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R.C.A. MINNITT

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by

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ABSTRACT

Six petrographically related plutonic phases of the Vioolsdrif Suite include basic-ultrabasic intrusives, diorite, tonalite, granodiorite, adamellite, and leucogranite. A mineralogical and chemical continuum from mafic, low-silica intrusives to acid, high-silica types in the Vioolsdrif Suite is complemented by variations in the volcanic rocks of the Orange River Group which range from basaltic andesite to andesite, dacite, and rhyolite. The petrographic parallelism suggests an underlying genetic link between the volcanic and plutonic assemblages in which successive fractionation of cumulate phases (Vioolsdrif Suite) from an evolving magma resulted in differentiated residual liquids (Orange River Group). Fractionation of anhydrous olivine, clinopyroxene, orthopyroxene and minor plagioclase from a primary magma produced cumulus-enriched liquids which were tectonically emplaced as serpentinite, troctolite, pyroxenite, and gabbro bodies throughout the Richtersveld Province. Increased water vapour pressure initiated amphibole fractionation and samples of residual liquids were extruded to surface where they cooled as basaltic andesites. Continued amphibole fractionation from basaltic andesite produced residual liquids of andesitic composition. Amphibole-enriched cumulates were emplaced as hornblendites. Amphibole-plagioclase-metal oxide cumulates, represented by diorititic granitoids, were fractionated from andesitic magmas producing residual liquids of dacitic composition. Residual liquids of rhyolite composition formed by separation of granodiorite mineralogy (quartz, plagioclase, amphibole, K-feldspar, biotite) from dacitic magmas. Plutonic crystallization of the rhyolitic liquids so produced gave rise to adamellite (quartz, plagioclase, K-feldspar biotite). Major-element chemistry of granodiorite and dacite are very similar, as is that of adamellite and rhyolite, suggesting that the plutonic and volcanic pairs were derived from the same liquid, but that they cooled and solidified in different physical environments. While the magma chamber fractionated plutonic phases of the Vioolsdrif Suite at depth, it extruded contemporaneous and consanguineous residual liquids as volcanic ejecta at surface to form the Orange River Group.

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INTRODUCTION

Detailed field mapping in the vicinity of the Haib copper prospect in southern Namibia (Figure 1) has shown that the Tsams Formation of the Orange River Group consists of six volcanic rock types. Assemblages of these include mafic volcanics, feldspar

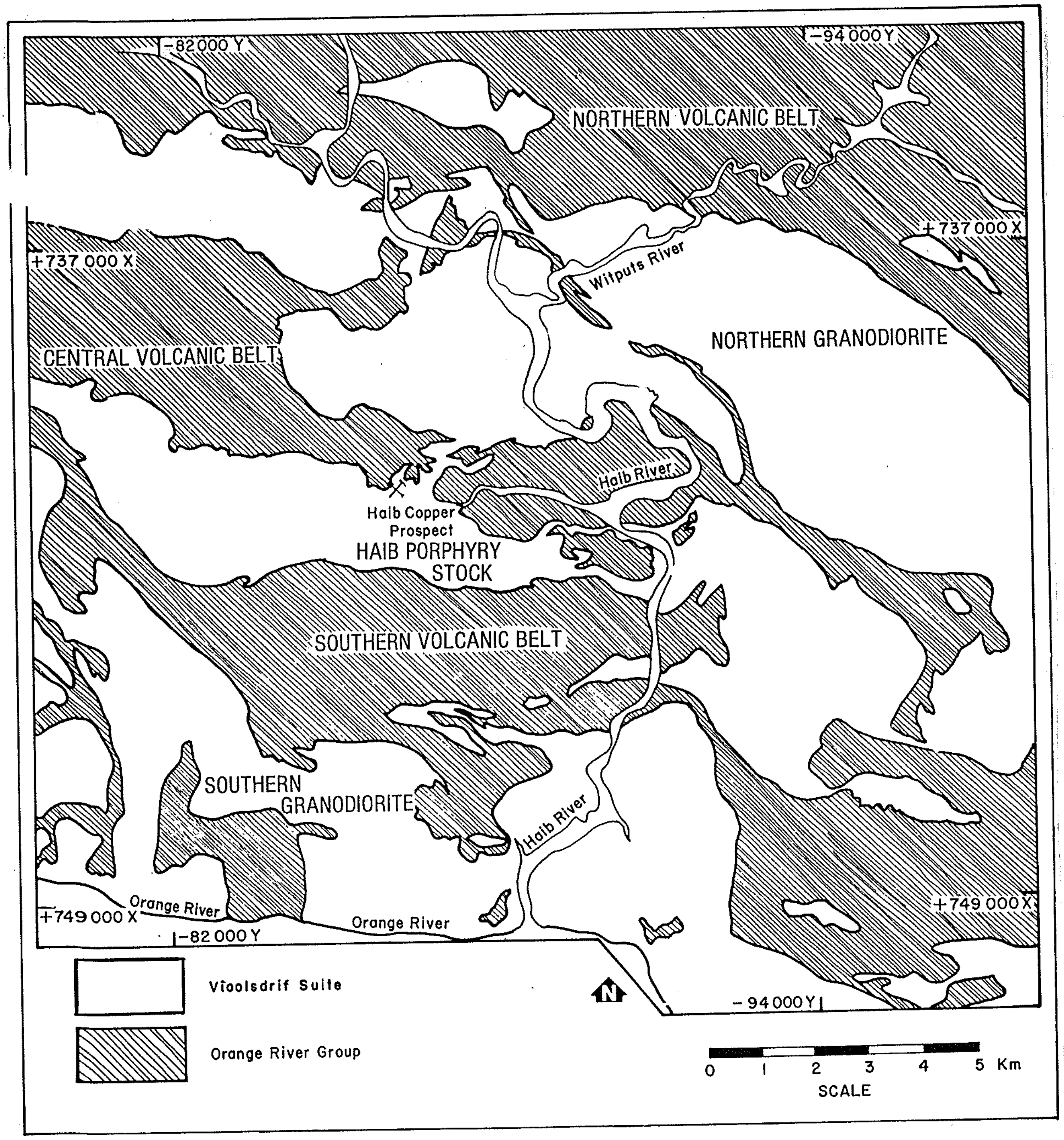

Figure 1: The distribution of the volcanic and plutonic assemblages of the Orange River Group and the Vioolsdrif Suite, respectively, constituting the Richtersveld Province basement in the study-area. The distribution of the northern, central, and southern volcanic belts relative to the main granodiorite bodies and the Haib porphyry stock is also shown.

porphyries, bedded mafic tuffs, mafic quartz-feldspar porphyries, rhyolites and acid volcanics. These volcanic rocks are preserved in approximately linear, sub-parallel belts which are separated from one another by composite intrusives of the Vioolsdrif Suite. The Tsams Formation is approximately 6km thick and consists of massive flows, agglomerates and tuffaceous rocks all of which were subaerially deposited and generally have porphyritic textures.

