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Aspects of magmatic evolution on Réunion Island

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As with the Hawaiian islands, the volcanic construction of Réunion can be related to two main phases of activity—a shield-forming stage of predominantly olivine–basalt composition, and a declining stage comprising more varied products (basalt–trachyte). The older of the two Réunion volcanoes (Piton des Neiges) appears to have completed both these stages, but the younger volcano (Piton de la Fournaise) is still in the shield-forming stage, and is lagging approximately 1.5 Ma* behind Piton des Neiges in its evolution.

The chemical data indicate a considerable degree of coherence between the various rock types produced during the different stages of development, and it is concluded that they all stem from essentially the same hypersthene-normative, picritic, primitive magma, generated by partial melting of peridotite in the low-velocity layer of the upper mantle. The shield-forming lavas are believed to represent relatively rapid ascent of this magma, only modified by olivine fractionation, but the declining stage seems to require intermediate-depth fractionation (olivine + pyroxene) to account for its initially nepheline-normative character, followed by high level fractionation (olivine + plagioclase + pyroxene + magnetite, etc.) to produce the hawaiite–mugearite–benmoreite–trachyte sequence.

Volume considerations appear to favour an open system of basalt extraction, involving a relatively modest (7 to 15 %) degree of partial melting and continuous replenishment of the mantle source beneath Réunion, rather than a closed system with its restricted basalt potential even if as much as 50 % partial melting is postulated.

* 1 Ma = 1 million years.

1. INTRODUCTION

From a study of oceanic island volcanoes, notably those of the Hawaiian archipelago (Stearns 1966), it has long been recognized that such structures display a growth sequence which can be conveniently divided into a series of stages. Generally there appear to be two main stages developed. First, there is the shield-forming stage, the great bulk of which is beneath sea level; this stage appears to represent a relatively fast rate of construction, with the prolific outpouring of rather uniform basalts (in the accessible parts of the shields, at least). Secondly, there is a declining stage of activity, in which the shields are capped by relatively small amounts of lava (estimated to average about 1% of the total bulk for Hawaiian volcanoes (Macdonald 1968)). During this stage eruptions are generally less frequent than in the shield-forming stage, and a relatively wide spectrum of composition (from basalts to trachytes or phonolites) is characteristically represented. In certain cases a third phase of activity has occurred, following a long period of quiescence and erosion. This rejuvenation stage, if developed, generally produces an even smaller volume of erupted material than the declining stage, and it displays a reversion to a more basic composition. Typical representatives are strongly alkalic basalts, sometimes ranging to basanites and nephelinites.

Despite the general acceptance of this pattern of physiographic evolution of oceanic shield volcanoes, the idea of a corresponding magmatic evolution, although implied by Powers (1935, 1955) and Macdonald (1949, 1968) for the Hawaiian volcanoes, has been rather neglected. By contrast there has been more emphasis in recent years on the fundamental aspects of magma generation and segregation, and this has naturally concentrated attention on the relatively 'primitive' shield-building lavas of the oceanic volcanoes, although comprehensive schemes for the production of a wide variety of magma types (including the typical declining stage and rejuvenation stage lavas) have been developed at the same time (O'Hara 1965; Green 1969).

In re-emphasizing the essential coherence of the magmatic and physiographic evolution of oceanic shield volcanoes, it is not intended to imply that the lava types characteristic of any one stage necessarily bear a parent–daughter relationship to those of preceding or succeeding stages, or that any single mechanism can be used to account for the whole of the recorded variation in composition. Rather it is recognized that the volcanic evolution is the result of a complex history involving the generation and accumulation of magma within the mantle, the probability of fractionation and the interaction of magma with wall-rock during the process of upward migration, and the likelihood of high-level differentiation within the volcanic pile itself. Undoubtedly there are many variations on this theme, and these may be of considerable regional significance, as suggested by McBirney & Gass (1967). However, the overall simplicity of pattern and its repetition in widely separated parts of the ocean basins, is taken to indicate that the particular combination of thermal, chemical and tectonic conditions responsible for its development (however complex the detailed evolution in individual cases) is of considerable significance in discussing the structure of the Earth beneath the oceans.

In the following account, the volcanic and magmatic evolution of Réunion is considered as a complex but coherent history, and is compared with the situation represented by other oceanic shield volcanoes, especially the Hawaiian volcanoes.

2. General geology of Réunion

The island of Réunion provides a particularly instructive example of a large oceanic shield volcano. Not only is the structure relatively simple, involving only two main centres of eruption, but the island is distinctive in that it has been extensively uplifted during its development (Upton & Wadsworth 1970). This uplift, coupled with local erosion, has produced striking vertical relief, so that an unusually lengthy history of volcanic activity is recorded stratigraphically.

General accounts of the geology of Réunion have been presented by Lacroix (1936) and Bussière (1959), with more recent summaries by Upton & Wadsworth (1965, 1970). From the available bathymetric data (Fisher, Johnson & Heezen 1967) it can be shown that the volcanic edifice forms an enormous elliptical shield, with major and minor axes of 240 and 200 km respectively at its base, and rises from -4 km to a height of $+3$ km. Thus the overall volume is at least 90000 km^3, and may be significantly greater if the volcanic pile is bi-convex rather than plano-convex, in profile (Jackson & Wright 1970).

The upper subaerial part of the structure forms two separate volcanic centres. The older of these, Piton des Neiges, retains its overall constructional shape, but, as the result of local dissection, there is vertical relief of nearly 2.5 km within 5 km of the summit, providing direct evidence of more than 2 Ma of volcanic activity. Two main stages of development have been recognized (Upton & Wadsworth 1965) analogous to Kohala volcano, Hawaii (Macdonald & Katsura 1964). An earlier shield-forming stage (Oceanite Series), older than 0.4 Ma (McDougall 1971), is overlain by a declining stage capping of alkalic lavas (Differentiated Series), younger than 0.35 Ma. The shield-forming succession of Piton des Neiges has been subdivided into the Older Oceanite Series and Younger Oceanite Series on the basis of their field characteristics (Upton & Wadsworth 1969). The older group ($>$ 2 Ma) is believed to represent the later part of the submarine phase of volcanic construction while the younger group represents the establishment of the subaerial shield.

The other volcanic centre, Piton de la Fournaise, is active, and is clearly still in the main shield-forming stage of development, equivalent to the Younger Oceanite Series of Piton des Neiges. Although there is no direct evidence of its submarine history there has been sufficient dissection of the outer flanks to reveal a volcanic sequence representing subaerial activity during the past 0.35 Ma (McDougall 1971). Taken together, the two volcanic centres give a clear indication of an evolutionary pattern, with Piton de la Fournaise lagging some 1.5 Ma behind Piton des Neiges in its development.

3. Chemistry

(a) *Introduction*

Although a considerable number of chemical analyses of Réunion rocks were presented by Lacroix (1936), the majority of these relate to Piton de la Fournaise. More recent analytical information on the rocks of Piton des Neiges was given by Upton & Wadsworth (1966), but again the emphasis was on the shield-forming lavas, especially the aphyric basalts. Apart from the early analyses (reported by Lacroix), which established the overall trend of chemical variation, and a detailed study of a strongly differentiated minor intrusion (Upton & Wadsworth 1967), the chemistry of the Differentiated Series has not hitherto been seriously investigated.

(*b*) *Shield stage*

Of the 52 new chemical analyses (major oxides and trace elements) presented in this account, only seventeen refer to the shield-forming stage (table 1). It was felt that the chemistry of Piton de la Fournaise had already been adequately covered, so only four new analyses, representing the extreme range from oceanite to olivine-depleted basalt (table 1, columns 1 to 4) are given. The remaining analyses of shield-forming rocks (lavas and minor intrusions) are from Piton des Neiges, including both the Older and Younger Oceanite Series. Again these cover the complete range from oceanite to low-Mg basalts (table 1, columns 5 to 17), and are shown in order of increasing iron enrichment (regardless of stratigraphic position). Trace element data for previously analysed (major oxides only) Réunion basalts (Upton & Wadsworth 1966) are given in table 2.

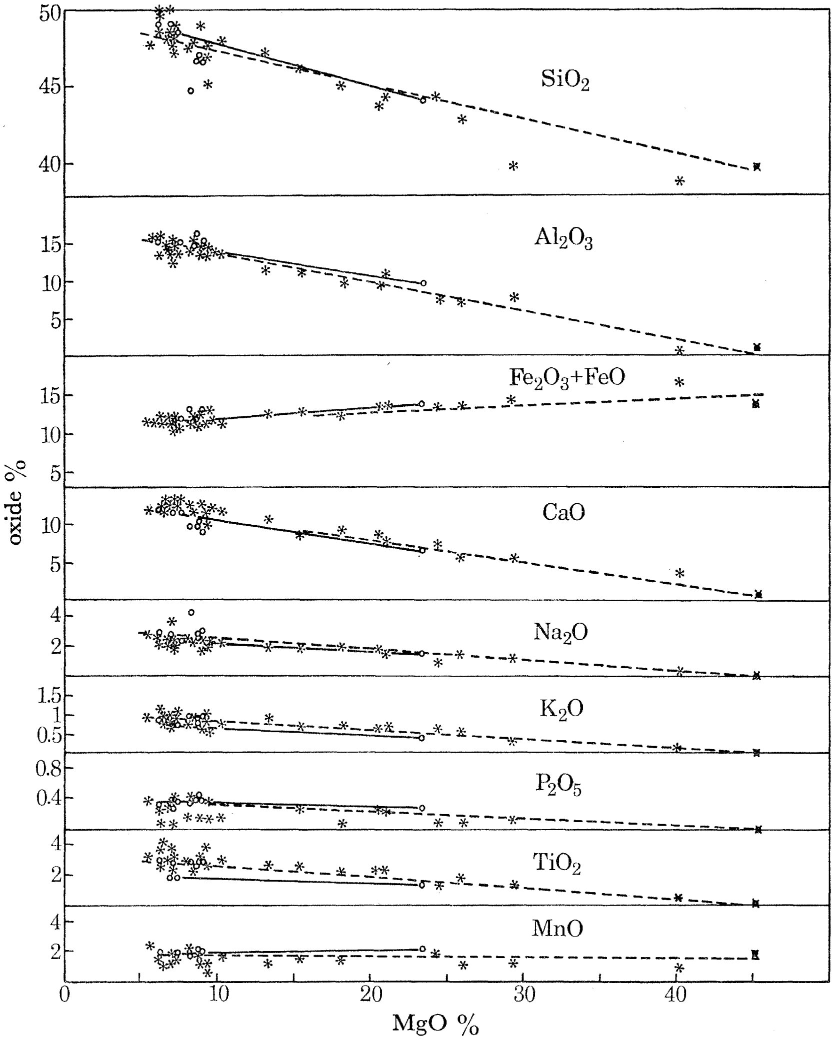

FIGURE 1. Major oxides plotted against MgO for the lavas of Piton de la Fournaise; showing olivine-control line (– – –) and tie-lines between whole rock–groundmass pairs (——). ○, lavas; ✳, older analyses from Lacroix (1936); ✱, olivine phenocrysts from Re 331.

Taken together, the shield-forming rocks of both volcanoes are predominantly olivine–

hypersthene-normative. One or two are just quartz-normative, but this is almost certainly the result of secondary oxidation, and the only nepheline-normative example is an oceanite flow from the Older Oceanite Series (Re 595).

