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DISTRIBUTION AND CHARACTERISTICS OF DIKES IN THE SOUTHEAST PART OF THE KOOLAU RANGE

by Bigelow, Gordon E.

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ABSTRACT

Exposed dikes and sills trending southwest and roughly perpendicular to the primary Koolau rift zone in the Waialae-Palolo area of Oahu are hypersthene-bearing tholeiitic basalts, intrusive equivalents of the basalt lava flows of the Koolau Series. Thin section studies of 26 intrusives from this area, including 9 modal point counts, were carried out during June-November, 1967. No Honolulu Series intrusives were found along a line joining Kaau Crater, Mauumae, Kaimuki and Diamond Head, an alleged secondary rift of the Koolau volcano. Bouguer anomaly maps show no indications of substantial intrusive bodies along the southeast Honolulu Series trends, so simple dike feeders are inferred.

Intrusives studied were typically porphyritic with a fine-grained, hypocrystalline matrix, commonly intersertal in the coarser centers to hyaloophitic at chilled margins. No nepheline, melilite nor phenocryst augite was observed. Olivine was less than 5% of modal volume except in the Waialaenui 'bud.' Labradorite of intermediate composition occurs as phenocrysts, normally zoned, and matrix laths with clinopyroxene and ores. Proportions of augite and pigeonite could not be determined due to the small size of the crystals and their abundant inclusions of opaque minerals. Refractive index of tachylite in chilled margins indicates approximately 50% silica content.

The suggested crystallization sequence is as follows: Olivine formed earliest, occasionally preceded by minor magnetite; orthopyroxene and plagioclase next, in close association, with precedence uncertain. Orthopyroxene separation ceases before groundmass formation, but plagioclase continues to crystallize at increasingly numerous nuclei

with clinopyroxenes and ores. The remaining fluid finally congeals to dark brown tachylite filled with ore dust and incipient clinopyroxene crystals.

The modal count indicates an inverse relation in abundance of clinopyroxene to orthopyroxene. Further data are needed to confirm this. Plagioclase and magnetite are antipathetic throughout these rocks, despite the intimacy of magnetite with all other major species present.

Orthopyroxene and plagioclase are commonly associated in glomerocrysts which may eventually be useful as a basis to infer flow properties and crystallization sequences in magmas during emplacement.

SETTING AND PROCEDURE

Introduction

Intrusive bodies in the leeward slope of the Koolau Range, Oahu, have been shown to outcrop along trends closely parallel to the inferred secondary rift zones of Honolulu Series volcanics (Wentworth and Jones, 1940, p. 981). The Kaau rift, subject of this study, was held by Winchell (1947, p. 19) to be an underdeveloped primary south rift of the Koolau volcano. Four distinct Honolulu Series vents occur aligned S 25 W from Kaau Crater through Mauumae, Kaimuki and Diamond Head. Several other sites on windward Oahu suggest the continuation of the Kaau rift northeastward.

Though conspicuous in topographic expression, the Honolulu Series rifts do not seem to contain substantial intrusive bodies. A Bouguer gravity anomaly map of Oahu (Strange, Machesky and Woollard, 1965, p. 351) clearly suggests concentration of high density material along the primary northwest-trending Koolau rift. This anomaly has been interpreted as a volcanic plug (Adams and Furumoto, 1965, p. 296). The Koko, Kaau, Tantalus and Haiku rifts of the Honolulu Series show no corresponding gravity effects. The feeders of the Honolulu Series eruptions thus are probably simple dikes.

Dikes in the Palolo and Waialaenui Valleys consistently strike along the Kaau rift or parallel to the primary northwest rift of the Koolau volcano. The exploitation of this alleged Koolau zone of crustal weakness by highly fluid Honolulu Series eruptives suggested the possibility that some of the intrusives now exposed in the deeply incised Palolo and Waialaenui Valleys might be derived from these late-stage subsilicic magmas.

This study is a petrographic examination of 26 intrusives along the trend of the Kaau rift. Outcrop maps prepared by Stearns (1939) and by Wentworth and Jones (1940) indicate approximately 100 intrusive bodies located in this area. Exposures seldom exceed 20 feet, however, and are often less than 10 feet. The marked parallelism of these outcrops strongly suggests that many dikes mapped separately are actually coextensive under the mantle of soil and vegetation.

Field Procedure

Field work occupied 36 days in locating, mapping and sampling intrusives in the Pukele (west) and Waiomao (east) branches of the Palolo Valley and in the Waialaenui Valley. Dikes were sampled at centers and margins. For larger intrusives several samples were taken at intervals inward from margins.