The Vioolsdrif Suite consists of six petrologically related plutonic phases including basic-ultrabasic intrusives, diorite, tonalite, granodiorite, adamellite, and leucogranite. A mineralogical continuum from mafic, low-silica instrusives to acid, high-silica types characterizes the Vioolsdrif Suite. This compositional continuum in the plutonic rocks is complemented by a change in composition of the volcanic rocks of the Orange River Group from basaltic andesite, through andesite and dacite to rhyolite and acid volcanic rocks. The chemical and petrological similarities between the Orange River Group and the Vioolsdrif Suite have been noted by Blignault (1974, 1977), Minnitt (1979) and Reid (1974, 1977, 1979). The chemical compositions of the calc-alkaline metalavas and granitoids were examined by Reid (1977) and Minnitt (1979) from which sources most of the geochemical data used in this study were drawn. The volcanic rocks of the Orange River Group have been geochemically subdivided into four main groups including basaltic andesite, andesite, dacite, and rhyolite. The subdivisions and classification of volcanic rocks proposed by Reid (1977) are applied in this study.

The melts from which the volcanic rocks were derived have been shown by Minnitt (1979) to be related to one another by fractional crystallization of a range of minerals including amphibole, plagioclase, K-feldspar, and biotite. Reid (1979) also demonstrated the derivation of the volcanic rocks by fractional crystallization of orthopyroxene, clinopyroxene, plagioclase, and titanomagnetite. Furthermore, Minnitt (1979, 1992) demonstrated that the plutonic phases of the Vioolsdrif Suite were also related to one another by processes of fractional crystallization. The possibility that the Richtersveld Province comprises a number of batholiths, of the type envisaged by Hamilton and Meyers (1967), in which plutonic rocks of a batholith intrude a carapace-like cover of its own volcanic ejecta implies a close genetic link between the volcanic and plutonic assemblages. The petrogenetic link between the volcanic rocks of the Orange River Group and the granitic rocks of the Vioolsdrif Suite is examined in the light of their major-and trace-element compositions. Relevant mineralogical relationships between the plutonic rocks and their extrusive equivalents are also examined.

PETROGENESIS OF THE ORANGE RIVER GROUP

Detailed chemical investigation of lavas from the Orange River Group by Reid (1977, 1979) indicated that the range of compositions from basaltic andesite, through andesite and dacite to rhyolite can be explained by a stepwise crystal fractionation model. He suggested that the basaltic andesite-dacitic compositions were produced by progressive removal of orthopyroxene, clinopyroxene, plagioclase and titanomagnetite. Removal of hornblende, biotite, plagioclase and titanomagnetite from a parental dacite was considered by Reid (1979) to be the means of generating porphyritic rhyolites. He also suggested that the basaltic andesites were not primary magmas, but were derived from a more basic primary basaltic precursor by 5-10 per cent olivine fractionation.

While the above model is geochemically feasible, it fails to geologically identify the materials fractionated from the parental and evolved liquids in the field. In the fractionation steps from basaltic andesite to dacite almost 73 per cent of the original magma is removed as a crystallite assemblage consisting of orthopyroxene, clinopyroxene, plagioclase, and magnetite. Pyroxene occur as volumetrically minor intrusives and can not be reconciled with the large amount of pyroxenite fractionation required by this model. A second weakness of the model proposed by Reid (1979) is that it fails to reconcile the very marked chemical and petrological similarities between the volcanic rocks and the plutonic rocks which intrude them.

A mechanism for the evolution of the Orange River Group volcanics by fractionation of anhydrous phases, followed by amphibole and predominantly amphibole-plagioclase fractionation from an early parental magma of basaltic composition, was suggested by Minnitt (1979). Fractionation in the earliest stages was dominated by separation of olivine, clinopyroxene, and orthopyroxene, with lesser amounts of plagioclase. The olivine-clinopyroxene-orthopyroxene-plagioclase cumulates were later emplaced as serpentinite, troctolite, and pyroxenite bodies throughout the Richtersveld Province. Fractionation of these anhydrous assemblages caused increases in water-vapour pressure of the magma, which together with decreasing temperature, resulted in the emergence of amphibole as the dominant liquidus phase. Residual liquids produced by amphibole and amphibole-plagioclase fractionation were extruded to surface as basaltic andesites. Amphibole and amphibole-plagioclase cumulates formed in this way were intruded as hornblendites, perknite, and gabbro bodies. Continued amphibole-plagioclase fractionation from magmas of basaltic andesite composition gave rise to residual liquids of andesite composition.

As amphibole and plagioclase cumulate phases (now represented by the diorites and tonalites of the Vioolsdrif Suite) were fractionated from magmas of andesitic composition, residual liquids of dacitic composition were produced. Crystallization of granodioritic mineralogy from dacitic magmas and the appearance of K-feldspar and biotite as liquidus phases, as a result of decreases in magma temperatures and increases in water-vapour pressure, gave rise to the formation of residual liquids of rhyolitic composition. The final step in the fractionation history of the Vioolsdrif Suite is represented by the adamellites which are considered to have formed from rhyolitic magmas which crystallized at depth. Leucogranites have been shown to be the last phase of fractionation from adamellite magmas, but there is no geochemical evidence at present to indicate a definite genetic link between the leucogranites and acid volcanic tuffaceous rocks of the Orange River Group.

MINERALOGICAL SIMILARITIES BETWEEN THE VOLCANIC AND PLUTONIC SUITES

Even though there are differences in the proportions and textures of the minerals present, the marked mineralogical similarity between volcanic and correspondingly evolved plutonic rock types suggests that there has been an almost parallel mineralogical evolution in the Orange River Group and the Vioolsdrif Suite. Apart from the bulk mineralogy, phenocrysts in the extrusives of the Orange River Group volcanic rocks can be related to the main liquidus phases of the Vioolsdrif Suite. Basaltic andesite usually contains amphibole and plagioclase pheocrysts, the latter minerals being the main constituents of diorites. Andesites and dacites contain quartz, pseudomorphed amphibole, and plagioclase phenocrysts, with the latter mineral predominating as the phenocryst phase. These minerals occur as the cumulus phases in granodiorite. Rhyolites contain biotite and K-feldspar phenocrysts with the complementary granitic phase (namely adamellite) being characterized by cumulus K-feldspar and biotite.

The similarities in mineralogy of the various components of the Vioolsdrift Suite and the Orange River Group are summarized in Table 1. The formation of alteration mineral assemblages is related to deuteric or metamorphic effects within the central portions of the Richtersveld Province. As the edge of the Province is approached higher metamorphic grades are encountered which Blignault (1977) and Beukes (1973) related to the Namaqua Orogeny 1000Ma-1300Ma ago.

