

## Melting relations of some lavas of Réunion Island, Indian Ocean

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**SUMMARY.** The one-atmosphere experimental melting and crystallization relations of some basic lavas of Réunion Island, Indian Ocean, are investigated. They comprise products of the extinct volcano Piton des Neiges and the active volcano Piton de la Fournaise. New data and interpretations are presented for the 1939 oceanite and its contained glass, originally described by Lacroix (1939a). The liquidus *v.* iron enrichment curves for these Réunion lavas fall about 20 °C above those of the lavas of Kilauea, Hawaii. The primitive liquid reaching the surface contained about 10 % MgO.

THE island of Réunion is built of lavas of two shield volcanoes, Piton des Neiges (3069 m) and Piton de la Fournaise (2631 m). The former is extinct and deeply eroded, exposing a complex of intrusions ranging from picrite to quartz syenite. The volcanic succession revealed in Piton des Neiges is of an older series dominated by olivine basalts, referred to as the Oceanite Series, and a younger series ranging from feldsparphyric basalts through intermediate lavas to trachytes, known as the Differentiated Series. The most recent study of the geology of this volcano is given by Upton and Wadsworth (1966, 1967).

Lacroix, in a series of contributions (1936, 1939a, 1939b), has devoted attention in particular to the still-active volcano Piton de la Fournaise, with publication of numerous chemical analyses of its basalts. More recently, age determinations and Sr isotope ratio measurements have been carried out by McDougall and Compston (1965). According to these investigations the  $^{87}\text{Sr}/^{86}\text{Sr}$  values for the basalts and an oceanite from Réunion fall within an extremely narrow range, from 0.7040 to 0.7046, and no difference exists between the ratios for rocks of Piton des Neiges and Piton de la Fournaise, indicating that the source region for both these volcanoes was very homogeneous in its  $^{87}\text{Sr}$  abundance.

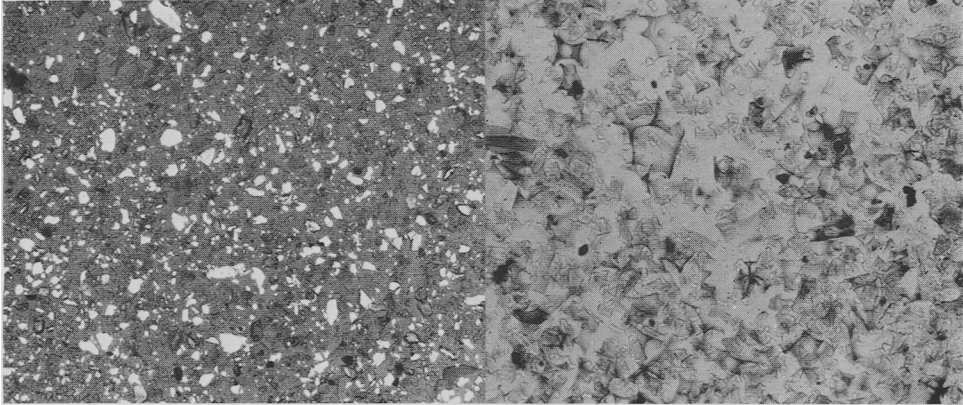
Melting experiments have been carried out on oceanites and basalts from both Piton des Neiges and Piton de la Fournaise. Some of these rocks have already been described and analysed (Upton and Wadsworth, 1966), but in other cases hitherto unpublished analyses are presented. In addition to this recently collected material,

