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A COMPLEX BASALT-MUGEARITE SILL IN PITON DES NEIGES VOLCANO, REUNION

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ABSTRACT

An extensive suite of minor intrusions, contemporaneous with the late-stage differentiated lavas of Piton des Neiges volcano, occurs within an old agglomeratic complex. An 8-m sill within this suite is strongly differentiated with a basaltic centre (Thorton Tuttle Index 27.6), residual veins of benmoreite (T. T. Index 75.2), and still more extreme veinlets of quartz trachyte. Although gravitative settling of olivine, augite and ore *in situ* is believed to be responsible for some of the observed variation, the over-all composition of the sill is considerably more basic than the mugearite which forms the chilled contacts. It is therefore concluded that considerable magmatic differentiation must have preceded the emplacement of the sill. This probably took place in a dyke-like magma body with a compositional gradient from mugearite at the top to olivine basalt in the lower parts.

INTRODUCTION

The island of Reunion, in the western Indian Ocean, has the form of a volcanic doublet overlying a great volcanic complex rising from the deep ocean floor. The southeastern component of this doublet is still highly active and erupts relatively undifferentiated, olivine-rich basalts of mildly alkaline or transitional type (Coombs, 1963; Upton and Wadsworth, 1966). The northwestern volcano however has been inactive a sufficient time for erosional processes to have hollowed out amphitheatre-headed valleys up to 2500 meters deep in the volcanic pile. This deeply dissected volcano, Piton des Neiges, reaches 3069 meters above sea level.

The structure of Piton des Neiges is comparable to that of Hawaiian volcanoes which have evolved through a primitive shield-building stage, into a declining stage in which differentiated alkalic lavas are emitted (Macdonald, 1949). Thus the visible succession of Piton des Neiges is broadly divided into two units (Upton and Wadsworth, 1965). The lower series of olivine-rich basalts (Oceanite Series), closely comparable to those comprising the active volcano, is overlain by a veneer of younger lavas and pyroclastic rocks (Differentiated Series). These younger rocks thin rapidly away from the center and are separated from the lower 'shield-building' series by an erosional surface. The most abundant lavas in the Differentiated Series are feldsparphyric basalts, which also carry phenocrysts of olivine, augite and magnetite. These are the 'basaltes labradoriques' of Lacroix (1936). Associated with the feldsparphyric basalts are intermediate alkalic lavas ranging through hawaiite and mugearite to trachyte.

In the central part of the volcano the Differentiated Series overlies a great thickness of agglomeratic rocks derived by the disruption of earlier olivine-rich lavas. These agglomerates underwent severe hydrothermal alteration with extensive zeolitisation, prior to the extrusion of the Differentiated Series. Within a roughly circular area of 10 km radius from the estimated position of the main volcanic vent, the agglomerates

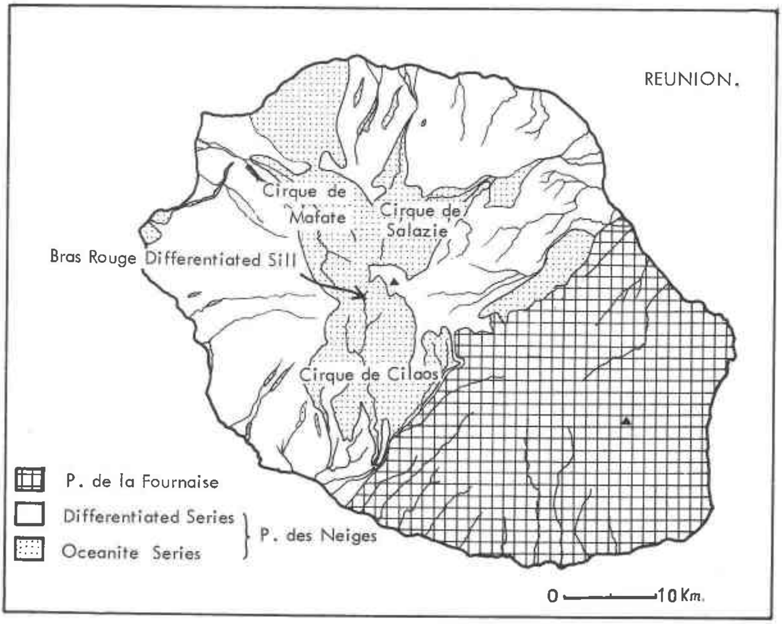

FIG. 1. Simplified map of Reunion, showing principal localities referred to in the text.

are intruded by numerous hypabyssal sheets, ranging in thickness from a few centimeters to over 100 meters. The intensity of this sheet-swarm appears to increase inwards towards the core of the volcano, and the intrusions are excellently displayed within the accessible parts of the upper gorges of the Bras Rouge river, Cirque de Cilaos, and the Rivière des Fleurs Jaunes, Cirque de Salazie (Fig. 1). In spite of much local variability in form and attitude, there is an over-all dip towards the N.E. at angles between 10° and 40°.

The earliest members of this intrusive complex are similar in composition to the lavas of the Oceanite Series, and presumably predate the eruption of the Differentiated Series. However, the majority of the intrusions are more alkalic, and cover the same compositional range as the lavas of the Differentiated Series and they are therefore assumed to be contemporaneous with them.

