GEOLOGY OF LEHUA AND KAULA ISLANDS

By

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INTRODUCTION

LOCATION

The islets of Lehua and Kaula are small, uninhabited, and virtually uninhabitable remnants of crescentic rims of tuff craters. Their positions with respect to Kauai and Niihau, the most westerly of the inhabited Hawaiian islands, are shown in figure 1.

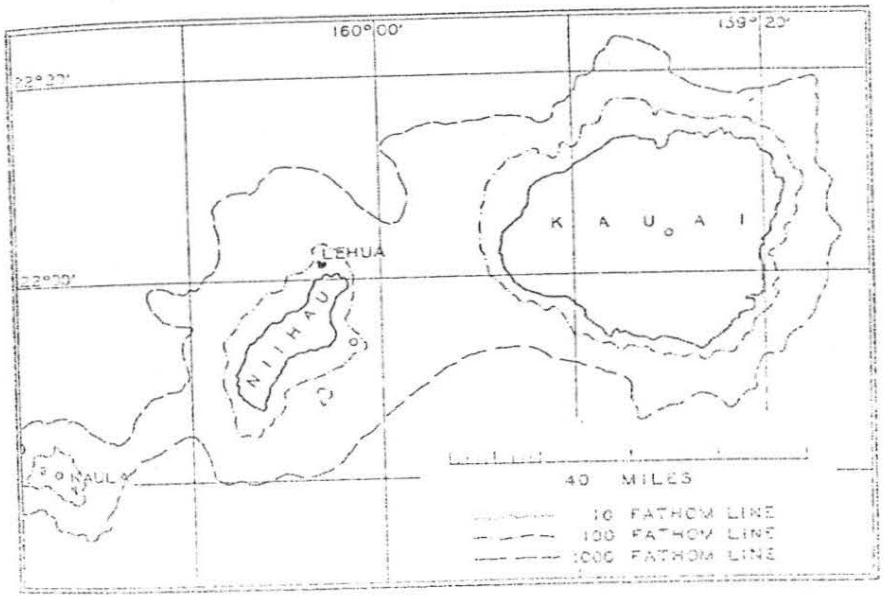


FIGURE 1.—Map showing the positions of Lehua and Kaula with respect to Kauai and Niihau. Based on U. S. Coast and Geodetic Survey, Chart 4117 (Oahu to Niihau), ed. March, 1933. Circles indicate assumed position of original summit craters.

Lehua is separated from Niihau by "Lehua Channel", about 3,800 feet wide and navigable by moderately-sized vessels commanded by persons familiar with these waters (18)[1]. From Kauai, Lehua appears to be several miles from Niihau because the curvature of the earth hides the low northern plain of Niihau. As determined by the U. S. Coast and Geodetic Survey (15, p. 42), the triangulation station on the summit of Lehua lies in longitude 160° 06′ 03.722″ West and latitude 22° 01′ 19.592″ North, "Old Hawaiian Datum". Lehua is readily visible from Kauai as the distance between the two is about 18 land miles. Soundings show a depth of less than 500 fathoms in mid-channel.

