

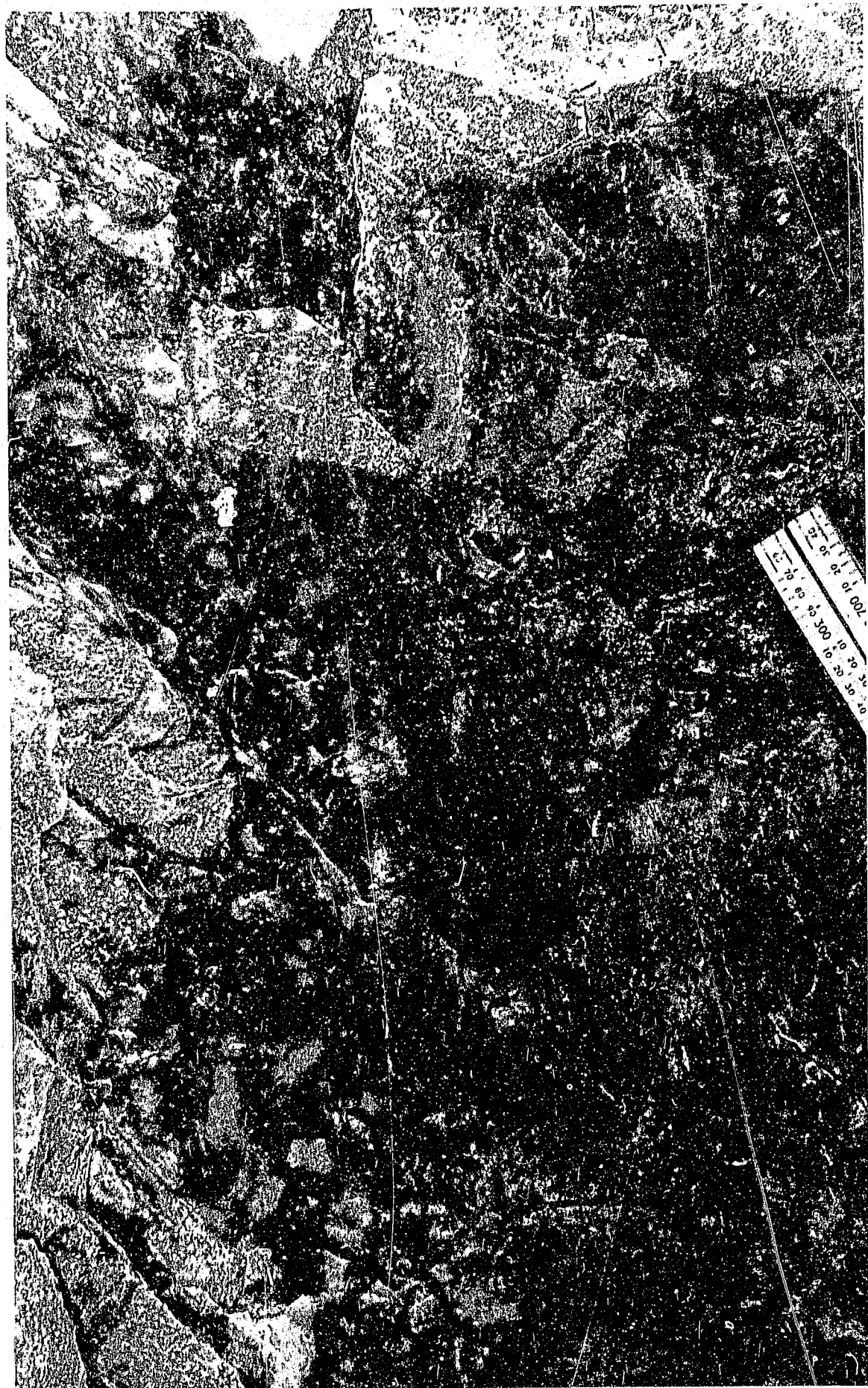


Plate 3.10

The transition between the laminar and non-laminar flow textures .
fifteen centimetres from the bottom contact of No. 8 sill.

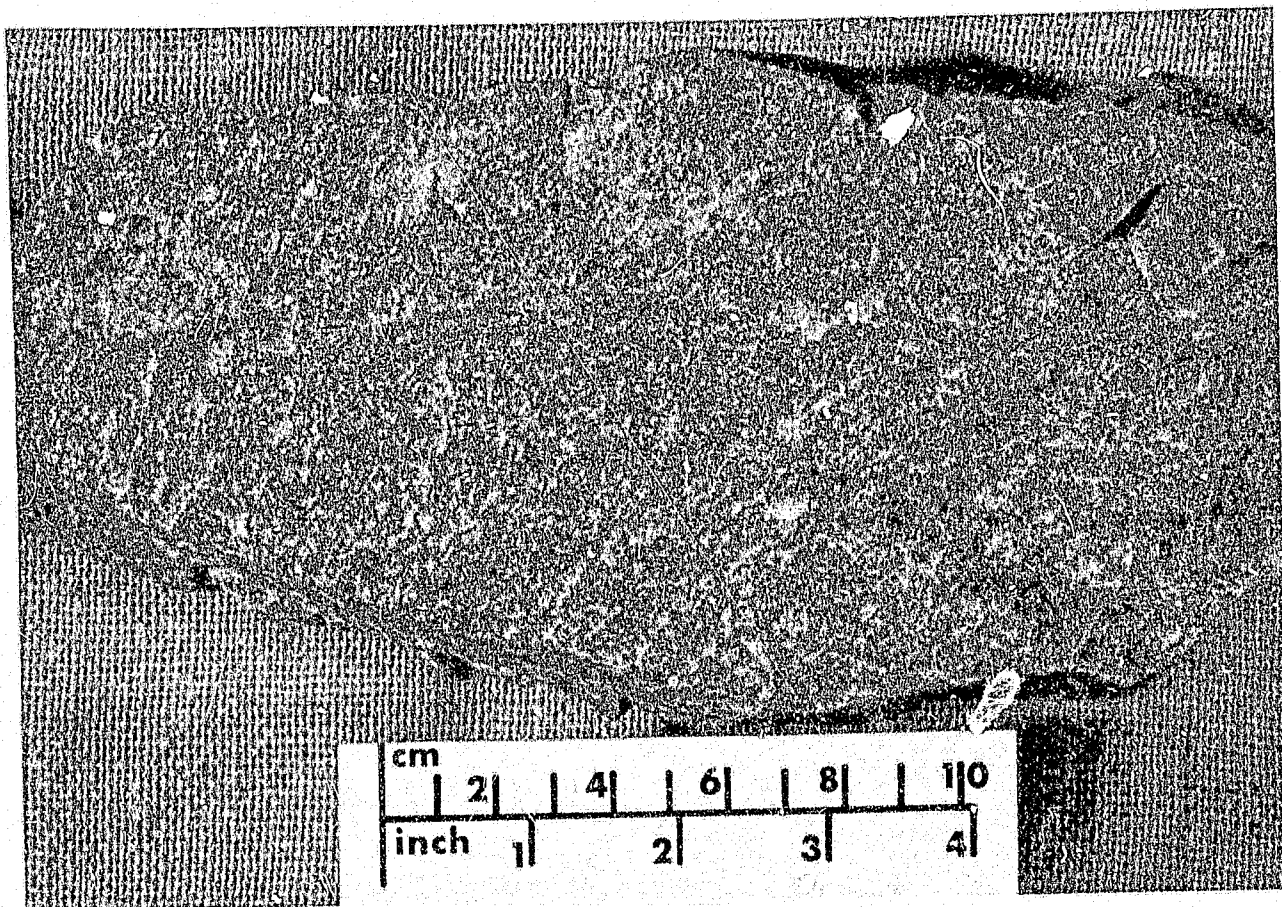


Plate 3.11

Non-laminar flow texture in No. 1 sill formed of red aplite whorls set in an aplite of more normal colours. (Photograph by M. Hudson)

rock matrix. This change in grain size is responsible for the slight colour contrast. Brown biotite is the main micaceous mineral in the nodules; it has a larger grain size than the matrix (0,1 millimetre) and occurs in bands which define the whorl-like pattern in hand specimen. Within one of the nodules, a ghost felspar phenocryst, that has been arrested in the process of recrystallising to a grain size equivalent to the matrix (Plate 3.9) is visible. This may indicate that the nodules are formed as a result of a polygonisation process. In a specimen collected by W.D. Ortlepp from an unknown locality in the mine, an original porphyritic texture with plagioclase phenocrysts is still visible in a very fine groundmass; again indicating pseudomorphic replacement by the matrix.

3.4 Primary flow structures

Both laminar and non-laminar flow structures are found in the sills, particularly near the contact, although the non-laminar ones are often hard to see because of the poor colour contrast in the fine grained rock. However, in Plate 3.10 parallel planes of laminar flow are present up to 15 centimetres from the bottom contact, when there is an abrupt change to a non-laminar, whorl-like structure. Further away from the contact the whorls become less well-defined and wider apart. This is the best-known example of a transition from laminar to non-laminar flow within the sills but a possible transition can be seen in Plate 3.1. Sometimes more than one transition occurs within one section but the whorls nearer the centre of the sill are not as well-defined. Occasionally the whorls are a different colour from the host rock, as in Plate 3.11.

3.5 Nodules outside the sills

3.5.1 Macroscopic description

Several nodules of aphanitic material were found in green chloritic

quartzite approximately 10 metres above Sill No. 6. Detailed examination of one of these nodules showed it to consist of a green, translucent material enclosed in a 1 centimetre diameter core of medium grained sulphide. The nodule itself is 2 - 3 centimetres and is surrounded by a 1 centimetre wide mantle of black quartzite.

3.5.2 Microscopic description

The central core consists of disseminated pyrrhotite with a fine grained anhedral form. Outside this central core the main mineral is untwinned feldspar with numerous inclusions of epidote. The grains are irregular in shape and up to 0,4 millimetre in diameter. Amongst the feldspar grains there are some grains of quartz and towards the contact of the nodule chlorite becomes abundant.

3.6 Samples outside E.R.P.M.

3.6.1 Macroscopic description

Two specimens from the New Kleinfontein Gold Mine have been examined. These rocks are similar to material found in the central zone of the sills on E.R.P.M. One has a light grey aphanitic matrix enclosing quartz and feldspar phenocrysts and small mica aggregates. The other appears to be white in colour with no phenocrysts or mica aggregates; however, detailed examination of the aphanitic matrix shows it to be made up of white spherules set in a light grey groundmass. The spherules are between 1 - 2 millimetres in diameter. The rock is also brecciated, with mica and quartz filling the voids. Similar brecciated rocks are found in E.R.P.M. but the spherulitic texture has not been seen in hand specimen.

One specimen from the City Deep Gold Mine has also been examined. This rock has an aphanitic matrix with phenocrysts of quartz and feldspar, like the occurrences on E.R.P.M. However, it is much darker in colour, due to a relatively high concentration of mica aligned in two planar

fabric directions.

3.6.2 Microscopic description

The sample from New Kleinfontein, which contained white spherules in hand specimen, is almost completely formed of an aggregate of felspar spherulites set in a matrix that comprises about 10% of the rock and is composed mainly of polygonal quartz with lesser amounts of felspar. The felspar is chloritised and saussuritised. The overall appearance of the rock is similar to that of the "Mylonite Dyke" in the East Rand Basin as sketched by Whiteside (1950). The other specimen from New Kleinfontein is indistinguishable microscopically from the sills in E.R.P.M. The sample from City Deep only differs from the E.R.P.M. occurrences in that the felspar phenocrysts are euhedral.

3.7 Petrography of associated features and younger faults

There are three known types of intrusives, and one example of faulting which appears to be associated with the emplacement of the aplite sills. The intrusions are:-

1. A clastic sill
2. A quartz - chlorite - calcite sill
3. A felsic intrusive of unknown geometry

3.7.1 Clastic sill

The geometry of this sill has been given in the description of the morphology of the sills (Chapter 2.1). In hand specimen this rock is indistinguishable from a pure sedimentary quartzite; it is medium grained (size between 1 - 2 millimetres) and it appears to be composed only of quartz.

Microscopically it is seen to consist totally of quartz which shows

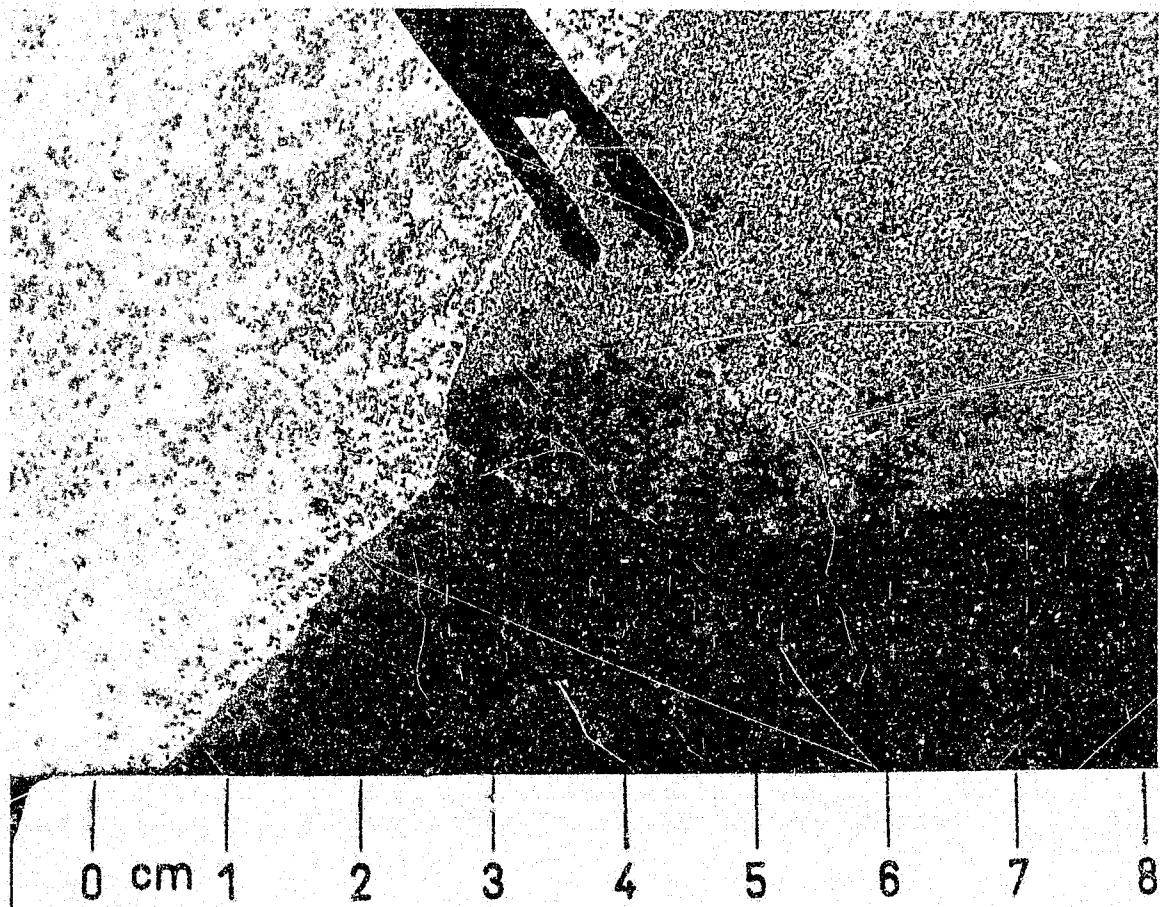


Plate 3.12

The abrupt transition from the dark brown to light brown quartz-chlorite-calcite intrusion within Sill No. 6. The large scale relationships are shown in Plate 3.1 in the bottom of the photograph.
(Photograph by M. Hudson)

Plate 3.13

The gradational transition from the dark brown to light brown quartz-chlorite-calcite intrusion within Sill No. 6. The photograph overlaps with Plate 3.1.

