Art. XIX.—*Notes on Hawaiian Petrology;* by Sidney Powers.

Contents.

Introduction.

The Hawaiian Islands are composed principally of olivine basalt with subordinate amount of olivine-free basalt and minor occurrences of trachyte, nephelite basalt, gabbro, trachyandesite, and a few other types as decribed by Dr. Whitman Cross.[1] The distribution of the rarer types and their relation to phases of vulcanism has not been emphasized and forms the subject of a portion of the present paper. There is also given a description of new occurrences of trachyte on Molokai and on the north, northeast, and south sides of West Maui, of very large olivine nodules in a picritic basalt on Kauai, and of extensive deposits of volcanic breccia on West Maui. Attention is also called to the arrangement of subsidiary cones on the younger volcanoes.

All the islands of the group were visited by the writer in 1915, with the aid of a Sheldon Travelling Fellowship from Harvard University, and a few notes concerning the rocks found on them are given below. The islands Niihau and Kahoolawe were never before examined geologically. It is shown that Haleakala, the recently extinct volcano forming East Maui, was last active about 1750. Hualalai, on Hawaii, was probably active as late as 1840-41.

[1] U. S. Geological Survey, Professional Paper 88, 1915.

This paper presents the conclusions of the writer on a variety of subjects. It is presented as his contribution to the knowledge of the geology of the Hawaiian Islands. It is by no means complete on any one of the subjects treated. Petrographic descriptions are given only to substantiate conclusions. Dr. Whitman Cross has the collections of rocks and has very kindly offered to study them petrographically. However, the writer prefers to publish at this time the scattered notes which follow rather than to postpone the publication for complete corroboration. Sincere thanks are due to Professors R. A. Daly and J. E. Wolff of Harvard University, for making this investigation possible, and to Professor Daly, to Dr. T. A. Jaggar, and to Dr. Whitman Cross for kindly criticizing the manuscript.

General Observations.

Necker.—Necker Island is one of the western Hawaiian group, 250 miles northwest of Kauai. The island is described as the "remains of a soil-capped volcanic crater" 300 feet high, ¾ mile long, and 500 feet wide at the widest part.[2] A specimen of basalt collected on this island for Professor W. A. Bryan, of the College of Hawaii, Honolulu, is a fine-grained rock composed of phenocrysts of feldspar and smaller phenocrysts of olivine in a fine-grained groundmass. The groundmass shows under the microscope part ophitic, part poikilitic texture and is composed of labradorite feldspar, slightly titaniferous augite, olivine, magnetite, and apatite.

Nihoa.—Nihoa Island rises abruptly from the sea 120 miles northwest of Kauai. Professor Bryan collected a specimen of altered basalt from the island. The rock is an olivine basalt, and consists of large olivine crystals between feebly poikilitic feldspar laths in an aphanitic, partly glassy groundmass in which magnetite and thin feldspar laths are visible.

Niihau.—Niihau (fig. 1) is a desert island consisting of a fragment of an original island[3] bounded on three sides by a low plain. The surface of the plain is an ele-

[2] W. A. Bryan: Natural History of Hawaii, Honolulu, 1915, p. 98; also described by Carl Elschner, The Leeward Islands of the Hawaiian Group, reprinted from the *Sunday Advertiser,* Honolulu, 1915, 68p.

[3] S. Powers: Tectonic lines in the Hawaiian Islands, Bull. Geol. Soc. Amer., vol. 28, p. 513-514, 1917.

vated coral reef partly covered by flows that have come from about 10 small cones and 3 small pit-craters. Kawaihoa Crater on the extreme southern end of the

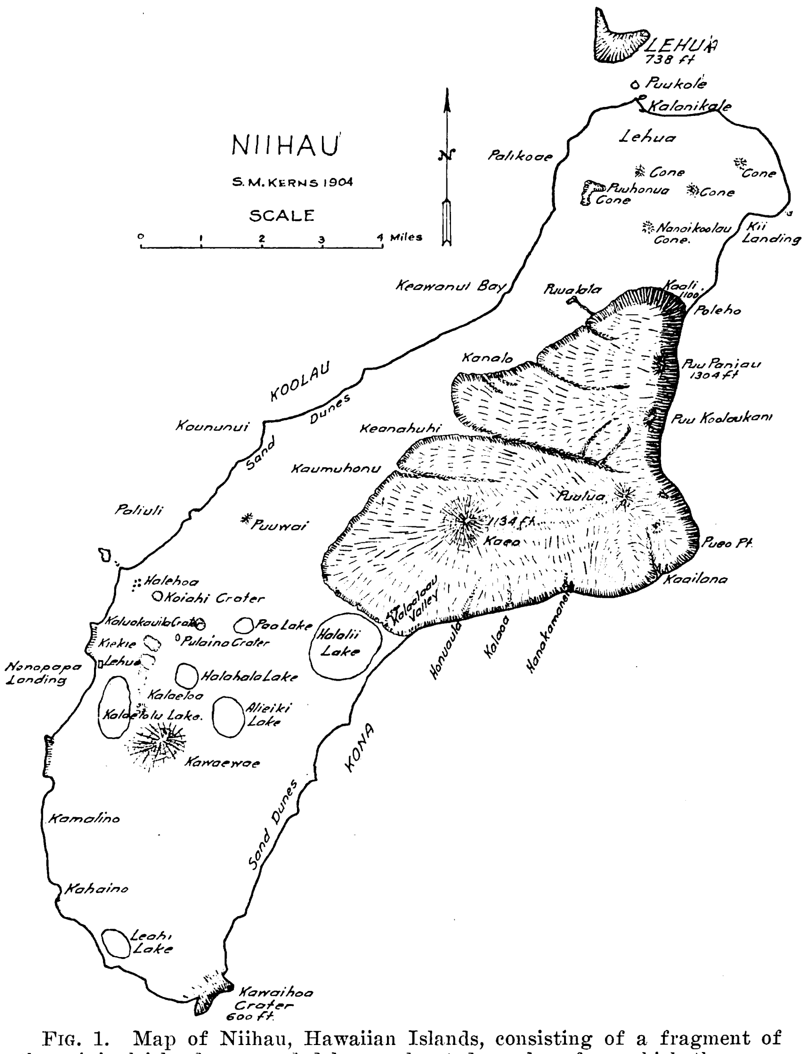

FIG. 1. Map of Niihau, Hawaiian Islands, consisting of a fragment of the original island surrounded by an elevated coral reef on which there are young cones and craters.

island and the islands Lehua and Kaula are composed of tuff of unknown composition. The flows comprising the original island, as seen from the west side, range in thickness from 5 to 30 feet and are composed of aphanitic basalt, occasionally showing small olivine phenocrysts. The flows dip westward at an angle of only 1 to 2 degrees. Four cones are situated on the plateau-like summit of the old Island. The young cones near the Nonopapa landing are composed of olivine basalt. Several pieces of white pumice have been found on the island—evidently material drifted from some far-away volcano.