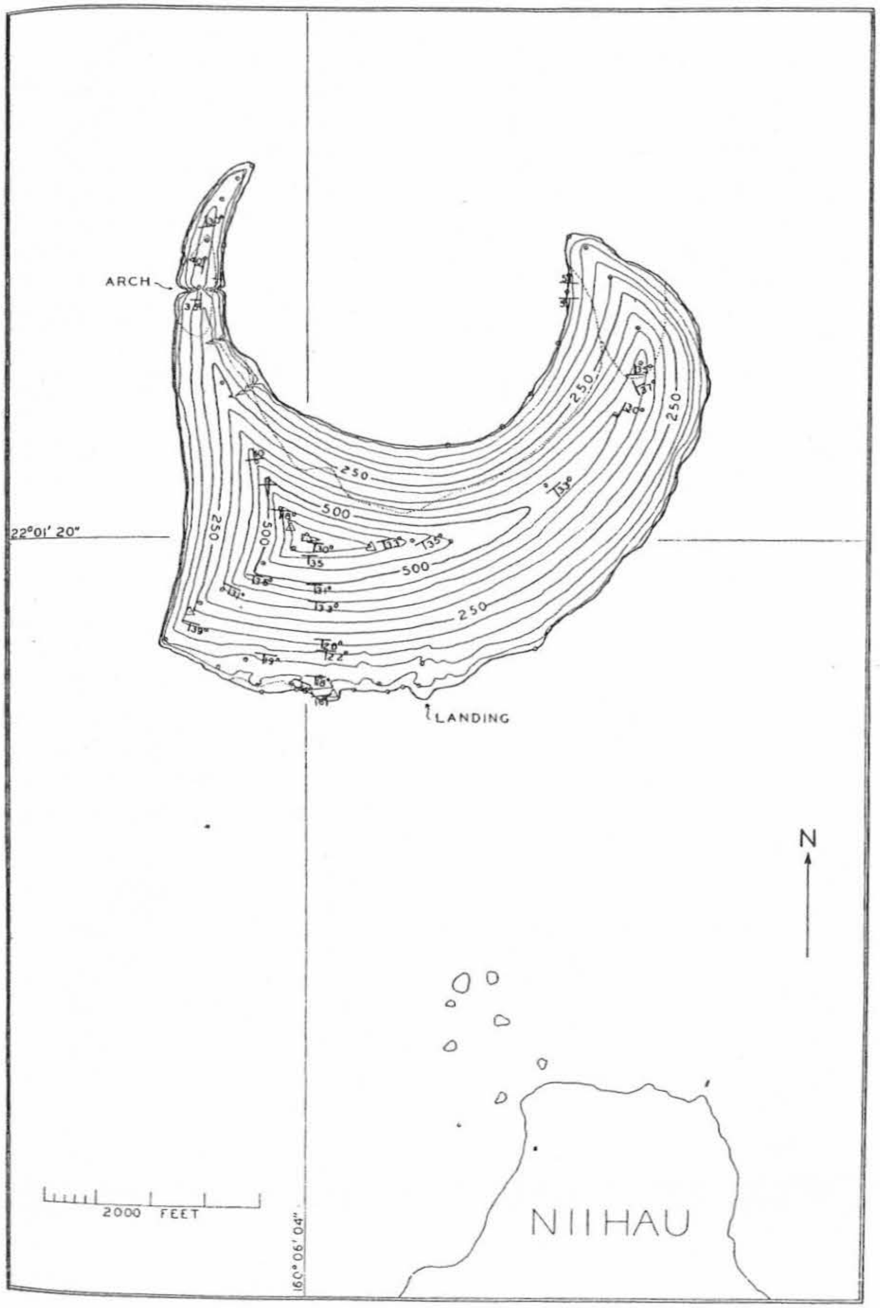
[1] Numbers in parentheses refer to Literature Cited p. 31.

Kaula lies about 38 miles southwest of Lehua, or about 23 miles west-southwest of Kawaihoa Point, a recent volcanic cone at the south end of Niihau. Soundings show depths of as much as 877 fathoms between Kaula and Niihau. Kaula has not been occupied as a triangulation station, but the location of its highest point is given by the U. S. Coast and Geodetic Survey (15, p. 44) as longitude 160° 32′ 39.34″ West and latitude 21° 39′ 28.83″ North.

PREVIOUS STUDIES

So far as I know, no intensive study has been made of the geology of either Lehua or Kaula. Brigham (3) apparently confused the islet of Kaula with Kawaihoa Point, for he describes Kaula as seen from Waimea, Kauai, from which place it is not visible. He makes the strikingly good generalization that Kauai, Niihau, and Kaula constitute a single volcanic structure. He also suggests that Niihau was once a part of Kauai and that it was separated from the Napali coast and moved southwestward some 35 miles. Such a horizontal shift seems improbable.