TABLE I. *Analyses and CIPW norms of Réunion lavas*

	875G	875G exp	1939p	REg	Re 114	Re 168	Re 331	Re 331gm	Re 343	Re 171	Re 134	Re 69	Re 180	Re 332
SiO <sub>2</sub>	45.84	—	—	48.56	44.17	47.28	43.57	49.77	45.10	47.38	46.78	48.45	48.40	45.85
Al <sub>2</sub> O <sub>3</sub>	12.26	—	—	14.38	9.05	14.55	8.10	14.83	10.43	14.88	14.30	14.71	15.57	15.92
Fe <sub>2</sub> O <sub>3</sub>	0.79	2.07	—	2.34	3.96	2.45	2.86	3.21	3.47	4.34	3.97	4.42	3.00	7.99
FeO	11.32	10.93	—	8.94	9.41	9.70	9.58	6.68	8.92	7.80	8.59	7.40	8.96	6.82
MnO	0.15	—	—	0.20	0.22	0.18	0.23	0.15	0.19	0.20	0.20	0.17	0.18	0.82
MgO	15.21	21.29	—	18.72	23.27	17.18	20.87	5.69	15.74	8.80	9.71	5.19	5.19	4.81
CaO	9.34	—	—	11.44	6.37	10.03	5.68	11.90	8.59	10.12	9.43	11.06	11.34	9.51
Na <sub>2</sub> O	1.41	—	—	2.65	1.45	2.76	1.16	2.64	1.80	2.98	2.49	2.48	2.73	3.34
K <sub>2</sub> O	0.74	—	—	0.77	0.40	0.84	0.31	0.75	0.57	0.79	0.55	0.48	0.49	1.19
H <sub>2</sub> O+	0.28	—	—	0.07	0.18	0.23	0.24	1.12	1.97	0.20	0.95	1.27	1.05	0.39
H <sub>2</sub> O-	0.22	—	—	nil	—	0.08	—	0.17	0.75	—	—	0.25	0.14	0.10
TiO <sub>2</sub>	2.40	—	—	3.02	1.41	2.75	1.28	2.38	1.88	2.51	3.43	2.17	2.37	3.06
P <sub>2</sub> O <sub>5</sub>	0.10	—	—	0.29	—	0.44	0.04	0.40	0.31	0.12	0.35	0.37	0.40	0.48
CO <sub>2</sub>	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total	100.06	—	—	99.84	100.18	100.05	100.19	99.78	99.72	100.53	99.90	99.80	99.82	100.34
Qz	—	—	—	—	2.36	—	—	2.36	—	—	—	3.97	—	—
Or	4.45	—	—	4.45	12.27	4.96	1.83	4.43	3.37	4.65	3.33	2.84	0.37	7.03
Ab	12.05	—	—	22.53	17.00	23.52	0.82	22.34	18.23	25.13	2.08	20.99	21.70	28.50
An	24.74	—	—	25.02	24.74	24.74	1.99	20.40	18.70	18.81	26.24	27.59	28.78	24.93
Di	16.78	—	—	24.35	10.09	17.96	7.88	24.56	17.47	18.16	14.66	20.02	20.42	14.28
Hy	7.64	—	—	7.44	9.24	3.22	3.22	8.30	10.92	2.75	13.11	13.39	13.28	4.28
Il	27.91	—	—	6.19	39.24	15.34	48.86	—	22.00	12.63	9.35	4.12	—	4.69
Pl	4.56	—	—	5.78	2.68	5.22	2.43	4.52	3.57	4.76	4.35	6.12	4.50	7.14
Mt	1.16	—	—	3.25	5.74	3.55	4.5	4.52	5.63	6.29	5.78	6.41	4.85	11.44
Ap	0.34	—	—	0.67	0.69	0.94	0.28	0.85	0.60	0.90	0.78	0.70	0.85	1.14
Rest	0.50	—	—	0.07	0.18	0.31	0.28	1.29	2.72	0.49	1.25	1.52	1.19	0.55
Total	100.13	—	—	99.75	100.19	99.96	100.18	99.70	99.67	100.57	100.07	99.74	99.74	100.36