Basic and ultrabasic intrusives have highly variable mineralogies including hydrous and anhydrous mafic phases that have produced amphibole-plagioclase, amphibole-orthopyroxene-clinopyroxene,olivine-pyroxene-amphibole,olivine-clinopyroxene-plagioclase and orthopyroxene-clinopyroxene assemblages. These assemblages accompanied by minor amounts of biotite, chlorite, or epidote occur as relatively small pods, preferentially emplaced along regional lineaments. Middlemost (1964) reported that peridotite bodies are extensively serpentinized. Biotite, chlorite, serpentinite and epidote formed either as products of later low-grade metamorphism or as high-temperature assemblages which equilibrated at the lower-temperature site at which they were emplaced.

Granitic textures in diorites and tonalites of the Vioolsdrif Suite differ markedly from the volcanic textures preserved in the basaltic andesite and andesitic volcanic rocks, but the mineralogy of the two groups is comparable (Table 1). The mineral assemblage in these groups of rocks is dominated by amphibole and plagioclase and biotite-magnetite-epidote pseudomorphs after amphibole, with quartz, biotite, chlorite, and titanomagnetite occurring as subordinate phases. Reid (1977) reported the occurrence of orthopyroxene in the diorites, but this mineral was not seen in any of the volcanics from the mafic lava unit. Plagioclase and amphibole are variably saussuritized, with epidote and biotite being the predominant alteration products. Sericite occurs in minor amounts as an alteration product of the plagioclase.

The mineralogical similarity between granodiorite and dacite (feldspar porphyry) is partially masked, firstly, by the difference in proportions of the mineral phases and, secondly, by the metamorphic imprint. Minerals constituting these rock-types include quartz, plagioclase, biotite, and K-feldspar, with epidote, sericite, and chlorite representing the alteration or retrograde metamorphic minerals. Biotite is the most abundant mineral in the groundmass of the feldspar porphyries, but it may also occur in aggregates together with epidote and opaque minerals. According to Blignault (1977), these aggregates probably represent the retrograde metamorphic products of high-temperature pyriboles. In granodiorites, the biotite-epidote-rutile-opaque mineral aggregates can locally be identified as pseudomorphs after hornblende. In the feldspar porphyries and granodiorites, therefore,

TABLE 1

MINERALOGICAL SIMILARITIES BETWEEN THE VIOOLSDRIF SUITE AND THE ORANGE RIVER GROUP

Vioolsdrif Suite		Basic-ultrabasic intrusives	Diorite	Granodiorite	Adamellite	Leucogranite
Orange River Group		No volcanic equivalent	Basaltic andesite-andesite	Dacite	Rhyolite	Acid Volcanics
Igneous Mineralogy		Highly variable, includes hydrous and anhydrous mineral assemblages. Olivine-clinopyroxene-orthopyroxene. Amphibole-orthopyroxene Amphibole-plagioclase Olivine-plagioclase clinopyroxene-orthopyroxene	Quartz Amphibole Plagioclase Minor orthopyroxene	Quartz Amphibole Biotite Plagioclase K-feldspar	Quartz Biotite Plagioclase K-feldspar	Quartz Plagioclase K-feldspar Minor biotite
Alteration Mineralogy	Deuteric	Mainly epidote	Mainly epidote Minor sericite Minor chlorite	Sericite Epidote Chlorite	Mainly sericite Minor epidote Minor chlorite	Mainly sericite
	Metamorphic	Biotite (Retrograde)	Biotite Actinolite (Retrograde) Hornblende (Progade ?)	Biotite (Retrograde)	Biotite (Prograde)	Biotite (Prograde)

there is evidence to support the proposition that biotite represents a retrograde metamorphic product. Locally, biotite may be replaced by chlorite, while plagioclase is replaced by epidote and sericite. K-feldspar is more abundant in granodiorites than in feldspar porphyries, but in the latter rock type small K-feldspar phenocrysts are locally present.

Adamellites and rhyolites display the most obvious similarities in mineralogy, comprising quartz, plagioclase, biotite, K-feldspar, and sericite. In both rock types, the characteristic feature is the appearance of K-feldspar as a major rock-forming mineral (Table 1). In rhyolites, K-feldspar occurs mainly as phenocrysts in a fine-grained quartzo-feldspathic matrix whereas, in the adamellites, K-feldspar solidified as a cumulate phase rather than as an interstitial or intercumulus phase. A marked similarity in the mineralogy of leucogranites and the acid volcanic unit has been recognised. The predominant minerals constituting these rock types include quartz, plagioclase, K-feldspar, minor amounts of biotite, epidote, and sericite. Furthermore, the leucogranite and the acid volcanic unit represent the acid end-members of the plutonic and volcanic assemblages, respectively.

MAJOR ELEMENT CHEMISTRY

Variations in chemical composition of the Vioolsdrif Suite and the Orange River Group are represented in the major element analyses in Table 2, and in binary diagrams of Al_2O_3 vs SiO_2, Al_2O_3 vs MgO, and TiO_2 vs MgO as shown in Figures 2-4. Attention is drawn to the complementary nature of the volcanic and plutonic suites in these diagrams. The trends formed by plotting these oxides display a marked change in slope at the point where the basaltic andesite-andesite trend is replaced by the diorite-rhyolite trend. The mechanism for the evolution of the components of the Orange River Group by fractionation of the Vioolsdrif Suite is schematically shown in the inset of each of the binary diagrams.

Separation of amphibole from a primitive liquid, which previously experienced fractionation of anhydrous phases, resulted in the formation of basalitic andesite liquids ranging in MgO content from 8,5 to 4,5% (Figures 2 and 3). Continued fractionation of amphibole drove low-MgO residual liquids with basaltic andesite compositions into the andesite field, where MgO content may vary from 4,5% to as low as 1%. In Figures 2-4 the back projection along the andesite-basaltic andesite trend coincides with a field of amphibole compositions. These compositions were derived from analyses by Reid (1977) of amphiboles from the pyroxenites of the Swartkop Complex, and from the analysis of an amphibolite dyke (Table 2, Column 1), from the vicinity of the Haib copper prospect.