Petrologically, the more alkalic members of this younger intrusive suite are characterized by the absence of olivine, the principal ferro-magnesian minerals being augite, amphibole, magnetite and a strongly-coloured (iron-rich) chlorite. The amphibole is usually a pale brown, weakly pleochroic variety, occurring as slender prisms, and referred to by Lacroix (1936) as lanéite. Commonly it is zoned outwards to riebeckite-arfvedsonite, this feature being most marked in the extreme differentiates (quartz-syenites), where it is sometimes overgrown by aegirine and associated with small quantities of aenigmatite. All these intermediate rocks are distinctly over saturated, and quartz appears either interstitially or in small ocelli. Calcite is also a characteristic accessory, occurring in the same manner as the quartz, and believed to be of primary magmatic origin.

The nomenclature of these rocks is not straightforward. Although the equivalent extrusive rocks can usually be referred to one or other member of the series basalt—hawaiite—mugearite—benmoreite (or tristanite) —trachyte, only the end members are adequately covered by plutonic terms. Tilley and Muir (1964) have pointed out that the term akerite is appropriate for the plutonic equivalent of benmoreite, and Lacroix (1936) has used this term to describe an intermediate rock from the Bras Rouge river, but so far no generally acceptable terms for the plutonic equivalents of hawaiite and mugearite appear to have been suggested. Further difficulty is introduced by the fact that many of the intrusions in Reunion are not sufficiently coarse-grained for conventional plutonic nomenclature (where it exists) to be applied. Therefore, in this account, the appropriate volcanic terms are used as adjectives (*i.e.*, hawaiitic, mugearitic) to indicate composition regardless of grain size. In fact most of the rocks described are relatively fine-grained, and the occasional anomalies produced by this scheme seem to be worth accepting in the interests of consistency, especially where diverse differentiation products occur in a single intrusion. One exception is made, and that is the use of the term quartz-syenite to describe the relatively coarse-grained material which forms thick, rather uniform sheets of the most alkalic differentiates.

Although a considerable range of composition is represented by this intrusive suite as a whole, very few of the individual members display compositional variations. Even the quartz-syenite sheets, up to 100 meters in thickness, appear to be homogeneous apart from a few pegmatitic veinlets and schlieren. However, in the upper course of the Bras

Rouge, a sill only 8 meters thick was found to be strikingly differentiated. From the field evidence it was apparent that basaltic and trachytic extremes were represented within this comparatively thin sheet, and therefore a suite of specimens was collected for a more detailed petrological and chemical investigation. In fact, the rocks of this sill show a range in SiO_2 content of at least 17 percent, and a Differentiation Index (Thornton and Tuttle, 1960) extending from 28 to at least 75. The distribution and relationships of the various rock types are more complex than was indicated by the original field work, and it is now clear that the sampling of the sill was not adequate for a comprehensive study of the variations within it. However, it is believed that the main features have been documented, and that a reasonable account of its petrogenesis can be given.

Field Relations

The sill forms a waterfall (Fig. 6) in the Bras Rouge, close to the 1000-meter contour. Immediately above it the path leading from Cilaos township to Col Taibit (on the arête between the cirques of Cilaos and Mafate) crosses the river. The sill is approximately horizontal, and a complete section from top to bottom is exposed in the main river, while another section, slightly less perfect, is displayed in a small tributary entering the Bras Rouge from the northwest. As far as can be ascertained in this limited lateral exposure of the sill, there are no younger intrusions crossing it. The country rock is a complex involving the agglomerates which are encountered beneath the main lava succession in the deeper parts of the cirques, a number of minor sheets, and, possibly, some highly altered thin lava flows interbedded with the agglomerates.

The sill can be divided into a number of units, purely on the basis of a field inspection. At the upper and lower contacts there are chilled margins, which are black and flinty for several millimeters inwards from the extreme edge. The main part of the sill can clearly be divided into two parts; the lower 6 meters consist of relatively dark-colored rock, overlain by an upper, lighter-colored portion, approximately 2 meters thick. These appear to grade imperceptibly, with reduction in grain size, into the lower and upper chilled margins respectively. Although the junction between these two units is concordant with the contacts of the sill as a whole, it is slightly irregular in detail, with fragments of the lower, more basic part apparently incorporated and partially digested in the upper part. The actual junction is gradational over two or three centimeters. The lower, basic part of the sill is cut by subhorizontal leucocratic sheets (Fig. 7) which are generally thickest (up to 15 cm) at a height of 5 to 6 meters above the base of the sill. These veins appear to be continuous with the lighter colored material immediately overlying the lower part of the sill. They show no trace of chilling against the more basic rock, but they display a trachytoid flow pattern parallel to their margins. The upper pair of the sill is cut by very thin (2–4 mm) subparallel veinlets of even more leucocratic material, and small vesicular cavities (up to 4 mm in diameter), filled with megascopic crystals of quartz and calcite, are