875G 'Basalt Pumice' (oceanite) eruption of 6 Jan. 1939, Piton de la Fournaise, Réunion (Lacroix, 1939, p. 407, analysis 3).  
 875G exp Crushed sample of 875G used for melting experiments, (analyst J. H. Scoon).  
 1939p 'Basalt Pumice' (oceanite), 1939, Piton de la Fournaise, Réunion (analyst, J. Esson).  
 REg Glass fraction of 1939p (analyst J. H. Scoon).  
 Re 114 Oceanite, 1961 lava, Piton de la Fournaise, Réunion (analyst, Geochemical Laboratories, Manchester University).  
 Re 168 Basalt from massive flow. Scarp of Plateau des Basaltes. Sentier Mouton, Rempart des Sables, Piton de la Fournaise (Upton and Wadsworth, 1966).  
 Re 331 Oceanite from highest flow in Oceanite series, 6 km from the mouth of Rivière des Galets, Piton des Neiges (analysis, Geochemical Laboratories, Manchester University).  
 Re 331gm Groundmass of oceanite Re 331 (Upton and Wadsworth, 1966).  
 Re 343 Basalt, Oceanite series, Piton des Neiges, from roadside just S of tunnel 1 km NW of Ilet du Palmiste Rouge, Cirque de Cilaos (Upton and Wadsworth, 1966).  
 Re 171 Basalt, Oceanite series, Grand Bassin, Piton des Neiges, Réunion (analyst, Geochemical Laboratories, Manchester University).  
 Re 134 Basalt, Grand Bassin, Piton des Neiges, (analysis, Geochemical Laboratories, Manchester University).  
 Re 69 Basalt with scattered olivine phenocrysts removed, Oceanite Series, Piton des Neiges, from roadside Ilet Rond, entrance to Cirque de Cilaos (Upton and Wadsworth, 1966).  
 Re 180 Basalt, Oceanite series, from Bois Court path above Grand Bassin, Piton des Neiges (Upton and Wadsworth, 1966).  
 Re 332 Basaltic Hawaiite, lowest flow of Differentiated Series, immediately overlying Re 331, Piton des Neiges, Réunion (analyst, W. J. Wadsworth).

two samples of basalts (verging on oceanites) from Lacroix's original collection of the products of the 1939 eruption of Piton de la Fournaise have also been studied. We are greatly indebted to Dr. F. Conqu  r   of the Department of Mineralogy of the Museum National d'Histoire Naturelle, Paris, for forwarding us these two specimens.



FIGS. 1 and 2: FIG. 1 (left). Crushed fragments of 1939 Piton de la Fournaise basaltic pumice in oil ( $n = 1.58$ ). Note abundant fragments of olivine phenocrysts, white or grey with high relief. Half-crossed nicols  $\times 12\frac{1}{2}$ . FIG. 2 (right). Oil mount of powder from the bottom of the bottle containing the pumice fragments shown in fig. 1. Note the total absence of olivine phenocrysts. The powder was formed by abrasion of the vesiculated interior of the pumice fragments. Half-crossed nicols  $\times 12\frac{1}{2}$ . The liquid mount has  $n = 1.58$ .

The chemical data are presented in table I. The rock types range from true oceanites (picrite basalts) from both volcanoes, to basalts, principally from Piton des Neiges, and include also a basaltic hawaiite from the Differentiated Series (Re 332). The range in silica percentage is from  $\text{SiO}_2$  43.57 to 49.77, and in iron enrichment, defined as the ratio  $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$ , from 0.31<sub>6</sub> to 0.75<sub>4</sub>. These values relate to whole rocks and groundmass or glassy fractions separately analysed.

The 'basalt' specimens of Lacroix are in effect oceanites of the eruption of 1939 at Piton de la Fournaise. One of these rocks (875G), erupted on 6 January, was analysed by Raoult (Lacroix, 1939a, p. 408). The second sample (1939<sub>p</sub>) was also erupted in 1939, but the date not further specified. Analysis of the first specimen (875G) showed 15.21 % MgO and 45.84 %  $\text{SiO}_2$  and is quoted here in table I no. 1. Both samples are of identical appearance, consisting of two parts: light-brown coloured glass, finely vesiculated and containing scarce fine olivines, and irregular seams of a dark slaggy material, which forms the borders of larger vesicles. These seams are not vesiculated and prove to be composed of olivines wrapped in dark glass.

