

THE 1959-60 ERUPTION OF KILAUEA VOLCANO HAWAII

PETROGRAPHY OF
THE LAVAS

GEOLOGICAL SURVEY
PROFESSIONAL PAPER 537-D



Petrography of the Lavas of the 1959-60 Eruption of Kilauea Volcano, Hawaii

By D. H. RICHTER *and* K. J. MURATA

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*A detailed picture of changes in lava
mineralogy with respect to time,
temperature, and bulk composition*



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 20 cents (paper cover)

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PETROGRAPHY OF THE LAVAS OF THE 1959-60 ERUPTION OF KILAUEA VOLCANO, HAWAII

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ABSTRACT

Petrographic studies of a suite of lava samples, collected throughout the 1959-60 eruption of Kilauea volcano, have yielded a detailed picture of the changes in lava mineralogy with respect to time, temperature, and bulk chemistry. The results are explained in terms of fractional crystallization of basaltic magmas and of the mixing of two magmas of different vintage.

The earliest and coolest lavas of the 1959 summit phase of the eruption were characterized by moderately abundant microphenocrysts of olivine (Fa₁₇₋₁₈), augite (En₅₀Fs₁₀Wo₄₀), and plagioclase (An₆₄). These lavas evidently represented the upper part of the magma body at the summit, and the minerals were separating out of the melt under equilibrium conditions.

The later lavas of the summit eruption, representing the lower and hotter part of the magma body, contained no phenocrysts of augite or of plagioclase but only coarse, euhedral to rounded phenocrysts of a less fayalitic olivine (Fa₁₂₋₁₄). This olivine is the first silicate mineral to separate from the primitive melt and settles in the melt to form picritic magmas. The further cooling of the olivine-depleted restmagma leads to the stage of crystallization manifested in the earliest lavas of the eruption, described above.

Petrographically, the 1960 flank-phase lavas of the eruption can be divided into two distinct magma types: (1) a cooler early-1960 type characterized by phenocrysts of plagioclase (An₇₂₋₈₀), augite (En_{47.8}Fs_{12.3}Wo_{40.1}), small euhedral olivines (Fa₂₀₋₂₄), larger rounded olivines (Fa₁₂₋₁₆), and minor hypersthene (Fs₂₀₋₂₅) and (2) a hotter late-1960 type containing principally large euhedral to slightly rounded phenocrysts of olivine (Fa₁₂₋₁₆) accompanied by minor amounts of rounded residual phenocrysts of augite and plagioclase.

Lavas of the intermediate period of the flank eruption point to an intermixing of the cooler early-1960 type of magma and the hotter late-1960 type. All phenocrystic minerals of the early-1960 magma type (except olivine Fa₁₂₋₁₆) are to be seen in various stages of resorption, and a concomitant rapid increase in the amount of coarse phenocrysts of olivine Fa₁₂₋₁₆ marks the transition to the late-1960 type of magma.

By correlating the petrographic data on the lavas with temperatures measured during their eruption, the following schemes of crystallization of the 1959 summit and the 1960 flank magmas have been derived. The observed range of temperature over which a mineral separated from the magma is given; where only one temperature is given, it denotes the point of the initial separation of the mineral.

<i>Mineral</i>	<i>Approximate temperature of separation (°C)</i>
Summit magma :	
Olivine, Fa ₁₂₋₁₄ -----	1180-1125
Augite, En ₅₀ Fs ₁₀ Wo ₄₀ -----	1120
Olivine, Fa ₁₇₋₁₈ -----	1100
Plagioclase, An ₆₄ -----	1090
Flank magmas :	
Olivine, Fa ₁₂₋₁₆ -----	1080-1055
Augite, En ₄₈ Fs ₁₂ Wo ₄₀ -----	1080
Plagioclase, An ₇₂₋₈₆ -----	1070
Hypersthene, Fs ₂₀₋₂₅ -----	1060
Olivine, Fa ₂₀₋₂₄ -----	1055

The order of the first separation of the major phases from primitive Kilauea magma is olivine-augite-plagioclase. This same order was obtained in laboratory quenching experiments by other researchers on dry melts of Kilauea lavas of similar composition. However, the liquidus temperatures and the indicated temperatures of complete crystallization of the magmas, derived from the data of the 1959-60 eruption, are appreciably lower than those determined in the quenching experiments.

INTRODUCTION

Kilauea and Mauna Lao volcanoes on the Island of Hawaii have poured out vast quantities of tholeiitic lavas within historic (post-1790) time. The study of these lavas by many investigators over the years has demonstrated the importance of fractional crystallization of olivine in the first stage of differentiation of the primitive magmas. But in general, the eruptive regimens of these volcanoes apparently do not allow the primitive magmas to pass much beyond this first stage of differentiation, so that the simple mineralogy of most of the historic flows is monotonously similar.

The 1959-60 eruption of Kilauea, consisting of both a summit and a flank phase, yielded lavas whose composition and mineralogy varied to an unusual degree. The usual phenocrysts of olivine were abundant in the hottest lavas of the summit phase; but in the cooler lavas of both the summit and flank phases, notable amounts of clinopyroxene and plagioclase phenocrysts were

present. These lavas thus afforded an opportunity to study somewhat more advanced stages of basaltic differentiation. Because of a timely augmentation in the staff and laboratory facilities of the Hawaiian Volcano Observatory in 1958, it was possible to measure many chemical and physical parameters of eruptive activity more or less simultaneously. As a result, the fractional crystallization of Kilauea magma was revealed in fascinating detail.

The chemical compositions of the lavas, of the phenocrystic minerals, and of basaltic glasses separated from some of the lavas are given by Murata and Richter (1966). These data have been freely drawn upon in the present study; conversely, the results of the petrographic investigation have been used as a guide in interpreting the trends of chemical variation. This correlation of chemical and mineralogic information, in conjunction with the known temperatures of the lavas, has yielded a consistent scheme of differentiation of the primitive Kilauea magma.

ACKNOWLEDGMENTS

Throughout the eruption, assistance in collection of lava and pumice samples was received from staff members of Hawaii National Park and from the writers' colleagues of the Hawaiian Volcano Observatory. R. T. Okamura isolated concentrates of phenocrystic minerals from the lavas. F. H. Hildebrand determined the composition of many olivine crystals by means of their X-ray spacing. H. A. Powers was very helpful with various aspects of the study.

PREVIOUS STUDIES

The main petrographic features of Kilauea lavas are conveniently summarized by Macdonald (1949a, b). Lavas containing variable amounts of phenocrystic olivine are the most abundant, those with phenocrystic augite and plagioclase are less common, and those with phenocrystic hypersthene are rare. Depending on the rate of cooling of the extruded lava, the groundmass ranges from basaltic glass typically charged with micro-lites of opaque minerals to intergranular intergrowths of clinopyroxene, plagioclase, and opaque minerals.

