

Petrology, Mineralogy,
and Geochemistry of the
East Molokai Volcanic Series, Hawaii

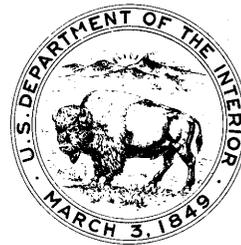
GEOLOGICAL SURVEY PROFESSIONAL PAPER 961



Petrology, Mineralogy, and Geochemistry of the East Molokai Volcanic Series, Hawaii

By MELVIN H. BEESON

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PETROLOGY, MINERALOGY, AND GEOCHEMISTRY OF THE EAST MOLOKAI VOLCANIC SERIES, HAWAII

By MELVIN H. BEESON

ABSTRACT

The Kalaupapa section, a 305-m (1,000-ft)-thick section of mostly porphyritic lavas that range from transitional tholeiitic to alkalic to distinctly alkalic, is exposed along the trail that leads up the cliff southwest of Kalaupapa on East Molokai Volcano, Hawaii. On the basis of whole-rock composition, the section was divided into eight subsections characterized by enrichment upward in the section in Na_2O , K_2O , and Al_2O_3 and depletion in MgO , NiO , and Cr_2O_3 . Enrichment in Na_2O , K_2O , and P_2O_5 and depletion in NiO and Cr_2O_3 are also evident upward in the section as a whole. Olivine and clinopyroxene phenocryst content of the lavas decreases and plagioclase phenocryst content increases (with minor variations) upward in the subsections.

Analyses of phenocrysts and some groundmass minerals also show variation up the section. Clinopyroxene increases upward in Na_2O and TiO_2 content and decreases in MgO ; olivine increases upward in FeO , CaO , and MnO content and decreases in MgO ; and plagioclase increases upward in Na_2O and K_2O content and decreases in Al_2O_3 and CaO . Plagioclase also shows an upward increase in K_2O in the subsections.

Phenocryst-free compositions were determined by subtracting phenocrysts from the whole-rock compositions on the basis of their modal amounts and compositions. The subsections defined on the basis of whole-rock compositions also remain intact when defined on the basis of phenocryst-free compositions; therefore, not all the chemical variation in the subsections can be attributed to variation in phenocryst content.

The subsections are believed to represent distinct magmatic batches similar to the ones that were proposed to explain the chemical variation of tholeiites and the eruptive histories of Hawaiian volcanoes and that were recently confirmed from a detailed study of the lavas of Kilauea. Concentrations of phenocrysts in some lavas mask trends in composition. Calculation of phenocryst-free compositions has, to a first approximation, removed variation of the whole-rock compositions resulting from shallow fractional crystallization and has revealed earlier (and deeper) fractionation dominantly controlled by aluminous clinopyroxene. The more fractionated character of the subsections in the upper part of the section, starting with olivine basalt and ending with mugearite, perhaps reflects changing conditions in the zone of magma generation prior to phenocryst growth.

INTRODUCTION

The island of Molokai, a volcanic doublet, is the fifth in size of the islands of the Hawaiian Archipelago, which extends about 2,500 km (1,554 mi) southeastward across the central Pacific Ocean from Kure on the northwest to Hawaii on the southeast (fig. 1). The broadly linear chain of islands that make up the ar-

chipelago caps the Hawaiian Ridge. The ridge is bordered by the Hawaiian Moat (or Deep) which is in turn bordered by the Hawaiian Arch (or Rise). These three topographic features, the ridge, moat, and arch, are superposed on a broad elongate topographic high, the Hawaiian Swell (Betz and Hess, 1942; Dietz and Menard, 1953). Dana (1849, 1890) recognized from geomorphic evidence that extinction of the chain progressed from northwest to southeast, and McDougall (1964) confirmed the general progression with potassium-argon ages of lavas from Kauai, Oahu, Molokai, Maui, and Hawaii. The general progression of ages of the Hawaiian-Emperor chain and its relation to Cenozoic circumpacific tectonics have been described by Jackson, Silver, and Dalrymple (1972) and Dalrymple, Silver, and Jackson (1973). Fiske and Jackson (1972) investigated the influence of regional structure and local gravitational stresses on the orientation and growth of Hawaiian volcanic rifts. Macdonald and Abbott (1970) gave an excellent summary of the geomorphology of the Hawaiian Islands and of the processes that formed and are continuing to form them. Their summary contains a geologic sketch of each of the major

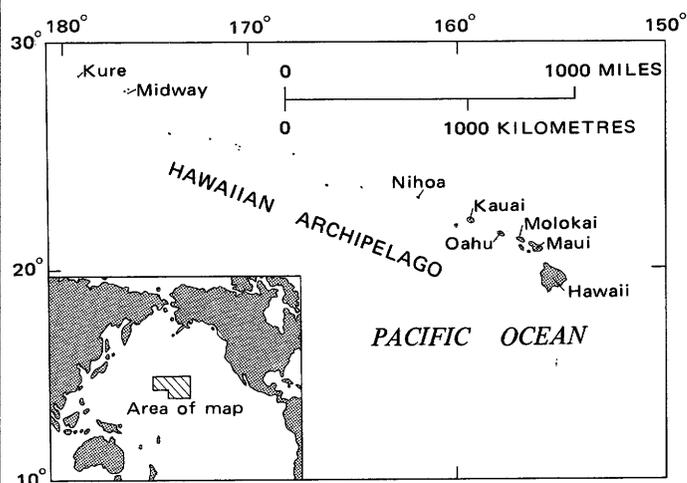


FIGURE 1.—Index map of the Hawaiian Archipelago (after Jackson, 1968, Fig. 1).

windward islands (extending from Kauai to Hawaii) and the leeward islands (extending from Kure to Nihoa) as a group.

Molokai is an elongate island 78×16 km (48.5×10 mi), with its long dimensions oriented east-west (fig. 2). It is made up of two coalescing volcanoes, West Molokai¹ Volcano, which rises 421 m (1,380 ft) above sea level, and East Molokai Volcano, which rises 1,515 m (4,970 ft) above sea level. Both East and West Molokai Volcanoes are elongate in plan reflecting the structural control of several major rift zones. West Molokai has three rift zones oriented due east, northwest, and west-southwest. East Molokai probably was controlled by stress patterns set up in the edifice of the older West Molokai Volcano whose sloping apron it pierced (Fiske and Jackson, 1972). West Molokai is believed by Fiske and Jackson (1972) to have grown as an "isolated" edifice that was influenced by the regional structure of

the Pacific basin. However, if the prolongation of the west-southwest rift of West Molokai Volcano (Penguin Bank) is an older independent shield built along the same trend as the main rift zone of West Molokai Volcano (Macdonald and Abbott, 1970), then the orientation of the rift system of West Molokai reflects gravitational stress patterns set up in this older independent shield.

The north coast of Molokai, especially its eastern part, is bounded by a spectacular pali (cliff) that is locally more than 915 m (3,000 ft) high. Several deep amphitheater-shaped valleys, notably Wailau, Pelekunu, and Waikolu, have been cut into the pali. Two of these, Wailau and Pelekunu, dominate the drainage system of the northern coast, probably because they head in the highly altered, and therefore easily eroded, rocks of the caldera complex. The drainage system on the south (leeward) flank of East Molokai is not so deeply incised as the drainage system of the northern coast, because it receives far less rainfall. Flat-topped interfluves along the south flank permit reasonably re-

¹West Molokai Volcano is also referred to as Mauna Loa, but this name is not used here to avoid confusion with the better known Mauna Loa of the island of Hawaii.

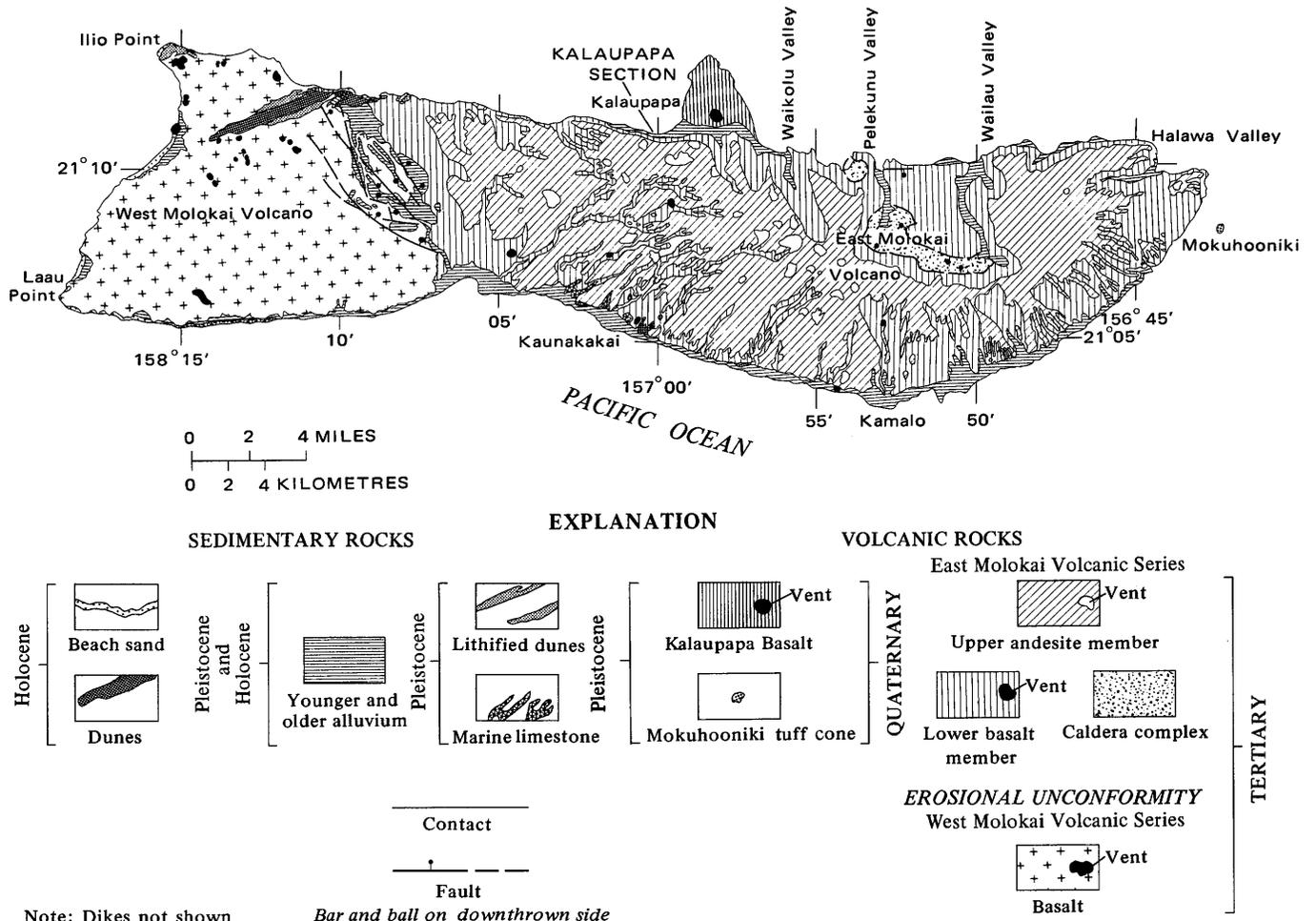


FIGURE 2.—Geologic map of island of Molokai showing location of Kalaupapa section (after Stearns, 1946, fig. 18; Stearns and Macdonald, 1947).

liable reconstruction of the preerosional edifice, which shows that, disregarding subsidence, East Molokai was never much higher than its present 1,515-m (4,970-ft) elevation. However, considering possible subsidence of $2,300 \text{ m} \pm 500 \text{ m}$ ($7,550 \pm 1,640 \text{ ft}$), calculated from data of Moore (1970), it may have reached an elevation of $3,815 \pm 500 \text{ m}$ ($12,500 \pm 1,640 \text{ ft}$), nearly as high as Mauna Loa and Mauna Kea on the island of Hawaii.

West Molokai, the smaller and older of the two Molokai volcanoes, is made up of thin-bedded flows of tholeiitic basalt with many thin ($< \frac{1}{2} \text{ m}$) interlayers of vitric tuff. It never formed a caldera or had significant eruptions of alkalic basalt (Macdonald and Abbott, 1970).

East Molokai, on the other hand, has a well-developed caldera stage and erupted about 490 m (1,610 ft) of transitional and alkalic lavas in the Kalaupapa area some 70 m (230 ft) of which are mugearite and hawaiite (the upper member of Stearns and Macdonald (1947)). McDougall (1964) dated the mugearites of the upper member at 1.31–1.41 m.y. (million years) and several flows in the upper part of the alkalic basalt flows (the lower member of Stearns and Macdonald (1947)) at 1.48–1.49 m.y. The tholeiitic lavas of East Molokai have not yet been dated, and so the absolute chronology of the major parts of the two edifices remains in doubt.

PREVIOUS INVESTIGATIONS

The earliest work on the petrology of Molokai was done by Möhle (1902), who studied 50 samples from various localities scattered over the island but concentrated mostly along the northern pali (cliff) in the vicinity of Kalaupapa. Möhle (1902) considered the lavas of Molokai to be of typical basaltic character consisting of plagioclase, augite, olivine, and magnetite. He distinguished three groups connected by intermediate rocks: (1) olivine-bearing basalts in which olivine content is not high, (2) rocks in which olivine is rare or entirely lacking, and (3) rocks in which olivine is abundant and augite rare or lacking. He also reported a nepheline-bearing rock from Kalae. Stearns and Macdonald (1947) reported rocks corresponding to the first and second groups but found none that correspond to Möhle's third group on Molokai or any of the other Hawaiian islands. Because they did not find any nepheline-bearing rocks on Molokai, they concluded that some of the rocks studied by Möhle (1902) were mislabeled and actually came from Oahu. Lindgren (1903) made the first field study of Molokai to evaluate the water resources but paid little attention to petrology, except to note that the rocks were normal somewhat glassy feldspar basalts containing olivine and a few plagioclase phenocrysts. While exploring the headwaters of Wailau Stream, he

did note a coarse-grained intrusive rock that he termed a very coarse grained olivine diabase.

Powers (1920) visited all the windward islands and judged Wailau (East Molokai) Volcano to consist largely of feldspar basalt with rare alkali trachyte. He was the first to recognize that the Kalaupapa peninsula, north of the pali, is a young olivine basalt cone and not part of a sunken area as Lindgren (1903) believed.

The most comprehensive petrographic study of Molokai was made by Stearns and Macdonald (1947). Although their report was primarily concerned with ground water resources of Molokai, it gives the most detailed account of the geology and the only geologic map of Molokai to date. The lavas of West Molokai Volcano are described as basalts, olivine basalts, and picrites of primitive type. Because the flows are very thin, less than 1 m thick, and are poorer in olivine phenocrysts than is common in Hawaiian tholeiites, they are considered by Stearns and Macdonald (1947) to have been erupted in a very fluid condition. Only a thin discontinuous cap of alkalic olivine basalt and hawaiite is reported on West Molokai (Macdonald and Abbott, 1970).

Stearns and Macdonald (1947) reported the petrology of the stratigraphic section measured along the trail that leads down the great northern pali southwest of Kalaupapa—the subject of this study. This stratigraphic section, considered by them to be characteristic of the East Molokai Volcanic Series, is designated its type section and is herein referred to as the Kalaupapa section (fig. 2).

Stearns and Macdonald (1947) reported that augite phenocrysts are about as abundant as olivine phenocrysts and that these phenocrysts constitute 40–60 percent of the rock. However, no flows observed in the Kalaupapa section that contain more than 5 percent olivine phenocrysts have nearly equal abundances of augite and olivine phenocrysts. Augite phenocrysts are generally only about a third as abundant as olivine, and in only one sample does the augite phenocryst content amount to about 60 percent of the olivine phenocryst content. Phenocrysts constitute more than 20 percent of many rocks, but none in which modes were made exceed 30 percent of the rock, and none that I observed approach the 40–60 percent reported by Stearns and Macdonald (1947).

The general life history of Hawaiian volcanoes has been divided into four stages (Macdonald and Abbott, 1970; modified from Stearns, 1946):

1. Youthful stage, characterized by a shield, consisting almost entirely of thin basalt flows, that has been built by frequent eruption of very fluid tholeiitic lavas. The lavas of this stage range from basalt almost free of olivine phenocrysts to oceanites con-

taining more than 50 percent olivine phenocrysts (Macdonald and Katsura, 1962; Macdonald and Abbott, 1970).

2. Mature stage, characterized by a caldera complex that formed by repeated collapse of the summit area and infilling of the resulting caldera by lava. Activity during the mature stage was still vigorous, and many of the tholeiitic lava flows produced were thicker than in the youthful stage because they were ponded in the caldera.
3. Old stage, characterized by a cap of alkalic basalt that was built over the top and upper flanks of the shield and that thins away from the summit. Eruptions at this stage were less frequent and more explosive and produced thicker flows and steeper slopes than the earlier tholeiitic eruptions. The lava flows of this stage are commonly separated by weathered zones and a few soil zones or local erosional unconformities.
4. Rejuvenated stage, following a long period of volcanic quiescence. The flows of this stage are separated from those of the previous stage by a profound erosional unconformity. Many occur as intracanyon flows. Most lavas of this stage are critically undersaturated and contain nepheline or nepheline and melilite (Winchell, 1947; Jackson and Wright, 1970; Macdonald and Abbott, 1970).

This history is an idealized scheme, for not all volcanoes show the entire sequence and the sequence may be terminated at any stage. West Molokai Volcano, for example, ceased eruption before reaching the mature stage and has no caldera and few alkalic flows. East Molokai Volcano, on the other hand, has as complete a sequence as any of the volcanoes in the Hawaiian chain. It is probably just entering the rejuvenated stage. Post-erosional eruptions have formed the Kalaupapa Peninsula and Mokuhooniki Island, but unlike most of the posterosional lavas of Kauai (the Koloa Volcanic Series) and Oahu (the Honolulu Volcanic Series), these contain no nepheline.

PURPOSE AND SCOPE

This study was undertaken to determine what, if any, systematic changes in chemistry and petrology of the lavas could be detected through the stratigraphic section and how removal of phenocrysts from the whole-rock compositions affects the fractionation trends. All too frequently, chemical analyses from an area are plotted with little or no stratigraphic control, making it impossible to relate the presumed fractionation trends to stratigraphy. Because analysis of all phenocryst minerals was required to determine the phenocryst-free compositions, an evaluation of the variation of mineral

compositions in different parts of the section was also possible.

Most of the original plan to sample lavas of the tholeiitic suite and work upward into the alkalic suite has been accomplished. The flows in the lower part of the section are petrologically alkalic but are compositionally tholeiitic. They are probably best classified as transitional between tholeiitic and alkalic. The flows in the upper part of the section are unquestionably alkalic. Several stratigraphic sections were sampled, but detailed work has been done only on the Kalaupapa section (fig. 3). A reasonably complete sampling of the upper 305 m (1,000 ft) of the section was made, but only sparse sampling was done in the lower 180 m (600 ft), which is largely covered by talus.

Flows presumed to be tholeiitic have been sampled in Pelekunu and Waikolu Valleys, but limited time and difficult topography prevented sampling of a complete section. None of the rocks of the caldera complex that are exposed in Pelekunu and Wailau Valleys have been included in this study, but they merit a study in themselves inasmuch as the structure of this exhumed caldera complex appears to be similar to the one developing on Kilauea.

Acknowledgments.—Grateful appreciation is expressed to those in U.S. Geological Survey who provided technical assistance during this study. V. C. Smith and R. L. Rahill performed chemical analyses, and Keith Bargar separated and X-rayed olivine alteration products. Helpful discussions and critical reviews of E. D. Jackson, R. G. Coleman, K. J. Murata, and T. L. Wright of the U.S. Geological Survey, and of A. C. Waters, R. S. Coë, and O. T. Tobisch of the University of California, Santa Cruz, are sincerely appreciated. Field assistance by my wife, Naomi K. Beeson, is gratefully acknowledged.

ANALYTICAL PROCEDURES

After preliminary petrographic examination of all the samples taken from the Kalaupapa section, 26 samples from 24 flows were selected for further study. Whole-rock compositions were determined in the analytical laboratories of the U.S. Geological Survey in Denver, Colo., and phenocryst and groundmass minerals were analyzed by the author. In order to assure that the phenocryst modes would be representative of the sample analyzed for whole-rock chemistry, two slabs were taken from opposite sides of the samples submitted for whole-rock analysis. These two slabs were fine ground with 600-mesh abrasive, sprayed with plastic, and inscribed with a 1-cm² grid. Using a 10×10 mm reticle, 121 points were counted in each of the 1-cm squares. A drop of distilled water between the rock slab and the reticle significantly improved the visibility of



FIGURE 3.—Oblique aerial photograph of pali near Kalaupapa peninsula showing trail along which Kalaupapa section was sampled. A–Z, sample localities from base of section upward. Pali is about 490 m (1,610 ft) high. View to south. Photograph by U.S. Navy.

the phenocrysts. Following the procedure of Jackson and Ross (1956), a minimum of 1,000 points was counted for each sample, and with few exceptions, an area at least 100 times that of the largest phenocryst was covered. The volume percent mode was converted to weight percent using an estimated average density of 3.5 for olivine, 3.35 for clinopyroxene, 2.7 for plagioclase, and 2.9 for the groundmass. The mineral densities were calculated from end-member densities and average phenocryst compositions, and the groundmass density was estimated from densities of crystalline rocks (Daly and others, 1966).

X-ray diffractograms of olivine alteration rims were made with $\text{CuK}\alpha$ radiation using a Phillips X-ray generator and diffraction unit equipped with a graphite crystal monochromator. Mineral analyses were made with an ARL EMX-SM electron microprobe using natural mineral standards. All data were corrected for drift, background, matrix absorption, characteristic fluorescence, and atomic number effects (Beeson, 1967; Beaman and Isasi, 1970). During analysis of phenocrysts, the beam was scanned rapidly over a $10 \times 10 \mu\text{m}$ raster, which helps to even out inhomogeneities and gives a better average composition. The mineral analyses are believed accurate to ± 2 percent of the amount present for major elements and ± 10 percent of the amount present for minor elements.

The phenocryst compositions were subtracted from the whole-rock composition in proportion to their modal abundance. Because some of the olivine phenocrysts are altered, it was deemed advisable to make modes for the amounts of fresh and altered olivine and subtract appropriate amounts of fresh and altered olivine. This procedure appears to have been justified because two samples, I and M, with relatively abundant and the most severely altered olivine phenocrysts, do not depart appreciably from the trend established by the samples with relatively few olivine phenocrysts and those in which olivine phenocrysts are only slightly altered.

It is recognized that subtraction of phenocryst compositions derived by microprobe analysis yields only a first approximation to phenocryst-free lava compositions because of the inhomogeneity of the phenocrysts as a whole. Neither chromite inclusions in olivine, magnetite inclusions in plagioclase, nor other inclusions in the phenocrysts have been taken into account.

STRATIGRAPHY AND PETROLOGY

Three stratigraphic sections of the East Molokai Volcanic Series were sampled on a flow-by-flow basis: one along the trail to Kalaupapa, one along the road leading into Halawa Valley from the south, and one up Lama Loa Head north of Halawa Valley. The Kalaupapa section was selected for detailed study because it is thickest

and exposes rocks lower in the volcanic pile than the other two. The two sections in Halawa Valley contain fewer olivine phenocrysts relative to plagioclase and are much like the upper part of Kalaupapa section in that respect.

No attempt was made to trace the flows laterally because of the steep slope, but samples were taken up the trail on the assumption that vertical position can be directly correlated with stratigraphic position. Such an assumption is reasonable because no evidence of erosional unconformities was seen and in general, even in a late mature stage, the frequency of eruption of Hawaiian volcanoes is high enough to prevent development of extensive stream channels. Flows are commonly separated by weathered aa clinkers and in a few places by baked red soil zones, usually less than about $\frac{1}{3}$ m (1 ft) thick. Compared with the West Molokai Volcanic Series, there seem to be fewer vitric ash beds separating lava flows, which is curious in light of the fact that the flows in the Kalaupapa section are mostly alkalic, and they tend to be erupted more explosively than tholeiitic ones.

Because sills are present in some Hawaii sections, coarsely crystalline dense rocks without clinkers were looked for, but none were found. Presumably none of the flows sampled are really sills.

The Kalaupapa section lies about 12 km (6.8 mi) west-northwest of the caldera complex, as shown by Stearns and Macdonald (1947) (fig. 2). On the basis of gravity contours (Moore and Krivoy, 1965) and extrapolation of dikes that crop out on the pali due south of Kalaupapa, the section lies about 1 km (.62 mi) south of the west-northwest rift zone.

Wright and Fiske (1971) presented a model for the conduit system of the east rift of Kilauea, in which magma from the summit area migrates outward along separate subparallel conduits. The magma is stored in pockets along the rift zone where it may be fractionated to various degrees and later flushed by batches of unfractionated lava migrating outward from the summit. Lavas in the Kalaupapa section may have originated in this general setting. As a result, the compositional variations may not be typical of summit lavas but rather of lavas from rift-zone eruptions. Nonetheless, any long-term variation in the lavas, not related to fractional crystallization in the shallow rift-zone chambers, should provide information on deeper (more fundamental?) changes in magma composition. It cannot be definitely established that all or part of the lavas in the Kalaupapa section were derived from rift-zone eruptions, but by analogy with Kilauea, most of the flows near the rift zone are probably not summit eruptions. The gentle (2°) slope of the flows away from the rift zone in the Kalaupapa section argues for this rift-zone origin.

It is unlikely that the Kalaupapa section records the entire history of the East Molokai Volcanic Series. The period represented by accumulation of this section probably also includes many hiatuses resulting from a statistical distribution of the lavas from a volcano erupting frequently enough to maintain a nearly symmetrical form.

Stearns and Macdonald (1947) divided the East Molokai Volcanic Series into two members: (1) a lower member composed of basalts, olivine basalts, and picrite-basalts of the primitive and ankaramite types (2) and an upper member composed of andesine andesites (hawaiites), oligoclase andesites (mugearites), and trachytes. Picrites of the primitive type are reported to be present in the lower part of the lower member, and picrites of the ankaramite type are reported to be present in the upper part of the lower member. All the "little differentiated" lavas of the lower member are not tholeiitic as McDougall (1964) presumed, though the lavas of the lower part of the lower member, which Stearns and Macdonald (1947) described as containing picrites of the primitive type, probably are tholeiitic. The lavas of the upper part of the lower member, which McDougall dated and which Stearns and Macdonald (1947) described as containing picrites of ankaramite type, are distinctly alkalic.

No picrites of the primitive type were observed in the upper two-thirds of the Kalaupapa section, which was sampled in detail, or in the lower third, which was only sparsely sampled because it was covered by talus. Samples from the base of the pali about 1 km (0.62 mi) east of the Kalaupapa section were found to contain augite as phenocrysts and in the groundmass but no pigeonite or hypersthene. Petrologically they, and presumably the rest of the flows in the section, are alkalic.

Rocks that are apparently tholeiitic crop out at the east side of the mouth of Waikolu Valley. The flows are very thin bedded, $\frac{1}{3}$ – $1\frac{1}{2}$ m (1–4 ft) thick, with thin unweathered clinkers separating them, and they contain almost no olivine either as phenocrysts or in the groundmass. In these respects they resemble the tholeiitic rocks of West Molokai but differ in that they contain no vitric tuff beds between flows. This section of tholeiites(?) (fig. 4) is unusual and may be unique in the Hawaiian Islands. Other basalts, more typical of the Hawaiian tholeiites, are exposed outside the caldera complex in Pelekunu and Wailau Valleys.

Approximately 80 flows are present in the Kalaupapa section. The flows of the lower member range in thickness from about 1 to 20 m (3–70 ft) and average about 6 m (20 ft). Those of the upper member range in thickness from about 6 to 24 m (20–80 ft) and average about 9 m (30 ft).

McDougall (1964) obtained potassium-argon ages for



FIGURE 4.—Thin-bedded flows of tholeiitic basalt exposed along north coast of Molokai just west of mouth of Waikolu Valley. Average thickness of flows is about 0.7 m (2 ft.)

three flows in this section. One hawaiite flow from the upper member at an elevation of 457 m (1,500 ft) gave ages of 1.44–1.46 m.y., and two adjacent flows from the lower member at an elevation of 350 m (1,150 ft) gave ages of 1.47 and 1.49 m.y. for the upper and lower flows, respectively. Extrapolations based on these ages indicate that the 490-m (1,610 ft) Kalaupapa section could have accumulated in as little as 0.05 or as much as 0.22 m.y. If it is assumed that the section accumulated in about 0.14 m.y. (the average of the two extreme ages given above) and that there were 80 flows in the section, then the frequency of eruption was less than 2,000 years. Further extrapolations based on the ages provided by McDougall (1964) indicate that the base of the section could be as young as 1.5 or as old as 1.65 m.y., though the maximum age is not tenable because the natural remanent magnetism polarity of the entire section is reversed (Sherman Grommé, Edward Mankinen, and Monte Marshall, oral commun., 1972). It is improbable that the Gilsá event of the Matuyama epoch (from 1.64 to 1.79 m.y., Cox, 1969), a period of 150,000 years, would not be recorded by flows erupting with a 2,000-year frequency. The section was probably built in less than 0.22 m.y.; this agrees with the work of McDougall (1964) and McDougall and Swanson (1972), who concluded that any of the volcanic edifices in Hawaii could have been built in 0.5 m.y. or less.