In each of the binary diagrams (Figures 2-4), there is a marked change in slope from the basaltic andesite-andesite trend to the diorite-rhyolite trend. This is due to the separation of amphibole and plagioclase assemblages (diorite-tonalite granitoids) together with minor amounts of biotite, quartz, and titanomagnetite from liquids of andesitic composition. Residual liquids of dacitic composition were derived after diorite-tonalite fractionation from liquids of andesitic compositions. The marked similarity in major- and trace-element chemistry between the granodiorites and dacites is probably due to the extrusion of dacites on to surface before excessive granodiorite fractionation occurred. Fractionation of granodiorite from dacitic liquids was accomplished by removal of a somewhat different

TABLE 2

GEOCHEMICAL ANALYSES OF VIOOLSDRIF SUITE PLUTONIC ROCKS AND ORANGE RIVER GROUP VOLCANIC ROCKS

ROCK TYPE	HORNBLENDITE DYKE	DIORITE	TONALITE	GRANODIORITE	ADAMELLITE	LEUCOGRANITE	BASALTIC ANDESITE	ANDESITE	DACITE	RHYOLITE
COLUMN	1	2	3	4	5	6	7	8	9	10
n	1	5	11	19	27	20	5	18	18	14
SiO_2	45,82	55,70	60,30	64,40	68,38	75,69	54,95	59,10	65,68	73,77
TiO_2	0,79	0,95	0,88	0,55	0,48	0,18	0,73	0,74	0,59	0,36
Al_2O_3	9,60	17,30	17,20	15,51	14,86	13,15	14,94	16,10	15,73	13,75
Fe_2O_3	4,47	-	-	2,35	1,98	0,63	3,40	3,11	2,32	1,21
FeO	9,01	8,10	6,20	1,51	2,02	0,57	5,49	4,04	2,40	1,46
MnO	0,21	0,12	0,12	0,08	0,07	0,03	0,16	0,12	0,09	0,04
MgO	16,00	4,60	2,80	2,69	1,56	0,23	8,09	4,90	2,26	0,60
CaO	7,89	7,80	6,00	3,89	2,92	0,73	8,29	6,35	4,16	1,31
Na_2O	0,23	2,60	3,20	3,43	3,05	3,16	1,87	2,59	2,81	3,33
K_2O	1,09	2,20	2,90	4,07	4,52	5,45	1,86	2,74	3,82	4,83
P_2O_5	0,25	0,40	0,30	0,17	0,14	0,04	0,23	0,23	0,16	0,07
Total	95,36	99,77	99,90	99,65	99,90	99,86	100,01	100,02	100,02	99,90

Column 1: Analysis of hornblende dyke, Haib Copper Prospect, Minnitt (1979)
Column 2: Average of 5 analyses of diorite, Reid (1977)
Column 3: Average of 11 analyses of tonalite, Reid (1977)
Column 4: Average of 19 analyses of granodiorite, Reid (1977) and Minnitt (1979)
Column 5: Average of 27 analyses of adamellite, Reid (1977) and Minnitt (1979)
Column 6 : Average of 20 analyses of leucogranite, Reid (1977) and Minnitt (1979)
Column 7 : Average of 5 analyses of basaltic andesite, Reid (1979)
Column 8 : Average of 18 analyses of andesite, Reid (1979)
Column 9 : Average of 18 analyses of dacite, Reid (1979)
Column 10: Average of 14 analyses of rhyolite, Reid (1979)

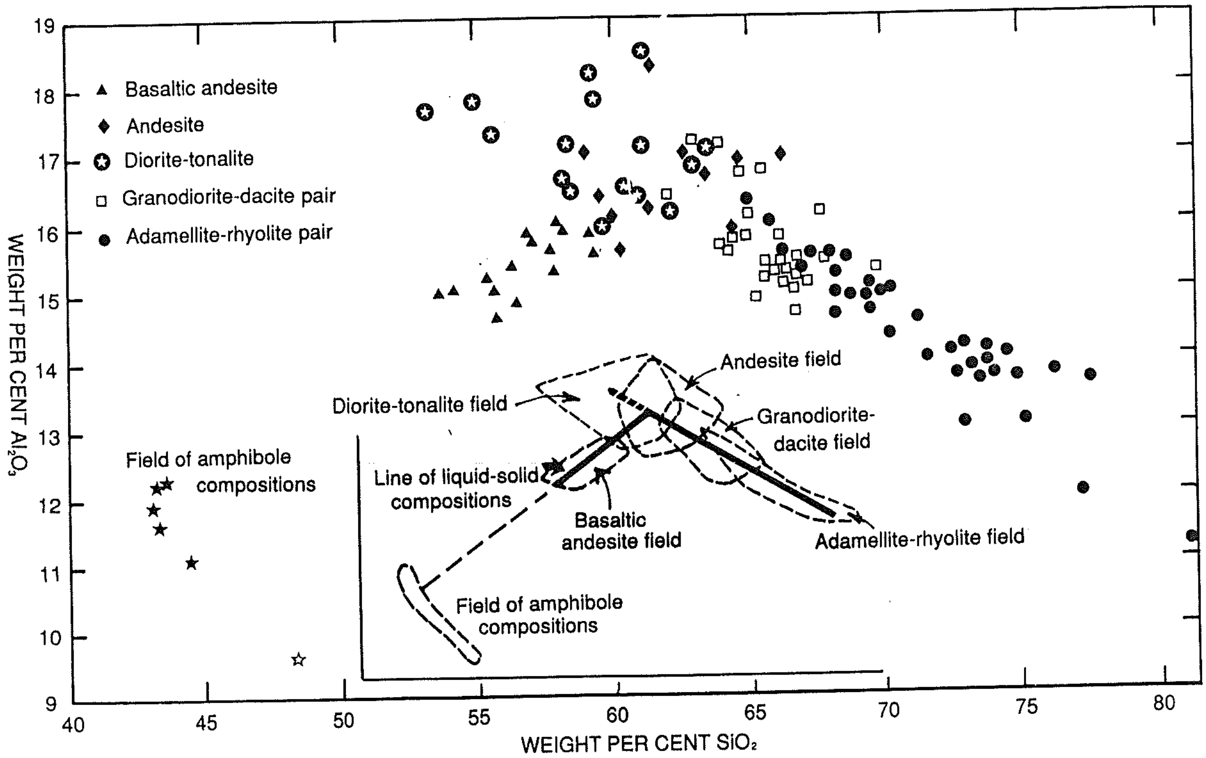

Figure 2: A plot of weight percent Al_2O_3 against SiO_2 for the volcanic rocks of the Orange River Group and the plutonic rocks of the Vioolsdrif Suite. The field of amphibole compositions analysed by Reid (1977) from pyroxenites is also shown. The line of liquid-solid compositions indicates the path of the evolving magma.