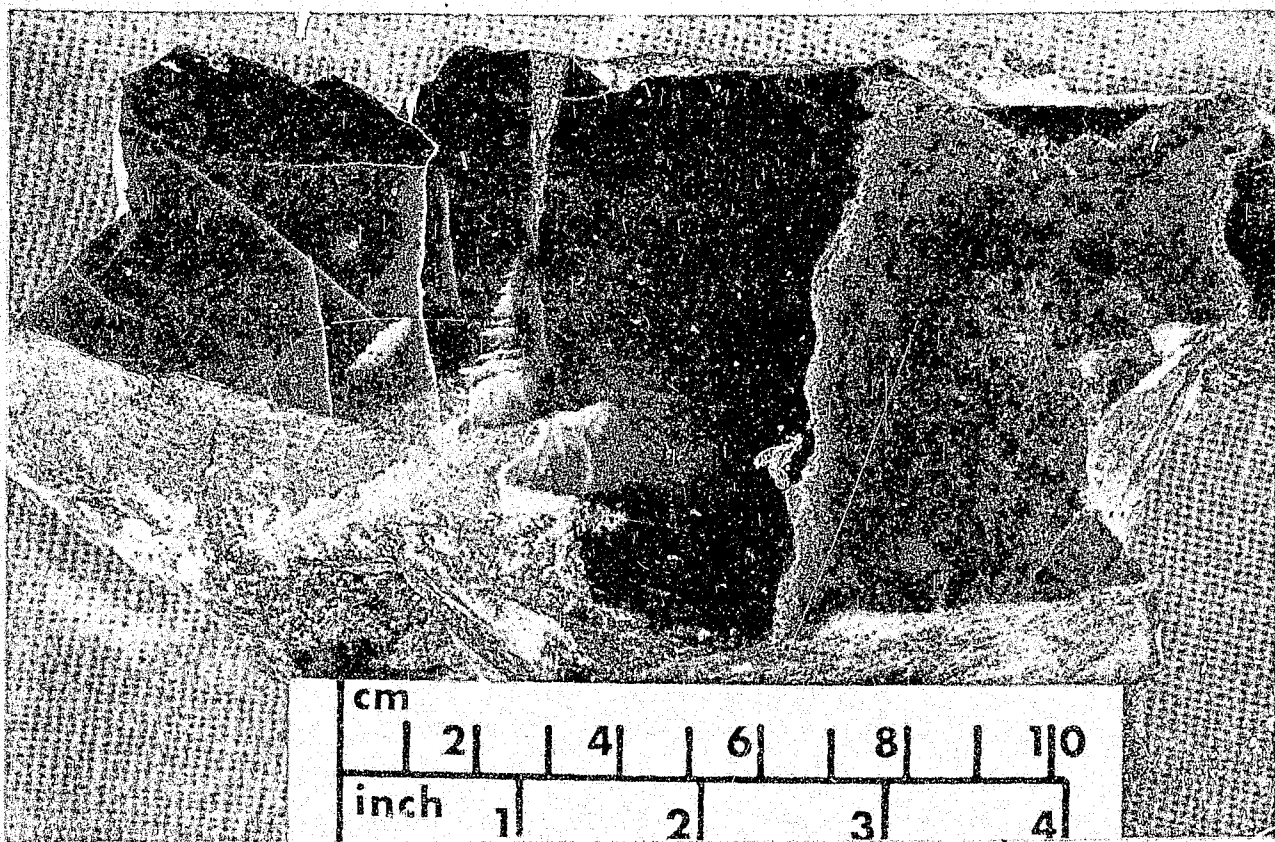


Plate 3.14

The details of the intersection of the quartz-chlorite-calcite intrusion with Sill No. 5 near its termination. (Photograph by M. Hudson)

undulose extinction and recrystallisation around the edges of the larger grains and in cross-cutting bands. One quartz vein contains syntaxial growths of quartz as defined by Durney and Ramsay (1973); these syntaxial fibres also show undulose extinction and recrystallisation to secondary quartz. Another vein, of feldspar and chlorite pseudomorphic after feldspar, has a composite fibre growth (Durney and Ramsay, 1973); this vein is cut by another containing quartz, carbonate and zircon (uncertain identification).

3.7.2 Quartz - chlorite - calcite sill

Only two occurrences of this type of sill are known; one in association with Sill No. 5, which is illustrated in Figure 2.2 and the other with Sill No. 6 (Plates 3.1, 3.12 and 3.13). This rock is normally fine grained but it may be porphyritic with 2 millimetres long ellipsoids of anhedral phenocrysts of quartz. These ellipsoids are often mantled by green mica. The groundmass is usually khaki in colour but at the contact it forms a light brown rim. This rim may also be porphyritic with pale green anhedral phenocrysts of mica in an off-white aphanitic groundmass (Plate 3.14). In the sill associated with the aplite Sill No. 6, the intrusive changes laterally into a dark brown and slightly coarser grain size material which contains patches of medium grained granular material with a higher quartz content. These patches are up to 3 - 4 centimetres in length and are probably partially assimilated xenoliths. There are two types of transition from the khaki coloured rock to the dark brown; a gradational change (Plate 3.13) and an abrupt change (Plates 3.1 and 3.12).

In thin section, the groundmass of the rock is seen to be made of quartz, chlorite and calcite in roughly equal proportions, with minor amounts of pyrrhotite. The concentrations of the major minerals vary

greatly within the rock, and the quartz phenocrysts are composed of a mosaic of recrystallised quartz grains but some do have the bipyramidal form of β quartz in the xenoliths. This suggests the xenoliths may sometimes be altered fragments of aplite. These xenoliths are only known in the dark brown variety of this mafic sill, which is only known within the aplite sills.

3.7.3 Felsic intrusive

This intrusive does not resemble the aplite sills in texture, but it does in composition and is similar in both composition and texture to the lowermost sill in the Rand Deep Borehole described by Weber (1909). It was only found in the roof of F69W stope where it cuts across Sill No. 8. The contact with the main sill is bounded by a dark border which on closer inspection is seen to be gradational. Because of the limited exposure, the structure of the intrusive is unknown, but it must be relatively flat because it does not occur in the floor of the stope.

The rock is medium grained and consists mainly of quartz and felspar with minor amounts of mica. Phenocrysts of felspar and β quartz form between 5 - 10% of the rock; these show little or no magmatic corrosion. Mixed with the felspar phenocrysts is a high concentration of pale biotite (approximately 5% of total rock) this mineral is also distributed through the rock in low concentrations.

3.7.4 Younger faulting

In Figure 2.6 the relationship of the only known post-sill fault is shown. This fault has a near vertical dip and it displaces Sill No. 5 by 0,8 - 1,0 metre in a normal sense. The fault fill between the offsets of the sills is aphanitic with euhedral bipyramidal quartz megacrysts.

The colour is a dirty, light yellow, in contrast to the light brown of the aplite, but microscopically it is indistinguishable from the aplite. Away from the sill the gouge material has a dark grey to dark green colour and is filled with fine grained chlorite and quartz. Microscopically it is composed of 80% quartz which is fine grained and angular. This quartz is set in a finer matrix of chlorite and biotite. Because of the aplitic nature of part of the fault fill, the faulting must have taken place while the magma was still molten.

3.8 Contact effect on adjacent rocks

The aplite sills have been observed cutting through sediments, dykes and a fault.

3.8.1 Adjacent sediments

A petrographic examination was done on the chlorite rich quartzites adjacent to No. 3 sill, the samples being collected from a borehole core. No macroscopic effect due to the sills can be seen, and microscopically the only effect is a marked recrystallisation of the quartz component of the sediment to form polygonal grains of a much reduced size (less than 0,1 millimetre in diameter). This recrystallisation affected about 5 - 20% of the grains at a distance of 3 metres from the sill and about 50% of the grains within a few centimetres of the contact. Usually the recrystallised grains are associated with sericite.

3.8.2 Adjacent mafic dykes

Only one of the dykes which are cut by the sills showed a metamorphic effect. In this dyke there was a marked increase in the carbonate content of the dyke within 5 centimetres of the contact.

3.8.3 Adjacent fault zone

The fault zone, which is between 0,5 and 1 metre wide, occurs in H74E

stope. Away from the sill intersection it is like most other faults and shear zones in the mine; these have a dark green to black colour, being filled with chlorite, quartz and occasional pyrite crystals. However, within a metre of the sill, the fault zone is a light grey colour and is cut by quartz filled fractures. Microscopically the rock is composed of quartz with a typical mylonite texture and it appears that the sill has silicified the fault zone. This later silicification has prevented percolating fluids from depositing secondary chlorite, as has happened further away from the sill.

3.9 Petrogenesis

3.9.1 Temperature of the magma

The phenocrysts may provide an indication of the temperature of the magma during intrusion. Possible geothermometers include β quartz high albite structured plagioclase, perthites and magnetite, as listed in Table 3.2.

Table 3.2

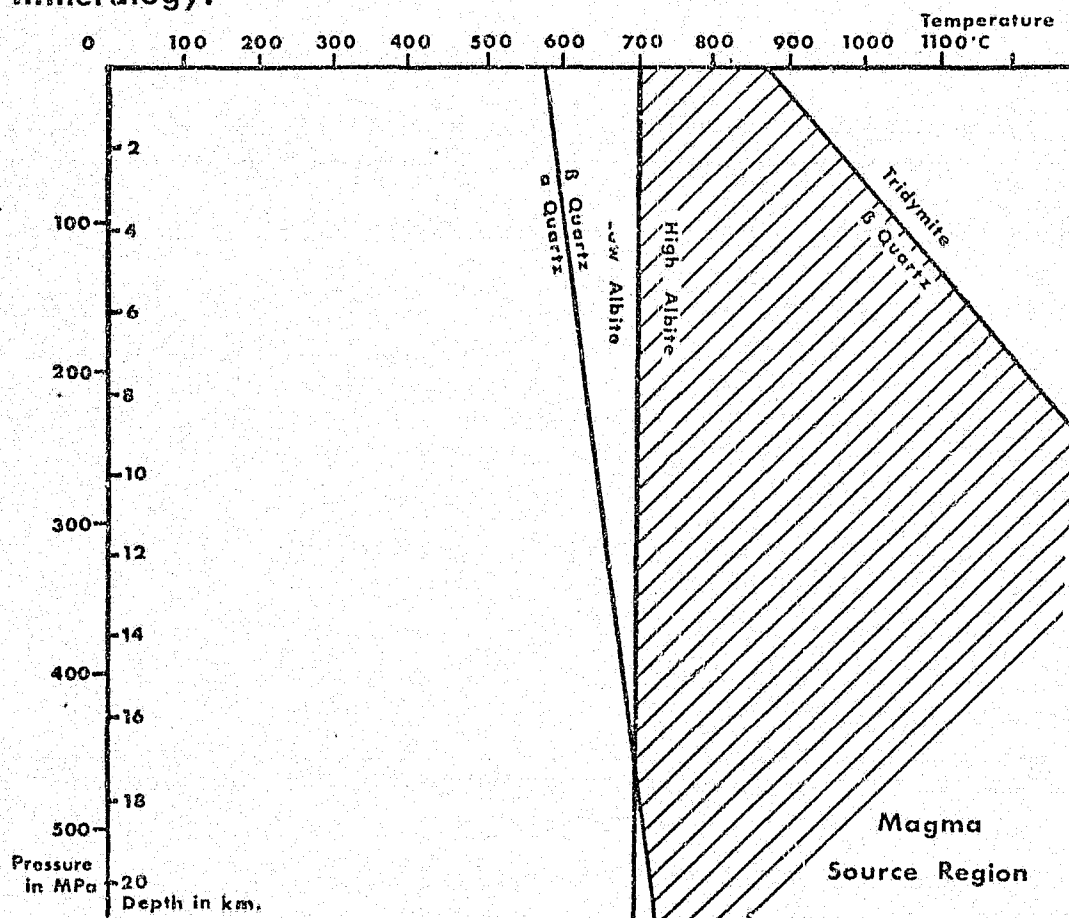
The temperature of the magma as indicated by the mineralogy

<u>Mineral</u>	<u>Temperature</u>	<u>Comments</u>	<u>Reference</u>
Magnetite	> 1594° C	Unreliable	Deer et al. (1962) Vol. 5, p.71 Mehnert (1968) p.114
β Quartz	> 573° C	Reliable	Deer et al. (1962) Vol. 4, p.198
Plagioclase	> 700° C	Reliable	Deer et al. (1962) Vol. 4, p.69
Perthite	630 - 700° C	Unreliable	Deer et al. (1962) Vol. 4, p.69

The α - β quartz transition is probably the best of these temperature indicators. It shows a minimum temperature of 573° C at atmospheric pressure with an increase of 1° C for every 4MPa increase in confining pressure (Deer et al., 1962, Vol. 4, p.98). The plagioclase inversion

Pressure-temperature conditions of the source region, as indicated by the mineralogy.

Figure 3.2



temperature is not as well established as that for quartz but is also reliable. The temperature for perthite was obtained by applying the curve in Deer et al. (1962, Vol. 4, p.69) to the composition of the orthoperthite determined for the sills. This temperature agrees with that indicated by β quartz and high albite, but it is not as reliable because little is known about the mechanism of replacement of plagioclase by orthoclase or the exsolution of the two minerals. Finally the extremely high temperature indicated by magnetite was determined experimentally for an iron-oxide system and is probably not applicable to a silicate magma containing trace amounts of fluorite. Rather the fluorite probably acts as a flux, in the same way as apatite does (Hilpotts, 1967); this would reduce the temperature of crystallisation of the magnetite (Maske, 1974, personal communication). Also Mehnert (1968) regards the magnetite-ilmenite geothermometer as unreliable. Figure 3.2 summarises the experimental data available on the two reliable temperature indicators, and demarcates the possible temperatures of the magma.

3.2 Crystallisation sequence

The presence of phenocrysts automatically implies that there are two stages to the cooling of the material making up the sills. A slow cooling stage during which the phenocrysts formed, which must have occurred prior to the second rapid stage during the intrusion of the sills. The minerals formed during the first stage are:- quartz, felspar, magnetite and the fluorite in the ellipsoids. The possibility that the clusters of felspar phenocrysts in acid dykes and sills represent xenoliths of an older igneous rock, or relicts of a melted source rock, has been considered by Carmichael and Smith (1959) for the felsites in N. Ireland; these workers concluded that the clusters could not be remnants of another rock, as the felspar is in equilibrium with the matrix. Applying this to the aplite

sills in E.R.P.M., suggests that the feldspars were originally in equilibrium with the magma but that by forming clusters, possibly due to surface tension (Emeleus and Smith, 1959), they have partially shielded themselves from the changing magma conditions prior to intrusion, and consequently show negligible zoning. This is in contrast to the single crystals which show considerable interaction with the magma. The development of the perthites is also thought to have occurred during this early stage, possibly by one of the exsolution processes described by Alling (1932).

The initial cooling stage was terminated by the injection of the magma into the sills where a much faster cooling rate was encountered.

According to Barker (1970) the granophyric intergrowths seen in the matrix indicate rapid crystallisation and the smaller they are the faster the rate of crystallisation. Such intergrowths are only known in nature in extrusive rocks or hypabyssal aplites, but they have been produced experimentally by hydrothermal devitrification of glasses at high temperatures and pressures (Schloemer, 1964). This suggests that the groundmass cooled extremely quickly to produce the aphanitic texture; and Barker (1970) estimates a time limit of 60 years for cooling to produce this texture. The nodules within the sills might represent recrystallisation to a smaller grain size due to a high volatile content, after the main body had solidified.

4. GEOCHRONOLOGY

This chapter is concerned with the rubidium-strontium geochronology of the aplite sills occurring in E.R.P.M. Prior to this study there had been speculation as to the age of these sills.

One possibility is that the sills are related to the felsic intrusions in the Johannesburg-Pretoria granite dome. Anhaeusser (1973) postulated that these felsic intrusives might represent a late stage remobilised phase of the granite host rock; this granite has been dated at $3200 \pm 27^*$ m.y. by Allsopp (1961), using the Rb-Sr isochron technique. Willemse (1933) thought that these intrusions in the granite might have intruded prior to the extrusion of the Ventersdorp lavas. Dates on these lavas range from 2318 ± 43 m.y. to $2238 \pm 110^{**}$ m.y., the first is a Rb-Sr isochron age (Crampton, 1973), while the second is the youngest of a series of U-Pb, zircon ages (van Niekerk and Burger, 1964, van Niekerk, 1968). Both dates are from rocks in the acid phase at the top of the sequence. As another possibility, Ferguson (1973, personal communication) inferred from the petrology that the sills on E.R.P.M. might be associated with the Pilanesberg igneous province, which has been dated at 1290 ± 61 m.y. (Schreiner and van Niekerk, 1958) and $1330 \pm 80^{**}$ m.y. (van Niekerk, 1962).