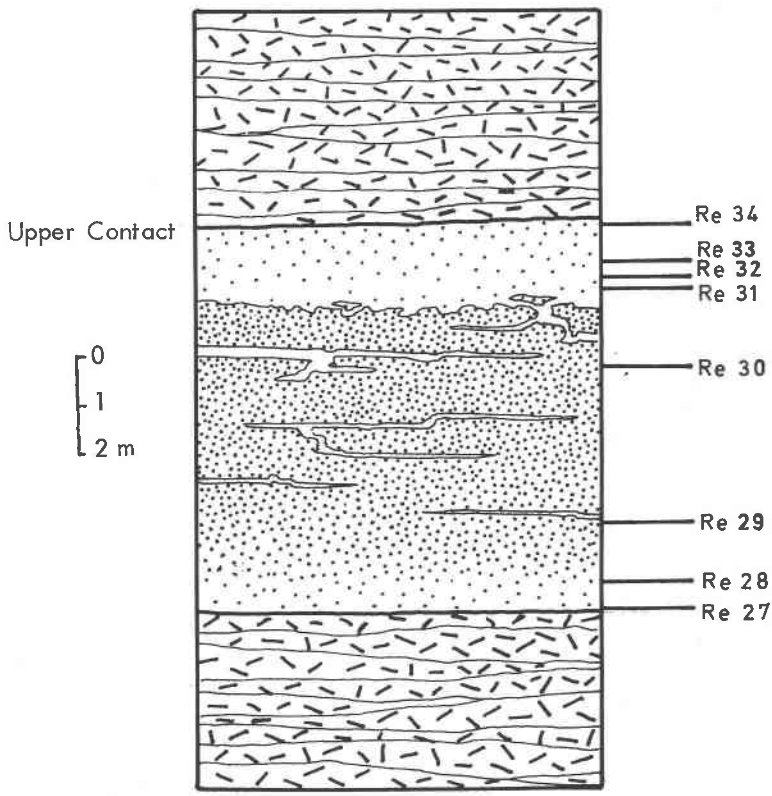

FIG. 2. Diagrammatic cross-section of the sill, showing the relative heights of specimens.

locally abundant. There are also small dark xenoliths, believed to represent pieces of basalt in an advanced stage of digestion. A few small patches of coarse-grained leucocratic rock were observed, but it is not clear whether these represent late-stage segregations of inclusions of syenite. A diagrammatic representation of the various subdivisions of the sill, with an indication of the sampled horizons, is shown in Figure 2.

The field evidence was taken to indicate that *in situ* fractional crystallization of basaltic magma (represented by the chilled margins) resulted in the upward segregation of an alkalic residue, which locally reinjected its complementary basic fraction, and itself differentiated further to give the leucocratic veinlets in the upper part of the sill. Subsequent petrological and chemical studies have shown that the situation is considerably more complex, and that although some *in situ* differentiation must have occurred, by no means all of the sill's distinctive features can be explained on this basis. The main points to emerge are summarized as follows.—

1. The chilled margins are mugearitic in composition, not basaltic.
2. The chilled margins do not correspond in composition to the weighted average composition of the rocks comprising the interior of the sill.
3. The most basic rocks are encountered towards the top of the lower part of the sill, and there appears to be a complete gradation in composition and grain size from the mugearitic lower chill upwards into this basic material.
4. A similar trend seems to be shown in the upper part of the sill, downwards from the chilled margin, but it is less extreme, and is masked by changes due to the concentration of the alkalic residuum in this part of the sill.

Petrography

The lower part of the sill.

The lower chilled margin (Re 27) contains small phenocrysts (approximately 5% by volume) in an indeterminate, semiopaque groundmass, with small calcite-filled ocelli. Most of the phenocrysts are feldspars, including both plagioclase (An_{30}) and a slightly perthitic alkali feldspar. Occasional phenocrysts of magnetite, augite and brown basaltic hornblende also occur.

From the chilled margin to the highest level sampled in the lower part of the sill (at 5 m. above the base) there is a progressive increase in grain size, with a corresponding reduction in the porphyritic appearance as the groundmass crystals approach the 'phenocrysts' in size. The groundmass plagioclase becomes more calcic, with the core compositions ranging through An_{47} (Re 28) to An_{61} (Re 29) and An_{81} (Re 30A). All these feldspars exhibit strong normal continuous zoning towards an alkali feldspar (Na-K analysis of feldspar fractions in Re 28 suggests a weight percent range from An_{40} Ab_{55} Or_5 to An_{10} Ab_{60} Or_{30}), (Fig. 3). Plagioclase becomes more abundant upwards, and augite and altered olivine (Re 30A) take the place of chlorite and amphibole (Re 28 and 29). The amphibole in these rocks is the variety 'lanéite', ($\gamma \wedge c = 22°$, α pale cinnamon brown, β light brown, γ light apple green) zoned outwards to a member of the riebeckite-arfvedsonite series. It is generally associated with a tangled aggregate of greenish-brown chlorite, in a manner which suggests that the amphibole is being replaced by the chlorite. Interstitial calcite is relatively abundant throughout the lower part of the sill, and small amounts of quartz are found in all but the most basic material.

One of the most distinctive features of the intermediate rocks in the lower part of the sill (Re 28 and 29) is the porphyritic appearance due to the presence of relatively large plagioclase crystals. These possess a zone of sieve-texture, presumably the result of resorption, which separates their relatively sodic, and apparently xenocrystic, cores from the outermost zones. The latter are similar in composition and zoning to the groundmass plagioclase of the host rock (Fig. 9). In Re 28, these xenocrysts are relatively abundant, and it has been possible to establish that there is a range in the core compositions from An_{28} to An_{41}. The most sodic xenocrysts also show the most prominent zone of sieve-texture, but this feature disappears as the xenocryst cores approach the groundmass feldspars in composition (An_{47} in Re 28). In Re 29, fewer xenocrysts are found, and the only three measurements possible all gave the same core composition (An_{50}). However, the xenocrysts are more calcic in this more basic host rock; Re 29 has groundmass plagioclase of An_{61}.