The impression received from Lacroix's account is that this analysis, with 15.21 % MgO, refers to a completely glassy basalt and this conception has been repeated in the literature (Wadsworth, 1967). The analysed material must, however, have contained olivine phenocrysts in part from the slaggy borders of the larger vesicles. In the two photomicrographs presented here (figs. 1 and 2), the first is of a mount of the

crushed fragments of the Piton de la Fournaise oceanite (1939<sub>p</sub>) in oil ( $n = 1.58$ ) showing abundant olivine phenocrysts; the second (fig. 2) is of a mount representing the powder found in the bottom of the bottle containing the pumice fragments of the oceanite. This powder is totally free from olivine phenocrysts and is formed by abrasion of the friable vesiculated interior of the pumice fragments, in which process glass shards are separated from olivine crystals. During the shaking of the bottle, the olivines segregate from the shards in the abraded material, owing to their shape and density. It seems evident that Lacroix, in describing his analysed rock as a glass, must have studied such an abraded fraction of the friable pumice and deemed it to be wholly representative of the analysed material.

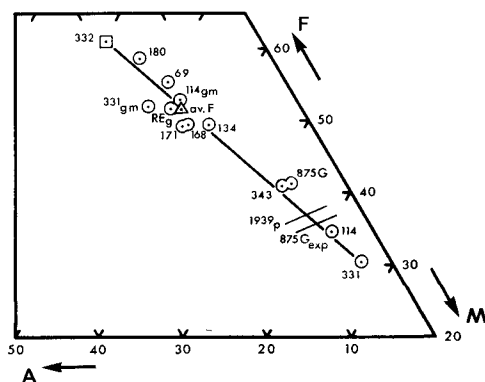


FIG. 3. FMA ( $\text{FeO} + \text{Fe}_2\text{O}_3 - \text{MgO} - \text{Na}_2\text{O} + \text{K}_2\text{O}$ ) plot of experimentally studied lavas of Réunion. Points refer to analyses so designated in table I. Re 332 has been shown with a different symbol from the other specimens to emphasize that it comes from the Differentiated Series of Piton des Neiges. In addition av. F represents the plot of the average of 33 basalts from Piton de la Fournaise, calculated by Upton and Wadsworth (1966). The lines marked 875G exp and 1939<sub>p</sub> give the trends of the partially analysed samples, based on their iron-magnesium ratios.

TABLE II

	RE <sub>g</sub>	114 <sub>gm</sub>	AvF
SiO <sub>2</sub>	48.56	48.73	47.98
Al <sub>2</sub> O <sub>3</sub>	14.38	14.44	13.92
Fe <sub>2</sub> O <sub>3</sub>	2.34	3.76	2.60
FeO	8.94	7.88	9.05
MnO	0.20	0.18	0.13
MgO	7.18	7.37	7.67
CaO	11.44	11.30	11.61
Na <sub>2</sub> O	2.65	2.39	2.34
K <sub>2</sub> O	0.77	0.64	0.89
TiO <sub>2</sub>	3.02	2.37	2.98
P <sub>2</sub> O <sub>5</sub>	0.29	0.39	0.25
H <sub>2</sub> O+	0.07	0.35	0.80
H <sub>2</sub> O-	nil	0.03	0.21
	99.84	99.83	100.43

RE<sub>g</sub> Glass from oceanite 1939<sub>p</sub> (table I). Iron enrichment 0.61<sub>1</sub>.  
 114<sub>gm</sub> Groundmass of 1961 oceanite (Re 114), Piton de la Fournaise (Upton and Wadsworth, 1966). Iron enrichment 0.61<sub>2</sub>.  
 AvF Average of 33 basalts from Piton de la Fournaise (Upton and Wadsworth, 1966). Iron enrichment 0.60<sub>5</sub>.

The material of fig. 2 must, in fact, have the composition of RE<sub>g</sub>, a pure glass separated from 1939<sub>p</sub> with only 7.18 % of MgO (table I, RE<sub>g</sub>). If an analysis of such a composite rock is to be representative, sampling of a large mass would be required.