Besides the acid rocks at the top of the Ventersdorp system (du Toit, 1954, p.193), there are also similar rocks at the top of the Transvaal system (Button, 1973, p.310-312), and others associated with the Pilanesberg province (Fockema, 1949). The study described here was undertaken to discover which, if any, of these occurrences are related to the sills occurring in the Witwatersrand sediments.

* All errors are expressed as one standard deviation unless marked.

** Form of the error not given.

4.1 Physical relationship with other structural features

The dykes on E.R.P.M. have been divided into four age groups, and the faults into two, on the basis of their orientation and petrography (Jeffery, 1975). Both fault sets and two of the dyke sets have proved to be older than the sills, while there is no knowledge of the relationship to the other two dyke sets, which are considered to be of Bushveld age (1954 m.y., Davies et al., 1970) from their petrography (Jeffery, 1975).

4.2 Sample selection and preparation

All the samples of aplite used in the radiometric dating were taken from borehole cores, except the large hand specimen (H75II), and they all came from Sill Nos. 1 and 3 in the Lower Hercules section. Initially a selection of samples was made from specimens for which chemical data was available, to ensure a large spread in the Rb/Sr ratio. The selected samples came from both the central and contact zones. The size of the samples was generally 20 - 30 grams or 200 - 300 grams, except for H75II which was in excess of 2 kilograms.

As an unorthodox crushing procedure was used on the initial samples, more material of H75II was crushed in a conventional manner (H75IID) to ascertain whether the first crushing procedure affected the apparent age. The unorthodox procedure entailed crushing in a carbon steel jaw crusher followed by sieving with coarse nylon mesh, to remove the fines which contained visible amounts of steel slivers. This was done on the assumption that the remaining coarse fraction of this aphanitic rock would be representative, and free of iron contamination. This coarse fraction was then crushed in an agate mill.

As more data became available it was found that the steel slivers only caused minor contamination, but the sieving had removed some of the

Table 4.1

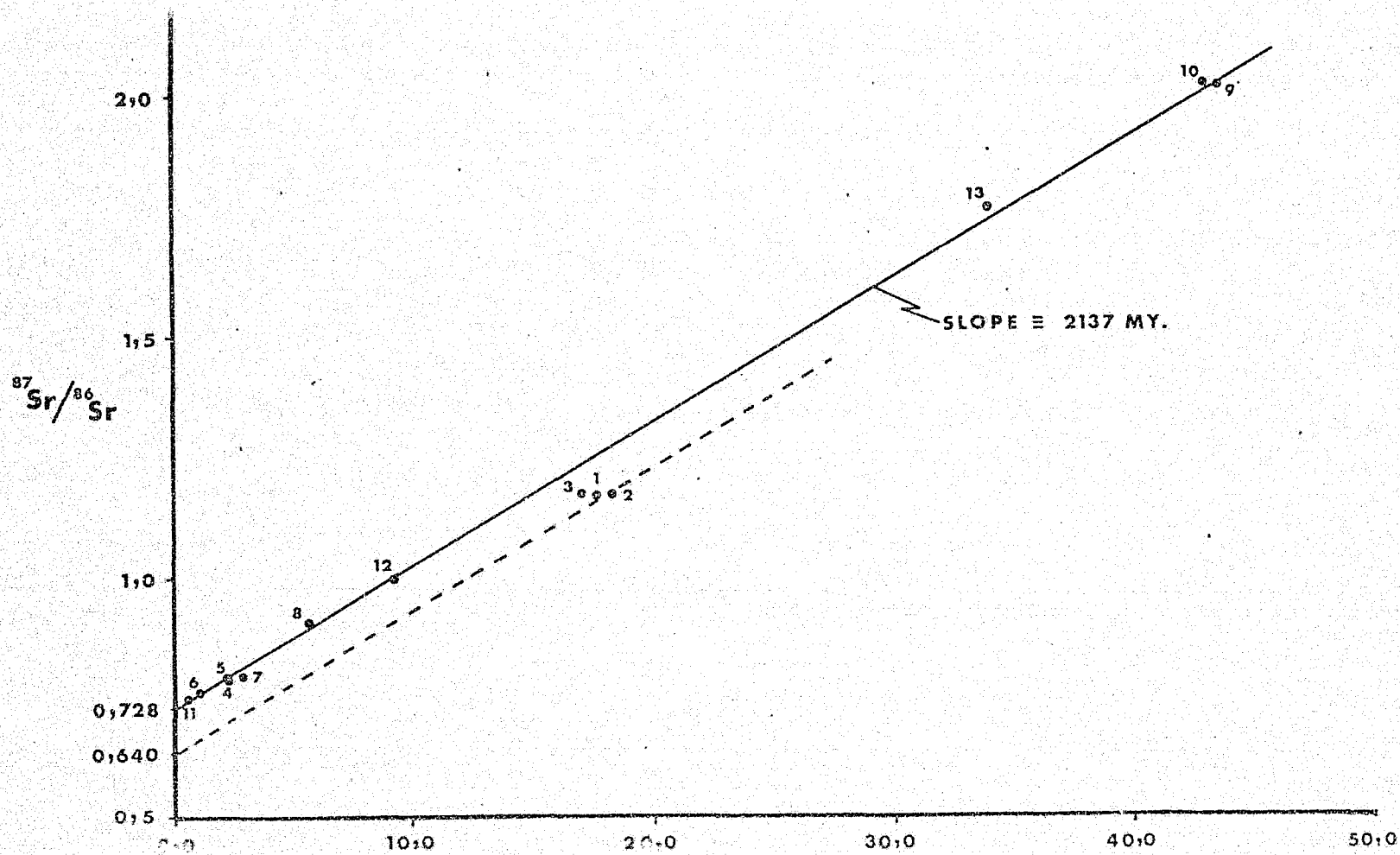
Rb-Sr data for the aplite sills

Sample	Sill No.	Distance from contact (metres)	Zone	Quartz	Approximate mineralogy**		
					Kfels	Ab	Fluorite
H75II	1	1,5	Central	26	22	48	0,5
H75II							
H75IID	1	1,5	Central				
H75IID							
BC1/1,2	3	1,2	Central	26	17	53	0,6
BC1/1,2							
BC1/2,70	3	0,05	Contact	33	-	57	0,2
BC3/2,6	3	0,20	Central	26	11	58	0,6
BC3/2,6							
BC3/2,8	3	0,05	Contact	40	-	35	0,2
BC3/2,8							
BC5/0,01	3	0,01	Contact	56	-	4	0,2
BC5/0,01							
BC7/3,20	1	0,15	Contact	24	1	61	0,5
BC7/3,33	1	0,02	Contact	56	-	2	-
BC7/3,34	1	0,01	Contact	55	-	2	0,4

** Mineral composition after sieving, based on mesonorms, except where mica (muscovite and biotite) is known to be absent so is not calculated, but is left as kfelspar.

No. in File 4.5	Sample	87Rb		86Sr		K/Rb	Ca/Sr	87Rb/86Sr		87Sr/86Sr	Individual ages using 0,728 as initial ratio (m.y.)
		ppm	ppm	ppm	ppm						
1	H75II	46,74	2,64	180	75,9	17,47	1,174			1834	
	H75II	47,63									
2	H75IID	47,33	2,58	180	75,9	18,11	1,176			1778	
3	H75IID*	46,32	2,70	180	75,9	17,00	1,177			1896	
4	BC1/1,2*	18,01	7,57	386	17,9	2,351	0,788			1992	
5	BC1/1,2	17,18	7,35	386	17,9	2,311	0,785			1905	
	BC1/2,70	8,15									
6	BC1/2,70	8,28	8,06	230	8,0	1,015	0,757			2370	
7	BC3/2,6	13,44	4,60	332	23,5	2,887	0,798			1845	
	BC3/2,6	12,10									
8	BC3/2,8	34,56	6,11	149	7,4	5,592	0,905			2304	
	BC3/2,8	37,70									
9	BC5/0,01	84,54	1,92	124	35,2	43,45	2,019			2114	
10	BC5/0,01	83,81	1,93	124	35,2	42,86	2,026			2155	
11	BC7/3,20	4,83	8,37	124	29,8	0,571	0,743			2477	
12	BC7/3,33	60,43	6,49	167	4,5	9,20	0,998			2119	
13	BC7/3,34	77,29	2,26	135	32,2	33,87	1,767			2184	

* Indicates samples separately dissolved for Rb and Sr.



phyllosilicates. In effect the sieving resulted in a partial mineral separation; therefore a second selection of unsieved samples was also used for radiometric dating. The possible effects of this sieving will be given later. A brief description of the samples and details of the crushing procedure used in each case is given in Appendix A.

The chemical and mass-spectrometer procedures used are those described by Allsopp et al. (1968), except for the loading of the strontium samples. The procedure for strontium was to load the samples onto a rhenium centre filament in phosphoric acid.

4.3 Results

The data are listed in Table 4.1 together with approximate mineralogy, and illustrated in Figure 4.1. The ^{87}Rb and ^{86}Sr concentrations were determined by isotope dilution, while the potassium, calcium and total strontium were determined by X-Ray fluorescence. From Figure 4.1 it can be seen that a good isochron is defined by six samples, while one sample (point Nos. 1, 2 and 3) lies a considerable way off. Taking $\lambda = 1,39 \times 10^{-11} \text{ yr}^{-1}$, a best fit was computed for the data, excluding H75II, using the method of York (1966). The results are:-

Age $2145 \pm 14 \text{ m.y.}$
Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio $0,7228 \pm 0,0053$
(Errors expressed as one standard deviation)

The individual ages using this initial ratio are also given in Table 4.1. The best fit was also calculated for the six contact zone samples giving the following result:-

Age $2137 \pm 17 \text{ m.y.}$
Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio $0,7277 \pm 0,0070$

4.4 Discussion

Since rubidium can substitute for potassium and strontium for calcium or sodium (Nagasawa and Schnetzler, 1971) in the crystal lattice of minerals, the minerals that are important in Rb-Sr work are those with potassium, sodium or calcium as a major element. In the sills, such minerals are muscovite, biotite, orthoclase, albite-oligoclase, fluorite, calcite and epidote; the last three only occur in trace quantities. From experimental evidence muscovite is the potassium rich mineral that has the greatest retention of radiogenic strontium (Arriens et al., 1966). Biotite and orthoclase have progressively lower retention capabilities, and the strontium lost by these minerals is usually taken into calcium rich phases (Arriens et al., 1966) in close physical proximity. The philosophy behind the whole rock technique is that the potassium rich phases may give low apparent ages and the calcium rich phases give high apparent ages, but the whole rock should have remained a closed system for Rb-Sr and therefore give a true age. However, an open system may exist, which results in a whole rock apparent age that is too low.

H75II lies significantly off the main isochron and indicates an apparent age of 1820 m.y. The possibility that this sample had a lower initial ratio and essentially the same age, is not feasible since (as shown by the dotted line, Figure 6.1) the required initial ratio would be 0.640 i.e. lower than the primitive value.

Sieving cannot account for the lower apparent age of H75II because it removes mineral phases which have different rubidium and strontium concentrations from those of the average rock, therefore, changing the rubidium and strontium content of the analysed sample. Such a change would move the plotted point along the isochron, but not off the isochron unless the individual minerals constitute an open system. However, this

is not the case because:-

- (1) Data for H75II was obtained from sieved and unsieved samples and
- (2) The isochron is defined by both sieved and unsieved samples.

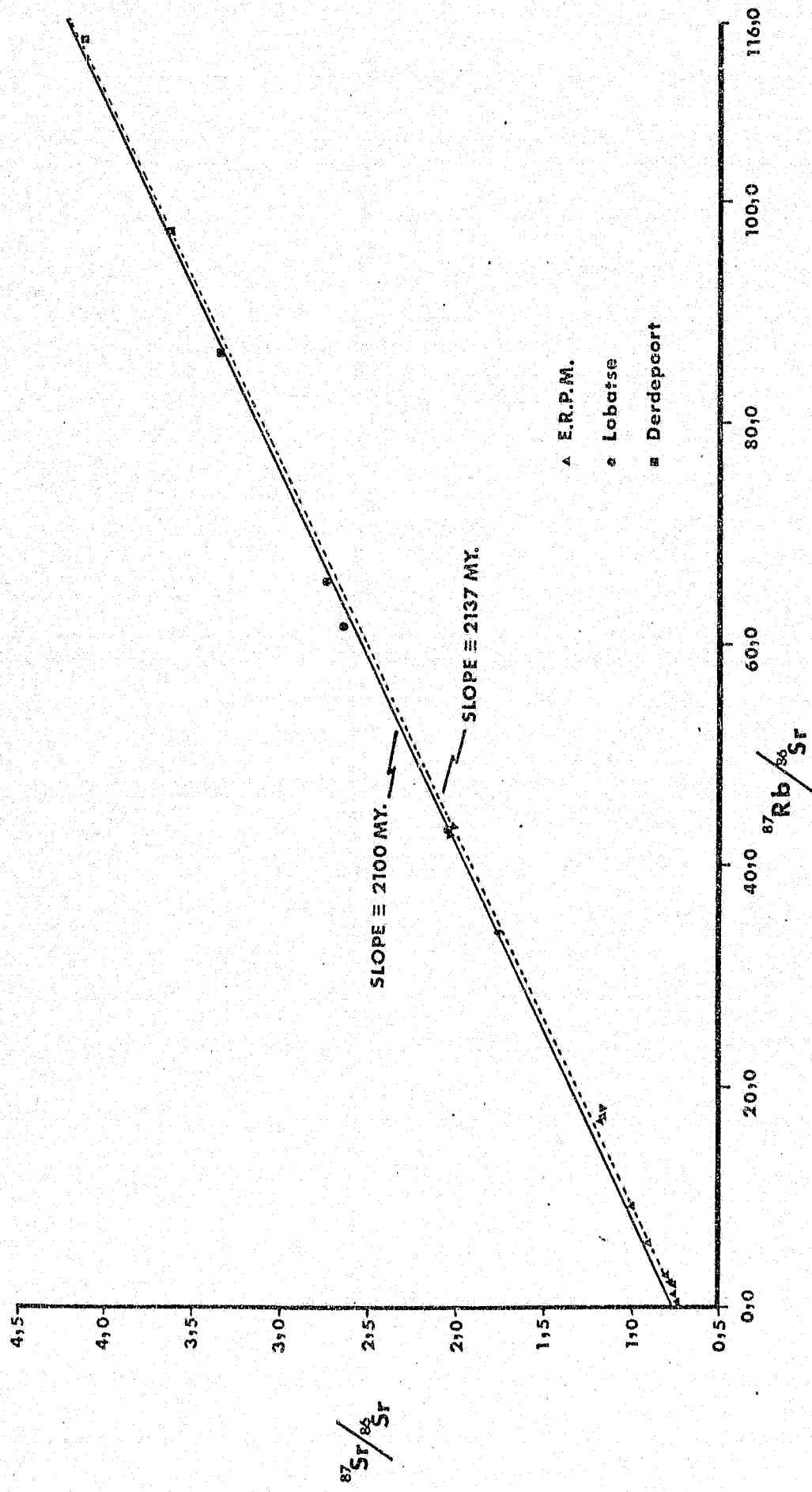
There are three possible explanations for the central zone specimens giving anomalous results: The first is diffusion of radiogenic strontium down a temperature gradient (Allsopp, 1974, personal communication). Although at an early stage of the intrusion there was probably a temperature difference of approximately 500°C between the contact and the central zone, this gradient would have been very short-lived. Jaeger (1958, 1961) has shown that an intrusion of the thickness and composition of the sills should solidify within a week and the ambient temperature should drop to about 400°C within sixty days (assuming that the magma was at a 1000°C and intruded rocks at 200°C , the contact being at approximately 500°C). Because of this very short time span it would be impossible to detect any isotopic diffusion.