Kauai.—Kauai is composed principally of olivine basalt. Of the 110 specimens collected on all sides of the island, 82% are found to contain olivine visible with a hand lens. About 30 young cones and craters are found on the east and south sides of the island and these, with the exception of Kilauea Crater, appear to consist of normal basalt and basaltic ash. The cones are notably arranged in lines more or less radial to the center of the original volcano.

Oahu.—Oahu is composed of the older Waianæ (Kaala) Range, in which feldspar basalt is the conspicuous rock-type, and the younger Koolau Range, concerning the petrography of which little is known on account of its topographic features. Of the older volcano only 5 young cones remain, the Laeloa craters of Hitchcock,[4] composed of nephelite basalt and arranged along a line tangential to the range. On the flank of the younger range about 39 distinct cones are found, of which eleven consist of tuff or basalt containing nephelite with or without melilite, the remainder of normal basalt or of basaltic ash.

Molokai.—Molokai consists of the low Mauna Loa on the west and a fragment of Wailau volcano[5] on the east. The major portion of the latter volcano has subsided, leaving a fault-scarp on the north side of the island.

Specimens of rock from Mauna Loa, Molokai, are difficult to collect on account of the absence of deep valleys. Basalt filled with olivine is found on the south and southwest sides while feldspar basalt with conspicuous tablets of plagioclase in a bluish rock occurs with olivine basalt and aphanitic olivine-free basalt near the center of the old volcano on the east and northeast sides of the mountain. The basalt weathers rapidly in this hot, arid region and when the wind sweeps away the red residual soil hard

[4] Geology of Oahu, Bull. Geol. Soc. Amer., vol. 11, p. 36, 1900.
[5] S. Powers: Tectonic lines on the Hawaiian Islands, Bull. Geol. Soc. Amer., vol. 28, p. 513, 1917.

nodules and masses of white or grey clay remain. Fragments of some of the nodules on the application of water swell to many times their original size. A bed of white clay 10 feet in thickness is reported on the northwest side of the island.

Wailau volcano is judged to have consisted largely of feldspar basalt with rare alkali trachyte. In composition and appearance the lavas of Kohala, on Hawaii, most nearly resembles this volcano. A greyish blue feldspar basalt with feldspar crystals sometimes one or two inches long and 1/4 inch thick compose a number of flows along the south shore and in the gulches on the north. Olivine basalt dikes occur in Halawa and in Wailau gulches, and gabbro, as described below, is found in Wailau gulch. Kalaupapa, the peninsula north of the fault-scarp, now used as a leper colony, is composed of young olivine basalt which has poured out of three small vents arranged in a line perpendicular to the main fault.

Lanai.—Lanai appears to be composed of olivine and feldspar basalt in about equal amounts. The original center of eruption has been degraded, but several broad depressions resembling small bolsons occur south of the present summit. These depressions may represent secondary craters or possibly wind-blown depressions. *Aa* flows of much younger age than the major portion of the mountain occur on the southeast and north sides. That on the north, near Maunalei valley, is the less weathered. Nodules of clay like those so common on West Molokai and a few nodules of chert are found in the residual soil of the south side of the island.

Kahoolawe.—Kahoolawe is a barren island west of Haleakala inhabited by one Japanese caretaker. The vegetation has been destroyed by sheep and goats so that the surface of the island is barren, weathering basalt forming a red residual soil. Clouds of the soil blow out to sea with the strong trade winds. Seven cones and four cone-craters are shown on the U. S. Coast & Geodetic Survey contour map of the island (fig. 2).

Specimens were collected near Conradt's landing on the north side of the island. The shore cliffs are composed of a fine-grained, minutely vesicular olivine basalt of grey color which, under the microscope, shows olivine phenocrysts in a groundmass of glass, small feldspar laths, augite and magnetite crystals, and masses of limonite, the latter being in part in branching patterns.

East of the house fine-grained basalt of light grey color was collected. Microscopically the rock is uniform in grain and slightly glassy in composition, with ophitic and diabasic augites between feldspar laths. Magnetite is quite abundant in shreddy aggregates growing around the other crystals and sometimes included in them. Olivine crystals with limonite rims are present.

Pebbles of fine-grained, grey basalt were collected on the beach. They resemble in color a rock described to the writer as occurring on the southwest side of the

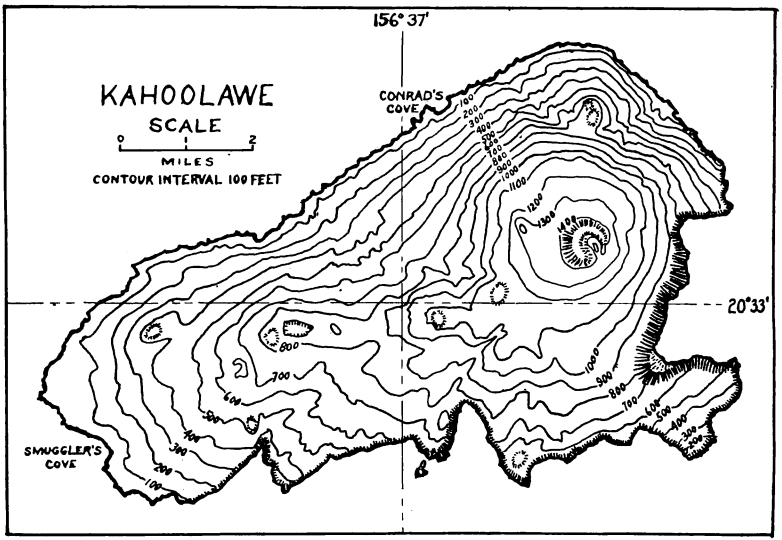

FIG. 2. Map of Kahoolawe, Hawaiian Islands, showing cones and craters. (Topography, U. S. Coast and Geodetic Survey.)

island. One specimen in this section is seen to be an altered tuff[6] with fragments of glass and calcic plagioclase accompanied by grains and granular aggregates of some other material imbedded in a very fine cryptocrystalline groundmass. The other material for the most part appears to be melilite, with a moderately high mean refraction, very low double refraction, parallel extinction on poor cleavage, and shows alteration products that look like zeolites. Some other material of higher double refraction may be pyroxene. The other specimen of grey

[6] The writer is indebted to Professor Charles H. Warren, of the Massachusetts Institute of Technology, for this microscopic description.

basalt from the beach is a fine-grained augite basalt free from olivine.

Maui.—The volcano of West Maui, as judged from the exposures and stream pebbles, has been built largely of olivine basalt. Covering portions of the eroded older rocks there is a veneer of trachyte as described later.

West Maui contains one feature not observed elsewhere. Deposits of fragments of subangular to rounded stratified material are found in Launiopoko, Waikapu, and Iao valleys and these streams are at present engaged in cutting into these deposits which rest unconformably on the sides of the older valleys. Ukumehame and Olowalu gulches were not examined and therefore it is not known whether or not the fragmental material is found there. None was seen in Kanaha Gulch above Lahaina.

