ECONOMIC GEOLOGY RESEARCH UNIT

University of the Witwatersrand
Johannesburg

TRACE-ELEMENT MODELS FOR THE EVOLUTION OF THE VIOOLSDRIF SUITE, RICHTERSVELD PROVINCE, SOUTHERN NAMIBIA

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INFORMATION CIRCULAR No. 246

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by

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January, 1992

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

ISBN 1 874856 68 0

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ABSTRACT

Basement rocks of the Richtersveld Province in the vicinity of the Haib copper prospect in southern Namibia are comprised primarily of volcanic sequences of the Orange River Group and granitoids of the Vioolsdrif Suite. Six intrusive phases including basic-ultrabasic intrusives, diorite, tonalite, granodiorite, adamellite and leucogranite, constitute the Vioolsdrif Suite. These phases are petrologically related, the oldest being mafic in composition, with subsequent phases becoming progressively leucocratic with decreasing age. The copper-molybdenum bearing quartz-feldspar porphyry is mineralogically and geochemically intermediate in composition between the granodiorite and adamellite.

The mineralogical evolution of the Vioolsdrif Suite in the Haib area includes the disappearance of hornblende which is replaced by biotite in the acid, leucocratic end-members. The change in morphology of K-feldspar from an interstitial phase in diorite, tonalite and granodiorite, to an anhedral cumulus phase in adamellite and leucogranite, has a direct influence on the trace element composition of the rocks. Destruction of Ba, Rb and Sr trace elements among the different phases of the Vioolsdrif Suite have been examined and provide a means of tracking the crystallization history of the suite. The appearance of K-feldspar on the liquidus of the cooling magma had a pronounced effect on the trace element composition of the solids which were subsequently formed. The older more mafic phases namely, diorite, tonalite and granodiorite evolved by fractional crystallization of quartz, plagioclase and amphibole whereas the younger phases evolved by fractionation of quartz, plagioclase, K-feldspar, biotite and minor amounts of amphibole.

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TRACE-ELEMENT MODELS FOR THE EVOLUTION OF THE VIOOLSDRIF SUITE, RICHTERSVELD PROVINCE, SOUTHERN NAMIBIA

INTRODUCTION

The Richtersveld Province refers to a geological region of Precambrian basement rocks developed in the northwestern Cape Province and southern Namibia, which are exposed in two areas along the lower portions of the Orange River. Centred around the confluence of the Haib and Orange rivers is an east - west trending, ovid exposure of basement rocks, some 65km by 40km, extending from Goodhouse in the east to Noordoewer in the west. A second exposure of Richtersveld basement occurs in a north - south trending zone about 150km long and 25km wide, along the eastern flank of the Orange River. The two areas are separated by a cover of Nama Group sediments which form the north - south trending Neint - Nababeep Plateau (Figure 1). In the west the Richtersveld Province is overlain by a late Precambrian geosynclinal accumulation of sedimentary and volcanic rocks referred to as the Gariep Group, and it abuts against the Namaqua Province with a tectonic contact along its southern and northwestern boundaries.

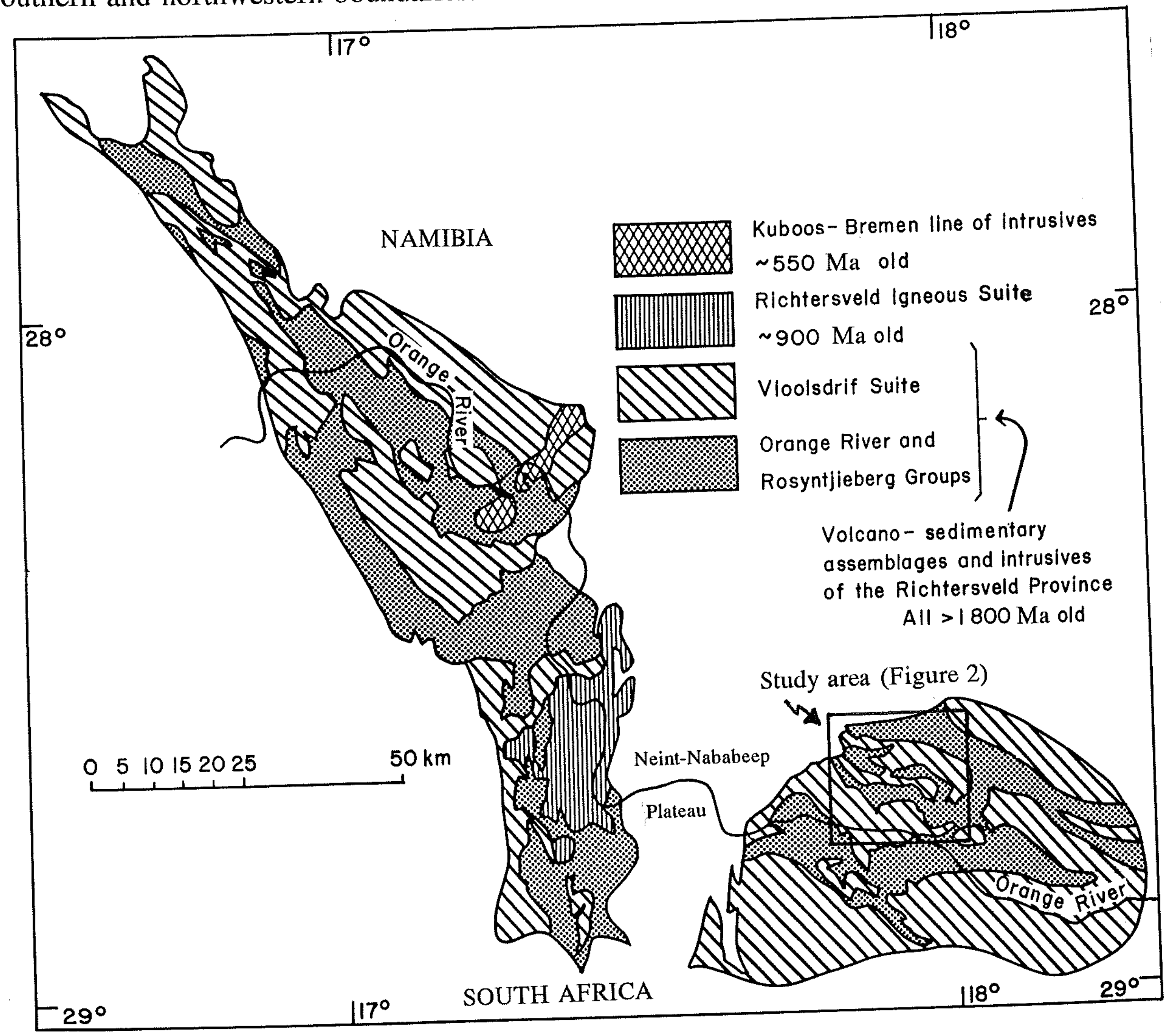


Figure 1: *A schematic representation of the four main geological components of the Richtersveld Province. The Richtersveld Igneous Suite and the Kuboos-Bremen intrusive events were superimposed on the older volcano-plutonic assemblage constituting the basement geology of the Richtersveld Province.*

Intrusive and extrusive episodes which generated the rock assemblages comprising the Richtersveld Province can be divided into four tectono-thermal events spanning approximately 1500 Ma of geological time. The oldest of these assemblages is a succession of volcano-sedimentary rocks referred to as the Orange River Group which includes basaltic andesites, andesites, dacites and a variety of rhyolitic and acid tuffaceous rocks. Radiometric dating of the volcanics in the Haib area using the Rb - Sr method, has yielded ages of between 1970 ±70 Ma and 2020 ±70 Ma (Reid, 1977).