Twenty-six samples from 24 flows were selected for detailed petrographic examination, whole-rock chemical analysis, and modal determination of phenocryst

content. Electron microprobe analysis of olivine, clinopyroxene, and plagioclase phenocrysts, chromite microphenocrysts, and olivine, clinopyroxene, plagioclase, and opaque minerals in the groundmass was made on 25 of these samples. The 26 samples analyzed have been lettered from A to Z from the base of the section upward. The section is not continuously exposed. Several gaps are present in the record between flows A and B, E and F, and Q and R where one or more flows may be covered by talus. Most of the analyzed samples were taken from near the base of the flows. Two exceptions are sample G, taken from near the top of a flow about 1.2 m (4 ft) thick, and sample I, taken near the center of a flow about 9 m (30 ft) thick. Samples were analyzed from two horizons in two of the flows. These are samples L and M from near the base and top, respectively, of a flow about 9 m (30 ft) thick, and samples O and P from near the base and top, respectively, of a flow about 3.5 m (12 ft) thick.

One of the most striking aspects of the lavas in the Kalaupapa section, in comparison with alkalic basalts of most other Hawaiian volcanoes, is the abundance of plagioclase phenocrysts relative to augite and olivine. Most of the flows in the Kalaupapa section are porphyritic except for a few in the upper third of the section. The porphyritic flows commonly contain more than 20 percent phenocrysts, but none in which modes were made contained more than 30 percent phenocrysts. This is contrary to the assertion of Stearns and Macdonald (1947) that augite phenocrysts are generally about equal in abundance or slightly more abundant than olivine and together constitute 40–60 percent of the rock. From the geometry of packing of equal-sized spheres alone, these abundances seem too high. For cubic open packing, the phenocryst content would be 52 percent, and for cubic closed packing, it would be 74 percent. If a lava contained 40–60 percent of phenocrysts, its mobility would be substantially reduced because the phenocrysts would be touching rather than free floating.

The section studied was divided into a series of subsections on the basis of the whole-rock composition, but division on the basis of phenocryst content would have yielded the same subsections. Olivine phenocrysts are most abundant in the lower flows of the subsections, decreasing upward to almost zero in the uppermost flows of the subsections (fig. 5). In a broad way, the amount of augite phenocrysts decreases with the decrease in amount of olivine phenocrysts, but augite phenocrysts are usually only about a third as abundant as olivine phenocrysts. Of the 19 samples containing more than 5 percent phenocrysts, only one has appreciably more than a third as much augite as olivine

phenocryst content; in it, augite is about 60 percent as abundant as olivine. The plagioclase phenocryst content does not vary with olivine content in as systematic a manner, although, in a very crude way, it does increase upward in both the entire section and the subsections.

None of the flows in this section merit the designation of "ankaramite"² as defined by LaCroix (1916), because the augite phenocryst content is not equal to, nor does it exceed, that of olivine in any of them, and plagioclase phenocrysts are abundant.

Olivine phenocrysts almost invariably have deep-red to reddish-yellow alteration rims usually accounting for 10–20 percent of the grain. These alteration rims follow the outline of the phenocryst even when it is strongly

²LaCroix defines ankaramite as being "olivine-bearing and melanocratic, rich in pyroxenes up to 1 cm (0.4 in) in diameter, and somewhat fewer and smaller olivines. The compact groundmass is composed of large microlites of augite and titanomagnetite, and a little biotite and labradorite" (translation from Johannsen, 1938).

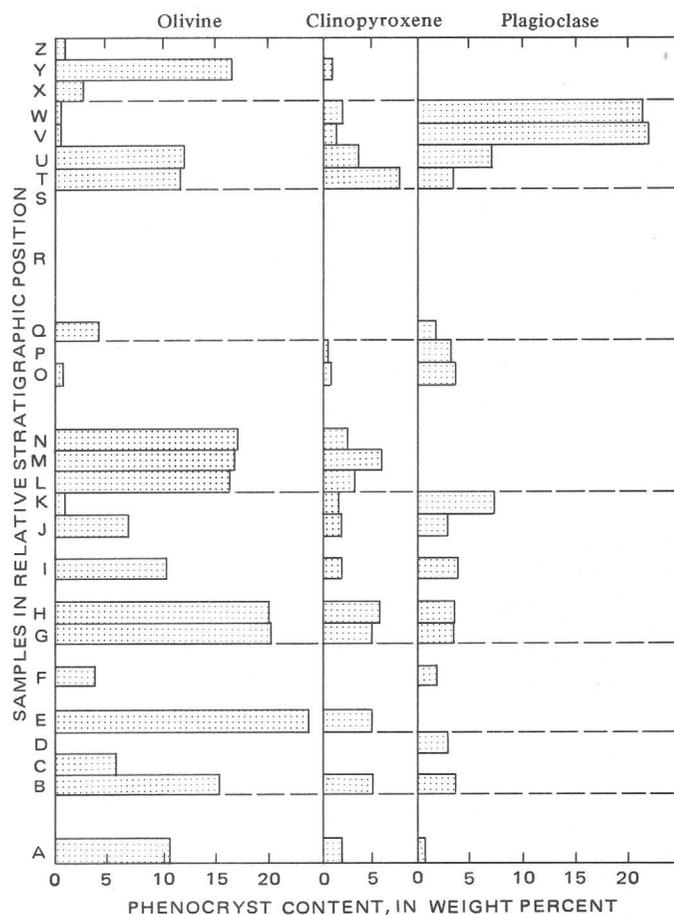


FIGURE 5.— Histogram showing phenocryst content (in weight percent) of lavas of Kalaupapa section. Dashed horizontal lines separate eight subsections delimited on the basis of whole-rock chemistry.

resorbed and are nowhere truncated by a resorption surface. Fresh growths of olivine over deep-red alteration rims and in optical continuity with the core are common (figs. 6A, B). These fresh overgrowths led Stearns and Macdonald (1947) to suggest, and I concur, that the alteration was intratelluric after a period or periods of resorption and preceding intrusion or extrusion. A porphyritic dike observed near the head of

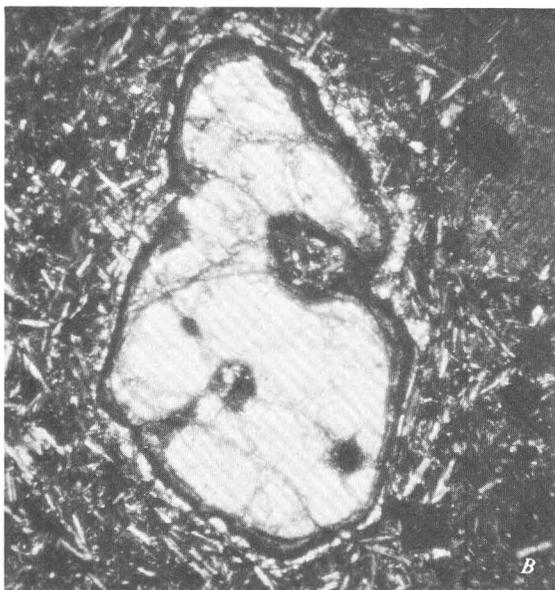
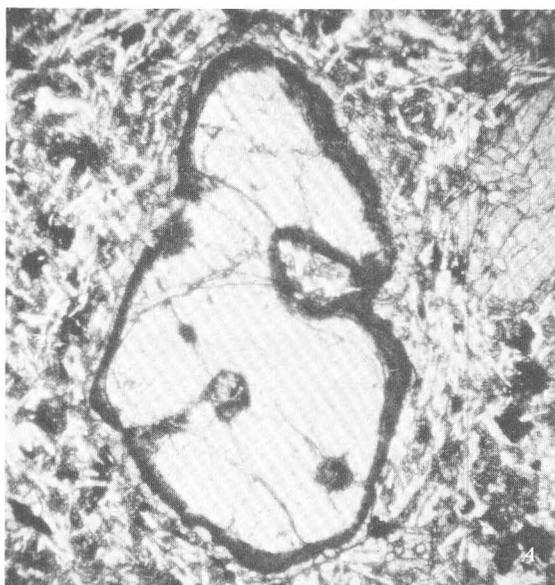


FIGURE 6.—Photomicrographs of a resorbed olivine phenocryst from Kalaupapa section showing intratelluric alteration and fresh overgrowth. Olivine phenocryst is 1.8 mm (0.07 in.) long. A. Plane light. B. Crossed nicols.

Waikolu Valley provides further evidence of intratelluric alteration of olivine. Olivine phenocrysts near the center of this dike are rimmed with fresh overgrowths, but those phenocrysts in the chilled margin of the dike have no fresh overgrowths. Similar overgrowths have been reported in the literature (Möhle, 1902; Ross and Shannon, 1925; Tomkeiff, 1934; Sheppard, 1962) and have been ascribed either to selective alteration of a shell of iron-rich olivine or to intratelluric alteration followed by regrowth after intrusion or extrusion. Microprobe analyses (presented in the section "Compositional Variation of Olivine") of many fresh olivine overgrowths show them to be invariably richer in iron than either the phenocryst core or the altered zone, and on the basis of this evidence, the selective alteration origin, in these lavas at least, is not tenable. It is possible in most samples to identify the intratelluric alteration even when it has been overprinted with later deuteric alteration or weathering. The intratelluric alteration product is deep red and forms a narrow rim usually surrounding the entire phenocryst (with or without the fresh overgrowth). It follows in detail the resorbed shape of the grain, with few incursions along fractures, and is quite sharp in its contact with fresh core of the phenocryst. By contrast the deuteric alteration product is reddish yellow to reddish brown and forms broad feathery incursions into the phenocryst although concentrated mostly along the edge of fractures. In vertically reflected light and at high optical magnification (about $\times 1,000$), the intratelluric alteration rims show a higher reflectivity than either the unaltered cores or the overgrowths. This high reflectivity results from tiny highly reflecting grains dispersed throughout the alteration rim. Some of the grains (about $0.3\text{--}0.5\ \mu\text{m}$ in diameter) are optically resolvable, but apparently many more are too small to be resolved with a $\times 100/1.30$ NA oil immersion objective. Further evidence (presented in the section "Compositional Variation of Olivine") indicates that the intratelluric alteration product is dispersed hematite with some associated magnetite-pyroxene symplectites rather than "iddingsite" (smectite-chlorite, Wilshire, 1958).

Some of the phenocrysts have a complex history of growth, resorption, alteration, and regrowth. One phenocryst exhibits particularly well the stages: (1) growth, (2) resorption, (3) alteration (hematitic), (4) regrowth, (5) resorption, and (6) further alteration (hematitic) (fig. 7). Olivine phenocrysts showing more than one stage of growth that is interrupted by resorption or alteration, such as the one just described, occur sporadically. They coexist with the more common olivine phenocrysts showing only one stage of growth, indicating that at least two generations of olivine

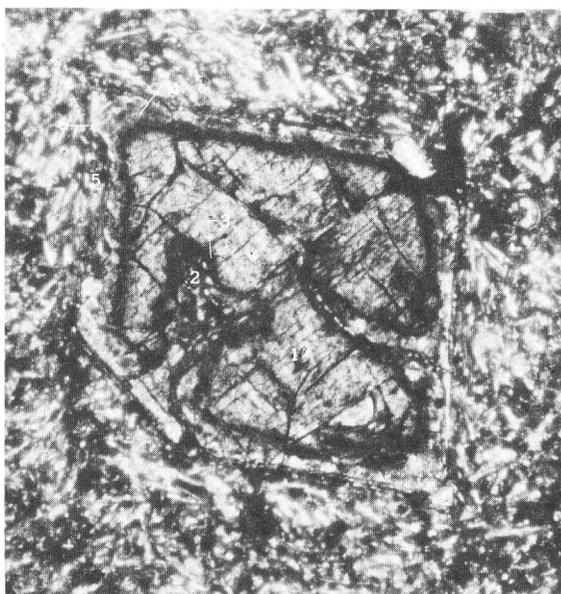


FIGURE 7.—Photomicrograph of an olivine phenocryst from Kalaupapa section showing (1) growth, (2) resorption, (3) alteration (hematitic), (4) regrowth, (5) resorption, and (6) further alteration (hematitic). Olivine phenocryst is 1.8 mm (0.07 in.) long. Crossed nicols.

are present in some of the rocks from the Kalaupapa section.

Small chromite grains occur as inclusions in olivine phenocrysts and as separate microphenocrysts in the groundmass. These inclusions and the chemical trends in the subsections, outlined later, argue for coprecipitation of olivine and chromite from the basaltic magmas.

A few black augite phenocrysts as large as 1 cm (0.4 in) long are present, but most are less than 0.5 cm (0.2 in). Most augite phenocrysts are euhedral, but some grains have been slightly resorbed, and some overgrowths may be present. Most augites have a thin purplish-brown rim that is richer in 'FeO' and TiO_2 than the core. This rim also may include tiny groundmass minerals. The composition of the titaniferous rim is similar to that of the groundmass augite. Two small augite phenocrysts from different flows showed reversals of this general zoning trend, but because both of them show patchy, or hourglass zoning (Strong, 1969), the reversals may only be apparent, having resulted from an accident of crystal growth, and therefore have no bearing on compositional trends in the rest magma.

Opaque inclusions, probably chromite, and inclusions of fresh to partially altered olivine are found in many augite phenocrysts.

Most plagioclase phenocrysts are less than 0.5 cm (0.2 in) long, but a few are longer than 1 cm (0.4 in). Most plagioclase phenocrysts have had as complex a history as olivine. In addition to normal and oscillatory zoning,

they show healed fractures and patchy-appearing areas (figs. 8A, 8B) possibly due to remelting. Some grains show zoning that somewhat resembles the hourglass zoning of augite.

Opaque inclusions, probably magnetite, are rather abundant in the plagioclase phenocrysts. They are faintly green only on the thinnest edges and appear as tabular bodies along planes parallel to (010) twin planes. In reflected light under high magnification, they seem to be concentrations of many tiny grains. High-temperature disordered plagioclase can accommodate more iron, probably as Fe_2O_3 , in its lattice that may exsolve at lower temperatures. Brown (1967) suggested that the exsolution may accompany inversion of plagioclase from one structural state to another. Poldervaart and Gilkey (1954) proposed that extraneous material may be introduced along minute surfaces of discontinuity, such as stacking faults, that are likely to

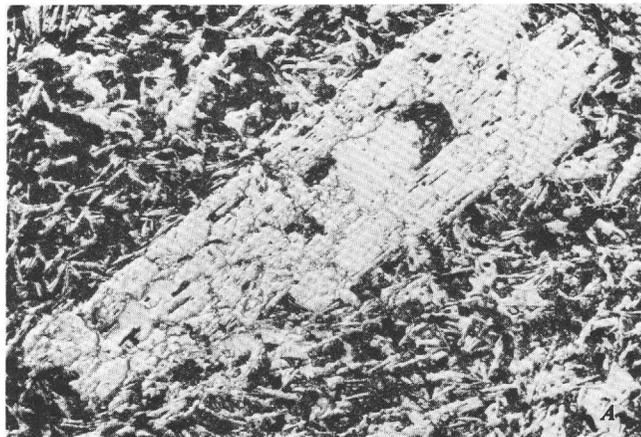


FIGURE 8.—Photomicrographs of a plagioclase phenocryst from Kalaupapa section showing tabular opaque (magnetite) inclusions oriented parallel to (010) twin planes. Plagioclase phenocryst is 4 mm (0.16 in.) long. A. Plane light. B. Crossed nicols. Note patchy zoning and healed fractures near lower left end of phenocryst.

occur in intermediate plagioclase. Because of its complex zoning, the average composition determined for plagioclase can be only approximate, in spite of the attempt to minimize the effects of zoning by scanning the beam during microprobe analysis.

Benson and Turner (1940), quoted in Muir and Tilley (1961, p. 198), reported that the mugearites from Dune-din, New Zealand, contain 2 percent K_2O but that no potassium feldspar is found in the groundmass and concluded that all the K_2O may be in the plagioclase. Sample Z, also a mugearite, contains 2.05 percent K_2O and is 75 percent normative feldspar. The plagioclase in this sample contains 2.36 percent K_2O , and thus plagioclase accounts for about 85 percent of the K_2O in the rock. There may be about 3 percent potassium feldspar in the groundmass, or more likely, the interstitial plagioclase, which was not analyzed, is more potassic than the distinct laths of plagioclase in the groundmass, which were analyzed.

Plagioclase phenocrysts include olivine, some fresh and some partially altered, and augite. No plagioclase has been observed as distinct inclusions in olivine, though it may be partly intergrown with olivine. Few plagioclase inclusions have been found in augite. Augite and olivine apparently crystallized simultaneously, as each has been found as inclusions in the other. The general sequence of crystallization of phenocrysts seems to have been olivine, augite, plagioclase, with a period of augite growth overlapping that of olivine at an earlier stage of crystallization and that of plagioclase at a later stage.

All the phenocryst minerals also occur in clusters, but their grain size is commonly, though not invariably, smaller than that of the discrete phenocrysts. Some olivine grains in the clusters are altered on all sides, even though they are partly enclosed by plagioclase or augite. By contrast, others are altered only on the side exposed to the magma. Fresh overgrowths, if present, occur only on the side of the olivine grain exposed to the magma. No fresh overgrowths have been observed on olivine grains that are included in augite or plagioclase. The aggregation of the minerals into clusters apparently took place both before and after intratelluric alteration of the olivine, but not after the fresh overgrowth was added.

Opaque minerals also occur as microphenocrysts in these lavas. For the most part they are chromite similar in composition to the chromite included in olivine (see the section "Compositional Variation of Opaque Minerals), but some of them are zoned continuously from chromite cores to ulvöspinel rims. A discussion of these zoned oxides is beyond the scope of this paper. Anderson and Wright (1972) observed reversed zoning of oxides in some Hawaiian tholeiites (MgO and Cr_2O_3 increasing

toward margins). They considered this as supporting evidence for mixing of magmas, one of which was more fractionated than the other. No such reversed zoning of chromite was observed in the Kalaupapa section.

Cr_2O_3 shows a marked decrease upward in the subsections. Chromite contains the bulk of the Cr_2O_3 in the rock, and only 0.5 percent chromite could account for the maximum Cr_2O_3 content observed; therefore, no determination of the modal amount of chromite in the lavas was made, nor is Cr_2O_3 considered in the magnesium variation diagrams for phenocryst-free compositions.

The groundmass of most samples of the lower member of the East Molokai Volcanic Series is holocrystalline and has an intergranular texture. Hypocrystalline patches occur near vesicles in some of these otherwise holocrystalline samples. The few samples that are hypocrystalline have intersertal textures. The major constituents of the groundmass are feldspar, clinopyroxene, and olivine. Stearns and Macdonald (1947) reported the clinopyroxene in most samples to be pigeonite, but microprobe analysis shows them to range from subcalcic to calcic augite. Opaque minerals occur as well-defined equant to elongate grains of about 0.05 mm (0.002 in.). Microprobe analysis shows that both titaniferous magnetite and ilmenite are commonly present in the groundmass. Acicular apatite crystals, present in most of the samples, are especially abundant in flows in the uppermost parts of the subsections.

The groundmass of most samples of the upper member of the East Molokai Volcanic Series has pilotaxitic to trachytic texture and an average grain size of about 0.04–0.1 mm (0.0016–0.004 in.). However, the lowermost sample from the upper member, sample X, has a subophitic texture and average grain size of about 0.15 mm (0.006 in.). Major constituents of the lavas of the upper member are plagioclase (potassic andesine), olivine, and colorless to pale-purplish-brown augite. In some samples olivine is more abundant in the groundmass than is augite. Accessory minerals are acicular apatite, magnetite, and ilmenite. Tiny biotite grains were identified in one sample.

WHOLE-ROCK COMPOSITIONS

The whole-rock composition for each sample is given in table 1. Dry-reduced compositions were determined by recalculating total iron as 'FeO,' subtracting H_2O and CO_2 , and then normalizing to 100 percent. The dry-reduced compositions are used in all diagrams to facilitate comparison with the microprobe analyses of minerals from which Fe^{+2} and Fe^{+3} cannot be evaluated.

All the lavas from the Kalaupapa section are hypersthene normative, and nine are quartz normative (table 1), possibly owing partly to oxidation during

weathering. However, no modal hypersthene (or pigeonite) was observed. None of the lavas from the Kalaupapa section are nepheline normative.

A plot of the dry-reduced whole-rock compositions on a total alkali-silica diagram (fig. 9), the diagram that Macdonald (1968) considered to be the best criterion to separate rocks of the alkalic suite from those of the tholeiitic suite, shows that most of the samples plot in the alkalic field. Eight samples plot in the tholeiitic field, but petrographic criteria suggest that they are alkalic. Because of this discordance between the petrologic classification and the chemical classification based on the total alkali-silica diagram, the whole-rock compositions were also plotted on an olivine, nepheline, silica ternary diagram (Poldervaart, 1964). On this diagram only three of the analyses plot in the tholeiitic field (fig. 10). Irvine and Baragar (1971) proposed new tholeiitic-alkalic boundary lines for both the total alkali-silica and olivine, nepheline, silica diagrams. By using their boundary lines, 16 lavas plot in the tholeiitic field in the total alkali-silica diagram (fig. 9), and of these, 14 plot in the tholeiitic field in the olivine, nepheline, silica diagram (fig. 10).

When the boundary lines proposed by Irvine and Baragar (1971) are used, the division of the rocks of the Kalaupapa section into tholeiitic and alkalic suites on the total alkali-silica and olivine, nepheline, silica diagrams is in good agreement. However, the Irvine and Baragar boundary lines increase the discordance be-

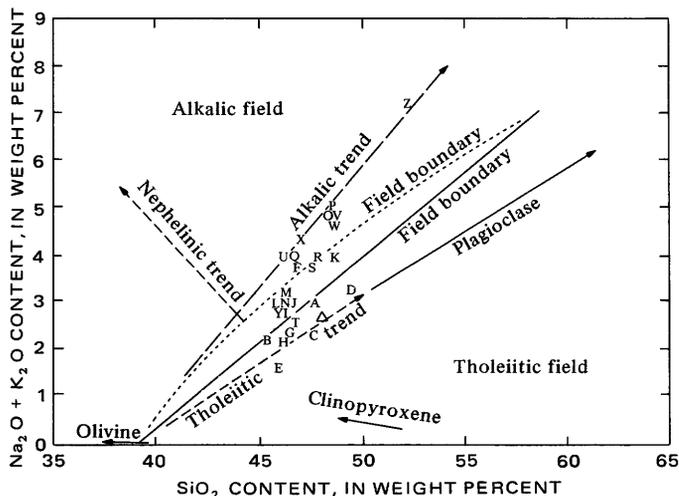


FIGURE 9.—Total alkali-silica diagram of dry-reduced whole-rock compositions from Kalaupapa section. A–Z, samples from base of section upward. Solid arrows, trends of clinopyroxene (augite), olivine, and plagioclase compositions from base of section upward. Open triangle, clinopyroxene in a garnet clinopyroxenite xenolith (68SAL-11) from Salt Lake Crater reported by Beeson and Jackson (1970). Dashed arrows, nephelinitic, alkalic, and tholeiitic trends and field boundary (solid line) from Macdonald (1968). Field boundary (dotted line) proposed by Irvine and Baragar (1971).

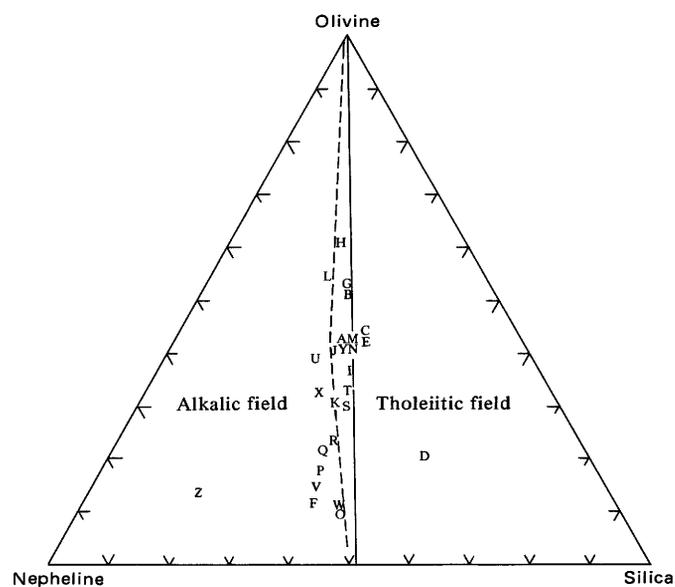


FIGURE 10.—Olivine, nepheline, silica diagram of dry-reduced whole-rock compositions from Kalaupapa section. Solid line, field boundary proposed by Poldervaart (1964); dashed line, field boundary proposed by Irvine and Baragar (1971). A–Z, samples from base of section upward.

tween the petrologic and chemical classification of Hawaiian basalts, and especially of basalts of the Kalaupapa section. The boundary lines proposed by Macdonald (1968) and Poldervaart (1964) are therefore preferred for Hawaiian basalts. A similar discordance between chemical and mineralogic classifications based on feldspar compositions was noted by Keil, Fodor, and Bunch (1972) in lavas from Maui, which they considered to be transitional between tholeiitic and alkalic suites. In general the basalts in the lower part of the Kalaupapa section defy a common chemical and petrologic classification and are better considered as transitional between tholeiitic and alkalic.

The trend that the lavas from the Kalaupapa section define (fig. 9) is at a steeper angle to the alkalic-tholeiitic field boundary of Macdonald (1968) than is the general trend of Hawaiian alkalic lavas that he presented. Conservatively, the trend of the Kalaupapa lavas is about 30° to Macdonald's alkalic trend. It appears that there is less olivine control³ for the lavas of the Kalaupapa section than for the Hawaiian alkalic lavas in general and that the trend of the lavas is rotated toward Macdonald's nephelinitic trend. Macdonald

³Powers (1955) drew lines that he called "olivine control" lines, in an oxide-oxide diagram from plots of olivine phenocrysts into the field of basalts. These olivine control lines indicate the straight-line variation that would result from changing the amount of olivine in any plotted rock composition through which the lines are drawn. Comparable control lines can be drawn for other minerals. Wright (1971) noted that if more than one mineral controls the chemical variation, unique control lines cannot generally be defined. However, the sense in which deviations occur from lines that define dominantly a single-mineral control may indicate which additional mineral species is causing the chemical variation.

(1968) compared trends of alkalic and nephelinitic lavas from Hawaii with experimental ones determined by Green and Ringwood (1967), pointing out that progressing from high to low pressures, the fractionation trend shifts from nephelinitic through alkalic to tholeiitic trends of the Hawaiian suites. In terms of mineralogy and considering only $\text{Na}_2\text{O} + \text{K}_2\text{O}$ and SiO_2 , the control shifts from clinopyroxene through orthopyroxene to olivine + plagioclase.

Figure 11 shows the Kalaupapa lavas on an AFM (alkali, iron, magnesium) diagram on which the general field of Hawaiian lavas has been outlined (Macdonald, 1968). The Kalaupapa lavas fall to the iron-rich side of the field but totally within it. The compositional range of olivine and augite phenocrysts from these lavas, indicated by arrows, shows that in an AFM diagram olivine control cannot be separated from augite control. It was shown earlier that the amount of augite phenocrysts varies directly with that of olivine, and this type of plot emphasizes the trend.

It is apparent (fig. 11) that the fractionation trend does not progress continuously from "primitive" lavas with a high MgO/FeO ratio to a "fractionated" lava with a low MgO/FeO ratio going from flows A to Z, but rather several successive flows plot along a trend only to be interrupted by a discontinuity marking an abrupt increase in the MgO/FeO ratio to start anew the fractionation trend. Also the talus-covered gaps discussed earlier must be considered when the fractionation pattern is being examined.

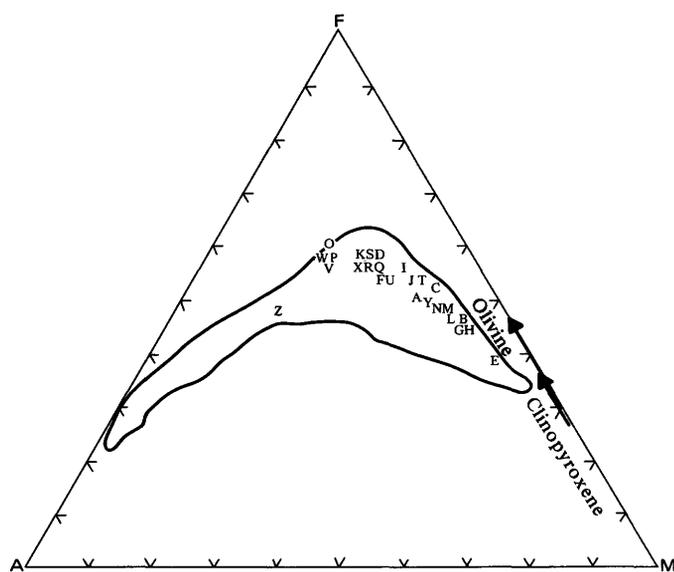


FIGURE 11.—AFM diagram of dry-reduced whole-rock compositions from Kalaupapa section. Outlined area, field of Hawaiian basalts (Macdonald, 1968). A–Z, samples from base of section upward. Arrows, compositional range of olivine and clinopyroxene (augite) phenocrysts from base of section upward.