Bishop (2) circumnavigated both Kaula and Lehua and gives brief descriptions of them as remnants of asymmetrical tuff crater rims. He found about 200 degrees of crest line arc surviving on Lehua and about 140 degrees on Kaula. Some of his party rowed 200 feet into the cave on Kaula. Dana (6), Hitchcock (11), and Bryan (4) give abstracts of Bishop's findings but add no new data. Dana (6, pp. 311-312) noted the alinement of the southwest cliffed coast of Niihau with the northwest (Napali) coast of Kauai and thought they were genetically related to a single line along which downfaulting had taken place. There is no evidence that he thought in 1890 that Niihau had been torn from Kauai, though he was of this opinion earlier (6; 10, p. 52; 17, p. 514). The short article by Friedlaender (8) is based on a sketch map and photographs furnished him



by Mr. A. E. Arledge, then Superintendent of Lighthouses. Friedlaender speaks of numerous unconformities ("vielfach diskordanten Schichten") but there is only one unconformity on Kaula. Palmer (16) circumnavigated and photographed Kaula in 1923, and studied a few rock and soil specimens collected by Mr. Frederick A. Edgecomb and various photographs taken by Mr. Edgecomb in 1925. Relevant data are repeated in the present paper. Hinds (10) shows clearly that Kauai, Niihau, and Kaula are independent volcanic domes, together constituting a unit in the structure of the Hawaiian islands. Although unable to visit Lehua, he describes it briefly and notes the wave-cut bench. The United States Coast Pilot Notes (18) gives a brief description of Kaula and Lehua. The U. S. Coast and Geodetic Survey Chart 4117 shows both Kaula and Lehua, and the 10, 100, and 1,000 fathom submarine contour lines around them.

Maps

For the field work on Lehua a new map (fig. 2) was made by using an 18 by 24 inch plane-table and a light explorer's type alidade.

Orientation was by backsighting on the "Gam" triangulation station 2¼ miles away on Niihau. Nine points were located on the inner shore line of Lehua by the depression angle method, working from two points on the crest line. Six points were similarly located on the south outer shore. The rest of the shore line was taken from the U. S. Geological Survey map (Kii sheet) with some adjustment. The contouring of the inner slope and part of the outer slope was controlled by intersections on 12 points and stadia measurements to 27 points. Much of the outer slope is difficult of access and offers problems in visibility because of the pronounced convex curvature; so for this region the contouring was taken from the U. S. Geological Survey map with a little obviously necessary alteration.

The dips and strikes of the tuff beds, the courses of the unconformities, and the magnetic declinations were observed independently of the plane-table work and were later tied in by locations based on barometric elevations and by backsights on three or more known points. The bearings thus taken are "magnetic" bearings but application of the "three-point" problem made their conversion to "true" bearings fairly simple.

The map of Kaula (fig. 3) was prepared quite differently.

A vertical airplane photograph was taken by the Eleventh Photo Section, Air Corps, U. S. Army, on July 10, 1924. On the basis of a pantograph enlargement, the study of various other photographs, and some transit work in July, 1925, Mr. Frederick A. Edgecomb prepared a contour map on a scale of 200 feet to the inch with a contour interval of 50 feet. The orientation of this map was determined by bearings taken by the lighthouse tender *Kukui*. This map is in general very satisfactory. However, since a few corrections seemed possible and a circumnavigation of the island showed that the geologic structure was relatively simple, it was decided to devote most of the time available to checking the topographic map. Flags were set at 11 points including one near the summit in a pipe set in concrete by Mr. Edgecomb in 1925 and one wedged into a crack in the wave-cut bench on the inner side of North Horn. This last flag was not occupied as a transit station, but the other ten flags were, as was also a flagless station. Orientation was by backsighting onto the highest point of Lehua which, unfortunately, was at no time during the work sharply outlined. So far as intervisibility allowed, azimuths and vertical angles were taken from each of the 11 stations to each of the others. The measurement of a base line on the curving rim of a tuff crater is difficult. The procedure adopted was to measure three chords connecting four of the stations and to compute from each short chord the length of the longest chord joining the most remote of the four stations, which was to be used as the final "base line". The length finally adopted