The second alternative is diffusion of radiogenic strontium out of the central zone into suitable "sinks". Two potential sinks exist within the sills, namely:- the mineralised joints, and a narrow calcium rich band within the contact zone. The first is unlikely because of the relatively large distances between joints and samples (> 1 metre). The second possibility is also unlikely because it should affect the contact zone specimens more than those from the central zone and should appear in the isotopic results as a large scatter about the isochron.

The third alternative, that mineralogical factors have resulted in a greater radiogenic strontium loss from the central zone, compared to the contact zone, is the most likely explanation for the anomalous

Isochron diagram for the felsic rocks from E.R.P.M., Derdepoort and Lobatse.

Figure 4.2



results. As shown in Table 4.1, the central zone samples all have major amounts of orthoclase, while those on the contact have none, being mainly composed of mica, albite and quartz. As already mentioned, orthoclase has a poor Sr retention capability, and the loss of strontium is usually caused by some thermal event (Arriens et al., 1966). Thus it appears that such an event might have occurred after solidification resulting in an open system, during which the orthoclase lost part or all of its radiogenic strontium, and the micas and plagioclases lost minor or negligible amounts. The apparent age of the orthoclase rich samples could give the time when this thermal event ceased. Alternatively, there has been gradual strontium loss through time; in both cases the apparent age of the contact zone samples is a minimum age for the sills. Point H75II lies so far off the line because it has a very high rubidium content in the orthoclase and proportionally more radiogenic strontium was generated and lost, compared to the other central zone specimens.

This brings in the problem of the reliability of the results. According to the preferred interpretation, the apparent age of the central zone specimens does not represent the age of the sills. However, the age given by the contact zone samples of 2137 m.y. agrees very well with the 2150 m.y. age determined by Crampton (1973) for some undifferentiated felsites within the felsic rocks above the mafic phase of the Ventersdorp lavas, in the north west Transvaal. The results of Crampton (1973) are co-linear with the results of Snelling and Rex (1967), (see Table 4.2 and Figure 4.2) for the Plantation quartz porphyry sill, near Lobatse in Botswana.

Table 4.2

Rb-Sr ratios for rocks possibly related to the aplite

<u>Sample</u>		<u>Rb</u> <u>ppm</u>	<u>Sr</u> <u>ppm</u>	<u>$^{87}\text{Rb}/^{86}\text{Sr}$</u>	<u>$^{87}\text{Sr}/^{86}\text{Sr}$</u>	<u>Individual</u> <u>ages*</u> <u>m.y.</u>
Plantation sill	(1)	356	19,85	16,60	2,6375	2197
Plantation sill	(1)	340,6	24,11	43,35	2,0578	2175
Plantation sill	(1)	225,8	11,94	65,67	2,742	2173
FJC 8 Derdepoort	(2)	253,6	10,7	86,15	3,314	2127
HP 1 Derdepoort	(2)	196,5	6,6	114,26	4,116	2102
HP 2 Derdepoort	(2)	146,9	5,6	97,46	3,638	2115

(1) Snelling and Rex (1967)

(2) Crampton (1973)

* Calculated by the writer using an initial ratio of 0,728 which is the ratio determined for the contact zone.

These two occurrences, which are more than a hundred kilometres apart, and are over 260 kilometres from E.R.P.M., also have high initial ratios but not necessarily the same, and it seems likely in view of their similar apparent ages that they are related in origin.

This would mean that around 2100 m.y. ago there was a widespread but minor event, when felsic material was rapidly injected as sills and dykes, and possibly even extruded. This seems more likely than Crampton's (1973) suggestion that the ages represent a partial resetting of the radioactive clocks during the emplacement of the Bushveld Complex. Such a resetting would demand that the rocks further away would give the oldest age (Hart et al., 1966) and those nearest the youngest; such a spread is not observed. In Table 4.3 the determined radiometric date has been inserted in a stratigraphic column of other radiometric dates, where it occurs between the Ongeluk lavas of the Transvaal system and the Bushveld rocks. In such a position it might be tentatively correlated with the

Plot of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio versus age.

Figure 4.3

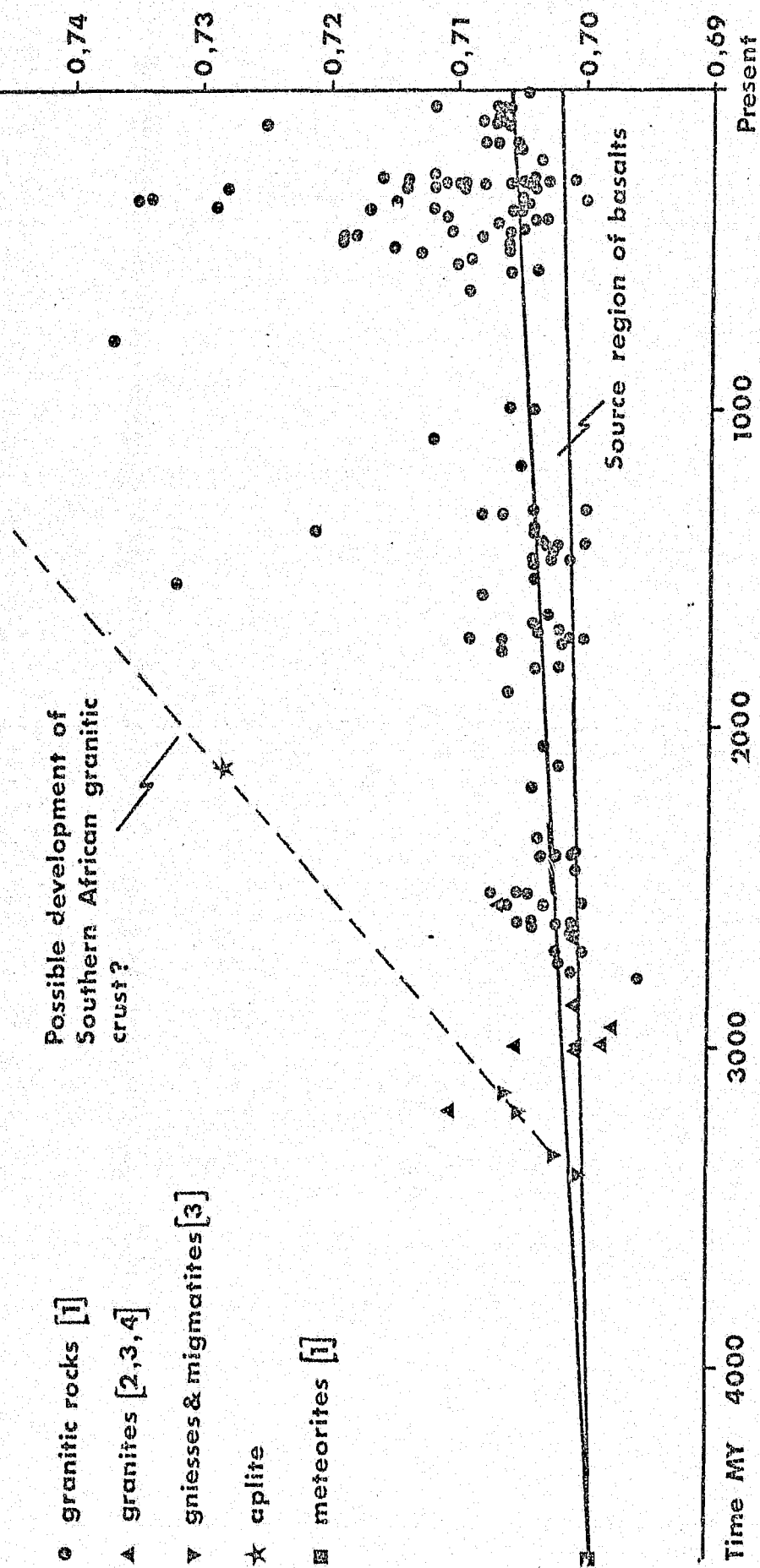


Figure 4.3

Plot of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio versus time after Faure and Powell (1972).

The triangle symbols are for granitic rocks from the Eastern Transvaal and Swaziland.

References

- (1) Faure and Powell (1972)
- (2) Allsopp and Koble (1965)
- (3) Davies and Allsopp (1975), samples from the Ancient Gneiss Complex
- (4) de Gasparis (1967)

acid rocks at Dullstroom in the Transvaal, which are the uppermost unit of the Transvaal system (Button, 1973).

Table 4.3

Position of the aplite in the radiometric stratigraphic column in Southern Africa

<u>System</u>	<u>Rock Type</u>	<u>Method</u>	<u>Age in m.y.</u>	<u>Reference</u>
BIC	Bushveld Granite (zircon and biotite)	U-Pb Rb-Sr	1950 $\pm$ 51	Nicolaysen et al. (1958)
BIC	Gabroic rock in mafic phase (biotite)	Rb-Sr	2050 $\pm$ 51	Nicolaysen et al. (1958)
Transvaal (?)	Aplite sills (whole rock)	Rb-Sr isochron	2100 $\pm$ 0,5	Snelling and Rex (1967), Crampton (1973) This work
Transvaal	Ongeluk lavas (whole rock)	Rb-Sr isochron	2224 $\pm$ 21	Crampton (1973)
Ventersdorp	Quartz porphyry (zircon)	U-Pb	2300 $\pm$ 100*	van Niekerk and Burger (1968)
Ventersdorp	Felsites (whole rock)	Rb-Sr isochron	2318 $\pm$ 43	Crampton (1973)
Ventersdorp	Mica tuffs - 2 samples (whole rock)	Rb-Sr	2330	Wyatt (unpublished)

* Form of error not given

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is a useful indicator of the petrogenesis of the sills. Rocks with a high value for the ratio may be derived from (1) remelted rock; (2) magma which has been heavily contaminated by older rocks through which it passed; or (3) rocks which have been re-homogenised in situ by some thermal event (Allsopp, 1974, personal communication, Moorbath and Bell, 1965, Faure and Powell, 1972, Lussiaa-Berdou-Polve and Vidal, 1973). Considering that the ratio is well above the mantle evolution trend (Faure and Powell, 1972; Figure 4.3), it is unlikely that the sills represent contaminated differentiated mantle material such as is commonly found at the top of a magmatic suite. Also, as there is no

evidence of metamorphism of the sills, re-homogenisation seems unlikely. Thus it appears that the sills are derived from the remelting or partial melting of some pre-existing rock; considering the petrology and chemistry of the sills, this source rock is likely to be the granite basement which underlies the Witwatersrand system. The heat source that caused the anatexis is possibly related to the preliminary thermal activity that must have proceeded the Bushveld Igneous Complex.

A rough estimate of the age of the postulated source rock can be obtained by calculating weighted average abundances of rubidium and strontium from the distribution curves across the sills and then calculating the approximate $^{87}\text{Rb}/^{86}\text{Sr}$ ratio for the sills ($^{87}\text{Rb} = \text{Rb}/2,6$, $^{86}\text{Sr} = \text{Sr}/10,4$; 2,6 and 10,4 are average isotopic ratios experimentally determined). These numbers together with an assumed initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the granitic source rock of 0,705 (based on the work of Davies and Allsopp, 1975) plus the determined initial ratio of the sills gives a single, int age for the source rock prior to the local anatexis. As rubidium is preferentially taken into a partial melt, these give calculated ages that tend to underestimate the true age. The results of these calculations are given in Table 4.4.

Table 4.4

Results of calculations for the age of the source rock

<u>Sill No.</u>	<u>Chemical traverse</u>	<u>Estimated $^{87}\text{Rb}/^{86}\text{Sr}$</u>	<u>Age at time of intrusion m.y.</u>	<u>Apparent age of formation w.r.t. present m.y.</u>
1	BC7	1,416	1159	3298
3	BC5	1,762	933	3070

The ages agree with other radiometric dates obtained from granitic basement in South Africa and Swaziland (ranging from 2800 - 3400 m.y., Davies and Allsopp, 1975).

The occurrence of such high primary ratios is rare, more so considering the age of the rock. This is clear from Figure 4.3 in which the primary ratio of the sills is plotted against time; together with other available data. However, if the rocks in the N.W. Transvaal and Botswana are related in their origin to those in the Witwatersrand, they might give lower initial ratios because of the large amounts of granite with an age of 2700 m.y. (Crampton, 1973, Allsopp, 1974, personal communication) which have low initial ratios.

5. CHEMISTRY

The geochemical work on the aplite sills was done with the main aim of providing information on the generation of the magma and its cooling history once it had been emplaced; results should also support petrological and isotopic work.

5.1 Sample selection and method of analysis

In order to compare the individual sills, samples were selected from typical central zone material of all sills, and abnormal features within the sills. To study the chemical variations due to cooling, a large number of samples taken at intervals across the sills were analysed.

In the first case, the samples selected from the central zone were all greater than 2 kilograms and had no signs of secondary alteration. One or more samples were taken from each sill, except for Sill No. 2, which was too altered, and Sill Nos. 5 and 7. Samples of similar size and freshness were taken of any abnormal feature.

The five traverses were taken across three of the sills (Nos. 1, 3 and 6). Four of the sample traverses were from diamond drill cores, and the fifth was collected from an exposure in a stope. The samples collected in the stope were 1 - 2 kilograms in weight; two of the borehole cores were sampled at regular intervals across the sills (BC1 and BC3) with samples weighing between 200 - 300 grams, but the other two cores (BC5 and BC7) were sampled with greater emphasis on the contact zone, and the sample size reduced to a minimum of 20 - 30 grams. These very small samples were taken to ensure complete coverage of the variation in the contact zone, which, being only 10 centimetres wide would have been contained in a single 300 grams sample. Sizes of 20 - 30 grams are much smaller than those recommended by Wager and Brown (1960) in order to achieve a representative sample, but the results obtained are consistent within the aplite for most elements. The adjacent quartzites were sampled

in a similar manner to study possible metasomatic effects of the sills. Samples weighed about 100 grams, but the results of the analyses are not consistent for most elements.

The preparation of the selected samples has been described in Section 4.1. The analytical procedures used are those of Norrish and Chappel (1967) and Norrish and Hutton (1969), as used in the Geology Department of the University of the Witwatersrand (McCarthy, 1975). The specific conditions and techniques used are listed in Appendix B.

5.2 Results

The detailed analytical results are listed in Appendix B. From this data, some major element chemistry, together with the analyses of the acid intrusives occurring in the Johannesburg-Pretoria granite dome (felsitic and microgranitic dykes), (Anhaeusser, 1973) were subjected to an R, Q mode analysis using a cluster computer programme written by B. Wishart, Computing Laboratory, University of St. Andrews. The parameters used in this cluster analysis are weight per cent SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O and P_2O_5 and the technique has been described by Lenthall (1972). The results of the analysis showed that the rocks clustered into the following four groups (at a distance coefficient of 5):-

1. All samples of central zone material, for all sills except for 9 and 10.
2. All contact zone samples (i.e. within 10 centimetres of the contact).
3. A group of four analyses, consisting of samples from Sill Nos. 9 and 10 together with the granitic intrusives in the granite dome.