The section has been divided into several subsections on the basis of where abrupt increases in the MgO/FeO ratio occur. The subsections that have been delimited are A, BCD, EF, GHIJK, LMNOP (L and M, and O and P are samples from different levels of two flows), QRS, TUVW, and XYZ. The gap between A and B is considerable, and so A must stand alone as a subsection. A small gap between E and F leaves only two samples in this subsection. The samples in subsection QRS show very little variation and conceivably represent surges of the same flow. Subsection XYZ has a discordance at Y marking a regression from hawaiite back to alkalic basalt and probably represents segments of two subsections. This regression is significant because it shows that regression to more "primitive" lavas can occur in all stages of fractionation and not only within the fields of transitional and alkalic basalts.

In an approximate way, the lowermost flows of the progressively higher subsections are more fractionated than those of the lower subsections; also the uppermost flows of the progressively higher subsections are more fractionated than those of the lower subsections. The fractionation pattern is thus one of several steps forward and a jump back, starting at rocks transitional from tholeiite to alkali olivine basalt and culminating in mugearite.

Magnesia variation diagrams of dry-reduced whole-rock compositions (fig. 12) give some idea as to what minerals control the fractionation. The minerals that occur as phenocrysts (olivine, augite, and plagioclase) control the major elements, especially in the lower part of the section. The abrupt drop of FeO and TiO_2 in sample Z indicates control by ilmenite or ulvöspinel late in the section. Chromite, which occurs as inclusions in olivine and as microphenocrysts in the groundmass, controls the Cr_2O_3 content almost entirely. The subsections that were delimited from the AFM diagram correspond precisely to those delimited from magnesia variation diagrams on the basis of the elements that typically are used as fractionation indicators, that is, Na_2O , K_2O , and TiO_2 as well as Cr_2O_3 and NiO .

Variation diagrams have been criticized as indicators of fractionation in recent years, especially by Chayes (1971). Each oxide in the analyses was therefore plotted against relative stratigraphic position (fig. 13) to bypass the "closure restraint" discussed by Chayes. In the subsections, SiO_2 , Al_2O_3 , Na_2O , K_2O , TiO_2 , and P_2O_5 increase rather consistently and sometimes dramatically. If an envelope were drawn to include all the analyses, it would show that there is a general increase of these oxides up the entire section, substantiating the conclusion, indicated by the AFM diagram (fig. 11) that the subsections become progressively more fractionated up section.

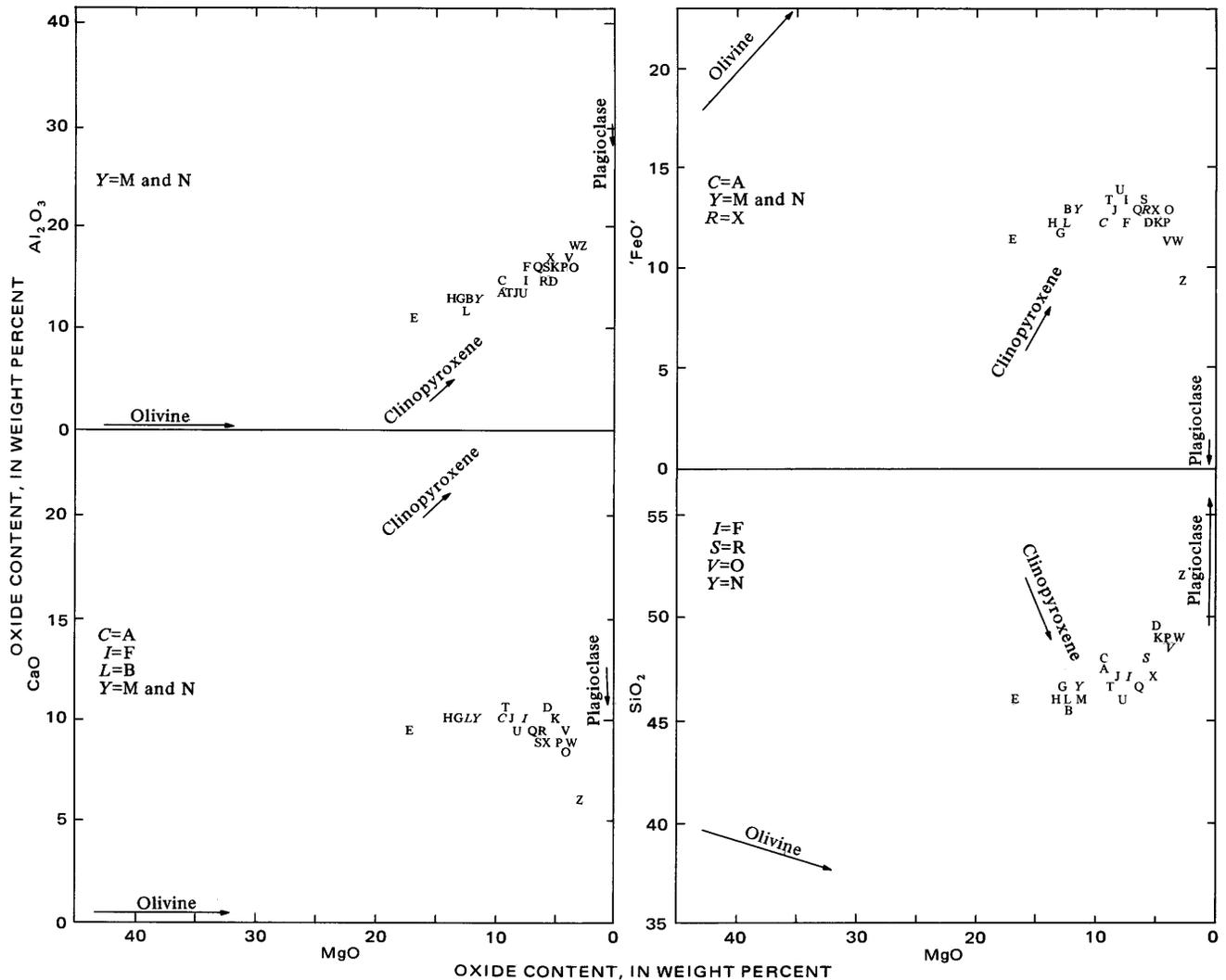


FIGURE 12.—Magnesia variation diagram of dry-reduced whole-rock compositions from Kalaupapa section. A–Z, samples from base of section upward. Italicized symbols indicate coincidence of two or more points. Coincident points shown in left part of each diagram. Arrows, ranges in olivine, plagioclase, and clinopyroxene (augite) compositions from base of section upward and are not to be confused with “control lines.”

In a similar manner, three oxides (MgO, NiO, and Cr_2O_3) decrease upward in both the subsections and the whole section. NiO and Cr_2O_3 may show as much as a 75 percent decrease from the lower to upper flows in a subsection. NiO and Cr_2O_3 in these lavas are very sensitive indicators of fractionation involving olivine, in which most of the NiO resides, and chromite, in which most of the Cr_2O_3 resides. The close parallelism in variation of these two oxides indicates coprecipitation of chromite and olivine in early stages of fractionation.

Because of the close relation between the variation of the phenocryst content and the compositional variation of the lavas, it is important to examine the compositional variations of the lavas with the contribution made by phenocryst content removed (phenocryst-free

compositions) to see if any significant compositional variations in the lavas are masked by phenocryst concentrations.

PHENOCRYST-FREE COMPOSITIONS

The phenocryst compositions can be effectively subtracted from the whole-rock compositions with magnesia variation diagrams (Powers, 1955) if the only phenocryst mineral in the lava is olivine. The lavas from the Kalaupapa section, however, contain as many as three kinds of phenocrysts, and they cannot be so conveniently removed diagrammatically. The phenocrysts therefore were subtracted from the dry-reduced whole-rock composition on the basis of their modes and compositions.

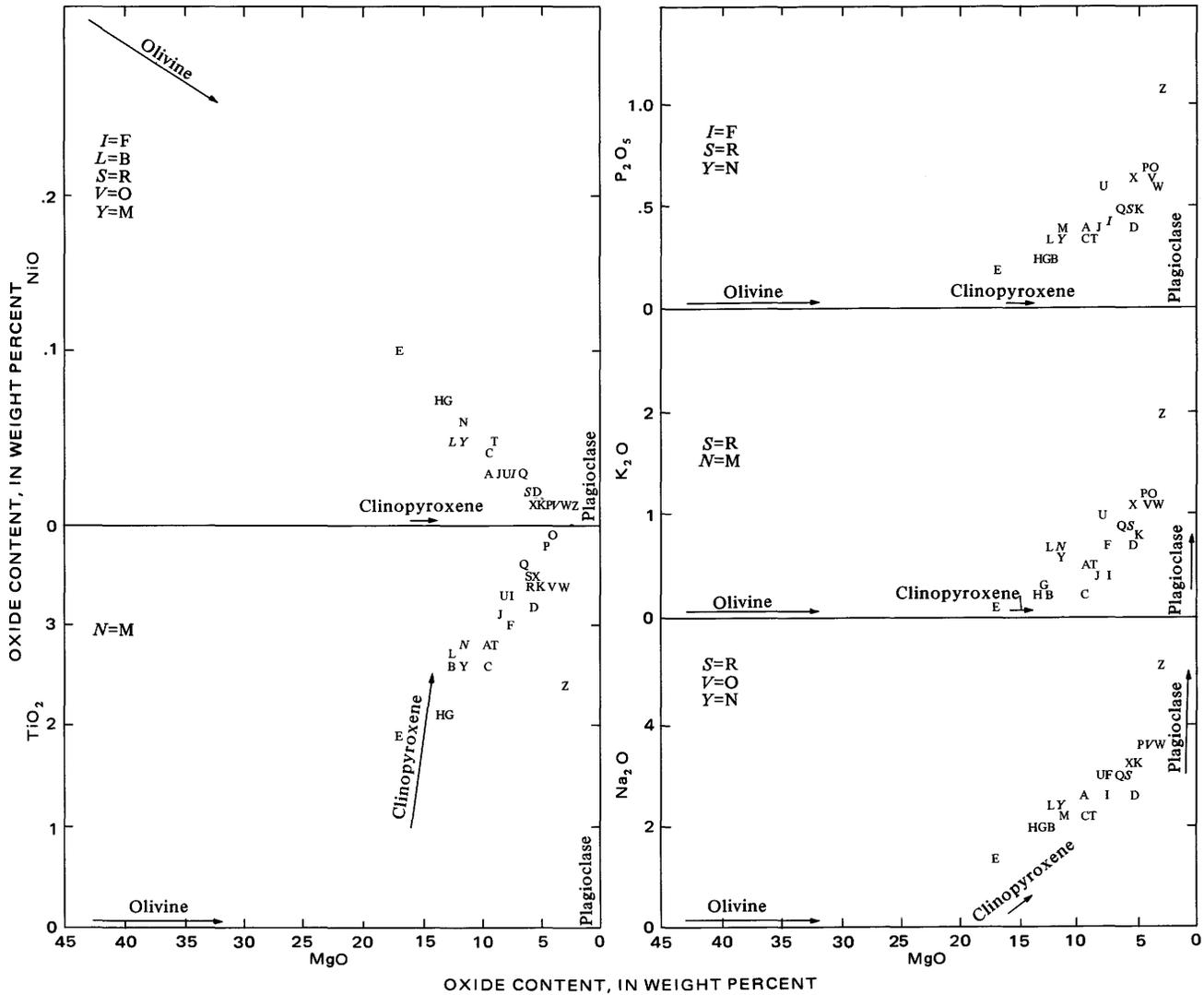


FIGURE 12.—Continued.

Compositions and normative minerals of these phenocryst-free lavas are given in table 2. The total alkali-silica diagram for phenocryst-free compositions (fig. 14) shows that six of the samples plot in the tholeiitic field as compared to eight in the corresponding whole-rock diagram (fig. 9), and most of these six samples have shifted toward the field boundary line of Macdonald (1968). It is significant that the data show less scatter than in the whole-rock diagram and the trend is at a steeper angle to the alkali trend (rotated more toward the nephelinitic trend) of Macdonald than the trend of the whole-rock compositions. The trend of the phenocryst-free compositions can be attributed almost entirely to variation in the amount of clinopyroxene in the lavas and shows little or no olivine or plagioclase control. The AFM diagram (fig. 15) shows that the phenocryst-free compositions, like the dry-reduced

whole-rock compositions, plot toward the iron-rich side of the field of Hawaiian rocks as given by Macdonald (1968), with only two falling just outside of this field. Removal of the phenocrysts has not produced any rock compositions for which there are no natural counterparts in Hawaiian lavas. The main effect of phenocryst removal has been to shorten the range of MgO/FeO' ratios from the high side (compare fig. 11 with fig. 15). This is expected because the part of the trend in the AFM diagram (represented by these compositions) results mainly from augite plus olivine control, and phenocrysts of these two minerals have been removed.

The magnesia variation diagrams for phenocryst-free compositions (fig. 16) provide a more complete picture of how removal of phenocrysts has affected the lavas (compare the dry-reduced whole-rock magnesia variation diagrams (figs. 12, 16)). Both SiO₂ and Al₂O₃ exhibited

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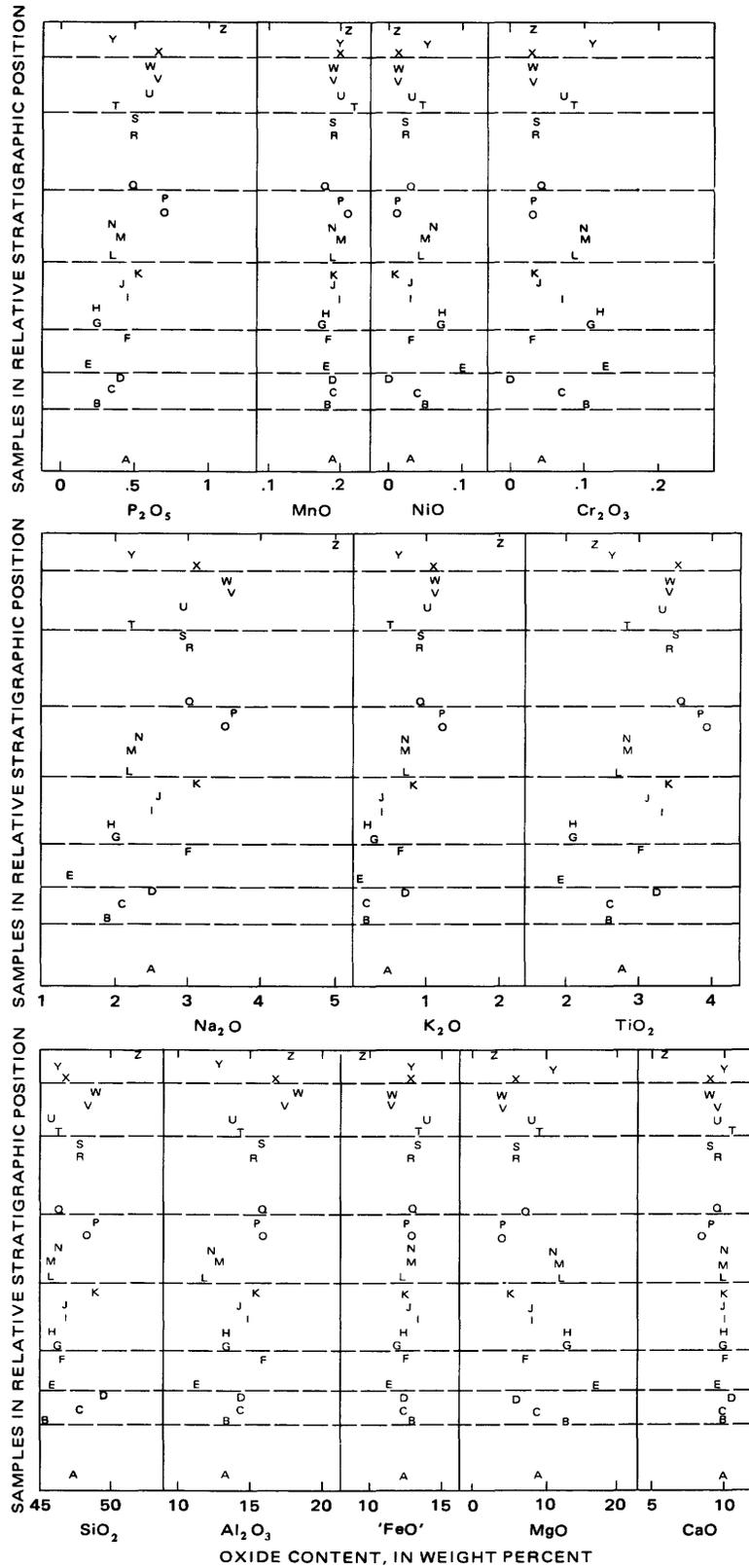


FIGURE 13.—Weight percent of oxides in dry-reduced whole-rock compositions from Kalaupapa section plotted against relative stratigraphic position. A-Z, samples from base of section upward. Dashed horizontal lines, subsections delimited on basis of abrupt increase in ratio of MgO/'FeO' and phenocryst content (fig. 5).

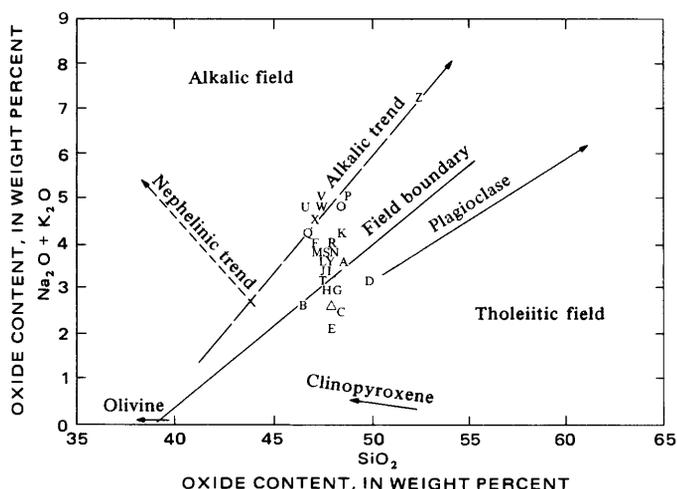


FIGURE 14.—Total alkali-silica diagram of phenocryst-free compositions from Kalaupapa section. A-Z, samples from base of section upward. Solid arrows, trends of olivine, clinopyroxene (augite), and plagioclase from base of section upward. Open triangle, clinopyroxene in a garnet clinopyroxene xenolith from Salt Lake Crater reported by Beeson and Jackson (1970). Field boundary from Macdonald (1968).

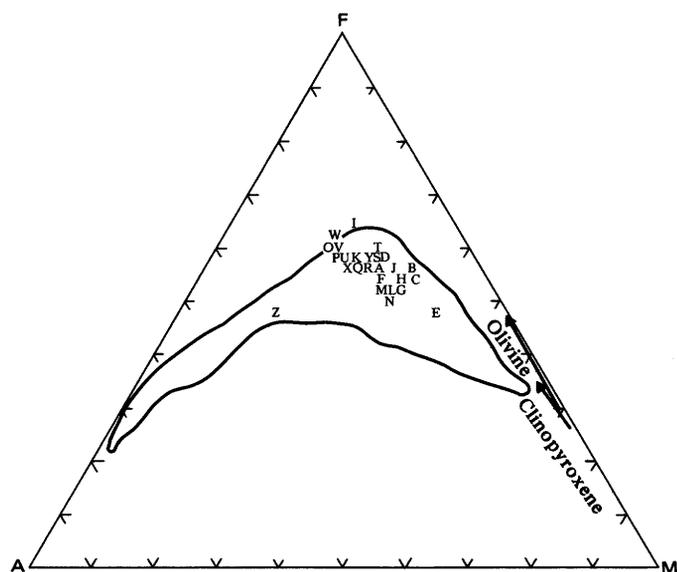


FIGURE 15.—AFM diagram of phenocryst-free compositions from Kalaupapa section. A-Z, samples from base of section upward. Outlined area, field of Hawaiian basalts from Macdonald (1968). Arrows, compositional range of olivine and clinopyroxene (augite) from base of section upward.

marked olivine control in the whole-rock lavas, but removal of the phenocrysts has telescoped the trend to such an extent that it ceases to exist, leaving a trendless cluster of points. Thus any systematic variation in SiO_2 and Al_2O_3 in the whole-rock chemistry is primarily the result of the relative amounts of phenocrysts, especially olivine, in the lavas.

The contents of 'FeO', CaO, Na_2O , K_2O , P_2O_5 , and TiO_2

in the whole-rock magnesia variation diagram (fig. 12) all form trends indicating control by one or more of the phenocryst minerals, olivine, clinopyroxene, or plagioclase, with olivine generally dominating. The abrupt decrease in 'FeO' and TiO_2 in the uppermost flows indicates late-stage fraction of ilmenite, ulvöspinel, or other Fe-Ti oxides. The trends of the phenocryst-free compositions for 'FeO', CaO, Na_2O , K_2O , P_2O_5 , and TiO_2 (fig. 16) leave little doubt that clinopyroxene is the dominant controlling mineral, except the late decreases in 'FeO' and TiO_2 . It is significant that the trends for 'FeO', CaO, K_2O , and P_2O_5 in particular are at high angles to what they would be if olivine were the controlling mineral. The narrowness of the trend defined by these elements indicates that there is very little residual olivine control in spite of the possible additive errors in the modes and microprobe analyses.

Variation in NiO and Cr_2O_3 content are completely controlled by olivine and chromite, respectively, and therefore need not be considered in the phenocryst-free compositions.

Stearns and Macdonald (1942) envisioned a magma body beneath Hawaiian volcanoes that is zoned from hawaiite at the top to picrite at the bottom. Differentiation in the magma body was considered by them to be primarily the result of settling of olivine, clinopyroxene, and plagioclase, aided by volatile transfer of certain substances (particularly the alkalis) to the upper part of the magma body. Tapping of the magma body at different levels would yield magmas of different compositions and phenocryst contents. Murata and Richter (1966a, b) showed for the 1959-60 Kilauea Iki eruption that the olivine phenocryst content of the erupting lavas was directly related to the rate of discharge. They suggested that strong currents of magma erode beds of previously sedimented olivine crystals lying on the bottom of the magma chamber. In both the Stearns and Macdonald (1942) and the Murata and Richter (1966a, b) models, fractionation occurs in a shallow magma chamber. The phenocryst content of the lavas depends on the level at which the magma chamber is tapped or on the rate at which it is discharged. In either case, mechanical processes can introduce chemical variation in the lavas that masks more subtle, but possibly more significant, chemical variation. Subtraction of the phenocrysts from the lavas in the Kalaupapa section has, to a first approximation, removed compositional variation resulting from shallow fractional crystallization, the rate of discharge, and postextrusion settling of phenocrysts. The compositional variation of the phenocryst-free lavas allows us to discern an earlier fractionation event, one that occurred before fractional crystallization in the shallow magma chamber. At present there is no evidence to suggest whether the earlier

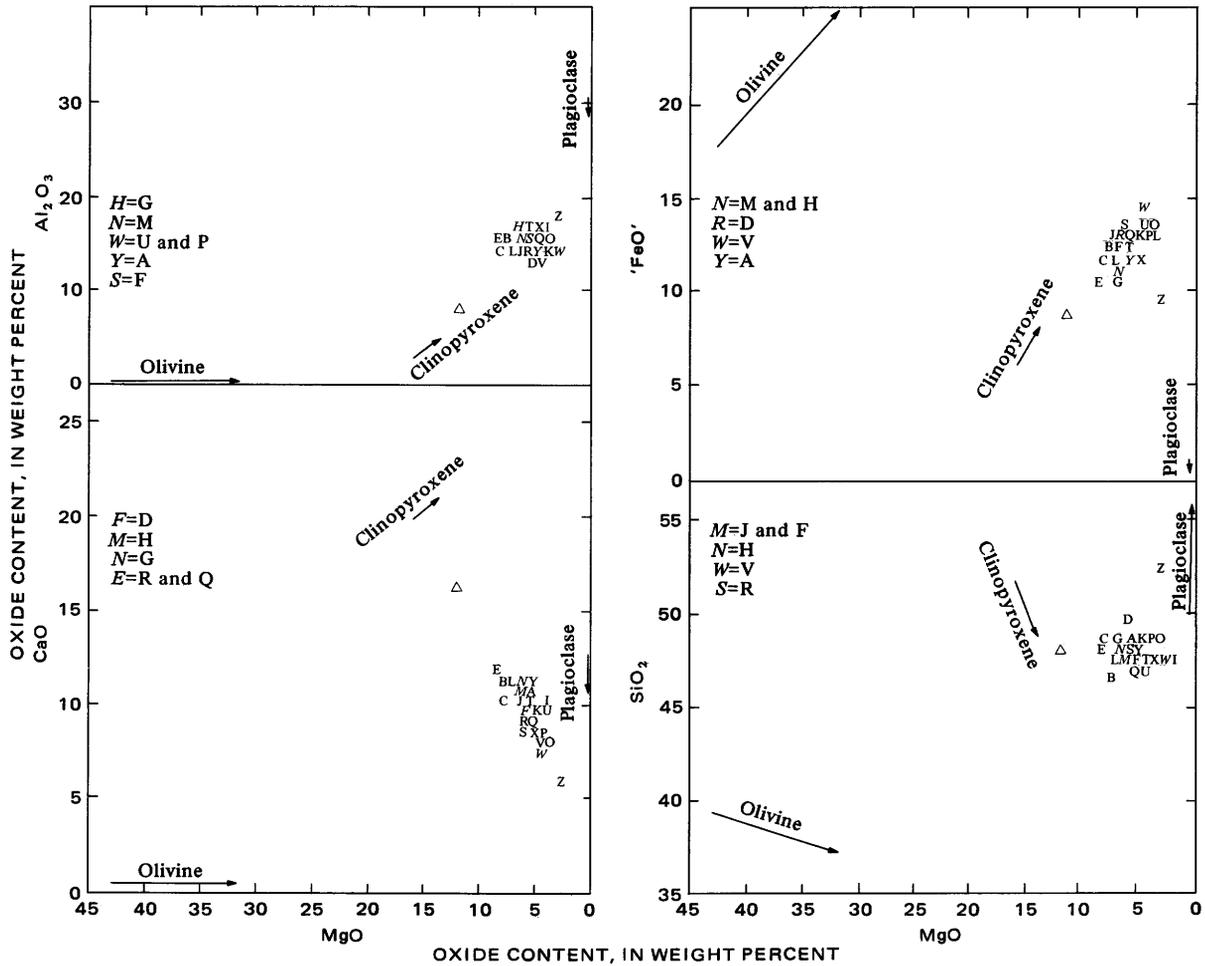


FIGURE 16.—Magnesia variation diagram of phenocryst-free compositions of Kalaupapa section. A–Z, samples from base of section upward. Italicized letters indicate coincidence of two or more points. Coincident points are shown in left part of each diagram. Arrows, ranges of olivine, clinopyroxene (augite), and plagioclase from base of section upward and are not to be confused with “control lines.” Open triangle, clinopyroxene in a garnet clinopyroxenite xenolith from Salt Lake Crater (Beeson and Jackson, 1970).

fractionation event involved fractional fusion or fractional crystallization. However, it is evident from the variation shown in the phenocryst-free compositions that the mineral controlling the earlier fractionation was aluminous clinopyroxene.

It should not be inferred that the phenocryst-free compositions represent primary lavas. The primary lavas are almost certainly richer in magnesia than these (Wright, 1971). It is clear, however, that most of the compositional variation imposed on the lavas by olivine fractionation was removed in the calculation of phenocryst-free compositions.