Plots of various major oxides against MgO (figures 1 and 2) demonstrate the main chemical features of the shield-forming lavas and associated minor intrusions. All the previously published chemical analyses (Lacroix 1936; Upton & Wadsworth 1966) are used in these diagrams, together with data from a suite of hypabyssal differentiates found as pyroclastic debris in a subsidiary vent of Oceanite Series age at Cap la Houssaye (Upton & Wadsworth 1971). It is clear that olivine addition or subtraction was the main cause of variation, and this is emphasized by the whole rock/groundmass tie lines, and by the one-atmosphere melting experiments on selected lavas (Tilley, Thompson, Wadsworth & Upton 1971), as well as by the general petrographic evidence (notably the distribution of olivine phenocrysts). Chemically, the most evolved or olivine-depleted lavas are characterized by SiO_2, 48 to 49%, MgO, 5 to 6%, and

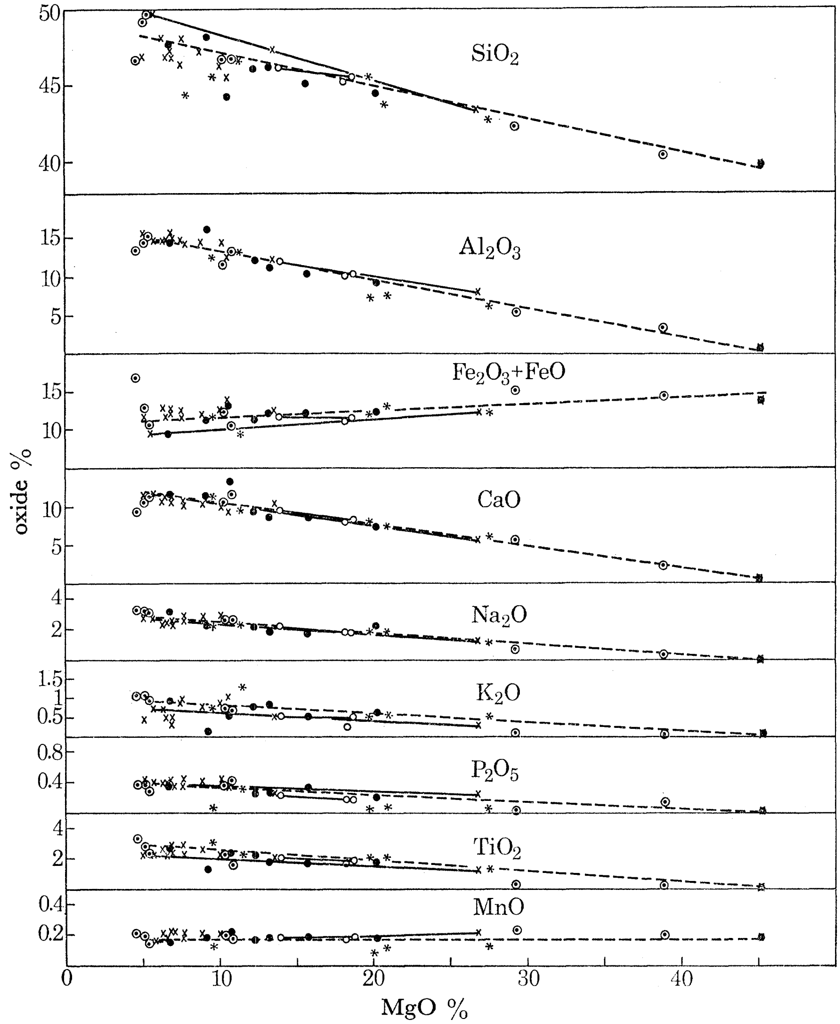

Figure 2. Major oxides plotted against MgO for the lavas and minor intrusions of the Oceanite Series of Piton des Neiges, showing olivine-control line (– – –) and tie-lines between whole rock–groundmass pairs (——). ×, lavas; ●, Oceanite Series minor intrusives; ⊙, coarse grained blocks from Cap de la Houssage agglomerate; *, ✱, as in figure 1.

TABLE 1. ANALYSES OF SHIELD-STAGE BASALTS AND OCEANITES

	(1) Re 114	(2) Re 637	(3) Re 638	(4) Re 634	(5) Re 331	(6) Re 595	(7) Re 604	(8) Re 600	(9) Re 75	(10) Re 134	(11) Re 171	(12) Re 463	(13) Re 124	(14) Re 178	(15) Re 390	(16) Re 391	(17) Re 127
SiO_2	44.17	46.66	49.10	49.15	43.57	44.50	46.15	45.57	47.12	46.78	47.38	48.20	47.35	46.98	47.32	48.02	48.14
Al_2O_3	9.05	14.51	14.91	14.79	8.10	9.31	10.44	10.62	12.01	14.30	14.88	14.24	15.27	15.79	15.02	14.85	15.93
Fe_2O_3	3.96	2.77	6.55	1.59	2.86	2.30	1.24	1.92	1.65	3.97	4.34	2.46	2.79	4.30	3.61	4.72	4.04
FeO	9.41	9.68	4.81	9.96	9.58	10.07	10.28	10.12	9.93	8.59	7.80	9.25	9.14	7.75	8.70	7.69	7.45
MgO	23.27	8.92	6.84	6.03	26·87	20.20	18.65	18.16	13.88	9.71	8.80	7.62	6.88	6.81	6.95	6.39	5.60
CaO	6.37	8.86	11.21	10.99	5.68	7.32	8.32	8.11	9.21	9.43	10.12	10.68	12.05	10.93	11.27	10.70	11.09
Na_2O	1.45	2.83	2.57	2.87	1.16	2.11	1.81	1.81	2.15	2.49	2.98	2.69	2.50	2.27	2.44	2.39	2.64
K_2O	0.40	0.89	0.74	0.81	0.31	0.60	0.50	0.30	0.59	0.55	0.79	0.87	0.42	0.39	0.50	0.70	0.65
H_2O+	0.18	1.50	0.34	0.14	0.24	1.84	0.24	1.51	0.64	0.95	0.20	0.40	0.56	1.57	0.87	1.37	0.72
TiO_2	1.41	2.84	2.62	2.99	1.28	1.80	1.77	1.77	2.02	2.43	2.51	2.81	2.47	2.59	2.49	2.57	2.67
P_2O_5	0.29	0.35	0.27	0.31	0.27	0.20	0.18	0.18	0.21	0.35	0.41	0.36	0.29	0.43	0.38	0.37	0.30
MnO	0.22	0.18	0.17	0.18	0.23	0.18	0.18	0.17	0.18	0.20	0.20	0.19	0.20	0.22	0.21	0.21	0.19
CO_2	—	—	—	—	0.04	—	—	—	—	0.15	0.12	0.07	0.13	0.19	0.05	0.07	0.28
total	100.18	99.99	100.13	99.81	100.19	100.43	99.76	100.24	99.59	99.90	100.53	99.84	100.05	100.22	99.81	100.05	99.70
Q	—	—	3.68	—	—	—	—	—	—	—	—	—	—	1.08	—	2.21	1.20
Or	2.36	5.34	4.38	4.80	1.83	3.60	2.97	1.80	3.52	3.23	4.65	5.17	2.51	2.28	2.99	4.19	3.84
Ab	12.27	24.31	21.79	24.36	9.82	15.51	15.39	15.51	18.38	21.08	25.13	22.89	21.14	19.20	20.87	20.49	22.34
An	17.00	24.63	27.01	25.16	15.99	14.36	18.98	20.22	21.60	26.24	24.81	24.34	29.21	31.77	28.87	28.09	29.69
Ne	—	—	—	—	—	1.40	—	—	—	—	—	—	—	—	—	—	—
Di	10.09	14.31	20.97	22.61	8.30	16.88	17.08	15.48	18.66	14.66	18.16	21.22	23.41	15.83	20.40	18.35	18.90
Hy	9.24	5.50	7.35	8.74	7.88	—	4.65	8.16	7.93	13.11	2.75	8.24	6.26	16.16	13.01	13.75	11.12
Ol	39.94	15.53	—	5.57	48.86	40.92	35.33	32.17	23.11	9.35	12.63	8.17	7.45	—	2.87	—	—
Il	2.68	5.48	4.99	5.70	2.43	3.47	3.38	3.40	3.88	4.61	4.76	5.37	4.69	4.92	4.73	4.94	5.07
Mt	5.74	4.08	8.48†	2.31	4.15	3.38	1.81	2.82	2.42	5.76	6.29	3.59	4.05	6.22	5.29	6.93	5.85
Ap	0.69	0.84	0.64	0.74	0.64	0.48	0.43	0.43	0.50	0.78	0.90	0.86	0.62	0.93	0.91	0.89	0.65
differentiation index	14.6	29.7	29.9	29.2	11.7	20.5	18.4	17.3	21.9	24.3	29.8	28.05	23.7	22.6	23.9	26.9	27.4
$\dfrac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	0.36_5	0.58_2	0.62_4	0.65_7	0.31_6	0.38_0	0.38_2	0.39_9	0.45_5	0.56_4	0.58_0	0.60_0	0.63_4	0.63_9	0.63_9	0.66_0	0.67_2
Modal data (in vol. per cent)																	
groundmass	55	> 95	> 95	~ 95	47	66	69	65	81	> 95	> 95	73	75	> 95	> 95	> 95	> 95

† Plus 0.71 hm.

	Phenocrysts																
Ol	45	—	—	tr	53	34	31	30	18	—	—	9	6	—	—	—	—
plag	—	—	—	tr	—	—	—	5	1	—	—	8	16	—	—	—	—
cpx	—	—	—	tr	—	—	—	—	—	—	—	10	3	—	—	—	—
	trace elements (by X-ray fluorescence)																
Zr	95	220	180	205	155	125	110	115	145	170	190	205	150	185	175	180	210
Cr	1330	285	125	5	1400	740	790	745	600	340	155	350	210	135	165	115	115
V	190	270	280	295	195	210	215	235	225	250	230	265	260	265	280	280	235
Y	22	40	30	42	30	22	20	25	32	35	35	40	30	35	35	40	37
Ni	1100	230	100	75	1200	835	800	700	660	740	140	1010	520	290	620	480	520
Sr	185	380	310	340	295	215	240	245	90	340	390	365	360	400	340	325	385
Ba	230	280	190	210	205	180	160	170	260	250	345	310	305	305	270	310	290
Rb	7	20	15	15	10	15	7	< 5	10	< 5	15	20	< 5	< 5	< 5	10	7
Zn	100	115	150	105	80	100	95	110	100	95	80	85	100	105	90	90	95
Cu	130	80	95	135	120	95	105	95	220	90	130	130	110	100	140	155	100

Specimen localities

Piton de la Fournaise

Re 114	1961 Oceanite flow: Route Nationale N2, Grand Brulé
Re 637	Glassy spatter beneath lava flow, near Col Lacroix, Plaine des Sables
Re 638	Stalactites of glassy basalt from lava cave, Chapelle de Rosemont, Enclos Fouqué
Re 634	Basalt from floor of Cratère Bory

Piton des Neiges

Re 331	Highest flow in Oceanite Series, 6 km from mouth of R. des Galets
Re 595	Part of an olivine-rich flow unit in Older Oceanite Series. Loose block below road bridge over Bras de Benjoin, Cirque de Cilaos
Re 604	Oceanite centre of dyke, Bras de Cilaos, Petit Serré
Re 600	Oceanite centre of thin sheet cutting older Oceanite Series lavas; le Pavillon, Cirque de Cilaos
Re 75	Chilled margin of Petit Serré dyke (see Re 604)
Re 134	Basalt flow from Younger Oceanite Series; on path from Bois Court to Grand Bassin
Re 171	Thick columnar basalt flow from Younger Oceanite Series; above water-fall, Grand Bassin
Re 463	Basalt flow from Younger Oceanite Series; from the top of the R. de St Denis gorge, Grande Montagne
Re 124	Basalt flow from Younger Oceanite Series; on path from Bois Court to Grand Bassin (lower in succession than Re 134)
Re 178	Basalt flow from Younger Oceanite Series; near base of Grand Bassin–Bois Court succession (above Re 171)
Re 390	Basalt flow from Younger Oceanite Series; Piton Crête Dos d'Ane
Re 391	Flow immediately beneath Re 390
Re 127	Basalt flow from Younger Oceanite Series; on path from Bois Court to Grand Bassin (between Re 124 and Re 134).

