	89.85	173.45	64.93	13.11	1.91				6.96	1.07

Loskop Dam: Dullstroom Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
HMF	50.52	36.91	71.51	28.56	5.77	1.33	4.64	4.29	2.22	2.31	0.34
HMF	67	30.59	57.34	23.41	4.76	1.06	4.05	3.57	1.84	1.94	0.29
HMF	69	30.27	58.68	24.30	4.89	1.17	4.24	3.91	1.99	2.15	0.32
Fe-Ti-P	145.48	49.22	95.51	43.65	9.37	2.23	8.35	8.30	4.27	4.58	0.67
Fe-Ti-P	1350	57.22	105.80	48.74	10.21	2.36	9.00	8.57	4.27	4.49	0.67
LMF	11	60.18	115.20	48.41	9.81	1.89	8.42	8.22	4.32	4.74	0.60
LMF	19	60.62	114.30	49.11	10.07	1.96	8.39	8.12	4.17	4.54	0.64
LMF	63	62.27	120.80	50.43	10.60	2.13	9.01	9.01	4.70	5.10	0.76

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Loskop Dam: Damwal Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LMF	89	58.90	111.50	47.15	9.83	1.89	8.17	7.85	4.07	4.38	0.66
LMF	95	59.76	113.90	48.43	10.02	1.96	8.28	7.89	4.05	4.41	0.66
LMF	113	63.37	119.10	50.55	10.38	1.97	8.51	8.41	4.43	4.84	0.73
LMF	134.13	58.30	109.90	46.92	9.63	1.93	8.11	7.63	3.97	4.30	0.65
LMF	136	60.71	112.20	48.35	9.76	2.04	8.57	7.86	4.11	4.51	0.68
LMF	152	56.89	107.30	46.04	9.52	1.87	8.13	7.80	4.01	4.43	0.65
LMF	155	61.03	116.80	51.84	11.08	2.50	9.55	9.39	4.96	5.39	0.83
LMF	164.16	61.52	118.50	50.77	10.54	2.16	9.15	8.89	5.71	5.19	0.77

Loskop Dam: Kwaggasnek Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LMF	172.17	70.08	131.50	55.93	11.64	2.21	9.90	10.15	5.49	5.98	0.89
LMF	181	70.63	133.20	56.03	11.47	2.11	9.77	9.79	5.29	5.83	0.88

Loskop Dam: Schrikkloof Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LMF	189	72.09	134.70	56.84	11.51	1.91	9.53	10.06	5.41	6.00	0.89
LMF	196	76.43	137.10	57.38	11.60	1.88	9.63	9.99	5.45	5.85	0.85

Rooiberg Fragment: Schrikkloof Formation

Magma Type	Sample Number	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu
LMF	70	88.35	184.94	59.80	13.64	1.67				6.83	0.83
LMF	73	79.33	161.49	62.58	12.59	1.95				6.77	0.94

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Appendix J: Analytical Methods

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Analytical Methods

After crushing in primary and secondary jaw crushers, chips (< 3mm) were reduced to less than 200-mesh powder in a tungsten carbide mill. Alliquots of these powders were used for all analytical procedures.

Microprobe analyses

Nine major elements were analysed by the electron microprobe (Jeol Superprobe, 733), at the University of Pretoria. The acceleration voltage was 20kv for all analyses, with a beam current of 2×10^{-8}A measured and monitored in a Faraday cage. Peak and background counting times were 20 and 10sec, respectively, measured with a focused beam. The standard deviation was calculated from double analyses of identical spots (Table J1) with the formula given by Kaiser and Specker (1956). In-house standards were used for CaO (Wollastonite), SiO_2 (natural Quartz) and FeO (natural Hematite); TiO_2, Al_2O_3, MnO, Mgo, and Cr were compared to pure oxides, whereas international standards were applied to determine Na_2O (Omphacite) and K_2O (Sanidine). Fe_2O_3 and Fe^{3+}n of clinopyroxenes and the olivine (Appendix F) were calculated according to the method defined by Finger (1972).

	Range (wt.%)	1S	Range (wt.%)	1S
SiO_2	36.00 - 53.00	0.161		
TiO_2	0.08 - 1.00	0.011		
Al_2O_3	0.50 - 1.80	0.017	3.00 - 8.00	0.063
FeO	7.00 - 15.00	0.115	20.00 - 30.00	0.212
MnO	0.50 - 1.20	0.0003		
MgO	2.00 - 6.00	0.037	10.00 - 18.00	0.072
CaO	< 10.00	0.054	14.00 - 22.20	0.072
Na_2O	0.10 - 0.80	0.023		
K_2O	0.01 - 0.45	0.005		
Cr_2O_3	0.01 - 0.04	0.007		

Table J1: Standard deviations (1S = 1 sigma) for the elements analysed with the microprobe as estimated from duplicate analyses. All iron is expressed as FeO.