Beeson and Jackson (1970) showed that the nephelinitic suite on Oahu, the Honolulu Volcanic Series, could have been derived by partial fusion of a garnet pyroxenite at a depth of about 100 km and that clinopyroxene would be the last mineral to melt. The lavas in

the Kalaupapa section may also be the product of fractional fusion of a garnet pyroxenite. If all minerals in the garnet pyroxenite except clinopyroxene were entirely melted, then the trends in the phenocryst-free lavas could be produced by the varying amounts of the clinopyroxene that is melted. Clinopyroxene from a garnet pyroxenite parent would be considerably more aluminous than the phenocrysts; in fact the lack of a trend of Al_2O_3 and SiO_2 (fig. 16) demands that the Al_2O_3 and SiO_2 content of the controlling clinopyroxene approach that of the lavas. The composition of clinopyroxene from a garnet pyroxenite xenolith from Salt Lake Crater, Hawaii (Beeson and Jackson, 1970), is plotted in figure 16. Except for Na_2O , it falls between the composition of the clinopyroxene phenocrysts and that of the phenocryst-free lavas. Clinopyroxenes, such as the ones analyzed from Hawaiian garnet pyroxene-

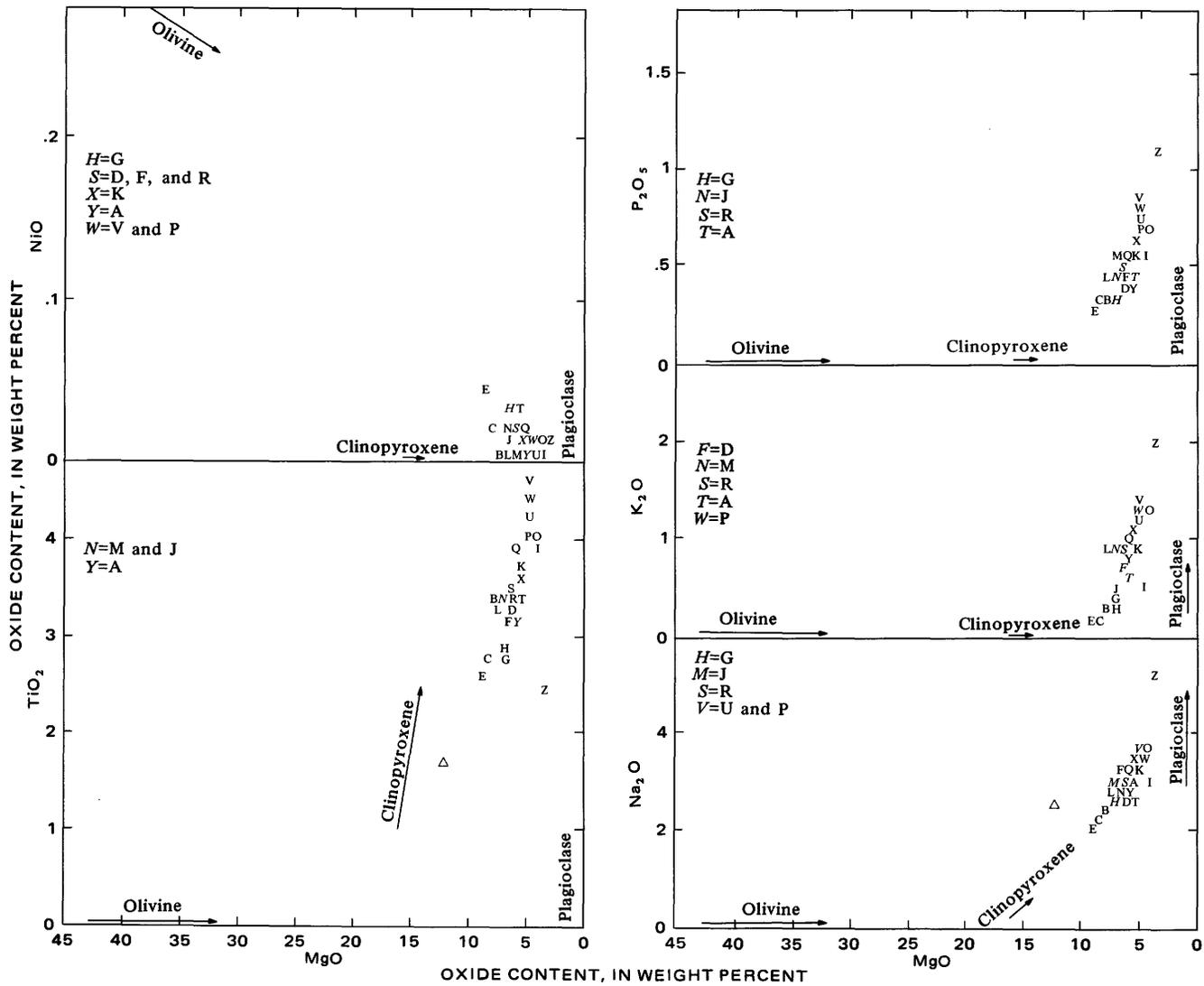


FIGURE 16.—Continued.

nites, may be responsible for the variations seen in the phenocryst-free lavas.

Green (1971) devised a petrogenetic grid from which pressures of origin and degrees of partial melting of mantle-derived basalts can be determined from magma compositions. This grid shows that alkali olivine basalt, such as that in the Kalaupapa section, could originate from 10 to 20 percent partial melting of this pyrolite mantle at depths of 45–60 km (23–37 mi) and that clinopyroxene would be a residual phase (along with olivine) remaining after extraction of the magma.

As an alternative to the fractional fusion hypothesis, the compositional variation could result from the fractional crystallization in a deep (45–75 km, 28–46.5 mi) magma chamber in which clinopyroxene could be a liquidus mineral (Green and Ringwood, 1967). The composition of the liquidus clinopyroxene would proba-

bly be similar to that from the garnet pyroxenite described above. My evidence does not discriminate between fractional fusion or fractional crystallization.

A necessary product of fractional crystallization of the lava at pressures of 15–25 kilobars would be clinopyroxene cumulates on the floor of the magma chamber, and later eruptions probably would incorporate fragments of the clinopyroxene cumulate and transport them to the surface where they would be found as xenoliths. The work of Jackson (1968), however, shows a decided lack of clinopyroxene cumulate xenoliths from the alkalic lavas of Hualalai and Mauna Kea. Many of the wehrlite xenoliths from these lavas, however, contain abundant veins of clinopyroxene, and some of the wehrlites appear to have been soaked in clinopyroxene. The possibility therefore exists that the clinopyroxene cumulates could have been destroyed by a metamorphic

event. On the other hand, Hualalai has not yet reached the stage of eruption that the Kalaupapa section represents, and clinopyroxene xenoliths therefore should not necessarily be expected. Neither East Molokai Volcano nor Kohala Volcano on the island of Hawaii, which are more like each other and less like some of the other Hawaiian volcanoes, contain many xenoliths. It might therefore be argued that they are unique and an absence of xenoliths is characteristic of them.

Many of the lavas in the southwestern United States (Wilshire and others, 1971), Australia (Binns, 1969; Binns and others, 1970), and Hawaii (observed by me) that contain ultramafic xenoliths also contain black, aluminous, iron-rich clinopyroxene megacrysts. There is no great difference between the composition of these megacrysts and the clinopyroxene from the garnet pyroxenite xenolith (68SAL-11) described by Beeson and Jackson (1970). Both are thus prospective products of deep fractional crystallization.

Murata (1960) indicated that fractional crystallization of clinopyroxene appears to be the principal mechanism by which tholeiitic magmas are converted to alkalic magmas. Yoder and Tilley (1962), though recognizing the importance of pyroxene fractionation, objected to Murata's scheme and example. Later Tilley and Yoder (1964) proposed a "pyroxenite stage" in basalt genesis, suggesting that at pressures corresponding to upper mantle conditions, extraction of orthopyroxene and clinopyroxene from an olivine-rich tholeiitic liquid leads to the generation of an undersaturated residual liquid of alkali olivine basalt.

The lavas in the Kalaupapa section range from basalts transitional between tholeiitic and alkalic to basalts that are unquestionably alkalic. Clinopyroxene clearly exhibits marked control in the fractionation of these lavas, but whether the transitional lavas were derived from a tholeiitic parent by clinopyroxene fractionation alone is an open question. Certainly desilication of a tholeiitic magma to produce the transitional basalts could not have been accomplished by fractionation of clinopyroxene, because the silica content of the controlling clinopyroxene is very near that of the transitional and alkalic lavas. If desilication is necessary to derive an alkalic magma from a tholeiitic one, then another mineral (possibly orthopyroxene) or a different mechanism must be sought to accomplish it.

Removal of the phenocrysts has allowed us to look back beyond the fractional crystallization in a shallow chamber to a fractionation event controlled by clinopyroxene. If we concede that an alkalic lava may be derived from a tholeiitic parent magma through a process involving desilication, then there must be a fractionation event farther removed from the ones we have been able to define. If, on the other hand, alkalic magmas

have been derived by fractional fusion of some primary mantle material, then we have identified clinopyroxene as the mineral controlling the compositional variation during partial fusion. If a magma produced by partial fusion of a garnet pyroxenite is fractionated at a depth at which clinopyroxene is the liquidus mineral, then little disturbance of the trend will occur because aluminous clinopyroxene would be the controlling mineral in both events.

Now that it has been established that the Kalaupapa section can be divided into subsections either chemically or petrographically on the basis of phenocryst content and that much of the chemical variation can be attributed to phenocryst content, the question arises as to how the subsections originated. Powers (1955) proposed a "batch" concept for explaining the difference between historic and prehistoric tholeiitic lavas of Kilauea and Mauna Loa. Wright and Fiske (1971) confirmed and further refined the batch concept for the tholeiitic lavas of Kilauea. They identified three groups of summit lavas from Kilauea (pre-1750, 1750-1895, and 1911-present day) that can be distinguished chemically with little overlap. They also show on a lesser scale that each Kilauean summit eruption in the 20th century as a chemistry that is distinctive with respect to the chemistry of every other summit eruption. Briefly the batch concept supposes that magma is generated in the mantle on an episodic rather than a continuous basis and that each batch has a characteristic composition. It is suggested here that the subsections delimited in the Kalaupapa section may represent batches of magma injected into the rift zone and subsequently fractionally crystallized and erupted and that the batch concept is applicable to alkalic as well as tholeiitic Hawaiian lavas.

Because much of the compositional variation in each subsection can be attributed to phenocryst content, it is necessary to evaluate how removal of the phenocrysts affects the interpretation that subsections are the expression of magmatic batches. This can best be seen in figure 17, in which the phenocryst-free compositions are plotted against relative stratigraphic position. Several oxides, SiO₂, Al₂O₃, and MgO, that show especially strong subsection variation in the whole-rock compositions (fig. 13) show little variation in the phenocryst-free compositions (fig. 17.) All these oxides are especially sensitive to olivine control, and Al₂O₃, to plagioclase control. In the whole-rock compositions (fig. 13), 'FeO' shows little subsection variation but in the phenocryst-free compositions (fig. 17) shows distinct subsection variation. Subsection variation of Na₂O, K₂O, and P₂O₅ in the phenocryst-free compositions (fig. 17) is nearly the same as it is in the whole-rock compositions. Two oxides, MnO and CaO, that show almost no

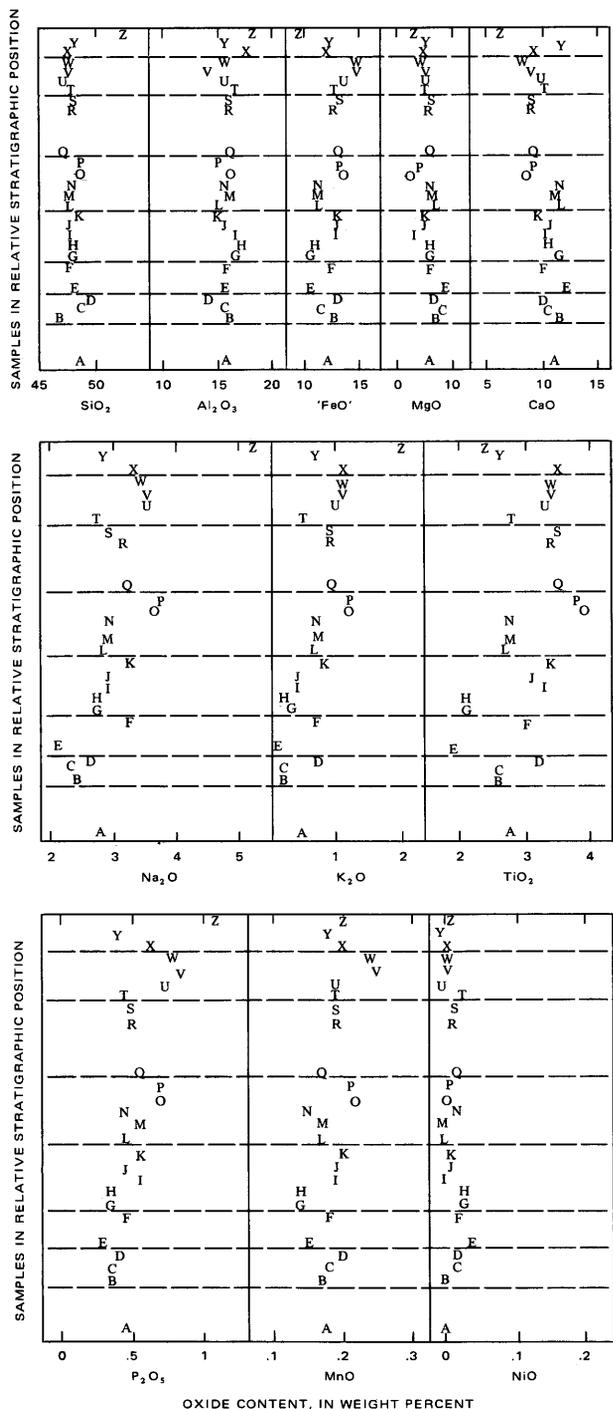


FIGURE 17.—Weight percent of oxides in phenocryst-free compositions from Kalaupapa section plotted against relative stratigraphic position. Dashed horizontal lines, subsections delimited on basis of abrupt increase in ratio of MgO/FeO' of whole-rock compositions (fig. 13) and phenocryst content (fig. 5). A-Z, samples from base of section upward.

variation in the whole-rock compositions (fig. 13) show marked subsection variation in the phenocryst-free compositions (fig. 17). CaO variation in the phenocryst-

free compositions is the result of its concentration in clinopyroxene, which controls compositional variation in the phenocryst-free lavas. It is not obvious why MnO shows so little variation in the whole-rock compositions but does show marked variation in the phenocryst-free compositions. MnO, unlike CaO, is not concentrated in clinopyroxene; instead, like NiO, it is concentrated in olivine. Nonetheless, discontinuities in the MnO variation delimit the same subsection as do variations in the whole-rock compositions and the phenocryst content. Likewise, the CaO variation in the phenocryst-free compositions defines the same subsections; each subsection starts at the higher CaO contents and decreases upward in the subsection, then abruptly increases at the base of the following subsection. The distinct subsections, and accordingly the batches, can be seen in the phenocryst-free compositions as well as in the whole-rock compositions.

No modes were made for the chromite microphenocrysts because, judging from Cr₂O₃ content of the lavas, less than 0.5 percent of chromite would be present. As a result, variation of Cr₂O₃ has not been considered in the phenocryst-free compositions.

MINERALOGY

COMPOSITIONAL VARIATION OF OLIVINE

Olivine occurs in the Kalaupapa lavas as phenocrysts, in clusters (usually of smaller grain size than the phenocrysts), in the groundmass, and as fresh overgrowths mantling altered olivine grains. The analyses of olivines are given in table 3, and the analyses for alteration rims of olivine are given in table 4. During the electron microprobe analysis of the phenocrysts and clusters, the electron beam was scanned rapidly over a 10×10μm area to help even out inhomogeneities and to obtain, as nearly as possible, an average composition. No special attempt was made to avoid tiny inclusions or microfractures that may have trapped polishing compound (alumina), and as a consequence the values for Al₂O₃ are on the order of .0X rather than nearly zero as Smith (1966) and Simkin and Smith (1970), among others, have shown for most olivines. The Al₂O₃ values for olivine in no way affect the conclusions reached in this paper.

The plots of CaO, MnO, NiO, and TiO₂ versus 'FeO' (fig. 18) and the plots of olivine composition versus relative stratigraphic position (fig. 19) show that composition does not differ consistently in the central part of the phenocrysts, the rims of the phenocrysts, or in the olivine of the clusters.⁴ The few grains identified opti-

⁴In the remainder of this report, the description of olivine phenocryst compositions also applies to the olivine of the clusters.

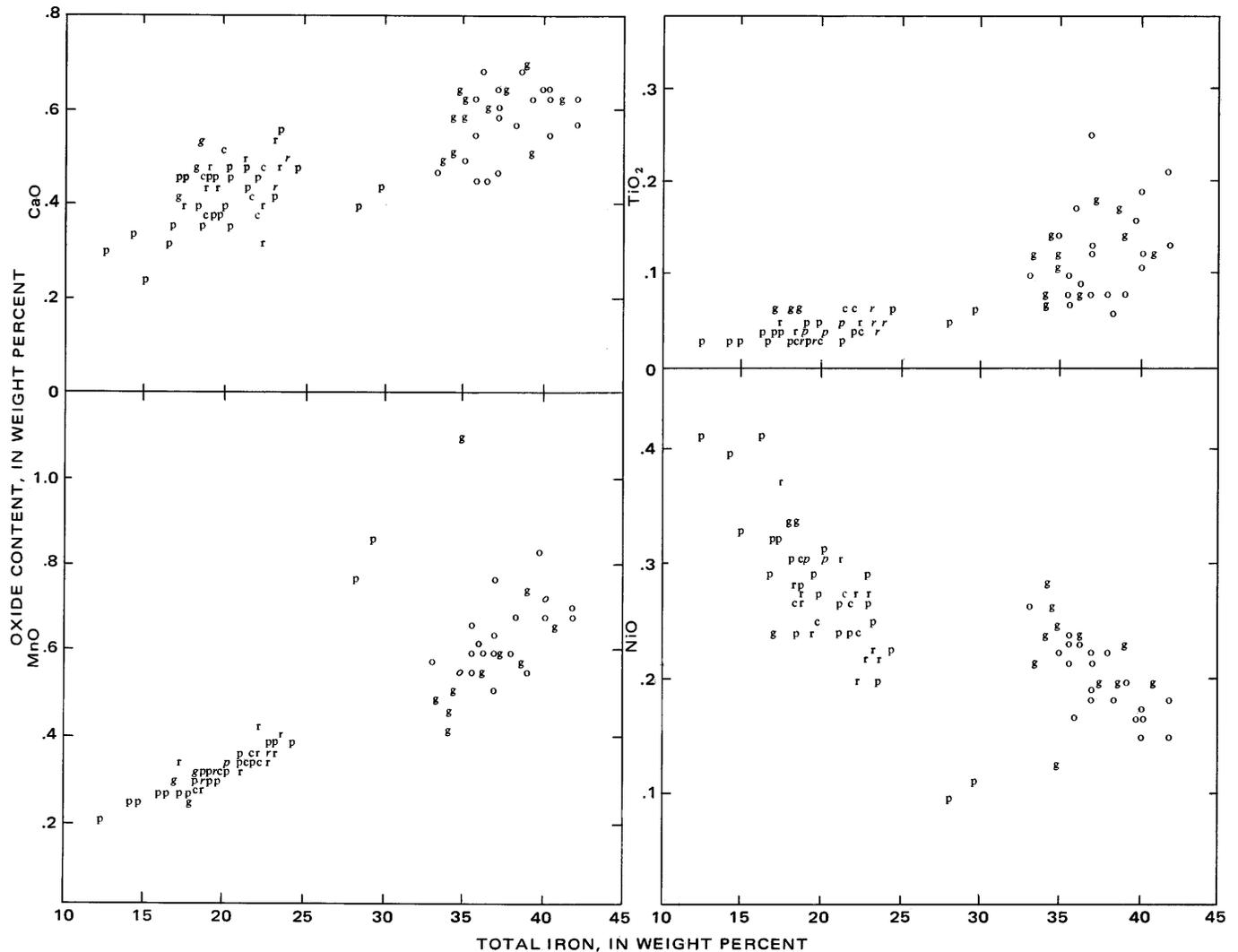


FIGURE 18.—Total iron-variation diagram of olivine from Kalaupapa section. c, central part of an olivine grain in a cluster; g, groundmass olivine; o, fresh overgrowth on olivine phenocryst, in cluster, or in altered groundmass grain; p, central part of phenocryst; and r, rim of phenocryst but inside of alteration rim, if present. Italicized symbols indicate coincidence of two or more points.

cally as groundmass olivine that plot in the field of phenocrysts in all probability are corners of olivine phenocrysts rather than groundmass olivine. For the purpose of subtracting phenocryst compositions from the whole-rock compositions, some olivine in clusters has been averaged with phenocryst compositions, especially where data on phenocrysts in a particular rock were scarce.

The lack of a consistent chemical difference between the groundmass olivine and the fresh overgrowths indicates that they are coeval.⁵

With increasing 'FeO' in the olivines, MnO content increases and NiO decreases (fig. 18). Apparently CaO

⁵In the remainder of this report, the description of groundmass olivine composition also applies to the fresh overgrowth.

increases with 'FeO' also, but because of the scatter of the data, the trend is not so evident as for NiO and MnO. There seems to be no variation of TiO₂ with 'FeO' in the phenocrysts (fig. 18), even though there is little scatter in the data.

Shaw and Jackson (1973) noted that 100Mg/Mg+Fe for early-formed phenocrysts in Kilauean and Mauna Loan tholeiites determined by Wright (1971) are in fair agreement with those of dunite xenoliths. They believed that the tholeiites are compositionally as well as spatially linked to the dunite xenoliths. However, Shaw and Jackson (1973) did not indicate whether minor-element concentrations in these two types of olivines are also similar. White (1966) reported earlier that olivine phenocrysts from Hawaiian alkalic lavas tend to

the very low NiO content of the whole rock (0.006, which is rounded to 0.01 in table 1).

It is not clear why the data of Simkin and Smith (1970) do not show any pressure effect, but variation resulting from pressure effects may have been masked by variations caused by compositional variations of the lavas that include the olivine.

The NiO content of olivines in the Kalaupapa section is near the upper limit of values determined by both Forbes and Banno (1966) and Simkin and Smith (1970), and the NiO content of the whole rock is appreciably higher than those determined by Gunn (1971) for the tholeiitic lavas of Kilauea Iki and Makaopuhi. Forbes and Banno suggested that high NiO and MgO characterize "primitive basalts" whether tholeiitic or alkalic, and on the basis of these criteria, the Kalaupapa lavas are indeed "primitive" and have not been fractionated to any extent, especially not by separation of olivine, which is particularly efficient in reducing the NiO content in lavas.

The MnO content correlates positively with 'FeO' content of olivine (fig. 18), a conclusion also reached by Simkin and Smith (1970). There is appreciably more scatter in the MnO content of groundmass olivine than in olivine phenocrysts. From these data there is no reason to suspect pressure control of MnO content in the olivines. The MnO content of the phenocrysts and the one groundmass olivine in sample Z (the same sample as the one with exceptionally low NiO values) is far greater than that for olivine of similar 'FeO' content from the other lavas. This may be the result of bulk composition of the host rock, as Simkin and Smith (1970) suggested for some of the samples in their study, but is not simply because the rock has a higher MnO content, as sample Z contains no more MnO than the other rocks in the section. Nor does it seem to be related to the degree of undersaturation of the lavas, as Simkin and Smith (1970) suggested, because sample Z is not appreciably more undersaturated than seven other rocks in the section that contain normative nepheline (when the CIPW norms are calculated from a dry-reduced basis). Sample Z, however, is set off from the other rocks in the section in that it contains considerably more SiO₂, P₂O₅, Na₂O, and K₂O and less CaO and (for its MgO content) less TiO₂. Hence, it appears to be more fractionated.

The CaO content of the olivines shows only a weakly positive correlation with 'FeO.' Simkin and Smith (1970) recorded a rather good separation of CaO between olivines from deep-seated plutonic rocks and ultramafic inclusions and those from hypabyssal and extrusive rocks. They suggested that because the CaO content is related to crystallization environment, it may be helpful in distinguishing olivine xenocrysts from olivine phenocrysts in lavas. Phenocrysts from the Kalaupapa lavas contain less CaO than the groundmass

olivines (fig. 18) and thus tend to support the argument of Simkin and Smith (1970) for pressure control, but the large amount of scatter in the data shown here does not allow a conclusive statement.

The TiO₂ content shows no correlation with 'FeO' (fig. 18); the groundmass olivine, however, contains considerably more TiO₂ than the olivine phenocrysts. The high TiO₂ content of the groundmass olivine is not necessarily a result of pressure, as was suggested for the high NiO content, because the TiO₂ content of the rest magma increases, up to a point, as crystallization proceeds, and a higher TiO₂ content in the groundmass olivine (like that of the groundmass clinopyroxene) is expected.

There is little or no overlap of MgO, FeO, SiO₂, MnO, and TiO₂ content of the unaltered olivine phenocrysts and unaltered groundmass olivine (fig. 19). The SiO₂ and MgO content of both the phenocrysts and groundmass olivine decreases and the 'FeO,' CaO, and MnO content increases upward in the section; the increase in MnO and CaO is more pronounced in the groundmass olivine than in the olivine phenocrysts.

The composition of the intratelluric alteration rims on the olivine grains was determined along with the fresh olivine (analyses given in table 4) and was found in almost all cases to contain more 'FeO' than the core of the phenocrysts but less 'FeO' than the fresh overgrowths. If there were no change in the Mg/Fe ratio during alteration of the olivine margins, then Mg/Fe decreases continuously from olivine phenocrysts to groundmass olivine. However, the compositions of alteration products in the interiors of some olivine phenocrysts indicate that the Mg/Fe ratio is reduced during alteration, suggesting that the gaps between phenocryst and groundmass olivine compositions shown in figure 19 may indeed be real.

X-ray diffractograms have been made of two samples (A and E) having distinct intratelluric alteration rims but little or no deuteric alteration of the olivine cores. One of these samples (A) has fresh overgrowths; the other sample (E) has none. Magnetite, hematite, and pyroxene (enstatite) were identified from the diffractogram of sample E. The magnetite occurs in symplectic intergrowths with pyroxene at the extreme margins of the altered olivine grains and is similar to intergrowths described by Haggerty and Baker (1967). The phase dispersed throughout the alteration rim is presumed to be mostly hematite. Hematite could not definitely be identified from X-ray diffractogram of sample A, but optical comparison with sample E shows that minute grains of hematite (mostly less than 0.5 μm in diameter) are dispersed throughout the alteration rim. No magnetite pyroxene symplectites were observed in sample A. No "iddingsite" (smectite-chlorite, Wilshire, 1958) or other minerals having a 1.4 nm (14 Å) peak were iden-

tified in either of these samples, although mica (illite?) may be present in sample A. There is only a few percent of water in the intratelluric alteration products if the iron is considered to be present as Fe₂O₃ (table 4), whereas more than 9 percent water is present in an average iddingsite (Wilshire, 1958). The available evidence therefore indicates that the intratelluric alteration product is dispersed hematite with some associated magnetite-pyroxene symplectite rather than "iddingsite" (smectite-chlorite).

The alteration rims contain about the same minor-element content as the fresh olivine, with the exception of Al₂O₃ which is consistently higher in the altered rims.⁶

COMPOSITIONAL VARIATION OF CLINOPYROXENE

Clinopyroxene that occurs as phenocrysts (and microphenocrysts), in clusters with plagioclase and olivine, and in the groundmass has been analyzed with the electron microprobe. Table 5 gives analyses of clinopyroxenes in the Kalaupapa section. Figure 20 shows the clinopyroxenes plotted on the pyroxene quadrilateral. Nearly all of them plot in the augite field; a few plot in the calcic augite (salite) field, and one plots in the subcalcic augite field (Brown, 1967). Fodor and Bunch (1972) showed that, for the island of Maui, tholeiitic basalts can be separated from alkalic and

⁶The possibility that the high Al₂O₃ content of the altered olivine rims may be due to contamination by polishing compound (alumina) is not ruled out by the data presented here.

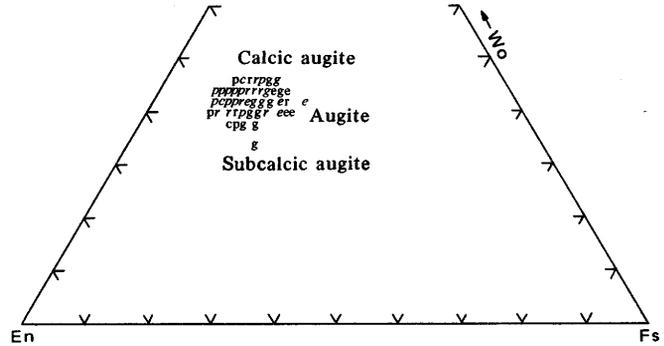


FIGURE 20.—Composition of clinopyroxenes in Kalaupapa section on pyroxene quadrilateral. p, central part of a phenocryst or microphenocryst; r, rim of a phenocryst or microphenocryst; c, central part of a clinopyroxene (augite) grain in a cluster; g, groundmass clinopyroxene; and e, rim (edge) of a clinopyroxene grain in a cluster. Italicized symbols indicate coincidence of two or more points. En, enstatite; Wo, wollastonite; Fs, ferrosilite.

nephelinic basalts on the basis of CaO content of the clinopyroxenes; the range of wollastonite is 30–40 in tholeiites, 38–48 in alkalic basalts, and 47–51 in nephelinic basalts. All but one of the analyzed clinopyroxenes from the Kalaupapa section plot in the field of alkalic basalts on this scheme. A few plot in the tholeiitic field, which overlaps the alkalic field on the low-wollastonite side, and a few plot in the nephelinic field, which overlaps the alkalic field on the high-wollastonite side.