All major oxide analyses (except Re 595, Re 600, Re 604, Re 634, Re 637, Re 638) by Chemical Laboratory, Department of Geology, University of Manchester

Trace elements (and Re 595–638): Grant Institute of Geology, Edinburgh University the appearance of minor normative quartz, although this feature is just about cancelled out by standardizing Fe_2O_3 to 1.5 %.

(c) *Declining stage*

The 35 new chemical analyses of Differentiated Series of rocks are referred to tables 3 and 4. Table 3 contains material which is believed to represent a reasonable approximation to liquid compositions. This includes extracted groundmass material, aphyric lavas (< 2 % phenocrysts), porphyritic lavas with less than 15 % phenocryst content (with three or four phenocryst phases represented) and in three cases (Re 100, Re 363, Re 364) more strongly porphyritic lavas of benmoreite–trachyte composition, where the likelihood of effective crystal accumulation is considered to be minimal. Also included in table 3 are analyses of certain aphyric minor intrusions, and the relatively coarse-grained (and aphyric) syenite masses. Table 4 displays the analyses of the more porphyritic basic lavas (basalts and hawaiites), where the phenocrysts exceed 15 %, and where in many cases, there appears to have been pronounced plagioclase concentration.

TABLE 2. TRACE ELEMENTS CONTENT OF BASALTS FROM WHICH MAJOR ELEMENTS HAVE ALREADY BEEN PUBLISHED (UPTON & WADSWORTH 1966, Table 1)

	Re 168	Re 343	Re 243	Re 170	Re 180	Re 69
Zr	210	160	155	210	195	175
Cr	265	950	600	190	70	180
V	225	360	225	260	275	290
Y	32	27	30	< 5	35	40
Ni	230	740	730	150	70	150
Sr	425	300	270	395	390	335
Ba	410	235	137	265	205	180
Rb	25	7	5	18	5	7
Zn	90	115	110	100	100	90
Cu	180	150	200	170	170	250

Analyses by X-ray fluorescence at Grant Institute of Geology, University of Edinburgh.

The basis of subdivision of the Differentiated Series into basalt, hawaiite, mugearite, benmoreite and trachyte is similar to that used by Thompson, Esson & Dunham (1971) for the Skye lavas, and is broadly equivalent to the nomenclature suggested by Tilley & Muir (1964). The main criteria are shown in table 5.

The average composition of each of these groups is shown in table 6. Aphyric basalts appear to be scarce in the Differentiated Series, and only one analysis of groundmass material from a porphyritic basalt (Re 512) is available. However, this is considered to be a reasonably close approximation to the most basic liquids reaching the surface at this stage. The most basic aphyric lavas and minor intrusions are hawaiitic in composition, and these were certainly available for eruption early in Differentiated Series times.

The normative compositions are of interest: with Fe_2O_3 standardized to 2 % the average basalt, hawaiite and mugearite are nepheline-normative, while the average benmoreite and trachyte are quartz-normative. Comparable results are reported by Macdonald (1968) for Hawaii, and by Thompson *et al.* (1971) for Skye.

As with the shield-forming lavas, the major oxides are plotted against MgO (figure 3), and the variation among the more basic rocks again appears to be related to olivine addition or subtraction. However, the trend for rocks with < 6 % MgO shows an abrupt deflexion from the olivine control line. This can be explained in terms of fractionation of plagioclase, augite and magnetite, as well as olivine; all these phases appear as phenocrysts in the Differentiated Series (figure 4).

Although the hawaiite–mugearite–benmoreite–trachyte series is believed to have stemmed from liquids of basaltic composition (similar to the basalt of table 6) this fractionation sequence

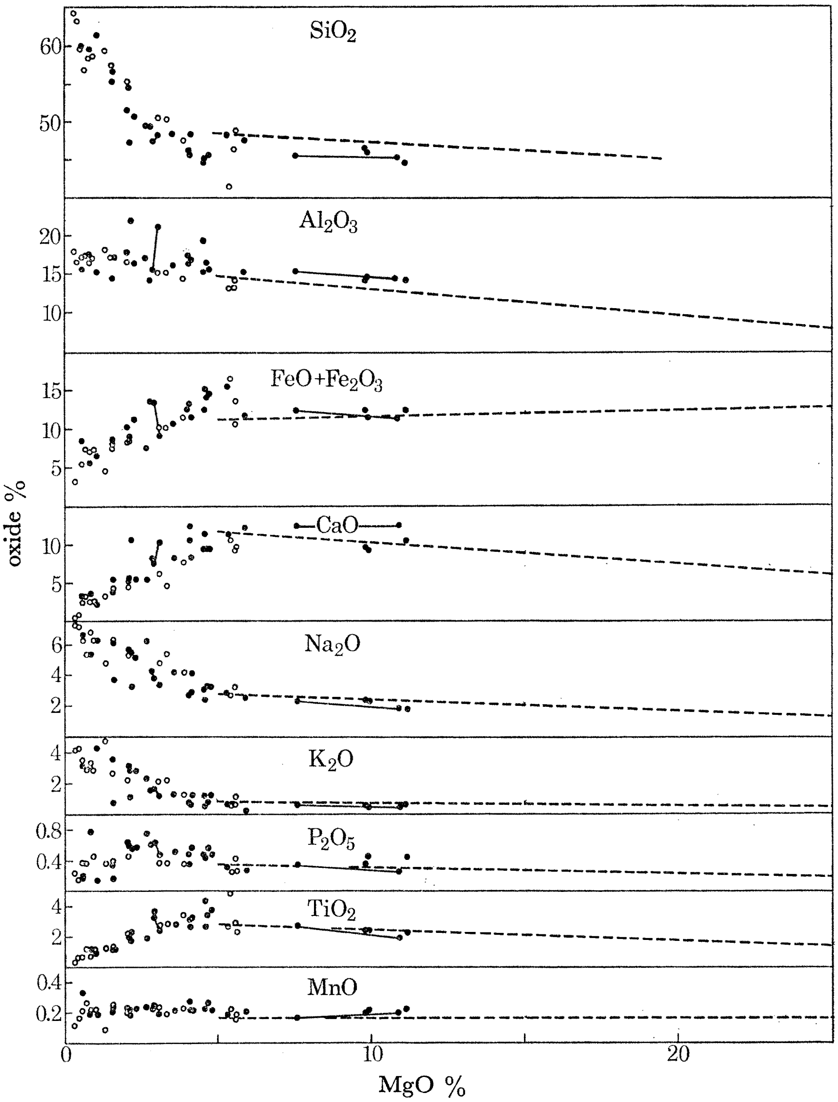

FIGURE 3. Major oxides plotted against MgO for the Differentiated Series of Piton des Neiges; showing olivine-control line (– – –) from figures 1 and 2, and whole rock–groundmass tie-lines (——). ●, lavas; ○, intrusives.

cannot simply be regarded as a continuation from the most evolved (Mg-depleted) shield-stage basalts. The latter are distinctly richer in SiO_2 and poorer in alkalies (figure 5) and iron than the most basic aphyric members of the Differentiated Series, and the change from shield to declining stage compositions cannot therefore be conveniently explained as the result of fractionation involving the low pressure mineral phases.

	basalt	hawaiites							mugearites					
	(1) Re 512G	(2) Re 350†	(3) Re 424	(4) Re 415	(5) Re 332	(6) Re 2	(7) Re 272†	(8) Re 86G	(9) Re 482	(10) Re 228†	(11) Re 410†	(12) Re 197†	(13) Re 196†	(14) Re 201†
SiO_2	45.99	46.7	44.92	45.68	45.85	46.50	48.3	47.54	49.37	49.0	52.0	50.9	54.4	51.4
Al_2O_3	15.65	14.1	15.16	16.77	15.92	13.55	16.9	15.98	14.08	15.6	18.8	16.8	18.0	16.8
Fe_2O_3	5.95	4.7	2.53	4.76	7.89	5.21	2.5	5.38	6.67	6.4	2.1	5.0	2.2	3.7
FeO	6.50	9.8	12.50	9.39	6.82	8.76	8.8	8.38	7.12	5.0	6.8	6.1	6.2	6.4
MgO	7.66	5.2	4.59	4.74	4.81	5.56	4.3	2.93	2.88	3.2	2.9	2.3	2.1	2.1
CaO	12.60	11.1	9.34	9.60	9.51	9.15	9.0	7.88	8.16	7.9	7.8	5.4	5.4	5.2
Na_2O	2.39	2.92	3.19	3.39	3.34	3.36	3.67	3.84	4.02	4.18	4.59	5.17	5.37	5.63
K_2O	0.71	1.01	0.79	0.79	1.19	1.20	1.62	1.58	1.53	1.59	2.10	2.99	2.90	3.13
H_2O+	0.12	0.36	0.80	0.38	0.39	2.96	0.68	1.51	0.76	2.39	0.78	0.74	0.47	0.88
TiO_2	2.18	3.40	4.42	3.39	3.76	2.97	3.36	3.63	3.29	2.86	2.28	1.88	1.76	1.78
P_2O_5	0.32	0.35	0.49	0.58	0.48	0.40	0.47	0.61	0.60	1.10	0.80	0.59	0.55	0.60
MnO	0.16	0.20	0.26	0.27	0.22	0.18	0.22	0.24	0.23	0.22	0.19	0.23	0.21	0.22
CO_2	—	—	0.98	—	—	0.65	0.07	—	0.67	0.85	0.20	—	—	—
total	100.23	99.8(4)	99.97	99.74	100.34‡	100.45	99.9(7)	99.70§	99.38	100.2(9)	101.3(4)	98.1(0)	99.5(6)	97.8(4)
CIPW norms														
Q	—	—	—	—	—	—	—	0.06	4.32	4.04	—	—	—	—
Or	4.19	6.00	4.71	4.70	7.03	7.27	9.64	9.53	9.17	9.60	12.34	18.14	17.29	19.08
Ab	20.20	24.83	27.21	28.86	28.26	29.16	30.17	33.15	34.48	36.12	38.63	39.88	44.96	38.87
An	29.84	22.49	24.91	28.38	24.93	18.82	25.04	22.14	16.07	19.51	24.36	14.17	16.59	11.68
Ne	—	—	—	—	—	—	0.61	—	—	—	—	2.72	0.47	5.56
Di	24.19	24.96	10.27	12.86	14.90	16.90	13.49	11.21	13.40	5.99	6.35	7.69	5.69	9.07
Hy	0.06	1.65	8.08	1.06	4.28	7.71	—	7.45	3.43	5.36	1.32	—	—	—
Ol	8.02	5.88	9.24	9.34	0.69	4.13	9.68	—	—	—	7.39	4.82	7.08	5.24
Il	4.14	6.49	8.46	6.48	7.14	5.78	6.43	7.03	6.33	5.55	4.31	3.66	3.37	3.49
Mt	8.62	6.88	3.70	6.94	11.44	7.75	3.67	7.96	9.80	8.59	2.97	7.49	3.23	5.55
Ap	0.76	0.83	1.17	1.38	1.14	0.97	1.12	1.47	1.44	2.66	1.88	1.43	1.31	1.47
Hm	—	—	—	—	—	—	—	—	—	0.61	—	—	—	—
Co	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Cc	—	—	2.25	—	—	1.52	0.16	—	1.54	1.97	0.45	—	—	—
differentiation index	24.4	30.8	31.9	33.6	35.3	36.4	40.4	42.7	48.0	49.8	51.0	60.7	62.7	63.5
$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	0.61_9	0.73_6	0.76_6	0.74_9	0.75	0.71_5	0.72_4	0.82_4	0.82_7	0.78_1	0.75_4	0.82_8	0.80_0	0.84_1
modal data (in vol %)														
groundmass	> 98	> 98	> 98	87.9	> 98	> 98	> 98	> 98	> 98	> 98	85.2	> 98	95.8	> 98
phenocrysts														
Ol	—	—	—	3.4	—	—	—	—	—	—	1.7	—	tr	—
Plag	—	tr	—	6.4	—	—	tr	—	—	tr	12.3	—	4.2	—
Cpx	—	—	—	1.0	—	—	tr	—	—	—	tr	—	tr	—
ore	—	—	—	1.3	—	—	tr	—	—	—	0.8	—	tr	—
trace elements (by X-ray fluorescence)														
Zr	125	205	150	155	215	195	290	245	280	270	360	480	460	500
Cr	110	35	< 5	< 5	< 5	< 5	15	< 5	< 5	10	10	5	5	5
V	340	400	355	350	310	440	150	190	190	70	40	50	45	45
Y	22	27	32	30	37	30	32	27	50	37	35	55	45	60
Ni	120	35	10	10	10	30	< 10	10	10	< 10	< 10	< 10	< 10	< 10
Sr	390	390	550	555	525	460	810	475	495	750	850	590	630	585
Ba	310	300	450	450	425	465	625	540	605	560	785	925	950	990
Rb	10	22	22	20	27	22	40	40	37	40	50	85	80	90
Zn	65	95	70	80	95	90	70	85	100	110	70	105	80	110
Cu	270	230	110	100	30	50	20	50	< 10	< 10	30	< 10	10	< 10