Kilauea lavas, along with those of Mauna Loa, represent the general tholeiitic type of basaltic magma that characterizes the major shield-building stage of Hawaiian volcanoes (Stearns and Macdonald, 1946; Tilley, 1950; Powers, 1955). Lavas of the alkalic-basalt magma type typically constitute the late outpourings of the senescent or extinct volcanoes (Hualalai, Mauna Kea, and Kohala) on the Island of Hawaii. The principal mineralogical differences between the two basalt types are in the groundmass minerals. The groundmass

of the tholeiites contains plagioclase and augite and (or) subcalcic augite, whereas that of the alkalic basalts contains plagioclase and augite (generally alkalic) together with olivine. Moreover, hypersthene is absent from the alkalic basalts. Tholeiitic basalts with less than about 10 percent modal phenocrystic olivine are oversaturated, whereas the alkalic basalts, regardless of their phenocrystic content, are undersaturated.

No lavas with alkalic affinities have yet been found in samples from Mauna Loa or Kilauea. Although the residual melt collected from directly below the crust in the 1959 Kilauea Iki lava lake 7 months after the eruption had a chemical composition approaching that of hawaiite of the alkalic-basalt series (Macdonald and Katsura, 1961), subsequent investigations indicate that this relatively alkali-rich melt is transient and upon crystallization reverts to a normal tholeiitic basalt (Richter and Moore, 1966).

Slight but persistent differences exist between the composition of tholeiitic lavas of Kilauea and Mauna Loa (Macdonald, 1949a; Powers, 1955). Mauna Loa lavas tend to be slightly more siliceous and somewhat poorer in calcium oxide as well as in alkalis, and these differences are reflected by the more common occurrence of hypersthene phenocrysts in Mauna Loa lavas (Tilley and Scoon, 1961). In addition to these differences between the lavas of the two volcanoes, Powers (1955) noted that the primitive tholeiitic magma of each volcano has fluctuated in composition within the period represented by its accessible lavas. He concluded that all Kilauea lavas erupted in historic time were derived from a single large batch of magma, which was generated in the mantle more than a century ago and has been erupted in small amounts ever since. Prehistoric (pre-1790) lavas have compositions that suggest derivation from one or more earlier batches of primitive magma. As shown by Murata and Richter (1966), the composition of the 1959 summit lavas indicates a clear affinity to the historic primitive magma.

The 1840 and the 1954-55 eruptions of Kilauea, like that of 1959-60, involved an initial activity in the summit region which was followed by a major outbreak on the flank along the east rift zone. The 1840 summit lava was olivine-poor basalt, whereas the flank lava was picrite. The summit and flank lavas were interpreted as representing the upper, olivine-depleted part and the lower, olivine-enriched part, respectively, of the magma column. A separation of minor amounts of augite and plagioclase was also indicated by the differences in lava composition (Macdonald, 1944, 1949b; Muir and Tilley, 1957).

The 1954 summit and the 1955 flank lavas were uniformly poor in olivine, and the latter lavas contained

phenocrysts of augite and plagioclase in unusual abundance (Macdonald, 1955; Macdonald and Eaton, 1957; Tilley, 1960). The genetic relationship among the 1954-55 lavas has become clarified through the present study of similar lavas produced in the 1959-60 eruption.

The coarse green phenocrysts of olivine, so common in Kilauea lavas, have $2V$ close to 90° and hence a fayalite content of about 13 mole percent. Only four analyses of Kilauea olivines have been published, and they average 13.0 ± 2.0 mole percent fayalite. The total range of fayalite content reported for unaltered Kilauea olivines by previous workers, on the basis of optical or X-ray measurements, is Fa_{11-26} . However, as well shown by Muir and Tilley (1963), physical methods of determining the composition do not always yield concordant results when applied to Kilauea olivines. Depending on the property measured ($2V$, indices of refraction, or X-ray spacings), the indicated compositions may differ by as much as 10 mole percent fayalite. The difficulty arises in part from the fact that the available determinative curves are based mostly on olivines from plutonic and hypabyssal rocks, and they do not seem to hold accurately for olivines of volcanic rocks (Chudoba and Frechen, 1943). Further work on determinative methods for volcanic olivines is much needed.

It commonly is accepted that the low-iron olivine of tholeiitic magmas has a discontinuous reaction relationship with the cooling melt, but convincing petrographic evidence for this relationship has not been found among Kilauea lavas. Fine-grained coronas of enstatite-magnetite that rim olivine phenocrysts are observed in some lavas of Kilauea, but Muir and Tilley (1957) have shown that these are products of partial oxidation of the olivines rather than a reaction of the olivines with the melt. Rounding and embayment of olivine phenocrysts are commonly manifested, but these features may be due to a continuous reaction of the phenocrysts with melts of varying temperature and composition.

The rarer phenocrysts of augite, plagioclase, and hypersthene in Kilauea lavas have been studied by Macdonald (1949a) and by Muir and Tilley (1957, 1963). The latter authors gave the analyses of two phenocrystic augites, one from an 1840 flow and another from a flow of the 1921 eruption. The two augites have very similar compositions, averaging $En_{48.7}Fs_{10.7}Wo_{40.6}$. Muir and Tilley (1963) noted also that the optics of augite phenocrysts from Hawaiian tholeiites tended to indicate too femic a composition and ascribed this to the possible influence of chromium oxide, which commonly is present in excess of 0.5 percent in such phenocrysts.

Plagioclase phenocrysts in Kilauea lavas range in composition from An_{72} to An_{50} , and hypersthene phenocrysts, noted hitherto from only two lavas, have not been

closely characterized (Muir and Tilley, 1963). Hypersthene in the gabbroic rock of the Uwekahuna laccolith of Kilauea has a composition of $En_{73.4}Fs_{21.3}Wo_{5.3}$ (Muir and Tilley, 1957). The groundmass minerals of Kilauea lavas have been studied by several investigators, but these minerals will not be reviewed here because they play no role in the pre-eruptive differentiation of magmas.

Existing information on phenocrystic minerals, thus, suggests that the only phases that participate in the differentiation of Kilauea magmas are olivine, augite, plagioclase, and minor hypersthene, in various proportions. The compositions of some of the lavas also suggest the occasional involvement of opaque minerals, but phenocrysts of opaque minerals, other than the early spinel found embedded in olivine, are rare.

PETROGRAPHY

The lavas erupted during the 1959-60 eruption range from tholeiitic olivine basalt, with a minimum SiO_2 content of 46.7 percent, to tholeiitic basalt, with a maximum SiO_2 content of 50.8 percent. All the lavas are porphyritic and exhibit a relatively wide variety in the type and amount of phenocrystic minerals present. Magnesian olivine is the principal and usually the only phenocryst present in those lavas containing less than 49.4 percent SiO_2 . Above 49.4 percent SiO_2 , phenocrysts and clots of clinopyroxene and plagioclase become increasingly more abundant; and at about 50.2 percent SiO_2 , hypersthene appears. The texture and mineralogy of the groundmass depends almost entirely on the cooling history of the lava. Where rapidly cooled, such as in the flow tops and pyroclastic debris from the fire fountains, the groundmass is completely glassy. With slower cooling, as in the center of the thick flows, the texture becomes hyalo-ophitic to intersertal. Small laths of plagioclase, stubby prisms and anhedral grains of clinopyroxene, and microlitic growths of opaque minerals constitute the groundmass minerals where present.

Owing to the pumiceous nature of most of the samples collected during the eruption, not all the lavas chemically analyzed were useful for study in thin section. However, there were sufficient relatively dense rocks collected from time to time to supplement the analyzed samples and to trace adequately the changes in mineralogy with respect to time, temperature, and bulk chemical composition.