Figure 21 shows the trends of the clinopyroxene com-

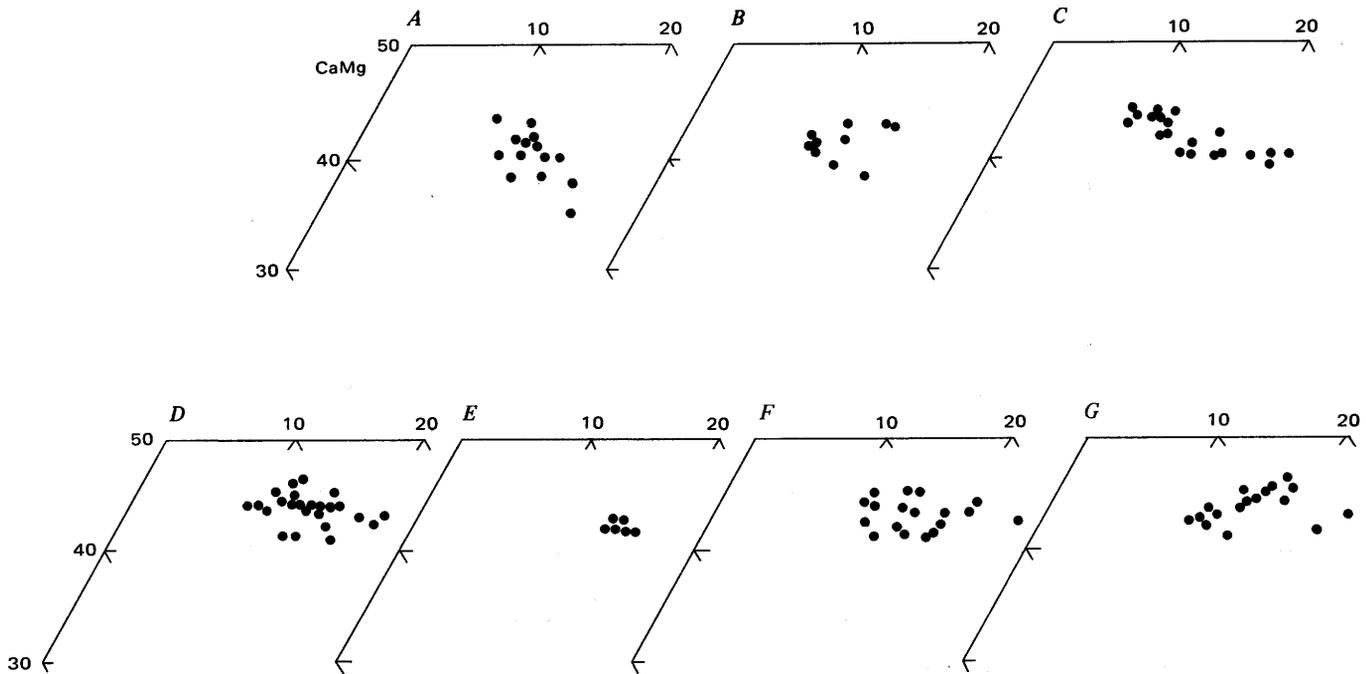


FIGURE 21.—Compositional variation of clinopyroxenes in subsections of Kalaupapa section plotted on a part of pyroxene quadrilateral. A, subsection A and BCD; B, subsection EF; C, subsection GHIJK; D, subsection LMNOP; E, subsection QRS; F, subsection TUVW; G, subsection XYZ.

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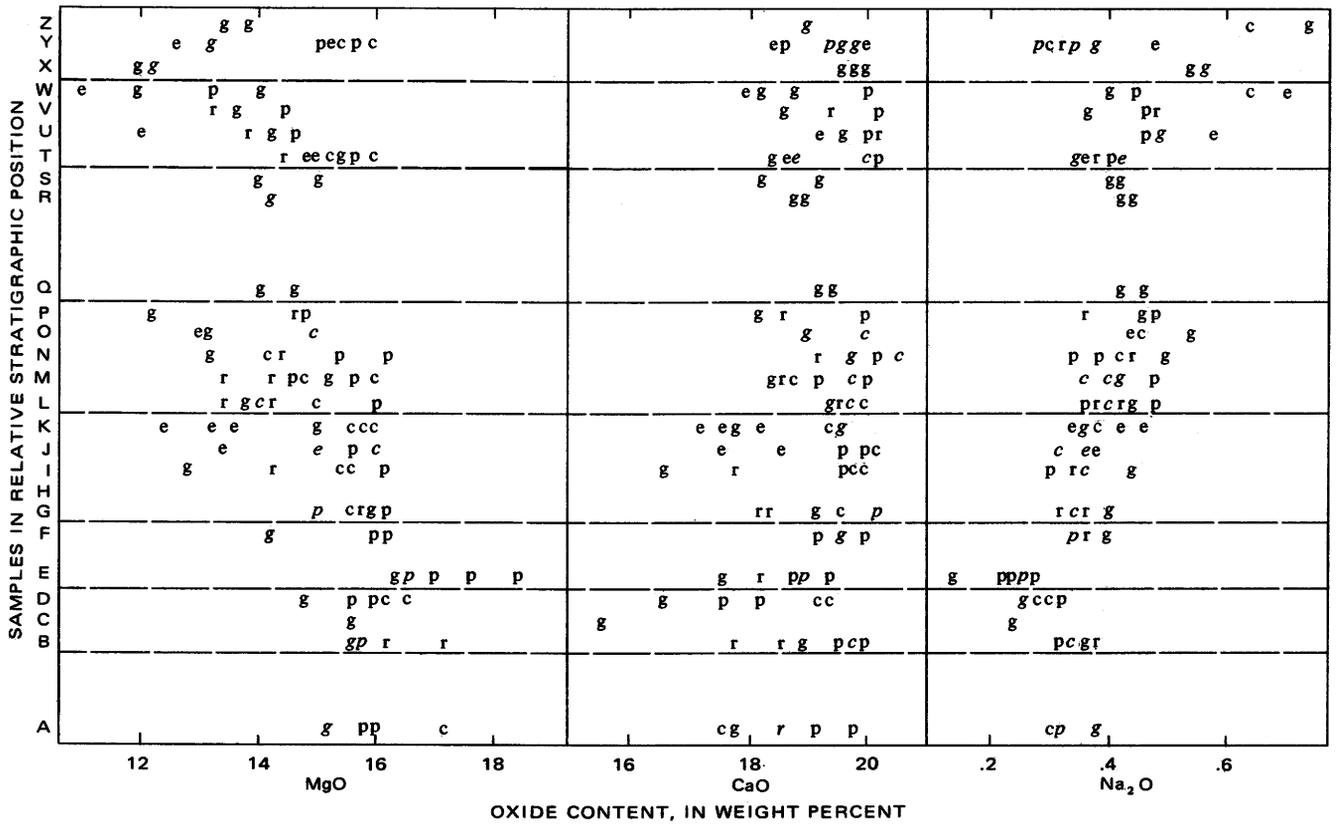
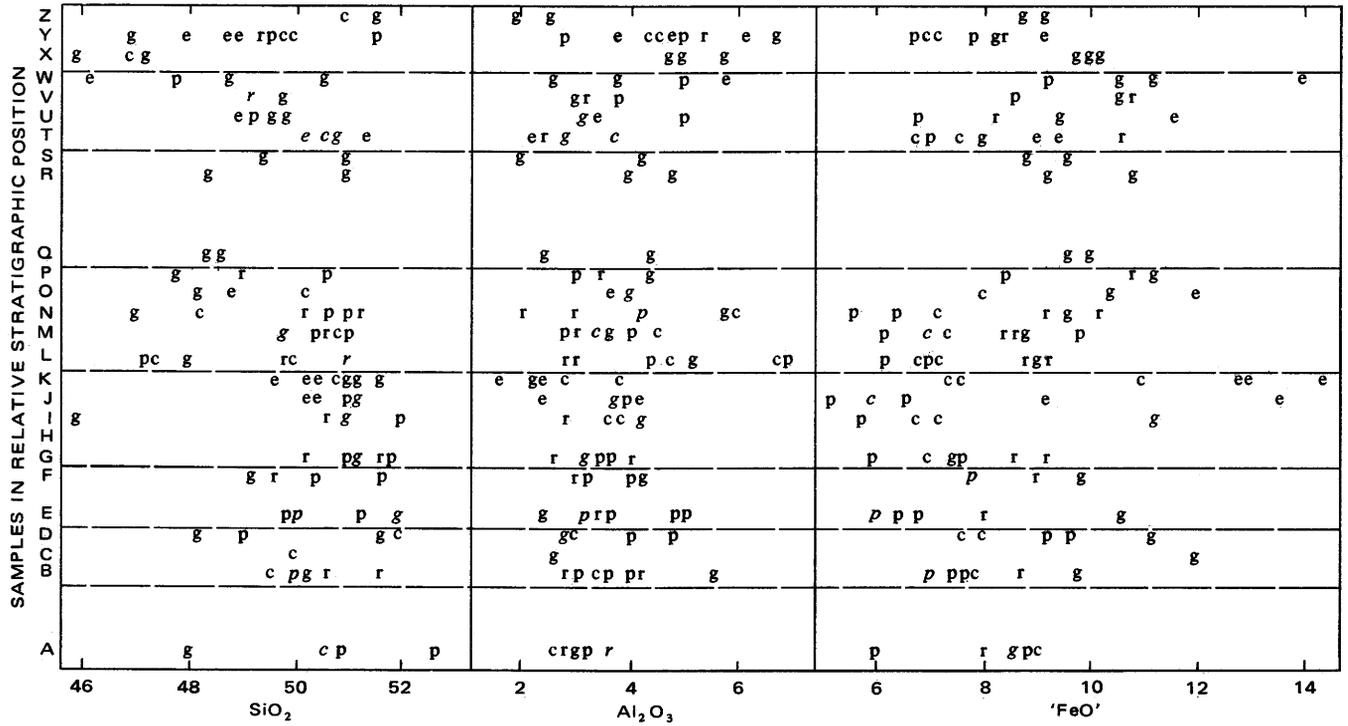


FIGURE 22.—Weight percent of oxides of clinopyroxene from Kalaupapa section plotted against relative stratigraphic position. A-Z, samples from base of section upward. p, central part of a phenocryst or microphenocryst; r, rim of a phenocryst or microphenocryst; c, central part of a clinopyroxene grain in a cluster; e, rim (edge) of clinopyroxene grain in a cluster; and g, groundmass clinopyroxene. Dashed horizontal lines delimit subsections. Italicized symbols indicate coincidence of two or more points.

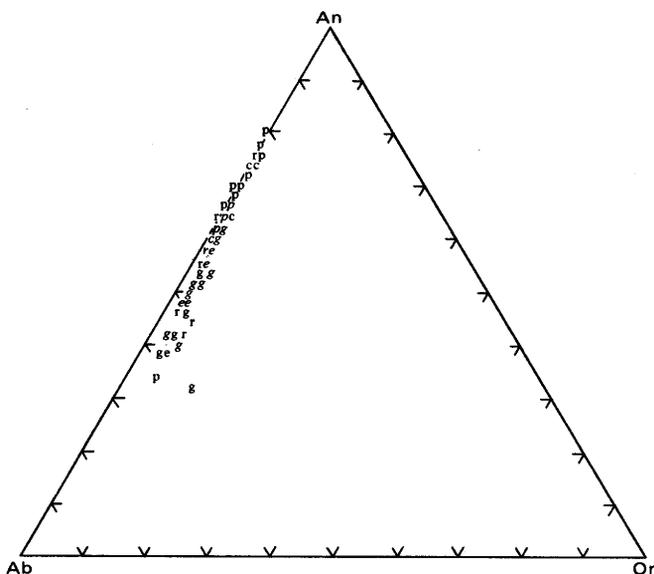


FIGURE 23.—Ab, Or, An diagram of plagioclase from Kalaupapa section. p, central part of phenocryst or microphenocryst; r, rim of phenocryst or microphenocryst; c, central part of plagioclase grain in a cluster; e, rim (edge) of a plagioclase grain in a cluster; and g, groundmass plagioclase lath. Italicized symbols indicate coincidence of two or more points.

plagioclase analyses. Most of the plagioclase grains that occur as phenocrysts and microphenocrysts, or in clusters, range in composition from An_{80}, Ab_{20}, Or_0 to An_{58}, Ab_{40}, Or_2 , although two microphenocrysts (both from sample Z, a mugearite) are as low as An_{49}, Ab_{48}, Or_3 . One grain in sample X that was first classified as a microphenocryst contains An_{34}, Ab_{61}, Or_5 , but reexamination shows that it may be a groundmass lath. Groundmass laths range in composition from $An_{61.5}, Ab_{36.5}, Or_2$ to An_{39}, Ab_{57}, Or_4 , overlapping the composition of phenocrysts, microphenocrysts, and plagioclase of clusters. The lowest An and highest Or and Ab groundmass plagioclase (fig. 23) is from sample Z and is not included with the basalt ranges.

In the entire Kalaupapa section, the compositions of phenocryst and groundmass plagioclase overlap considerably, but in single samples, the compositions, with a few exceptions, do not overlap. Despite the scatter of data points in figure 24, the Na_2O content increases and the CaO content decreases upward in the section.

Sample Z is very close to the composition of the average mugearite given by Macdonald and Abbott (1970) and, by definition, should contain oligoclase, but it contains andesine instead. A similar discrepancy was noted by Keil, Fodor, and Bunch (1972) in the lavas of West Maui and Haleakala volcanoes.

The groundmass, rim, and edge plagioclase compositions emphasize the more fractionated character of the lavas in the upper parts of the subsections. $Na_2O, K_2O,$ and BaO increase and CaO and Al_2O_3 decrease upward in the subsections (fig. 24).

COMPOSITIONAL VARIATION OF OPAQUE MINERALS

A wide variety of oxide phases showing extensive solid solution among the various end members is present in the lavas of the Kalaupapa section (table 7). Some chromite grains that occur as microphenocrysts in the groundmass as well as inclusions in olivine contain more than 50 percent Cr_2O_3 . Many of those not entirely enclosed in olivine phenocrysts are continuously zoned from a core of chromite to margins of ulvöspinel (usually on the titaniferous magnetite side of stoichiometric ulvöspinel). Brown (1967) indicated that "there is no evidence from the large fractionated intrusions, particularly the Bushveld, of a continuous series of spinels from chromites to titaniferous magnetites." However, continuous solid solution between chromite and ulvöspinel has been reported in the tholeiitic lavas of Kilauea Iki and Makaopuhi, Hawaii (Evans and Wright, 1972), from the lunar rocks by several investigators (Agrell and others, 1970; Haggerty, 1972; and others), as well as that reported here.

The microphenocrysts range in diameter mostly from 100 to 250 μm , but a few are larger than 250 μm . The groundmass minerals are ilmenite, ulvöspinel to titaniferous magnetite, and (rarely) rutile. The opaque minerals in the groundmass, though generally smaller than the microphenocrysts, are in places as large as some of the smaller microphenocrysts, and opaque minerals tend to cluster so that clots of tiny octahedra or other crystal forms are easily mistaken for microphenocrysts. Hence some that were assumed to be microphenocrysts on the basis of their size turned out to be groundmass in their composition. Some of the points plotted as microphenocrysts in figures 25 and 26 should more reasonably be plotted as groundmass grains.

The groundmass opaque minerals are usually unmixed, as a lattice network of ilmenite lamellae in titaniferous magnetite, as titaniferous magnetite with patches of ilmenite (usually toward the edge of the grain), or as half ilmenite and half titaniferous magnetite sandwiched between two ilmenite patches. Several tiny TiO_2 -rich areas (approaching rutile) were observed, one of which is included in table 7 and figures 25 and 26.

The exsolved phases usually have gradational contacts with the host. In order to obtain analyses that total roughly to 100 percent, at least two areas were selected in each grain, one giving a maximum TiO_2 and the other giving a minimum TiO_2 content. This procedure biases the analyses toward TiO_2 -rich and TiO_2 -poor end members, but in spite of this bias, the solid solution shown between ilmenite and titaniferous magnetite and between ulvöspinel and chromite is complete and must be real. In fact, complete solid solution was detected in a single grain containing more than 30 percent Cr_2O_3 and less than 4 percent TiO_2 in the chromite core and more

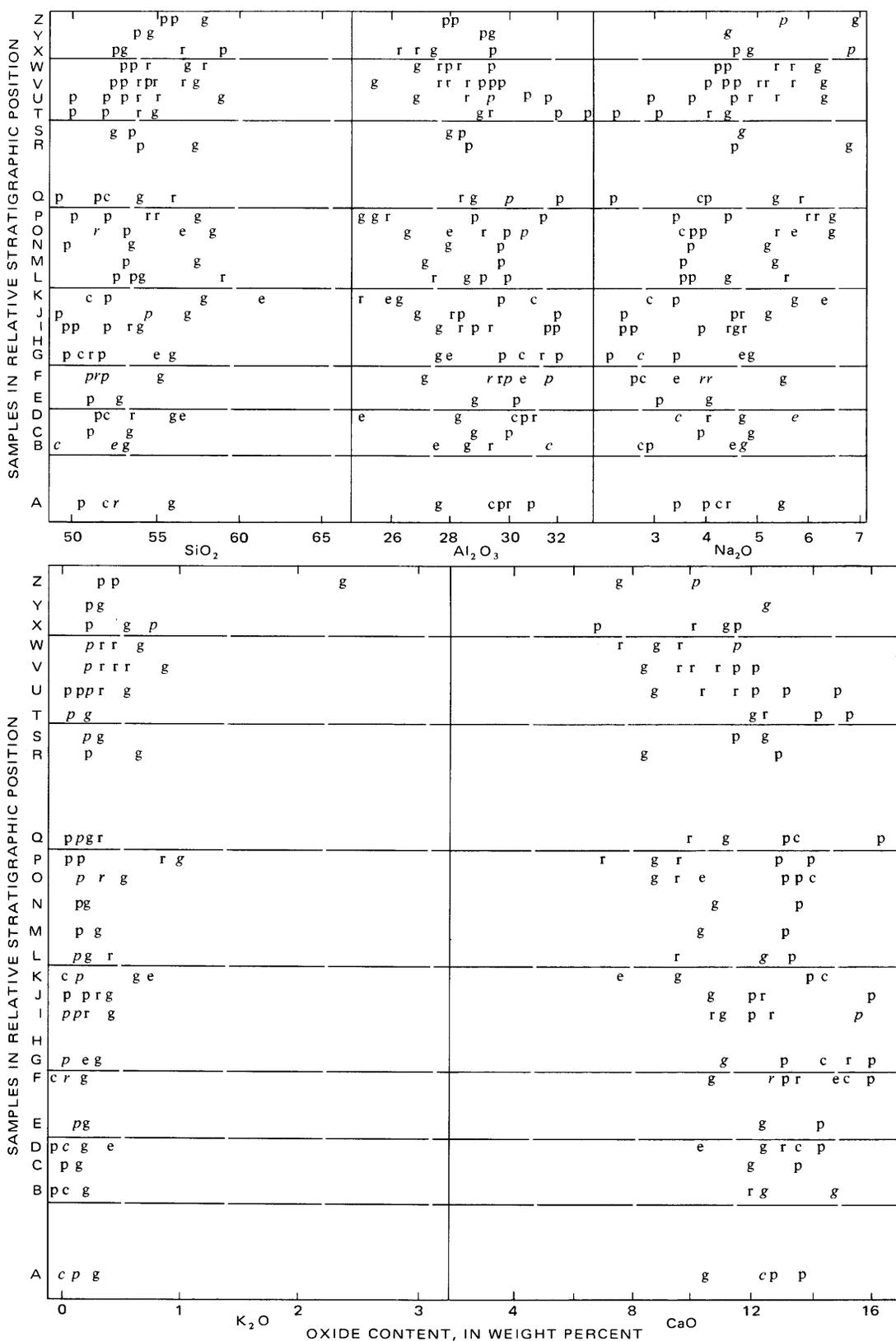


FIGURE 24.—Weight percent of oxides in plagioclase from Kalaupapa section plotted against relative stratigraphic positions. A–Z, samples from base of section upward. p, central part of phenocryst or microphenocryst; r, rim of phenocryst or microphenocryst; c, central part of a plagioclase grain in a cluster; e, rim (edge) of a plagioclase grain in a cluster; and g, groundmass plagioclase lath. Italicized symbols indicate coincidence of two or more points. Figure continued on following page.

than 22 percent TiO₂ and less than 3 percent Cr₂O₃ in the ulvöspinel rim.

Major elements in the chromite show marked variation with Cr₂O₃ content (fig. 25). Al₂O₃ and MgO decrease almost to zero as Cr₂O₃ decreases to zero, and TiO₂ and 'FeO' increase as Cr₂O₃ decreases, becoming more scattered near zero Cr₂O₃ content. At zero Cr₂O₃, 'FeO' and TiO₂ range from values expected for titaniferous magnetite almost to rutile (fig. 25). Because it is not possible to separate Fe³⁺ from Fe²⁺ with the electron microprobe, no evaluation of mineral variations on the FeO-TiO₂-Fe₂O₃ diagram has been attempted. The total iron could be partitioned between FeO and Fe₂O₃ if it is assumed that there are no defect structures present, but such an exercise is beyond the scope of this paper.

SUMMARY

To unravel the detailed compositional variation of a volcanic sequence, closely spaced sampling and firm stratigraphic control are necessary. This type of sampling of the Kalaupapa section revealed that the fractionation trend is discontinuous; it proceeds with several steps forward toward more fractionated compositions and then reverts abruptly to a less fractionated

composition. The Kalaupapa section can be divided into eight subsections on the basis of the discontinuous fractionation trend. These subsections are the same as the ones that would result from dividing the section on the basis of phenocryst content of the lavas. The upper subsections are generally more fractionated than the lower ones.

Petrologically the lavas in the lower part of the section are alkalic, but chemically they are tholeiitic and are best classified as transitional between tholeiitic and alkalic basalt. The lavas in the upper part of the section are, by any classification, alkalic.

The subsections are believed to have resulted from distinct magmatic batches that are generated in the mantle on a periodic rather than a continuous basis. Similar batches were first proposed by Powers (1955) to explain chemical variation of tholeiites and eruptive histories of Hawaiian volcanoes and were later used by Wright and Fiske (1971) to explain the compositional differences between historic and prehistoric lavas of Kilauea.

Subtraction of the phenocryst content from the dry-reduced whole-rock compositions removes compositional variation that results largely from shallow frac-

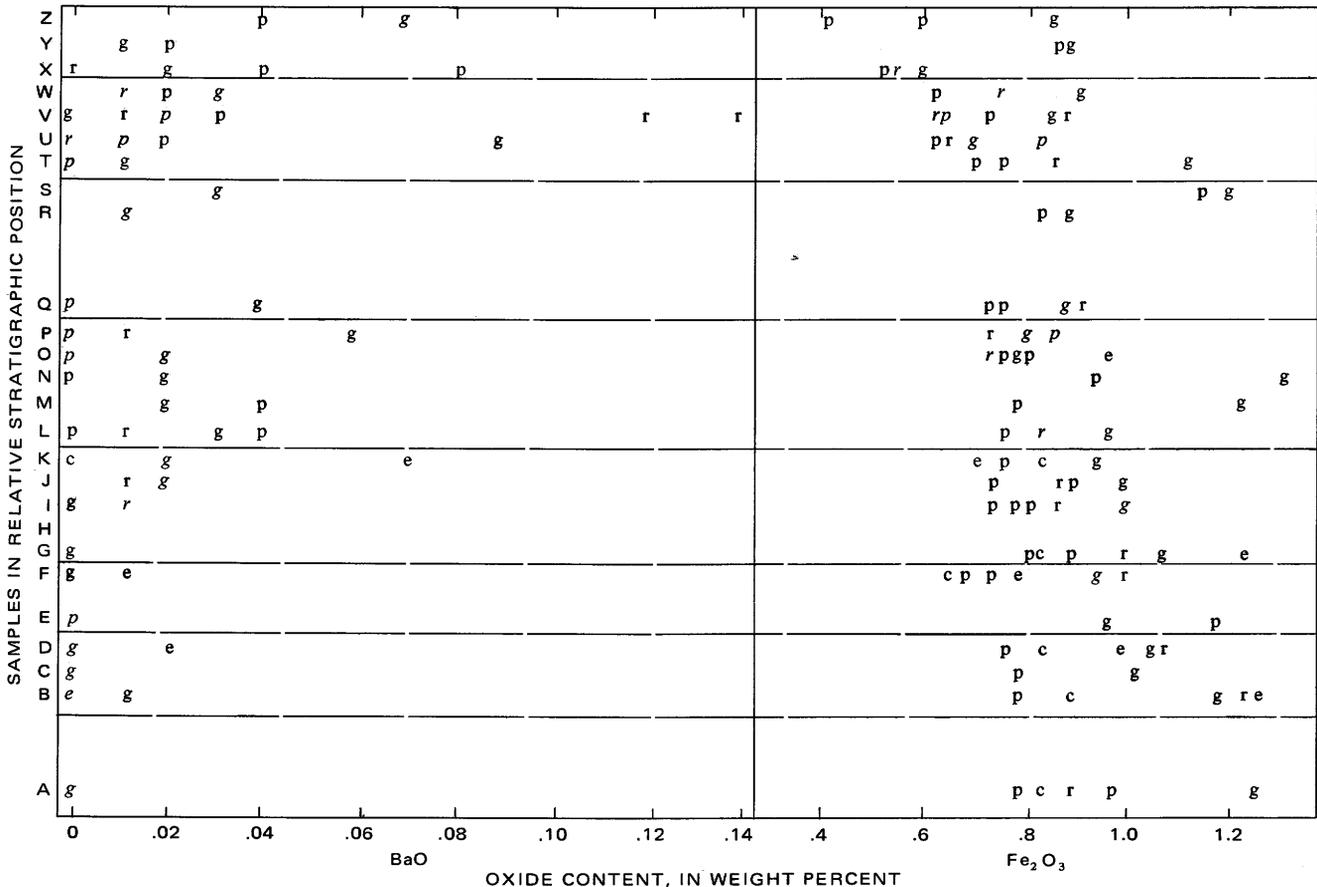


FIGURE 24.—Continued.

tional crystallization and allows identification of a deeper (more fundamental) fractionation trend mostly

controlled by aluminous clinopyroxene. The subsections defined by the whole-rock compositions are also seen in the phenocryst-free compositions. Therefore the subsections are not the result of shallow fractional crystallization alone. The trends of the phenocryst-free compositions could be produced either by deep 45–75 km, 28–46.5 mi) fractional crystallization of an aluminous clinopyroxene or from partial melting of a garnet pyroxenite leaving a residuum of aluminous clinopyroxenite. Although addition or removal of aluminous clinopyroxene can account for most of the trends in these transitional and alkalic lavas, desilication of tholeiitic magma to produce an alkalic one cannot, because the silica content of the aluminous clinopyroxene is very close to that of the lavas.

The most fayalitic olivine phenocryst contains less iron than the least fayalitic groundmass olivine. NiO content of the groundmass olivine and the olivine phenocrysts decreases with increasing 'FeO' content along separate but parallel trends (fig. 18). Extrapolation of these trends to a common 'FeO' content shows the groundmass olivine to contain more NiO than the olivine phenocrysts. It is possible that these differences in NiO content result from crystallization of the phenocrysts at higher pressures than the groundmass olivine.

Clinopyroxene compositions near the base of the section (in the two lowest subsections) trend toward subcalcic augite, as is typical of tholeiitic lavas (fig. 22). This is supporting evidence that the lower part of the section, if not tholeiite, is transitional between tholeiitic and alkalic basalt. Clinopyroxene compositions in the upper part of the section trend toward ferroaugite, as is typical of alkalic lavas. The composition of clinopyroxenes in these lavas provides as reliable a distinction between tholeiitic and alkalic lavas as whole-rock compositions.

Plagioclase increases in Na_2O and K_2O and decreases in CaO and Al_2O_3 upward in the section. K_2O also increases in the groundmass plagioclase in the upper flows of the subsections (fig. 24).

Chromite crystallized simultaneously with olivine and is present in the groundmass and as inclusions in olivine phenocrysts. Solid solution between chromite and ulvöspinel is continuous (figs. 25, 26). The other groundmass oxide minerals range from titaniferous magnetite through ulvöspinel to rutile and commonly show a variety of unmixing textures.

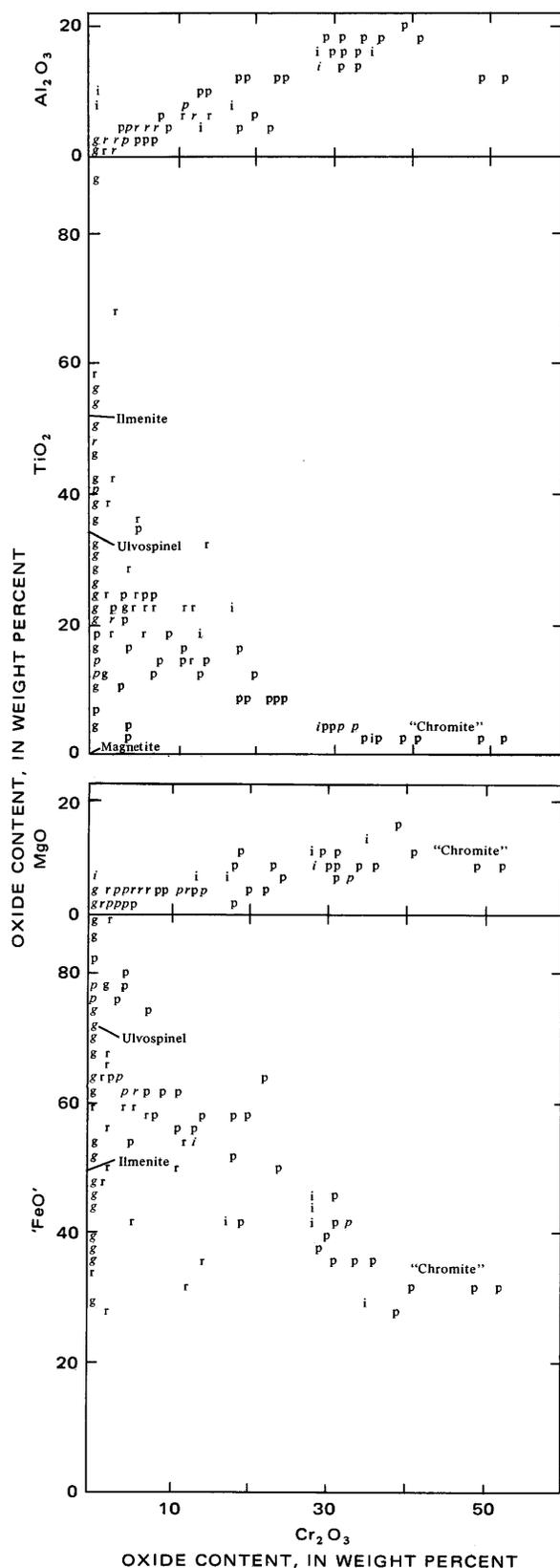


FIGURE 25.—Variation of Cr_2O_3 in opaque minerals from Kalaupapa section plotted relative to Al_2O_3 , TiO_2 , MgO , and 'FeO'. p, microphenocryst; r, rim of phenocryst; e, edge of groundmass grain; i, inclusion in olivine; and g, groundmass grain. Italicized symbols indicate coincidence of two or more points.