Locations were established by Brunton compass, using utility poles and power lines as reference. The original plan was to use outcrop maps of previous workers as a guide to dike concentrations. Heavy vegetation and rugged topography prevented the precision in location necessary to utilize these aids, however. Dikes were then sought much as a mother lode is found from placers. Fragments of the dense, angular dike material, easily recognizable among the stream boulders, were traced upstream until they notably thinned or changed character. Talus was then pursued upslope to the outcrop. Dikes and sills totally obscured by vegetation were found in this manner. In most cases it was impossible to determine whether exposures located in this study correspond to those mapped by Stearns and by Wentworth and Jones.

The three ridges adjoining the Palolo and Waialaenui Valleys were also explored. Soil and vegetation cover all but the expansive 'buds' (Wentworth and Jones, 1940, p. 989) on the east slope of the Waialaenui Valley.

The vicinity of Kaau Crater was searched with particular thoroughness. Its proximity to the primary Koolau rift and the abundance of intrusives already mapped on its eastern flank made it a promising site for Honolulu Series intrusives. The exposed portions of Mauumae and Kaimuki dome were examined (no dikes) and the rim and crater of Diamond Head (no dikes). Hitchcock (1900, p. 45) described a basalt dike 3-6 feet wide, striking N 50° W, dipping 80° northeast on the southeast side of Diamond Head. He indicated an exposure of several hundred feet and structural relations suggesting origin later than Diamond Head tuff. He held it to resemble Kaimuki basalt. Wentworth (1926, p. 44-45) found two dikes at this location, one of them varying 4 inches to 2 feet in thickness.

A search of the area in August, 1967, disclosed no exposure. Much of the area has now been enclosed by retaining walls and other construction.

Field Structures and Relations

The deep dissection of the southern slope of the Koolau dome has formed a series of steep-sided, southwest-trending ridges with intervening valleys concentrating drainage rather abruptly in the uplands. The dome consists of lava flows, usually 4-12 feet in thickness, dipping gently southward in the area studied and showing little evidence of weathering between flows. The texture varies from coarsely vesicular and clinkery material on the tops and bottoms to dense, vertically-jointed blocks in the centers of flows. Lava tubes are common, but are generally small and only a few feet in length. None was found to have been filled by intrusion, though such fillings have been observed elsewhere in the Koolau Range.

Dikes commonly intersect the flows at high angles, near the normal to the flow plane. Of the intrusives observed, 13 dip less than 65°, however, and five were below 35°. Dike trends are commonly near S 45-55° W and S 40-50° E, but vary widely. Limited exposures preclude accurate determination of dip in many dikes (see Appendix).

The dike fissures appear structurally continuous across numerous subjacent flows, i.e., the system of flows has yielded as a structural unit. Even small dike stringers an inch or two thick seldom give expression to structural individuality of flows. This integrity of the flow system complicates the interpretation of intrusive bodies whose limited exposure dips approximately with the flows. Dikes are occasionally found with low dips in an attitude approaching that of the lava beds. In such cases, the relatively unconsolidated clinker between flows was not observed to offer a plane of weakness. Thus the interpretation of apparently conformable intrusives as sills required extreme caution in observing the contact, and often remained in doubt. The dips of five intrusives tentatively identified as sills ranged 5°-14°.

Variations in joints, banding and vesiculation have been related to depth of emplacement (Wentworth and Jones, 1940, p. 990-995) in these leeward Koolau intrusives. The comparatively limited field observations of this study support their conclusion that columnar jointing in dikes increases with depth of emplacement. Proportional volume of vesicles in the intrusive rock did not seem to decrease at lower elevations, however. Dikes at the head of the Kaau outlet stream, for example, averaged 2% vesicular volume whereas those near its foot, 500 feet below, averaged approximately the same for one group and 9% for another. These comparisons are based on center samples from the dikes.

Admittedly, the same dikes probably were not being sampled at both elevations, a qualification which may be significant if the intrusive material varied considerably in gaseous content at the time of emplacement; or if some dikes failed to reach the surface of the dome, trapping their volatiles temporarily. Because the surrounding rocks are quite permeable and show no marked indications of metasomatic effects, trapping of gases seems unlikely.

Dikes ranged in thickness from glassy stringers a fraction of an inch across and lensing out completely, to a dense, massively jointed holocrystalline body 78 inches wide.

Laboratory Procedure

At least five thin sections were prepared from samplings of each intrusive. A general petrographic description of each intrusive was then completed. Nine modal analyses (1000 points each) were performed, including two on different thin sections of the same dike. Powdered samples were prepared for each intrusive and oil immersion studies conducted to determine composition of feldspars, ferromagnesian minerals, and interstitial glass. Composition of matrix feldspar was determined by maximum extinction angles of microlites. (See Appendix for error data.)

PETROGRAPHY

The dikes and sills of this area are typically porphyritic with a fine-grained, hypocrystalline matrix, commonly intersertal in the coarser centers to hyaloophitic at the chilled margins. Phenocrysts constitute 1-40% of the rock consisting of olivine, orthopyroxene, plagioclase and, rarely, magnetite in widely varying combinations.