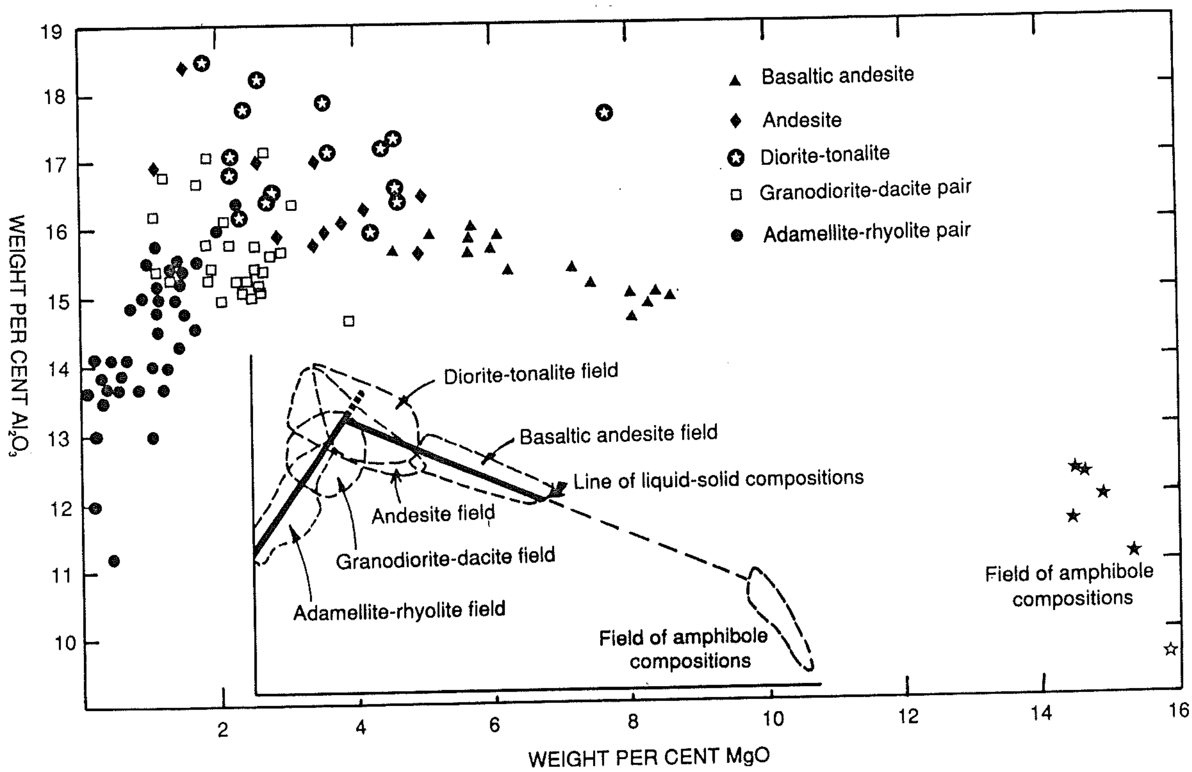

Figure 3: A plot of weight percent Al_2O_3 against MgO for the volcanic rocks of the Orange River Group and the plutonic rocks of the Vioolsdrif Suite. The field of amphibole compositions analysed by Reid (1977) from pyroxenites is also shown.

mineral assemblage than that represented by the diorite-tonalite rock types. The mineral phases which were fractionated include quartz, plagioclase, amphibole, biotite, and minor amounts of K-feldspar, and constitute the main mineralogy of the granodiorites (Table4, Column 2).

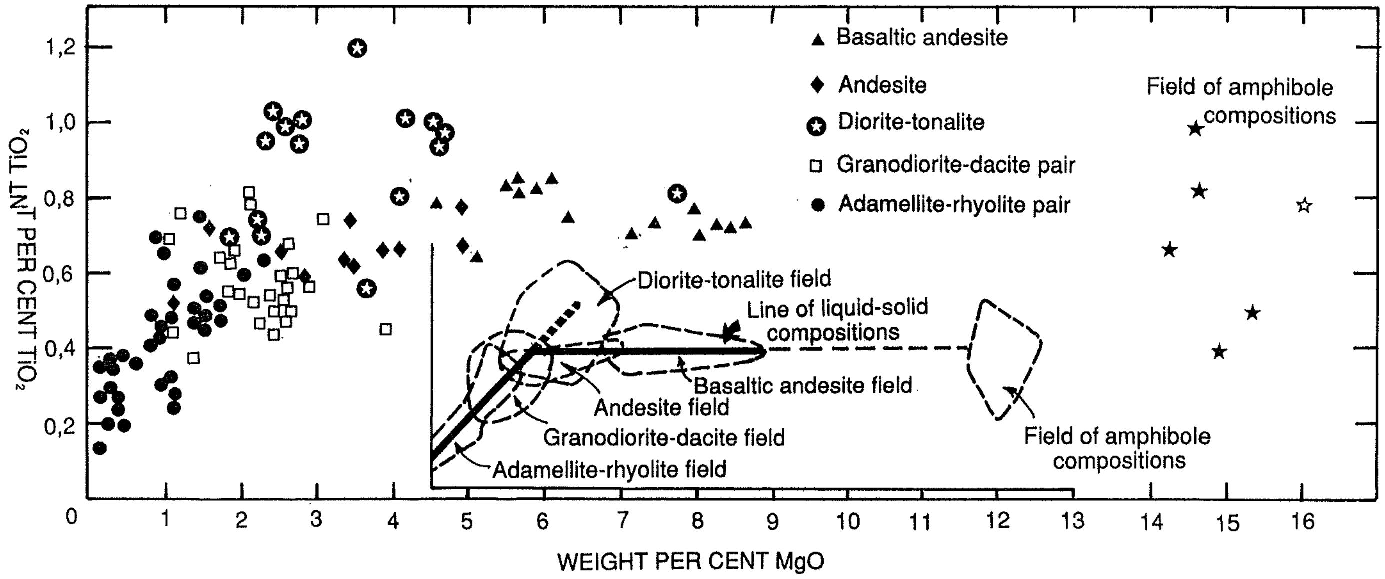

Figure 4: A plot of weight percent TiO_2 against MgO for the volcanic rocks of the Orange River Group and the plutonic rocks of the Vioolsdrif Suite. The field of amphibole compositions analysed by Reid (1977) from pyroxenites is also shown.

Geological field relationships to the southwest of the Haib copper prospect show gradational contacts between a granodiorite stock and an overlying feldspar porphyry (dacite) and provides evidence that the granodiorite stock represented a magma body which, prior to solidification, fed the overlying volcanic flows. The similarity in major-element chemistry between dacitic volcanics and granodiorite instrusives (Table 2, Columns 4 and 9) further substantiates the suggestion that the granodiorite represents plutonically crystallized dacitic magma. Geological field relationships which suggest genetic links between adamellites and rhyolitic volcanic rocks are not as clearly displayed as those between granodiorite and dacite. Thick units of rhyolite are developed to the north of the Haib copper prospect, and in the area of their thickest development the rhyolite units are intruded by adamellite plugs. The association is complemented by a marked similarity in the major-element compositions of rhyolitic volcanics and adamellites (Table 2, Columns 5 and 10). Residual liquids of rhyolitic composition are considered to have been derived by fractionation of granodiorite from dacitic parent liquids. The rhyolitic liquids, part of which were extruded on surface, then fractionated the minerals quartz, plagioclase, K-feldspar, biotite, and minor hornblende, which are now preserved as the adamellite phases of the Vioolsdrif Suite (Table 1, Column 4 and Table 4, Column 3). This similarity in major-element composition of different phases of plutonic and volcanic rocks suggest that both suites of rocks were derived from the same liquid, but that they cooled and solidified in different physical environments.