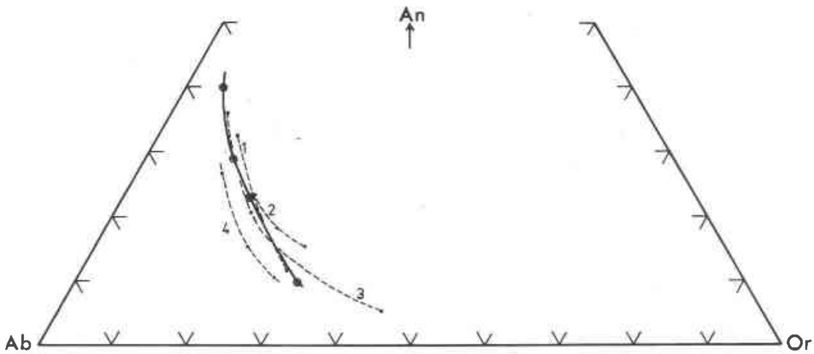

FIG. 3. Diagram showing range of feldspar fractions (firm line) from mugearitic rock (Re 28) based on analyses for Na_2O and K_2O, compared with those from hawaiites and mugearites of Hawaii and Otago. See Muir and Tilley (1961) 1. Hawaiite, Mauna Kea, Hawaii. 2. Mugearite, Jeffrey's Hill, Otago, 3. Mugearite, Scrogg's Hill, Otago. 4.Mugearite, Puu Kawaiwai, Kohala, Hawaii.

The upper part of the sill.

The upper chilled margin (Re 34) is generally similar to the lower one, except that the alkali feldspar is much more coarsely exsolved (Fig. 8.). Between the upper chilled margin and a point about two thirds of the way down to the junction between the lower and upper parts of the sill, three horizons have been sampled (Re 33, 32 and 31). These show a downward increase in grain size and in anorthite content of the cores to the groundmass feldspars, ranging from An_{30} in the chilled margin to An_{53} in Re 31. Plagioclase xenocrysts with reversed zonation are also common in this part of the sill, and again they show a considerable range of core compositions (at least An_{30} to An_{43}) at any one horizon; it cannot be demonstrated that there is an over-all tendency for them to become more calcic as the host rocks become more basic, because the range in composition represented by the sequence Re 33–32–31 is small. The ferromagnesian minerals are characteristically augite, 'lanéite' (zoned to riebeckite-arfvedsonite), chlorite and magnetite; apatite, calcite and quartz are also typically present. In all these respects Re 33, 32 and 31 are similar, with a mirror-image relationship, to Re 28 and 29, above the lower chilled margin. However, these rocks from the upper part of the sill are generally lighter in color than their counterparts beneath, and are also distinctive in containing considerably more quartz, which together with calcite, occurs as the infilling to small vesicles. The quartz shows patchy extinction and is obviously considerably strained.

The late-stage sheets.

One of the leucocratic sheets which cut the lower part of the sill was sampled (Re 30B) 5 meters above the lower contact, at the same level as host rock sample (Re 30A). The sheet is aphyric and trachytoid in texture (Fig. 10). The slender feldspar laths are strongly zoned from andesine to alkali feldspar, and are accompanied by euhedral, acicular crystals of brown hornblende. These differ in habit, and in having a smaller extinction angle ($\gamma \wedge c = 13°$), than the basaltic hornblende phenocrysts of the chilled margins. They differ from the zoned 'lanéites' in the intermediate parts of the sill in being more strongly colored and pleochroic. Magnetite, chlorite, apatite and interstitial calcite and quartz (typically strained) are also present. From the field evidence, it is believed that the material immediately overlying the lower, more basic, part of the sill passes gradationally into the veins and sheets from which Re 30B was taken.

One of the very thin, irregular veinlets which are found in the upper part of the sill has been sectioned in Re 32. It is relatively coarse-grained, and consists of euhedral crystals of sanidine cryptoperthite ($2V_\alpha = 45°$) growing roughly perpendicular to the walls (Fig. 11). In the more central parts of the vein, and mainly interstitial to the feldspars, are patches of quartz and calcite. Small grains of magnetite and zoned hornblende (lanéite) are also present.

The petrography, with modal analyses, of the entire sill is summarised in Table 1.

Discussion

Six of the sill rocks have been chemically analysed (Table 2). These include all four samples (Re 27, 28, 29, 30A) from the lower part of the sill, together with the leucocratic sheet material from the Re 30 horizon (Re 30B), and one sample from the upper part of the sill (Re 33). All the rocks have distinctly high ferric/ferrous ratios and haematite in their norms. From the petrographic evidence, it is reasonably certain that Re 27, 28, 29 and 30B approximate to liquid compositions. By comparison with the averages of Hawaiian analyses in the basalt-trachyte sequence (Macdonald and Katsura, 1964) and with the Differentiation Index of Hawaiian and Hebridean rocks in this range (Tilley and Muir, 1964) it is clear that Re 27 and 28 are mugearitic, Re 29 is hawaiitic and Re 30B is benmoreitic in composition. It is probable that the most extreme differentiates are represented by the thin veinlets of quartz-trachyte in the upper part of the sill but these were not analysed because of the insufficiency of material.