Olivine comprises 1-4% of the dikes and sills, though occasionally it was not observed in entire sections. It may constitute 20% by volume of the larger intrusives. Crystals range in size from matrix grains .02-0.1 mm across to phenocrysts 3.0 mm across. Individuals 1.0-1.5 mm long are common. Y-indices of 1.686-1.692 indicate compositions in the range Fo_{80-85}. Iddingsite rims are common, but are generally not well developed and frequently do not appear in an entire section. They manifest no relation to crystal size. In the Waialaenui bud their formation was more advanced, sometimes consuming entire large olivine phenocrysts. Hematite flakes sometimes appear in these rims in parallel arrangement or with their long dimension normal to the olivine margins. Parts of these rims showing variable coloration have indices considerably below olivine, perhaps an alteration product of the olivine (serpentine?). Overgrowths of pyroxene are rare and were not observed to accompany iddingsite. Second generations of late-growth olivine beyond iddingsite rims do not occur. Some olivine phenocrysts are euhedral, especially in dike margins, but more commonly rounded or deeply embayed crystals contain invasions of late-formed matrix minerals and glass. Infrequent cores of olivine in orthopyroxene phenocrysts have reacted almost completely. Long, very thin survivals of larger olivine phenocrysts are common.

Orthopyroxene shares with olivine the early phenocryst role (Cross, 1915, p. 19). Sizes range from 0.3-1.5 mm, apparently not extending into the groundmass size. $2V_x$ ranges of 80-85 and Z indices of 1.685-1.690 indicate compositions of En_{79-84}.

Orthopyroxene phenocrysts comprise 0.1-6.5% of the volume of dikes and sills, usually exceeding the olivine fraction. There is an apparent inverse relation between phenocryst abundance of orthopyroxene and groundmass abundance of clinopyroxene in these rocks.

The orthopyroxenes are typically clear and optically homogeneous. Inclusions of magnetite are not common. Exsolution lamellae were not observed. In thin sections of .04-.05 mm thickness distinct pleochroism was noted, from brownish pink in the fast direction to bluish green in the slow direction. Orthopyroxene phenocrysts also are distinctly rounded by resorption, but are only occasionally embayed. They frequently form cumuloporphyritic clusters alone or with feldspar phenocrysts of comparable size, often in subradial arrangement. Some stand distinctly apart from such clots, however, as do all of those with olivine cores. Olivine phenocrysts do not enter glomerocrysts. Orthopyroxene phenocrysts with clinopyroxene jackets rarely occur. This is the only association of clinopyroxene with the phenocryst phase and the rims probably formed during the period of groundmass crystallization.

Feldspar phenocrysts are evident in most of the intrusive bodies examined. Individuals 1.3-1.5 mm long are not unusual in the cumuloporphyry. Y indices of 1.560-1.567 indicate compositions An_{55-68} with the most frequent range 1.562-1.563 (An_{58-62}) corresponding to an intermediate labradorite. Larger phenocrysts show normal zoning in a thin outer rim. Carlsbad and pericline twinning are common, albite twins poorly and infrequently developed. A continuous gradation in crystal size extends into the groundmass stage. These matrix laths are generally .01-0.1 mm long. Measurement of microlite extinction angles indicates compositions of An_{56-65}. Total feldspar comprises 32-50% by volume of these rocks. Orthoclase and sanidine occur in micropegmatite in the Palolo Quarry intrusive.

Augite with $2V_z$ of 57-62 (determined by Kamb's method), pigeonite with $2V_z$ of 13-27 (determined by Tobi's method) and 'subcalcic augite' (Kuno and Nagashima, 1952, p. 1000) with $2V_z$ of 31-37 (Tobi) have been identified as grains .005-.15 mm across, but individuals with measurable optical properties are rare. Grains of clinopyroxene are characteristically pale brown, anhedral and interstitial to the feldspars. Clinopyroxenes constitute 29-39% of the volume in these intrusives. Because they are so small, inclusion-ridden, and do not manifest definable linear properties, composition of the clinopyroxenes remains in doubt. Birefringence is difficult to observe because of the optical effect of inclusions and the small sizes of the crystals themselves, which resulted in overlapping adjacent feldspars below the plane of focus of the microscope. The most useful data were obtained by choosing crystals with highest apparent birefringence and determining maximum indices in oil immersion. This procedure yields maximum slow direction values of 1.706-1.723. Without basis to determine calcium content, these data are not sufficient to establish the magnesium: iron ratio. Judgments cannot be made, therefore, as to the proportions of pigeonite, augite and possible intermediate compositions in these rocks.