	(15) Re 104†	(16) Re 356†	(17) Re 100	(18) Re 371†	(19) Re 52	(20) Re 363†	(21) Re 1	(22) Re 364	(23) Re 315	(24) Re 16	(25) Re 9
SiO_2	55.1	57.4	59.39	59.9	56.99	56.7	58.46	61.02	59.46	63.04	64.09
Al_2O_3	17.1	17.2	17.98	15.9	17.53	14.5	17.09	15.20	17.39	16.90	18.00
Fe_2O_3	2.7	4.0	1.37	2.2	2.48	4.4	5.17	3.65	1.54	1.87	1.40
FeO	5.7	3.1	4.53	6.5	4.96	4.6	2.17	3.05	4.00	2.60	1.80
MgO	1.6	1.6	0.78	0.6	0.71	1.6	0.98	1.08	0.55	0.47	0.31
CaO	4.1	4.6	3.99	3.3	3.21	3.3	2.65	2.38	2.65	1.00	0.74
Na_2O	6.01	6.44	5.40	6.58	5.48	5.72	6.35	6.39	6.39	7.29	7.30
K_2O	3.60	2.68	3.08	3.19	2.99	3.68	2.92	4.31	3.54	4.38	4.15
H_2O+	0.38	0.88	0.71	0.16	1.66	0.87	1.40	1.07	0.36	0.28	0.29
TiO_2	1.36	1.34	1.05	0.82	1.01	1.24	1.00	0.90	0.60	0.55	0.49
P_2O_5	0.36	0.39	0.79	0.18	0.36	0.14	0.43	0.11	0.36	0.15	0.21
MnO	0.21	0.25	0.19	0.34	0.27	0.24	0.21	0.19	0.21	0.17	0.12
CO_2	—	0.31	0.40	—	2.46	1.49	0.99	0.67	3.24	0.97	0.86
total	98.2 (2)	100.1 (9)	99.66	99.6 (7)	100.11	98.4 (8)	99.82	100.02	100.29	99.67	99.76
CIPW norms											
Q	—	0.88	7.22	—	10.11	3.62	7.23	3.63	5.52	1.99	4.61
Or	21.74	15.95	18.39	18.94	18.00	22.28	17.53	25.74	21.26	26.13	24.78
Ab	45.09	54.88	46.16	55.95	47.24	49.59	54.58	54.64	54.94	62.27	62.41
An	9.25	10.18	12.23	4.45	—	3.09	4.15	0.06	—	—	—
Ne	3.74	—	—	—	—	—	—	—	—	—	—
Di	7.68	6.53	—	9.44	—	2.54	—	5.57	—	—	—
Hy	—	1.56	7.83	5.97	7.81	6.13	2.48	1.48	6.95	3.84	2.36
Ol	5.03	—	—	0.11	—	—	—	—	—	—	—
Il	2.64	2.56	2.01	1.56	1.95	2.41	1.93	1.73	1.16	1.05	0.94
Mt	3.96	5.81	2.01	3.15	3.66	6.52	4.86	5.35	2.27	2.74	2.05
Ap	0.87	0.93	1.89	0.43	0.87	0.34	1.03	0.26	0.87	0.36	0.50
Hm	—	—	—	—	—	—	1.90	—	—	—	—
Co	—	—	1.34	—	5.38	—	2.02	—	3.10	0.17	1.51
Cc	—	0.71	0.92	—	4.98	3.47	2.29	1.54	3.95	1.45	0.84
differentiation index	70.6	71.7	71.8	74.9	75.4	75.5	79.3	84.0	81.7	90.4	91.8
$\dfrac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	0.84_0	0.81_6	0.88_3	0.93_5	0.91_3	0.84_9	0.88_2	0.86_1	0.91_0	0.90_5	0.91_2
modal data (in vol %)											
groundmass	98.4	> 98	72.6	> 98	> 98	**	> 98	**			
phenocrysts											
Ol	0.5	—	1.2	—	—		—				
Plag	1.1	tr	24.3	—	—		tr				
Cpx	tr	—	0.7	—	—		—				
ore	tr	—	1.2	—	—		—				
trace elements (by X-ray fluorescence)											
Zr	640	415	495	590	530	560	495	850	540	645	445
Cr	10	17	15	10	7	40	7	12	12	7	15
V	10	20	20	< 5	< 5	65	5	45	5	5	5
Y	50	55	37	80	70	65	60	100	52	55	45
Ni	< 10	< 10	< 10	< 10	< 10	30	< 10	10	< 10	< 10	< 10
Sr	495	630	660	320	395	155	280	110	305	45	55
Ba	1070	865	905	1270	700	1110	1065	532	820	855	835
Rb	115	50	115	80	110	90	85	130	115	130	120
Zn	120	110	70	155	140	165	95	195	85	95	60
Cu	< 10	< 10	< 10	< 10	< 10	40	< 10	10	< 10	< 10	< 10

† X-ray fluorescence analysis for Si, Al, total Fe, Mg, Ca. ‡ Includes H_2O^- 0.16. § Includes H_2O^- 0.41.

** Welded tuffs of rather variable texture; dominated by anorthoclase phenocrysts (~ 25 %), but with some plagioclase, pyroxene and ore phenocrysts.

Table 3. (*cont.*)

Specimen localities

Re 512G	Groundmass of basalt flow, Re 512 (see table 4)
Re 350	Roadside flow between Rivière and Ilet Rond
Re 424	Flow from Sentier des Pecheurs, above R. des Marsouins, Takamaka
Re 415	Flow from Petit Centrale, Takamaka
Re 332	Lowest flow of Differentiated Series (immediately overlying Re 331; table 1) 6 km from mouth of R. des Galets
Re 2	Minor intrusive sheet; near Bras Rouge, Cirque de Cilaos
Re 272	Flow from summit massif of Piton des Neiges, below Caverne des Anglais
Re 86G	Groundmass of Re 86 (see table 4)
Re 482	20 m flow overlying conglomerates; R. St Etienne, west of Ravine Cabris
Re 228	2 m flow from Belouve succession; above Hellbourg, Cirque de Salazie.
Re 410	Flow above main path W. from Petit Central, Takamaka
Re 197	Flow from Plateau de Belouve (near top of Belouve succession). Cirque de Salazie
Re 196	Flow from Plateau de Belouve (approximately the same horizon as Re 197), Cirque de Salazie
Re 201	Flow from just below the edge of Plateau de Belouve, on path to Hellbourg (below Re 196), Cirque de Salazie
Re 104	Flow from summit massif of Piton des Neiges, on Cilaos path, just below crest of Coteau Kerveguen (above Re 86)
Re 356	Centre of intrusive sheet forming river bed at Roche Plate, Cirque de Salazie
Re 100	Relatively recent flow from summit of Piton des Neiges, Coteau Kerveguen, close to Caverne Dufourg
Re 371	Flow beside bridge over R. du Mat, near St André
Re 52	Steeply inclined intrusive sheet; Bras Rouge, W. of Cilaos, Cirque de Cilaos
Re 363	Loose block from columnar jointed ash-flow; roadside north-east of Salazie, Cirque de Salazie
Re 1	Minor intrusion between Cilaos and Bras Rouge, Cirque de Cilaos
Re 364	Loose block from columnar jointed ash-flow; roadside, northeast of Salazie, Cirque de Salazie
Re 315	Loose block from microsyenite intrusion; Trou Blanc, Cirque de Salazie
Re 16	Lower part of massive syenite intrusion of la Chapelle, Bras Rouge, Cirque de Cilaos
Re 9	Upper part of la Chappelle syenite; Bras Rouge, Cirque de Cilaos

Analyses: X-ray fluorescence analyses: Grant Institute of Geology, Edinburgh University.
All other analyses: Chemical Laboratory, Department of Geology, University of Manchester.

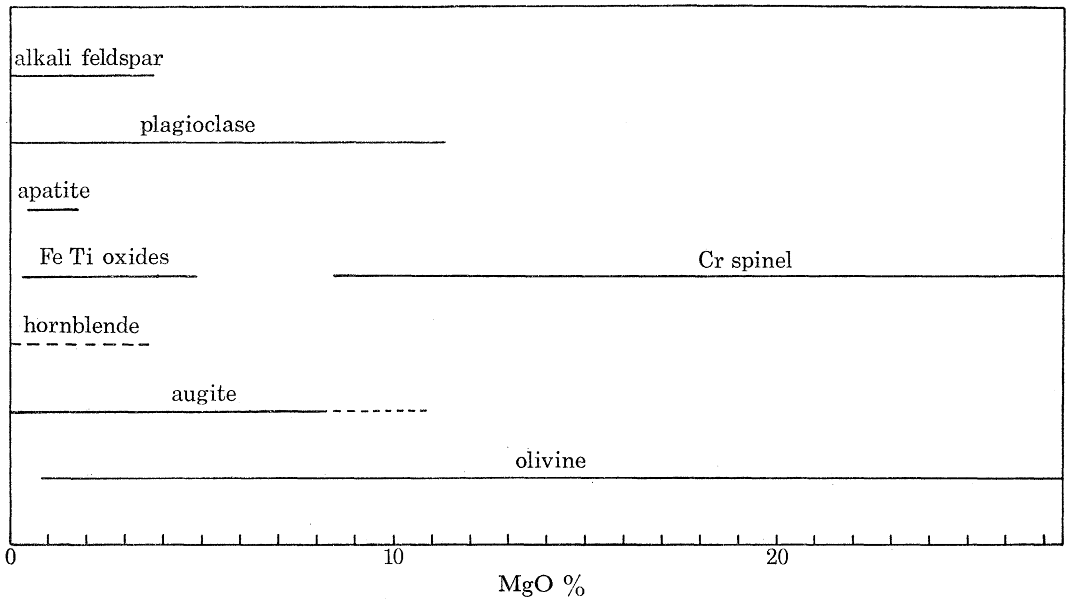

Figure 4. Phenocryst occurrence plotted against MgO content for all Reunion rocks (shield and declining stages).