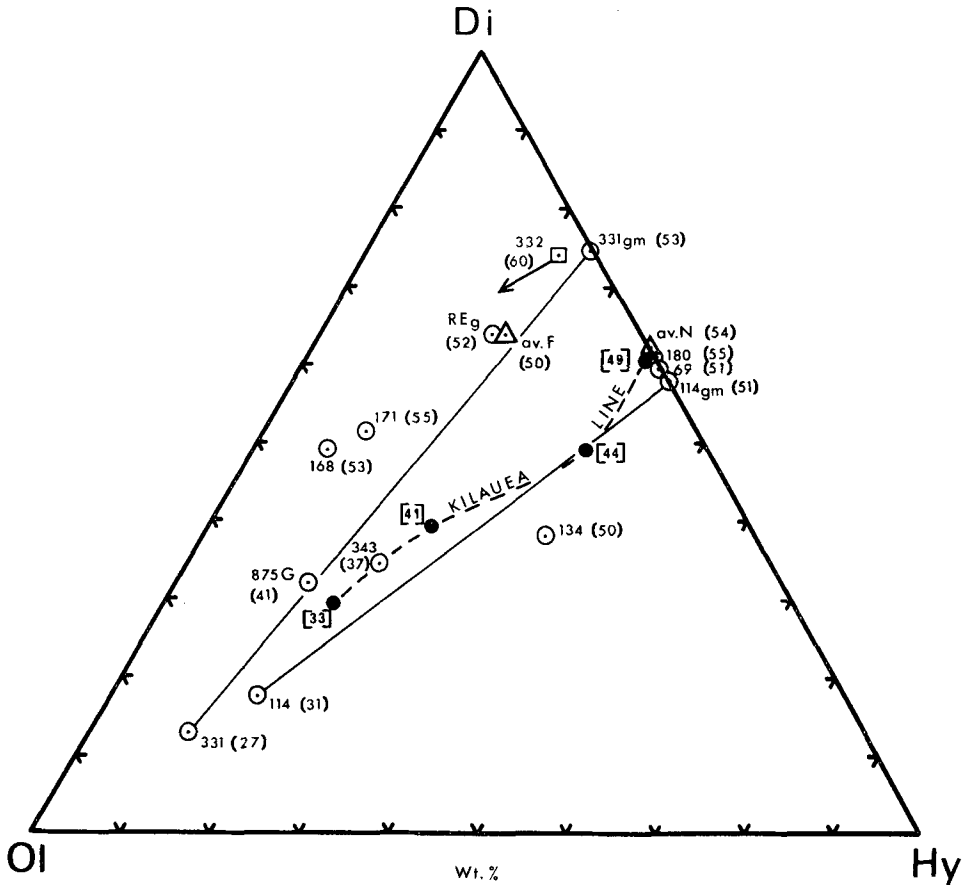


FIG. 4. Normative diopside, hypersthene, and olivine (recalculated to 100) plotted for the Réunion lavas. In addition are plotted the averages F (cf. fig. 3) and N; the latter being the average of 4 basalts of the Oceanite Series of Piton des Neiges (Upton and Wadsworth, 1966). The plot of the Kilauea Series, dashed line joining solid circles, is drawn for comparison. The lines 331–331<sub>gm</sub> and 114–114<sub>gm</sub> join the compositions of oceanites and their respective groundmasses. Figures in brackets give the total normative feldspar content for these lavas.

As anomalous results were found in the melting work using Lacroix's analysis for our crushed material, we have carried out melting experiments on a sample actually reanalysed for MgO, FeO, and Fe<sub>2</sub>O<sub>3</sub> (table I, analysis 875G exp). This material proved even richer in olivine than is represented by the material shown in fig. 1. The melting data are in accord with the iron enrichment of this reanalysed sample (875G exp, fig. 8).