The conglomerate, as it may be called, in each case fills an older, precipitously V-shaped valley and has become so well consolidated that it stands in vertical cliffs. In Launiopoko Gulch it occurs at an elevation of 1220 feet above sea-level on the west side of the stream just below the first water tunnel. In one vertical section 20 feet are exposed, showing blocks ½ foot to 5 feet in length in a sandy or tuffaceous matrix. Near the second tunnel, at an elevation of 1,360 feet, a thickness of 40 feet of the conglomerate, showing very coarse, unsorted blocks, occurs at and above the present stream bed. Toward the head of the gulch, at an elevation of 2,150 feet, 20 feet of conglomerate is exposed and in it are fragments of a true breccia 6 by 5 by 4 feet in diameter and lenses of water-worn pebbles.

Waikapu Gulch presents similar beds. Gravels occur at the entrance, near the flume, on the south side of the valley at an elevation of 1,000 feet and in the bottom of the gulch, 200 feet below. The deposits continue up the valley to an elevation of 900 feet, but they were not observed above the intake tunnel, elevation 1,050 feet, although at this place they form cliffs 60 feet high. The dip of the conglomerate beds is downstream at an angle of 6 degrees. The beds are sorted into coarse and fine, the subangular blocks in the former being 6 to 12 inches long, those in the latter 2 to 3 inches.

At the entrance to the Iao valley gravels are found at an elevation of 550 feet, 25 feet above the stream. Coarser gravels occur in a 20-foot vertical exposure at an elevation of 660 feet and other exposures are found north of Mr. W. H. Field's house, Kapaniwai. At the bridge near the Needle, elevation 900 feet, the stream is cutting into gravels and in the center of the valley there is a hill of decomposed rock consisting of angular and subangular fragments ½ inch to 3 inches in diameter.

The existence of similar deposits in three valleys at elevations ranging from 550 to 2,150 feet call for similar explanations. The partly stratified material might represent a volcanic breccia, mud-flow, or landslide material partly reassorted by the stream; or a true conglomerate deposited from a rapid, yet overloaded stream. It is difficult to account for the deposition of all the material in normal stream erosion as there appears to have been no agency which would cause a very rapidly flowing stream to drop gravels which would build so thick a deposit in a very steep-sided valley when the stream debouched from the valley over a steep talus cone. The gravels in the Launiopoko valley are found well toward its head where the stream must have been actively cutting. Also, there is no indication of a submergence of the island below present sea-level. In view of the evidence against normal stream-gravel origin, it is suggested that volcanic explosions took place long after the main volcano became extinct and that the conglomerate represents a breccia thus blown out and in part reassorted by the stream during the process of accumulation. The amphitheatral head of the Iao valley might be pointed to as excavated in part at least by such explosions, both because of its size, its geographically central position, and because of the large deposits of breccia near the narrow mouth. But normal stream erosion, given sufficient time under the existing climatic conditions with enormous precipitation on the high mountains and extremely little precipitation at sea-level, could excavate the Iao valley. The exact source of the explosions therefore remains uncertain, but it was probably near the head of the present Iao valley.

Haleakala, the volcano which built East Maui, is as yet only slightly dissected. The younger flows of this volcano and those of Mauna Kea, Hawaii, closely resemble each other in appearance—dense, aphanitic, bluish rocks —and in composition, olivine basalt to trachyandesite.

Haleakala has always been classed as an extinct volcano because no traditions concerning activity were re-

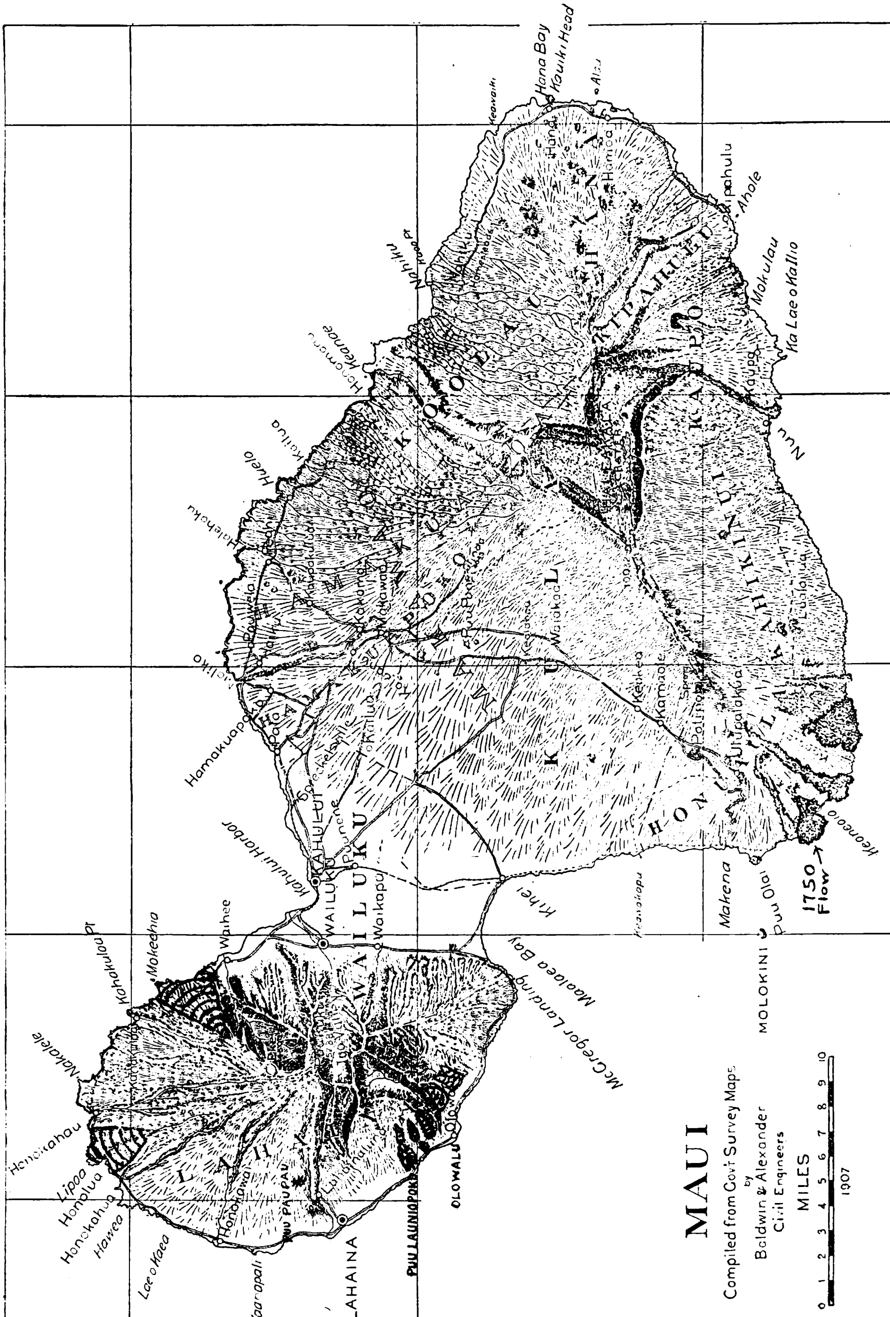

FIG. 3. Map of Maui, Hawaiian Islands, showing the distribution of trachyte (heavier shading) on West Maui superimposed on the older basalts, and the location of the 1750 flow on the southwest flank of Haleakala, entering the sea north of Keoneoio. The only occurrence of nephelite basalt known on Maui is in Kaupo gap, Haleakala, 2 miles north of the settlement Kaupo. (Map reproduced by the permission of C. H. Baldwin.)

ported to the early missionaries. Mr. L. A. Thurston, of Honolulu, has, however, authenticated a tradition to the effect that there was a lava flow from the southwest side of the mountain near sea-level about 1750.[7] The event took place about three generations ago and part of a Hawaiian village was destroyed by the lava.