EAST MOLOKAI VOLCANIC SERIES

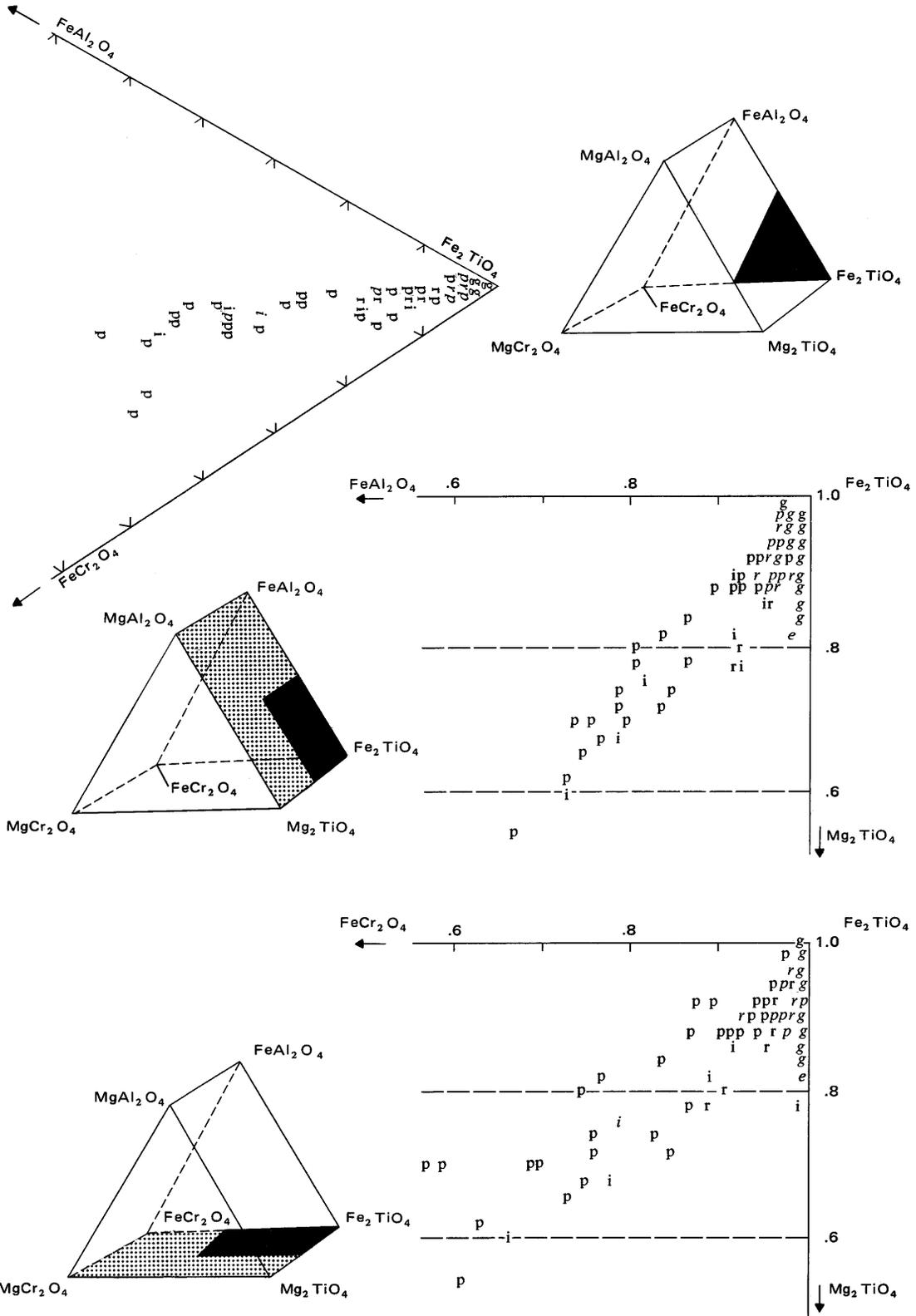


FIGURE 26.—Compositional variation of opaque minerals from Kalaupapa section on $FeAl_2O_4 - Fe_2TiO_4 - FeCr_2O_4 - MgAl_2O_4 - Mg_2TiO_4 - MgCr_2O_4$ trigonal prism. Points plotting away from $Fe_2TiO_4 - Mg_2TiO_4$ edge represent those with increasing chromite content. p, microphenocryst; r, rim of phenocryst; e, edge of groundmass grain; i, inclusion in olivine; and g, groundmass grain. Italicized symbols indicate coincidence of two or more points.

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TABLES 1-7

TABLE 1.—*Chemical analyses of whole rocks from the Kalaupapa section*

[Localities A-Z are shown in fig. 3. Dry-reduced compositions are plotted to facilitate comparison with microprobe analyses of minerals for which FeO and Fe₂O₃ cannot be separated. They were determined by recalculating total iron as FeO, subtracting H₂O and CO₂, then normalizing to 100 percent. Analysts: V. C. Smith, except Cr₂O₃ and NiO by R. L. Rahill]

	KLPA-1	KLPA-2	KLPA-3	KLPA-4	KLPA-5A	KLPA-7A	KLPA-8B	KLPA-9A	KLPA-11	KLPA-14A	KLPA-15A	KLPA-16A	KLPA-16B
	A	B	C	D	E	F	G	H	I	J	K	L	M
Chemical analyses (weight percent)													
SiO ₂	47.38	45.14	46.92	49.04	45.64	46.48	45.99	45.36	45.77	46.47	48.48	46.05	45.42
Al ₂ O ₃	13.50	13.28	14.24	14.33	11.32	15.57	13.14	13.07	14.87	14.31	15.42	12.12	12.53
Fe ₂ O ₃	3.18	5.65	4.09	5.94	4.49	4.25	4.59	6.64	4.56	3.21	2.32	2.58	7.04
FeO	9.74	7.67	8.64	7.14	7.57	8.64	7.84	6.30	9.13	10.08	10.08	10.36	6.57
MgO	9.24	12.42	9.18	5.66	16.98	7.19	12.87	13.07	7.45	8.33	5.09	12.34	11.43
CaO	9.92	10.14	9.92	10.26	9.44	9.75	9.90	9.63	9.59	10.00	10.12	10.06	9.60
Na ₂ O	2.58	1.94	2.10	2.59	1.47	3.02	2.02	1.96	2.48	2.68	3.16	2.30	2.26
K ₂ O	0.54	0.19	0.17	0.64	0.14	0.68	0.26	0.23	0.40	0.43	0.79	0.69	0.68
H ₂ O	0.21	0.36	0.83	0.34	0.26	0.41	0.42	0.58	1.20	0.37			0.50
TiO ₂	2.81	2.61	2.55	3.20	1.87	3.00	2.09	2.08	3.25	3.06	3.38	2.68	2.70
P ₂ O ₅	0.40	0.26	0.32	0.41	0.21	0.42	0.26	0.26	0.44	0.42	0.51	0.35	0.40
MnO	0.19	0.18	0.19	0.19	0.18	0.18	0.17	0.18	0.20	0.19	0.19	0.19	0.20
CO ₂	0.02	0.01	0.01		0.01	0.01	0.01	0.01			0.01	0.01	
S													
CH ₂ O ₃	0.04	0.10	0.06	0.03	0.13	0.03	0.11	0.12	0.07	0.04	0.03	0.09	0.10
NiO	0.03	0.05	0.04	0.02	0.10	0.03	0.07	0.07	0.03	0.03	0.01	0.05	0.05
TOTAL	99.78	100.00	99.26	99.79	99.83	99.66	99.74	99.56	99.44	99.62	99.59	99.87	99.48
CIPW Norms													
Q			0.023	5.667									
OR	3.198	1.123	1.012	3.790	0.829	4.032	1.540	1.365	2.377	2.551	4.688	4.083	4.039
AB	21.879	16.416	17.902	21.962	12.460	25.642	17.137	16.658	21.103	22.764	26.849	19.487	19.223
AN	23.712	26.966	29.142	25.638	23.916	27.012	26.086	26.301	28.420	25.844	25.662	20.735	22.151
NE													
WO	9.546	9.009	7.628	9.472	9.001	7.811	8.931	8.315	6.903	8.852	8.911	11.225	9.644
EN	14.177	18.642	23.033	14.126	21.384	8.905	17.352	22.151	16.914	11.422	10.111	8.049	19.628
FS	6.770	3.280	8.712	3.289	3.793	3.860	4.059	2.043	7.289	6.153	9.059	3.360	1.492
FO	6.227	8.612			14.700	6.351	10.360	7.389	1.223	6.589	1.834	15.924	6.298
FA	3.278	1.670			2.874	3.034	2.671	0.751	0.581	3.912	1.811	7.327	0.528
MT	4.621	8.192	5.974	8.631	6.521	6.183	6.672	9.670	6.649	4.672	3.378	3.746	10.261
CM	0.059	0.147	0.089	0.044	0.192	0.044	0.162	0.178	0.104	0.059	0.044	0.133	0.148
HM													
IL	5.349	4.957	4.879	6.090	3.558	5.717	3.980	3.968	6.207	5.834	6.446	5.097	5.155
AP	0.950	0.616	0.764	0.973	0.498	0.998	0.617	0.619	1.048	0.999	1.213	0.830	0.952
PR													
CC	0.046	0.023	0.023		0.023	0.023	0.023	0.023			0.023	0.023	
TOTAL	99.811	99.654	99.181	99.682	99.749	99.611	99.592	99.430	98.817	99.651	100.028	100.018	99.519
SALIC	48.790	44.505	48.079	57.057	37.205	56.685	44.764	44.324	51.900	51.159	57.199	44.305	45.414
FEMIC	51.022	55.149	51.102	42.625	62.544	42.926	54.828	55.106	46.917	48.493	42.829	55.713	54.104
DI	18.488	17.084	14.683	18.045	17.071	15.087	17.016	15.650	13.332	17.201	17.592	21.662	18.121
DIWO	9.546	9.009	7.628	9.472	9.001	7.811	8.931	8.315	6.903	8.852	8.911	11.225	9.644
DIEN	6.051	6.867	5.119	6.954	6.854	5.076	6.552	6.715	4.493	5.426	4.579	7.363	7.879
DIFS	2.890	1.208	1.936	1.619	1.216	2.200	1.533	0.619	1.936	2.923	4.102	3.074	0.599
HY	12.005	13.848	24.691	8.842	17.107	5.488	13.326	16.859	17.774	9.226	10.488	0.973	12.642
HYEN	8.125	11.775	17.915	7.172	14.530	3.829	10.800	15.436	12.421	5.996	5.532	0.686	11.749
HYFS	3.880	2.072	6.776	1.670	2.578	1.660	2.526	1.424	5.353	3.230	4.956	0.286	0.893
OL	9.505	10.283			17.574	9.385	13.031	8.140	1.803	10.502	3.645	23.251	6.826
OLFO	6.227	8.612			14.700	6.351	10.360	7.389	1.223	6.589	1.834	15.924	6.298
OLFA	3.278	1.670			2.874	3.034	2.671	0.751	0.581	3.912	1.811	7.327	0.528

TABLE 1.—Chemical analyses of whole rocks from the Kalaupapa section—Continued

	KLPA-17A	KLPA-19B	KLPA-19D	KLPA-20A	KLPA-23B	KLPA-25A	KLPA-27	KLPA-28	KLPA-29	KLPA-39	KLPA-31	KLPA-32	KLPA-33
	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Chemical analyses (weight percent)													
SI02	45.54	47.34	47.98	45.77	47.18	46.69	45.52	45.64	48.15	47.76	46.30	45.82	51.40
AL203	12.50	15.72	15.41	15.50	15.20	15.65	13.95	14.04	17.20	17.88	16.58	12.68	17.67
FE203	6.71	7.90	4.57	7.86	5.36	4.85	8.48	4.09	4.52	7.13	3.32	6.08	5.11
FEO	6.79	5.49	8.29	5.85	7.83	8.59	5.37	10.16	7.20	4.69	9.54	7.35	4.95
MGO	11.29	4.00	4.31	6.46	5.90	5.91	8.91	8.11	3.78	3.53	5.55	11.24	2.97
CAO	9.65	8.34	8.81	9.16	9.56	8.67	10.01	9.17	9.36	8.93	8.73	9.64	6.04
NA2O	2.31	3.54	3.62	3.00	3.05	2.88	2.16	2.96	3.66	3.49	3.17	2.27	5.08
K2O	0.68	1.20	1.20	0.88	0.85	0.89	0.45	0.98	1.12	1.06	1.10	0.63	2.00
H2O	0.10	0.33	0.16	0.48	0.29	0.81	0.84	0.36	0.20	0.58	0.85	0.56	0.38
YI02	2.72	3.78	3.76	3.56	3.39	3.39	2.76	3.30	3.40	3.29	3.47	2.61	2.34
P2O5	0.36	0.67	0.68	0.51	0.48	0.48	0.36	0.59	0.62	0.59	0.62	0.32	1.09
MNO	0.19	0.20	0.20	0.18	0.19	0.19	0.20	0.20	0.19	0.19	0.20	0.20	0.21
CO2		0.01						0.01					
S								0.01					
CR203	0.10	0.03	0.03	0.05	0.03	0.03	0.08	0.06	0.03	0.03	0.03	0.11	0.03
NIO	0.05	0.01	0.01	0.03	0.02	0.02	0.05	0.03	0.01	0.01	0.01	0.05	0.01
TOTAL	98.99	98.56	99.03	99.29	99.33	99.05	99.14	99.71	99.44	99.16	99.47	99.56	99.28
CIPW Norms													
Q		3.198	0.071	0.569	0.223	0.276	1.913			2.954			
OR	4.059	7.195	7.161	5.237	5.057	5.310	2.682	5.808	6.656	6.317	6.535	3.739	11.904
AB	19.746	30.392	30.931	25.567	25.982	24.603	18.436	25.120	31.144	29.782	26.967	19.293	43.297
AN	21.952	23.802	22.472	26.415	25.444	27.407	27.274	22.193	27.348	30.245	27.910	22.648	19.646
NE													
WO	10.035	5.709	7.172	6.679	7.994	5.366	8.536	8.143	6.378	4.403	4.826	9.724	1.404
EN	18.608	10.108	10.839	16.204	14.793	14.860	22.383	6.182	9.449	8.866	6.415	18.083	7.432
FS	1.845		5.657		4.747	6.595		3.116	4.234		4.367	2.925	1.393
FO	6.865							9.863	0.012		5.243	7.032	0.013
FA	0.750							5.479	0.006		3.933	1.254	0.003
MT	9.828	7.484	6.691	9.206	7.824	7.099	10.080	5.947	6.590	6.238	4.839	8.854	7.463
CM	0.149	0.045	0.045	0.074	0.044	0.045	0.119	0.089	0.044	0.045	0.044	0.163	0.045
HM		2.853		1.567				1.601			2.888		
IL	5.219	7.284	7.211	6.810	6.482	6.500	5.287	6.286	6.494	6.301	6.625	4.979	4.476
AP	0.861	1.610	1.626	1.217	1.145	1.148	0.860	1.402	1.477	1.409	1.476	0.761	2.600
PR								0.019					
CC		0.023						0.023					
TOTAL	99.918	99.702	99.876	99.544	99.734	99.209	99.172	99.668	99.833	99.448	99.180	99.455	99.676
SALIC	45.757	64.586	60.635	57.788	56.706	57.596	50.305	53.120	65.148	69.298	61.411	45.680	74.847
FEMIC	54.161	35.116	39.241	41.756	43.029	41.613	48.867	46.548	34.685	30.150	37.769	53.774	24.829
DI	18.900	10.642	13.924	12.452	15.329	10.372	15.914	15.794	12.330	8.208	9.444	18.416	2.665
DIWO	10.035	5.709	7.172	6.679	7.994	5.366	8.536	8.143	6.378	4.403	4.826	9.724	1.404
DIEN	8.065	4.934	4.436	5.773	5.553	3.467	7.378	5.087	4.111	3.805	2.748	7.482	1.062
DIFS	0.800		2.315		1.782	1.539		2.564	1.842		1.870	1.211	0.199
HY	11.589	5.174	9.745	10.431	12.205	16.449	15.005	1.648	7.731	5.061	6.164	12.315	7.564
HYEN	10.544	5.174	6.403	10.431	9.240	11.393	15.005	1.096	5.339	5.061	3.667	10.601	6.370
HYFS	1.046		3.342		2.965	5.056		0.552	2.392		2.496	1.715	1.194
OL	7.615							15.342	0.019		9.175	8.285	0.016
OLFO	6.865							9.863	0.012		5.243	7.032	0.013
OLFA	0.750							5.479	0.006		3.933	1.254	0.003

TABLES 1-7

TABLE 2.—Chemical analyses of rocks on a phenocryst-free basis from the Kalaupapa section

[Localities A-Z are shown in fig. 3. Values determined by subtracting phenocrysts from the dry-reduced whole-rock compositions on the basis of modal amounts (fig. 5) and compositions of the phenocrysts (tables 3-7)]

	KLPA-1	KLPA-2	KLPA-3	KLPA-4	KLPA-5A	KLPA-7A	KLPA-8B	KLPA-9A	KLPA-11	KLPA-14A	KLPA-15A	KLPA-16A	KLPA-16B
	A	B	C	D	E	F	G	H	I	J	K	L	M
	Chemical analyses (weight percent)												
SiO ₂	48.68	46.39	48.47	49.58	47.93	47.30	48.38	47.78	47.65	47.45	48.67	47.60	47.60
Al ₂ O ₃	15.29	15.79	15.40	14.04	15.61	16.13	16.62	16.91	16.56	15.25	14.76	14.85	16.09
FeO	12.08	12.46	11.73	13.00	10.38	12.46	10.50	11.05	13.01	12.94	13.09	11.36	10.96
MgO	5.63	7.41	7.85	5.85	8.73	6.15	6.26	6.49	4.23	6.35	5.03	6.91	6.36
CaO	10.86	11.31	10.71	10.24	11.93	10.14	11.67	11.22	10.43	10.43	9.83	11.63	10.94
Na ₂ O	2.95	2.41	2.27	2.61	2.04	3.19	2.70	2.66	2.91	2.96	3.25	2.84	2.94
K ₂ O	0.62	0.25	0.18	0.67	0.19	0.73	0.36	0.32	0.49	0.48	0.87	0.85	0.89
TiO ₂	3.21	3.37	2.76	3.34	2.56	3.22	2.85	2.90	3.92	3.43	3.71	3.27	3.43
P ₂ O ₅	0.46	0.34	0.35	0.42	0.29	0.46	0.36	0.37	0.54	0.47	0.56	0.43	0.53
MnO	0.18	0.17	0.18	0.20	0.15	0.18	0.14	0.14	0.19	0.19	0.20	0.17	0.17
CH ₂ O ₃	0.03	0.11	0.07	0.03	0.14	0.03	0.13	0.13	0.06	0.03	0.03	0.09	0.10
NiO			0.02	0.02	0.04	0.02	0.03	0.03		0.01	0.01		
TOTAL	99.99	100.01	99.99	100.00	99.99	100.01	100.00	100.00	99.99	99.99	100.01	100.00	100.01
	CIPW Norms												
OR	3.664	1.477	1.064	3.959	1.123	4.313	2.127	1.891	2.896	2.837	5.141	5.023	5.259
AB	24.965	20.391	19.210	22.085	17.264	24.795	22.847	22.508	24.626	25.049	27.498	20.965	23.818
AN	26.650	31.525	31.302	24.615	32.878	27.534	32.166	33.255	30.679	26.909	23.114	25.261	28.075
NE						1.189						1.661	0.573
WO	10.116	9.335	8.162	9.788	10.195	8.251	9.761	8.347	7.324	9.089	9.182	12.370	9.491
EN	7.428	6.695	14.081	12.689	12.974	3.774	8.397	7.665	6.777	5.562	6.005	6.310	4.809
FS	9.107	6.362	12.454	16.319	8.987	4.412	7.958	7.446	11.399	6.486	8.760	5.757	4.460
FO	4.621	8.239	3.834	1.318	6.146	8.088	5.041	5.956	2.634	7.186	4.570	7.638	7.729
FA	6.244	8.629	3.737	1.868	4.692	10.421	5.265	6.376	4.882	9.235	7.346	7.678	7.900
CM	0.044	0.162	0.103	0.044	0.206	0.044	0.191	0.191	0.088	0.044	0.044	0.133	0.147
IL	6.097	6.400	5.242	6.343	4.862	6.115	5.413	5.508	7.446	6.515	7.045	6.210	6.514
AP	1.090	0.805	0.829	0.995	0.687	1.089	0.853	0.876	1.279	1.113	1.326	1.018	1.255
TOTAL	100.026	100.020	100.019	100.023	100.015	100.025	100.019	100.020	100.030	100.026	100.031	100.024	100.029
SALIC	55.278	53.393	51.576	50.659	51.265	57.832	57.140	57.654	58.201	54.795	55.752	52.910	57.724
FEMIC	44.747	46.627	48.443	49.364	48.750	42.193	42.879	42.365	41.829	45.231	44.279	47.114	42.305
DI	20.183	18.467	16.108	19.561	19.962	16.436	19.307	16.523	14.770	18.105	18.428	24.437	18.760
DIWO	10.116	9.335	8.162	9.788	10.195	8.251	9.761	8.347	7.324	9.089	9.182	12.370	9.491
DIEN	4.523	4.682	4.216	4.275	5.770	3.774	4.901	4.147	2.776	4.162	3.761	6.310	4.809
DIFS	5.545	4.449	3.729	5.498	3.997	4.412	4.645	4.029	4.670	4.854	5.486	5.757	4.460
HY	6.468	3.925	18.589	19.235	12.194	6.810	6.934	10.730	3.033	5.519			
HYEN	2.906	2.013	9.865	8.414	7.204	3.496	3.517	4.001	1.400	2.245			
MYFS	3.562	1.913	8.725	10.821	4.990	3.313	3.417	6.729	1.633	3.274			
OL	10.865	16.868	7.572	3.186	10.838	18.509	10.306	12.332	7.516	16.421	11.916	15.316	15.629
OLFO	4.621	8.239	3.834	1.318	6.146	8.088	5.041	5.956	2.634	7.186	4.570	7.638	7.729
OLFA	6.244	8.629	3.737	1.868	4.692	10.421	5.265	6.376	4.882	9.235	7.346	7.678	7.900

TABLE 2.—Chemical analyses of rocks on a phenocryst-free basis from the Kalaupapa section—Continued

	KLPA-17A	KLPA-19B	KLPA-19D	KLPA-20A	KLPA-23B	KLPA-25A	KLPA-27	KLPA-28	KLPA-29	KLPA-30	KLPA-31	KLPA-32	KLPA-33
	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Chemical analyses (weight percent)													
SiO ₂	48.01	48.56	48.74	47.05	47.90	47.76	47.59	46.85	47.39	47.41	47.36	47.98	52.41
Al ₂ O ₃	15.58	15.80	15.19	16.20	15.43	16.01	16.57	15.35	13.90	15.43	17.28	15.47	18.13
FeO	10.77	13.29	12.95	12.82	12.84	13.25	12.39	13.36	14.67	14.44	12.24	12.21	9.44
MgO	6.30	4.03	4.44	5.53	5.99	6.05	5.42	4.72	4.69	4.32	5.05	5.34	2.78
CaO	11.48	8.36	8.78	9.60	9.71	8.87	10.56	9.76	8.61	8.11	9.10	11.57	6.19
Na ₂ O	2.89	3.67	3.70	3.20	3.10	2.95	2.69	3.52	3.57	3.44	3.32	2.78	5.21
K ₂ O	0.85	1.27	1.27	0.95	0.86	0.91	0.58	1.25	1.43	1.34	1.15	0.77	2.05
TiO ₂	3.37	4.03	3.96	3.85	3.44	3.47	3.44	4.18	4.58	4.41	3.62	3.17	2.41
P ₂ O ₅	0.46	0.72	0.72	0.55	0.49	0.49	0.47	0.76	0.84	0.80	0.65	0.40	1.12
MnO	0.15	0.22	0.21	0.17	0.19	0.19	0.19	0.19	0.25	0.24	0.20	0.18	0.20
Cr ₂ O ₃	0.11	0.03	0.03	0.05	0.03	0.03	0.06	0.06	0.04	0.04	0.03	0.12	0.03
NiO	0.02	0.01	0.01	0.02	0.02	0.02	0.03		0.01	0.01	0.01		0.01
TOTAL	99.99	99.99	100.00	99.99	100.00	100.00	99.99	100.00	99.98	99.99	100.01	99.99	99.98
CIPW Norms													
OR	5.023	7.506	7.505	5.614	5.082	5.377	3.428	7.387	8.452	7.919	6.795	4.551	12.116
AB	23.520	31.058	31.308	26.018	26.231	24.962	22.764	24.321	28.412	29.111	27.392	23.526	42.619
AN	27.031	22.889	21.088	27.036	25.647	27.755	31.428	22.392	17.683	22.706	28.848	27.461	20.032
NE	0.507			0.576				2.960	0.977		0.378		0.799
WO	11.241	5.797	7.418	7.098	8.068	5.448	7.472	8.794	8.163	5.138	5.030	11.411	1.404
EN	5.715	3.280	3.157	3.120	4.678	5.949	7.213	3.517	3.079	2.952	2.152	5.281	0.484
FS	5.256	5.932	5.032	3.962	5.726	7.487	9.312	5.366	5.225	5.396	2.885	6.917	0.959
FO	6.991	4.735	5.536	7.466	7.176	6.390	4.406	5.773	6.029	5.471	7.305	5.620	4.514
FA	7.087	9.438	9.724	10.450	9.680	8.863	6.268	9.705	11.277	11.020	10.793	8.111	9.856
CM	0.162	0.044	0.044	0.074	0.044	0.044	0.088	0.088	0.059	0.059	0.044	0.177	0.044
IL	6.401	7.655	7.521	7.313	6.533	6.590	6.534	7.939	8.700	8.376	6.874	6.021	4.578
AP	1.090	1.706	1.705	1.303	1.161	1.161	1.113	1.800	1.990	1.895	1.539	0.948	2.653
TOTAL	100.025	100.039	100.039	100.030	100.027	100.027	100.025	100.042	100.046	100.044	100.036	100.023	100.060
SALIC	56.082	61.453	59.901	59.244	56.960	58.095	57.620	57.059	55.523	59.736	63.413	55.538	75.567
FEMIC	43.943	38.587	40.138	40.786	43.067	41.932	42.405	42.982	44.523	40.308	36.623	44.485	24.493
DI	22.212	11.719	14.933	14.180	16.097	10.880	14.934	17.678	16.468	10.390	10.067	22.820	2.847
DIWO	11.241	5.797	7.418	7.098	8.068	5.448	7.472	8.794	8.163	5.138	5.030	11.411	1.404
DIEN	5.715	2.109	2.897	3.120	3.610	2.405	3.257	3.517	3.079	1.857	2.152	4.940	0.484
DIFS	5.256	3.813	4.617	3.962	4.419	3.027	4.205	5.366	5.225	3.395	2.885	6.469	0.959
HY		3.291	0.675		2.376	8.004	9.062			3.096		0.789	
HYEN		1.172	0.260		1.068	3.544	3.956			1.095		0.342	
HYFS		2.119	0.415		1.307	4.460	5.107			2.001		0.448	
OL	14.078	14.173	15.260	17.916	16.855	15.254	10.673	15.477	17.306	16.492	18.098	13.731	14.370
OLFO	6.991	4.735	5.536	7.466	7.176	6.390	4.406	5.773	6.029	5.471	7.305	5.620	4.514
OLFA	7.087	9.438	9.724	10.450	9.680	8.863	6.268	9.705	11.277	11.020	10.793	8.111	9.856

TABLES 1-7

TABLE 3.—Chemical analyses of olivines from the Kalaupapa section

[Localities A-Z are shown in fig. 3. Plotting symbols are p=central part of phenocrysts, r=rims of phenocrysts but inside the alteration rim, if present, c=central part of an olivine grain in a cluster, g=groundmass olivine, and o=fresh overgrowth on olivine phenocryst, in cluster or altered groundmass grain]