Some of the chemical characters of the rock types experimentally studied are revealed in figs. 3 to 7. Fig. 3 shows the  $(\text{FeO} + \text{Fe}_2\text{O}_3)$ -MgO-alkalis relationship; the trend extends from the oceanite (Re 331) to the basaltic hawaiiite (Re 332). The plot of the glass of the 1939 oceanite ( $\text{RE}_g$ ) is close to that of the crystalline groundmass of the oceanite (Re 114) and also to that of an average composition of 33 basalts of Piton de la Fournaise (table II). No glass more basic than that of  $\text{RE}_g$  has been recognized.

Fig. 4 portrays the normative diopside-hypersthene-olivine relationships of the suite, which are also compared with a typical Kilauea, Hawaii, series. The straight lines 331-331<sub>gm</sub> and 114-114<sub>gm</sub> join the whole rock and groundmass compositions of the oceanites Re 331 (27) and Re 114 (31). These contain abundant phenocrystic olivine, which was removed from them before the chemical analyses of the groundmasses were made. The increase in total normative feldspar of the successions—shown in brackets against the points on the diagram—indicate that olivine is the main constituent removed in the differentiation course. The rock type Re 332, which is shown as a plotted point near the diopside-hypersthene join, although an alkali rock, crystallized in an oxidizing environment, is rich in magnetite and shows a high content of  $\text{Fe}_2\text{O}_3$  (7.89%), which is responsible for the normative hypersthene. If the  $\text{Fe}_2\text{O}_3$  content is adjusted to 2.0%, the analysis becomes nepheline-normative (2.34%). This change is indicated on fig. 4 by the arrowed line from the point directed to the diopside-olivine join.

The role of olivine as the prime extract in the differentiation of the oceanites is emphasized further in the plot of the MgO-SiO<sub>2</sub> variation (fig. 5). Remote from this trend is the point representing the basaltic hawaiiite, where plagioclase is the dominant separating phase. The anomalous position of Re 332, relative to the basalts, is also revealed in fig. 6, which plots SiO<sub>2</sub> versus total alkalis. The SiO<sub>2</sub>-iron enrichment trend is shown in fig. 7. It is clear that, as a whole, the Oceanite Series of Piton des Neiges and the lavas of Piton de la Fournaise occupy a transitional position between the typical tholeiites of Hawaii and alkali olivine basalts; as becomes apparent, too,

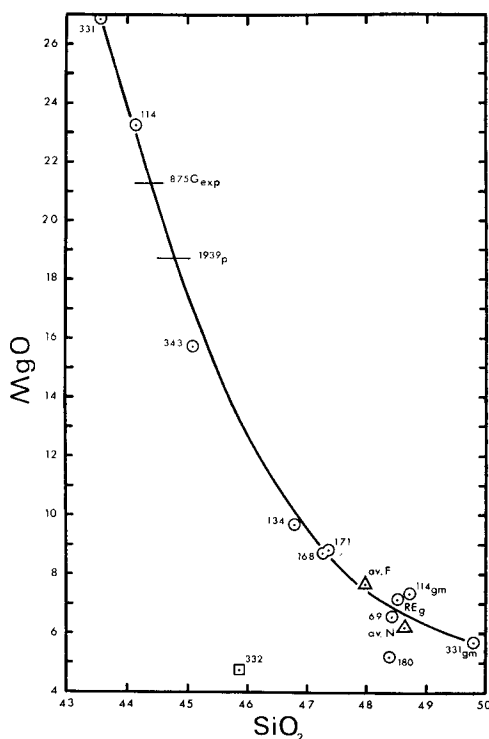
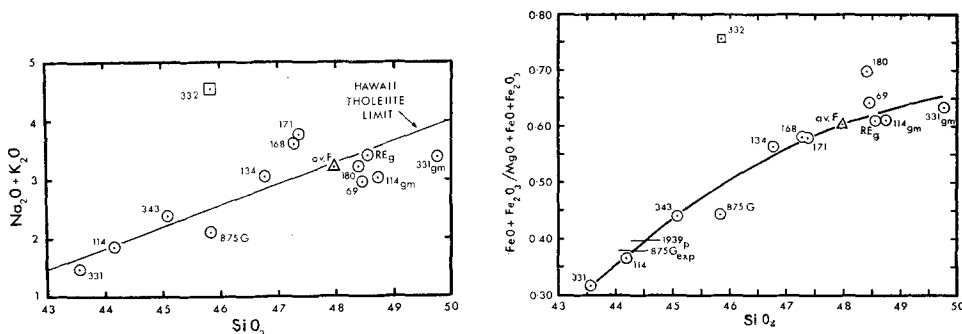