Table 5.1

Average compositions of the four groups of the cluster analysis

	<u>Central Zone</u>	<u>Contact Zone</u>	<u>Sills 9 and 10 plus microgranite intrusions</u>	<u>Felsic Dykes</u>
SiO ₂	74,12	77,48	70,98	75,28
TiO ₂	0,06	0,07	0,29	0,05
Al ₂ O ₃	13,29	12,98	13,97	13,57
Fe ₂ O ₃	0,18	0,59	0,97	0,22
FeO	1,06	0,80	2,33	0,70
MnO	0,04	0,03	0,07	0,03
MgO	0,90	0,61	1,32	0,12
CaO	0,43	0,44	2,39	0,31
Na ₂ O	6,61	1,92	3,56	4,11
K ₂ O	2,95	3,43	2,62	5,05
P ₂ O ₅	0,05	0,05	0,09	0,01

Table 5.2

Statistics of the average composition of the central zone samples

	<u>Mean %</u>	<u>Std. Dev. %</u>	<u>Range %</u>	<u>No. of samples</u>
SiO ₂	74,12	0,61	71,52-75,94	20
TiO ₂	0,06	0,00	0,05-0,06	20
Al ₂ O ₃	13,28	0,66	12,77-16,14	20
Fe ₂ O ₃	0,18	0,18	0,00-0,74	19
FeO	1,06	0,34	0,57-1,29	19
*MnO	0,04	0,02	0,02-0,06	20
MgO	0,90	0,21	0,17-1,14	20
CaO	0,43	0,44	0,10-1,91	20
Na ₂ O	6,61	1,04	3,83-8,96	20
K ₂ O	2,95	1,04	0,22-3,82	20
H ₂ O ⁺	0,17	0,17	0,01-0,69	20
H ₂ O ⁻	0,02	0,02	0,00-0,23	20
*P ₂ O ₅	0,05	0,00	0,04-0,06	20
CO ₂	0,38	0,34	0,10-1,53	20
F	0,12	0,03	0,03-0,18	20
Cl	0,01	0,009	0,00-0,04	20
S	0,02	0,04	0,00-0,15	20
Rb	87 ppm	46 ppm	44-178 ppm	13
Sr	67 ppm	21 ppm	25-86 ppm	13
Au	0,28 ppm	0,05 ppm	0,12-0,58 ppm	4
Na ₂ O/K ₂ O	2,24	8,8	0,19-40,73	20
Per Alkaline Index	1,07	0,11	0,64-1,17	20

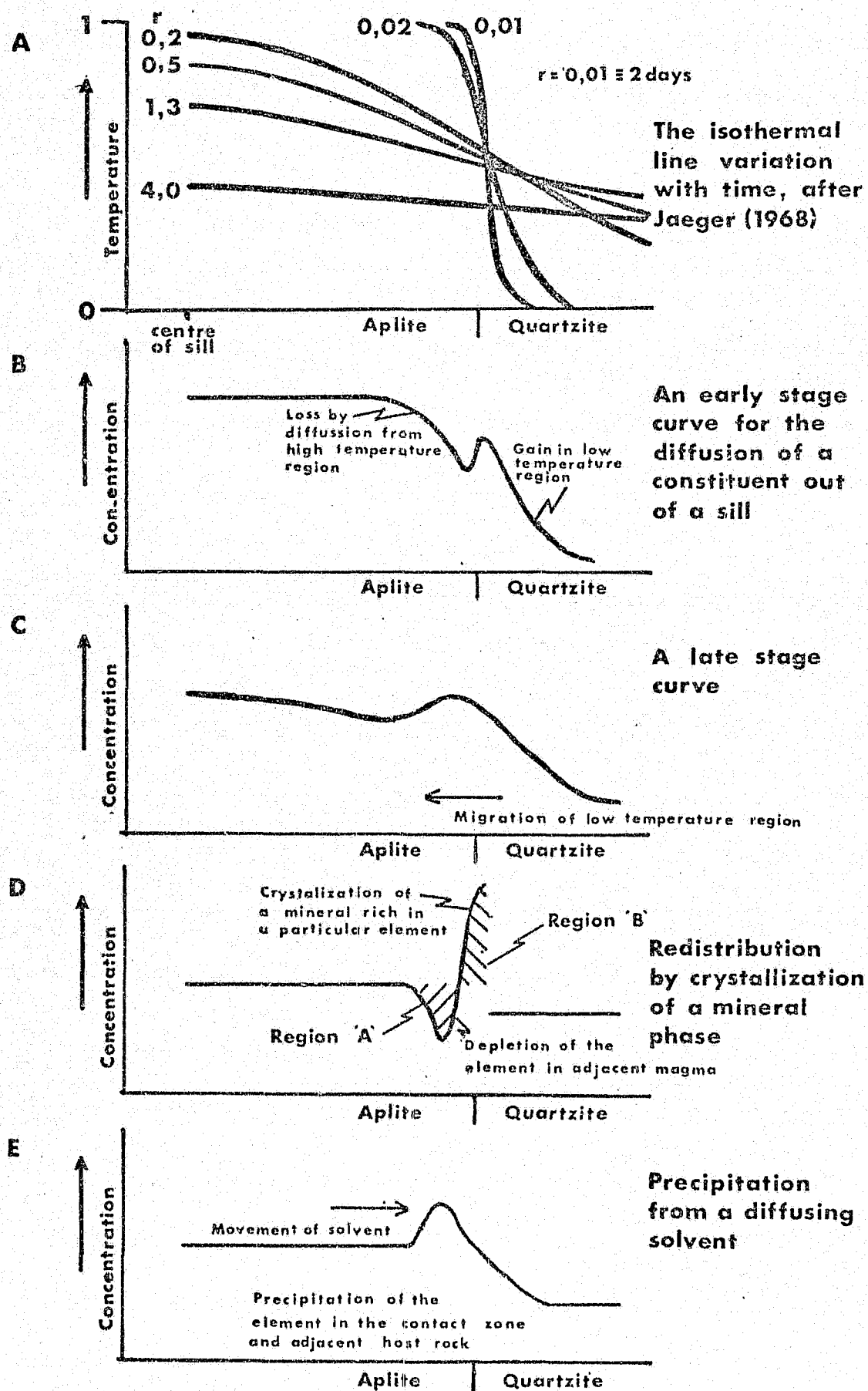
* Concentrations at or near the detection limit

Table 5.3

The C.I.P.W. norm for the average central zone sample

<u>Mineral</u>	<u>WT %</u>
Calcite	0,89
Pyrrhotite	0,04
Ilmenite	0,11
Orthoclase	17,23
Albite	51,39
Acmite	0,69
Na Metasil	0,75
Enstatite	2,29
Ferrosilite	1,92
Quartz	24,01
Fluorite	0,73
Total	<u>100,1</u>

The concentration variation at the contact due to different processes, idealized. Figure 5.1



4. A group of four analyses consisting of the samples from the felsic dykes in the granite dome.

In other words, the rocks divided into the original sample groups and not into individual sills, except for sills 9 and 10. This suggests that the sills cannot be distinguished on the major elements used in the analysis. The average chemistry of the four groups are listed in Table 5.1. The average chemistry of the central zone samples together with the standard deviations and ranges of the constituents are listed in Table 5.2. Table 5.3 gives the calculated C.I.P.W. norms for the average central zone material.

From the variation in chemistry across the sills, it is possible to speculate on the gross movements of a number of constituents, listed in Table 5.4. This information is inferred from the detailed distribution curves of the constituents across the sills (Appendix B, Figures I - XVI). The method of inference is illustrated in Figure 5.1, where various models for diffusion of elements of the sills into adjacent wall rock are considered. These models are seriously affected by temperature and rate of cooling as shown in Figure 5.1A for several theoretical curves with different ' $\sqrt{t}$ ' values (defined in the list of symbols). Because the temperature governs the mobility of all constituents, and the crystallisation of the various phases, the magnitude of the diffusion curves (Figure 5.1B, 5.1C) will be reduced, and broadened, as they move towards the centre of the sills in response to the falling temperature. In Figure 5.1D the high and low concentrations near the contact are the result of the crystallisation at the contact of a mineral containing a higher concentration of the constituent than the magma as a whole, so in order to crystallise the mineral some portion of the magma will be depleted in that constituent. If the areas 'A' and 'B' are equal, it is

Table 5.4

Gross movement of elements

<u>Net Loss</u>	<u>Net Gain</u>	<u>Re-adjustment by crystallisation and/or a density contrast or some other process</u>
Silica	Aluminium (?)	Aluminium
Sodium	Iron	Calcium
Potassium (?)	Magnesium	Sodium Potassium
Water	Calcium (?)	Water
Carbon Dioxide	Potassium (?)	Carbon Dioxide
Chlorine	Carbon Dioxide (?)	Strontium
Fluorine	Sulphur	Rubidium
Rubidium	Gold (?)	

Elements which show a decrease in concentration from the adjacent
quartzite towards the aplite sills are:-

Aluminium
Iron
Carbon Dioxide
Sulphur
Gold (?)

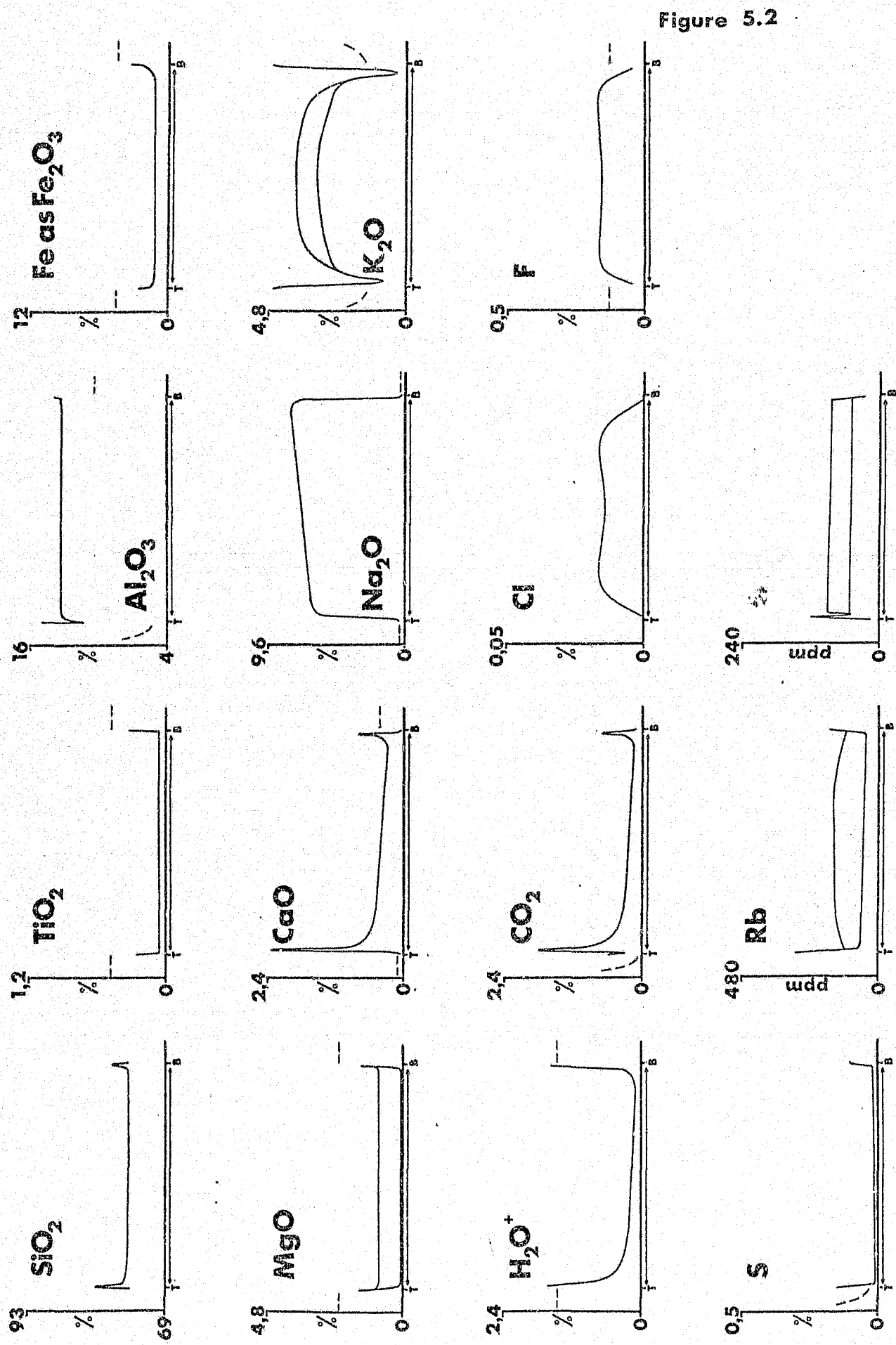


Figure 5.2

Figure 5.2

The generalised concentration curves across the sills for the major elements above their detection limits, and some trace elements. The detailed data is illustrated in the figures in Appendix B.

The solid line is the concentration of the constituent within the sill; two lines mark the different levels of concentration the particular constituent can have. The dashed line is the approximate concentration in the adjacent quartzites. The line with arrow heads between the symbols 'T' and 'B' marks the extent of the sill between the top and bottom contact.

inferred that there has been no loss or gain in the total amount of the constituent within the sill during the crystallisation. Figure 5.1E shows the form of the distribution curve for an element precipitated from a diffusing solvent at the cold contact and possibly in the adjacent quartzite. The specific constituents will be discussed in turn to evaluate these concepts.

5.2.1 Silica

Though silica is taken into an anatectic melt in large quantities, its distribution is shown in Figure 5.2 and in detail in Appendix B, Figure I. The highest concentrations are in the contact zones with the central zone having an approximately constant amount. The upper contact zone has a more pronounced maximum which appears to be unrelated to the silica concentration of the adjacent quartzite.

5.2.2 Titanium

During an anatectic process titanium is left in the residual component of the source rock (Mehnert, 1968, p.251), so that its concentration in a melt should be small. Figure 5.2 shows its distribution within the sills is markedly constant, with no sign of a redistribution; though the small samples in contact with the quartzite do show a sharp increase.

5.2.3 Aluminium

During anatexis aluminium is evenly distributed between the melt and the residual component of the source rock (Mehnert, 1968, p.261) and like silica, its distribution curve is unaffected by the aluminium concentration in the adjacent quartzites. A noticeable feature of the maxima and minima which occur in the contact zone, is that those in the lower contact zone are insignificant, while those in the upper contact zone are pronounced. The area contained in the maximum peak (i.e. area 'B' Figure 5.1) is

roughly equivalent to the area contained in the minimum peak (i.e. area 'A', Figure 5.1); which probably means there has been no appreciable loss or gain of aluminium. However, the concentration in the adjacent quartzites decreases towards the contact, and from the shape of the curve it appears that there has been a net gain of aluminium by diffusion.

5.2.4 Iron

Iron is a very refractory element (Mehnert, 1968, p.251) and so its concentration would be low in an anatectic melt. As for titanium, the total concentration is constant within the sills, except for the small increase near the contacts. This is supported by the small decrease in the iron content of the quartzites towards the contact.

5.2.5 Magnesium

Magnesium is the element with the most pronounced refractive habit during anatexis (Mehnert, 1968, p.251) and, like iron, it also shows an increasing concentration towards the contact. Within the central zone there are two distinct levels of concentration; one at 0,8%, the other at approximately zero. There is no correlation between the level of concentration and a sampling group or any particular sill.

5.2.6 Calcium

Calcium can be either concentrated (Mehnert, 1968, p.251) or depleted (James and Hamilton, 1969) in a melt. The distribution of calcium within the sill (Figure 5.2) shows the smallest concentration immediately adjacent to the contact, with a pronounced maximum a short distance from the contact. The maximum in the upper contact zone is 2,5 times greater than in the lower contact zone. This difference with the increasing calcium concentration towards the top of the central zone and the large difference in area within the maximum and minimum peaks shows

that there has been considerable movement of calcium.

5.2.7 Sodium

Sodium like silica is taken into an anatectic melt in large quantities but the amount is strongly controlled by the environmental conditions of the source region. In the sills negligible concentrations of sodium occur on the contact of the sills (Figure 5.2) but these rapidly increase to a maximum 10 - 15 centimetres from the contact, the greatest amounts being near the lower contact.

5.2.8 Potassium

The amount of potassium taken into an anatectic melt is generally inversely related to the amount of sodium. The distribution within the sills (Figure 5.2) has large positive and negative peaks near the contacts, but the area within the negative peak is considerably larger than that within the positive peak indicating potassium loss from the sills but the concentrations in the quartzite suggest contamination of the sills. The concentration within the central zone is not uniform, rather, the various traverses show a number of levels of potassium concentration. (See Appendix Figure IX).

5.2.9 Water

Water probably gets concentrated in the melt during anatexis, and its distribution in the aplite (Figure 5.2) follows, as expected, the mica distribution (Figure 3.1), in that the maximum concentration is in the contacts, and the minimum in the central zone. The concentration in the central zone tends to increase upwards.

5.2.10 Carbon dioxide

Carbon dioxide forms part of the volatile phase that is generally assumed to be concentrated in a melt. The distribution within the sills (Figure 5.2) is very similar to calcium. However, the carbon dioxide

concentration in the adjacent quartzites decreases towards the aplite, which suggests that the aplite has been contaminated by carbon dioxide.

5.2.11 Chlorine

Chlorine is also part of the volatile phase and the wide scatter of concentrations cannot be due to inaccuracies in determination. A crude idealised distribution shows minima 10 - 15 centimetres from the contact and in the centre of the sills, with maximum concentrations towards the upper and lower limits of the central zone.