	A					B			C		D		
	-1PC p	-1PEO o	-2PC p	-2PEO o	-3MPF o	-1PC p	-1PE r	-2PC p	-1PC p	-2PC p	-3G g	-1CC c	-CEO o
SI02	38.70	36.20	39.70	36.80	36.60	39.20	38.50	39.30	39.70	39.10	36.40	38.10	35.70
AL203	0.06	0.07	0.06	0.07	0.09	0.04	0.04	0.08	0.12	0.07	0.11	0.08	0.11
FEO	19.10	36.40	18.10	33.20	35.40	19.30	22.20	16.40	12.50	18.50	34.30	21.80	36.90
MGO	40.70	26.00	42.20	29.20	27.10	40.60	37.80	42.90	46.00	40.90	27.30	37.80	25.00
CAO	0.38	0.47	0.40	0.48	0.47	0.38	0.33	0.33	0.31	0.36	0.52	0.39	0.48
TI02	0.05	0.09	0.03	0.10	0.08	0.03	0.04	0.04	0.03	0.03	0.07	0.06	0.25
MNO	0.30	0.59	0.27	0.57	0.54	0.31	0.41	0.26	0.20	0.28	0.47	0.36	0.50
NIO	0.30	0.23	0.30	0.26	0.24	0.29	0.27	0.41	0.41	0.24	0.29	0.26	0.22
CR203	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.07	0.03	0.05	0.03	0.04
TOTAL	99.62	100.09	101.10	100.72	100.56	100.19	99.63	99.76	99.34	99.51	99.51	98.88	99.20

D (cont'd)	E		F			G				I			
	-2G g	L-1PC p	L-2PC p	L-1CC p	L-2PC c	L-1PC p	L-1PE r	L-2PC p	L-2PE r	L-3G g	L-1PC p	L-1PE r	L-2CC c
SI02	36.20	39.00	39.40	38.50	39.00	39.10	38.20	37.60	37.70	35.30	38.20	38.40	37.30
AL203	0.10	0.06	0.06	0.07	0.05	0.07	0.11	0.06	0.06	0.10	0.05	0.09	0.10
FEO	33.60	16.80	14.80	19.90	18.80	21.80	18.40	20.10	19.40	39.20	21.20	21.20	22.10
MGO	27.90	42.00	44.00	39.60	40.90	39.20	41.20	39.40	39.80	23.80	38.80	38.80	37.40
CAO	0.51	0.37	0.25	0.41	0.38	0.47	0.54	0.47	0.44	0.53	0.49	0.51	0.48
TI02	0.12	0.03	0.03	0.05	0.04	0.04	0.04	0.04	0.03	0.14	0.03	0.05	0.04
MNO	0.48	0.26	0.24	0.29	0.29	0.33	0.31	0.33	0.31	0.74	0.33	0.31	0.34
NIO	0.21	0.29	0.33	0.27	0.30	0.24	0.28	0.30	0.24	0.23	0.26	0.30	0.24
CR203	0.04	0.04	0.03	0.03	0.03	0.02	0.04	0.02	0.03	0.04	0.03	0.04	0.03
TOTAL	99.16	98.85	99.14	99.12	99.79	101.27	99.12	98.32	98.01	100.08	99.39	99.70	98.03

I (cont'd)	J			K				L					
	L-3PC p	L-4G g	OL-1P p	OL-1P r	OL1PE o	OL-2C c	OL-3G g	OL-1P p	OL-1P r	OL1PE o	L1MPE o	OL-1P p	OL1PE o
SI02	39.10	36.00	38.60	38.30	35.90	38.60	37.00	38.70	38.80	35.80	36.10	38.70	34.80
AL203	0.05	0.10	0.06	0.09	0.05	0.10	0.15	0.10	0.09	0.08	0.07	0.06	0.07
FEO	17.00	34.50	19.00	18.80	37.90	18.50	35.00	18.90	18.70	35.60	36.90	20.10	39.20
MGO	42.00	27.20	40.80	40.30	24.20	41.10	27.70	40.70	40.90	26.60	26.10	40.00	22.70
CAO	0.47	0.67	0.47	0.45	0.59	0.47	0.61	0.47	0.49	0.57	0.60	0.48	0.63
TI02	0.04	0.14	0.03	0.03	0.08	0.03	0.04	0.04	0.03	0.10	0.08	0.04	0.08
MNO	0.28	0.50	0.29	0.27	0.60	0.27	0.54	0.31	0.29	0.59	0.59	0.31	0.56
NIO	0.32	0.26	0.30	0.27	0.22	0.26	0.25	0.28	0.26	0.23	0.19	0.30	0.20
CR203	0.05	0.03	0.04	0.04	0.04	0.03	0.04	0.04	0.03	0.04	0.03	0.03	0.03
TOTAL	99.31	99.40	99.59	98.55	99.58	99.36	101.40	99.54	99.59	99.61	100.66	100.02	98.27

TABLE 3.—Chemical analyses of olivines from the Kalaupapa section—Continued

	L (cont'd)		M		N		O		P		Q		
	OL-2G g	OL-1P p	OL-2P p	L3MPE o	OL-1P p	OL-1P r	OL1PE o	OL-2G g	OL-2G g	OL-1P p	OL-1P r	OL-2C c	OL-3G g
SiO ₂	36.10	37.80	38.70	35.90	38.50	38.40	35.00	35.20	35.60	38.00	38.10	38.60	38.60
Al ₂ O ₃	0.10	0.06	0.06	0.09	0.05	0.06	0.09	0.10	0.11	0.04	0.04	0.11	0.10
FeO	34.30	24.20	17.30	37.00	23.40	23.20	38.30	40.90	38.70	23.60	23.80	19.80	18.10
MgO	27.40	36.00	41.90	25.20	37.80	37.80	23.90	23.00	24.50	37.40	37.30	40.30	41.00
CaO	0.60	0.48	0.47	0.66	0.56	0.49	0.71	0.65	0.72	0.50	0.51	0.53	0.48
TiO ₂	0.08	0.06	0.04	0.13	0.04	0.04	0.06	0.12	0.17	0.05	0.05	0.03	0.06
MnO	0.42	0.38	0.27	0.63	0.37	0.36	0.68	0.65	0.58	0.40	0.40	0.30	0.24
NiO	0.24	0.22	0.32	0.21	0.25	0.22	0.18	0.20	0.20	0.20	0.21	0.25	0.34
CR ₂ O ₃	0.03	0.02	0.04	0.05	0.03	0.03	0.04	0.04	0.04	0.02	0.03	0.03	0.02
TOTAL	99.27	99.22	99.10	99.87	101.00	100.60	98.96	100.86	100.62	100.21	100.44	99.95	98.94

	Q (cont'd)		R		S		T				U		
	OL3GE o	OL-1G g	LIMPE o	OL-2G g	L-1PC p	L-1PE r	L-2PC p	L-2PE r	L-3G g	L-4CC c	L-1PC p	L-1PE r	L-1PE o
SiO ₂	36.60	35.70	36.30	36.30	38.50	39.30	38.50	38.50	39.40	38.30	38.20	38.60	36.60
Al ₂ O ₃	0.24	0.78	0.08	0.08	0.04	0.10	0.04	0.10	0.11	0.10	0.08	0.07	0.07
FeO	36.00	37.20	35.70	36.20	20.00	17.30	22.90	23.00	18.50	21.50	23.10	22.90	37.10
MgO	24.70	25.90	27.60	27.00	40.60	42.50	37.80	37.60	41.00	39.00	37.60	37.50	24.90
CaO	0.69	0.66	0.65	0.62	0.37	0.41	0.42	0.55	0.55	0.43	0.45	0.44	0.62
TiO ₂	0.17	0.18	0.07	0.08	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.12
MnO	0.61	0.60	0.66	0.56	0.32	0.34	0.36	0.33	0.31	0.34	0.38	0.36	0.77
NiO	0.16	0.20	0.21	0.24	0.31	0.37	0.29	0.27	0.34	0.27	0.26	0.21	0.18
CR ₂ O ₃	0.03	0.02	0.03	0.04	0.04	0.03	0.03	0.02	0.05	0.04	0.03	0.03	0.03
TOTAL	99.20	101.24	101.30	101.12	100.22	100.40	100.39	100.42	100.32	100.04	100.16	100.17	100.39

	U (cont'd)				V		W		X		Y		Z	
	L-2PC p	L-2PE r	L-2PE o	L-3GE o	LIMPE o	L-2GE o	L-2GE o	L-2PE o	L-3GE o	L-1PC p	L-2GC g	L-1MP p	L-2MP p	L-3G g
SiO ₂	38.20	38.40	36.50	35.90	35.80	35.80	35.80	36.10	35.30	39.80	39.40	37.50	37.20	35.90
Al ₂ O ₃	0.07	0.05	0.06	0.10	0.10	0.08	0.11	1.11	0.11	0.08	0.11	0.10	0.11	0.19
FeO	21.30	22.20	34.70	39.80	40.00	41.80	40.20	40.10	41.90	14.30	17.00	28.10	29.60	35.00
MgO	39.10	38.40	27.60	22.60	22.80	21.30	22.90	23.40	21.90	45.10	42.80	33.40	32.10	26.30
CaO	0.44	0.41	0.50	0.66	0.57	0.59	0.67	0.64	0.64	0.35	0.43	0.41	0.44	0.64
TiO ₂	0.05	0.05	0.14	0.16	0.12	0.21	0.11	0.19	0.13	0.03	0.06	0.05	0.06	0.12
MnO	0.35	0.36	0.55	0.83	0.68	0.70	0.72	0.73	0.69	0.25	0.28	0.78	0.85	1.10
NiO	0.24	0.20	0.22	0.16	0.17	0.18	0.16	0.15	0.15	0.39	0.24	0.09	0.11	0.12
CR ₂ O ₃	0.03	0.03	0.05	0.03	0.03	0.03	0.04	0.03	0.03	0.06	0.05	0.03	0.03	0.04
TOTAL	99.78	100.10	100.32	100.24	100.27	100.69	100.71	102.45	100.85	100.36	100.37	100.46	100.50	99.41

TABLES 1-7

TABLE 4.—*Chemical analyses of olivine alteration rims from the Kalaupapa section*
 [Localities A-Z are shown in fig. 3. Plotting symbol i=inclusion in olivine]

	A						B				C	
	1-1PI i	1-1PI i	1-2PI i	1-2PI i	13MPI i	13MPI i	2-1PI i	2-1PI i	2-2PI i	2-2PI i	3-1PI i	3-1PI i
SI02	37.20	37.20	37.60	37.60	36.80	36.80	36.50	36.50	36.00	36.00	34.00	34.00
AL203	0.39	0.39	0.20	0.20	0.38	0.38	0.76	0.76	0.68	0.68	0.98	0.98
FE203		30.40		25.30		32.80		30.20		29.50		37.40
FE0	27.30		22.80		29.60		27.10		26.50		33.70	
MGO	28.00	28.00	36.60	36.60	26.80	26.80	30.70	30.70	29.70	29.70	22.80	22.80
CAO	0.51	0.51	0.51	0.51	0.55	0.55	0.48	0.48	0.44	0.44	0.49	0.49
TI02	0.39	0.39	0.09	0.09	0.08	0.08	0.09	0.09	0.06	0.06	0.20	0.20
MNO	0.36	0.36	0.32	0.32	0.39	0.39	0.36	0.36	0.41	0.41	0.36	0.36
CR203	0.05	0.05	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05
NIO	0.26	0.26	0.28	0.28	0.22	0.22	0.25	0.25	0.23	0.23	0.28	0.28
TOTAL	94.46	97.56	98.43	100.93	94.86	98.06	96.28	99.38	94.06	97.06	92.86	96.56

	C (cont'd)		D		E						F	
	3-2PI i	3-2PI i	4-1CI i	4-1CI i	5R1PI i	5R1PI i	5R2PI i	5R2PI i	5R3GI i	5R3GI i	7A1CI i	7A1CI i
SI02	34.60	34.60	36.70	36.70	35.80	35.80	37.10	37.10	36.40	36.40	36.70	36.70
AL203	0.53	0.53	0.35	0.35	0.61	0.61	0.57	0.57	0.17	0.17	0.58	0.58
FE203		36.20		31.50		31.30		22.80		30.10		26.40
FE0	32.60		28.40		28.20		20.50		27.10		23.70	
MGO	23.40	23.40	26.30	26.30	27.30	27.30	36.60	36.60	31.90	31.90	33.60	33.60
CAO	0.52	0.52	0.60	0.60	0.62	0.62	0.47	0.47	0.43	0.43	0.45	0.45
TI02	0.08	0.08	0.11	0.11	0.05	0.05	0.07	0.07	0.06	0.06	0.21	0.21
MNO	0.32	0.32	0.41	0.41	0.37	0.37	0.38	0.38	0.38	0.38	0.28	0.28
CR203	0.05	0.05	0.04	0.04	0.06	0.06	0.04	0.04	0.03	0.03	0.03	0.03
NIO	0.26	0.26	0.24	0.24	0.27	0.27	0.31	0.31	0.30	0.30	0.27	0.27
TOTAL	92.36	95.96	93.15	96.25	93.28	96.38	96.04	98.34	96.77	99.77	95.82	98.52

	F (cont'd)				G				I			
	7A2PI i	7A2PI i	7A3GI i	7A3GI i	8R1PI i	8R1PI i	8R2PI i	8R2PI i	11PI0 i	11PI0 i	11PII i	11PII i
SI02	35.60	35.60	35.50	35.50	34.40	34.40	34.00	34.00	33.40	33.40	31.50	31.50
AL203	0.56	0.56	0.70	0.70	0.60	0.60	0.54	0.54	0.57	0.57	2.39	2.39
FE203		38.40		38.30		37.00		37.00		32.60		30.40
FE0	34.60		30.89		33.30		33.30		29.40		27.30	
MGO	22.00	22.00	24.80	24.80	23.20	23.20	22.10	22.10	26.70	26.70	24.60	24.60
CAO	0.67	0.67	0.68	0.68	0.68	0.68	0.65	0.65	0.55	0.55	0.62	0.62
TI02	0.23	0.23	0.23	0.23	0.17	0.17	0.15	0.15	0.24	0.24	0.09	0.09
MNO	0.39	0.39	0.37	0.37	0.41	0.41	0.42	0.42	0.35	0.35	0.28	0.28
CR203	0.03	0.03	0.03	0.03	0.05	0.05	0.03	0.03	0.04	0.04	0.05	0.05
NIO	0.26	0.26	0.22	0.22	0.23	0.23	0.28	0.28	0.22	0.22	0.25	0.25
TOTAL	94.34	98.14	93.42	100.83	93.04	96.74	91.47	95.17	91.47	94.67	87.08	90.18

TABLE 4.—Chemical analyses of olivine alteration rims from the Kalaupapa section—Continued

	I (cont'd)				J				K			
	12CII i	12CII i	12C10 i	12C10 i	113PI i	113PI i	4A1PI i	4A1PI i	5A1PI i	5A1PI i	A2MPI i	A2MPI i
SI02	32.40	32.40	33.90	33.90	33.50	33.50	34.40	34.40	34.70	34.70	35.30	35.30
AL203	0.90	0.90	0.50	0.50	0.59	0.59	0.46	0.46	0.46	0.46	0.48	0.48
FE203		30.40		34.90		38.20		34.10		32.30		32.00
FEO	27.40		31.40		34.30		30.60		29.00		28.80	
MGO	27.30	27.30	24.90	24.90	21.60	21.60	23.50	23.50	26.90	26.90	27.30	27.30
CAO	0.60	0.60	0.62	0.62	0.54	0.54	0.53	0.53	0.56	0.56	0.63	0.63
TIO2	0.17	0.17	0.39	0.39	0.20	0.20	0.17	0.17	0.10	0.10	0.14	0.14
MNO	0.33	0.33	0.56	0.56	0.35	0.35	0.39	0.39	0.38	0.38	0.43	0.43
CR203	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04
NIO	0.27	0.27	0.17	0.17	0.25	0.25	0.26	0.26	0.24	0.24	0.19	0.19
TOTAL	89.41	92.41	92.49	95.99	91.37	95.27	90.35	93.85	92.37	95.67	93.31	96.51

	L		M				N					
	6A1PI i	6A1PI i	B1PII i	B1PII i	B1PIR i	B1PIR i	6B2PI i	6B2PI i	A1PII i	A1PII i	A1PIR i	A1PIR i
SI02	36.00	36.00	34.00	34.00	34.60	34.60	34.40	34.40	32.10	32.10	35.10	35.10
AL203	0.28	0.28	0.82	0.82	0.79	0.79	0.61	0.61	1.23	1.23	0.84	0.84
FE203		29.70		33.30		35.50		34.20		36.30		33.10
FEO	26.70		30.00		32.00		30.80		32.70		29.80	
MGO	31.70	31.70	25.40	25.40	23.70	23.70	24.50	24.50	23.50	23.50	26.70	26.70
CAO	0.48	0.48	0.59	0.59	0.70	0.70	0.63	0.63	0.62	0.62	0.61	0.61
TIO2	0.08	0.08	0.06	0.06	0.11	0.11	0.13	0.13	0.08	0.08	0.27	0.27
MNO	0.30	0.30	0.36	0.36	0.41	0.41	0.33	0.33	0.41	0.41	0.36	0.36
CR203	0.03	0.03	0.02	0.02	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04
NIO	0.27	0.27	0.22	0.22	0.28	0.28	0.26	0.26	0.24	0.24	0.23	0.23
TOTAL	95.84	98.84	91.47	94.77	92.63	96.13	91.69	95.09	90.91	94.51	93.95	97.25

	N (cont'd)				P				Q			
	7A3GI i	7A3GI i	91PI0 i	91PI0 i	0A1PI i	0A1PI i	0A2CI i	0A2CI i	A3GCI i	A3GCI i	0A3GI i	0A3GI i
SI02	35.50	35.50	32.80	32.80	35.60	35.60	36.00	36.00	35.90	35.90	36.20	36.20
AL203	0.62	0.62	0.61	0.61	0.53	0.53	0.55	0.55	0.64	0.64	3.33	3.33
FE203		33.10		31.00		29.40		38.90		30.20		30.10
FEO	29.80		27.90		26.40		35.00		27.20		27.10	
MGO	26.30	26.30	25.00	25.00	31.20	31.20	24.80	24.80	28.90	28.90	28.90	28.90
CAO	0.73	0.73	0.70	0.70	0.55	0.55	0.60	0.60	0.74	0.74	0.62	0.62
TIO2	0.31	0.31	0.21	0.21	0.15	0.15	0.12	0.12	0.31	0.31	0.25	0.25
MNO	0.51	0.51	0.56	0.56	0.34	0.34	0.47	0.47	0.37	0.37	0.38	0.38
CR203	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NIO	0.27	0.27	0.21	0.21	0.22	0.22	0.22	0.22	0.28	0.28	0.18	0.18
TOTAL	94.08	97.38	88.02	91.12	95.02	98.02	97.79	101.69	94.37	97.37	96.99	99.99

TABLES 1-7

TABLE 4.—Chemical analyses of olivine alteration rims from the Kalaupapa section—Continued

	R		T				U					
	1MPCI i	1MPCI i	271PI i	271PI i	274CI i	274CI i	81PCI i	81PCI i	281PI i	281PI i	282PI i	282PI i
SI02	34.70	34.70	34.50	34.50	35.80	35.80	35.40	35.40	35.80	35.80	36.00	36.00
AL203	1.02	1.02	0.53	0.53	0.69	0.69	0.66	0.66	0.45	0.45	0.54	0.54
FE203		36.50		35.90		32.30		31.80		33.30		33.10
FE0	32.90		32.30		29.00		28.60		29.90		29.80	
MGO	24.00	24.00	24.10	24.10	27.90	27.90	27.70	27.70	26.00	26.00	26.70	26.70
CAO	0.66	0.66	0.63	0.63	0.63	0.63	0.61	0.61	0.62	0.62	0.57	0.57
TI02	0.10	0.10	0.46	0.46	0.14	0.14	0.06	0.06	0.09	0.09	0.09	0.09
MNO	0.46	0.46	0.46	0.46	0.35	0.35	0.39	0.39	0.45	0.45	0.38	0.38
CR203	0.03	0.03	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
NIO	0.19	0.19	0.25	0.25	0.28	0.28	0.25	0.25	0.21	0.21	0.21	0.21
TOTAL	94.06	97.66	93.27	96.87	94.83	98.13	93.70	96.90	93.55	96.95	94.32	97.62

	U (cont'd)		V		W		X				Y	
	283GI i	283GI i	291MP i	291MP i	01PCI i	01PCI i	12PCI i	12PCI i	136CI i	136CI i	321PI i	321PI i
SI02	36.60	36.60	35.10	35.10	31.80	31.80	34.80	34.80	35.20	35.20	36.30	36.30
AL203	0.57	0.57	0.71	0.71	1.76	1.76	1.11	1.11	0.45	0.45	0.65	0.65
FE203		31.60		34.30		41.00		39.40		40.50		31.70
FE0	28.40		30.80		36.90		30.10		36.50		28.60	
MGO	27.80	27.80	25.20	25.20	21.50	21.50	26.40	26.40	24.00	24.00	28.70	28.70
CAO	0.65	0.65	0.57	0.57	0.51	0.51	0.47	0.47	0.58	0.58	0.62	0.62
TI02	0.19	0.19	0.10	0.10	0.09	0.09	0.22	0.22	0.13	0.13	0.19	0.19
MNO	0.53	0.53	0.55	0.55	0.55	0.55	0.40	0.40	0.47	0.47	0.37	0.37
CR203	0.03	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
NIO	0.21	0.21	0.16	0.16	0.18	0.18	0.19	0.19	0.15	0.15	0.18	0.18
TOTAL	94.98	98.18	93.22	96.72	93.33	97.43	93.72	103.02	97.51	101.51	95.64	98.74

	Y (cont'd)		Z			
	322GI i	322GI i	31MPI i	31MPI i	32MPI i	32MPI i
SI02	36.50	36.50	32.70	32.70	34.70	34.70
AL203	0.78	0.78	1.25	1.25	0.59	0.59
FE203		39.10		40.90		39.00
FE0	35.20		36.80		35.10	
MGO	25.30	25.30	20.90	20.90	23.70	23.70
CAO	0.82	0.82	0.55	0.55	0.55	0.55
TI02	0.72	0.72	0.11	0.11	0.08	0.08
MNO	0.41	0.41	0.69	0.69	0.85	0.85
CR203	0.04	0.04	0.03	0.03	0.04	0.04
NIO	0.20	0.20	0.13	0.13	0.10	0.10
TOTAL	99.97	103.87	93.16	97.26	95.71	99.61

TABLE 5.—*Chemical analyses of clinopyroxenes from the Kalaupapa section*

[Localities A-Z are shown in fig. 3. Plotting symbols are p=central part of a phenocryst or microphenocryst, r=rim of a phenocryst or microphenocryst, c=central part of a clinopyroxene grain in a cluster, e=edge of a clinopyroxene grain in a cluster, and g=groundmass olivine]

	A					B					C		
	-1PC p	-1PE r	-2PC p	-2PE r	-3C c	-1PC p	-1PE r	-2PC p	-3PC p	-3PE r	-4CC c	-5G g	-1G g
SI02	52.60	50.50	50.70	49.00	50.60	50.00	51.50	49.50	50.10	50.50	49.60	50.20	49.90
AL203	3.54	3.70	3.27	2.81	2.62	3.56	4.27	2.96	4.00	2.81	3.33	5.53	2.51
FEO	6.10	8.60	8.70	8.00	9.00	7.50	7.10	7.40	7.00	8.70	7.80	9.70	12.00
MGO	16.10	15.30	15.80	15.20	17.30	15.80	17.30	15.60	15.70	16.20	15.60	15.60	15.50
CAO	20.80	19.60	20.20	19.70	18.50	20.90	19.70	20.70	21.00	18.90	20.80	20.00	16.50
NA20	0.32	0.36	0.33	0.39	0.31	0.34	0.35	0.34	0.33	0.38	0.34	0.37	0.25
TI02	1.04	1.78	1.51	1.63	1.06	1.35	1.70	1.28	1.26	1.43	1.32	2.00	1.23
MNO	0.13	0.21	0.18	0.20	0.18	0.15	0.24	0.16	0.15	0.23	0.16	0.24	0.28
CR203	0.64	0.20	0.08	0.06	0.14	0.20	0.03	0.10	0.45	0.03	0.12	0.06	0.18
TOTAL	101.27	100.25	100.77	96.99	99.71	99.80	102.19	98.04	99.99	99.18	99.07	103.70	98.35

	D					E						F	
	-1CC c	-2CC c	-3PC p	-4PC p	-5G g	X-1PC p	X-2PC p	X-2PE r	X-3PC p	X-4PC p	X-6G g	X-1PC p	X-2PC p
SI02	52.10	51.60	48.30	48.90	48.20	52.00	49.70	50.00	50.10	51.20	52.00	50.40	51.50
AL203	2.94	2.88	4.85	4.05	2.76	3.15	3.59	3.49	3.17	5.08	2.33	3.26	4.00
FEO	7.50	7.90	9.50	9.10	11.20	6.40	6.10	7.90	6.00	6.10	10.50	7.80	7.70
MGO	16.60	16.30	15.50	16.10	14.80	17.10	16.70	16.60	16.60	17.70	16.40	16.20	16.00
CAO	20.40	20.30	19.20	18.60	17.50	20.00	20.00	19.20	19.80	20.00	18.50	20.30	21.10
NA20	0.28	0.30	0.32	0.26	0.27	0.24	0.27	0.26	0.29	0.26	0.14	0.35	0.35
TI02	1.06	1.08	2.07	1.55	1.52	0.92	0.78	1.14	0.89	1.14	0.86	1.13	1.19
MNO	0.18	0.17	0.18	0.21	0.26	0.15	0.13	0.21	0.16	0.15	0.32	0.17	0.16
CR203	0.18	0.16	0.14	0.12	0.04	0.31	0.49	0.03	0.24	0.61	0.05	0.35	0.34
TOTAL	101.24	100.69	100.06	98.89	96.55	100.27	97.76	98.83	97.25	102.24	101.10	99.96	102.34

	F (cont'd)		G					I					J
	X-2PE r	X-3G g	X-1PC p	X-1PE r	X-2PC p	X-2PE r	X-3CC c	X-4G g	X-1PC p	X-1PE r	X-2C c	X-3C c	PX-1P p
SI02	49.50	49.30	51.70	50.30	51.00	51.60	51.30	51.30	51.90	50.50	50.90	51.10	51.30
AL203	3.02	4.20	3.52	3.97	3.48	2.52	3.15	3.23	3.62	2.78	3.65	3.86	3.96
FEO	8.90	9.80	5.90	8.60	7.60	9.30	6.90	7.40	5.70	11.10	7.20	6.70	5.30
MGO	14.30	14.30	16.20	15.00	15.00	15.70	15.50	16.00	16.30	14.30	15.60	15.40	16.10
CAO	20.60	20.50	21.20	19.30	21.20	19.40	20.70	20.30	20.50	18.90	21.10	20.90	21.10
NA20	0.36	0.41	0.35	0.37	0.40	0.32	0.35	0.41	0.31	0.35	0.36	0.36	0.32
TI02	1.66	2.42	0.95	1.80	1.45	1.47	1.22	1.33	0.87	1.58	1.46	1.44	1.89
MNO	0.18	0.16	0.15	0.25	0.20	0.22	0.17	0.28	0.15	0.13	0.17	0.16	0.13
CR203	0.07	0.10	0.65	0.08	0.16	0.07	0.21	0.04	0.62	0.64	0.18	0.33	0.72
TOTAL	98.59	101.19	100.62	99.67	100.49	100.60	99.50	100.29	99.97	100.28	100.62	100.25	100.82

TABLES 1-7

TABLE 5.—Chemical analyses of clinopyroxenes from the Kalaupapa section—Continued

	J (cont'd)					K						L	
	PX2PC p	PX3CC c	PX3CE e	PX4CC c	PX4CE e	PX1CC c	PX1CE e	X1CE2 e	PX-2C c	PX3CC c	PX3CE e	PX-5G g	PX1PC p
SI02	50.90	50.20	50.40	51.30	50.20	51.10	50.30	50.40	50.70	51.50	49.50	51.30	51.00
AL203	3.80	4.20	2.41	3.76	4.24	2.82	1.61	2.40	3.84	2.50	2.47	2.27	4.36
FEO	6.60	6.10	13.50	6.00	9.10	7.50	14.30	12.70	7.40	7.60	12.90	10.90	6.20
MGO	15.60	15.00	13.40	15.90	15.00	15.70	12.40	13.50	15.50	16.00	13.20	15.00	16.00
CAO	20.70	19.70	18.70	21.30	19.70	20.40	18.20	18.50	20.60	20.60	19.30	18.90	20.90
NA2O	0.36	0.36	0.37	0.33	0.38	0.36	0.35	0.46	0.38	0.37	0.42	0.37	0.36
TiO2	1.37	1.50	1.43	1.17	1.66	1.26	1.06	1.07	1.78	1.17	1.39	1.40	1.10
MNO	0.16	0.14	0.31	0.15	0.22	0.21	0.35	0.29	0.16	0.20	0.28	0.25	0.15
CR2O3	0.39	0.30	0.01	0.64	0.16	0.18	0.01	0.06	0.52	0.19	0.02	0.08	0.67
TOTAL	99.83	97.50	100.53	100.55	100.66	99.53	98.58	99.38	100.38	100.13	99.48	100.47	100.74