Modes of the rocks, expressed in volume percent, were determined with a point counter, utilizing at least 500 points per analysis. Olivine X-ray studies were made by Fred A. Hildebrand, U.S. Geological Survey, using the method of Yoder and Sahama (1957). Indices of

refraction were used to determine the compositions of the plagioclase, pyroxene, and some olivine.

The model analyses of 8 summit and 8 flank lavas are listed in table 1. These same modal data are also presented graphically, as a function of time, in a somewhat modified form in figure 1, together with the measured lava temperatures and bulk silica content.

THE SUMMIT LAVAS

With the exception of the relatively small volume of lava extruded during the first 2 days of eruption and the negligible quantity extruded in the last (17th) phase of the summit activity, there was no marked change in the gross mineralogy of the lavas. The great bulk of the summit lavas contain between approximately 4 and 30 mode percent of phenocrystic olivine set in a glassy or extremely fine grained intersertal groundmass. There were, however, changes in the amount and character of the olivine phenocrysts which appear to correlate with changes in temperature (and hence are directly related to the degree of crystallization) and with other physical parameters of the eruption. Phenocrysts and microphenocrysts of clinopyroxene and plagioclase were observed only in the early and extremely late lavas; no hypersthene was detected in any of the summit lavas.¹

Samples S-1 and S-3, erupted on November 14 and 16, 1959, respectively, are assumed to be typical of the early lavas, and they represent approximately 5 percent of the 30 million cubic meters poured into Kilauea Iki during the first phase of summit activity. Both samples contain relatively abundant microphenocrysts, as much as 0.3 mm long, of euhedral and skeletal olivine (Fa₁₈, determined by X-rays), euhedral to slightly rounded clinopyroxene (approx. En₅₀Fs₁₀Wo₄₀, deter-

mined from optical properties), and plagioclase (An₆₄, determined by index of refraction) in a dark-brown glassy matrix sprinkled with a few microlites of pyroxene, feldspar, and opaque minerals. Sample S-1 also contains a few larger phenocrysts (0.6-1.2 mm) of more magnesian olivine (Fa₁₃, determined by X-rays) that exhibit rounded crystal outlines. The smaller, more fayalitic olivines display a variety of remarkable skeletal forms, many with a characteristic "arrowhead" termination at one or more of the principal apexes (fig. 2). These skeletal olivines also contain irregular to rod-shaped inclusions of brown glass that generally are lighter in color and more transparent than the groundmass glass. The plagioclase microphenocrysts are unzoned and occur as individual laths in the groundmass or are intimately intergrown with stubby clinopyroxene prisms to form glomeroporphyritic clots. Both the clinopyroxene and plagioclase microphenocrysts appear to have sharper and better formed crystal outlines in sample S-1 than in sample S-3. This is especially true of the plagioclase crystals, many of which in sample S-3 have very ragged terminations and scalloped edges, apparently indicative of resorption.

The two chemically and physically different olivines in the early summit lavas apparently represent two distinct stages of olivine crystallization. The few large resorbed magnesium-rich phenocrysts of olivine (Fa₁₃) were undoubtedly not in equilibrium with the liquid (glass) in which they are now found, but evidently formed deeper in the eruption conduit under conditions of higher temperature and in a melt of lower silica content with a higher ratio of magnesia to iron. The assemblage clinopyroxene-plagioclase-olivine (Fa₁₈), on the other hand, does appear to be in equilibrium with the glass, which is in accord with the lower temperatures and relatively high bulk silica content of the lavas during the early part of the first summit phase.

By November 18, 1959, all traces of phenocrystic clinopyroxene, plagioclase, and the relatively high-

¹ Trace amounts of clinopyroxene and plagioclase phenocrysts were also found by Howard A. Powers (written commun., 1963) in concentrates of crystals from samples S-10, S-12, and S-14. In view of the relatively low observed temperatures of these samples, these additional data lead to a more consistent pattern of phenocryst distribution.

TABLE 1.—Modal composition of lavas of the 1959-60 Kilauea eruption, in volume percent
[Tr., trace]

	Summit lavas								Flank lavas							
	S-1	S-3	S-5	S-9	S-14	S-16	S-20	S-25	F-1	F-4	F-6	F-8	F-10	F-14	F-16	F-20
Phenocrysts:																
Olivine.....	3	5	30	14	4	24	21	6	2	1	1	5	9	13	14	8
Clinopyroxene.....	9	4	0	0	Tr. ¹	0	0	2	6	6	7	5	3	3	2	2
Plagioclase.....	1	2	0	0	Tr. ¹	0	0	1	9	9	10	4	2	<1	<1	1
Hypersthene.....	0	0	0	0	0	0	0	0	<1	<1	<1	<1	0	0	0	0
Glass or fine-grained groundmass.....	87	89	70	86	96	76	79	91	83	84	82	86	86	84	84	89

¹ Determined by Howard A. Powers from concentrates of bulk sample.