Angular interstices in the groundmass are filled by amber to dark brown tachylite with index from 1.576 to 1.588, indicating a composition of 49-51% silica (George, 1924, p. 365). In chilled margins this glass sometimes exceeds 80% of the bulk volume.

Dust and skeletal crystals of magnetite are abundant in interstitial glass and matrix pyroxene, often rendering these hosts virtually opaque. Subordinate ilmenite may usually be identified. The larger olivine and orthopyroxene phenocrysts contain few or no ore inclusions. Smaller (presumably later formed) individuals in the same section include an increasing proportion of these ores. There is a conspicuous absence of ore inclusions in feldspars. Even the microlites, whose growth may be marginally impaired by preexisting magnetite grains, stand out boldly in the groundmass between pyroxene and tachylite areas overrun by abundant octahedrons of magnetite and flakes of ilmenite.

Magnetite grains reach diameters of 0.3-0.4 mm in the Waialaenui bud and actually entered the phenocryst phase in the Palolo Quarry intrusive, attaining diameters of 1.0 mm in several sections. Ores make up 8-17% of the volume of these rocks, the most common counts falling in the 11-14% range. It is possible that ore content increases with elevation in these intrusives. Further modal counts would be required to confirm this.

Acicular apatite inclusions usually are recognizable in larger feldspar phenocrysts, especially in the Palolo intrusive and Waialaenui bud in which feldspar phenocrysts are particularly well developed. Apatite never exceeds 1% modal volume. Hematite occurs as minute red or black flakes along occasional joint fractures where minor alteration has taken place. It also appears as oriented inclusions in iddingsite rims on olivine phenocrysts. These inclusions are elongate flakes or shreds, black in reflected light. Total hematite exceeds 1% of the rock volume only in weathered material.

Vesicles comprise 1-10% of the total bulk, but may be entirely absent from denser portions. They are consistently circular in outline.

Traces of alteration products, mostly of low birefringence or isotropic and with indices 1.48-1.55 occur in vesicles and along infrequent fractures and joint planes. These occurrences are too small for critical determinations. Fibrous development often suggests zeolites or chalcedony. Bright red and green patches and strips are probably palagonitized glass.

Many vesicles seem simply to be voids defined by tangenitial feldspar microlites and intergranular pyroxene. Minor quartz was identified in Palolo Quarry micropegmatite. Needles of tridymite also are intergrown with the alkali feldspars of this body.

COMMENTARY

Source Magma

All intrusives sampled in this study are derived from tholeiitic magma. The dikes and sills are tholeiitic basalts in the sense defined by Macdonald and Katsura (1964, p. 89). Olivine is consistently less than 5% of the bulk. This is in contrast to the more olivine-rich Honolulu Series rocks. No occurrences of nepheline, melilite or augite phenocrysts, diagnostic of Honolulu Series mineralogy, were noted. Marginal glass in one dike containing only minor olivine as the crystalline phase has index 1.576, indicating about 51% silica (George, 1924, p. 365), which includes slight silica enrichment resulting from the separation of olivine. Another dike has traces of olivine and 5.0% hypersthene in a glass basis. The index of the glass is 1.588, indicating about 49% silica. Numerous analyses of Koolau basalts have shown silica contents of 48-52% (Wentworth and Winchell, 1947, p. 71). Honolulu Series basalts range from 36 to 45% silica (Winchell, 1947, p. 30).

The petrography of the intrusives studied here closely resembles descriptions of Koolau extrusives given by other authors (Cross, 1915, p. 18-20; Stearns and Vaksvik, 1935, p. 93; Wentworth and Winchell, 1947, p. 67-70). The greater vesiculation of the latter may be attributed to the effects of extrusion.

Aside from structural relations of material in place, dike rocks are distinguished from flow fragments in the field largely by the platy or splintery jointing and lack of conspicuous vesiculation in dike material. Iddingsite rims are never succeeded by fresh olivine growth in the intrusives observed. Such second generation olivine growth is common among Koolau extrusives (Wentworth and Winchell, 1947, p. 65) and Honolulu Series rocks (Winchell, 1947, p. 24).

Crystallization Sequence

Crystallization sequence, as inferred from textural relations, follows.

Olivine clearly crystallized first, usually reacted with the melt and was slightly altered to iddingsite, probably during concentration or upward migration of volatiles. Orthopyroxene and feldspar followed olivine after a considerable interval. In several dikes olivine phenocrysts, alone in glass at dike margins, were well developed. In some margins these phenocrysts were sharply euhedral, indicating that resorption had not yet begun. In other dikes resorption was already well advanced in these solitary phenocrysts.

The complicated interactions of feldspar and orthopyroxene cannot be generalized. A few intrusives show unequivocal precedence of one to the other, but contemporaneous growth is the rule. Minor ore inclusions occasionally appear in orthopyroxenes, but were not observed in the feldspars. This might suggest earlier crystallization of the feldspar; but the feldspar-magnetite antipathy persists even to the fine matrix material. It apparently is not a reliable criterion of crystallization sequence.