Of the other two analysed samples, Re 30A is very low in silica and alkalies, but high in total iron, titanium and calcium. This rock is correspondingly rich in ferromagnesian minerals (augite, opaque oxides and serpentine pseudomorphs after olivine) and is probably an accumulitic rock. Consequently, the composition plots close to the Mg-Fe side of the FMA diagram (Fig. 4) outside the broad band defined by the compositions of the Reunion lavas (Upton and Wadsworth, 1966). Re 33, from the upper part of the sill, has strong petrographic affinities with Re 28,

TABLE 1

		Plagioclase compositions[1] (cores)			Modal percentages								
		Pheno-crysts	Ground-mass	Xeno-crysts	Feldspar	Olivine pseudomorphs	Augite	Ore	Biotite	Amphibole	Chlorite	Quartz	Calcite
Upper Chill	Re 34	An_{30}	—	—	(phenocrysts) 4.1	—	(phenocrysts) 0.3	(phenocrysts) 0.8	—	—	—	—	—
Upper part of sill	Re 33	—	An_{46}	An_{30}-An_{48}	64.9	—	3.6	8.3	—	2.1	18.3	1.0	1.7
	Re 32	—	An_{53}	An_{32}-An_{43}	68.1	—	10.3	7.0	3.1	1.4	7.1	0.9	2.1
	Re 31	—	An_{53}	An_{33}-An_{41}	59.0	—	4.0	6.8	—	2.3	11.8	7.0	9.1
Late-stage vein	Re 30B	—	sodic andesine	—	74.6	—	—	3.9	—	11.5	6.5	1.9	1.5
Lower part of sill	Re 30A	—	An_{81}	—	52.0	5.1	22.0	12.4	2.5	—	0.9	—	5.0
	Re 29	—	An_{61}	An_{50}	59.3	tr	6.5	12.9	2.1	1.6	11.1	0.7	5.8
	Re 28	—	An_{47}	An_{28}-An_{41}	67.3	—	1.3	8.4	—	amphibole+chlorite 16.2		0.5	6.2
Lower Chill	Re 27	An_{30}	—	—	(phenocrysts) 4.5	—	(phenocrysts) 0.7	(phenocrysts) 0.7	—	(phenocrysts) tr	—	—	—

[1] Based on measurement of maximum extinction angle in zone ⊥ (010) using curves for volcanic feldspars from Tobi (1963).

notably in terms of the groundmass and xenocryst feldspar composition, but it is distinctly richer in silica and, on chemical grounds alone, it might reasonably be classified as a benmoreite. However, from the petrographic evidence and the fact that much of the silica occurs within the vesicles, it is thought that Re 33 was originally a mugearite (like Re 28) but subsequently modified through interaction with the residual liquids produced by the fractional crystallization of the magma in the central part of the sill. Re 31 and Re 32 have probably suffered similar modifica-

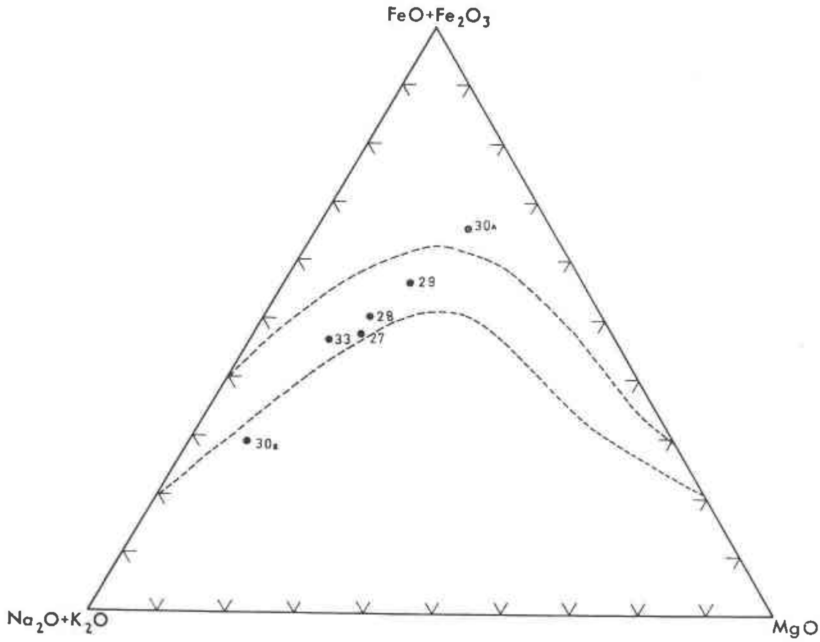

FIG. 4. FMA diagram showing positions of sill rocks (numbered) in relation to the overall composition trend of Reunion lavas (between the dashed lines).

tion and for this reason are not exactly the same as any of the rocks in the lower part of the sill. As has already been noted, the upper and lower chilled margins (as represented by Re 34 and Re 27) are not identical, the upper chill rock showing much more strongly pronounced exsolution in the alkali feldspar. This difference may have been caused through upward diffusion of water, from the hydrous residual liquids produced within the sill, promoting more extensive exsolution than was possible for the alkali feldspar in the lower contact zone. As soon as influx of new magma from the feeding conduit came to a close, *in situ* differentiation commenced within the slowly cooling interior. A combination of crystal