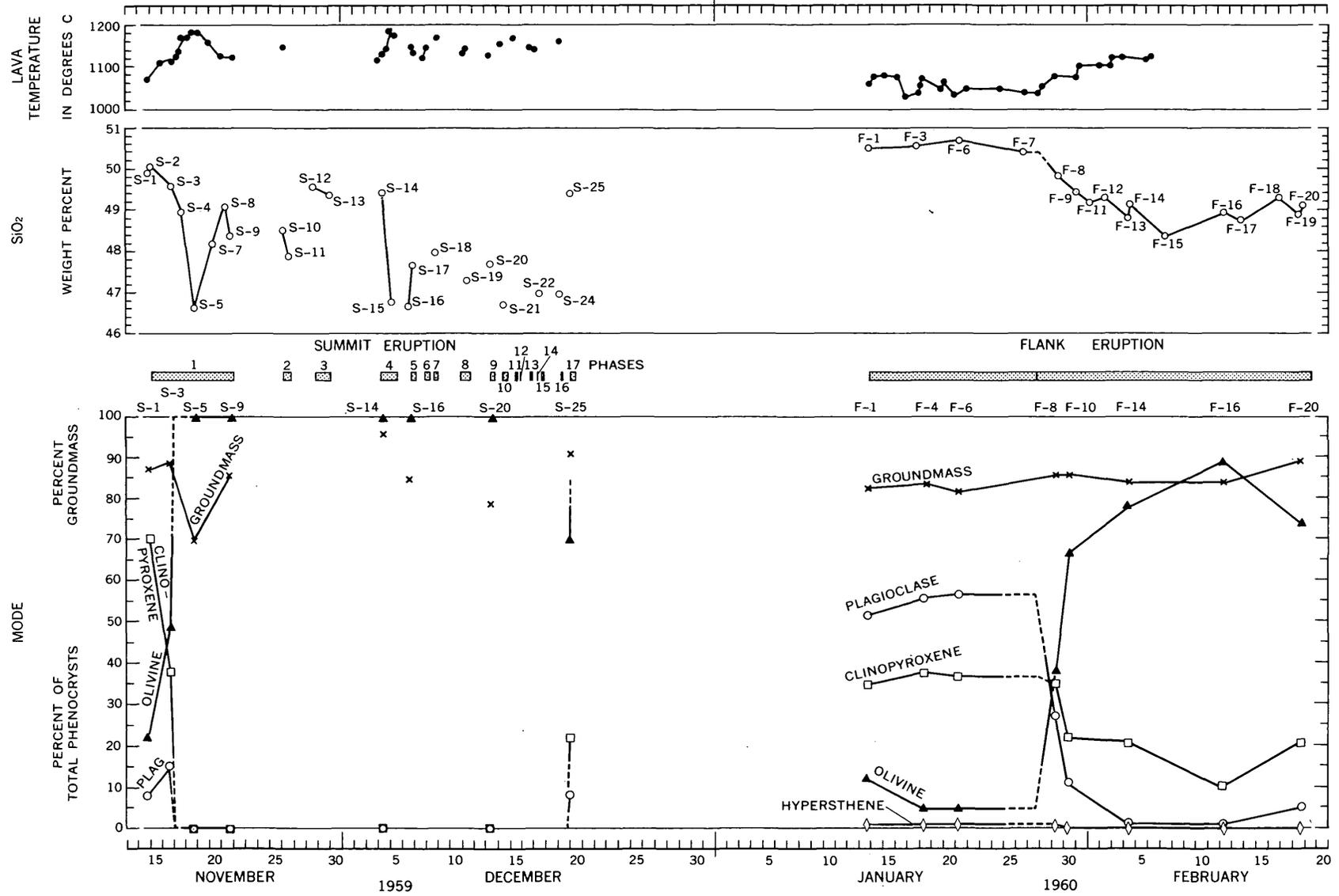


FIGURE 1.—Temperature, bulk silica content, eruptive interval, and mode of 1959–60 lavas as a function of time. In the mode, the amount of groundmass is expressed as volume percent of vesicle-free lava. The relative amounts of the several phenocrystic minerals are expressed as volume percent of total phenocrysts.

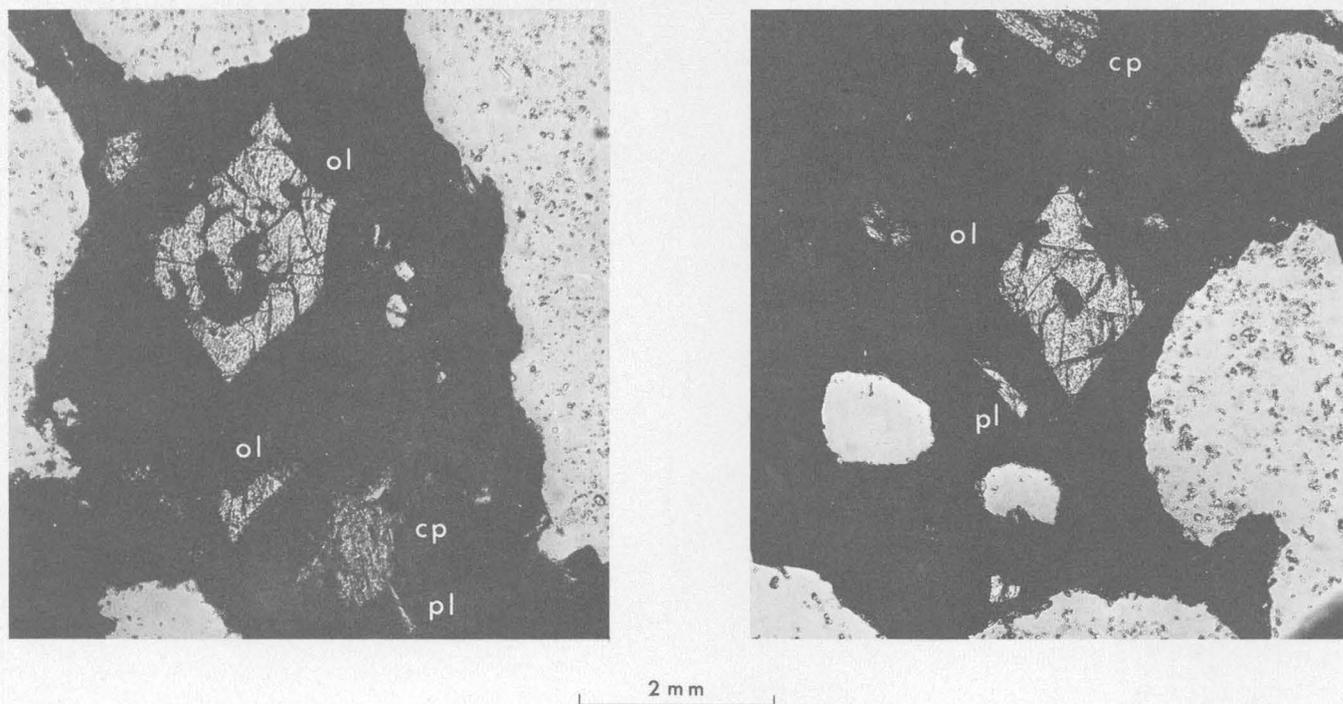


FIGURE 2.—Photomicrographs of skeletal olivine microphenocrysts (ol) in sample S-3, erupted November 16, 1959. Microphenocrysts of plagioclase (pl) and clinopyroxene (cp) are also scattered throughout the dense black groundmass glass. Large light-gray areas are vesicles. Note the "arrowhead" projections at the apexes of the olivine crystals and the irregular inclusions of brown (black) glass within the crystals. The large olivine crystal (left photomicrograph) and the small V-shaped one below it are in optical continuity.

fayalite olivine had disappeared. Sample S-5, a pumice erupted on November 18, contains approximately 30 percent large olivine phenocrysts, as much as 4 mm in diameter, in the mode. The olivine phenocrysts are mostly euhedral; a few exhibit incipient rounding of the crystal form. Partial chemical analyses of large olivine phenocrysts separated from pumice erupted November 17 (sample S-4) and November 19 (sample S-6) indicate an Fa content of 12.5 mole percent in the olivines of both samples, suggesting that olivine of sample S-5 has that composition.

Sample S-9, of spatter and pumice thrown out by the lava fountain at 8:00 p.m. on November 21, represents the last lava extruded during the week-long first phase of summit activity. Mineralogically, the material is very similar to most of the summit lavas. Olivine is the only phenocryst present; it occurs as large crystals, as much as 4 mm in diameter, set in a glassy groundmass rendered opaque by abundant microlites. The olivine phenocrysts in this sample, however, all show marked rounding and some show strong embayment, due to magmatic resorption (fig. 3).

Sample S-14 is a flow lava collected less than 200 feet from the vent during the fourth phase of activity on December 4. Again, the lava consists of olivine pheno-

crysts in a very dark glassy to microcrystalline groundmass. The olivine phenocrysts are sparse, smaller in size (as much as 2 mm in diameter) than observed in most of the summit lavas, and are rounded and deeply embayed by resorption.

Samples S-16 and S-20, erupted December 6 and 13, respectively, are representative of two of the shorter intermediate phases (fifth and ninth) of the summit eruption. Although sample S-16 is a pumice and sample S-20 is a pond lava collected about 750 meters from the vent, they are mineralogically and chemically similar. Both contain abundant large phenocrysts of olivine, as much as 3 mm in diameter, set in a dark glassy to microcrystalline groundmass. The olivine phenocrysts are strikingly euhedral (fig. 4) and in sample S-20 contain 12.5 mole percent Fa (partial chemical analysis).