The 1750 flow, east of Makana, issued from the black, breached cone called Pimoa. The rock is a very fresh aa basalt filled with olivine crystals. The aa streams have covered other fresh flows in the vicinity and have coalesced to form a rounded peninsula (fig. 3). No stone walls were seen covered by the youngest lava[8] as were covered by the Hualalai flow of 1801, but none would be expected in such a barren waste of lava flows unless within a few yards of the shore. The appearance of the lava and of the Pimoa cone from which it came, at an elevation of about 1,100 feet, are in accord with the tradition. This flow probably was the closing activity of the volcano as the cones in the crater of Haleakala must be dated as earlier. The volcano now appears to be extinct in spite of reports from one ranch on the side of the mountain that occasional underground rumblings are heard.

Rows of young cones are found on the sides of Haleakala arranged, in general, along lines radiating from the summit of the mountain. From many of the cones radial flows may be traced. Several rows of ash cones extend toward Hana, on the east side of the mountain, but the tropical jungle prevents an examination of the upper cones. Puu Kauiki, on the shore, is a red lapilli and ash cone traversed by olivine-basalt dikes. Parallel rows of cones extend from White's Hill the highest point of the mountain, toward Ulupalakua on the southwest. Near Ulupalakua they diverge into many lines from which the recent flows in that vicinity have poured into the sea. One of these lines of weakness in the mountain runs through Puu Olai, a red ash and lapilli cone near Makana, and through Molokini, the semi-circular tuff crater[9] be-

[7] Father Ed. Bailey was told in 1900 or thereabouts by a native that when the latter's great grandfather was a boy about 10 years of age a lava flow destroyed their village (Honoualua), running around a house from which a woman and child failed to escape.

[8] W. A. Bryan reports that a stone wall was buried by this flow (Natural History of Hawaii, Honolulu, 1915, p. 147) but this was not found by the writer.

[9] This tuff, of unknown composition, resembles that composing Diamond Head and Punchbowl, but no specimens of hard basalt were present in the collection of material made for the writer by the vessel of the Lighthouse Service.

tween Maui and Kahloolawe. Another line appears to extend in the direction of the summit of Kahoolawe, as if that island had arisen on the line as a volcano subsidiary to Haleakala. Few cones are found on the western side of the mountain, toward West Maui, and fewer cones, except those composed of trachyte, are found on the deeply-dissected West Maui Volcano.

Hawaii.—The Kohala Mountains, forming the oldest volcanic center on Hawaii, also show a number of radial rows of young cones. On the northwest flank of the volcano a row of large cones, from which lava flows have come, points directly toward Haleakala, which is a much younger volcano than Kahala, and suggests that Haleakala may bear the same subsidiary relation to Kohala that Kahoolawe bears to Haleakala.

Mauna Kea has more cones on its flanks than any other volcano in the Hawaiian Islands. The original summit sink, if one existed comparable to Mokuaweoweo on Mauna Loa, was completely buried by the ash eruptions. at the closing stages of activity in pre-historic times.

Mauna Kea lavas are not exposed in deep gulches and therefore only the surficial flows may be studied. From an ascent of the mountain, Daly finds evidence of a basaltic base capped by younger flows of trachyandesite which are partly covered by ash.[10] One of the younger flows has never been noted—a flow at Laupahoehoe which is younger than the wave-cut cliff which bounds Hawaii from Hilo to Waipio valley. The Laupahoehoe basalt issued from fissures near the mouth of the valley by that name and spread out into a small peninsula which projects beyond the sea-cliffs. This is the most recent flow near the base of the mountain.

Hualalai was last in activity with a lava flow in 1801, the flow being observed by one of the earlier mariners, but smoke issued from the mountain as late as 1823 and possibly as late as 1840-41.[11] Instead of a single flow in 1801, as has been previously supposed, two main streams of lava poured from the mountain and several ash cones were formed. An ascent of the mountain in 1915 from McGuire's ranch, together with a review of the Hawaiian traditions concerning the activity at the time, has shown. that the eruption took place along one or more radial fissure-lines extending from near the summit of the moun-

[10] Magmatic differentiation in Hawaii, Jour. Geol., vol. 19, p. 299.
[11] J. D. Dana, U. S. Exploring Expedition 1838-42, Geology, p. 215.

tain in a northwest direction toward the sea near Makalawena. The greatest, and probably the first 1801 outbreak, occurred near the summit of the mountain at Kaupulehu, and from it lava streamed to the sea near Kiholo, 11 miles distant, destroying the Paiea fishpond and the Hawaiian villages at the shore. Farther down the mountain three small flows, each a hundred yards in length, are seen emanating from the same line of weakness at elevations of 2,400 to 4,000 feet; and 110 feet below the Kona-Kohala highway the Huehue flow broke out of a little cavern in the older pahoehoe at an elevation of 2,200 feet, flowed over a stone wall and poured down the slope of the mountain. The flow was apparently fed from a number of openings now concealed by the lava, as in the center of the flow, far below the road, there is a blackened cone. The flow entered the sea between Keahole Point and Makalawena. While the Huehue flow and the smaller flows above are pahoehoe, the larger flow on the north is aa.

Mauna Loa is being built up by flows from two major lines of weakness, a west-east line running from Mokuaweoweo in the direction of Olaa and a northeast-southwest line extending toward Kahuka. Flows have alternated on the two sides for a number of years until in May, 1916, and again in September, 1919, flows appeared in Kahuku near the 1907 flow.[12] Many cones are seen along the first line and it will be possible to study them with the new trail up the mountain. On the other side of the mountain cones are not as abundant. One of the larger, Puu o Keokeo, does not represent a separate crater as has been supposed.[13] Along the southwest shore from Kapua to Ka Lae rows of cones are seen following the shore-line. It is possible that these cones owe their origin to the reaction of seawater on the hot lava pouring into the sea, as was apparently the origin of the Nanawale cones in Puna at the end of the principal 1840 flow from Kilauea, and of the cones at the end of the 1868 Mauna Loa flow in Kau.[14] No similar tangential

[12] H. O. Wood: Notes on the 1916 eruption of Mauna Loa, Jour. Geol., vol. 25, pp. 322-336, 467-488, 1917.

[13] A suggestion by S. E. Bishop cited by Hitchcock in Hawaii and its Volcanoes, Honolulu, 1911, p. 148.

[14] Mentioned by W. L. Green, Vestiges of a molten Globe, vol. 2, p. 178, Honolulu, 1887. Also see observations by Rev. T. Coan on the 1885 Mauna Loa flow, cited by W. T. Brigham, Volcanoes of Kilauea and Mauna Loa, Mem. B. P. Bishop Museum, Honolulu, vol. 2, No. 4, p. 74, 1909.

lines of cones were seen farther up on the Mauna Loa mountain side.