TRACE-ELEMENT CHEMISTRY

The close genetic relationship between the various phases of the volcanic and plutonic suites which is evident in the major element chemistry is complemented by the trace-element data for both suites. Trace-element modelling using Ba, Rb, and Sr was undertaken according to the principles applied to the granitic rocks of the Vioolsdrif Suite by Minnitt (1979, 1992). Trace-element solid/liquid partition coefficients for the various minerals which are fractionated from liquid melts, are listed in Table 3. These data together with the average mineralogy of diorite, granodiorite, and adamellite, listed in Table 4, were used to calculate bulk partition coefficients (D) for trace-elements in the various rock types from assumed initial trace-element concentrations (Co), as given in Table 5.

TABLE 3

CRYSTAL/LIQUID PARTITION COEFFICIENTS

Column	1	2	3	4	5
Mineral	Quartz	Plagioclase	K-feldspar	Biotite	Hornblende
Element					
Rb	0,0001	0,04	0,80	3,0	0,014
Sr	0,0001	3,35	3,60	0,4	0,002
Ba	0,0001	0,40	6,00	6,0	0,.044

Columns 1-4 : after McCarthy and Hasty (1976)
Column 5 : after Arth and Hanson (1975)

TABLE 4

MINERALOGY OF THE GRANITOID ASSEMBLAGES FRACTIONATED FROM THE ORANGE RIVER GROUP VOLCANICS

ROCK TYPE	DIORITE	GRANODIORITE	ADAMELLITE
MINERAL			
QUARTZ	15	18	25
PLAGIOCLASE	30	25	30
K-FELDSPAR	-	3	25
HORNBLENDE	25	11	3
BIOTITE	-	3	8
INTERCULUMUS LIQUID	30	40	9

TABLE 5

ASSUMED INITIAL TRACE-ELEMENT CONCENTRATIONS (Co)

BULK PARTITION COEFFICIENTS (D), AND PERCENTAGE CRYSTALLIZATION (f), FOR LIQUIDS OF THE ORANGE RIVER GROUP AND CUMULATES OF THE VIOOLSDRIF SUITE

CUMULATE-LIQUID PAIR	DIORITE ANDESITE	GRANODIORITE DACITE	ADAMELLITE RHYOLITE
Co(Rb)	110	140	178
Co(Ba)	900	1 103	1 182
Co(Sr)	600	538	488
D(Rb)	0,3155	0,52554	0,54242
D(Ba)	0,4310	0,86484	2,19132
D(Sr)	1,3055	1,35772	2,02706
f	0,30	0,40	0,70

Variations in trace-element compositions for the models were calculated using the equations of Neumann et al., (1954). Trace-element models for Ba versus Rb and Sr versus Rb in the cumulate-liquid pairs namely, the Vioolsdrif Suite and Orange River Group, are shown in Figures 4 and 5, respectively.

In the models diorite-andesite and granodiorite-dacite paired assemblages consist of liquid melt plus varying proportions of cumulus amphibole and plagioclase. The adamellite-rhyolite pair includes K-feldspar and biotite as important cumulus phases. Amphibole-plagioclase fractionation is represented on the line of liquid compositions between points A and C (Figures 5 and 6). At point C, K-feldspar becomes a liquidus phase, whilst biotite replaces amphibole as the major mafic mineral to crystallize from the melt. The slope of the line of liquid compositions changes from positive to negative at point C in the Ba versus Rb rubidium plot (Figure 5) and becomes steeper at point C in the Sr versus Rb plot (Figure 6).

Binary diagrams comparing Ba, Sr, and Rb trace-element compositions of the cumulate-liquid pairs diorite-andesite, granodiorite-dacite and adamellite-rhyolite are shown in Figures 7 and 8. Because of the lack of trace-element data for the complementary amphibolies, no attempt was made to model the basaltic andesite-amphibolite system. Basaltic andesite compositions are plotted on Figures 6 and 7, and help to emphasize the progressive changes in trace-element composition of the volcanic assemblage, with progressive differentiation. Comparison of the model curves of predicted behaviour of trace-

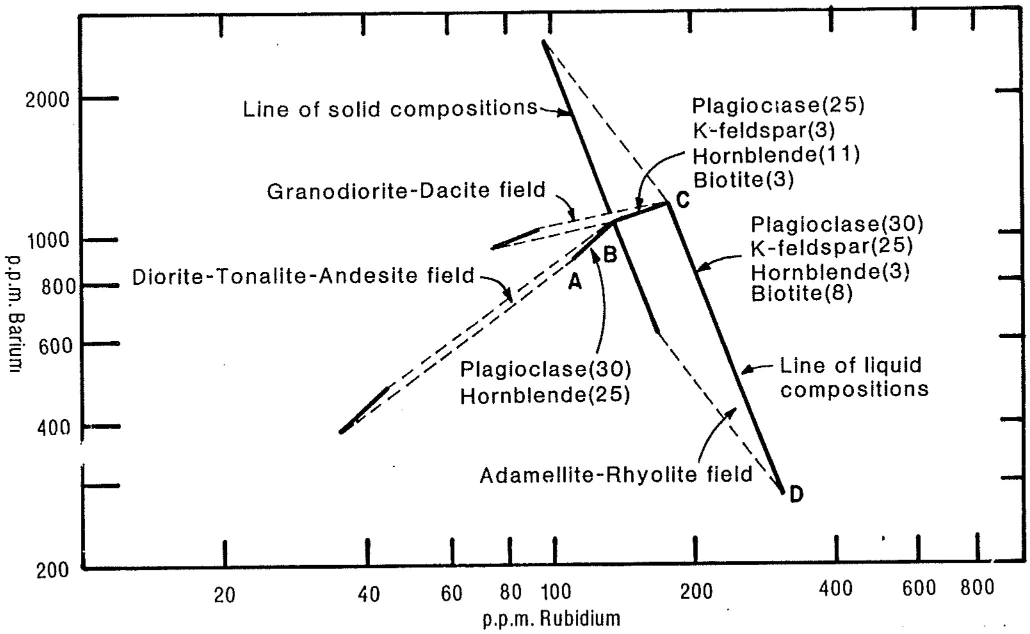

Figure 5: A plot of Ba versus Rb, showing models of the three main fields defined by the intermediate calc-alkaline rock types of the Orange River Group volcanics and the Vioolsdrif Suite plutonic rocks. The assemblages shown on the line of liquid compositions represent the phases fractionated from the liquid. Figures in parenthesis refer to the volume percentage of the fractionated cumulate mineral phases (Table 4).