As mentioned previously, the very small volume of lava erupted during the last (17th) phase of the summit activity also contained minor amounts of phenocrystic clinopyroxene and plagioclase. Sample S-25, of the short flow extruded during this phase, contains large phenocrysts of euhedral to partly rounded olivine and microphenocrysts of olivine, clinopyroxene, and plagioclase in a dark glassy groundmass. No attempt was

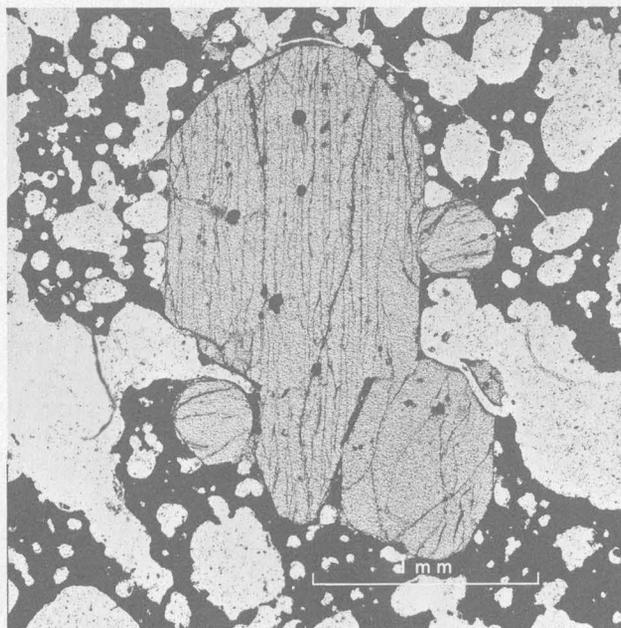


FIGURE 3.—Photomicrograph of large resorbed olivine phenocrysts in sample S-9, erupted November 21, 1959. Matrix groundmass (black) contains abundant equidimensional vesicles (light gray).

made to separate the minerals for determinative purposes.

The general correlation between the fayalite content of olivine phenocrysts and the temperature of their separation from the melt is in accord with the well-known melting relationships in the system forsterite-fayalite (Bowen and Schairer, 1935). In addition, the crystal habit of unresorbed olivine crystals seems to be temperature dependent. Phenocrysts that separated from many of the hotter melts were large and euhedral (fig. 4), whereas those that separated from the cooler melts were small and skeletal (fig. 2). These differences in crystal habit are probably due in part to a decrease in the kinetics of crystallization of the slowly cooling melt and in part to a shorter period of growth for olivines of the cooler melts. Very similar differences in the habit of olivine phenocrysts were observed experimentally by Kopecký and Voldán (1959) in their study of the crystallization of basaltic glasses at different temperatures.

THE FLANK LAVAS

Unlike the lavas erupted at the summit, the flank lavas underwent an extreme and abrupt change in composition during the course of the 5-week flank eruption between January 13 and February 19, 1960. Moreover, the early flank lavas, which contained relatively abundant phenocrysts of plagioclase and clinopyroxene, and minor olivine and hypersthene, were markedly dif-

ferent from any of the summit lavas; only during the last 2 weeks of eruption did the composition of the flank lavas approach that of the summit lavas (fig. 1, samples F-10 to F-20). The early flank lavas did, on the other hand, bear a remarkable mineralogical and chemical similarity to the late lavas of the 1955 eruption that occurred in the same general area of the east rift zone.

The abrupt change in composition of the flank lavas occurred with dramatic suddenness on the evening of January 27. At 21^h45^m on that date, the vents in the main eruptive area ceased fountaining, and for 5 minutes all was quiet. Then eruption resumed, both from the old vents and from a line of new vents extending more than 300 meters to the northeast on strike with the old vents.

Almost immediately after the resumption of activity, a decided decrease in viscosity of the lavas was observed. Temperatures in the core of the fountains increased from 1040°C, just prior to the change in eruptive pattern, to 1060°C on the morning of January 28, a few hours after the change. By the morning of January 29, temperatures had increased still further to 1080°C, and large phenocrysts of olivine were abundant in the lavas. Both the temperature and olivine content continued to increase through the next week, the temperatures reaching a maximum 1125°C on February 6—the last date of temperature observations; a parallel drop was observed in silica content, from 49.87 percent on January 29 to 48.4 percent on February 7.

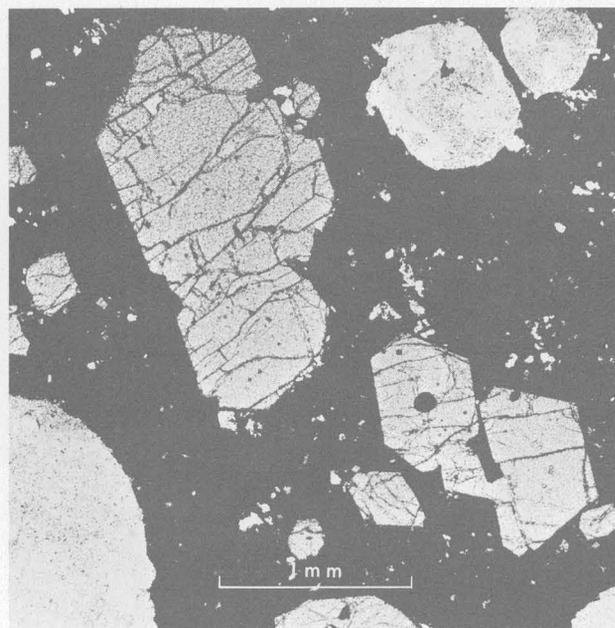


FIGURE 4.—Photomicrograph of large euhedral olivine phenocrysts in sample S-20, erupted December 13, 1959.

Flow samples F-1, -4, and -6 collected on January 13, 18, and 21, respectively, apparently are typical of the early flank lavas erupted before the marked change in magma composition on January 27. The three samples are remarkably similar, both chemically and mineralogically, and do not hint at any trend by which the change on January 27 might have been anticipated (fig. 1). The rocks, which are highly vesicular, contain phenocrysts of plagioclase, clinopyroxene, olivine, and hypersthene, in order of decreasing abundance, set in a dark glassy groundmass constituting approximately 83 percent, by volume, of the solid rock (fig. 5).

Plagioclase, which composes more than half (52-57 percent) of the total phenocrysts, ranges in size from large equant euhedral and subhedral crystals 2 mm in diameter to small needlelike crystals less than 0.1 mm long. The bulk of the plagioclase appears to fall in the composition range An_{72-66} (determined by indices of refraction); minor zoning to An_{64-56} was observed only in some of the larger crystals. Clots of plagioclase and clinopyroxene crystals are very common, and a few of the large plagioclase crystals contain small clinopyroxene inclusions in rows parallel to one or more of the principal plagioclase faces (fig. 5).