The Kilauean pit craters will form another interesting field for investigation when trails are cut through the jungle from the row of pit-craters stretching from Kilauea, Keanakakoi, and Kilauea Iki through Alæ Alæ, Makaopuhi, and Napau to the row of cones in Puna near the 1840 flows. The transition between pit-crater and cone may be found to be a cone like Puu Huluhulu or the Cone Crater on the Kau Desert, with a large and deep pit in the center.

Although Rev. Titus Coan was living in Hilo at the time of the 1840 flow, all the flows of that date were not visited by him. Nor were they all visited by Wilkes, who arrived shortly after the flows ceased moving, if the native traditions are to be believed. These traditions speak of a flow not mapped by Wilkes, between Keiheiahulu and Kehena, in Puna, which crossed the Hilo-Kalapana road near Kalapana. The freshness of this flow favors the tradition that it is 1840 in date.

Pillow lavas have never been observed on the Hawaiian Islands, unless in a flow seen in cross section by Doctor T. A. Jaggar and the writer between Waipio and Waimanu valleys on the shore of Hawaii. The small tongues of pahoehoe lava which are so abundant at Kilauea are very different from true pillows seen elsewhere in the field.[15] Unfortunately the lavas which have run into the sea cannot be examined to determine if pillows have been formed by reaction with sea-water.

Distribution of Rarer Types.

Trachyte.—In the midst of the floods of olivine basalt which have poured from the slopes of Hualalai and of Mauna Loa, on Hawaii, around the north flank of the former, Dr. Cross found in 1902 the first trachyte, so described, noted on the Hawaiian Islands,[16] but Dr. E. S. Dana had already described a rock of unusual character, later shown to be trachyte, from Puu Launiopoko and from Puu Paupau (Mt. Ball) on West Maui.[17] The next

[15] At Porcupine, Ontario, and near Victoria, Vancouver Island. Professor J. V. Lewis, in a paper on the origin of pillow lavas (Bull. Geol. Soc. Amer., vol. 25, pp. 591-654, 1914), classes these tongues of pahoehoe as pillows. The best photographs published of the tongues are by I. Friedlaender, Ueber die Kleinformen der vulkanischen Produkte, Zeit. f. Vulk., Bd. 1, Hft. 1, 2, 4; especially Heft. 4, p. 51, "Zungenformes Ende eines Pahoehoe-Ström."

[16] Jour. Geol., vol. 12, pp. 510-23, 1904.

[17] This Journal, (3), vol. 37, pp. 441-67, 1889.

most salic lava known on the islands is one described by A. B. Lyons from the Waimea side of the Kohala Mountains,[18] Hawaii. Several new occurrences of trachyte were found by the writer on West Maui (fig. 3): on the northeast side of the volcano between Waihee and Kahakuloa gulches; on the north side between Honokahau and Honakahua gulches; and on the south side in the vicinity of Olowalu. One new occurrence was also found on Molokai.

On Hawaii the trachyte described by Dr. Cross from Puu Waawaa and from Puu Anahulu occurs in the former case as a cone of stratified ash, in the latter case as a terrace presenting steep faces on the south and west sides. Puu Waawaa is dissected by many ravines and is much older than the flows from Mauna Hualalai which surround it. The Puu Anahulu terrace, as seen from the south, appears to form a slope more nearly horizontal than that over which the flows from the south have streamed, but as seen from the north the terrace is clearly a portion of the normal slope of Mauna Kea. The terrace has been overrun by a pahoehoe basalt flow which may be seen to overlie the rough surface of the trachyte.

The Puu Anahulu trachyte represents a flow at least 5 miles in length and over 100 feet in thickness at the lower end. The source of the flow is believed to have been one of the visible volcanoes. Moreover, the conclusion is reached from a comparison of features at Puu Anahulu and Puu Waawaa with those of flows from Mauna Loa and of tuff cones on Oahu that no great age can be assigned to the trachyte of either of these occurrences and that the terrace represents a normal slope rather than an uplift or wave-cut bench. A careful search for elevated shorelines around the island of Hawaii from sea-level to an elevation of over 1,500 feet, made by Dr. T. A. Jaggar and the writer, showed sea-worn coral fragments and beach pebbles at various elevations up to 1,325 feet (at the residence of Miss Paris, Kealakakua), but as the Hawaiians carried such material inland long distances for house sites and for religious purposes, no positive proof of recent elevation of over 20 feet (that at Mahukona) anywhere around the island was found.[19]

[18] Idem, (4), vol. 2, pp. 421-9, 1896.

[19] C. E. Dutton (Hawaiian Volcanoes, U. S. Geol. Surv., 4th Ann. Rept., 1882-3, p. 98) speaks of three terraces at Hilea indicating uplift. Examination of similar terraces in several places showed that they have been constructed by lava flows.

No trachyte was noted in the field in the Kohala Mountains. The flows forming the sides of Waipio and Pololu gulches are in part composed of basalt, bluish grey in color with abundant feldspars and very little olivine seen in the hand-specimen. Similar feldspar basalts are characteristic of Wailau volcano, East Molokai.

On Maui the trachyte occurs as flows, cones, and, in one instance, probably as a volcanic neck. In every case observed the trachyte is younger than the main mountain mass and probably appeared when the dissection of the latter was well under way. The major portion of the erosian of the volcano followed the trachyte eruptions. West of Puu Launiopoko an olivine basalt flow may be younger than the trachyte, but the two rocks were not observed in contact.

Puu Paupau, above Lahaina, is a double conical hill, surmounting a spur between two gulches and composed of light-grey, schistose trachyte. The next exposure of trachyte to the southeast is Puu Launiopoko (there is an excellent exposure on the Lahaina-Wailuku highway). Above Puu Launiopoko on a facet at an elevation of 1,400 feet there is a flow of trachyte, evidently derived from a fissure eruption. Puu Kilea, back of Olowalu, and two nameless cones between Puu Kilea and Puu Launiopoko are composed of similar rock. A light-colored rock, apparently trachyte, is seen on the triangular erosional facets between Launiopoko and Ukumehame gulches and trachyte flows occur on the gently sloping plain west of the mouth of Olowalu Gulch. On the west side of Ukumehame Gulch, at the entrance, there is an inaccessible mass of white rock, apparently a volcanic neck of trachyte.[20] This rock may be seen from the Interisland steamers passing Maui.

Trachyte flows cover an area about 3½ miles in width and extend to an elevation of over 1,000 feet between Waihee and Hakahue gulches northwest of Wailuku. The trachyte has a maximum thickness of over 30 feet on the sides of Waiolai and other gulches. Besides the thin flows which cover the region the rock comprises cones, such as Puu Olai. Trachyte flows of an aggregate thickness of over 30 feet cover the facets between Honokahau and Honokahua gulches on the north side of West Maui, a distance of 2½ miles as traversed by the trail around the island.