(*d*) *Trace elements*

The trace element data (from tables 1 to 4) are plotted against MgO content in figure 6 and are also compatible with the thesis that magma compositions were dictated by olivine fractionation until the MgO in the liquids was reduced to approximately 6%, when more complex crystal fractionation started. However, the positive correlation of chromium with

MgO is likely to be more intimately associated with subordinate chrome-spinel fractionation than with the forsteritic olivines. Zr, Y, Ba and Rb are clearly concentrated in the rocks with least MgO; these at the same time showing the lowest values for Cr, Ni and Cu. K/Rb values for the Differentiated Series rocks are distinctly lower than those for the primitive shield-forming rocks.

Whereas the Sr, Ba, Rb, Zn and Cu values for the most basic Differentiated Series compositions appear to be essentially the same as those for shield-forming rocks of similar MgO content, this is not so for the other five trace elements determined. Thus, Zr, Cr, Y and Ni are consistently lower in the more basic Differentiated Series rocks than they are in corresponding shield rocks while V appears to be higher. This difference in trace element content between the Differentiated Series basalts and the shield-forming basalts must be considered in the light of the SiO_2, alkalis and iron differences that have already been referred to.

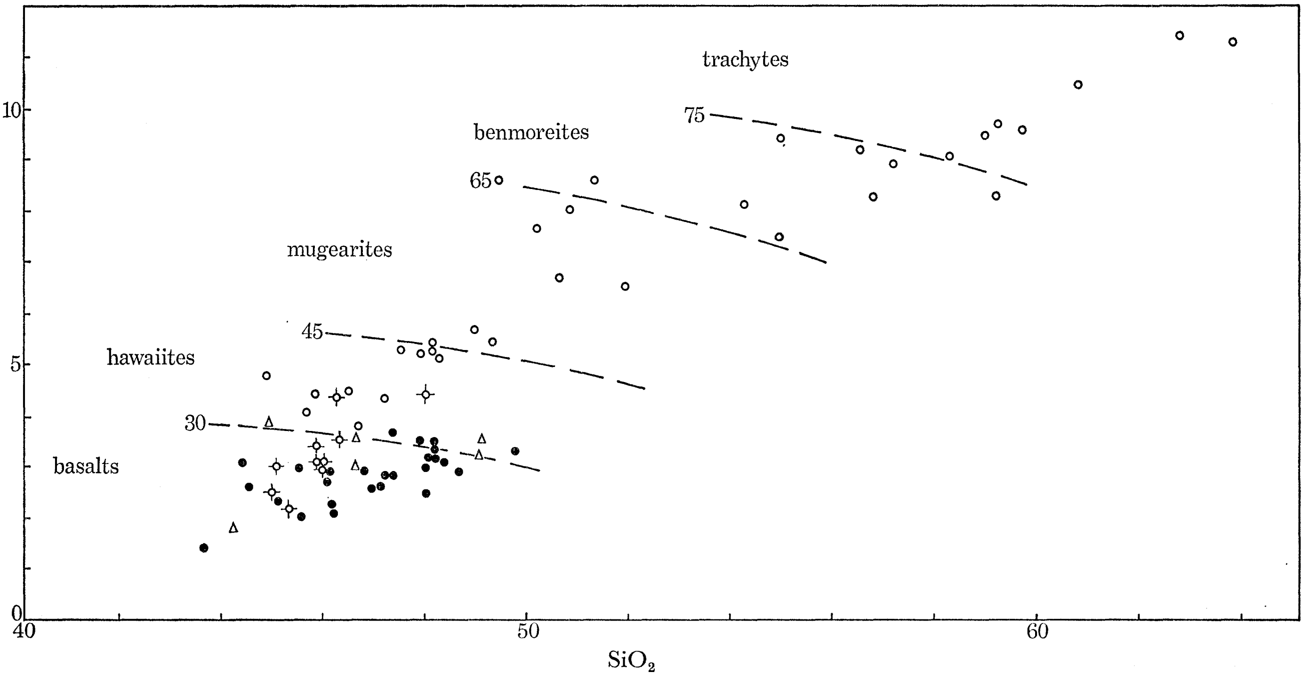

FIGURE 5. Plot of Na_2O+K_2O against SiO_2 for analysed rocks (this paper and Upton & Wadsworth 1966, 1967) from both shield and declining stages. △, Piton de la Fournaise lavas; ●, Oceanite series of Piton des Neiges; ○, Differentiated Series of Piton des Neiges (aphyric and with relatively low phenocryst contents); ⌖, strongly porphyritic rocks (probably cumulates) from Differentiated Series of Piton des Neiges; — —, Differentiation Index contours.

4. PETROLOGY OF THE DIFFERENTIATED SERIES

(a) *Introduction*

Although the shield oceanites and basalts of both Réunion volcanoes have already been described in considerable detail (Lacroix 1936; Upton & Wadsworth 1966, 1969), and are demonstrably rather uniform in composition, apart from variation in the olivine content, the Differentiated Series, which covers a wide range of compositions and textures, has been largely neglected. The following account, which is complementary to the chemical data of tables 3

TABLE 4. ANALYSES OF HIGHLY PORPHYRITIC LAVAS AND MINOR INTRUSIONS FROM THE DIFFERENTIATED SERIES

	(1) Re 512	(2) Re 520	(3) Re 471	(4) Re 335†	(5) Re 538	(6) Re 152	(7) Re 412†	(8) Re 86	(9) Re 204	(10) Re 202†
SiO_2	45.28	44.98	45.07	45.9	45.89	46.35	46.3	48.06	47.20	48.2
Al_2O_3	14.78	14.33	19.49	19.1	16.71	17.87	18.3	21.08	22.04	17.0
Fe_2O_3	4.86	3.11	5.38	8.1	3.06	1.49	3.0	3.94	2.79	5.0
FeO	6.55	9.42	6.89	3.5	10.09	11.34	7.8	5.21	6.39	6.7
MgO	10.92	11.23	4.57	4.0	4.11	4.03	3.8	3.18	2.23	4.2
CaO	12.62	10.68	11.74	12.6	12.51	10.70	10.2	10.30	10.82	8.4
Na_2O	1.75	1.99	2.48	2.44	2.75	2.89	3.26	3.44	3.36	4.01
K_2O	0.50	0.60	0.59	0.71	0.75	0.79	1.18	1.10	1.08	1.39
H_2O+	0.21	0.60	0.86	0.51	0.26	0.44	1.17	0.58	0.43	0.75
TiO_2	1.91	2.03	2.58	2.53	3.04	2.69	3.40	2.40	2.32	3.05
P_2O_5	0.24	0.43	0.43	0.24	0.33	0.49	0.37	0.47	0.55	0.56
MnO	0.20	0.21	0.23	0.16	0.18	0.21	0.18	0.18	0.19	0.21
CO_2	0.39	0.18	0.27	0.24	0.46	0.52	0.20	0.13	0.99	—
Total	100.21	99.79	100.53	100.0 (3)	100.14	99.81	99.1 (6)	100.07	100.39	99.5 (7)

† X-ray fluorescence analysis for Si, Al, total Fe, Mg, Ca.

CIPW norms										
Q	—	—	—	1.77	—	—	—	—	—	—
Or	2.95	3.57	3.50	4.22	4.44	4.70	7.11	6.53	6.38	8.32
Ab	14.81	16.97	21.04	20.76	22.34	24.60	27.81	29.25	28.43	34.37
An	30.99	28.62	40.41	39.28	31.07	33.66	32.45	39.02	41.87	24.59
Ne	—	—	—	—	0.52	—	0.18	—	—	—
Di	21.86	16.77	10.82	15.93	21.58	11.10	12.60	6.75	1.63	11.15
Hy	5.33	4.01	7.98	2.63	—	4.97	—	4.90	6.80	2.49
Ol	11.92	20.19	1.88	—	8.01	11.30	7.45	1.81	2.88	4.53
Il	3.63	3.89	4.91	4.83	5.78	5.14	6.59	4.58	4.41	5.87
Mt	7.05	4.54	7.82	4.37	4.44	2.17	4.47	5.74	4.05	7.33
Ap	0.57	1.03	1.02	0.57	0.78	1.17	0.89	1.12	1.30	1.34
Hm	—	—	—	5.09	—	—	—	—	—	—
Co	—	—	—	—	—	—	—	—	—	—
Cc	0.89	0.41	0.62	0.55	1.05	1.19	0.46	0.30	2.25	—
differentiation index	17.8	20.6	24.5	26.8	27.3	29.3	35.1	35.8	34.8	42.7
$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	0.51_1	0.52_7	0.72_9	0.74_4	0.76_2	0.76_1	0.74_0	0.74_1	0.80_5	0.73_6
groundmass	76.0	79.8	47.1	60.3	84.9	78.0	68.0	58.1	62.9	80.6
phenocrysts										
Ol	5.9	11.0	1.4	1.4	0.9	0.6	tr	1.8	2.2	3.4
Plag	9.7	2.1	50.0	38.3	14.2	21.4	32.0	39.6	31.0	14.4
Cpx	8.4	5.4	1.1	tr	tr	—	tr	tr	2.2	tr
Ore	—	1.7	0.4	tr	tr	—	—	0.5	1.7	1.6
trace elements (by X-ray fluorescence)										
Zr	90	105	130	140	155	95	220	160	190	280
Cr	210	315	< 5	< 5	5	5	22	5	5	5
V	290	305	310	300	380	340	200	150	145	125
Y	20	22	25	25	30	30	25	27	30	35
Ni	200	270	20	30	10	20	< 10	10	< 10	< 10
Sr	360	355	450	485	460	455	790	950	820	820
Ba	285	295	315	325	405	360	510	485	420	640
Rb	10	15	12	10	17	18	25	25	30	50
Zn	60	80	70	75	80	80	60	50	70	65
Cu	310	270	270	230	260	300	30	40	30	30

SPECIMEN LOCALITIES

Re 512	Lowest flow of Differentiated Series; Ravine des Colimacons, near St Leu
Re 520	Flow in succession between Plateau de Belouve and Plateau Mazerin; below Mazerin
Re 471	Flow below bridge over Grand Ravine, near Trois Bassins
Re 335	Flow from Ravine des Avirons, near Pointe des Avirons
Re 538	Flow from Ravine de la Fontaine; N. of la Fontaine
Re 152	One of lowest flows in Differentiated Series, above Grand Bassin
Re 412	Flow on path W. of Petit Central, Takamaka (below Re 410)
Re 86	Flow from summit massif of Piton des Neiges; on Cilaos path, below crest of Coteau Kerveguen
Re 204	Massive flow near top of Belouve succession; above Hellbourg, Cirque de Salazie
Re 202	Massive flow, next but one above Re 204

Analyses (same as for table 3).

and 4, outlines the principal petrological and mineralogical characteristics of the Differentiated Series rocks, both intrusive and extrusive.