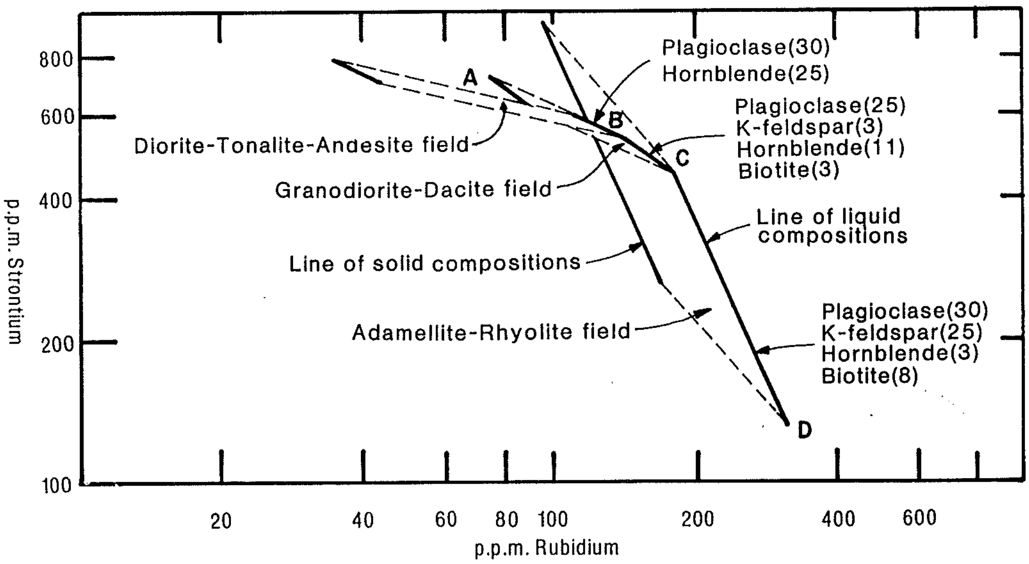

Figure 6: A plot of Sr versus Rb, showing models of the three main fields defined by intermediate calc-alkaline rock types of the Orange River Group volcanics and the Vioolsdrif Suite plutonics. The assemblages shown on the line of liquid compositions represent the phases fractionated from the liquid. Figures in parenthesis refer to the volume percentage of the fractionated cumulate mineral phases (Table 4).

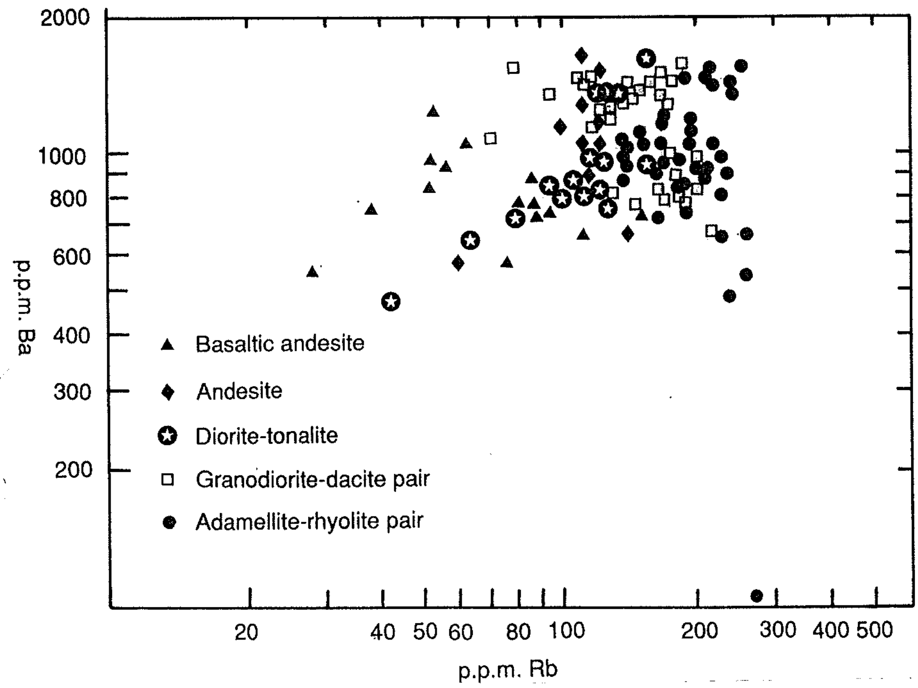

Figure 7: A plot of Ba versus Rb for basaltic andesite and cumulate-liquid pairs diorite-andesite, granodiorite-dacite, and adamellite-rhyolite, showing the positive trends produced by amphibole-plagioclase fractionation in the early end members and the negative trends produced by K-feldspar-biotite fractionation in the later end members.

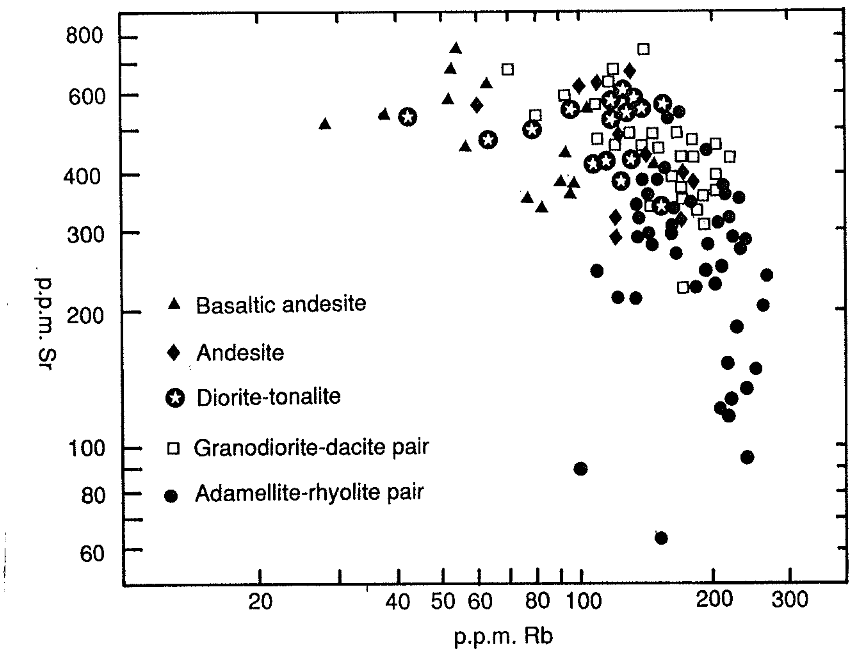

Figure 8: A plot of Sr versus Rb for basaltic andesites and the cumulate-liquid pairs diorite-andesite, granodiorite-dacite, and adamellite-rhyolite, showing the moderately negative trend in the early end members and the steeper negative trend in the later end members.

elements in cumulate-liquid pairs (Figures 4 and 5), with the real data from the Vioolsdrif Suite and Orange River Group (Figures 6 and 7) suggests a strong correlation between the model and real cooling history of these rock assemblages.