[20] S. Powers, Intrusive bodies at Kilauea, Zeitschr. Vulk., 3, p. 32, 1916.

Microscopic examination of thin-sections of the grey, banded trachyte from Waiolai gulch, on the northeast side of West Maui, shows bands of chlorite, biotite, apatite, and limonite and occasional large phenocrysts of olivine in a rock composed principally of oligoclase feldspar laths with minor amounts of orthoclase feldspar, some altered olivines, secondary limonite, hematite, and sericite, microlites of unknown composition, and glass. A polished section shows no magnetite.

Trachyte from Puu Paupau shows less alteration. The feldspar, which composes almost the entire rock, is an albite-oligoclase and the groundmass contains orthoclase feldspar, olivine, apatite, magnetite or ilmenite (identified in polished section), limonite, biotite, and glass.

A thin-section of the trachyte from Waihee valley shows an alkali feldspar similar to the others. The subordinate constituents are glass, magnetite or ilmenite (quite abundant as seen in polished section), ægirine augite in greenish yellow laths, and biotite and apatite.

From Molokai a schistose, grey trachyte was collected by the writer. The source of the specimen is believed to have been stream gravel near the mouth of Wailau gulch and the rock is judged to occur in place somewhere on the rim of the precipitous and very large gulch.

The rock is composed almost entirely of phenocrysts of oligoclase[21] feldspar with subsidiary amounts of brown hornblende (now almost wholly changed to granular aggregates of ore, brown hornblende, and to a nearly colorless mineral, probably an amphibole) and augite. The groundmass is finely crystalline and consists of oligoclase, rarely orthoclase, abundant small brown hornblende crystals, augite and magnetite. There is a nearly colorless prismoid material that is probably secondary amphibole derived from the breaking-up of the primary brown hornblende. This trachyte differs from those on Maui and Hawaii because of the absence of a plate-like arrangement of the feldspar.

It has been supposed by Daly[22] that the origin of the trachyte on the Hawaiian Islands is connected with the absorption of limestone by the basaltic magma and subsequent differentiation. While only a small amount of

[21] The writer is indebted to Professor Charles H. Warren, of the Massachusetts Institute of Technology, for the description of this rock.

[22] Magmatic differentiation in the Hawaiian Islands, Jour. Geol., vol. 19, p. 314, 1911.

limestone may be necessary to cause such differentiation in a large amount of basalt, there are grave difficulties connected with the application of the theory of limestone control to islands which, so far as known, are built almost wholly of basalt. It is true that limestone occurs as a thin veneer on the margins of Oahu; that a very small amount of elevated limestone occurs around Kauai and Niihau, and that a single elevated reef has been traced a short distance on southwestern Molokai. Moderately wide coral reefs surround portions of Niihau, Kauai, and Oahu, but the reefs around the other islands are of very limited extent. The tuff cones Ulupau Koko Crater, Makalapu, Punchbowl, and Diamond Head, on Oahu, contain fragments of coral, but only from the immediately underlying reef, and no cones on Molokai, Maui, Hawaii, or Kauai are known to contain such fragments. The greatest difficulty with the theory is the fact that no limestone has been found interstratified with the basalt flows in any canyon on the Islands, although erosion has exposed many sections 2,000 to 3,000 feet below the former summit crater.

In order to have limestone available for fluxing a basaltic magma, it must occur at a depth of several hundred feet, for lava is injected as dikes and through fissures to the surface with great rapidity. Limestone at the required depth would apparently have to represent a deep-sea deposit of considerable thickness rather than a coral-reef deposit unless this portion of the Pacific gradually subsided as the volcanoes were built up.[23] That such deep-sea deposits exist in the lower portions of the huge volcanic piles is subject to discussion.

Nephelite basalt.—Rocks containing nephelite, usually as a very subordinate constituent, have been identified on

[23] H. A. Pilsbry has accounted for the present distribution of the land shells of the family *Achatinellidae* over the Hawaiian Islands by submergence during the Late Pliocene or Pleistocene, progressively separating the various islands. He maintains that the differentiation of the modern families of land shells took place largely in the Mesozoic and that "the hypothesis that the Hawaiian volcanoes rise from a pre-existing mid-Pacific ridge, now lost by subsidence, gives room in time and space for the derivation of the peculiar fauna" (p. xlvii) (Manual of Conchology, Second Series, vol. 22, pp. xlii-xlvii, 1912-4; also quotation and map by W. A. Bryan, Natural History of Hawaii, Honolulu, 1915, pp. 121, 291). P. Marshall, B. Koto, and others, however, have shown that andesites are the type of volcanic rock associated with continents, and Marshall maps the northern limit of the former continent of Oceania on this basis as passing not far north of Fiji (Oceania, Handbuch der regionalen Geologie, Heidelberg, 1912, Bd. 7, Heft. 5, fig. 3, p. 5).

only four islands of the group, Kauai, Oahu, Molokai, and Maui, but their presence is suspected on and near Niihau and on Molokini, a small cone between East Maui and Kahoolawe. With very few known exceptions they are confined to local centers of eruption and all but six of the local centers are tuff cones. In each instance of a local center the eruption has been long after the main volcano became quiescent. There is also a striking connection between the tuff cones and the shore lines at the time of eruption. All the cones were erupted near or through shallow water. More striking yet is the fact that nephelite has been found in rocks from all but two of the tuff cones at sea level in the Hawaiian Islands which have been examined petrographically. The two exceptions are Koko Head and Koko Crater, but additional collections may show nephelite-bearing basalt in these cones.

A list of occurrences of nephelite-bearing rocks in local centers of eruption is given below. Most of the tuff cones of which specimens were not available to Doctor Cross are difficult of access and therefore few additions to his identifications are possible.

Kauai: Crater Hill (Kilauea Crater), tuff cone, melilite-nephelite basalt. (Cross, Powers)

West Oahu: Laeloa Craters (named by C. H. Hitchcock. 1900)

- Puu Palailai, lava cone, nephelite basalt? (Powers)
- Puu o Kopolei, lava cone, nephelite basanite. (Cross)
- Puu Kapuai, scoria and lava cone, nephelite basalt. (Cross)
- Puu Makakilo, scoria and lava cone, nephelite basalt. (Powers)

East Oahu:

- Diamond Head, tuff cone, nephelite basanite. (Cross)
- Punchbowl, tuff cone, nephelie basalt. (Cross)
- Salt Lake Craters (2) tuff cones, nephelite basalt. (Cross, Powers)
- Mauumae Cone, tuff and scoria (northwest side), melilite-nephelite basalt. (Powers)
- Rocky Hill, lava cone (Moilili Quarry and Honolulu black ash), melilite-nephelite basalt. (Cross)
- Ulupau Crater, tuff cone, melilite-nephelite basalt. (Powers)
- Puu Hawaii Loa, tuff cone, melilite-nephelite basalt. (Powers)
- Koko Head, tuff cone, olivine basalt. (Powers)
- Koko Crater, tuff cone, olivine basalt. (Powers)

The composition of the tuff in the following cones is unknown:

Near Niihau: Kaula and Lehua, tuff cones.
Niihau: Kawaihoa, tuff cone.
West Oahu: Puu Kuua, scoria and lava cone, one of the Laeloa Craters.
East Oahu: Makalapu Crater, interstratified tuff and coral limestone.
Moku Maui, Mokulua, and Rabbit Islands, dissected tuff cones.
East Maui-Kahoolawe:
Molokini Island, tuff cone.