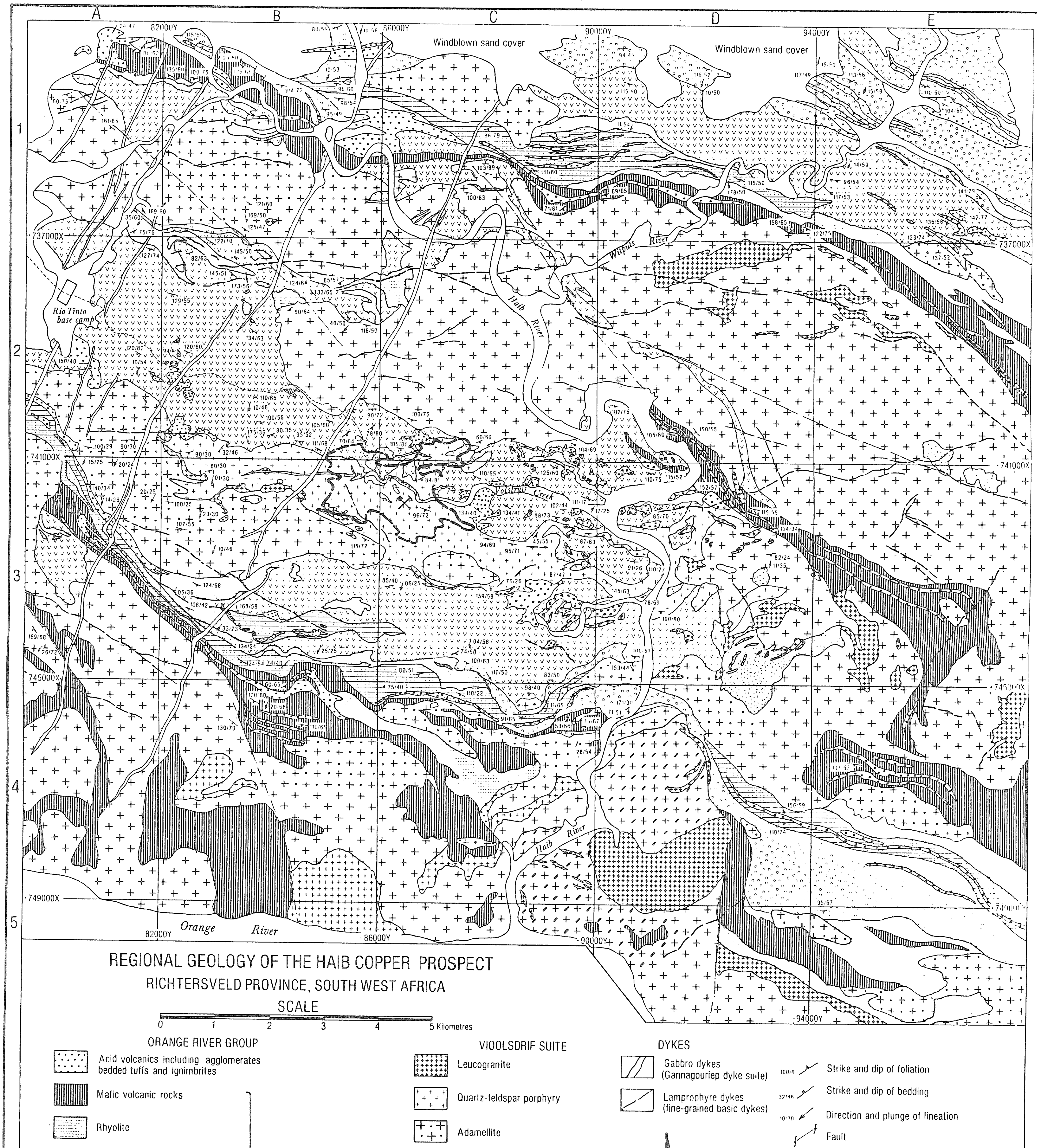
The volcano-sedimentary sequences are intruded by a complex granitoid suite which includes basic-ultrabasic complexes, diorite, tonalite, granodiorite, adamellite, leucogranite and minor amounts of mineralized porphyritic intrusives, and is termed the Vioolsdrif Suite. Whole rock Rb-Sr and Pb/Pb isotopic data indicate that the Vioolsdrif Suite was emplaced over a period of about 170 Ma during two phases of intrusive activity (Reid, 1979, 1982). Basic complexes were emplaced at 1971 ± 96 Ma, with diorite, tonalite and granodiorite being intruded at 1900 ± 3 Ma. The more acid rock types, adamellite and leucogranite,were emplaced at 1730 ± 20 Ma. A widely quoted age for the intrusion of the Vioolsdrif Suite is 1850 ± 50 Ma which was established by De Villiers and Burger (1967), using the U-Pb method.

The Richtersveld Province remained unaffected until approximately 900 Ma later when intrusion of the alkalic granites and syenites of the Richtersveld Igneous Suite heralded the onset of sedimentation in the adjacent Gariep basin at 920 ± 15 Ma. This was followed about 400 Ma later by the emplacement of the alkalic granites and carbonatites of the Kuboos-Bremen line of intrusives at about 550 ± 20 Ma ago (De Villiers and Burger, 1967), during the waning phases of the Gariepian orogeny.

The granitic rocks of the Vioolsdrif Suite, and particularly those developed in the vicinity of the Haib copper prospect, are the focus of attention in this paper. Detailed geological mapping at a scale of 1:10000 in the area surrounding the Haib copper prospect, was undertaken during the period 1975 to 1977, and is presented in Figure 2.

VIOOLSDRIF SUITE

A variety of names have been used to describe the granitic rocks of the Richtersveld Province. Rogers (1915) and Mathias (1940) used the terms "ancient gneiss" and "old granite" respectively, to describe the granites of the province. Gevers *et al.* (1937) considered all the rocks of the area to be part of the "old granite gneiss" and were the first investigators to attempt a subdivision of the granitic rocks, but their subdivision proved to be too unwieldy to be of much use. Coetzee (1941) in his description of the rocks in the Pella - Goodhouse area referred to the basement as granodiorite, whereas De Villiers and Söhnge (1959) referred to all the basement granite in the Richtersveld Province as "grey gneissic granite". McMillan (1968) proposed the term "Vioolsdrif Granite" for the extensively developed granodiorite in the Witputs - Sendelingsdrif area. Von Backström and De Villiers (1972) described the granite along the Orange River between Onseepkans and the Richtersveld as "grey gneissic granite". Blignault (1974) was the first to systematically map the different granite types comprising the Vioolsdrif Suite.



REGIONAL GEOLOGY OF THE HAIB COPPER PROSPECT
RICHTERSVELD PROVINCE, SOUTH WEST AFRICA

Figure 2

Six major rock types were identified including basic-ultrabasic intrusives, diorite, granodiorite, adamellite, leucogranite and tonalite, the latter being identified by Reid (1977) as an intermediate phase between diorite and granodiorite. Variations in the mineralogical composition of the phases of the Vioolsdrif Suite are summarized in the quartz-alkalis-plagioclase ternary diagram shown in Figure 3. The copper-molybdenum bearing quartz-feldspar porphyry is a locally developed phase of the adamellite. The igneous stratigraphy is also well established with the basic- ultrabasic intrusives being the oldest phase and the leucogranite being the youngest phase.

The Vioolsdrif Suite is comprised of composite calc-alkaline plutonic intrusives of batholithic proportions. A full range of the components of the Vioolsdrif Suite, from basic, hornblende-rich, low-silica intrusives, to acid, K-feldspar-rich high-silica intrusives is represented in the vicinity of the Haib copper prospect (Figure 2). Typically, the compositionally intermediate phases, namely granodiorite and adamellite, are more abundant than either the mafic or acid end-members of the suite. A summary of the main features of the Vioolsdrif Suite including ages, mineralogy, texture, volcanic intrusions and structural imprint is summarized in Table 1.