The successive steps in the trace-element behaviour as demonstrated above cannot be explained by continuous fractionation of orthopyroxene-clinopyroxene-plagioclase-magnetite fractionation as suggested by Reid (1979).

Fractionation of amphibole-plagioclase assemblages from andestitic liquids produced diorite cumulates and residual liquids of dacitic composition which were extruded on to surface. As mentioned earlier, the strong similarity between major- and trace-element chemistry of the dacitic and granodiorite rocks indicates that the dacitic liquids were extruded before excessive fractionation of granodiorite had occurred. Cumulates of granodiorite composition were produced by amphibole-plagioclase fractionation together with minor amounts of biotite and K-feldspar. During amphibole-plagioclase fractionation, the Ba-Rb curves are positive in both the model and real data (Figures 5 and 7), but the Sr-Rb curves are negative (Figures 6 and 7).

Fractionation of adamellites occurs when K-feldspar and biotite appear as major liquidus phases (Table 4, Column 3). Barium is progressively enriched in the volcanic and plutonic suites during amphibole-plagioclase fractionation, but K-feldspar-biotite fractionation causes major depletion in Ba content of the rocks (Figures 6 and 8). Rhyolitic volcanics are considered to be complementary liquids to the plutonic adamellite solids which crystallized at depth. The anticipated depletion of Ba in the rhyolites, as a result of K-feldspar and biotite fractionation, should be greater than geochemical analyses of these rocks indicate (Figure 7). This is partly related to the highly porphyritic character of the rhyolites. Barium-enriched K-feldspar pheonocrysts have not separated from the rhyolitic liquid because of the high viscosity of these magmas. Leucogranties are considered to be a late-stage crystallizate which contains very little or no mafic phases. Complementary volcanic extrusives to the leucogranites have not been positively identified on a geochemical basis, but the marked mineralogical similarity between leucogranites and acid volcanic tuffaceous rocks suggests that these rock-types may be genetically linked.

CONCLUSIONS

A model for the genetic link between the volcanic and plutonic suites of the Richtersveld Province as outlined above is schematically shown in Figure 9. Early amphibole cumulates settled to the base of the magma chamber and samples of magma were extruded on to surface to cool as flows of basaltic andesite composition and later, as amphibole fractionation proceeded, as flows of andesitic composition. The amphibole-cumulate-enriched liquids at the base of the magma chamber were later tectonically emplaced as amphibolite and hornblende dykes and pods. Successive fractionation of the diorite, granodiorite, and adamellite cumulates and extrusion of the related liquids dacite and rhyolite, gave rise to the Vioolsdrif Suite at depth and the Orange River Group on surface. Although only one system of fractionation and extrusion is shown in Figure 9, the Richtersveld Province, as a whole, might originally have consisted of many such systems.

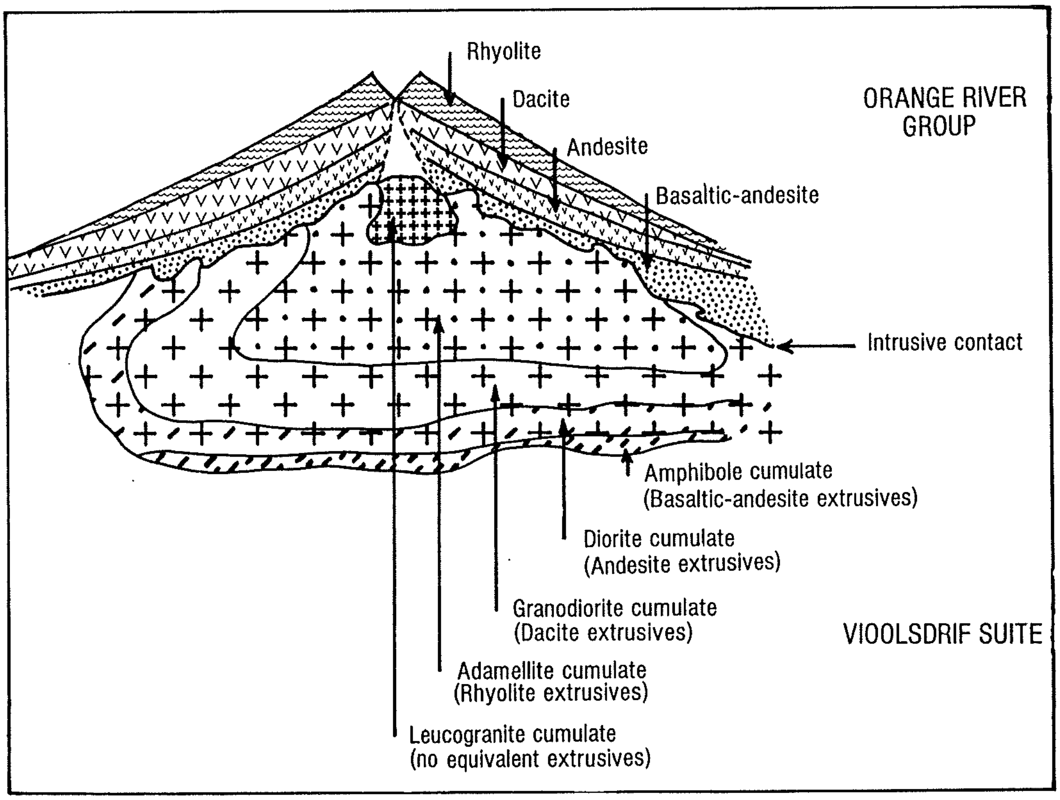

Figure 9: A schematic representation of the genetic relationship between the Orange River Group volcanics and the Vioolsdrif Suite plutonics. The Orange River Group represents the volcanic ejecta from a differentiating pluton at depth which intrudes its own cover-rocks.

In general terms, the batholith of granitoid rocks known as the Vioolsdrif Suite intruded the cover of its own volcanic ejecta, the latter comprising the Orange River Group. This model for the Richtersveld Province volcanic and plutonic rocks has been adapted from the work on the nature of batholiths by Hamilton and Meyers (1967). A survey of the features of batholiths in the United States carried out by these investigators indicated that batholiths are generally thin, having spread out laterally at shallow depth, and that many of them reach the surface and crystallize beneath a cover of their own volcanic ejecta which are contemporaneous and consanguineous with plutonic rocks. They also inferred that the magma originated in the lower crust or upper mantle. This concept is contrary to the idea that batholiths are thick masses which form beneath a deep cover of metamorphic rocks, and crystallize from melts mobilized at the levels exposed in gneissic and migmatitic terranes.

A significant strength of the model is that samples of liquid from a differentiated magma, now presented as the Orange River Group, as well as cumulus phases derived by fractionation of mineral phases from that magma, can be identified in the field. Furthermore, the close geochemical similarity between the cumulus phases in the Vioolsdrif Suite and the corresponding liquid phases of the Orange River Group can be reconciled by such a model.

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