TABLE 2. CHEMICAL ANALYSES AND NORMS OF SILL ROCKS

	Re 27	Re 28	Re 29	Re 30A	Re 33	Re 30 B
SiO_2	50.26	50.71	47.96	41.57	55.09	59.22
TiO_2	2.80	2.67	3.49	4.93	2.05	1.21
Al_2O_3	15.26	15.18	14.69	13.07	16.82	18.28
Fe_2O_3	5.55	5.86	6.63	9.86	5.61	3.01
FeO	4.74	4.44	5.20	6.93	3.04	1.60
MnO	0.18	0.23	0.21	0.22	0.20	0.09
MgO	3.34	3.06	3.93	5.64	2.14	1.28
CaO	4.84	6.42	7.99	10.82	4.79	3.27
Na_2O	5.49	4.73	4.01	2.58	5.38	4.91
K_2O	2.32	2.16	1.34	0.60	2.28	4.86
P_2O_5	0.36	0.39	0.34	0.24	0.43	0.35
H_2O	2.54	1.59	1.32	1.35	1.60	0.99
CO_2	2.14	2.31	2.23	1.78	0.43	0.30
S	0.07	0.06	0.04	0.23	0.03	0.12
Total	99.89	99.81	99.39	99.81	99.89	99.49
Qz	0.96	4.21	4.69	2.22	4.70	4.95
Or	13.71	12.76	7.92	3.55	13.47	28.72
Ab	46.46	40.02	33.93	21.83	45.52	41.55
An	8.13	13.81	18.13	22.31	15.01	12.04
C	0.74	—	—	—	—	0.53
Di	—	0.69	4.04	14.44	2.51	—
En	8.32	7.30	7.91	7.35	4.17	3.19
Mt	7.51	7.12	5.88	7.90	4.40	1.51
Hm	0.37	0.95	2.57	4.41	2.58	1.97
Il	5.31	5.07	6.63	9.36	3.89	2.30
Ap	0.85	0.92	0.81	0.57	1.01	0.83
Cc	4.87	5.25	5.07	4.05	0.98	0.68
Py	0.13	0.11	0.77	0.43	0.06	0.23
Or	20.1	19.2	13.2	7.4	18.2	34.9
Ab	68.0	60.1	56.6	45.8	61.5	50.5
An	11.9	20.7	30.2	46.8	20.3	14.6
Differentiation Index	61.1	57.0	46.5	27.6	63.7	75.2

Re 27	Lower chilled margin	
Re 28	0.6 m. above lower contact	*lower part of sill*
Re 29	1.8 m. above lower contact	*lower part of sill*
Re 30A	5 m. above lower contact	*lower part of sill*
Re 33	0.8 m. below upper contact	*upper part of sill*
Re 30B	Late-stage vein, cutting Re 30A	*upper part of sill*

Analyses at the Geochemical Laboratory, Grant Institute of Geology, Edinburgh, on material dried at 110°C for 2 hours.

settling (of augite, ore and olivine) in conjunction with some upward migration of the alkalic residuum, culminated in the production of the distinct interface separating essentially crystalline basic material (such as Re 30A), from an overlying fluid zone with a high liquid/crystal ratio. This graded upwards with continuous decrease in the liquid/crystal ratio into the completely solidified upper selvedge.

As the intrusion continued to loose heat, expulsion of relatively highly fractionated interstitial liquid from the upper part of the sill into the now coherent and consolidated basic rocks beneath is believed to have

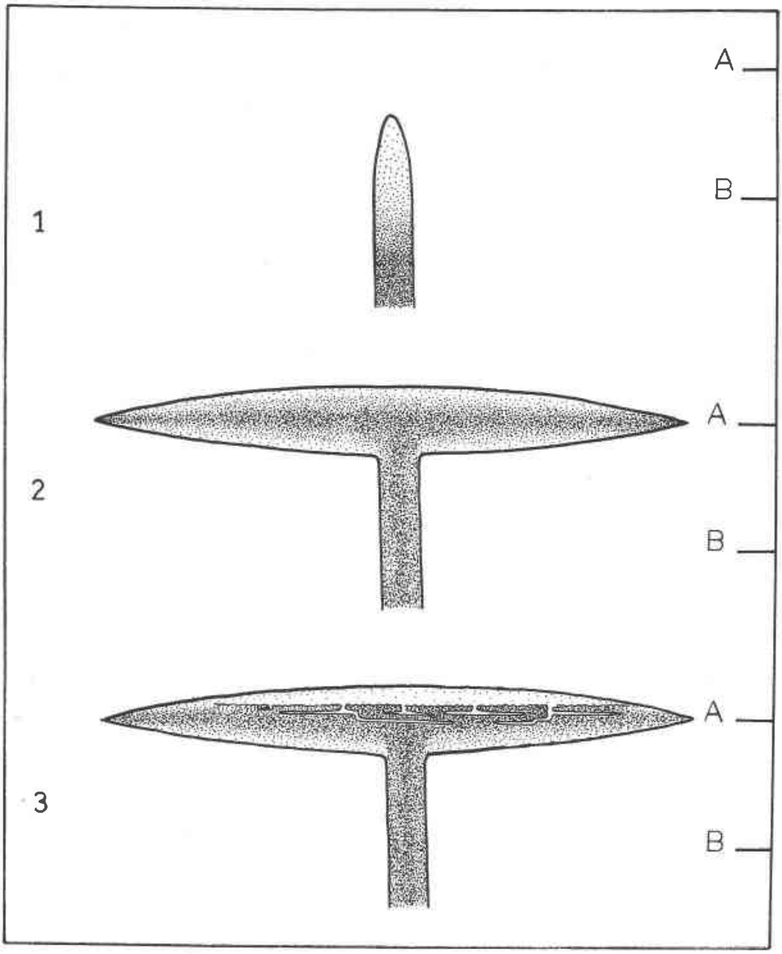

FIG. 5. Diagram showing three possible stages in the development of the sill at A, following initial fractionation in a subjacent magma column at B.