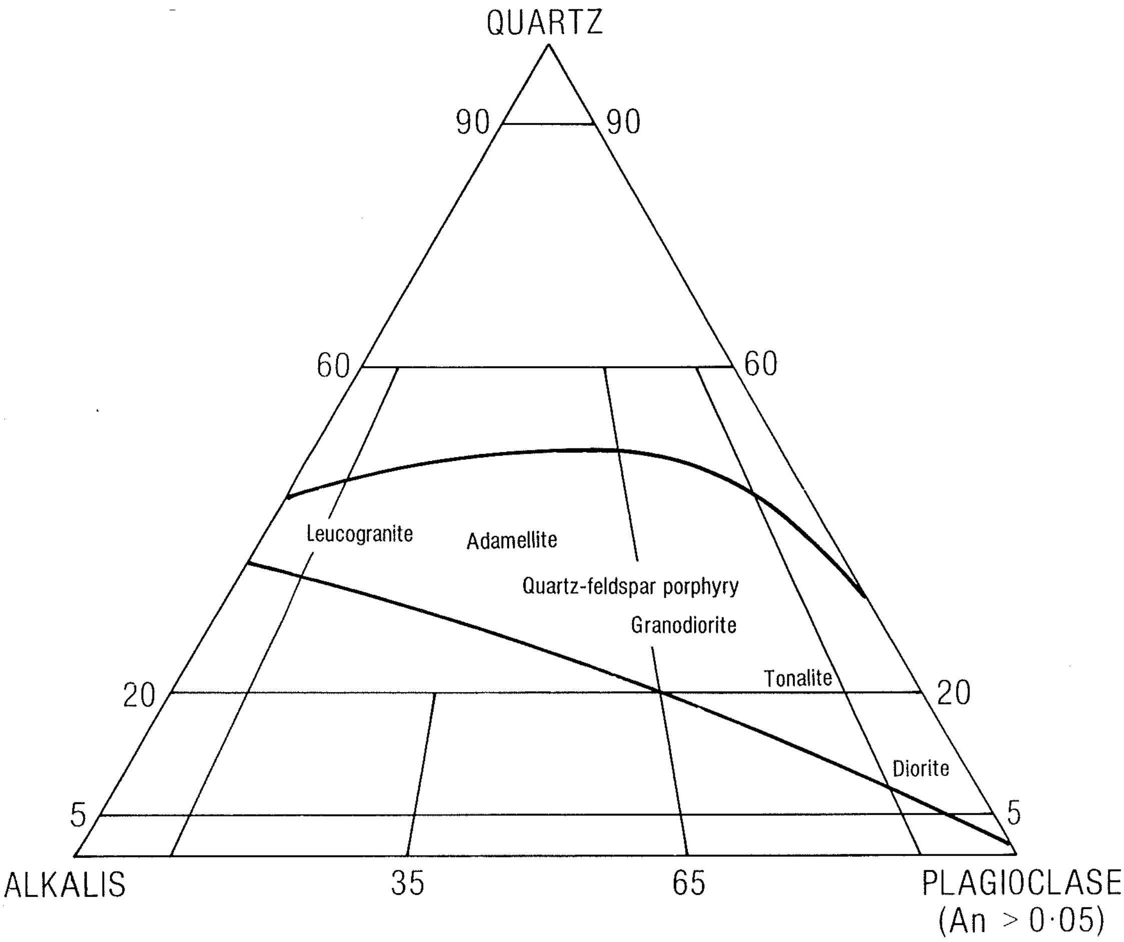


Figure 3: The solid lines enclose the bulk of the Vioolsdrif Suite, represented here in terms of quartz-alkalis-plagioclase, and showing the continuity of mineralogical compositions from diorite to leucogranite.

TABLE 1

THE RADIOMETRIC AGE-DATES AND THE MINERALOGICAL AND TEXTURAL PROPERTIES OF THE VIOOLSDRIF SUITE

ROCK TYPE	BASIC-ULTRABASIC INTRUSIVES	DIORITE	TONALITE	GRANODIOTITE	ADAMELLITE	QUARTZ-FELDSPAR	L1-LEUCOGRANITE	L2-LEUCOGRANITE
RADIOMETRIC AGE (Ma)	1900 ± 130	1975 ± 55	1965 ± 80	1925 ± 45	1800 ± 40	1800 - 1900	1730 - 1835	
MINERALOGY	Olivine Clinopyroxene Amphibole Plagioclase	Quartz Amphibole Minor orthopyroxene Biotite Plagioclase Epidote	Quartz Amphibole Biotite Plagioclase Epidote	Quartz (28) Amphibole Biotite (12) Plagioclase (47) K-feldspar (13) Epidote Sericite	Quartz (35) Biotite (7) Plagioclase (37) K-feldspar (21) Epidote Sericite	Quartz Biotite Plagioclase K-feldspar Epidote Sericite	Quartz (33) Biotite (5) Plagioclase (38) K-feldspar (24) Epidote Sericite	Quartz (39) Plagioclase (14) K-feldspar (47) Minor
TEXTURE	Coarse-to-medium-grained, equigranular	Medium-grained, equigranular	Medium-grained, equigranular	Medium-grained, equigranular	Generally porphyritic, maybe medium-grained, equigranular	Medium-grained, porphrytic	Medium-grained, equigranular, maybe porphyritic	Fine-to-medium-grained, equigranular
PHENOCRYSTS	-	-	-	-	K-feldspar	Quartz Plagioclase Biotite	K-feldspar	-
VOLCANIC INCLUSIONS	None	Abundant	Abundant	Moderate	Minor	None	None	None
FOLIATION	Locally strong	Strong	Strong	Locally strong to moderate	Locally strong	Locally moderate	None	None

Basic - ultrabasic intrusives

The basic and ultrabasic intrusives are the oldest phases of the Vioolsdrif Suite. Observations that the granodiorite and adamellite gneisses intrude the basic rocks are used to interpret the latter as scattered remnants of an extensive basic - ultrabasic basement which has been virtually obliterated by the intrusion of the Vioolsdrif granitoids. In the vicinity of Rooiberg (Figure 1), basic and ultrabasic rocks intrude the older volcanic extrusives of the Orange River Group (Middlemost, 1965; De Villiers and Söhnge, 1959). Contact relationships between the gabbro body and the surrounding granodiorite in the vicinity of the Haib copper prospect (Figure 2) may be intrusive or diffuse and locally gradational where the gabbro is partially assimilated by the granodiorite. Within the mushroom-shaped gabbro body are a number of concentrically arranged intrusive leucogranite veins. These data indicate that the basic - ultrabasic rocks were intruded after the extrusion of the Orange River Group, but prior to the emplacement of the Vioolsdrif batholiths.

The compositional range of basic and ultrabasic intrusives is wide and includes metagabbros, troctolites, serpentinites, peridotites, pyroxenites and hornblendites. Hornblendites examined by Middlemost (1965) consist mainly of hornblende and chlorite with minor amounts of epidote, plagioclase and sericite. Quartz, biotite, zoisite, calcite, apatite, clinopyroxene, serpentinite and opaque minerals are accessory components. Gabbroic rocks consist mainly of amphibole - chlorite - epidote pseudomorphs after clinopyroxene, together with plagioclase and opaque minerals.

In a study of the distribution of the basic intrusives in the Richtersveld and Namaqua provinces (with respect to the most prominent lineaments in the region) Minnitt (1979) demonstrated that there is a tendency for these complexes to occur somewhat more abundantly along northwest-trending lineaments and for a somewhat higher density of basic intrusives to occur where different sets of lineaments intersect.

Diorite

Diorites are the second oldest intrusive member of the Vioolsdrif Suite and are equigranular, medium- to coarse-grained, mesocratic rocks with a strong foliation fabric. Gevers *et al.* (1937) reported two phases of diorite as did Blignault (1977) who identified small, locally developed bodies of coarse-grained meladiorite and a more extensively developed medium-grained and less basic diorite. Two intrusive diorite bodies, each about 2km in diameter are exposed along the banks near the mouth of the Haib River (Figure 2; 4D). These bodies are penetratively foliated, and locally contain K-feldspar phenocrysts where adamellite has invaded the diorite. Diorites consist mainly of hornblende and plagioclase in approximately equal proportions, with stubby hornblende laths partially altered to biotite and chlorite. Quartz and alkali feldspar are also present in minor amounts.

Large, strongly foliated and partly assimilated rafts of mafic volcanics are incorporated in diorite, together with inclusions of gabbro and hornblendite. The pervasive nature of the foliation fabric suggests that the diorites were subject to an early structural imprint, not represented in the younger members of the Vioolsdrif Suite.

Tonalite

Tonalites are exposed along the northern bank of the Orange River, about 2km downstream of the Haib - Orange River confluence. The tonalites contain numerous rounded inclusions of mafic lava which have been assimilated to varying degrees by the tonalite. Contacts between tonalite and granodiorite are sharp.

The tonalite is a medium-grained, equigranular rock consisting predominantly of quartz, biotite, and subhedral to euhedral plagioclase, now altered to epidote and sericite. Biotite occurs as aggregates together with sphene and/or rutile and epidote. K-feldspar is also present in minor amounts. Tonalite is mineralogically intermediate between diorite and granodiorite.

Granodiorite

The granitic rocks surrounding the Haib copper prospect consist predominantly of granodiorite which forms large plutons separated from one another by arcuate belts of volcanic rock (Figure 2). The granodiorite is a mesocratic, medium-to coarse-grained rock consisting of quartz, plagioclase, K-feldspar and mafic minerals including hornblende and biotite. Biotite and epidote occur as aggregates, the products of hornblende alteration. Plagioclase phenocrysts are almost invariably sericitized and saussuritized to some degree. Minor amounts of sphene, rutile, leucoxene, zircon, and opaque minerals are also present. The average mode for granodiorite is presented in Table 1. The quantity of mafic minerals in the granodiorite also affects the colour and texture of the rock. The coarser-grained, more granular types have less mafic minerals, whereas the mafic-rich varieties tend to be more strongly foliated. Rounded and flattened xenoliths of mafic rock are ubiquitously developed in the granodiorite, but at lower density than in the tonalites or diorites. The presence of angular volcanic xenoliths along some contacts suggests that stoping may have been operative during intrusion. Locally developed foliated and concordant contacts between the volcanics and granodiorites suggest forceful emplacement of the granites which shouldered the volcanics aside.

Adamellite

In many exposures the adamellite appears to be a porphyritic phase of the granodiorite with phenocrysts of pink K-feldspar and a foliation fabric being the most conspicuous features of the granitoid. Microcline-microperthite phenocysts poikilitically enclose inclusions of the plagioclase, quartz, and biotite, indicating that the latter minerals had crystallized prior to K-feldspar. Minerals comprising the groundmass include quartz, plagioclase, K-feldspar, biotite, and chlorite. Sphene, rutile, apatite, magnetite, and zircon are accessory components. Alteration of plagioclase to sericite and epidote is common, as is biotite alteration to chlorite. Secondary K-feldspar growth on phenocrysts during deformation has resulted in the foliation fabric being deformed around them.