Orthorhombic pyroxene could not be identified in crystals less than .2 mm across and the limit is usually nearer .3 mm. Hypersthene crystallization apparently ceases before the groundmass period. Resorption suggests an interval during which orthopyroxenes were not in equilibrium with the melt. Such resorbed crystals often present their rounded surfaces to intimate contact with feldspar in glomerocrysts, interfering with growth of the latter sufficiently to suggest that resorption began, at least, substantially before the groundmass stage.

Feldspar phenocrysts grade imperceptibly into fine-grained microlites, indicating continuous separation to a sharp boundary with interstitial glass. Phenocrysts may be distinguished from matrix material, if desired, on the following basis:

Feldspars greater than a particular size, varying from one intrusive to another, are in random orientation or associated with orthopyroxene in glomerocrysts. Smaller feldspar laths commonly, though not invariably, form subparallel flow patterns around glomerocrysts and other phenocrysts.

A small quantity of ore may actually precede olivine in most of these intrusives, being, thus, the first solid phase formed. Octahedrons of magnetite and plates of ilmenite occur scantily in the mafic phenocrysts of dikes and sills. Most of the ore-mineral crystallization belongs to the groundmass phase. In hyaloophitic chilled borders a few magnetite and ilmenite inclusions appear in olivine, but ores in the marginal glass were beyond the resolving power of the microscope. With more gradual cooling skeletal magnetite crystals grow abundantly in and across matrix pyroxene and glass. The fine dust in tachylite indicates separation of the ore minerals to the very end of the liquid phase.

A gap is usually evident in the sizes of pyroxenes between smallest hypersthene and largest clinopyroxene. This probably represents a considerable interval of time, but also reflects the change in conditions between magma chamber or feeder and the ultimate site of emplacement. Clinopyroxene shells on euhedral orthopyroxene phenocrysts occasionally document a more intimate succession; but this is not commonly observed.

It is not contended that emplacement occurred in every case just as the melt approached an orthopyroxene-clinopyroxene inversion.

Optical homogeneity, and particularly the absence of exsolution lamellae, suggest that orthopyroxenes in these intrusions did not develop by inversion of earlier-formed clinopyroxene. Occasional olivine cores in orthopyroxene phenocrysts indicate formation of the latter in reaction rims.

Volume abundances of clinopyroxene and orthopyroxene seem to be in crude inverse relation. Perhaps early formation of orthopyroxene phenocrysts reflects lower temperature of initial crystallization, shortening the interval between beginning clinopyroxene separation and the ultimate freezing to glass. The substantial proportion of pigeonite observed in matrix material results from quenching of the melt, which prevents its inversion to orthopyroxene.

The clinopyroxenes are characteristically anhedral and interstitial to matrix plagioclase. Their intimate association with tachylite and the arrangement of magnetite and ilmenite inclusions in orderly arrays across glass-pyroxene boundaries establishes the separation of clinopyroxenes to the very end of the groundmass crystallization period. Apparently pyroxene, labradorite and ores continued to form together until the remaining melt congealed to glass. Further minute crystallites of pyroxene and ore dust can be seen in this glass under high magnification.

Other Notes

Petrographic differences between Koolau lava flows and the dikes and sills in this area seem accountable in terms of a common magmatic origin. No new chemical analyses are presented here, but the petrographic evidence points to no essential differences between the chemistry of these intrusives and that of the flows enclosing them. This, perhaps, accounts for the negligible alteration of the country rock adjacent to these intrusives. Only a slight baked band appears, and that is often difficult to distinguish. No metasomatic effects were observed, suggesting that most volatile material was able to escape to the surface of the dome and/or the magma was originally poor in volatiles. The paucity of iddingsite rims on olivine phenocrysts indicates low volatile content (Edwards, 1938, p. 280). These rims showed greatest development in the Waialaenui buds which may have been near the flow surface at the time of intrusion, thus having opportunity to release contained gases. Whether appreciable liquid magma escaped upward from these bodies remains undetermined.

It is clear that intrusives of the Waialae-Palolo area are much less abundant and show less evidence of metasomatic effects on the intruded rocks than do intrusives of the dike complex on windward Oahu (Stearns, 1940, p. 49). Intersecting dikes were not observed (except for minor stringers), so relative ages of samples examined in this study could not be assessed.

Feldspar-magnetite Relations

The antipathy between feldspar and magnetite in these rocks is worthy of further comment. Formation of magnetite in the intratelluric stage is suggested by well-formed octahedrons occurring as inclusions in olivine and, rarely, in orthopyroxene phenocrysts. Most of the magnetite formed in the groundmass period alongside plagioclase laths, but was not included in them. In view of the positions of feldspar and magnetite in the crystalloblastic series, it seems that the crystallizing force of feldspar could not effectively restrain growth of the magnetite structure. Pyroxenes, which do host abundant matrix magnetite in these rocks, have substantially more crystallizing force than plagioclase. Evidently factors other than lattice strength are decisive.