5.2.12 Fluorine

Fluorine behaves similarly to chlorine in peralkaline rocks but is more mobile (Noble et al., 1967) which results in a higher initial concentration in the melt and a proportionally greater loss on crystallisation. The distribution in the sills is similar to chlorine except the concentration is about ten times larger, and is detectable in the quartzites.

5.2.13 Sulphur

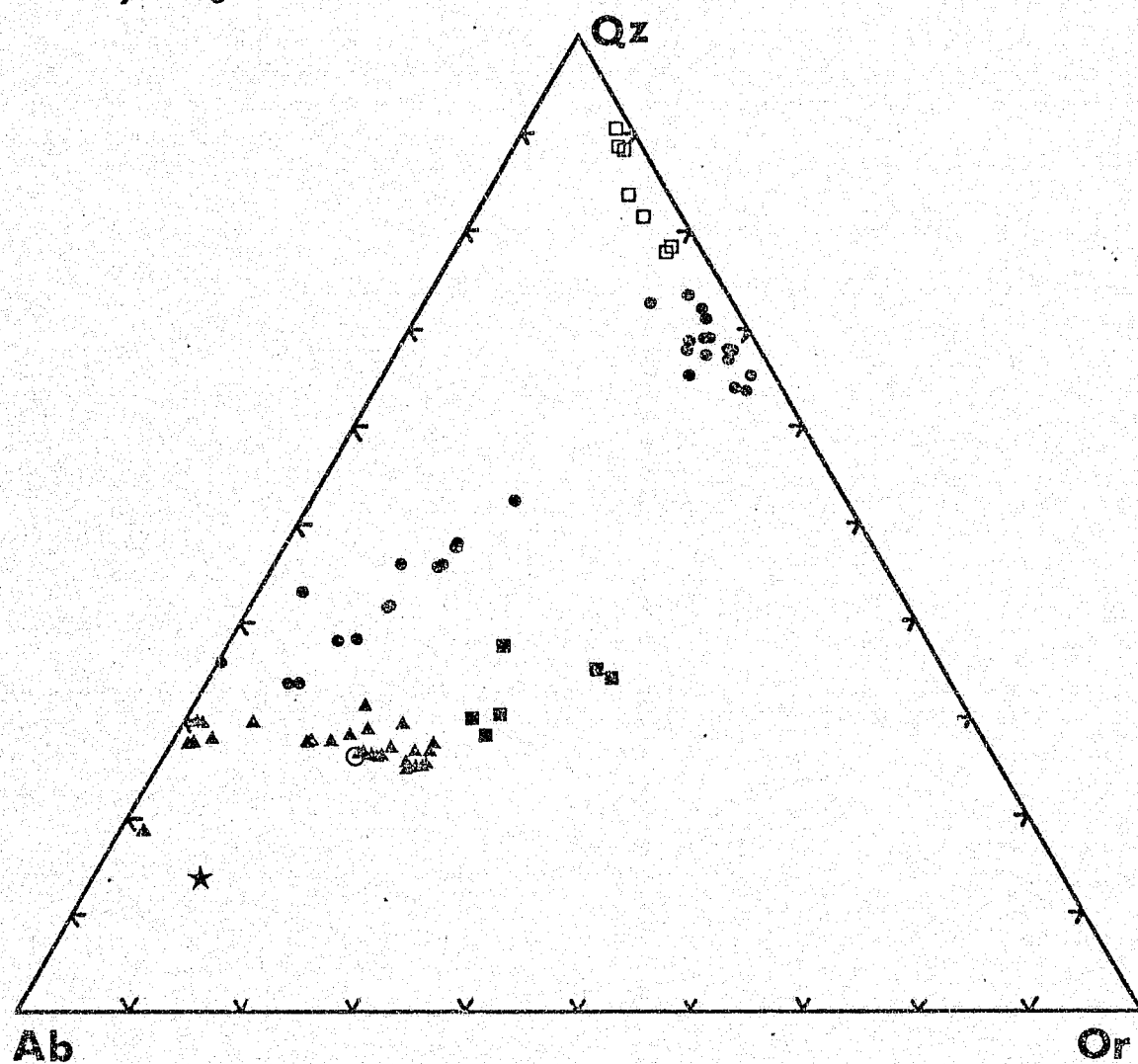
Sulphur which generally is present in negligible amounts in the sills, shows a marked increase in concentration at the contacts with a corresponding decrease towards the contact in the adjacent quartzites. The maximum concentration at the top contact is marginally larger than the maximum at the bottom, which suggests that some movement of sulphur within the sills may have occurred.

5.2.14 Rubidium

Rubidium is an incompatible element and, as such, it is preferentially concentrated in an initial melt during anatexis or the final melt fractionation (Heier, 1970). Within the aplite there are two levels of concentration in the central zone, and though the distribution within

Position of central & contact zone samples in the quartz-albite-orthoclase ternary diagram.

Figure 5.3



▲ central zone

• contact zone

★ associated felsic intrusive

○ aplite sill from City Deep, Weber 1909

■ acid intrusives in the Johannesburg - Pretoria dome, Anhaeusser 1973

□ adjacent quartzite in E.R.P.M.

the sill was expected to be similar to potassium, because of the similar atomic properties, it lacks the large negative peak.

5.2.15 Strontium

Strontium should correlate with sodium in the albite grains (Nagasawa and Schnetzler, 1971) and to a lesser degree with calcium, because of the atomic radius and ionic charge, but the distribution curve (Figure 5.2) shows a slight correlation with calcium and not sodium.

5.3 Possible causes of variations

A number of processes can potentially explain the chemical variations observed within the sills. These are: (1) fractionation; (2) diffusion down a temperature gradient or across a concentration change; (3) transportation as a solute in a more mobile phase; (4) taken into an early mineral phase, crystallising at the contact, or (5) movement by density contrast.

- (1) In figure 5.3 all the data are plotted on a quartz-albite-orthoclase diagram; where the composition of the aplite moves towards the albite corner as the distance from the contact increases. If fractionation was the operative process the composition should follow the reverse path, that is, away from the albite corner (Tuttle and Bowen, 1958). For this reason fractionation is ruled out as a possible process.
- (2) Diffusion down a temperature gradient should result in an exponential distribution curve. Such a process is thought to account for a number of element variations reported here, namely, sodium in the contact zone, chlorine, fluorine and possibly potassium and water. The diffusion of sodium might

have occurred at high temperatures, while part of the sill was still molten in order to account for the narrow zone that is affected. The movement of chlorine and fluorine have been studied by a number of workers who found that peralkaline rocks have high initial concentrations (Lovering, 1966; Zies, 1960; Noble et al., 1967) which are nearly completely lost on crystallisation (Noble et al., 1967); while the distribution across the sills suggests that there might have been some loss.

The form of the distribution curve for diffusion down a concentration gradient is also exponential, either out of the sills or into the sills. A number of constituents could be explained by such diffusion out of the sills, namely:- calcium in the immediate contact zone, sodium and chlorine. Constituents that may have moved into the sills by such a process are:- titanium, iron, magnesium, potassium (?) and sulphur.

- (3) A volatile phase, consisting of water, chlorine, fluorine and possibly carbon dioxide could have transported some constituents out of the sills and precipitated them in the cooler contact zone; these constituents are silica, potassium, rubidium and possibly sodium to some extent.
- (4) The oxides thought to be redistributed by initial crystallisation of minerals at the contact are Al_2O_3 , K_2O and H_2O . The major mineral phases at the contact consist of muscovite and biotite which are rich in these three oxides. Also the crystallisation of plagioclase seems to have adjusted the concentration of calcium and indirectly carbon dioxide.

- (5) The oxides which have moved in response to a density contrast are calcium oxide, carbon dioxide and sodium oxide. The first two are concentrated in the top contact of the sills, while sodium oxide is concentrated in the bottom of the sills.

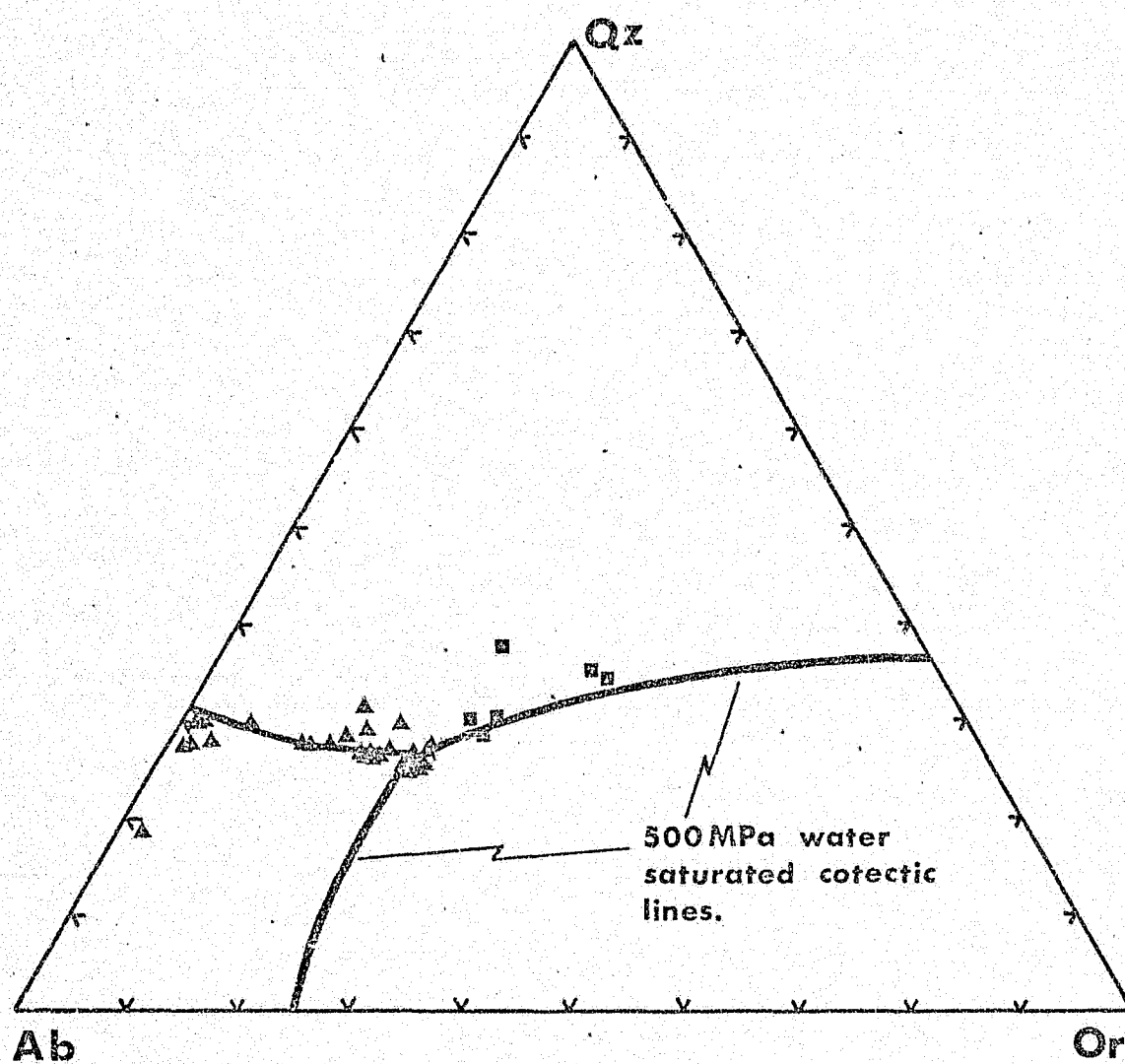
Besides the variations across the sills, magnesium, potassium, rubidium and strontium have two distinct concentration levels within the central zone. Potassium appears to be correlated with rubidium and inversely with strontium, but the magnesium concentration is independent of the concentration of the other elements. This variation in chemistry is thought to be a primary feature of the magma, and the different concentration levels indicate that the magma is relatively unmixed. Further evidence of unmixing is provided by the distribution of the red aplite, which occurs in small regions covering the total thickness of the sill. However, partial mixing of red and grey aplite can be seen in the non-laminar texture shown in Plate 3.11. These various magma compositions have probably not been injected immediately after generation; rather, they probably remained in an unmixed state in the source region.

5.4 Origin of the magma

The isotopic work suggested that the aplite sills were possibly derived from the melting, or partial melting of basement granitic rocks, which were approximately 3200 m.y. old. The leucotonalite gneisses of the Ancient Gneiss Complex seem particularly important source rocks (Figure 4.3). However, Noble (1968) and Bailey and Schairer (1966) agree that peralkaline rocks, such as these aplite sills, cannot be derived from such sub-aluminous granitic rocks; although Bailey and Schairer (1966) say that a peralkaline rock could be generated from a sub-aluminous rock, by extensive fractionation of anorthite out of a

Position of central zone samples
with respect to experimental
work.

Figure 5.4

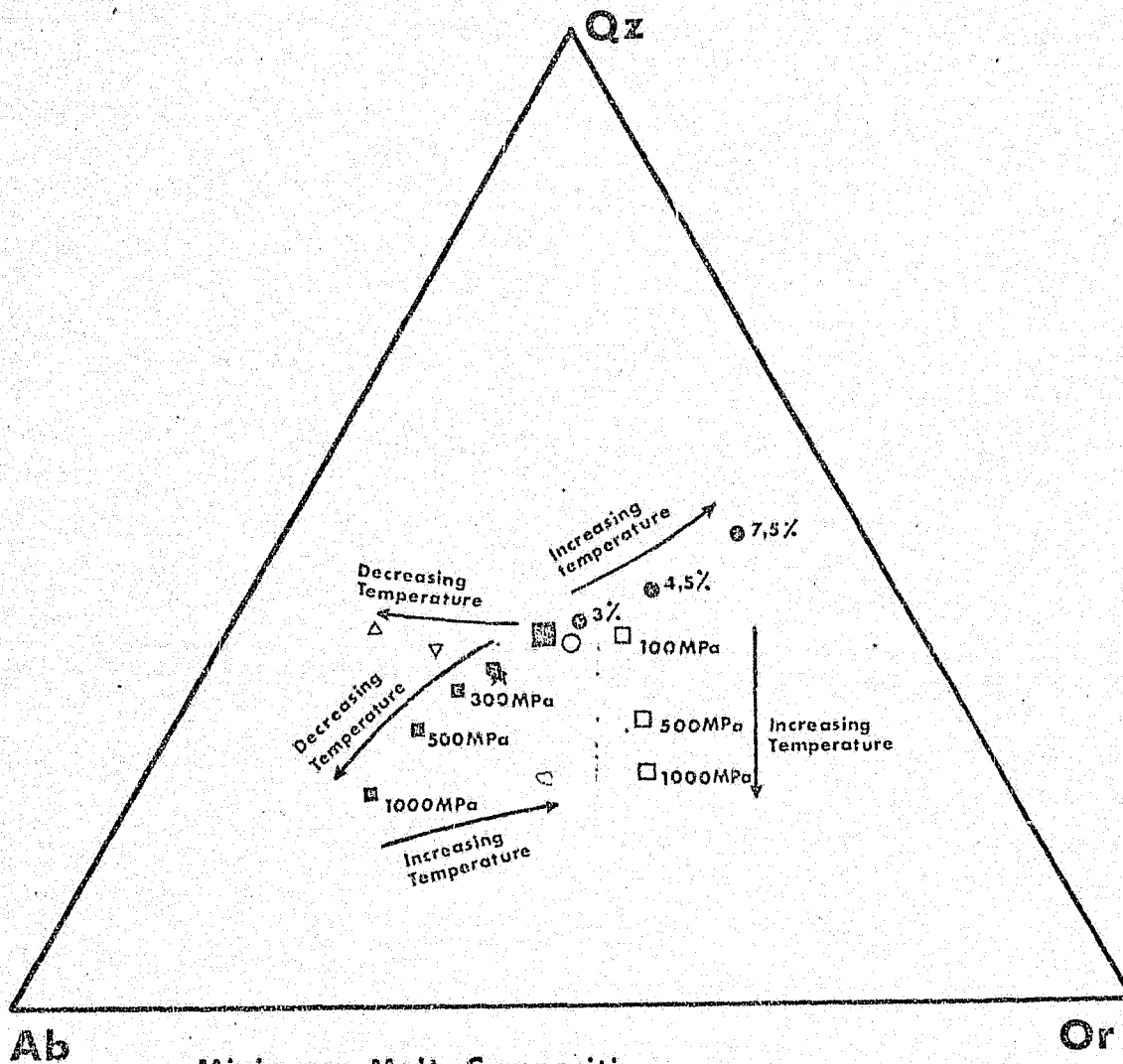


▲ central zone samples

■ acid intrusive in the granite dome

The experimental curves are taken from
Luth et al (1964).