(*b*) *Lava-flows*

Although the lavas range from basalts to trachytes they display a bimodal grouping into: (i) conspicuously feldsparphyric types (generally basalts and hawaiites); (ii) lighter coloured types in which phenocrysts are both small and scarce, and which typically possess a fine trachytoid flow texture (generally hawaiites, mugearites and benmoreites). All the Differentiated Series lavas are feldsparphyric to some extent (even in cases where the total phenocryst content is less than 2 %, occasional plagioclase microphenocrysts are found). It follows that no flows are

TABLE 5. CLASSIFICATION OF BASALT–TRACHYTE SERIES

	basalt	hawaiite	mugearite	benmoreite	trachyte
differentiation index	< 30	30–45	45–65	65–75	> 75
normative $\frac{\text{An}}{\text{An+Ab}}$ (approx.)	> 50	50–30	30–15	15–5	< 5
Na_2O+K_2O	< 3.5	3.5–5.5	5.5–8.5	8.5–10	10–11

TABLE 6. REUNION AVERAGE ANALYSES (100 %, WATER-FREE, STANDARD Fe_2O_3 BASIS)

	(1)	(2A)	(2B)	(3A)	(3B)	(4)	(5)
	basalt	hawaiite		mugearite		benmoreite	trachyte
SiO_2	46.0	47.1		52.1		58.5	59.6
Al_2O_3	15.7	15.7		17.1		17.8	16.2
Fe_2O_3	2.0	2.0	(4.7)	2.0	(4.4)	2.0	2.0
FeO	10.1	11.8	(9.2)	8.7	(6.3)	5.2	5.8
MgO	7.7	4.7		2.6		1.3	1.0
CaO	12.6	9.5		6.9		4.3	3.1
Na_2O	2.4	3.5		4.9		6.1	6.2
K_2O	0.7	1.2		2.4		2.8	3.5
TiO_2	2.2	3.7		2.3		1.3	2.3
P_2O_5	0.3	0.5		0.7		0.5	0.2
MnO	0.2	0.2		0.2		0.2	0.2
				CIPW norms			
Q	—	—	(—)	—	(—)	0.9	1.8
Or	4.1	7.1	(7.1)	14.2	(14.2)	16.6	20.7
Ab	15.2	26.6	(29.7)	38.2	(41.2)	51.6	52.5
An	30.0	23.6	(22.8)	17.6	(17.6)	12.9	6.0
Ne	2.8	1.6	(—)	1.8	(0.1)	—	—
Di	25.0	16.9	(17.3)	10.2	(10.0)	4.4	6.8
Hy	—	—	(1.1)	—	(—)	7.2	4.6
Ol	15.0	13.0	(6.9)	9.1	(4.5)	—	—
Il	4.2	7.0	(7.0)	4.4	(4.4)	2.5	4.4
Mt	2.9	2.9	(6.8)	2.9	(6.4)	2.9	2.9
Ap	0.7	1.2	(1.2)	1.6	(1.6)	1.2	0.5

1 Basalt Re 512G (Groundmass of porphyritic basalt, Re 512).
2 Average hawaiite (table 3, columns 2–8).
3 Average mugearite (table 3, columns 9–14).
4 Average benmoreite (table 3, columns 15–17).
5 Average trachyte (table 3, columns 18–22).
Hawaiite and mugearite norms in brackets (2B and 3B) refer to analyses with unmodified Fe_2O_3/FeO.

known in this series with only olivine (+spinel) or olivine + pyroxene phenocryst assemblages. The commonest assemblages are:

1. olivine + plagioclase
2. olivine + plagioclase + augite
3. olivine + plagioclase + augite + magnetite

Other phenocryst assemblages recorded are as follows:

4. plagioclase
5. plagioclase + augite
6. plagioclase + augite + FeTi oxide
7. plagioclase + olivine + FeTi oxide
8. plagioclase + FeTi oxide
9. plagioclase + hornblende + FeTi oxide
10. plagioclase + olivine + hornblende + FeTi oxide
11. plagioclase + olivine + augite + FeTi oxide + apatite
12. plagioclase + olivine + augite + hornblende + FeTi oxide
13. plagioclase + olivine + augite + anorthoclase
14. plagioclase + augite + FeTi oxide + anorthoclase + biotite
15. plagioclase + augite + olivine + FeTi oxide + anorthoclase

The hornblende and biotite phenocrysts invariably show evidence of resorption, and are normally surrounded by reaction zones of opaque oxides. Alkali feldspar phenocrysts have only been found in the trachytic ash-flow deposits (and in certain mugearitic intrusives), while quartz phenocrysts are entirely absent.

The strongly feldsparphyric basalts and hawaiites are spread over much of the lower western flanks of the volcano. Similar lavas occur in the west wall of Cirque de Mafate, the Belouve escarpment in Cirque de Salazie and in the gorges of the Bras de la Plaine and the Rivière des Marsouins (for specific localities, see the geological map by Bussière 1967). A study of boulders in the rivers draining the great erosional cirques indicates that much of the inaccessible ridge of Le Gros Morne and most of the upper 1000 m of Piton des Neiges itself, must consist of such flows. The very severe nature of the terrain makes verification of this inference difficult but, if correct, it suggests that the highest and most central peaks of the volcano may be largely carved from a thick caldera-fill succession of these rocks. The implication of such a massive caldera-filling episode, following the termination of the primitive shield-building phase, is that the feldsparphyric basic lavas are volumetrically dominant among the Differentiated Series volcanics.

The accessible flank-flows of the feldsparphyric lavas are found to be dominantly as flows of up to 10 m thickness, showing no indication of *in situ* crystal settling (or flotation). The abundant plagioclase phenocrysts (An_{85}) may be accompanied by olivine, augite and FeTi oxide phenocrysts, set in a matrix of the same four phases. Small gabbroic inclusions, in varying states of disaggregation, occur sporadically in these flows. Most of these are composed of euhedral plagioclase and poikilitic augite. However, a relatively basic flow (Re 512, see table 4) immediately overlying the Oceanite Series in Ravine des Colimaçons, not only contains an unusually high proportion of olivine and augite phenocrysts compared with plagioclase, set in a basaltic groundmass (Re 512G, table 3), but also occasional dunite and wehrlite xenoliths as well as the more usual gabbroic types.

More nearly aphyric hawaiite, mugearite and benmoreite lavas, though frequently seen interspersed with feldsparphyric basalts and hawaiites, probably characterize the later (post-caldera filling) stages of activity. These too are thought to have been generally erupted from the summit region. Some thick sequences of the eastern flanks (e.g. Belouve plateau and Plaine des Marsouins) accumulated in deep radial gorges analogous to (but smaller than) the modern 'cirques'. Trachytic ash-flows (and intrusions) are likewise believed to be relatively youthful events in the history of the Differentiated Series. The youngest eruptive cycle appears to have involved the eruption of a sequence of mildly porphyritic benmoreite as flows which form the modern construction surface up to the present summit of Piton des Neiges. These distinctive flows contain phenocrysts of plagioclase, (An_{60}), olivine, augite, FeTi oxide and apatite, as well as much-resorbed and oxidized kaersutitic hornblende. There are also some small hornblende–gabbro xenoliths which comprise largely oxidized idiomorphic brown hornblende, andesine (*ca.* An_{60}), magnetite and apatite, with a little augite and interstitial olivine. A mantle of tuff on the upper constructional slopes around the north and western sides of Piton des Neiges probably represents the air-fall material accompanying these relatively recent (but undated) benmoreite eruptions.

(*c*) *Ash-flow deposits*

On the south side of the volcano, between Entredeux and the coast just northwest of St Pierre is a substantial deposit of fragmental rock consisting of unbedded, unsorted and loosely consolidated tuff, approximately 70 m thick, composed of highly vesicular pumice particles up to 20 cm diameter. It appears to be an unwelded ash-flow tuff and of interest from the variety of pumice fragments. Most are highly feldsparphyric basalt or hawaiite, others more closely resemble material from the nearly aphyric hawaiite–mugearite–benmoreite flows. Angular lithic fragments are relatively scarce but include feldspathic gabbros. The pumice particles have been strongly oxidized and no analyses have been made. However the ash-flow does suggest that a range of compositions was simultaneously available for eruption (possibly from composite magma bodies or from magma bodies showing a strong compositional gradient) and that these were intermixed as pumice fragments during the ash-flow propagation.

Although no trachyte lava flows occur, a thick and strikingly columnar-jointed succession of extrusive units forms part of the southeast wall of the Cirque de Salazie. These are extremely compact and flinty trachytic welded tuffs, consisting of rounded to subangular lithic particles (1 cm across) in a streaky matrix comprising ill-defined, dark flow-banded lenticles. Anorthoclase phenocrysts are plentiful in the matrix, less so in the lithic fragments. The overall appearance of these rocks differs considerably from the typical eutaxitic textures of welded tuffs and no unwelded facies of these flows have been recognized. The lithic fragments appear to range from benmoreite to trachyte in composition; they are holocrystalline, with trachytoid flow texture, and are sparsely feldsparphyric. Scarcer fragments of much altered olivine–gabbros also occur in these rocks. The matrix separating the lithic particles consists of streaky glass in varying stages of crystallization. Phenocrysts in this matrix include anorthoclase, andesine, ferro-augite, FeTi oxides and occasionally fayalitic olivine, partially replaced by carbonate. Analyses of two specimens (Re 363, Re 364) are given in table 3.

It is concluded that these units were erupted as ash-flows involving a mélange of gas, porphyritic trachyte magma, crystalline 'cognate' fragments with bulk compositions similar to or identical with that of the liquid fraction, and relatively scarce 'exotic' fragments of intrusive and extrusive wall rocks. These welded tuffs were probably erupted from a summit vent, and flowed northeast along a former river gorge lying to the southeast of the modern gorge of the Rivière du Mât, where they collapsed and produced several flows with thicknesses of the order of 100 m. The flows are envisaged as having retained much of their thermal energy even after their collapse, continuing to flow so that trachyte pumice particles became streaked out, largely losing their identity in the process. Degassing before and during collapse must have been almost complete in order to produce such highly compacted rocks. However, minute subspherical gas vesicles in the flow matrix (< 1 mm) indicate that some gas evolution continued after the flows had come to rest.

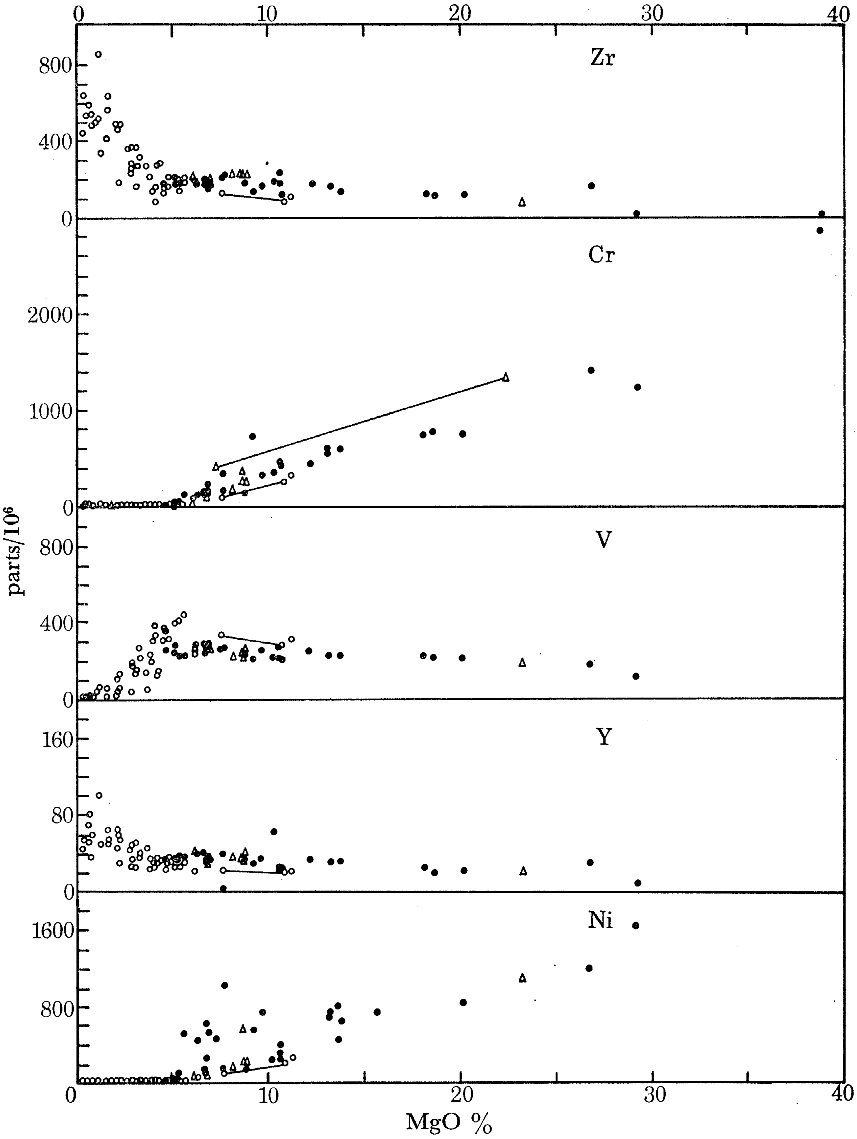

FIGURE 6*a*. Trace elements from Réunion rocks plotted against MgO. △, Piton de la Fournaise; ●, Piton des Neiges, Oceanite Series; ○, Piton des Neiges, Differentiated Series. Tie-lines indicate groundmass–whole rock pairs.