Major and trace elements

Major and trace elements were analysed by X-ray fluorescence spectrometry (Siemens SRS-1) at the University of Pretoria, described by Sharpe et al. (1983). Major elements except sodium, were determined on glass discs after the method of Norrish and Hutton (1969). H_2O^- and LOI were determined gravimetrically at temperatures of 110°C and 1050°C, respectively. Where necessary, the Fe_2O_3 content was corrected after the formula $\%Fe_2O_3 \leq \%TiO_2 + 1.5\%$ of Irvine and Baragar (1971). Sample preparation in the tungsten carbide mill variably contaminated the samples with up to 90ppm cobalt (Table J2), the amount being dependent on the hardness of the sample. the analytical accuracy of the major elements is better than 1% for elements with concentrations greater than 1% and better than 2% at lower concentrations. Accuracy of the trace elements is about 5% (for concentrations < 20ppm) and ±2% (for concentrations > 50ppm). The precision of the major and trace element analyses is similar to the accuracy at low levels but is ± 0.5% at concentrations of more than 5wt.% or 50ppm for major and trace element concentrations, respectively.

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	D-5(WC)	D-5(A)	D-8(WC)	D-8(A)	D-1(WC)	D-1(A)
SiO_2	57.54	57.40	67.75	67.50	70.51	70.22
TiO_2	1.49	1.50	0.64	0.64	0.40	0.39
Al_2O_3	12.29	12.39	12.99	12.94	12.71	12.77
FeO	11.17	11.08	5.69	5.74	4.59	4.74
MnO	0.15	0.15	0.13	0.13	0.10	0.11
MgO	5.27	5.24	1.76	1.72	2.78	2.78
CaO	7.90	7.96	5.31	5.36	3.84	3.94
Na_2O	2.54	2.61	2.67	2.89	1.98	2.10
K_2O	1.46	1.47	2.91	2.92	2.97	2.84
P_2O_5	0.15	0.16	0.14	0.15	0.09	0.10
Cr_2O_3	0.03	0.03	0.01	0.01	0.02	0.02
NiO	0.01	0.01	0.00	0.00	0.01	0.01
Nb	9	9	9	8	7	9
Zr	128	137	221	222	194	197
Y	20	21	29	30	21	22
Sr	311	334	284	289	254	265
Rb	64	68	81	84	112	108
Zn	84	85	68	67	76	79
Cu	119	114	24	15	5	0
Ni	72	72	26	11	53	42
Co	77	60	83	24	51	25
Cr	231	228	37	47	138	136
V	206	206	102	103	72	76
Ba	239	239	848	865	804	795
Sc	25	24	18	17	12	13
Ga	17	17	13	14	11	12
Hf	0	0	0	0	0	0
U	0	0	0	0	0	0
Th	12	12	15	18	14	15
Pb	3	3	9	8	7	7

Table J2: Major and trace element analyses of samples ground in a WC-mill (WC) compared with those prepared in an agate mill (A). All analyses are normalised to 100% (anhydrous) and total iron is expressed as FeO.

Rare earth elements

REE analyses were carried out by neutron activation using methods developed for the SLOWPOKE II reactor at the University of Toronto (Barnes and Gorton, 1984). the samples were weighed out (0.25gm) into 1.5 x 1.5cm plastic bags. They were then irradiated in one of SLOWPOKE II inner sites at a flux of 2.5×10^{11} $ncm^{-2}s^{-1}$ and counted (counting time: 10 000sec per sample) using a Ga detector with a resolution of 0.733KeV and 171KeV at 1300KeV. Counts from samples are directly compared with two in-house standards and a linear calibration was performed. Two counts are carried out; one at $\pm$7 days and the second at $\pm$40 days. The precision of the method is discussed in Barnes and Gorton (1984). Eu and Sm agree with recommended standard values to within 5%, La and Th to within 5-10%, Ce, Nd, Ta, and Yb to about 15%, and La and Hf to about 20%.

Tungsten contamination, introduced by the tungsten carbide mill, results in a high background and caused a marked deterioration in detection limit for some elements (Barnes and Gorton, 1984). This affected the elements Pr, Pm, Gd, Tb, Dy, Ho, Er and Tm, which were consequently excluded from the rare earth element interpretations.

References

Barnes, S.-J. and Gorton, M.P., 1984. Trace element analysis by neutron activation with a low flux reactor (Slowpoke-II): Results for

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international reference rocks. Geost. Newsletter., 8-1: 17-23.

Finger, L.W., 1972. The uncertainty in the calculated ferric iron content of a microprobe analysis. Carnegie Onst. Washington Year Book, 71: 600-603.

Irvine, T.N. and Baragar, W.R.A., 1971. A guide to the chemical classification of some common volcanic rocks. Can. J. Earth. Sci., 8-2, 523-548.

Kaiser, H. and Specker, H., 1956. Bewertung und Vergleich von Analysenverfahren. Z. Anal. Chem., 149: 44-66.

Norrish, K. and Hutton, J.T., 1969. An accurate x-ray spectrographic method for the analysis of a wide range of geological samples. Geochim. Cosmochim. Acta, 33: 431-453.

Sharpe, M.R., Brits, R. and Engelbrecht, J.P., 1983. Rare earth and trace element evidence pertaining to the petrogenesis of 2.3 Ga old continental andesites and other volcanic rocks from the Transvaal Sequence, South Africa. Inst. Geol. Res. Bushveld Complex, Univ. Pretoria, Res. Rep. 40: 62pp.

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