Figure 5.5



Ab

Minimum Melt Composition

Or

- water saturated at 100 MPa [1]
- water saturated [1 2]
- anhydrous [3]
- percentage anorthite content and water saturated at 100 MPa [4]
- ★ 5% Na_2SiO_3 water saturated at 100 MPa [5]
- ▽ 5% NaKSiO_3 water saturated at 100 MPa [5]
- △ 5% K_2SiO_3 water saturated at 100 MPa [5]
- 5% NaFeSiO_8 water saturated at 100 MPa [5]

Figure 5.5

Changes in the minimum melt composition with confining pressure and small changes in composition of the source material. The melt compositions are projected onto the quartz-albite-orthoclase ternary diagram from the apex of the relevant tetrahedron. In the case of anorthite content the points plotted are the piercing points, with the minimum melt plotting towards the anorthite free minimum melt composition.

Changes in the temperature of initial melting with the changing conditions is also plotted.

References

- (1) Tuttle and Bowen (1958)
- (2) Luth et al. (1964)
- (3) Luth (1969)
- (4) James and Hamilton (1969)
- (5) Thompson and MacKenzie (1967)

magma but is unlikely.

The temperature-pressure conditions during anatexis can be deduced by comparing the chemistry of the aplite with temperature-pressure conditions during experimental work done on the 'granite' and related systems. The composition of the central zone samples plot on the ternary eutectic point and the quartz-albite cotectic line of the saturated quartz-albite-orthoclase system at 500 MPa (Figure 5.4), determined by Luth et al. (1964). If this represented the conditions of the source region during anatexis it would mean that the composition of the aplite magma corresponded to the eutectic composition. When potassium was exhausted in the source region the composition of the magma would move along the quartz-albite cotectic line, as appears to be the case for the aplite. This means that the potassium concentration must have been less than the sodium concentration in order to be exhausted first.

Because of the number of parameters that affect the system, it is unrealistic to assume that the conditions of the source region are this simple. The effect of increasing pressure on the saturated system, considered above, is to move the cotectic minimum/tertiary eutectic towards the albite corner (Tuttle and Bowen, 1958; Luth et al., 1964).

In an anhydrous system, the cotectic minimum also moves away from quartz (Luth, 1969) but not as far as the saturated system for equivalent pressure increases. This means that in an unsaturated system, the minimum melt composition should lie between the saturated and anhydrous compositions.

The effect of other variables studied experimentally is summarised in Figure 5.5. The points plotted for increasing anorthite content are piercing points, and not projected eutectic compositions, as is the case for the other points and, thus, they only represent the composition of

Figure 5.6

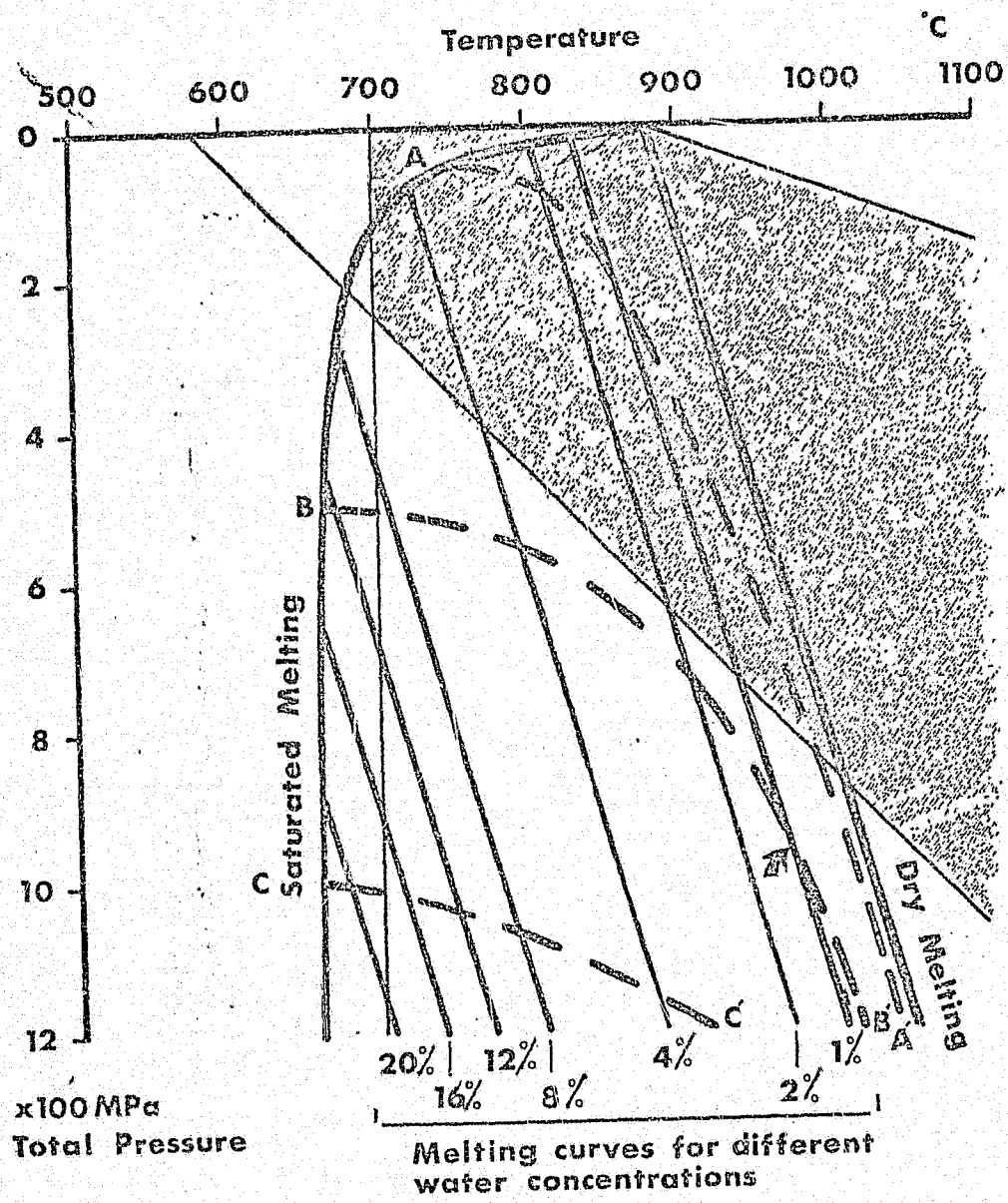


Figure 5.6

The effect of increasing temperature and pressure on the undersaturated melting lines in the 'granitic' system and consequently the variation in the partial pressure of water, after Brown (1970).

The saturated melting and the dry melting curves have been established experimentally, while the undersaturated melting curves have not. The curves A - A', B - B' and C - C' are the curves along which the partial pressure of water is constant. These have not been determined experimentally, but must be asymptotic to the dry melting curve and should intersect the saturated melting curve at a total pressure equal to the partial pressure. The curves are for partial pressures of 50MPa, 500MPa and 1000MPa respectively.

The pressure temperature conditions for the magma source region were estimated from the intersection of the 500MPa (B - B') constant partial pressure curve with the 1% melting line.

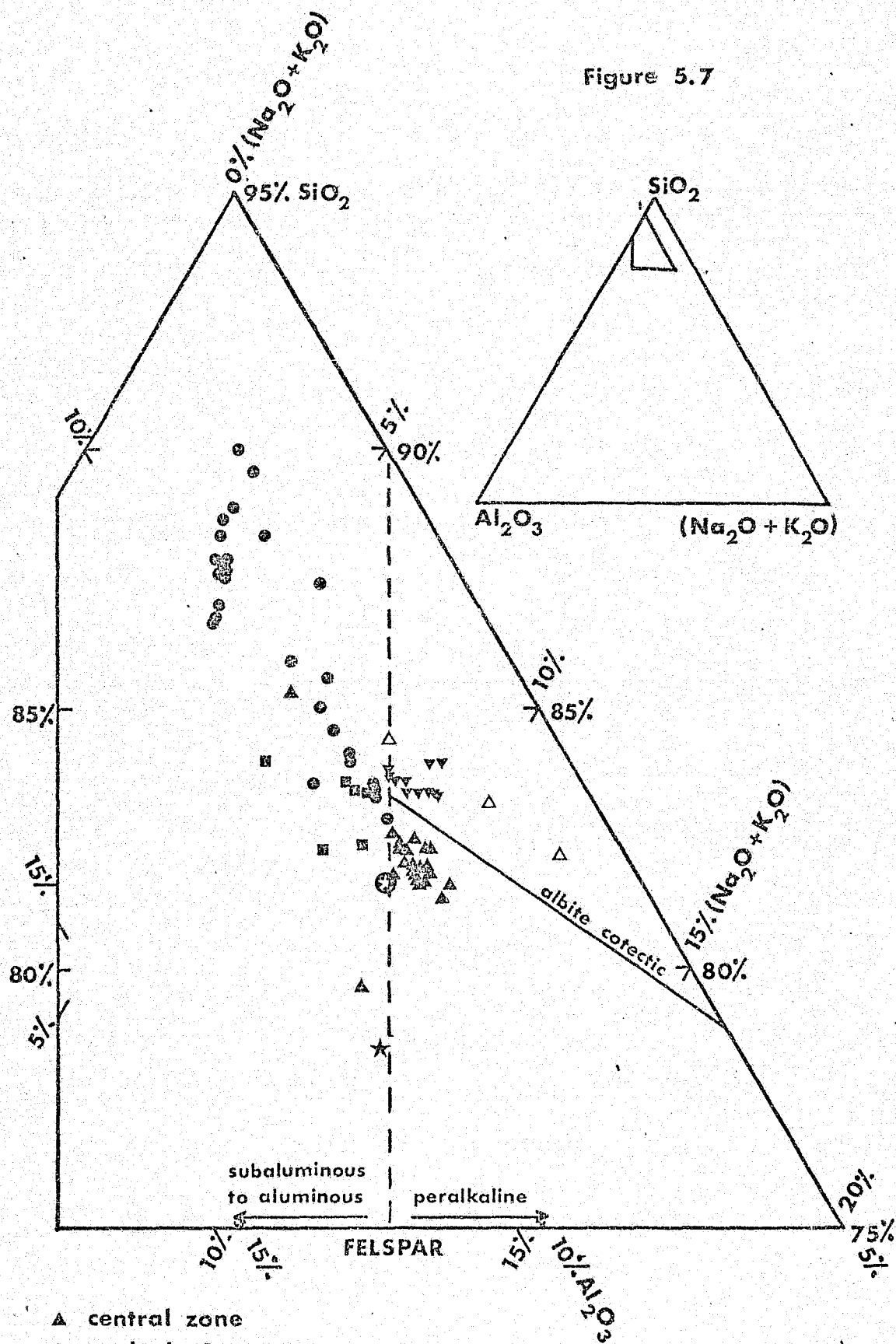
The shaded area is the pressure temperature region for the magma as indicated from the petrology (Figure 3.2). This does not necessarily contradict the conditions for the source region as the magma could have passed through the region indicated by the petrology with the subsequent crystallisation of the quartz and felspar.

the melt at the instant when one of the three phases (quartz-orthoclase-plagioclase) is exhausted. Prior to this, in the case of partial melting, the composition of the melt will plot at some point on the cotectic line with a lower calcium concentration than the original source material represented by the piercing point (Presnall and Bateman, 1973). From Figure 5.5 it can be seen that an increase in calcium content of the source region can be offset by an increase in pressure in the water saturated system or by excess sodium to some extent.

All the results in Figure 5.5, except those of Luth (1969), are for water saturated systems, and at 500 MPa a saturated melt would contain > 8% water (Tuttle and Bowen, 1958). The present water concentration of the central zone samples is less than 0,5% on average indicating that the initial melt must have been undersaturated. This agrees with the comment in Luth et al. (1964), that melts that are undersaturated in alumina as the aplite is, would also be undersaturated in water. Brown (1970) discussed the possibility that all anatectic melts are undersaturated in water.

Approximate temperatures and pressures for the anatectic formation of the aplite magma can be obtained from the theoretical curves of Brown (1970), if it is assumed that the composition of the anatectic melt formed with a partial pressure of water, has the same composition as a saturated melt in terms of quartz-albite-orthoclase (c.f. Figure 5.6). The temperature and pressure is given by the intersection of the constant partial pressure curve, with the melting line for a specific water concentration. In Figure 5.6 the water concentration is assumed to be 1% as the total volatile concentration at present is less than 1%. From this intersection point the conditions under which the aplite magma formed are approximately 950° C and 900 MPa (equivalent to a depth of 34 - 35

Figure 5.7



- ▲ central zone
- contact zone
- acid intrusives in the granite [1]
- ★ associated felsic intrusive
- ▼ continental comendites [2]
- △ eutectic composition [3]
- ⊙ eutectic composition [4]

Figure 5.7

An enlarged portion of the triangular variation diagram for molecular SiO_2 , Al_2O_3 and $(\text{Na}_2\text{O} + \text{K}_2\text{O})$, after Bailey and MacDonald (1970).

References

- (1) Anhaeusser (1973)
- (2) Bailey and MacDonald (1970)
- (3) Carmichael and MacKenzie (1963), reported by Bailey and MacDonald (1970). These eutectic points were determined together with the albite cotectic in a saturated system at 100MPa.
- (4) Luth et al. (1964). This eutectic point was determined at 500MPa in a saturated system.

This diagram shows that the contact zone samples have lost a large amount of alkalis and have moved from the central zone cluster, away from the pure alkali composition. The associated felsic intrusive is displaced towards the feldspar composition, supporting its origin by feldspar fractionation.

The eutectic compositions at 100MPa are parallel to the albite cotectic line and colinear with the continental comendites. It is not known how the cotectic line or eutectic compositions plot at 500MPa under water saturated conditions; therefore it is not known if the central zone cluster plots on a minimum melt composition with excess alkalis.

The dashed line in the figure is the intersection line with Figure 5.4 in the third dimension.