(*d*) *Intrusive rocks*

The Differentiated Series intrusives are well exposed in the central area of Piton des Neiges, notably in the gorges of the Bras Rouge (Cirque de Cilaos), Rivière du Mât, Rivière des Fleurs

Jaunes (Cirque de Salazie), and their tributaries. Although they represent the same range of magmas as gave rise to the lavas and ash-flows, chemically they are characterized by relatively high H_2O and CO_2 contents, and a high Fe_2O_3/FeO ratio. Mineralogically they are distinguished by the scarcity of olivine and the common occurrence of chlorites and amphiboles instead.

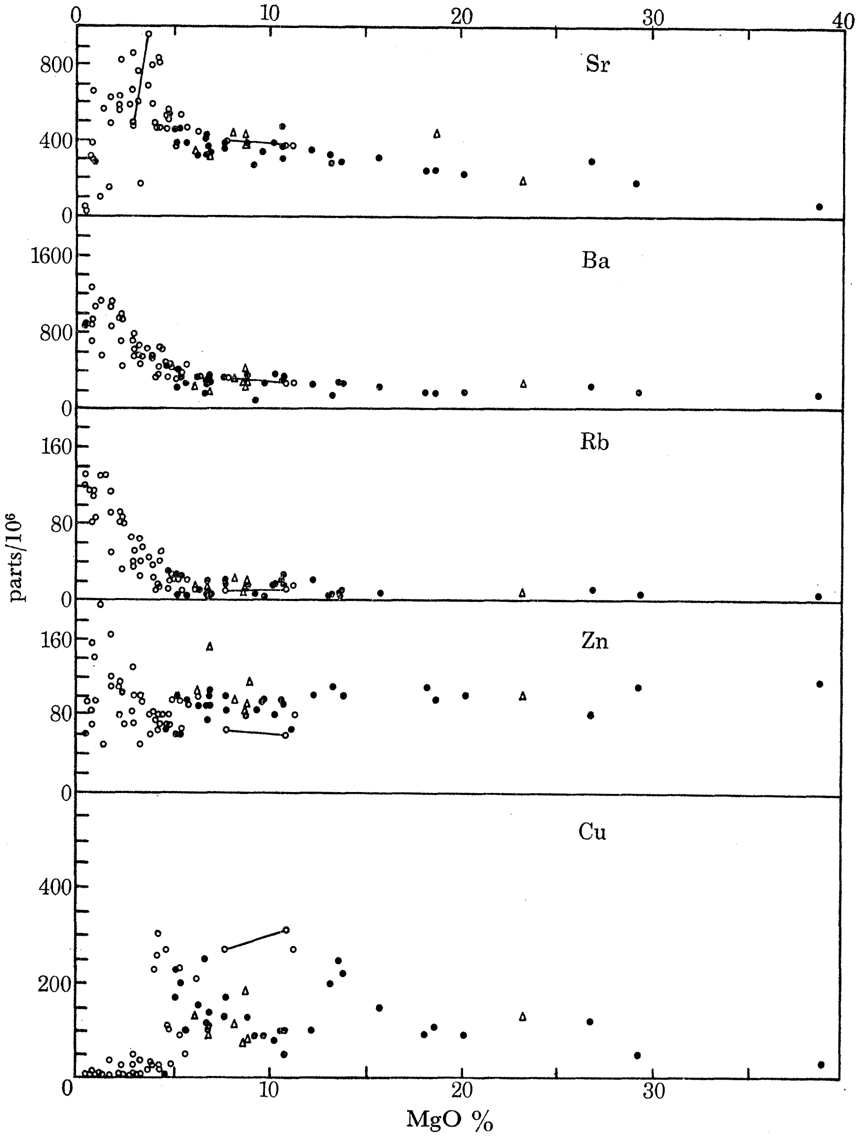

Figure 6*b*. For legend see facing page.

The phenocrysts of the more basic sheets include bytownite, augite and magnetite and, rarely, pseudomorphed olivines. There is thus a general qualitative resemblance to the feldsparphyric basalt–hawaiite extrusives, although the phenocrysts of the intrusives are invariably much resorbed and have often been severely altered. Among the more alkalic compositions (mugearite–benmoreite), relict phenocrysts of brown basaltic–hornblende occur, while occasional highly resorbed biotite phenocrysts have also been recorded locally. The common occurrence of both plagioclase (andesine) and alkali feldspar phenocrysts in the mugearite–benmoreite intrusions shows that the magmas passed at some stage through a field of two-feldspar crystallization, although the alkali feldspars generally show signs of resorption. Some of the intrusions, of which the Bras Rouge sill (Upton & Wadsworth 1967) is the best example, have 'two-feldspar' mugearitic chilled margins and 'one-feldspar' basalt–hawaiite centres. Further, the central parts of some of these sheets are conspicuously more felsparphyric than the marginal facies. From these it is deduced that magma bodies existed with compositional gradients from mugearite liquids above, to basalts with accumulated plagioclase phenocrysts below, and that these were tapped from above downwards to give rise to the composite sheets injected at high levels.

Even the thinner basic sheets ($<$ 2 m thick) commonly contain thin segregation veinlets of alkali feldspar, quartz and calcite, ± amphibole and chlorite. This strong tendency for over-saturated trachytic residua to become segregated from their parent magma suggests that the massive sheets of quartz–microsyenite, which are believed to be the intrusive equivalents of the less voluminous trachyte ash-flows, have originated from deep-seated and relatively large volumes of more basic magma. They appear to have been expelled upwards to crystallize at high levels within the volcanic pile, as the result of loss of volatiles.

These microsyenites consist of strongly zoned plagioclase (An_{40-25}) mantled by antiperthite or cryptoperthite ($Or_{38}Ab_{59}An_3$), idiomorphic augite and magnetite, interstitial amphibole (brown 'lanéite' zoned to riebeckite–arfvedsonite), chlorite, biotite, aegirine and aenigmatite. Quartz and calcite occur interstitially and the rocks contain small interstitial cavities presumably vacated by fugitive volatile components. Miarolitic veins of pegmatite ($<$ 1 cm thick) composed of sanidine, riebeckite–arfvedsonite, quartz and calcite, traverse the microsyenites. Thus, extreme fractionation of the Differentiated Series intrusives led to the production of carbonate-rich liquids of comenditic composition. Lacroix (1936, p. 229) described a pantelleritic rock with 68 % SiO_2, and 8.3 % normative acmite from Piton des Neiges. The occurrence of such a rock among the Differentiated Series volcanics would scarcely be surprising. However, the locality given by Lacroix for this specimen is almost certainly erroneous. In spite of careful search in the course of three visits to the volcano, no intrusions or extrusions of comendite or pantellerite were found; nor was any evidence found among the pebbles forming the deltas of the rivers draining the volcano.

The ubiquitous presence of chlorite (and the common occurrence of amphibole) in the Differentiated Series intrusions is believed to reflect original magmatic crystallization of hydrous magmas, rather than subsequent metamorphic effects. Not only are the Differentiated Series magmas suspected of having been water-saturated, but the abundance of calcite in the intrusives and the common occurrence of botryoidal calcite in the vesicles of the lavas also implies saturation with respect to CO_2. Further the relatively high Fe_2O_3/FeO ratios of the analysed Differentiated Series intrusives, the modal abundance of opaque oxides, and the low degree of absolute iron-enrichment displayed by this strongly differentiated suite of rocks, are believed to be linked with high P_{H_2O}, and P_{O_2} values in the parent magma. Thus, while the Differentiated Series lavas represent crystallization under 'dry' conditions at atmospheric pressure, the intrusive suite is believed to have crystallized under 'spilitic' conditions (Yoder 1967) with P_{H_2O} perhaps 300 to 500 bar (30 to 50 MPa), and the relict phenocrysts and xenoliths carried by the intrusions relate to amphibolite or gabbroic crystallization at rather greater depths.

5. Discussion

(a) *Primitive magma*

Although only very scanty information about the nature of the upper mantle and oceanic crust beneath Réunion is available, analogy with the Hawaiian islands (Jackson & Wright 1970) suggests that the primitive magma was generated by partial melting of peridotite (perhaps of garnet–lherzolite composition) in the low-velocity zone at depths of perhaps 60 to 90 km (equivalent to a pressure range of 20 to 30 kbar (2 to 3 GPa)). Experimental evidence (O'Hara & Yoder 1967; Ito & Kennedy 1967; Green & Ringwood 1967) indicates that the initial melts formed in this situation are likely to have been picritic and verging on hypersthene-normative. From such liquids, with MgO probably in excess of 20%, substantial amounts of olivine would have been precipitated on the way to the surface, and as shown by O'Hara (1965), it is unlikely that unmodified primary magma ever reached the surface. The importance of olivine fractionation in influencing the chemical and mineralogical variation of the shield lavas of Reunion has already been established, and it is clear that the scarce aphyric members of these suites represent relatively evolved (olivine-depleted) magmas. Further evidence of massive olivine fractionation within the rising magmas is provided by the widespread occurrence of dunite nodules, and by analogy with geophysical evidence from Hawaii (Kinoshita, Krivoy, Mabey & MacDonald 1963) there may be olivine cumulate cores (with high density and high seismic velocity) within the Reunion volcanoes.

In view of the ease with which olivines settle gravitationally in basalts, the occurrence of large olivine phenocrysts and dunite nodules (up to 500 g in mass) in many of the Réunion shield lavas suggests relatively fast upward accession of the magma. Jamieson (1970) observes that if one assumes the $\mathrm{d}T/\mathrm{d}P$ of an ascending magma is a measure of its rate of ascent, slowly rising tholeiite magmas will tend to attain the five-phase cpx + opx + ol + R(Al-bearing phase) + liquid equilibrium and may fractionate further if it is a reaction point. However, magmas ascending faster will tend to remain at temperatures above those of five-phase equilibrium. Since expansion of the olivine primary phase volume accompanies pressure decrease and any partial melt derived from peridotite must initially be in equilibrium with olivine, the compositions of these more rapidly ascending magmas will be strongly modified in terms of olivine content, but little in terms of other constituents. Hence, the very fact that the compositional variation of the Réunion shield-lavas appears to have been almost solely due to olivine-fractionation, also implies high ascent rates. (It should however be noted that there is no evidence that any Réunion magmas ever attained a low-pressure five-phase equilibrium involving orthopyroxene, a fact attributed to the relatively high alkali contents.)