Known occurrences of nephelite-bearing rocks other than those listed above are given by Doctor Cross as follows: The first three localities are near together and the rocks probably came from one or more flows of a single young and undescribed crater. The fourth locality, a dike, may have been one of the feeders of the tuff cones.

Oahu: Kalili Valley, north edge, nephelite-melilite basalt.
Gulick Stream, west of Kamehameha School, nephelite-melilite basalt.
Half a mile east of Bishop Museum, nephelite-melilite basalt.
Dike in the Pali, east side, nephelite basalt.
West Molokai: Kalæ (north of Kaunakakei on the road to Kalaupapa), nephelite basinite. (Möhle)[24]
West Maui: Waihee Valley (?)
Near Lahaina (Möhle)
East Maui: Near Vierra's Ranch, Kaupo Gap.

All the proved occurrences of nephelite rocks, with possibly four to six exceptions, fall into natural groups: a solitary tuff cone on the eastern shore of Kauai; the five Laeloa Craters of West Oahu, roughly aligned on the dissected south flank of the old volcano; six to nine craters in the formerly submerged area of East Oahu near Honolulu, and the two or more cones in the faulted and deeply dissected region of East Oahu 12 miles northeast of Honolulu. The age of the cones of East Oahu is Pleistocene, as the age of the coral reefs through which they broke is either Pliocene or Pleistocene. The tuff cones of the other islands appear to have suffered the same amount of erosion as those of East Oahu and they

[24] Neues Jahrb., Beilag. Band 15, pp. 67-71, 1902.

were possibly connected with the same volcanic activity. Puu Palailai, the lowest of the Laeloa craters of West Oahu, is at a slightly higher elevation than any coral limestone in the vicinity and no contact of the lava with the limestone is exposed. Therefore the age of these craters is undetermined.

Olivine nodules.—Along the line of a new ditch from the western portion of the Lihue district to Koloa, Kauai, about one mile northeast of Puu Kahoaea, a basalt filled with masses of olivine has been excavated. The olivine nodules vary in size, the largest being 6 to 8 inches in diameter. They are rounded or subangular in outline and of a uniform composition throughout. In most cases they are smooth and rounded on the outside and they can be broken from the matrix. Vesicles frequently occur clustered around the inclusions, but they are not found elsewhere in the rock. The matrix is a fine-grained picritic basalt or limburgite of dark grey color. Olivine phenocrysts are present and the groundmass is composed of augite, olivine, iron ores, and abundant glass with a very small amount of plagioclase feldspar. The inclusions are a dunite composed principally of olivine with a very subordinate amount of diallage and very rare specks of iron oxide.

The striking features of the nodules are large size and abundance. They compose about half the volume of the rock. They are usually very fresh and the individual olivine crystals are frequently a quarter of an inch in length.

On account of the deep weathering which the region has undergone, it is impossible to determine whether the nodule-bearing rock is part of a dike or a flow, but it is probably a flow, since the nodule-bearing rocks have a rather wide lateral distribution. The inclusions are found northward to the Peohia stream. Smaller nodules occur in the basalts near both ends of the new tunnel between the Komooloa and Palikea streams and a few are found in the Waiahi and Iliiliula stream beds. Similar nodules occur in the Hanapepe River, especially in the main stream above the falls[25] and a few are found in the flows on the east side of Nawiliwili Bay. Olivine bombs have been found on Hualalai and on Mauna Kea,[26] and olivine nodules have been reported from Oahu. A

[25] W. Cross, op. cit., p. 13; collected by the writer above the falls.
[26] R. A. Daly, Jour. Geol., vol. 19, pp. 301-3, 1911.

rounded olivine nodule one inch by half an inch in diameter was found at Kapulena, northeastern Hawaii, near Waipio Gulch in the lavas from Mauna Kea.

The origin of the xenoliths raises a number of questions which have been discussed for many years,[27] but which cannot be treated here. It is difficult to conceive of the formation of the nodules from pre-existing rocks as no rock masses of similar composition are known in the Hawaiian Islands. Therefore it appears that they are cognate xenoliths formed in the early crystallization of the magma in depth under such conditions that olivine and diallage crystals of comparatively large size and uniform grain were formed.

Recent investigations of artificial melts and of field evidence concerning crystallization and gravitative differentiation have shown the early formation and frequent segregation and settling of olivine and the later resorption of olivine in the normal course of crystallization.[28] It has been held by Bowen that the formation of monomineralic rocks is possible only in the earliest stages of slow crystallization and that in this process "there must be a considerable period during which olivine is separating alone and also a considerable period during which pyroxene and plagioclase, although separating together for the most part, form only a small fraction of the total mass (liquid and crystal)."[29] If sudden eruption took place, segregations of olivine in the magma at this period of crystallization would be carried to the surface in the same manner in which inclusions are carried upward in dikes[30] and the xenoliths of uniform composition and rounded to subangular form would be frozen in a rock of quite different composition. Resorption would be limited in amount owing to the lowering of the tempera-

[27] A bibliography of papers on the origin of olivine nodules is given by F. Zirkel, Über Urausscheidungen in Rheinischen Basalten, Abh. math.-phys. Kl. k. sächischen Ges. Wiss., 28, no. 3, Leipzig, 1903. Also see E. O. Hovey, Trans. Amer. Acad. Nat. Hist., vol. 13, 1894; C. H. Richardson, Science, Oct. 22, 1897; and H. Rosenbusch, Mikroskopische Physiographie, vol. 2, p. 1195.

[28] Bowen and Anderson, The binary system $MgO\text{-}Si_2$, this Journal, vol. 37, 1914; O. Anderson, The system anorthite-forsterite-silica, ibid., vol. 39, 1915; N. L. Bowen, The ternary system: diopside-forsterite-silica, ibid., vol. 38, 1914; N. L. Bowen, Crystallization-differentiation in silicate liquids, ibid., vol. 39, 1915; Powers and Lane, Magmatic differentiation in effusive rocks, Trans. Amer. Inst. Min. Eng., vol. 54, pp. 442-57, 1916.

[29] The later evolution of the igneous rocks, Jour. Geol., vol. 23, Supplement, p. 79, 1915.

[30] S. Powers: The origin of the inclusions in dikes, Jour. Geol., vol. 23, pp. 1-15, 166-182, 1915.

ture and most of the xenoliths should therefore be sharply separated from the matrix.

Gabbro intrusives.—Intrusive gabbro has been described by Lindgren[31] from the Wailau Canyon on Molokai, by Cross[32] from the Waimea Canyon on Kauai, and by Daly [33] from Uwekahuna, at Kilauea, Hawaii. In the first locality a tropical jungle conceals the parent body, at the second locality the rock (probably a dike) has not been seen in place, but at Uwekahuna the intrusive is seen in cross-section with upper and lower contacts within reach in a few places.[34] An inclusion of gabbro in basalt was found by the writer in the Hanalei Valley, Kauai. Very ample petrographic descriptions of the Wailau and of the Kauai gabbros under the name kauaiite (Iddings, Cross), and of the typical Uwekahuna gabbro have been published.