Clinopyroxene occurs as euhedral to subhedral stubby prisms ranging in size from 1.5 to 0.1 mm in diameter. Simple twins are common, and a few crystals exhibit exsolution lamellae of orthopyroxene. The composition of the early clinopyroxene, based on the analysis of

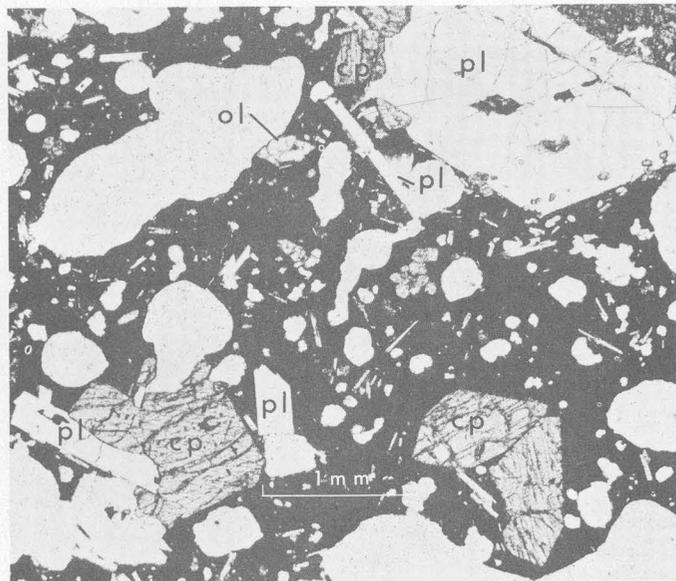


FIGURE 5.—Photomicrograph of flow sample F-1, erupted January 13, 1960, showing plagioclase (pl), clinopyroxene (cp), and olivine (ol) in dense black vesicular groundmass. Note the row of clinopyroxene inclusions along the bottom margin of the largest plagioclase phenocryst.

a pure concentrate separated from sample F-1, is $En_{47.6}$, $Fs_{12.3}$, $Wo_{40.1}$. (The analysis is given by Murata and Richter, 1966.)

The few olivine phenocrysts scattered through the early flank lavas appear to be of two distinct physical and chemical types, similar in some respects to those observed in the early summit lavas. One type occurs as large resorbed crystals as much as 1.2 mm in diameter, and the other—and possibly more common type—occurs as small euhedral crystals less than 0.5 mm in length. Although it was virtually impossible to separate the two types completely, X-ray studies of hand-picked larger olivine crystals from sample F-1 indicate a composition of Fa_{17} , whereas the smaller, apparently more euhedral olivines from the same sample have a composition of Fa_{24} . A partial chemical analysis of a pure olivine concentrate from sample F-1, which included both large and small crystals, gave an average composition of Fa_{21} . X-ray studies of olivines from the other early lavas also strongly suggest that the change in physical type is indicative of a change in composition: large olivine phenocrysts in sample F-2 (January 14) and sample F-6 contained Fa_{14} and Fa_{12} , respectively, and small euhedral olivines in sample F-4 contained Fa_{20} .

Hypersthene, the least abundant of the phenocrysts in the early flank lavas, was not recognized in any of the thin sections studied, but it was present in heavy-mineral fractions from all three samples. It occurs as equidimensional grains as much as 1 mm in diameter, and probably constitutes no more than 1 percent of the total phenocrysts. On the basis of index of refraction ($N_{\gamma} = 1.695 \pm 0.005$) and measured specific gravity (3.3), the composition of the hypersthene is approximately Fs_{20-25} .

Sample F-8, a pumice fragment erupted on January 29 approximately 30 hours after the change in eruptive activity, gives some idea of the abruptness and magnitude of the accompanying mineralogical changes and decrease in silica content. Plagioclase is no longer the predominant phenocryst; instead three minerals—olivine, clinopyroxene, and plagioclase—are present in roughly equal amounts, olivine being somewhat more abundant than the rest.

Many of the olivine phenocrysts have a fresh, "new" appearance. They occur as skeletal crystals as much as 1.5 mm in diameter and as large euhedral crystals, which show slight evidence of resorption, as much as 2.5 mm in diameter. The composition of the olivine ranges from Fa_{12} to Fa_{16} (determined by index of refraction). Small rounded grains of olivine, as much as 0.2 mm in diameter, are also present and may represent remnants of

the more fayalitic olivine of the early lavas, which had not been completely resorbed by the hotter melt.

The plagioclase phenocrysts (An_{72} , some zoned to An_{64}), besides being relatively abundant, also show the effects of the higher temperatures. The lathlike crystals exhibit rounded and ragged ends; some of the zoned crystals show selective resorption of the more calcic interiors (fig. 6).

Clinopyroxene in sample F-8 is the least affected of the phenocrystic minerals. Its mode, relative to the total phenocrysts, is virtually unchanged and most of the crystals are still euhedral; however, some exhibit slight rounding of the crystal faces, and a few are embayed by the groundmass glass.

A few grains of hypersthene are present in heavy-mineral separates of the sample, but in amounts noticeably less than in the early lavas.

By the next day (January 30), the effects of the compositional change and increase in temperature of the erupting lava were even more pronounced. Sample F-10, of a lava flow on that date, contains very abundant large slightly rounded olivine phenocrysts as much as 4 mm in diameter, as well as minor phenocrysts of plagioclase and clinopyroxene that show evidence of strong attack by the melt; in fact, the few plagioclase crystals still remaining are elongate small (less than 1 mm long) rounded grains that exhibit none of the selective resorption observed in the lavas of a day earlier (fig. 6B). One rounded crystal of olivine,

rimmed by an overgrowth of fine-grained clinopyroxene (augite?) crystals, is the only evidence of reaction noted in all the flank or summit lava samples. No hypersthene was observed in either the thin sections or in the heavy-mineral separates.

Samples collected on February 4 (F-12) and February 12 (F-16) contain 78 and 89 percent olivine, respectively, in the phenocrystic mode, and only 1 percent plagioclase. The olivine crystals continue to be large (as much as 3 mm in diameter) and euhedral to slightly rounded, whereas the minor clinopyroxene and rare plagioclase show more and more evidence of resorption. Composition of the rounder grains of plagioclase in sample F-14 is An_{70} .

The last flow (sample F-20) extruded during the flank eruption on February 18 shows a slight increase in the phenocrystic clinopyroxene and plagioclase contents. The olivine phenocrysts (Fa_{12} , determined by X-rays), although still large (as much as 4 mm in diameter), also show more pronounced rounding of their crystal form. The clinopyroxene phenocrysts are all rounded and have a maximum size of 0.7 mm. Some of the plagioclase phenocrysts (An_{70} , determined by index of refraction), on the other hand, tend to be slightly more euhedral, but most show the pronounced resorption characteristic of the plagioclase observed in the lavas of a few days earlier. A photomicrograph of a thin section from this February 18 flow is shown in figure 7.