Possibly, formation of magnetite was not continuous in these intrusives; but plagioclase crystallization encompasses such a wide interval that contemporaneous separation must have occurred. Contemporaneity is not necessary to make magnetite available for inclusion in feldspar, however. Earlier-formed magnetite could easily be included in late-formed plagioclase. This is undoubtedly the manner of inclusion of magnetite in olivine phenocrysts in these rocks. If olivine formed by epitaxis on early magnetite, the latter might be thus denied to early plagioclase phenocrysts; but when more than one such inclusion appears in optically continuous olivine this mechanism seems doubtful. The coalescence of several olivine crystals into an optically homogeneous aggregate is unlikely.

If, as Vogt (1921, p. 321) suggests (in an altogether different chemical environment), the magnetites cluster themselves by synneusis, this glomerocryst might serve as a condensation nucleus for early olivine. The magnetite inclusions in olivine phenocrysts of these rocks are not typically contact clustered, but they are distinctly localized. Such a mechanism can only account for the absence of magnetite in the larger phenocrysts of plagioclase. The inhospitality of matrix feldspars remains unexplained.

Apparently some unique magnetite-plagioclase antipathy is acting here. In other rocks feldspar commonly includes ores, though they may tend to favor pyroxene hosts.

It is tempting to suggest that iron is accommodated by intratelluric olivine and orthopyroxene at elevated temperatures, then released by the late resorption of the more iron-rich portions of these phenocrysts. This would effectively remove iron from the melt, possibly reducing its concentration sufficiently to prevent its solid-phase interation with feldspar forming well into the groundmass period. This would explain the scarcity of early magnetite and the relatively greater density of magnetite inclusions in the largest olivine phenocrysts. Large much-resorbed residuals hint that considerably more olivine may have formed at an early stage than has survived emplacement and cooling.

It is suggested, as a speculation, that in some of these intrusives a few grains of magnetite formed before olivine began to incorporate iron. Ore formation then ceased, both because the iron content of the melt was slightly diminished and because the established centers of magnetite nucleation were enclosed in the growing olivine phenocrysts. Orthopyroxene picked up the iron returned to the melt by olivine resorption as cooling proceeded. After an indeterminate interval, during which formation of orthopyroxene and plagioclase considerably diminished the liquid phase, the magma was intruded into the dike fissure and cooled rapidly. As other components of the melt were depleted the iron concentration increased. Much iron was accommodated by the clinopyroxenes forming in the groundmass.

The occurrence of magnetite included in these clinopyroxenes suggests exsolution. But unless striking changes in oxidation potential are postulated in magma at least several hundred feet beneath the shield surface, substantial quantities of ferric iron would have to be admitted into pyroxene structures on this hypothesis. In any case, it is doubtful that exsolution from pyroxenes could account for alignments of magnetite octahedrons that are continuous across pyroxene boundaries into glass. Lattice planes in pyroxene hosts do not seem to control magnetite alignment.

Apatite inclusions were observed only in plagioclase!

Cumuloporphyry

The phenomenon of cumuloporphyry (Johannsen, 1931, p. 203), though widespread in a great variety of rocks, has been neglected in the petrographic literature. It is sometimes used as a diagnostic property of igneous rocks on the assumption that the kinds of aggregates so designated could form only with the freedom of movement available in a melt (Vance and Gilreath, 1967, p. 529).

The relations between individual crystals in these aggregates cannot be explained as epitaxis. Crystal boundaries may be intimate, but the individuals, whether like or unlike species, show no tendency to grow around or jacket their neighbors. The association is most commonly tangency or slight intergrowth. Flow patterns in matrix feldspar microlites have piled against and streamed around each glomerocryst. Relative movement of these phenocryst clots with respect to the surrounding medium is unmistakable. They have behaved as coherent units, withstanding whatever forces attended this passage of the fluid.

Vance and Gilreath attribute the formation of glomerocrysts to a process (synneusis) dependent upon "...episodes of turbulence and their timing with respect to the crystallization sequence..." (p. 553).

Vogt (1921, p. 321) observed synneusis in cooling ore melts and slag, noting that magnetite and zincblende clusters formed within 30 minutes in an essentially static fluid. Spry (1953, p. 255) comments that velocities of magma movement in dikes are probably too low to generate substantial turbulence unless viscosity is very low due to superheating or unusually high volatile content. He held observable structures in bostonite dikes to indicate essentially laminar flow.