FIG. 5. MgO-SiO<sub>2</sub> plot of the experimentally studied lavas, with the MgO values of 8.75 G exp and 19.39<sub>p</sub>, shown as lines across the main trend.

from inspection of fig. 4, where they are compared with the Kilauea (Hawaiian) Series.

The results of the melting runs on the thirteen rocks are set out in table III, and the liquidus temperatures related to iron enrichment in fig. 8. The experiments were



FIGS. 6 and 7: FIG. 6 (left),  $\text{SiO}_2$ -alkalis plot of the Réunion lavas with the trend of the Hawaiian tholeiite limit indicated. FIG. 7 (right),  $\text{SiO}_2$  iron enrichment  $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$  plot of the Réunion lavas.

TABLE III. Results of melting experiments on lavas of Réunion

Spec. no.	Iron enrichment		<i>n</i> of glass
Re 331	0.31 <sub>6</sub>	ol (1522°); pl (1165°); cpx (1150°)	1-657
Re 114	0.35 <sub>6</sub>	ol (1470°); pl (1160°); cpx (1150°)	1-643
875G exp	0.37 <sub>9</sub>	ol (1443°); pl (1160°); cpx (1157°)	1-652
1939 <sub>p</sub>	0.39 <sub>7</sub>	ol (1422°); pl (1160°); cpx (1160°)	1-647
Re 343	0.44 <sub>0</sub>	ol (1370°); pl (1167°); cpx (1156°)	1-642
Re 134	0.56 <sub>4</sub>	ol (1240°); pl (1174°); cpx (1138°)	1-613
Re 171	0.58 <sub>0</sub>	ol (1220°); pl (1169°); cpx (1145°)	1-610
Re 168	0.58 <sub>2</sub>	ol (1234°); pl (1160°); cpx (1140°)	1-608
Re 331 <sub>gm</sub>	0.63 <sub>5</sub>	ol (1190°); pl (1179°); cpx (1179°)	1-595
Re 69	0.64 <sub>3</sub>	ol (1193°); pl (1170°); cpx (1153°)	1-606
RE <sub>g</sub>	0.61 <sub>1</sub>	ol (1178°); pl (1165°); cpx (1165°)	1-602
Re 180	0.69 <sub>7</sub>	ol (1192°); pl (1192°); cpx (1145°)	1-604
Re 332	0.75 <sub>4</sub>	pl (1185°); ol (1140°); cpx (1118°)	1-618

carried out in an argon atmosphere below 1230 °C and in air above this temperature. Capsules of silver-palladium alloy ( $\text{Ag}_{70}\text{Pd}_{30}$ ) were used in runs below 1150 °C and of platinum at higher temperatures (sealed when run in air). All runs were for one hour, except for some lower-temperature experiments, which required several hours to equilibrate. The succession of phases separating was olivine-plagioclase-clinopyroxene, except for Re 180, where olivine and plagioclase crystallized at the same time, and for Re 332, where plagioclase was the highest temperature phase, followed by olivine at 45 °C lower temperature. The most mafic 'aphyric' basalts studied were

Re 134, with 2.0 % olivine phenocrysts and Re 171, with 0.1 % olivine phenocrysts (3000 point modal analyses).