Table 5.5

Average composition of the aplite and possible related rock types

	A	B	C	D	E	F	G	H	I	J	K
SiO ₂	74,12	73,86	74,57	66,15	74,85	70,60	75,28	68,03	76,02	71,08	72,31
TiO ₂	0,06	0,20	0,17	0,62	0,15	0,43	0,05	0,29	0,70	0,04	0,42
Al ₂ O ₃	13,28	13,75	12,58	15,56	11,85	8,72	13,57	13,22	14,60	11,26	10,88
Fe ₂ O ₃	0,18	0,78	1,30	1,36	1,07	2,56	0,22	3,96	0,27	4,28	2,92
FeO	1,06	1,13	1,02	3,42	1,38	4,91	0,70	1,95	0,08	2,19	2,42
MnO	0,04*	0,05	0,05	0,08	0,10	0,23	0,03	0,14	-	0,11	0,14
MgO	0,90	0,26	0,11	1,94	0,01	0,12	0,12	0,02	0,04	0,25	0,16
CaO	0,43	0,72	0,61	4,65	0,33	0,46	0,31	0,59	0,34	0,84	0,68
Na ₂ O	6,61	3,51	4,13	3,90	4,80	6,60	4,11	7,73	7,08	4,92	5,17
K ₂ O	2,95	5,13	4,73	1,42	4,73	4,26	5,05	2,99	0,96	4,21	4,42
H ₂ O ⁺	0,17	0,47	0,66	0,69	0,13	0,19	0,41	0,24	0,34	0,39	0,45
H ₂ O ⁻	0,04	-	-	-	0,04	0,02	0,11	-	0,15	-	-
P ₂ O ₅	0,05*	0,14	0,07	0,21	0,00	0,06	0,01	0,05	-	0,07	0,03
CO ₂	0,38	-	-	-	-	0,00	0,06	-	-	-	-

A	aplite sills from E.R.P.M. (20)	B	alkali granite (48) Nockolds (1954)
C	alkali rhyolite (21) Nockolds (1954)	D	tonalites (58) Nockolds (1954)
E	comendite (3)** Noble (1968)	F	pantellerite (5)** Noble (1968)
G	felsite (4)** Anhaeusser (1973)	H	aegerine aplite (3)** MacDonald et al. (1973)
I	soda aplite Johannsen (1932)	J	peralkaline granite (53) Nockolds (1954)
		K	peralkaline rhyolite (39)
			(20) Refers to number of samples

* Approximate detection limit ** Averaged by the author

Table 5.5

Average composition of the aplite and possible related rock types

	A	B	C	D	E	F	G	H	I	J	K
SiO ₂	74,12	73,86	74,57	66,15	74,85	70,60	75,28	68,03	76,02	71,08	72,31
TiO ₂	0,06	0,20	0,17	0,62	0,15	0,43	0,05	0,29	0,70	0,04	0,42
Al ₂ O ₃	13,28	13,75	12,58	15,56	11,85	8,72	13,57	13,22	14,60	11,26	10,88
Fe ₂ O ₃	0,18	0,78	1,30	1,36	1,07	2,56	0,22	3,96	0,27	4,28	2,92
FeO	1,06	1,13	1,02	3,42	1,38	4,91	0,70	1,95	0,08	2,19	2,42
MnO	0,04*	0,05	0,05	0,08	0,10	0,23	0,03	0,14	-	0,11	0,14
MgO	0,90	0,26	0,11	1,94	0,01	0,12	0,12	0,02	0,04	0,25	0,16
CaO	0,43	0,72	0,61	4,55	0,33	0,46	0,31	0,59	0,34	0,84	0,68
Na ₂ O	6,61	3,51	4,13	3,90	4,80	6,50	4,11	7,73	7,08	4,92	5,17
K ₂ O	2,95	5,13	4,73	1,42	4,73	4,26	5,05	2,99	0,96	4,21	4,42
H ₂ O ⁺	0,17	0,47	0,66	0,69	0,13	0,19	0,41	0,24	0,34	0,39	0,45
H ₂ O ⁻	0,04	-	-	-	0,04	0,02	0,11	-	0,15	-	-
P ₂ O ₅	0,05*	0,14	0,07	0,21	0,00	0,06	0,01	0,05	-	0,07	0,03
CO ₂	0,38	-	-	-	-	0,00	0,06	-	-	-	-

A	aplite sills from E.R.P.M. (20)	B	alkali granite (48) Nockolds (1954)
C	alkali rhyolite (21) Nockolds (1954)	D	tonalites (58) Nockolds (1954)
E	comendite (3)** Noble (1968)	F	pantellerite (5)** Noble (1968)
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I	soda aplite Johannsen (1932)	J	peralkaline granite (53) Nockolds (1954)
		K	peralkaline rhyolite (39)
			(20) Refers to number of samples

* Approximate detection limit ** Averaged by the author

kilometres, assuming a density of $2,7 \times 10^3 \text{ Kg/m}^3$).

These inferred conditions do not take into account the calcium concentration of the source rock. This is probably offset by the excess sodium and possibly even higher pressures. In Figure 5.7 the plotted compositions of the central zone samples are displaced from the point representing the eutectic composition determined by Luth et al. (1964) toward the alkali (sodium) rich side of the diagram. Due to the lack of information on the calcium and water concentrations and the effect of excess sodium at the deduced pressures and temperature, the postulated temperature and pressure conditions can only be regarded as tentative. Also, if the original source rock is related to the Ancient Gneiss Complex of Swaziland, it must have had a low concentration of potassium and an excess of sodium; which agrees with the comments of Bailey and Schairer (1966) and Noble (1968) on the composition of other similar source rocks.

5.5 Similar rocks

In Table 5.5 the chemistry of the aplite is given with other analyses of rocks, in order to compare and, perhaps classify, the aplite with reference to other rocks. The parameters that are used to differentiate acidic rocks such as listed in Table 5.5 are:- $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio, $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$ ratio, atomic proportions of $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{Al}_2\text{O}_3$ which is the equivalent to the peralkaline index of Ussing (1912) and Edgar (1974), and the concentrations of iron and magnesium.

Because the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio is in excess of two, the aplite might belong to the tonalite suite, and because of the high alkali/calcium ratio, it could also correspond to an alkali granite. However, tonalites generally have a low alkali/calcium ratio, and alkali granites have a $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio of less than one, so that the aplite does not really belong to either group. In fact, hypabyssal rocks with a $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio

A typical difference between continental
comendites and the central zone aplite, when
compared with components other than SiO_2 , Al_2O_3 , Na_2O , and K_2O .

Figure 5.8

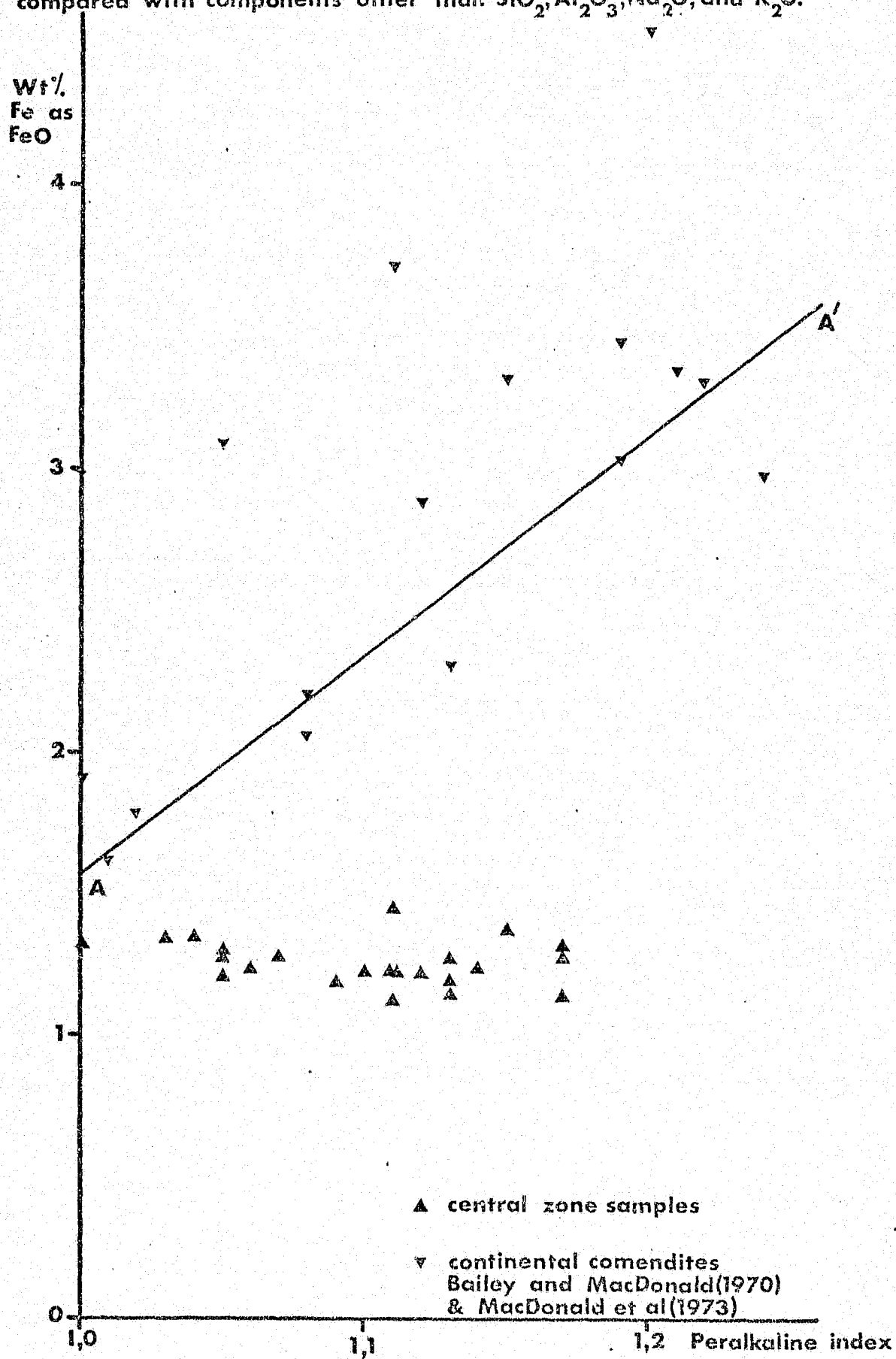


Figure 5.8

The aplite unlike other peralkaline rocks has a fairly constant iron concentration with its increasing sodium concentration. In the peralkaline rocks reported in the literature there is an increasing iron concentration with the increasing sodium concentration, and the line A - A' is Bailey and MacDonald's (1970) 'axis for continental comendites'. However, in general the peralkaline rocks reported in the literature plot above this line.

greater than one, and a very high alkali/calcium ratio are rare. Johannsen (1932, Vol. II, p.376) only reports three examples, one of which contained aegerine and, recently, another example has been reported (MacDonald et al., 1973) which also contains aegerine.

Since the peralkaline index is greater than one, the aplite is encompassed by the definition for peralkaline rocks (Shand, 1927, p.129). Generally peralkaline rocks have an exotic mineralogy due to their excess sodium concentration and their high content of rare earths and halides, but the aplite contains none of these exotic minerals. This poses a problem, for it is not known in which mineral phase the excess sodium is present, as all the known mineral phases are saturated or over-saturated with respect to aluminium.

Noble (1968) put forward a rough classification of peralkaline extrusives on the basis of their chemistry, and Bailey and MacDonald (1970) have listed various trends within peralkaline rocks. However, the results from E.R.P.M. do not fit or appear to be related to any other peralkaline group, if anything but $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-Na}_2\text{O-K}_2\text{O}$ are considered. This is illustrated in Figure 3.8.

Moreover, there is one striking difference between the evolution of the peralkaline aplites on E.R.P.M. and other reported peralkaline rocks. Most siliceous peralkaline rocks appear to be a minor product of fractionation of a large alkali magma body near to the surface (Noble, 1968; Bailey and Schairer, 1966; MacDonald et al., 1974). Therefore these rocks are closely associated with other alkali rocks such as trachytes and phonolites in space and time. By contrast the peralkaline aplites on E.R.P.M. appear to be a direct emplacement of an anatectic melt formed near the base of a continental crust.

The felsic intrusives that occur in the Johannesburg-Pretoria dome reported by Anhaeusser (1973) are similar in petrology and

chemistry to the aplite but, as pointed out in section 5.2, there are sufficient differences to distinguish between them. The main difference is in the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio but these analyses also plot in significantly different areas of Figures 5.3 and 5.7. This suggests that the magma for these intrusions formed under different pressure-temperature conditions to those on E.R.P.M. and the chemistry of the source region could have been sub-aluminous.

Therefore the chemistry of the aplite shows that it has a few similarities to peralkaline rocks, but it does not appear to be related to comendites and pantellerites. The difference is probably a result of the different genetic histories of the rocks, with pressure being a genetic parameter which differs to a large degree. The author has no knowledge of rocks with a similar chemistry and history from other localities.

5.6 Associated rocks

The associated felsic intrusion (F69C), as in its petrography, shows significant differences in chemistry from the central zone aplite. In the quartz-albite-orthoclase plot (Figure 5.3) the sample plots between the eutectic cluster and the albite corner. This suggests that the rock may have separated from the aplite magma at an early stage, after considerable crystallisation of albite from the albite magma, when the eutectic composition was further removed from the aplite end than the composition of the original anatectic melt. The albite crystals plus some magma solidified and was incorporated as a xenolith within the aplite sills.

The quartz-chlorite-calcite intrusives (Plate 3.1, Figure 2.5) have a chemistry that has affinities to carbonatites, because of the high calcite concentration (C.I.P.W. Norm = 30.3%, calculated from the chemistry in Table III, Appendix B). However, because of the high silica content (41.4%, Table III, Appendix B) they are not comparable to carbonatites.

This silica concentration is in all probability a result of contamination of the original magma by the adjacent quartzites and aplites, for a number of aplitic xenoliths have been found in the intrusion in a highly altered state.

5.7 Conclusion

In section 5.3 it was found that contamination of the aplite by the wall rock was minimal with the chemistry of the central zone corresponding to a eutectic composition. The alteration of the wall rock is small compared to that described by MacDonald et al. (1973) for peralkaline sills in South Greenland, which radically changed the chemistry of the olivine gabbro wall rock. This alteration was due to the chemical contrast between the olivine gabbro and the metasomatising fluids.

From the eutectic composition and the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio, it can be deduced that the aplite is an anatectic melt and the inferred temperature-pressure conditions of the source region are $\pm 950^\circ\text{C}$ and 900 MPa, and the composition of the source rock was low in potassium and had excess sodium. The anatexis took place between 34 - 35 kilometres below the surface of the earth, which was probably near the base of the continental crust.

6. ASSOCIATED TECTONICS

A number of tectonic features have been observed in association with the sills. These are:- a well developed joint set; zones of brecciation, younger quartz veins and a structural fabric.

6.1 Jointing

In deep level tabular mines there is a set of dominant mining induced joints in addition to those of geological origin. Outside of the sills these mining induced joints mask the geological jointing (Jeffery, 1975); these mining induced joints (called type 1 by McGarr, 1971a) normally dip towards the advancing stope at approximately 60° but are refracted as they pass through the sills. The sense of this refraction is inconsistent; sometimes the joints dip at a steeper angle within the sill and sometimes at a shallower angle. This refraction is not abrupt at the contact, but gradual, starting outside the sills with the joints curving until beyond the contact zone when they become planar again. Adjacent to the sills there is a zone in which the bedding plane partings are suppressed and the refraction of the type 1 joints begins. This zone is of the order of 10 centimetres thick.

6.1.1 Morphology of the geological joints

Geological sets of joints in the sills are assumed to be those which are mineralised; these minerals are listed in Table 3.1 but with the exception of quartz and chlorite most of them are rare. The joint walls are sharp and the minerals appear to be precipitated in an ever-widening fracture, similar to the dilation type of joint described by Durney and Ramsay (1973). Mineralisation has probably kept pace with the rate of dilation as there are no voids in the veins and the minerals are subhedral. The thickness of the mineral filling varies from a fraction of a millimetre up to two centimetres: bordering the wider joints there is an alternative zone, of bleached host rock, extending up to ten centimetres from the

joint. There are three types of joints present: the vast majority are vertical extension joints, a few are inclined shear joints and some extension joints occur in the plane of the sills. All exposures have some vertical extension joints but in a few areas of very high joint density, sets of joints 1 - 2 centimetres apart dominate the exposures. These areas of closely spaced jointing are listed below:-

Sill No. 1	H76E, H73E	Footwall drives
Sill No. 3	H73E, H74E	Footwall drives
Sill No. 4	H76W	Footwall drive
Sill No. 7	G76W	Stope

The significance of these areas of enhanced jointing is that they probably reflect the inhomogeneous nature of the stress conditions responsible for their formation. Most extension joints terminate in or near the diffuse boundary between the contact and central zones. However, in H76W footwall drive, unmineralised extensions of mineralised joints persist through the contact zone into the adjacent sediments. Unmineralised joints are also found radiating from the tips of the mineralised joints in the same locality, causing brecciation of the aplite, the lack of mineralisation in these radially arranged joints suggests that they form in response to the mining induced stresses at the ends of the geological joints.

The surfaces of the joints are essentially smooth with shallow indentations, but on some of the larger surfaces hackle marks are faintly defined by slight relief changes. At one exposure, a series of closely spaced, irregular, serrated ridges grade into randomly spaced triangular steplike features. These slickensided surfaces are entirely composed of chlorite on a stepped joint surface; the steps are formed by a dominant joint surface moving from one extension joint to an adjacent one. The

Author Fumerton S L

Name of thesis The Felsic intrusives in E.R.P.M. Boksburg 1975

PUBLISHER:

University of the Witwatersrand, Johannesburg

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