Flow properties in the intrusives of this study are less definitive than those examined by Spry; but the consistent parallelism of microlites in some samples suggests laminar flow. This does not preclude earlier episodes of turbulence at greater depth, however.

Vance and Gilreath also concluded from counting studies that phenocrysts have affinity for their own species and antipathy for unlike species in synneusis. Rogers and Bogy (1958, p. 471) found by counting studies in granites that like crystals were less likely to form in contact with each other. They contend this is due to (1) growth of one crystal preventing nucleation of others in the neighborhood and/or (2) early crystallization of like grains causing them to be isolated from each other by later-forming minerals.

The feldspar and orthopyroxene phenocrysts in this study show a marked tendency toward heterogeneous aggregates, though single-mineral clusters do rarely appear.

If flow patterns in igneous rocks are velocity-related, structures resulting from synneusis may eventually provide a basis to determine rates of magma movement during emplacement.

The question of mechanisms seems to be wide open. None of the authors cited mentioned the possibility that flow structures around glomerocrysts might result from gravity settling of these bodies in a static melt.

CONCLUSIONS

Exposed dikes and sills trending southwest and roughly perpendicular to the primary Koolau rift zone in the Waialae-Palolo area of Oahu are hypersthene-bearing tholeiitic rocks, intrusive equivalents of the Koolau Series basalts. No Honolulu Series intrusives have been located along a line joining Kaau Crater, Mauumae, Kaimuki dome and Diamond Head, an alleged secondary rift of the Koolau volcano.

Mineralogy of the Koolau intrusives displays a striking chemical and morphological constancy. Feldspar crystals in these rocks show a curious antipathy to ore inclusions. Cumuloporphyritic texture is strongly developed and may be related to flow patterns evident in groundmass minerals.

APPENDIX

Sources, Standards and Precision

Textural descriptions, unless otherwise specified, are based on nomenclature as defined in Johannson (1931, v. 1) and Williams, Turner and Gilbert (1954). Laboratory procedures in thin section preparation follow El-Hinnawi (1966), in point counting, Chayes (1956), in immersion method, Bloss (1961) and in mineral data, Heinrich (1965) and Winchell and Winchell (1951). The microlite extinction angle method for determination of plagioclase composition was described in Heinrich (1965, p. 362-363, 364), but was originated by Rosenbusch and later revised by Wulfing (1908).

Dips and strikes of dikes and sills were determined by Brunton compass and clinometer. Using exposures of only 5 to 20 feet along the strike made these measurements highly uncertain. Some dikes curved or bent through 10-20° within these exposures, casting considerable doubt on the averaged values used to represent their attitudes. Vertical exposures were commonly only a few inches, rarely several feet. In the latter case, when the clear margin of a dike was exposed as a continuous sheet and only slightly weathered, the choice of different locations on its flank resulted in 5-15° differences in measured dip. There is no standard to which these measurements can be compared. The values presented are averages of several readings taken by sighting in opposite directions along the strike direction. In both strike and dip the typical case involves variability of 10° in the attitude of the exposed part of the body. How representative these exposures are of the extended bodies remains speculative. Wider samplings by Wentworth and Jones

(1940, map, p. 981) and Stearns (1939) remain the basis for judgments on the attitudes of leeward Koolau intrusives.

Immersion oils used in this study were calibrated at intervals of .004. They were mixed in approximately equal proportions to halve the bracketing interval for a final Becke line determination in white light. Thus any particular index is known only to be within an oil interval .002 wide. If the central value of this range is assigned as the reading, its uncertainty is ± .001. The calibration of the oils is within ± .0002, so when possible errors are additive, maximum error is ± .0012. Bloss (1961, p. 58) gives the precision of this method as ± .002. This results in uncertainties of ± 4 modal per cent in Ca-Na content of plagioclase, ± 1 molecular per cent Mg in olivine and ± 2 molecular per cent Mg in orthopyroxene.

Plagioclase microlite extinction angle measurements vary ± 2° on repetition. This imprecision is somewhat offset by the number of readings taken: 15-30 for each intrusive sampled. The preponderance of values in a narrow range suggests that measurement error is not large in relation to the uncertainties of composition on which it is based. No data were available on the precision of this method (Wulfing's revision of the Rosenbusch curve was not available). Variability of ± 2° in extinction angles is equivalent to ± 2 modal per cent in Ca-Na content in the range studied here.

Measurements of optic axial angle (2V) by Tobi's (Bloss, 1961, p. 205) and Kamb's (Bloss, p. 179-180) methods were used to determine composition in olivine and pyroxenes. Results by the Kamb method were so erratic for orthopyroxene determinations that Wright's method (Bloss, p. 203) with precision ± 5° was found to be more reliable. Tobi's method, used to distinguish clinopyroxenes, reads within ± 3° on clear, centered figures in optically homogeneous material. The inclusion-ridden clinopyroxenes of these rocks seldom yield clear, undistorted figures. Values given for 2V of clinopyroxenes are based on a probability distribution of several hundred Tobi readings. Individual values may have an uncertainty range of ± 5°.