One of the major problems concerning the oceanic shield volcanoes is the sheer bulk of rather uniform magma erupted from one or more closely adjacent sites (on the same island) over a period of some millions of years, perhaps 3 to 5 Ma in the case of Réunion. There appear to be two main options available for the production of large volumes of basalt by partial melting of the mantle.

First, there is the closed system or static model in which all the magma is generated from mantle immediately underlying the volcano (Jackson & Wright 1970), without any means of renewal of this source once it has been depleted of its basalt fraction. In this case an overall limitation of the volume of mantle to produce the overlying volcanic pile is set by the vertical thickness of the low-velocity zone (approximately 200 km), but a much more significant constraint can be placed on the lateral extent of mantle material from which individual volcanoes are supplied (Murata 1970). This is based on the independent, but parallel, evolution of closely adjacent volcanoes (e.g. the five volcanoes of Hawaii), and implies that the source of the lavas is correspondingly limited in a lateral sense beneath each volcano. The distance between neighbouring summits on Hawaii is 35 to 40 km and this defines the maximum diameter of the subjacent cylindrical zone of magma extraction and evolution. On this basis a mantle 'cylinder', 37 km in diameter is indicated for Mauna Loa, and even with 50% (by weight) of partial melting, and fully effective extraction from the whole volume, the height of the 'cylinder' is calculated as 60 km (Murata 1970). A similar degree of partial melting is envisaged by Jackson & Wright (1970) for the production of the Koolau tholeiite shield on Oahu, and in this case there is independent evidence, in the form of a zonal arrangement of xenolith compositions, of the diameter of the mantle cylinder affected (*ca.* 30 km), and of the likely composition of the undepleted mantle outside this cylindrical zone.

Unlike the complexity of Hawaii with its five coalescing shields, the geometry of Réunion is sufficiently simple for a minimum estimate of the volume of Piton des Neiges to be made with confidence. By taking a NE–SW profile through the summit region, using the bathymetric data of Fisher *et al.* (1967), and assuming a plano-convex form, the volume of Piton des Neiges is very approximately 70000 km^3. Partial melting to the extent of 50% (mass) from a cylinder of 30 km diameter (the summits of the two volcanoes are 30 km apart), requires a vertical dimension of approximately 180 km to account for such a volume of extrusive material.

Secondly, there is the open system or dynamic model of magma generation, in which the mantle source beneath the volcano was itself replenished, either by lateral migration into it of basalt liquid generated elsewhere, or by lateral displacement of the volcano and oceanic lithosphere relative to the potentially productive low-velocity layer.

The closed system has the following advantages:

(i) It satisfactorily accounts for the independent activity and evolution of closely adjacent volcanoes.

(ii) It explains the minor differences in shield chemistry between neighbouring volcanoes, as recorded on Hawaii (Macdonald 1968), although not so far recognized on Réunion.

(iii) The extraction of substantial volumes of basalt from the subjacent mantle provide an explanation of the eventual subsidence of the volcanic structures, but Réunion is exceptional in this respect, in that it appears to have been strongly uplifted (Upton & Wadsworth 1970).

The main disadvantage of the closed system is the high degree of partial melting required to keep the size of the mantle 'cylinder' within reasonable limits, i.e. within the low-velocity layer. This is indicated by calculations for a volcano like Piton des Neiges, with a volume of 70000 km^3. Assuming 50% (mass) partial melting, the possible 'cylinder' dimensions would be:

diameter	30 km	height	180 km
	40 km		100 km
	50 km		65 km
	60 km		40 km

(with 10% partial melting, a 'cylinder' 60 km in diameter, taking up the whole vertical thickness of the low velocity layer (200 km) would be required).

The relatively high degree of partial melting implicit in the static model also leads to another difficulty, namely the unacceptably low concentration of 'incompatible' elements (Green &

Ringwood 1967) in the melt. The average 'enrichment factor' for such elements in the Réunion basalts is approximately 20, and it is suggested that this is most likely to have been attained by a moderate degree of partial melting (between 7 and 15%) initially, followed by a 30 to 70% concentration as the result of fractional crystallization during migration of the magma to the surface.

It might be argued that the relatively high 'enrichment factors' for the Réunion basalts do not necessarily imply such a modest degree of partial melting, but could have been developed as the result of wall-rock reaction processes (Green & Ringwood 1967). However, as O'Hara (1968) has pointed out, such processes may be effective for the first batch of magma moving through a conduit, but it is difficult to envisage them working with equal or increased efficiency for succeeding batches. Gast (1968) also noted that the opportunity for enrichment in incompatible elements is likely to decrease rapidly as small conduits (10 to 100 cm) coalesce into larger channels.

The open system has the advantage of allowing a smaller and generally more acceptable degree of partial melting, but it makes it more difficult to explain the shift of activity from one location to another nearby. (This migration cannot simply be the result of the completion of basalt extraction from one particular mantle 'cylinder' followed by the initiation of partial melting in an adjacent region, as might be the case with the static model.) Presumably the diversion of the supply of primitive magma from Piton des Neiges to Piton de la Fournaise is related to changing stress patterns in the lithosphere, possibly as the result of the lateral movement of oceanic lithosphere. Whatever the precise mechanism of magma generation, segregation and ascent, the compositional uniformity of the shield lavas of both volcanoes indicates considerable homogeneity in the source region, as well as the operation of similar degrees of partial melting and subsequent fractionation.

On balance, the open system, with its less extreme partial melting requirements, is preferred to the static model in accounting for the production of the voluminous shield basalts of Reunion.

(*b*) *Evolution of the Differentiated Series*

Although chronologically, and in terms of many chemical and mineralogical characteristics, the Differentiated Series appears to represent a natural development from the shield stage of magmatism, it has been shown (p. 113) that the change in composition from the shield to the declining stage cannot simply be related to the appearance of plagioclase, pyroxene and FeTi oxides, joining olivine as liquidus phases. On the other hand, there certainly seems to be no compelling reason to assume a separate, deeper-level source for the Differentiated Series magma, as inferred for the Hawaiian situation by Kuno, Yamasaki, Iida & Nayashima (1957), and by Yoder & Tilley (1962).

It is tentatively suggested that the initially nepheline-normative Differentiated Series liquids were produced from the same primary magma as fed the shield stage of activity, by fractionation at intermediate depths (probably in the 10 to 20 kbar (1 to 2 GPa) pressure range), involving the extraction of pyroxenes as well as olivine. The establishment of conditions which encouraged prolonged fractionation at these depths, rather than the relatively rapid ascent to high levels, as is believed to have occurred during shield formation, is probably connected with the diversion of the main magma supply from Piton des Neiges to Piton de la Fournaise. It is envisaged that a relatively stagnant body of magma was trapped beneath Piton des Neiges, when the site of the principal conduit system shifted, and that this underwent virtually closed-system crystal fractionation during the time interval (perhaps 100000 years) between the eruption of the youngest shield lavas and the earliest Differentiated Series flows. The main magmatic products of this episode are believed to have been nepheline-normative basalts and hawaiites.

The more extreme compositions of the Differentiated Series have clearly involved fractionation at much higher levels, and probably represent the eventual upward migration of magma from the relatively stagnant bodies into positions within or just below the volcanic superstructure (Upton & Wadsworth 1970). The reversion from nepheline-normative basalts and hawaiites to saturated and oversaturated mugearites, benmoreites and trachytes (and their intrusive equivalents) may possibly be explained by the extraction of nepheline-normative clinopyroxenes and amphiboles, and the onset of Fe–Ti oxide precipitation within the mugearite–benmoreite stage of differentiation may also have been a contributory factor.

Bryan (1970) has described, with examples from Socorro and Pantelleria, how peralkaline rhyolites can be derived from Ti-rich hawaiites by separation of Ti-rich oxides and pyroxenes. The peralkaline granite–pegmatoid segregations of the Réunion quartz-microsyenites may have formed in a similar fashion. However, in Réunion, any excess of alkalis is suspected to have been wholly lost in fugitive vapours from the miarolitic quartz-syenites and the trachytic welded-tuffs.

There is evidence to suggest that high-level fractionation gave rise to differentiated magma columns, with crystal-enriched, relatively basic lower portions overlain by aphyric alkalic liquids (Upton & Wadsworth 1967), and that the variety of lava types occurring in apparently haphazard sequence within the Differentiated Series results from these magma columns being tapped at various levels. In particular, the abundant feldsparphyric basalts and hawaiites are believed to represent considerable plagioclase accumulation by sinking, with some preferential ellutriation of feldspar with respect to olivine (± pyroxene and FeTi oxides). The highly calcic nature of the feldspar, together with the occurrence of allivalitic nodules involving cumulus plagioclase and olivine, indicate that feldspar flotation, as suggested by Tilley *et al.* (1965) for rocks of these compositions, did not take place.

6. CONCLUSIONS

Partial melting of garnet-peridotite at a depth between 60 and 100 km is believed to have been responsible for the genesis of some 100000 km^3 of relatively uniform hypersthene-normative olivine-basalts which have been erupted on Réunion over the last 3 to 5 Ma. The degree of partial melting is estimated to have been in the range 7 to 15%, and it therefore seems unlikely that such a volume of basalt can have been extracted from a static body of underlying mantle. Instead it seems more reasonable to consider that the mantle source has been steadily replenished by flow beneath the oceanic crust in the vicinity of Réunion. Such a model carries the implication of a lack of coupling between an upper lithospheric plate and the underlying mantle. The tectonic disturbances which occurred in the early history of Réunion (over 3 Ma ago), and give some indication of thrusting towards the northeast (Upton & Wadsworth 1969), were probably related to such a mechanism.

Olivine fractionation was clearly the dominant process modifying the primary magma before and during eruption in the main shield stage of development. More advanced fractionation, involving pyroxene and feldspar, appears to have been rare during this stage. The dunites, and the other rarer wehrlitic rocks found as nodules in the shield-lavas, are considered to be cumulates formed from the basalts and are not thought to represent refractory mantle remaining after the extraction of basalt. With the degree of partial melting suggested, the residual 'barren' mantle is considered to have been harzburgitic (or even lherzolitic) in composition, rather than dunitic or wehrlitic.

The declining stage of activity on Piton des Neiges produced the Differentiated Series volcanics, and is thought, on circumstantial evidence, to be due to extensive crystal fractionation of a relatively small body (perhaps only 100 km^3 in volume) of primitive magma that was left to stagnate at depths of 30 to 60 km beneath Piton des Neiges following the diversion of newly generated magma into the Piton de la Fournaise feeder-system. This intermediate level fractionation probably involved separation of olivine and pyroxenes (possibly also garnet), and led to the production of nepheline-normative basaltic and hawaiitic liquids. These in turn have undergone high-level fractionation involving plagioclase, augite, FeTi oxides, etc., as well as olivine, leading ultimately to the genesis of small quantities (perhaps 10 km^3) of quartz-trachyte magma.

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Discussion

PROFESSOR K. C. DUNHAM (*Institute of Geological Sciences*) asked whether the differentiated lava sequence showed alternations of normal olivine–basalt with the alkali hawaiite–trachyte series. Members of the differentiated series in the central part of the Skye lava plateau, which closely resembles that of Réunion, always appear interstratified with olivine basalts. This would not be easy to explain on the mechanism Dr Wadsworth had proposed.

DR W. J. WADSWORTH. Although the stratigraphic succession of the Réunion Differentiated Series does not reflect a simple progression from basaltic to alkalic compositions, there is no evidence of the prolonged availability of relatively primitive basalts throughout this stage of volcanic evolution. Perhaps the situation on Skye was different to the extent that magmatic differentiation occurred independently at a number of localized centres in a complex sub-volcanic network of conduits and small chambers (see Thompson *et al.* 1971) still connected to a supply of basalt magma from the upper mantle.