The Uwekahuna intrusive occurs in the walls of the Kilauean sink north of the crater Halamaumau and the base of the olivine gabbro is 40 feet above the floor of the crater. The intrusive is about 650 feet long and 68 feet in maximum height, but it may be composed of two masses. Chilled upper and lower contacts with a uniform-grained rock between, prove the intrusive character of the mass and suggest rapid cooling. Olivine is lacking at the upper contact in the chilled phase which is one foot thick, but in the second foot the olivine begins to appear abundantly as tiny phenocrysts and within three feet the rock assumes its normal grain. Gas tubes are very abundant at the upper contact. Olivine phenocrysts 1/16 inch in diameter are present in the chilled base of the intrusive, while they are ¾ inch in diameter in the normal rock.

Thin sections of the upper contact show it to be remarkably sharp considering the porous nature of the overlying pahoehoe. The latter is largely glass, with magnetite, augite, and tiny feldspar laths. Alteration of the magnetite and glass has produced limonite and hematite, staining the feldspar laths and giving the rock a dull reddish color. Frozen to the pahoehoe is a vesicular gabbro consisting principally of glass with specks of augite

[31] U. S. Geol. Surv., Water Supply Paper 77, p. 14, 1903.
[32] Op. cit., 1915, p. 14.
[33] Jour. Geol., vol. 19, pp. 291-4, 1911; Proc. Amer. Acad. Arts & Sci., vol. 47, pp. 115-6, 1911.
[34] S. Powers. Intrusive bodies at Kilauea, Zeitschr. Vulk., Bd. 3, pp. 28-33, figs. 1-5, 1915.

and magnetite, minute laths of feldspar, and small augite phenocrysts. One and one half inches below the contact the gabbro is a fine-grained, glassy rock showing feldspar, augite, and magnetite, but no olivine in thin section. Some of the magnetite is in rods with spicular outgrowths. The glass occurs in streaks and bands of dark color between bands filled with feldspar, augite and interstitial, translucent glass. In the glassy areas small augite phenocrysts occur, but they are filled with and surrounded by magnetite grains. Seven and one-half inches below the contact the gabbro is a uniformly medium-grained rock with a little glass in patches. The component minerals are feldspar, augite, and magnetite. No olivine is present.

A laccolithic origin has been ascribed to the Uwekahuna intrusive by Professor Daly in view of what he took to be doming in the overlying pahoehoe beds. This appearance may be induced by erosion and it is not seen when the body is viewed from its own level.

A comparison of a lava-tube at Haena, Kauai, with the above intrusion has led the writer to suggest[35] that the latter may be a filling of a lava-tube or of two tubes side by side. The Haena tube is at least 240 feet long, 200 feet wide, and 25 feet in height. The floor is covered by a deposit of sand and débris of unknown thickness, washed in from a talus cone at the entrance. Both the Haena tube and the Uwekahuna intrusive have a roof of finely-vesiculated pahoehoe of great rigidity.

In the Hanalei valley, Kauai, near the falls, the writer found an inclusion of gabbro in basalt. The gabbro is a coarse-grained rock with large feldspars and less conspicuous augites. Under the microscope the minerals in order of abundance are seen to be feldspar (partly oligoclase with a secondary generation which may be orthoclase), purple augite, limonite, magnetite, apatite, and biotite. The iron ores occur as skeletal crystals resembling Chinese characters, as in the Wailau and Kauai gabbros. No olivine was observed. The rock is free from the vesicles so abundant in the greater part of the Kauai gabbro and is finer grained and contains less augite than the Wailau gabbro.

Age Relations.

A certain sequence of events can be traced in the life-history of volcanoes, and especially in basaltic volcanoes,

[35] Loc. cit.

from the first outbreak to the close of activity, which is frequently a lava flow after the mountain has been covered by ash cones and perhaps buried under a layer of ash. It is with the events toward the close of the life of the volcano that this paper has dealt. The volcano increases in height by extravasation from a summit crater until the lava finds an easier path to the surface by fissuring the mountain, thus pouring out flows and building cones on the sides while a sink is gradually formed at the summit by successive inbreaks when the lava is withdrawn down the feeding tube at the close of an eruption. Mauna Loa and Kilauea have both been active through historic time in building up the floor of the summit sink as well as in pouring out flows through fissures down the sides of the mountain. Increasing viscosity of the magma may lead to the formation of domes of the Pélée type, as in the historic record of Kilauea, and to lessened activity with a longer period between great eruptions. Finally, the gaseous lava which reaches the summit sink may begin the formation of cones over the latter and at last bury it. Mauna Kea and Hualalai may have possessed summit sinks now buried, while the process of burial was not completed at Haleakala.

It has been seen that the cones on the sides of the mountain have a tendency to a definite arrangment along radial and occasionally along tangential lines. While one group of these cones is formed near the close of the activity of the main volcano, as those of Hualalai, Mauna Kea, and Haleakala, another group may be formed after the close of the main activity and after the volcano has been actively eroded for a long period of time, as on Niihau, Kauai, East Oahu, East Molokai, and West Maui. Especially apparent in the case of the two westernmost islands is the long interval between the close of the principal activity and the revival of activity in cone-building. Similarly, revival of activity may occur on Haleakala, Hualalai, or Mauna Kea after these mountains have been deeply dissected. That there may still be activity along the line of the extinct volcanoes is indicated by the fact that fish were reported to have died in large numbers off Molokai in 1859; that in 1868 and 1877, concomitantly with activity on Hawaii, the fish in the brackish water fish-pond Nomilo, an old crater on the shore of Kauai, were all killed; and by the fact that in 1868 one of the earthquake epicenters appears to have been south of Kauai.

Toward the close of the evolution of the volcanic edifice another change appears to take place occasionally—the appearance of the more unusual rock types. Trachyandesite, in contrast to basalt, is found on the summits of Haleakala and Mauna Kea; trachyte forms a veneer over portions of West Maui and Mauna Kea (where it has been overrun by Hualalai and Mauna Loa flows); nephelite-bearing rocks appear in the young tuff cones and flows on East and West Oahu, in a young crater on Kauai, and probably in the youngest tuff cones on other of the older islands. These rarer types are almost completely lacking, so far as known, in the older rocks of any of the main volcanoes. The occurrences of these rarer types, which must be differentiates of basalt, seem therefore to indicate that such differentiation is characteristic of the closing stages of the Hawaiian vulcanism and that this differentiation proceeds separately in separate volcanoes or possibly contemporaneously in pairs of connected volcanoes. Each volcano has arisen at an intersection in a fracture system in the earth's crust, has been fed from the same primal magma, and has finally lost connection with this source. When this takes place differentiation may proceed in the magma chambers of the larger volcanoes and the extreme products of Hawaiian vulcanism, nephelite basalt and trachyte, may appear either at the close of the main vulcanism or in a later phase after extensive erosion.