Porphyritic adamellites contain K-feldspar phenocrysts up to 15mm long in a foliated groundmass. The difficulty of distinguishing granodiorite from non-porphyritic adamellite without the aid of a thin-section was noted by Ritter (1975), who found that large tracts of adamellite in the central Richtersveld had previously been mapped as granodiorite by De Villiers and Söhnge (1959). The main difference between granodiorite and non-porphyritic adamellite is that the adamellites contain approximately equal proportions of oligoclase and alkali feldspar, whereas granodiorite contains more oligoclase and less alkali feldspar. The average mode for adamellite can be compared with that for granodiorite in Table 1.

The main difference between granodiorite and adamellite is in the proportion of plagioclase and potassium feldspar. Granodiorite contains nearly twice as much plagioclase as alkali feldspar, but in adamellite the ratio is approximately 3:2. In general, the change from granodiorite to adamellite occurs when plagioclase is less than 40 per cent in the modal analysis.

Indications that plagioclase crystallized prior to alkali feldspar in granodiorites is provided by the occurrence of plagioclase phenocrysts surrounded by interstitial alkali feldspar. The occurrence of plagioclase phenocrysts together with discreet, rounded or ovoid, microcline, perthite, or orthoclase grains in adamellite, indicates that plagioclase and K-feldspar crystallized together.

Leucogranite

The youngest phase of the Vioolsdrif Suite are the leucogranites, which different investigators have described under various names. Leucogranites found in the pegmatite area south of the Orange River were considered by the Gevers *et al.* (1937), to be acid differentiates from the Namaqualand granite massif. De Villiers and Söhnge (1959) referred to the light-grey granite in the area south of Rooiberg, but did not recognize leucogranite as a separate phase. Middlemost (1964) recognised a leucocratic granite variety associated with the adamellite gneiss. Both McMillan (1968) and Von Backström and De Villiers (1972) used the term aplite to describe leucogranite veins which they noted in the Lorelei and Onseepkans areas, respectively. Beukes (1973) used the term "younger leucocratic Vioolsdrif granite", to describe the final leucogranite phase of the Vioolsdrif Suite, and Ward (1974) used the term "aplogranitic".

The leucocratic mineralogy, the cross-cutting relationships with other phases of the Vioolsdrif Suite, and the absence of a foliation fabric are the distinctive features of the leucogranites. This suggests that the foliation event is older that 1730 Ma, which is the age Reid (1977) determined for the emplacement of leucogranite using the Th-Pb technique.

Two varieties of leucogranite have been distinguished in the field. Firstly, a distinctly reddish coloured, medium-to coarse- grained variety, referred to as L1-type leucogranites which occur as large sheet- or stock-like bodies. An L1-type leucogranite stock, approximately 3 km long and 600m wide is intruded into the granodiorite to the northeast of the Haib prospect (Figure 2;2D). This lenticular body has the form of a sill, approximately 50m thick which dips into the granodiorite at 20-30° to the north. Several smaller, flat, sheet-like intrusives are also emplaced into the granodiorite in this area (Figure 2; 2D). A number of large L1-leucogranite bodies are also present on the east side of the Haib River (Figure 2; 3D, 4D, 5D and 5E).

The coarse-grained L1-leucogranites consist of quartz, coarsely perthitic K-feldspar and microcline perthites and smaller subhedral to euhedral grains of altered plagioclase. Epidote, sericite, clay minerals and quartz constitute the interstitial filling between the large alkali feldspars.

Secondly, pale-pink, fine-to medium-grained, L2-type leucogranites which occur as sinuous veins or elongate bodies. Four elongate bodies of L2-leucogranite occur along the contact between the Haib porphyry stock and the adamellites. In the granidiorite stock northeast of the Haib prospect (Figure 2, 2D and 2E), thin leucogranite veins are located along shear zones. The distribution and shape of the elongate leucogranite intrusives appears to be controlled by fractures and shears in the granodiorite host along which these bodies were emplaced. L2-leucogranites consist of equigranular aggregates of quartz, plagioclase and K-feldspar with minor chlorite or biotite.

L2-leucogranites contain approximately twice as much alkali feldspar as they do plagioclase, and twice as much alkali feldspar as the L1-leucogranites. L1-leucogranites are richer in plagioclase than alkali feldspar, but both varieties contain about 40 per cent quartz.

TRACE ELEMENT MODELS

Theoretical considerations

In the succession from diorite to leucogranite it is possible to detect a marked change in mineralogy and morphology of the minerals constituting the spectrum of granitoids in the Vioolsdrif Suite. Textural, mineralogical and compositional gradations between members of the suite have been the subject of comment from as early as 1937, when Gevers and his co-workers noticed that the diorites are locally gradational into granodiorite. Inclusions of ultramafic rocks in gabbros become progressively less abundant in meladiorite and diorite, in addition to which there is a gradation in mineralogy and texture from gabbros, through meladiorite and diorite, to tonalite. Reid (1977) considered tonalite to be an intermediate phase between diorite and granodiorite. There is also a gradation between granodiorite and adamellite. In the larger granodiorite stocks to the east and north of the Haib prospect, granodiorite around the margins of the intrusive gives way to non-porphyritic adamellite near the centre of the stock. No field evidence for intrusive contacts between granodiorite and adamellite were noticed around the Haib prospect, but in two areas gradational contacts have been found. Compositional variations in the phases of the Vioolsdrif Suite as determined by Blignault (1974, 1977), Reid (1977) and Minnitt (1979), are summarized in the quartz-alkalis-plagioclase ternary diagram of Figure 3.

The relationships between the mineralogy and trace-element geochemistry of Archaean granites have been investigated by McCarthy and Robb (1977), and the theory and techniques which are briefly outlined below, have been applied to the Vioolsdrif Suite. The relationship between mineralogy and trace-element geochemistry forms the basis for the genetic history of the Vioolsdrif granitoids, and is consistent with the mineralogical gradation, major element geochemistry, age relationships and the relative volumes (surface areas) of granitoids comprising the suite.

Theoretical models describing the behaviour of trace-elements during magmatic processes have been derived by Neumann *et al.* (1954), Greenland (1970) and Shaw (1970). The equations derived by Neumann *et al.* (1954), based on the Rayleigh law have also been used in this study. Evidence to suggest that fractional crystallization in viscous granitic melts occurs by progressive, inward nucleation of crystals from the margins of the magma chamber has been put forward by Wolhuter (1973) and McCarthy and Robb (1977). According to Henry's law the ratio of the concentrations of trace-elements in the crystallizing solid phase and the melt is a constant which is independent of concentration as long as the solution is dilute. This ratio is referred to as the partition coefficient and for any mineral it may vary depending on the temperature, pressure, crystallographic site and magma composition from which the solid phase is crystallizing (McIntire, 1963; Banno and Matsui, 1973; Reid, 1977). A knowledge of the partition coefficients of the main mineral phases and trace-elements being considered is therefore essential for any quantitative evaluation of trace-element behaviour. Because the variation in partition coefficients is a complex function of pressure, temperature, and other physical factors, and because these physical factors cannot be quantitatively evaluated, constant partition coefficients have been applied throughout this study. The partition coefficients which have been used are listed in Table 2.

Partition coefficients which are greater than unity indicate that the trace-element is preferentially partitioned into the crystallizing solid phase. This process results in enrichment of the trace-element in the solid and depletion in the melt.

TABLE 2

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)

Partition coefficients of less than unity indicate depletion of the trace-element in the solid and enrichment in the liquid. However, solid phases with partition coefficients of less than one will display an increase in trace-element concentration with progressive crystallization, whereas those phases with coefficients greater than unity will display decreases in the concentration of the particular trace-element with progressive crystallization.

The reason for this is related to the equations governing the distribution of trace-elements, which shows that concentration of a trace-element in the crystallizing phase is a function of the initial concentration of the element in liquid. In order to determine the distribution of trace-elements in a whole-rock system, i.e. one with more than one mineral component, a bulk partition coefficient, K_D must be calculated. In addition, the amount of intercumulus liquid must also be accounted for, this having a partition coefficient of unity, since it neither depletes nor enriches the liquid in trace- elements. The following equation is used to derive the bulk partition coefficient for any mineral assemblage (rock).

$$K_{Dx} = n_iK_{ix} + n_jK_{jx} + n_kK_{kx} + \ldots\ldots\ldots\ldots\ldots + n_x$$

Where n_i = mass fraction of mineral i

K_{ix} = partition coefficient of element x into mineral i

K_{Dx} = bulk partition coefficient of element x into mineral assemblages i - j - k

n_x = mass fraction of intercumulus liquid

The equations used to calculate the trace-element composition of the solids and liquids were derived by Neumann *et al.* (1954), and are given below :

$$C_s/C_o = K(1 - f)^{(K-1)} \quad \text{and} \quad C_l/C_o = (1 - f)^{(K-1)}$$

Where,

C_s = concentration of the trace-element in the solid.