	L (cont'd)					M						N	
	PX1PF r	PX2PC p	PX2PE r	PX-3C c	PX-4C c	PX-5G g	PX1PC p	PX1PE r	PX2PC p	PX-3C c	PX-4C c	PX-5G g	PX1PC p
SI02	51.00	47.20	49.70	50.00	47.40	48.00	51.10	50.50	50.40	50.70	49.70	49.80	50.50
AL203	3.00	7.10	2.86	4.89	6.80	5.30	2.76	2.96	3.96	3.40	4.70	3.57	4.13
FEO	8.80	7.10	9.30	6.80	7.30	9.00	9.70	8.60	6.30	7.40	7.00	8.70	6.40
MGO	14.10	14.00	13.40	15.00	13.90	13.80	14.50	14.30	15.60	16.00	14.80	15.30	15.40
CAO	20.80	20.40	20.50	20.80	21.00	20.40	20.30	20.90	21.00	19.90	20.90	19.40	21.60
NA2O	0.42	0.48	0.39	0.40	0.40	0.45	0.48	0.43	0.37	0.41	0.37	0.42	0.39
TiO2	1.60	2.60	1.74	1.44	2.45	2.51	1.32	1.89	1.42	1.38	1.64	2.05	1.30
MNO	0.27	0.16	0.22	0.16	0.14	0.22	0.28	0.23	0.14	0.18	0.15	0.20	0.17
CR2O3	0.04	0.45	0.05	0.44	0.21	0.17	0.02	0.45	0.23	0.35	0.10	0.45	0.45
TOTAL	99.98	99.49	98.16	99.93	99.60	99.85	100.44	99.83	99.64	99.60	99.61	99.54	100.34

	N (cont'd)					O			P		Q		
	PX1PE r	PX2PC p	PX2PE r	PX-3C c	PX-4G g	PX1CC c	PX1CE e	PX-3G g	PX1PC p	PX1PE r	PX-2G g	PX-1G g	PX-2G g
SI02	50.30	50.90	51.20	48.20	47.00	50.20	48.80	48.30	50.60	49.10	47.80	48.40	48.60
AL203	2.95	4.26	1.99	5.97	5.81	3.92	3.69	4.00	3.03	3.49	4.37	2.50	4.36
FEO	9.10	5.50	10.10	7.20	9.60	7.90	12.00	10.40	8.40	10.70	11.20	9.90	9.50
MGO	14.40	16.30	14.40	14.30	13.10	14.90	12.90	13.10	14.80	14.50	12.20	14.60	13.90
CAO	20.90	21.30	20.20	21.60	20.80	21.10	20.00	20.00	21.00	19.50	19.30	20.40	20.20
NA2O	0.45	0.35	0.61	0.42	0.50	0.46	0.45	0.54	0.48	0.37	0.47	0.43	0.46
TiO2	1.79	0.96	1.27	2.24	2.73	1.77	2.52	2.76	1.48	2.56	2.97	1.59	2.82
MNO	0.23	0.12	0.30	0.17	0.19	0.16	0.22	0.21	0.26	0.27	0.23	0.25	0.21
CR2O3	0.07	0.74	0.02	0.45	0.04	0.13	0.05	0.01	0.02	0.02	0.05	0.03	0.05
TOTAL	100.19	100.43	100.09	100.55	99.77	100.54	100.63	99.36	100.06	100.51	98.59	98.10	100.10

TABLE 5.—Chemical analyses of clinopyroxenes from the Kalaupapa section—Continued

	R		S		T						U		
	PX-1G g	PX-2G g	PX-1G g	PX-2G g	X-1PC p	X-1PF p	X-2CC c	X-2CE e	X-3CC c	X-3CE e	X-4G g	X-1PC p	X-1PE r
SI02	48.40	50.90	49.40	50.90	50.30	50.80	50.30	50.20	50.50	51.40	50.80	49.20	49.80
AL203	4.90	4.07	4.29	2.04	3.80	2.32	3.80	2.83	3.71	2.20	2.86	4.97	3.21
FEO	9.10	10.70	9.60	8.80	7.00	10.50	7.50	9.40	6.80	8.90	8.00	6.80	8.20
MGO	14.30	14.20	14.00	15.00	15.60	14.40	15.10	15.00	15.90	14.80	15.40	14.60	13.80
CAO	20.10	19.80	19.30	20.20	21.30	19.80	21.10	19.80	21.10	19.70	19.40	21.00	21.20
NA20	0.44	0.43	0.43	0.41	0.41	0.38	0.42	0.36	0.35	0.43	0.35	0.46	0.49
TI02	2.59	1.81	2.13	1.45	1.26	1.55	1.62	1.81	1.21	1.28	1.40	1.73	1.72
MNO	0.21	0.24	0.21	0.22	0.16	0.13	0.18	0.28	0.17	0.27	0.38	0.15	0.17
CR203	0.20	0.02	0.15	0.15	0.32	0.19	0.27	0.02	0.33	0.02	0.01	0.37	0.10
TOTAL	100.24	102.17	99.51	99.17	100.15	100.07	100.29	99.70	100.07	99.00	98.60	99.28	98.69

	(cont'd)		V		W			X			Y		
	X-2CE e	X-3G g	X1MPC p	X1MPE r	X-2G g	X1MPC p	X1MPE e	X-2G g	X-3G g	X-1G g	X-2G g	X-3G g	X-1CC c
SI02	48.90	49.60	49.20	49.30	49.70	47.80	46.20	48.80	50.60	46.90	46.10	47.20	49.80
AL203	3.48	3.20	3.82	3.27	3.01	5.09	5.82	3.76	2.69	5.06	5.71	4.75	4.54
FEO	11.50	9.40	8.50	10.70	10.50	9.10	14.00	11.20	10.50	9.70	10.20	10.00	7.30
MGO	12.00	14.10	14.40	13.20	13.60	13.30	11.10	12.10	13.90	12.30	12.00	12.30	15.40
CAO	20.30	20.60	21.30	20.40	19.70	21.00	19.10	19.80	19.30	20.60	20.90	21.00	20.70
NA20	0.58	0.48	0.46	0.48	0.37	0.45	0.71	0.65	0.41	0.56	0.57	0.55	0.35
TI02	2.29	2.15	2.00	2.22	1.92	2.89	2.67	2.45	1.79	3.98	4.05	3.60	1.52
MNO	0.33	0.24	0.19	0.28	0.27	0.24	0.27	0.36	0.27	0.26	0.25	0.26	0.19
CR203	0.01	0.01	0.03	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.40
TOTAL	99.39	99.78	99.90	99.87	99.09	99.90	99.90	99.15	99.50	99.40	99.81	99.69	100.20

	Y (cont'd)						Z						
	X-1CE e	X-2PC p	X-2PE r	X-3CC c	X-3CE e	X4MPC p	X4MPE e	X-5G g	X-1G g	X-2G g	PX1PC p	PX1PE r	PX-2G g
SI02	48.70	49.60	49.40	49.90	49.00	51.60	47.90	47.00	51.00	51.60	49.90	49.60	49.50
AL203	3.85	4.97	5.39	4.47	4.76	2.83	6.29	6.72	2.68	2.03	4.27	3.49	3.17
FEO	11.00	7.80	8.40	6.90	9.10	6.80	9.20	8.20	9.20	8.80	7.90	12.80	13.90
MGO	12.60	14.90	13.30	16.10	15.30	15.50	13.10	13.30	13.40	13.80	15.30	12.40	11.30
CAO	20.40	20.40	20.90	20.50	19.40	19.70	21.00	20.80	20.10	20.00	19.90	19.30	19.80
NA20	0.49	0.35	0.33	0.31	0.29	0.29	0.38	0.39	0.74	0.64	0.44	0.38	0.42
TI02	2.28	1.79	2.06	1.55	2.36	0.98	2.50	2.70	1.36	1.39	1.60	2.14	1.97
MNO	0.32	0.20	0.19	0.20	0.23	0.21	0.20	0.22	0.42	0.38	0.20	0.28	0.34
CR203	0.04	0.40	0.17	0.38	0.19	0.32	0.28	0.19	0.02	0.03	0.21	0.05	0.04
TOTAL	99.68	100.41	100.14	100.31	100.63	98.23	100.85	99.52	98.92	98.67	99.72	100.44	100.44

TABLES 1-7

TABLE 6.—*Chemical analyses of plagioclases from the Kalaupapa section*

[Localities A-Z are shown in fig. 3. Plotting symbols are p=central part of a phenocryst or microphenocryst, r=rim of a phenocryst or microphenocryst, c=central part of a plagioclase grain in a cluster, e=rim (edge) of a plagioclase grain in a cluster, and g=groundmass plagioclase lath]

	A					B					C	
	-1PC p	-1PE r	-2C c	-3MP p	-4G g	-1PC p	-1PE r	-2CC c	-2CE e	-3G g	-1MP p	-2G g
SI02	50.50	52.70	52.20	52.50	55.90	49.10	52.60	48.80	52.70	53.10	51.10	53.30
AL203	30.70	30.20	29.60	30.00	27.70	31.80	29.50	31.60	27.40	28.80	30.20	29.10
FE203	0.77	0.89	0.83	0.95	1.25	0.78	1.20	0.89	1.24	1.16	0.78	1.01
CA0	13.40	12.40	12.30	12.80	10.40	14.60	11.90	14.90	12.20	12.20	13.40	11.90
NA20	3.61	4.37	4.31	4.11	5.59	3.00	4.64	2.83	4.57	4.64	3.88	4.82
K20	0.06	0.15	0.13	0.15	0.39	0.04	0.25	0.08	0.30	0.27	0.07	0.20
BA0									0.01			
TOTAL	99.04	100.71	99.37	100.51	101.23	99.32	100.09	99.10	98.41	100.18	99.43	100.33

	D					E		F				
	-1PC p	-1PE r	-2CC c	-2CE e	-3G g	C-1G g	C-2MP p	C-1CC c	C-1CE e	C-2PC p	C-2PE r	C-3PC p
SI02	51.50	53.30	51.80	56.40	55.80	53.20	51.10	50.90	51.80	52.00	51.30	50.90
AL203	30.90	31.00	30.50	25.00	28.40	28.90	30.60	31.60	30.80	30.30	29.80	31.70
FE203	0.74	1.06	0.82	0.98	1.02	0.96	1.15	0.64	0.77	0.68	0.97	0.73
CA0	14.30	13.30	13.70	10.30	12.50	12.30	14.40	15.30	14.80	13.10	13.70	15.90
NA20	3.45	4.09	3.46	5.61	4.71	4.05	3.15	2.84	3.36	3.92	3.85	2.71
K20	0.04	0.08	0.06	0.49	0.25	0.29	0.18	0.03	0.09	0.09	0.13	0.05
BA0				0.02					0.01			
TOTAL	100.93	102.83	100.34	98.80	102.68	99.70	100.58	101.31	101.63	100.09	99.75	101.99

	F (cont'd)											
	C-3PE r	C-4G g	C-1PC p	C-1PE r	C-2CC c	C-2C e	C-3MP p	C-4G g	C-1PC p	C-1PE r	C-2PC p	C-2PE r
SI02	51.60	55.30	49.40	51.00	50.50	55.00	51.60	56.20	49.80	53.60	49.60	53.40
AL203	29.70	27.30	32.10	31.40	30.80	28.20	29.80	27.70	31.70	29.70	32.00	28.30
FE203	0.94	0.92	0.79	0.98	0.82	1.20	0.87	1.06	0.77	0.86	0.80	0.97
CA0	12.60	10.70	16.00	15.30	14.50	11.30	13.20	11.00	15.70	12.90	15.50	10.90
NA20	4.00	5.58	2.20	2.74	2.83	4.69	3.44	4.90	2.62	4.33	2.50	4.70
K20	0.13	0.27	0.06	0.09	0.12	0.30	0.14	0.38	0.07	0.20	0.06	0.28
BA0											0.01	
TOTAL	98.97	100.07	100.55	101.51	99.57	100.69	99.05	101.24	100.66	101.59	100.47	98.56

TABLE 6.—Chemical analyses of plagioclases from the Kalaupapa section—Continued

	I (cont'd)		J				K				L	
	C-3MP p	C-4G g	PC1PC p	PC1PE r	PC2MP p	PC-3G g	PC1PC p	PC2CC c	PC2CE e	PC-3G g	PC1MP p	PC1MP r
SI02	52.00	54.10	49.20	54.40	54.60	57.20	51.90	51.00	61.50	57.90	53.50	58.90
AL203	28.90	27.90	31.90	28.20	28.50	27.00	29.90	31.20	26.10	26.20	29.40	27.60
FE203	0.73	0.97	0.73	0.86	0.89	0.98	0.76	0.82	0.69	0.94	0.82	0.82
CAO	12.00	11.00	15.90	12.40	12.10	10.70	13.90	14.30	7.60	9.50	12.50	9.50
NA20	3.92	4.61	2.50	4.67	4.57	5.19	3.44	2.90	6.33	5.62	3.81	5.46
K20	0.16	0.45	0.07	0.35	0.29	0.53	0.16	0.10	0.77	0.72	0.20	0.52
BAO			0.02	0.01	0.02	0.02	0.02		0.07	0.02	0.04	0.01
TOTAL	97.71	99.03	100.32	100.89	100.96	101.62	100.08	100.32	103.06	100.90	100.27	102.81

	L (cont'd)		M		N		O				P	
	PC2MP p	PC-3G g	PC1MP p	PC-2G g	PC1MP p	PC-2G g	PC1CC c	PC1CE e	PC2PC p	PC3MP p	PC-4G g	PC1PC p
SI02	52.50	54.00	52.80	57.50	49.50	53.60	51.50	56.60	51.50	52.80	58.70	50.00
AL203	30.20	28.60	29.90	27.30	29.90	28.00	30.90	28.10	30.80	30.20	26.50	31.50
FE203	0.74	0.95	0.77	1.21	0.94	1.29	0.73	0.95	0.80	0.74	0.78	0.80
CAO	13.30	12.50	13.20	10.60	13.40	10.70	14.10	10.20	13.60	13.30	8.80	14.00
NA20	3.67	4.41	3.65	5.32	3.73	5.20	3.53	5.75	3.77	3.99	6.50	3.50
K20	0.18	0.27	0.18	0.43	0.21	0.32	0.16	0.41	0.15	0.18	0.60	0.12
BAO		0.03	0.04	0.02		0.02				0.02	0.02	
TOTAL	100.59	100.76	100.54	102.38	97.68	99.13	100.92	102.01	100.62	101.23	101.90	99.92

	P (cont'd)		Q				R				S	
	PC1PE r	PC2MP p	PC-3G g	PC1PC p	PC1PF r	PC-2C c	PC3MP p	PC-4G g	PC1MP p	PC-2G g	PC1MP p	PC-2G g
SI02	54.70	52.10	57.40	48.80	56.00	51.80	51.50	54.20	54.10	57.60	53.40	52.50
AL203	25.40	29.10	25.30	31.90	28.40	30.20	30.30	28.90	28.90	25.90	28.40	28.00
FE203	0.84	0.86	0.81	0.73	0.91	0.87	0.75	0.87	0.83	0.87	1.14	1.19
CAO	9.50	12.80	8.90	16.50	9.90	13.50	13.00	11.20	12.80	8.40	11.50	12.30
NA20	5.96	4.37	6.52	2.34	5.78	3.89	4.10	5.36	4.54	6.81	4.74	4.66
K20	0.99	0.22	1.01	0.11	0.38	0.20	0.20	0.30	0.28	0.72	0.34	0.42
BAO			0.06					0.04	0.01	0.01	0.03	0.03
TOTAL	97.39	99.45	100.00	100.38	101.37	100.46	99.85	100.87	101.46	100.31	99.55	99.10

TABLES 1-7

TABLE 6.—Chemical analyses of plagioclases from the Kalaupapa section—Continued

	T				U				V			
	C-1PC p	C-1PE r	C-2MP p	C-3G g	C-1PC p	C-1PE r	C-2PC p	C-2PE r	C-3MP p	C-4G g	C-1PC p	C-1PE r
SI02	50.20	54.10	52.20	54.80	52.00	53.90	50.10	55.60	53.00	58.90	52.40	54.10
AL203	33.10	29.50	31.90	29.40	30.90	28.60	31.70	29.50	29.60	27.00	29.40	28.70
FE203	0.70	0.84	0.76	1.10	0.61	0.65	0.69	0.82	0.83	0.69	0.65	0.63
CAO	15.20	12.40	14.30	12.00	13.30	11.60	14.70	10.50	12.00	8.70	11.90	9.80
NA20	2.33	4.07	3.18	4.44	3.76	4.82	3.01	5.40	4.61	6.34	4.06	5.17
K2O	0.07	0.30	0.12	0.30	0.23	0.38	0.13	0.33	0.29	0.59	0.29	0.38
BAO				0.01	0.02	0.01			0.01	0.09	0.03	0.12
TOTAL	101.60	101.21	102.46	102.05	100.82	99.96	100.33	102.15	100.34	102.31	98.73	98.90

	V (cont'd)				W				X			
	C-2PC p	C-2PE r	C-3MP p	C-3MP r	C-4G g	C-1PC p	C-1PE r	C-2PC p	C-2PE r	C-4G g	C-1MP p	C-1PE r
SI02	54.60	55.10	53.20	56.60	57.50	52.90	54.50	53.40	57.80	57.00	52.30	56.60
AL203	29.80	27.70	29.70	28.00	25.50	29.50	28.40	28.00	27.80	27.00	29.70	27.00
FE203	0.72	0.87	0.65	0.62	0.84	0.63	0.76	0.75	0.75	0.90	0.55	0.54
CAO	11.80	10.70	12.00	10.00	8.60	11.50	7.60	11.60	9.50	8.80	11.70	9.90
NA20	4.54	5.08	4.43	5.73	6.28	4.33	5.36	4.22	5.73	6.13	4.48	6.74
K2O	0.26	0.55	0.27	0.47	0.94	0.29	0.39	0.28	0.46	0.66	0.31	0.82
BAO	0.02	0.01	0.02	0.14		0.01	0.01	0.02	0.03	0.03	0.04	
TOTAL	101.74	100.01	100.27	101.56	99.66	99.16	97.02	98.27	102.07	100.52	99.08	101.60

	X (cont'd)		Y		Z		
	C-2MP p	C-3G g	C-1MP p	C-2G g	C-1MP p	C-2MP p	C-3G g
SI02	59.10	53.10	53.90	54.70	55.70	56.00	57.80
AL203	26.20	27.50	29.20	29.60	28.10	28.50	23.10
FE203	0.51	0.59	0.86	0.87	0.60	0.40	0.84
CAO	6.80	11.30	12.20	12.40	10.10	10.10	7.50
NA20	6.83	4.80	4.35	4.47	5.56	5.57	6.97
K2O	0.82	0.55	0.32	0.43	0.41	0.50	2.36
BAO	0.08	0.02	0.02	0.01	0.07	0.04	0.07
TOTAL	100.34	97.86	100.85	102.48	100.54	101.11	98.64

TABLE 7.—Chemical analyses of opaque minerals from the Kalaupapa section

[Localities A-Z are shown in fig. 3. Plotting symbols are p=microphenocryst, r=rim of phenocryst, e=edge of groundmass grain, i=inclusion in olivine, and g=groundmass grain]

	A						B			C	D	E
	-1MPC p	-1MPE r	-2MPC p	-2MPE r	-3G g	-3G g	-1MP p	-2MP p	-3G g	-1G g	-1G g	L-1G g
AL203	14.30	2.67	13.40	2.45	1.90	0.40	2.68	4.36	1.32	0.51	2.67	0.54
FEO	41.10	66.40	45.90	68.40	75.30	45.10	74.70	64.00	35.70	52.60	74.00	48.90
MGO	6.80	3.62	5.40	3.03	1.29	2.49	3.90	4.85	4.38	1.77	0.70	5.45
TI02	3.46	20.20	4.45	20.40	16.50	48.50	11.80	8.60	55.60	45.70	20.30	43.00
CR203	33.30	2.29	31.40	2.00	0.40	0.04	7.35	22.00	0.03	0.02	0.01	0.28
TOTAL	98.96	95.18	100.55	96.28	95.39	96.53	100.43	103.81	97.03	100.60	97.68	98.17

	E (cont'd)		F				G					
	L-2G g	L-2GE e	T-1MP p	T-2I i	T-3G g	L-3GE e	CT1MP p	CT1MP p	MT-2G g	MT-2G g	IL-2G g	IL-2G g
AL203	0.53	0.88	3.77	16.60	0.69	1.47	17.70	18.80	2.43	2.53	0.41	0.33
FEO	51.20	46.20	62.40	41.10	71.20	52.10	36.50	35.50	78.50	78.30	48.00	47.20
MGO	5.59	5.29	3.04	10.30	1.45	1.73	8.60	8.50	1.02	0.95	1.98	2.01
TI02	41.00	39.20	18.40	4.73	22.50	30.90	2.84	2.98	12.20	11.90	47.40	47.50
CR203	0.28	0.26	8.60	27.70	0.04	0.01	36.20	34.40	0.50	0.08	0.20	0.03
TOTAL	98.60	91.83	96.21	100.43	95.90	86.21	101.84	100.18	94.65	93.76	97.99	97.07

	G (cont'd)			I						J		
	CT-3I i	CT-3I i	CT-3I i	T-1MP p	T-1MP p	T-1MP r	T-2MP r	T-2G g	T-2G g	MT-1I i	IL-1I i	MT-2G g
AL203	14.60	15.00	7.90	4.55	2.59	2.04	1.25	1.82	1.44	10.00	8.20	1.36
FEO	45.30	44.40	42.40	58.80	63.70	60.00	63.50	71.20	70.90	69.30	43.20	70.70
MGO	7.65	7.47	5.12	2.84	1.67	1.60	1.39	1.09	0.96	4.67	6.60	1.33
TI02	3.03	5.07	22.60	15.40	22.00	23.10	25.90	22.00	23.10	11.40	37.20	22.90
CR203	27.50	27.70	17.20	17.50	1.86	0.46	0.32	0.03	0.05	0.03	0.03	0.11
TOTAL	98.08	99.64	95.22	99.09	91.82	87.20	92.36	96.14	96.45	95.40	95.20	96.40

	K		L		M							
	IL-1G g	CT1MP p	MT1MP r	MT-2G g	CT1MP p	CT1MP p	CT1MP r	CT2MP p	CT2MP p	MT-3G g	MT-3G g	IL-3G g
AL203	0.20	15.90	2.33	1.62	12.40	12.60	6.60	11.70	11.60	1.99	0.51	0.30
FEO	49.00	42.60	63.90	63.10	44.10	50.30	35.70	32.00	31.20	74.90	52.40	37.00
MGO	0.88	6.10	2.23	2.17	8.90	5.03	4.72	7.41	7.47	3.45	3.51	2.82
TI02	48.90	4.23	25.00	27.40	7.30	8.40	31.90	1.87	1.75	10.00	35.90	48.40
CR203		33.10	0.65	0.04	22.50	23.70	14.20	48.70	51.90	0.12	0.03	
TOTAL	98.98	101.93	94.11	94.33	95.20	100.03	93.12	101.68	103.92	90.46	92.35	88.52

TABLES 1-7

TABLE 7.—Chemical analyses of opaque minerals from the Kalaupapa section—Continued

	M (cont'd)				N							
	RT-3G g	CT1MP p	CT1MP p	MT1MP r	MT1MP r	CT2MP p	CT2MP p	MT2MP r	MT2MP r	MT-3G g	MT-3G g	IL-3G g
AL203	1.92	17.70	18.30	5.23	5.51	16.60	16.60	3.18	3.69	1.85	2.86	0.41
FEO	5.29	37.70	35.30	50.30	53.40	40.10	41.30	62.10	59.60	64.40	75.10	40.20
MGO		10.00	10.40	3.42	3.45	8.60	7.92	3.96	4.00	2.05	2.23	4.06
TiO2	88.70	4.04	4.05	23.00	21.40	4.36	4.31	22.40	23.50	21.70	13.20	53.00
CR203	0.06	29.20	31.00	10.70	11.80	29.60	30.50	3.54	4.57	3.20	0.07	
TOTAL	95.97	98.64	99.05	92.65	95.56	99.26	100.63	95.18	95.36	93.20	93.46	97.67

	O								P			
	IL-3G g	MT1MP p	MT1MP p	IL1MP r	IL1MP r	MT2MP p	MT2MP p	IL2MP r	IL2MP r	IL-3G g	IL-3G g	CT-1I i
AL203	0.39	3.70	3.71	0.90	0.76	0.83	2.25	0.88	0.36	0.33	0.19	16.50
FEO	39.00	77.20	80.60	47.80	28.00	70.70	78.00	39.70	35.00	39.10	30.10	29.50
MGO	3.56	2.86	2.77	1.54	0.51	1.24	2.57	1.54	0.67	1.87	1.50	11.10
TiO2	53.00	3.32	2.94	38.40	67.50	18.30	5.80	49.90	58.90	53.80	56.90	2.86
CR203		3.88	4.33	1.33	1.60	0.03	0.08	0.01	0.03		0.01	34.70
TOTAL	95.95	90.96	94.35	89.97	98.37	91.10	88.70	92.03	94.96	95.10	88.70	94.66

	P (cont'd)				Q							
	CT-1I i	IL2MP p	IL-3G g	MT1MP p	MT1MP p	MT1MP r	MT1MP r	MT2MP p	MT2MP p	CT3MP p	CT3MP p	CT3MP r
AL203	4.80	0.30	0.34	9.90	9.30	3.22	3.18	2.36	3.04	12.80	12.50	5.80
FEO	54.10	46.80	45.80	55.00	58.50	61.70	59.60	62.00	61.20	41.30	52.10	31.60
MGO	5.17	1.09	1.02	4.05	4.11	3.76	4.28	3.72	3.61	9.10	7.80	4.70
TiO2	18.30	48.20	48.00	12.70	14.30	23.00	27.30	23.30	24.80	8.18	8.60	14.90
CR203	13.30			13.20	13.60	5.50	3.69	5.70	7.10	18.50	18.40	11.80
TOTAL	95.67	96.39	95.16	94.85	99.81	97.18	98.05	97.08	99.75	89.88	99.40	68.80

	Q (cont'd)						R					
	MT3MP r	MT4MP p	MT4MP p	MT4MP r	IL-5G g	IL-5G g	MT1MP p	MT1MP p	IL1MP r	IL1MP r	IL-2G g	IL-2G g
AL203	4.79	7.60	8.10	3.42	0.33	0.53	1.52	1.57	0.62	0.51	0.30	0.39
FEO	57.50	55.20	62.90	62.80	44.40	46.10	76.30	82.40	45.20	46.70	46.40	47.00
MGO	4.96	3.91	3.88	3.32	3.14	3.31	0.72	0.67	1.43	1.44	2.56	2.55
TiO2	21.60	14.30	15.70	17.80	49.80	50.10	14.20	11.60	48.60	48.60	49.50	50.40
CR203	6.50	11.00	10.90	5.90	0.03	0.03	0.20	0.05		0.01		0.01
TOTAL	95.35	92.01	101.48	93.24	97.67	100.07	92.94	96.29	95.85	97.26	98.76	100.35

TABLE 7.—Chemical analyses of opaque minerals from the Kalaupapa section—Continued

	S			T			U				V	
	IL-1G g	T-1MP p	LIMPE r	T-3G g	T-3G g	L-4G g	T-1MP p	T-1MP p	T-2MP p	T-3G g	T-1MP p	T-1MP p
AL203	0.39	6.50	0.63	2.53	0.39	0.27	5.70	4.28	4.09	1.13	2.62	2.58
FE0	38.30	57.00	49.80	85.50	61.20	44.10	58.40	62.30	64.20	69.80	75.80	53.10
MGO	2.17	3.08	3.33	1.18	2.79	3.99	4.76	4.75	3.87	1.32	1.25	2.00
TI02	56.30	11.60	41.50	4.39	29.60	49.30	14.30	16.00	19.70	25.00	9.90	34.00
CR203		20.30	1.67	0.07	0.02	0.02	8.20	3.95	2.87	0.05	3.37	5.40
TOTAL	97.16	98.48	96.93	93.67	94.00	97.68	91.36	91.28	94.73	97.30	92.94	97.08

	V (cont'd)			W		X		Y				
	T-2MP p	T-3G g	T-3G g	L-1G g	L-2G g	T-1G g	L-2G g	T-1MP p	T-1MP r	T-2MP p	L-2MP r	T-3G g
AL203	1.64	0.73	0.42	0.22	0.28	1.28	0.32	19.90	1.24	17.50	3.39	1.31
FE0	64.50	71.40	54.30	43.20	40.80	68.40	47.30	27.10	56.70	31.10	42.40	70.10
MGO	2.25	1.43	0.60	0.88	1.25	1.52	1.31	13.30	3.59	10.60	3.24	1.03
TI02	23.70	19.30	38.20	50.50	50.00	25.70	49.50	1.70	18.20	2.03	35.30	21.40
CR203	3.13	0.07	0.04	0.04	0.02	0.13	0.01	38.90	2.21	40.70	4.96	0.05
TOTAL	95.22	92.93	93.56	94.84	92.35	97.03	98.44	100.90	81.94	101.93	89.29	93.89

	Y (cont'd)			Z	
	T-3G g	T-1MP p	T-2MP p	T-3G g	L-4G g
AL203	1.08	1.58	1.69	1.57	0.42
FE0	48.70	69.10	69.00	70.50	43.40
MGO	1.56	3.28	2.87	2.76	3.47
TI02	31.40	22.50	22.60	21.40	49.80
CR203	0.04	0.09	0.14	0.04	0.02
TOTAL	82.78	96.55	96.30	96.27	97.11

TABLES 1-7