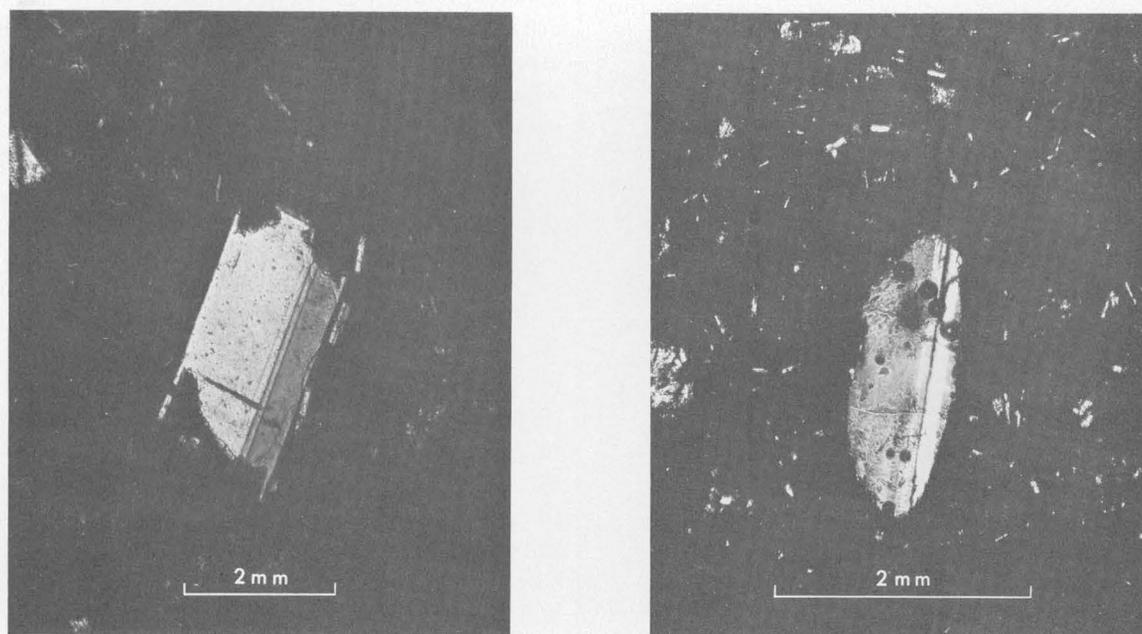


FIGURE 6.—Photomicrographs of resorbed plagioclase phenocrysts erupted after January 27, 1960. Compare with figure 5. *A* (left), Sample F-8, erupted January 29, 1960, showing selective resorption of more calcic interior of the plagioclase crystal; crossed nicols. *B* (right), Sample F-10, erupted January 30, 1960, showing complete rounding of feldspar crystal; crossed nicols.

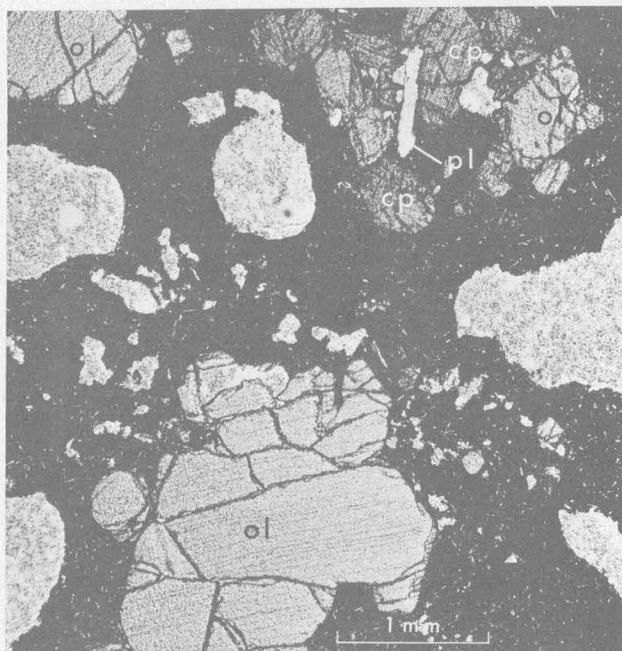


FIGURE 7.—Photomicrograph of flow sample F-20, erupted February 18, 1960, showing olivine (ol), clinopyroxene (cp), and plagioclase (pl) in a dense black vesicular groundmass. Compare with early flank lava in figure 5.

The mixing of magmas of different vintage, observed so clearly in the series of lavas of the 1960 flank eruption, emphasizes a process for which there was very little evidence in Hawaiian lavas studied heretofore. Mixed magmas have been recognized in many other volcanic provinces, such as the Medicine Lake highland of California (Anderson, 1941) and the San Juan region of Colorado (Larsen and others, 1938), largely by the presence of xenocrystic minerals in the lavas. The sequential changes observed petrographically in the 1960 flank lavas, correlated with concurrent data on volcanic activity, lava temperature, and lava composition, provide a most vivid picture of the mixing process.

The dissolution of phenocrysts, especially those of plagioclase, in the hotter melt also raises the interesting possibility of Kilauea magmas becoming more salic by melting the more fusible minerals of the wallrock. The importance of this process is difficult to assess because of its dependence on a complex interplay of thermal and chemical factors (Bowen, 1928). It probably is of only minor importance in tholeiitic magmas of Kilauea, as they generally have a short residence time within the volcanic edifice, but it may be highly significant in the generation of alkalic magmas in older, less vigorous Hawaiian volcanoes (Daly, 1944).

THERMAL DATA

Besides the obvious relationship between bulk composition and the phenocrystic mineral assemblage of the 1959-60 lavas, there is also a concomitant relationship between lava temperature and phenocrystic minerals. The 1959-60 eruption provided an excellent opportunity to measure lava temperatures with modern precision instruments. Temperatures were measured with incandescent filament-type optical pyrometers throughout each night of the eruption when and where conditions permitted. The methods utilized and precautions observed are outlined in the paper by Ault, Eaton, and Richter (1961) on lava temperatures in the 1959 summit phase of the eruption. Most of the temperatures were measured in the core of the erupting lava fountains whereas some of the samples studied were collected from flows at some distance from the fountains; therefore, some of the observed temperatures were possibly higher than the prevailing temperatures in the sampled flows. Because of unassessable factors such as these, plus possible inaccuracies in the temperature measurements, it should be stressed that the finite temperature stability limits proposed for the various minerals or mineral assemblages be used with prudence.

Moreover, unlike laboratory experiments in phase equilibria where temperature and other parameters can be varied or fixed as demanded, the data presented here are based almost entirely on the petrographic character of the lavas (preceding section), whose temperatures, in general, increased erratically from beginning to end of eruption. Equilibrium, therefore, was only approached from one direction (increasing temperatures); and where ambiguous criteria existed for establishing the stability or nonstability of a mineral phase in the melt, the final interpretation may be somewhat subjective.

The probable temperature stability fields for the phenocrystic minerals in both the summit and flank lavas of the 1959-60 eruption are shown in figure 8. The summit lavas containing roughly between 47 and 49 percent SiO_2 have a liquidus temperature of about 1180°C , with magnesian olivine (Fa_{14-12}) the first mineral to crystallize. At lower temperatures and a slightly greater silica content of the melt, lesser quantities of more fayalitic olivine (Fa_{18-17}) crystallize, and at about 1120°C clinopyroxene begins to form. At 1090°C plagioclase (An_{64}) begins to crystallize, and the 3 minerals crystallize together. The break in the olivine field between 1100°C and 1125°C , as shown in figure 8, is not meant to imply a discontinuity in olivine crystallization but merely denotes a lack of mineralogical data for this temperature interval. Olivine, progressively more fayalitic, evidently forms throughout the entire crystallization range of the lavas.