C_l = concentration of the trace-element in the liquid.

C_o = initial concentration of trace-element in the liquid.

K = bulk partition coefficient.

f = mass fraction of solids produced (percentage crystallization).

The information used to construct the model trace-element variation-diagrams (Figures 4 and 5) for the granitoids of the Vioolsdrif Suite is listed in Table 3, and was derived by applying the above equation to the trace-element data presented by Reid (1977).

Mineralogical evolution of the Vioolsdrif Suite

Occurrences of igneous sedimentation in granitic rocks, a feature indicative of fractional crystallization, have been reported by Emeleus (1963), Smith (1974), and Bateman *et al.* (1963). Such phenomena are uncommon and usually develop on a local scale only. On the basis of trace-element data, McCarthy and Hasty (1976) suggested that many granites have a cumulate character. This feature is the result of in-situ fractional crystallization, rather than of equilibrium crystallization, the latter mode being applied to the crystallization

TABLE 3

ASSUMED INITIAL TRACE-ELEMENT CONCENTRATIONS (Co), BULK PARTITION COEFFICIENTS (D), AND PERCENTAGE CRYSTALLIZATION (f) FOR MEMBERS OF THE VIOOLSDRIF SUITE

ROCK TYPE	DIORITE	TONALITE	GRANODIORITE	ADAMELLITE	LEUCOGRANITE	FINAL LIQUID COMPOSITION
Co(Rb)	80	97	139	189	339	1381
Co(Ba)	740	862	1175	1278	352	55
Co(Sr)	580	487	455	355	92	9
D(Rb)	0,1249	0,1655	0,40368	0,51562	0,3900	
D(Ba)	0,3154	0,2810	0,83538	2,07216	1,8100	
D(Sr)	1,7827	1,1605	1,48564	2,12332	2,0345	
f	0,20	0,35	0,40	0,70	0,90	

of granites by most researchers in granite terranes (McCarthy and Robb, 1977). Fractional crystallization will result in variations in mineralogy, mineral texture, and major- and trace-element composition, as crystallization proceeds. Sequential variations in cumulus-intercumulus mineral relationships in the Vioolsdrif Suite provide a basis for interpreting the variations in trace-element compositions of the various components of the suite.
The average mode of each component of the Vioolsdrif Suite has been calculated and is listed in Table 4 (A columns). The effects of alteration and metamorphism which result in sericitization and saussuritization do not affect the results because the alteration assemblages were produced after the trace-element patterns were established. Locally, where alteration has been intense, trace-elements may be redistributed, but the overall pattern remains intact. Retrogression of hornblende to biotite has made it necessary to establish the original amount of amphibole in the rock from the amount of biotite which is pseudomorphic after amphibole. The mineralogy in the B columns of Table 4 represent the estimated pristine modal composition of each component of the Vioolsdrif Suite. In addition, the intercumulus component of the rock has been considered to be a modal constituent.

The mineralogical changes through the Vioolsdrif Suite, as shown in Table 4, indicate a progressive decrease in the mafic minerals hornblende and biotite, as well as in plagioclase content. By contrast, quartz and K-feldspar progressively increase from diorite to leucogranite. It is also evident that the early components of the Vioolsdrift Suite are more mafic in composition than the later members. Winkler (1967), showed that increasing water-pressure causes the cotectic line in the granite system to move towards the more feldspathic compositions, and this may be partly responsible for the observed trend. The mineralogical evolution is, therefore, considered to be the result of two main processes which included, firstly, progressive increases in water-vapour pressure and, secondly, and more important, a progressive change in the cumulate character of the granitoids constituting the suite.

Variations in the mineralogy of solids crystallizing from the melt which produced the Vioolsdrif Suite also resulted in variations in the levels of trace-elements in the residual magma. The modelled changes in trace-element concentration in the melt, as a result of crystallization of the Vioolsdrif granitoids, will be examined first. Thereafter the trace-element variations in solid compositions, produced as a result of fractional crystallization from a melt of progressively changing trace-element composition, will be examined. Finally, the actual trace-element data from the Vioolsdrif Suite will be related to these models. It is proposed that the degree of correlation between the predicted behaviour and the real data provide an indication of the validity of the model.

Trace-element behaviour during fractional crystallization

Predicted variations in trace-element composition of the melt

The predicted variation in trace-element composition of the melt which gave rise to the spectrum of granitoids constituting the Vioolsdrif Suite is shown in the Ba versus Rb plot (Figure 4) and the Sr versus Rb plot (Figure 5). Inspection of crystal/liquid partition coefficients (Table 2) indicated that, unless biotite becomes a major crystallizing phase, Rb will be steadily enriched in the liquid, as crystallization proceeds.

TABLE 4

AVERAGE MODES OF THE COMPONENTS OF THE VIOOLSDRIF SUITE

COLUMN	1*		2		3		4		5	
ROCK TYPE	DIORITE		TONALITE		GRANODIORITE		ADAMELLITE		LEUCOGRANITE	
MINERAL	A	B	A	B	A	B	A	B	A	B
QUARTZ	5	5	30	30	23,8	22	26,0	25	32,7	33
PLAGIOCLASE	56	50	42	30	40,3	30	35,8	33	37,6	35
K-FELDSPAR	-	-	3	-	21,1	5	26,0	24	24,4	22
BIOTITE	-	-	15	-	14,8	2	12,2	8	5,4	5
HORNBLENDE	39	35	10	25	-	12	-	3	-	-
INTERCUMULUS LIQUID	-	10	-	15	-	29	-	7	-	5

Mineralogy in Columns A represents the altered mineralogy that was reported from direct thin-section investigation, it does not differentiate between cumulus and intercumulus mineralogy. Mineralogy in Columns B represents the probable pristine mineralogy which was responsible for trace-element distributions, prior to alteration of the mineral assemblages; the percentage intercumulus liquid has been estimated.

* data from Blignault (1977)

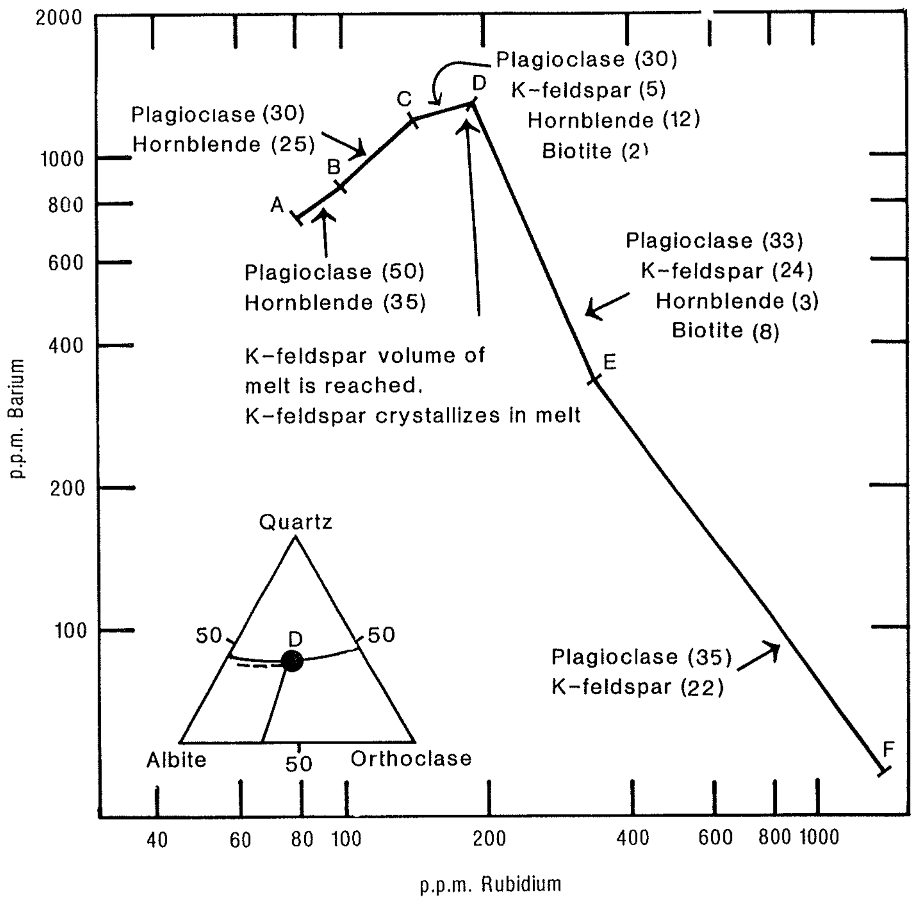


Figure 4: A plot of barium versus rubidium, showing the change in trace-element composition of a melt, as various mineral assemblages (shown in each segment of the curve) fractionate from the melt. In the quartz-albite-orthoclase ternary, the dotted line represents the crystallization curve from A to D. At point D, K-feldspar becomes a liquidus phase and is responsible for the change in slope at D.