Modal counts were based on 1000 points selected mechanically by the Unitron microscope stage with a click-stop attachment. A grid of points was established by parallel traverses spaced to cover the entire thin section. The areas of sections counted were all greater than 375 mm^2. No repeat counts were done to determine reproducibility; but 2 different thin sections from the center of dike 17 were counted to provide a measure of sampling error. The following variations in modal percentage were noted:

Feldspar	3.9
Clinopyroxene	4.7
Ores	0.1
Orthopyroxene	3.8
Olivine	1.4
Glass	2.5
Vesicles	0.6
Alteration	0.8
Other	1.1

Since analytical error for modal counts taken under these conditions is smaller (Chayes, 1956, p. 81-83), this sampling error defines the error range.

TABLE 1

MODAL ANALYSIS

							Modal Percentages						
Intrusive	Elevation	Width	Fpr	Cpx	Ore	Opx	Ol	Ap	Hem	Glass	Vesicl	alter	other
Waiomao dike 3	920 ft.	18-26"	50.4	39.1	9.1	0.2	x	0.3	x			0.2	0.7
Waiomao dike 7	1200	36-78	39.9	37.4	12.1	0.6	-	0.1	0.2	7.2	1.9	0.6	
Waialaenui dike 10	830	48-57	37.5	35.4	11.3	4.1	2.7	0.1	1.1	6.0	0.3	1.5	
Kaau str. dike 17 a	1500	14-16	32.1	29.1	14.5	6.5	1.8	0.4	0.1	11.8	1.6	1.0	1.1
17 b	1500	14-16	36.0	33.8	14.6	2.7	0.4	0.4	-	9.3	1.0	1.8	
Kaau str. dike 19	1480	16-20	31.8	31.5	17.1	5.0	0.2	0.1	0.6	10.5	1.5	1.7	
Waialaenui sill(?) 21	1070	26-35	38.2	34.6	11.6	2.2	0.2	0.3	0.9	9.0	1.2	1.7	0.1
Palolo Quarry pegmatite 24	560	indet.	50.6	38.4	7.7	0.1	-	0.9	1.3				1.0
Waialaenui bud 26	320	indet.	32.7	32.2	7.8	1.8	17.9	0.5	0.4	2.6	2.0	1.1	1.0

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PLATE I

Figure 1. Dike groundmass of labradorite laths with intergranular clinopyroxene and included magnetite. Polars not crossed, X230.

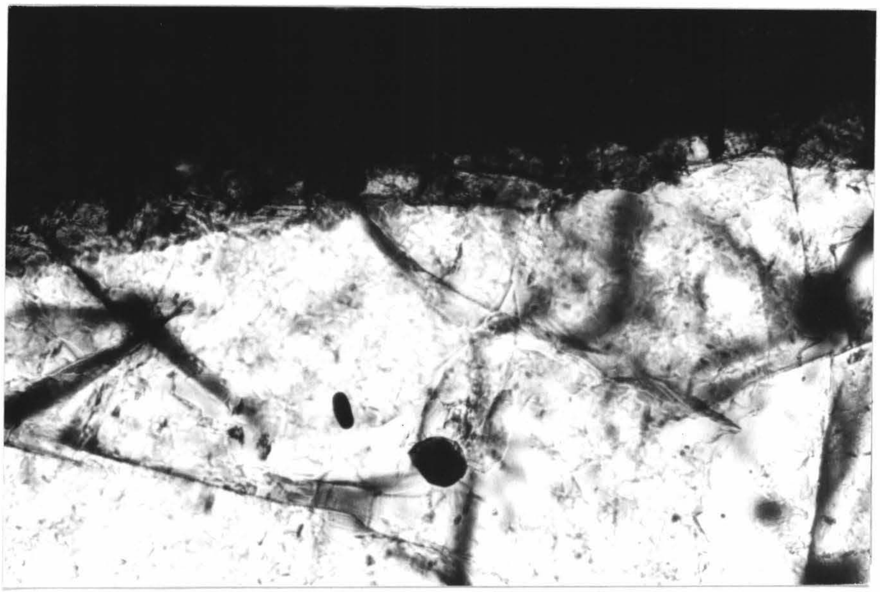

Figure 2. Olivine phenocryst with iddingsite rim containing parallel hematite flakes. Magnetite inclusion at bottom center. Polars not crossed, X230.

PLATE II

Figure 3. Zoned labradorite in matrix of labradorite laths, clinopyroxene and tachylite. Orthopyroxene phenocryst at lower left. Polars crossed, X70.

Figure 4. Orthopyroxene and labradorite in glomerocryst. Polars crossed, X85.