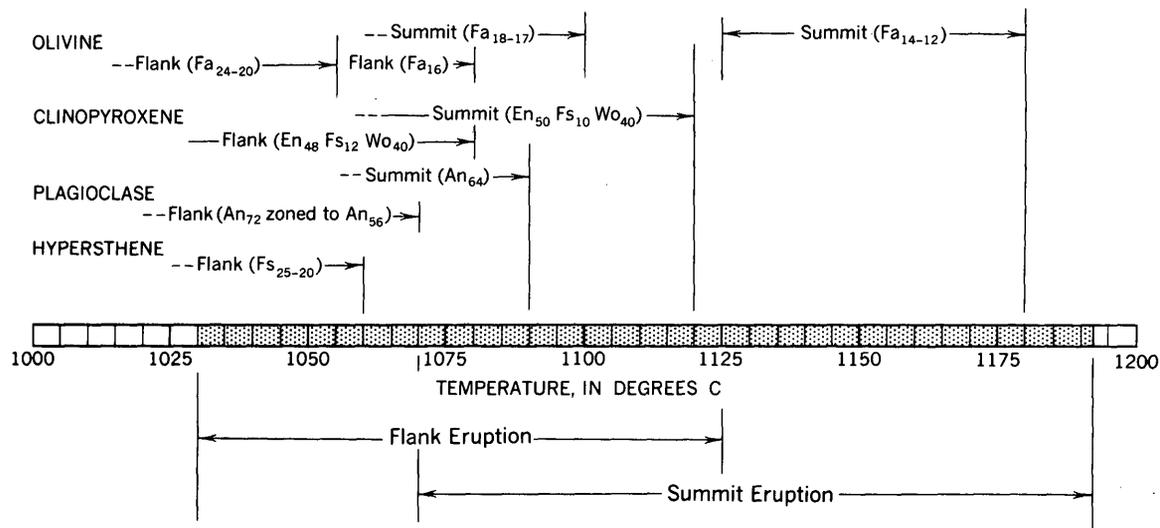


FIGURE 8.—Temperature stability fields for the phenocrystic minerals in the summit and flank lavas of the 1959-60 eruption.

The liquidus temperature of the early flank lavas (bulk silica content, 50.4 to 50.8 percent), on the other hand, is apparently about 1080°C, with olivine (Fa₁₆) and clinopyroxene appearing simultaneously. Plagioclase (An₆₆₋₇₂ zoned to An₅₆₋₆₄) apparently begins crystallization at slightly lower temperatures (1070°C) and hypersthene (Fs₂₅₋₂₀) still lower at about 1060°C. Although abundant olivine phenocrysts with a fayalite content as low as Fa₁₂ occur in the later and more mafic flank lavas, none appear to be in equilibrium with the melt. The late high-magnesian olivines are interpreted to be phenocrysts from a hotter, more primitive magma, such as that which fed the summit eruption and which evidently began to erupt and mix with the highly differentiated early flank lavas on January 27. Moreover, the minor amounts of large partially resorbed olivine phenocrysts (Fa₁₂₋₁₇) in the early flank lavas are not considered in this attempt to deduce stability fields for the phenocrystic minerals. They undoubtedly are not in equilibrium with the enclosing melt, but may represent additions from local hot spots within the flank-magma reservoir.

Except for olivine Fa₁₆ from the flank forming at lower temperatures than olivine Fa₁₈₋₁₇ from the summit and for the difference in the upper limit of stability in the two clinopyroxenes of virtually the same composition, the stability ranges proposed for the phenocrystic minerals from both eruptive phases are in general correspondence. These discrepancies may be due to errors in determinations of composition and temperature or to actual differences in the bulk composition of the two lavas.

The sequence of fractional crystallization manifested by summit and flank magmas is summarized in the fol-

lowing table. The temperature interval through which a mineral separated from the magma is given; where only one temperature is given, it denotes the point of the initial separation of the mineral.

Mineral	Approximate temperature of separation (°C)
Summit magma:	
Olivine, Fa ₁₂₋₁₄ -----	1180-1125
Augite, En ₅₀ Fs ₁₀ Wo ₄₀ -----	1120
Olivine, Fa ₁₇₋₁₈ -----	1100
Plagioclase, An ₆₄ -----	1090
Flank magmas:	
Olivine, Fa ₁₂₋₁₆ -----	1080-1055
Augite, En ₄₈ Fs ₁₂ Wo ₄₀ -----	1080
Plagioclase, An ₇₂₋₅₆ -----	1070
Hypersthene, Fs ₂₀₋₂₅ -----	1060
Olivine, Fa ₂₀₋₂₄ -----	1055

Qualitatively, these thermal data compare favorably with the results obtained by Yoder and Tilley (1957, 1962) in their melting experiments on Kilauea lavas. Both sets of data show that in tholeiitic lavas with a bulk silica content below about 50.2 percent, the order of crystallization with decreasing temperature is: (1) olivine, (2) clinopyroxene, and (3) plagioclase. However, quantitatively, the two sets of thermal data are not in good agreement; the temperatures obtained in the laboratory experiments are all consistently higher than the temperatures deduced for corresponding points in this study.

Yoder and Tilley (1962) found the liquidus of the 1921 Kilauea lava (49.16 percent SiO₂) to be approximately 1235° C, whereas the present study indicates liquidus temperatures on the order of 1180° C for lavas with even less SiO₂. Moreover, the temperature range of complete crystallization, as determined in the laboratory, is relatively small: 1060° to 1235° C for the

1921 Kilauea lava and 1065° to 1195° C for a prehistoric Kilauea lava. Yet in the 1959-60 lavas a glassy groundmass, constituting between 80 and 90 percent of the total rock, is present at temperatures as low as 1030° C. Also, optical pyrometer measurements of temperatures within the centers of thick flows indicate that at temperatures of 950° C the lava has a sufficiently low viscosity to be mobile.

These differences in thermal data between laboratory experiments on natural rocks and those deduced from field observations appear to be real. The reasons are probably manifold: a greater volatile content of the lavas in their natural environment compared to those remelted in the laboratory may be a determining factor, and the air oxidation of the samples during the melting experiments may be another. The fact that the compositions of the minerals obtained in the melting experiments are as yet unknown also precludes a close comparison between field and laboratory observations. Whatever the cause of the discrepancies, the field evidence indicates that stability temperatures of the crystalline phases in the naturally forming lavas are appreciably lower and cover a much larger range than those determined in laboratory phase-equilibria studies or in melting experiments on natural rocks.

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CHRONOLOGICAL NARRATIVE

**The 1959-60 Eruption
of Kilauea Volcano
Hawaii**



Lava fountain, 900 feet high, and full lava lake during the eighth phase of the summit eruption in Kilauea Iki Crater. The tops of rising lava jets appear as bright-orange patches through a shroud of cooler, darker falling clots of pumice, and a brown cloud of still cooler pumice fragments and dust drifts downwind left of the fountain. Sulfurous bluish fume rises from a floating island of cinder and pumice detached from the cone during the third phase. View west from Byron Ledge overlook. The slope of Mauna Loa rises gradually to the right in the background.