Biotite is part of the pristine mineralogy of granodiorites and adamellites (Table 4). Crystallization of mineral phases other than biotite all cause rubidium to be residually enriched in the liquid, and biotite never becomes abundant enough to overrule this effect and cause depletion of Rb in the residual liquid.

The partition coefficients of barium into plagioclase and hornblende indicate that fractional crystallization of these minerals should result in progressive enrichment of barium in the melt (Table 2). This is reflected in the positive slope of the barium concentration in the liquid from A to D (Figure 4). At point D, however, K-feldspar begins to crystallize, and Ba is strongly partitional into K-feldspar, resulting in massive depletion of this element in the remaining liquid. The kink at E in the trend from D to F is due to the disappearance of hornblende and biotite in the leucogranites as well as to the change in proportion of crystallizing plagioclase and K-feldspar. Plagioclase crystallization dominates in the first leg of the liquid composition diagram (Figure 5, Section A-B), during which stage Sr is partitioned into plagioclase and hence depleted in the melt. Strontium continues to be depleted from the melt in the second leg of the crystallization trend (Figure 5, Section B-C), but the rate of depletion is reduced because of the change in the proportions of the crystallizing minerals. From point C onwards the amount of hornblende crystallizing from the melt decreases, and plagioclase fractionation results in continued depletion of Sr in the melt (Figure 5, Section C-D). At point D, the K-feldspar liquidus in the quartz-albite-orthoclase ternary diagram is intersected and K-feldspar begins to crystallize together with quartz, plagioclase and a mafic mineral (see inset of Figure 4). The strong partitioning of strontium into K-feldspar and plagioclase is reflected in the rapid depletion of this trace-element in the residual melt during crystallization of these minerals late in the fractionation trend (Figure 5, Section D to F).

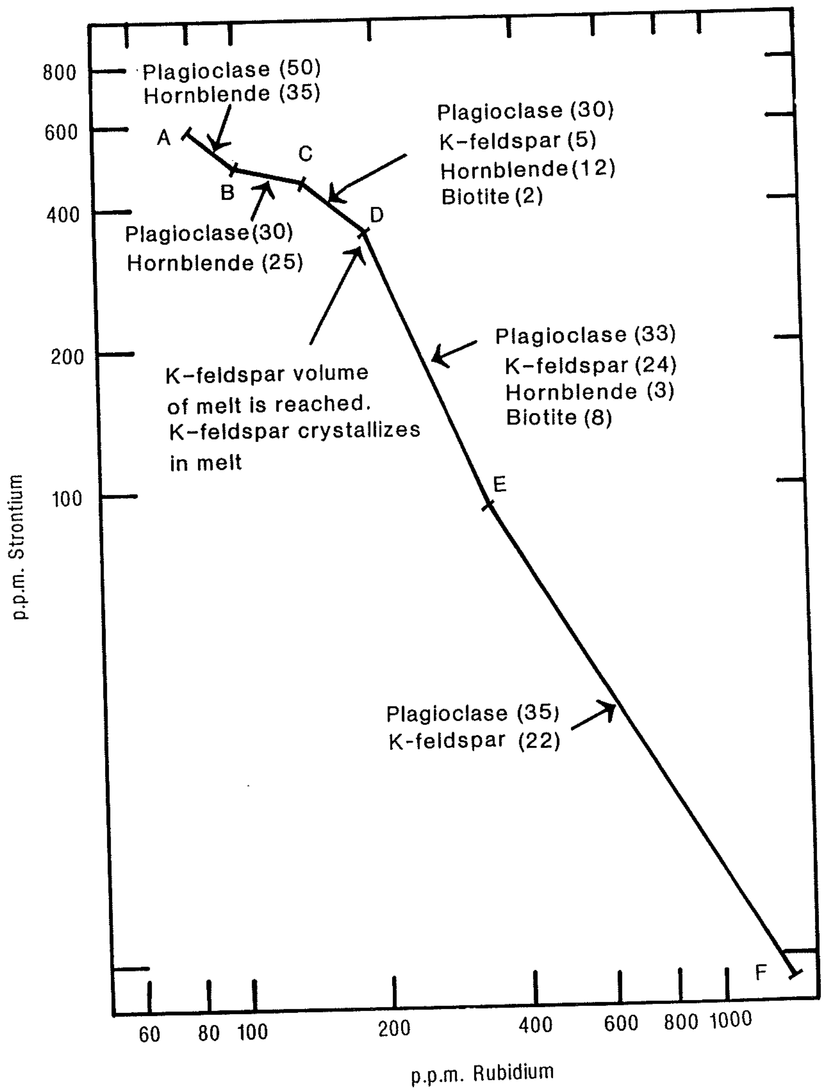


Figure 5: A plot of Sr versus Rb, showing the changes in trace-element composition of a melt as the various mineral assemblages (shown in each segment of the curve) fractionate from the melt. Figures in parenthesis represent the proportions of each of the fractionating minerals. At point D, K-feldspar becomes a liquidus phase and is responsible for the marked change in the slope of the curve beyond this point.

Predicted variations in trace-element composition of the solid

Progressive changes in trace-element concentration in the melts must, in terms of the partition laws, be reflected in progressive changes of trace-element concentration in the solids which crystallize from the melts. Whereas the changes in trace-element composition of the liquid phase are continuous, the composition of the solids crystallizing from the liquid exhibit markedly differing trace-element compositions. Solid compositions are shown, together with the liquid composition from which they were derived, in Figures 6 and 7. It is emphasized that the lines representing the solid phases in Figures 6 and 7 actually represent the composition of pure cumulate phases. As pointed out by McCarthy and Hasty (1976), perfect separation of cumulus phases from a melt is unlikely, and some trapped intercumulus liquid will be present; real rocks therefore consist of a combination of cumulus phases and trapped interstitial melt. This results in trace-element compositions of real rocks lying between pure melt and pure cumulate trends, i.e. within the parallelograms shown in Figures 6 and 7.

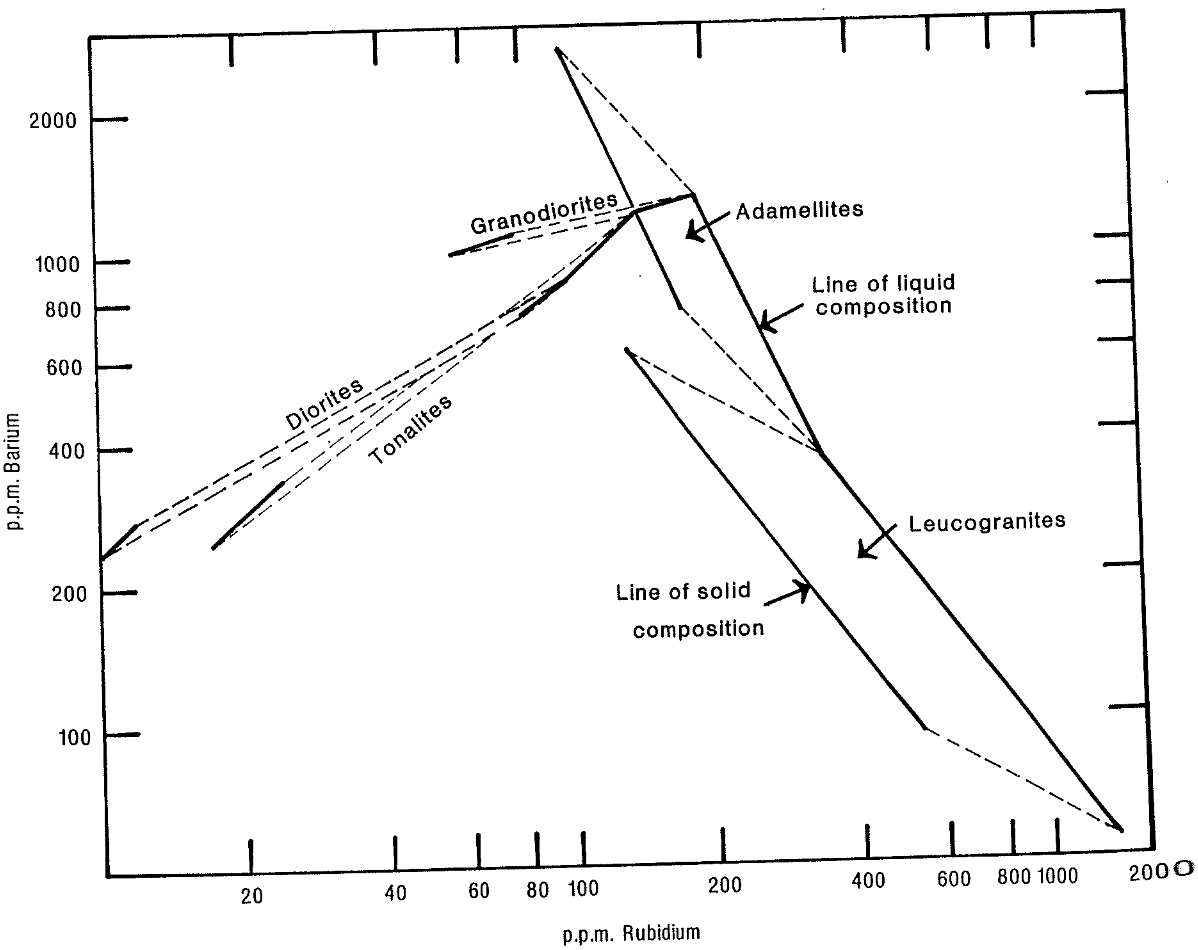


Figure 6: A plot of Ba versus Rb, showing that the continuous change in liquid composition produces solids of markedly different trace-element composition, as the proportion of the fractionating phases changes or as new minerals begin to fractionate. The dotted lines joining the trends of solid and liquid compositions define parallelograms which enclose the trace-element compositions of real rocks constituting the Vioolsdrif Suite.