Fractionation is clearly dominated by an olivine control, strikingly revealed in the upper (accumulative) curve of fig. 8. Plagioclase plays a significant role only at lower

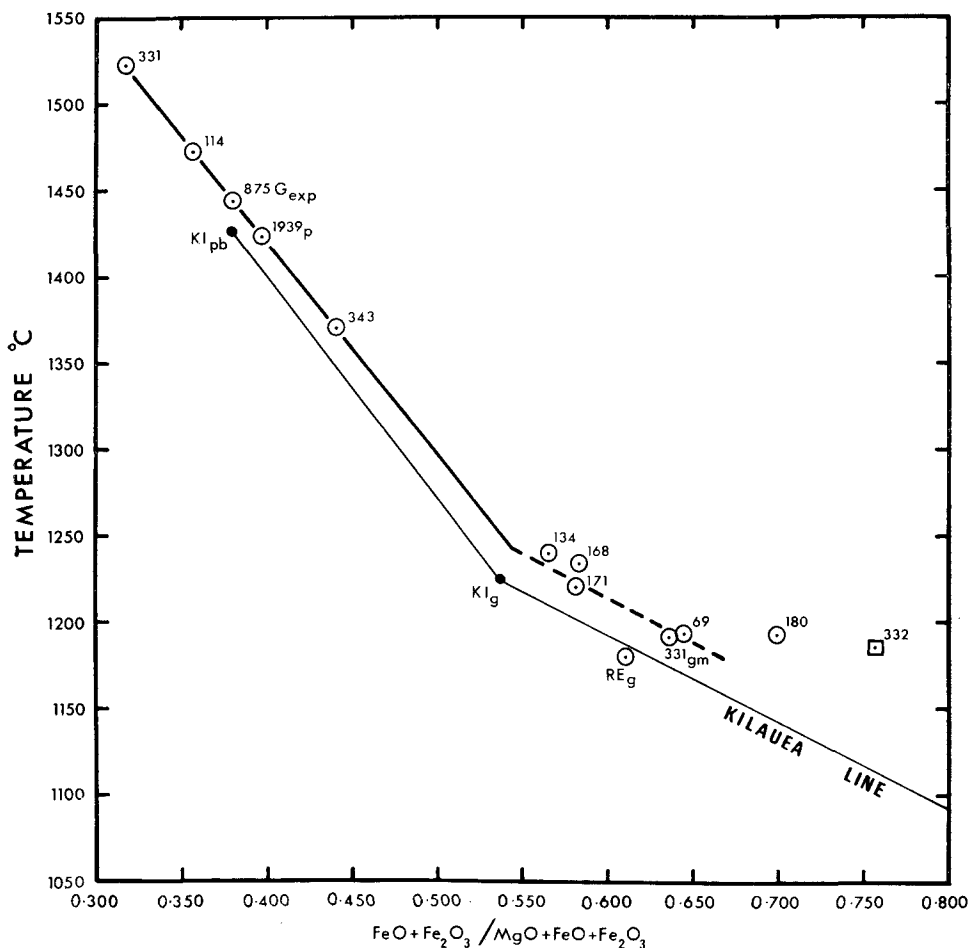


FIG. 8. Plot relating liquidus temperatures and iron enrichment for the experimentally investigated lavas of Réunion. The trend is compared with that of the Kilauea Series (Thompson and Tilley, 1969).

temperatures. Rocks Re 180 and Re 332 depart significantly from the iron enrichment v. temperature curve defined by the more mafic rocks. This is no doubt related to the prominent role of plagioclase as a liquidus phase in these two lavas, with factors other than iron enrichment also controlling the liquidus temperatures. The primitive liquid reaching the surface would appear to have an iron enrichment near 0.56 (i.e. near Re 134) where there is a change of slope in the liquidus v. iron-enrichment curve.



This would correspond to a liquid containing about 10 % MgO, which is in fact near the primitive low-pressure liquid for the Kilauea Series, Hawaii (iron enrichment  $\sim 0.53$ , MgO  $\sim 10$  %). At greater depth it is likely that an even more basic liquid, with higher olivine content, would have existed, but this does not appear to have reached the surface.

*Acknowledgements.* We are greatly indebted to Dr. F. Conqu  r   who has sent us from Paris two of the critical oceanite pumices studied by Lacroix from the 1939 eruption of Piton de la Fournaise, and to Dr. J. Esson and J. H. Scoon for providing analytical data on these specimens.

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[*Manuscript received 14 July 1970*]