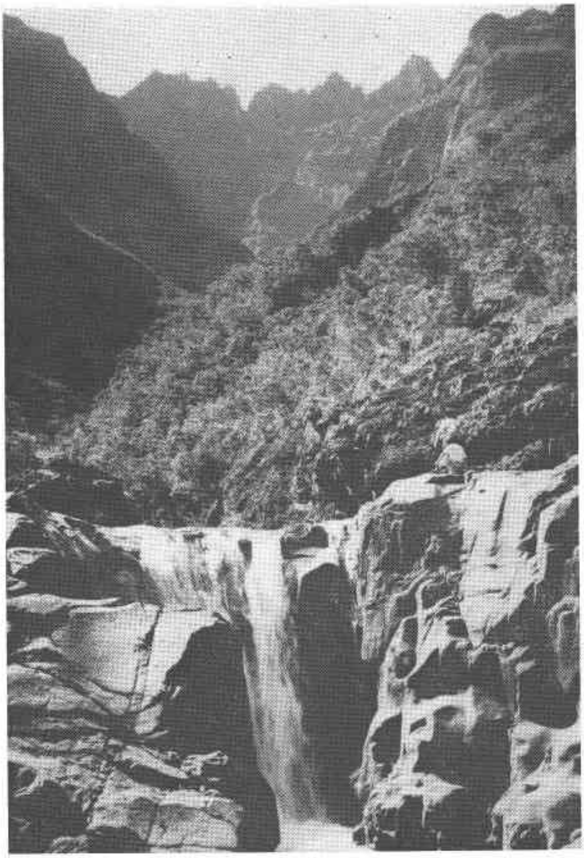

FIG. 6. A general view of the sill forming a waterfall in the Bras Rouge, looking toward the summit area of Piton des Neiges.

taken place. This expulsion of liquid, which led to the emplacement of the approximately horizontal sheets of trachytoid benmoreite in the lower sill unit, may have taken place at a stage when a CO_2-rich vapour phase was produced in the interstitial magma remaining in the upper sill. The volume increase during vapour separation may have provided the motivation for driving the alkalic residuum into incipient joint planes in the consolidated lower sill. There is no reason to invoke filter-pressing due to any tectonic disturbance in order to explain the 'auto-intrusive' phenomena observed.

The evidence so far shows that the mugearite of the chilled contacts, representing the earliest pulse of magma, cannot be parental to all the rock types in the sill. This applies especially to the most basic rocks (sample Re 30A) since these contained An_{81}+olivine+augite, whereas the mugearite magma contained An_{30}+alkali feldspar+hornblende as phenocrysts. This point is further confirmed by the chemical composition of the rocks, and most clearly by the strontium contents. Strontium was determined by X-ray fluorescence on eight specimens from the

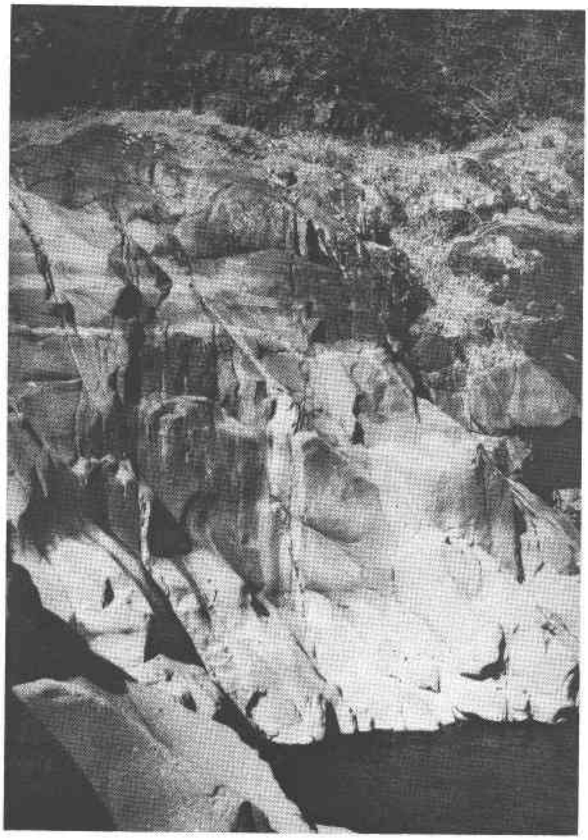

FIG. 7. A section through the sill, showing the benmoreitic sheets well developed towards the top of the lower part of the sill.

interior of the sill as well as on Re 27 and Re 34 from the lower and upper contact zones. The Sr contents from the two chill specimens are approximately 200 ppm. Values from the rocks of the interior, including the most acid and basic extremes, all lie between 500 and 950 ppm. The values for Na, K, Si and Al in the mugearite chill are undoubtedly much higher than they would be in a weighted average for the rocks comprising the remainder of the sill. The analyses of Re 27, 28 and 29 are taken to