Inspection of the bulk partition coefficients for Rb, Sr, and Ba into the components of the Vioolsdrif Suite (Table 3) indicates that all the coefficients of Rb are less than unity, those for Sr greater than unity, while, for Ba, two coefficients are greater than unity and three are less than unity. The relationships between the bulk partition coefficients for Rb, Sr, and Ba into the members of the Vioolsdrif Suite are reflected in Figures 6 and 7. In these figures, all solid compositions lie to the left-hand side of their corresponding segment on the line of liquid compositions, because the bulk partition coefficient for Rb into the Vioolsdrif Suite is less than one. The concentration of Ba in diorite, tonalite, and granodiorite is less than that of the liquids from which they crystallize (Figure 6), because the bulk partition coefficients of Ba into these phases is less than one (Table 3). Adamellites and leucogranites, however, contain a greater concentration of Ba than the liquid from which they crystallised, because the bulk partition coefficient of Ba into these phases is greater than one (Table 3). Similarly, the concentration of Sr in the Vioolsdrif Suite is always greater than the liquids from which the constituent phases crystallized (Figure 7), because the partition coefficient of Sr into all these phases is greater than unity (Table 3).

Trace-element composition of the Vioolsdrif Suite

Field investigations, mineralogical data, geochemical studies, and radiometric age-data all suggest that the granitoids constituting the Vioolsdrif Suite are genetically related. In addition, it has been established that there is a geochronological and geochemical continuum between the various remnants of the suite, the oldest members being the basic and ultrabasic rocks, with diorite, tonalite, granodiorite, adamellite, and leucogranites being successively younger in age. The genetic relationship and the geochemical continuum in the Vioolsdrif Suite are substantiated by the Rb, Ba, and Sr trace-element data described below. The close correlation between the model trends and real data for Ba versus Rb and Sr versus Rb can be seen by comparing Figure 6 with Figure 8 and Figure 7 with Figure 9.

The Ba-Rb trends for diorite and tonalite shown in both the model plot (Figure 6) and real data (Figure 8) are positive and as suggested above, these two rock types are considered to have originated as a result of fractional crystallization of varying proportions of hornblende and plagioclase. There is a marked change in the position and the slope of the trend produced by fractional crystallization of plagioclase and minor amounts of hornblende, biotite, and K-feldspar which give rise to the granodiorites. The real data for Ba and Rb in granodiorites (Figure 8) indicate that the trend is displaced to higher Ba values, that it is shorter than either the tonalite or diorite trends, and that the slope of the trend is positive, but less than that of the tonalite or diorite trends. Each of the former observations concerning the displacement, length and slope of the granodiorite trend in the real data plot (Figure 9) is identically reproduced by the field enclosing granodiorite compositions in the model trend (Figure 6).

Trends produced by the Ba-Rb data derived from adamellites and leucogranites are negative in both real and model data plots (Figures 6 and 8). In addition, the model plot indicated that there should be a broad distribution of data points, because the parallelograms enclosing adamellites and leucogranites are broader than those enclosing diorite, tonalite or granodiorite (Figure 6). This is borne out in the real data plot of Figure 8. The model Ba and Rb data for leucogranites (Figure 6) indicate that the latter rock type is derived from

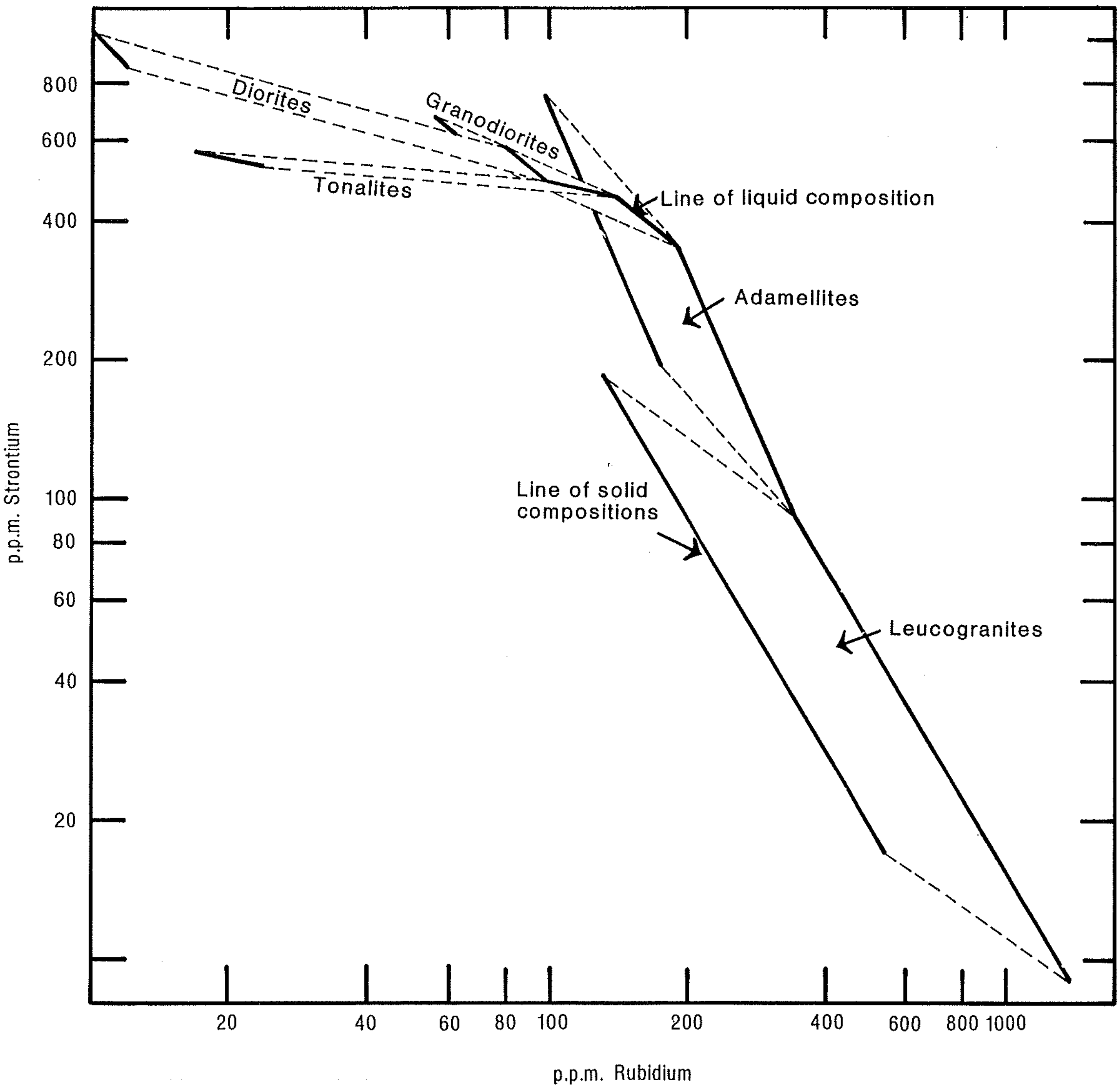


Figure 7: A plot of strontium versus rubidium, showing the continuous line of liquid compositions and the discontinuous lines representing the trace-element compositions of solids formed by fractionation from the melt. The dotted lines joining the solid compositions define parallelograms which enclose the trace-element compositions of the real rocks constituting the Vioolsdrif Suite.

adamellites by continued fractional crystallization of plagioclase and K-feldspar as concluded above. Ba-Rb data for leucogranites substantiate this conclusion, but these data are not definitive enough to separate the leucogranites into two separate groups as has occurred in the Sr-Rb plot (Figure 9).

In the model plot of Sr versus Rb only the trend produced by tonalite compositions is positive whereas all other trends are negative (Figure 7). However, in the model plot (Figure 7), it is predicted that the tonalite trend should be displaced to lower Sr compositions than granodiorite or diorite trends. The real data for tonalite compositions, however, produce

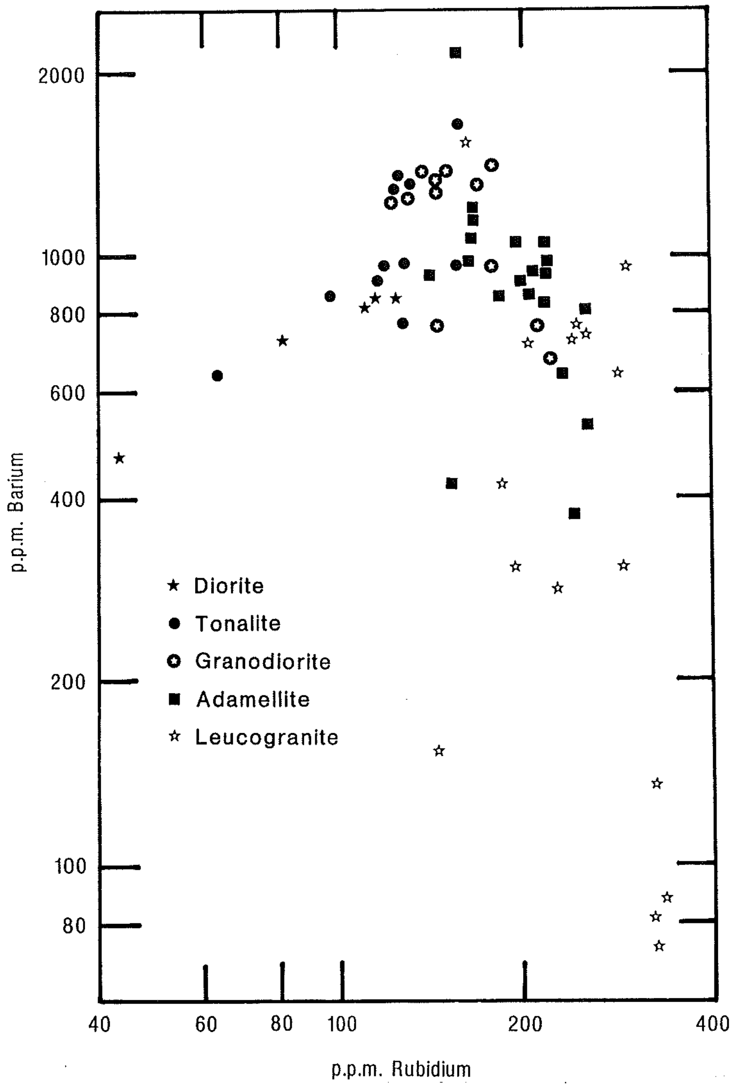


Figure 8: A plot of barium versus rubidium for the various rock types constituting the Vioolsdrif Suite. Symbols refer to the rock types shown in the figure. The shape of the fields defined by the distribution of the various rock types are similar in every respect to the fields outlined in Figure 6.

a trend which is above that of the diorite and granodiorite trends. This is the only anomalous feature in the trace-element data so far considered and it is possible that the Sr compositions in tonalites might have been affected by alteration processes.

Leucogranites in the real data plot (Figure 9) can be differentiated into two groups, these probably being related to the L_1- and L_2- leucogranite types which crystallized under subsolvus and hypersolvus conditions, respectively.

Observations relating to the displacement, length, width and slope of the parallelogram trends shown in the model plot (Figures 6 and 7) can be applied, with almost exact correspondence, to the real data plots (Figures 8 and 9). The high correlation between the model and real trace-element evolution of the components of the Vioolsdrif Suite suggests that fractional crystallization is a good approximation of the actual mechanism that took place in the cooling Vioolsdrif batholith.

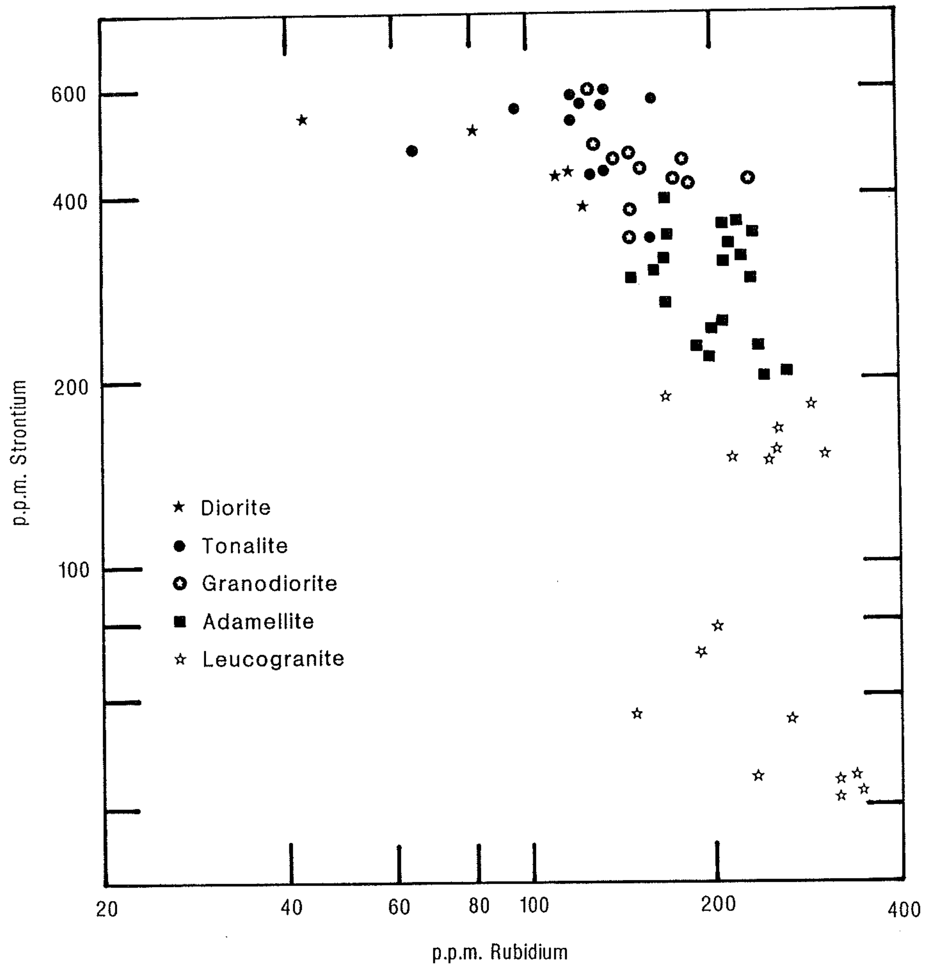


Figure 9: A plot of strontium versus rubidium for the various phases comprising the Vioolsdrif Suite. Symbols refer to rock types listed in the figure. The shapes of the fields defined by the distribution of the various rock types are similar in every respect to the fields outlined in Figure 7.

CONCLUSIONS

Evolution of the Vioolsdrif Suite is considered to have taken place largely as a result of fractional crystallization of a variety of minerals which varied in composition and modal proportion as crystallization proceeded. Crystallization of the earliest and oldest members of the Vioolsdrif Suite, viz. diorite, tonalite and granodiorite was dominated by quartz, plagioclase and hornblende with K-feldspar becoming increasingly more abundant as an interstitial phase. Crystallization of amphibole and plagioclase caused depletion of Sr in the melt, but Ba and Rb concentrations increased in the melt because neither of these elements was partitioned into plagioclase or hornblende. Crystallization of varying proportions of hornblende, plagioclase and quartz accounts for the variations in the slope of the lines representing the evolving liquid composition. In the granite system evolution of the Vioolsdrif Suite from diorite to granodiorite occurs predominantly along the quartz-plagioclase cotectic although early crystallization of diorite rocks may have taken place in the plagioclase field only.

Fractionation of a quartz-plagioclase-hornblende cumulus assemblage with intercumulus K-feldspar, continued until the K-feldspar liquidus was intersected and K-feldspar began to crystallize. Both Ba and Sr were strongly partitioned into K-feldspar and these trace-elements became strongly depleted in both melt and solid with progressive crystallization of K-feldspar. In addition to a change in the composition of the crystallizing feldspar phases there was also a change in the proportions and the composition of the mafic phases undergoing crystallization. Hornblende, which dominated in the evolution from diorite to granodiorite, was accompanied by biotite in the crystallization of adamellite and was completely replaced by biotite in leucogranite crystallization. Because Rb was not partitioned into K-feldspar this trace element continued to increase in concentration in the melt. However, because it was strongly partitioned into biotite the rate of increase in the liquid was not as marked as during the period of hornblende crystallization.

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