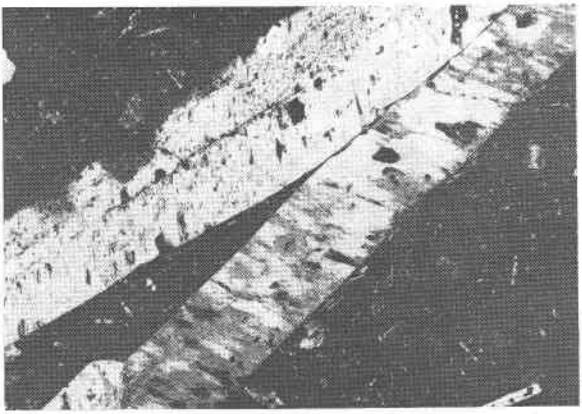

Fig. 8. Exsolved alkali feldspar phenocrysts in upper chill (Re 34); crossed polars, ×13.5.

indicate that magma of increasing basicity that was fed into the sill during emplacement. The final magma pulse, intruded into the sill center, is inferred to have been basaltic. Strong, *in situ* differentiation of this basalt magma imposed bilateral asymmetry and gave rise to accumulitic rocks (*e.g.*, Re 30A) and to an alkalic residuum which (1) modified the pre-existing upper, more or less, consolidated zones of the sill, and (2) gave rise to auto-intrusive phenomena, producing the benmoreite sheets within the lower, essentially solid, part of the sill. The small quartz-trachyte veins occurring within the upper part of the sill may well represent still later segregations of the final liquid fraction.

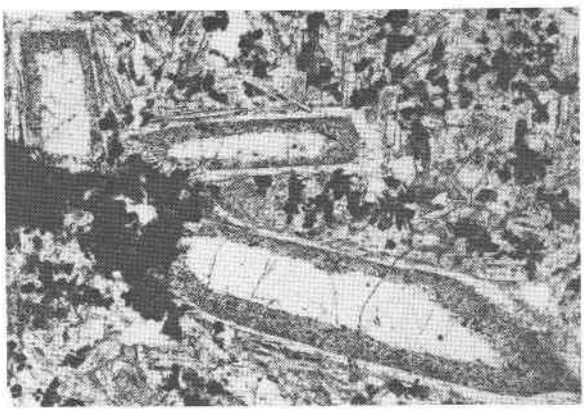

Fig. 9. Plagioclase phenocrysts (Re 28) showing partly resorbed core of relatively sodic material; uncrossed polars, ×11.5.

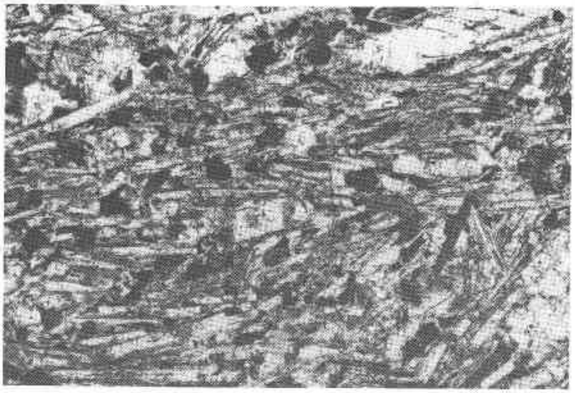

FIG. 10. Benmoreitic sheet (Re 30B) in lower part of sill: uncrossed polars, ×11.25.

The fact that the intrusion of the sill apparently involved a continuous suite of magmas of increasing basicity implies that an already differentiated magma column was being tapped. Probably the magma body was dyke-like in form (largely inhibiting convective mixing) with a mugearitic composition at its top. Such differentiation could be explained in terms of 'liquid fractionation' such as has been postulated for the analogous situation of the Victoria Land (Antarctic) quartz dolerite sills (Hamilton, 1965) where the chills are distinctly more silicic and alkalic than the bulk composition. However, it seems probable that crystal fractionation alone could have brought about the requisite degree of differentiation. Since the temperature at the top may be expected

FIG. 11. Extreme residual fraction consisting of alkali feldspar, quartz and calcite, as a veinlet cutting modified hawaiite (Re 32), in upper part of sill; uncrossed polars, ×23.

to fall faster than in the lower, better thermally insulated zones, the crystal/liquid equilibria would get progressively 'ahead' of those at lower levels. Immediately before the final intrusive act which produced the sill, it is suggested that the topmost magma was in equilibrium with five solid phases. Its composition lay within the 'two-feldspar field', olivine was no longer a stable phase and hornblende was crystallizing. At lower levels, only four crystal phases were separating (plagioclase, olivine, augite and ore) with compositions appropriate to the P.T. conditions prevailing at successive depths. Evidence for such a process operating in the pre-sill stage is preserved in the form of the plagioclase xenocrysts. These are believed to have settled out of the magma in which they originally crystallized, into more basic magma where they became partially resorbed before becoming protected by a mantle of more calcic plagioclase. Thus a column of originally homogeneous basalt magma with crystallisation proceeding more rapidly near the top is envisaged as gradually reaching a stage where the upper parts became first hawaiitic and then mugearitic by downward removal of the early crystal fractions and their complete or partial resorption in the lower liquids. The process may have led to trachyte production had it not been interrupted by the disturbance which led to sill formation.

The investigation of this small sill in the gorge of the Bras Rouge, taken in conjunction with Hamilton's (1965) work in the Antarctic, should serve as a reminder that the well established doctrine that the chilled margin to a differentiated basic intrusion represents the composition of the magma from which the whole body crystallised, is sometimes, and perhaps generally, fallacious.

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