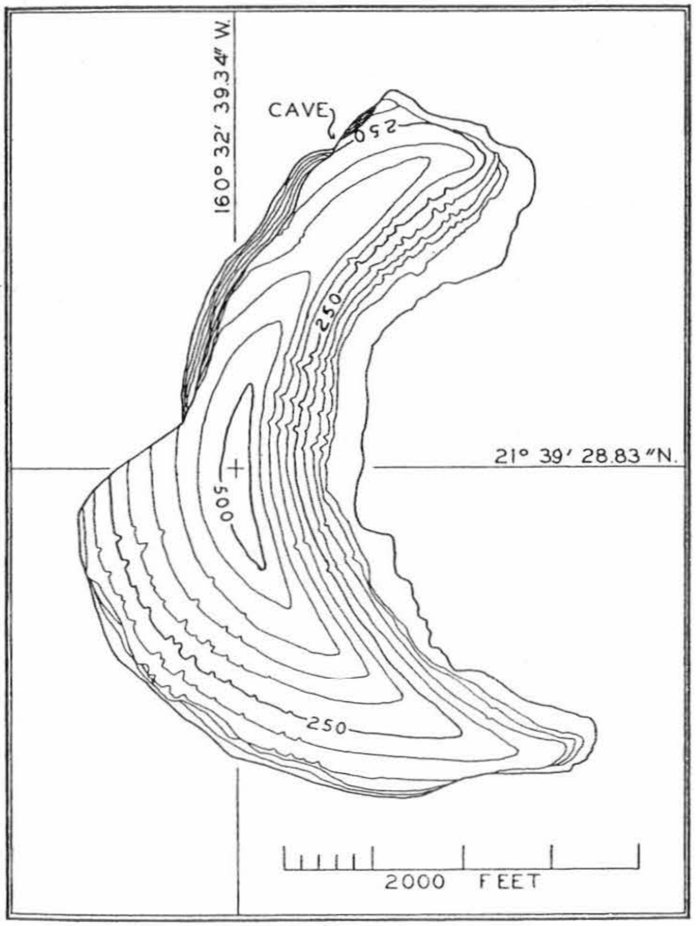


FIGURE 3.—Map of Kaula.

for this base line was an average gotten by weighting the computed lengths in inverse proportion to the number of times it was necessary to "break chain" in measuring the short chord on which the computed length was based. Working from this base line the latitudes and departures of the 11 flagged stations and the one flagless station were computed in the office. In addition, 29 points along the inner shore of Kaula were located by depression angles working from four crest line stations. The positions of the 11 stations on the crest were plotted on a sheet of drawing paper. A lantern slide had been made from the approximately vertical airplane photograph and was projected onto a drawing board arranged in an approximately vertical position. After considerable adjustment of the stereopticon, the image was made the right size, and further tilting and turning of the drawing board and paper got the image of the crest line into satisfactory agreement with the plotted positions of the crest line stations. In the absence of complicated apparatus this method provided for reasonably good rectification of the photograph. The images of the shore line, crest line, cliff tops, and gulches were then traced off onto the drawing paper. This gave a good rendition of the outlines of Kaula to which the contours of figure 3 were added on the basis of field notes and measurements made on numerous photographs of the islet taken from the *Kukui* as well as from points on the islet.

ACKNOWLEDGMENTS

The field work on Lehua was begun during a reconnaissance on September 22, 1928, and was completed on April 18-24, 1931. The field work on Kaula was done on August 17-19, 1932. I am deeply indebted to the Superintendents of the Nineteenth District of the U. S. Lighthouse Service for the opportunity of visiting Lehua and Kaula and for permission to travel on the tender *Kukui*, engaged in constructing lights on these islets. Mr. R. R. Tinkham arranged for the 1928 work, and his successor, Mr. Frederick A. Edgecomb, for the 1931 and 1932 work. Many favors rendered by various members of the *Kukui's* personnel are gratefully acknowledged. Mr. Edward L. Caum, author of a paper on the botany of Lehua and Kaula (5), rendered valuable help in connection with the mapping and photographing.

TOPOGRAPHY

GENERAL FEATURES

Lehua and Kaula are barren and possess little economic value, except as lighthouse sites. As described by Caum (5), the vegetation is scanty but the bird life abundant.

On the south slope of Lehua, near the cliff edge at an elevation of 60 or 65 feet, is the platform built of rocks which Mr. Kenneth P. Emory tells me was probably built by bird hunters, possibly by fishermen. No other features of archeologic or ethnologic interest were seen on Lehua. On the crest of the north rim of Kaula are three or four incomplete, low, stone enclosures, which seem to be windbreaks built and used rather recently, and perhaps still used at times by the fishermen who signal the positions of schools of fish to associates out on the water. On the inner slope, a short distance below the windbreaks, several walls have been built part way across the fronts of caves eroded by wind in weaker beds of tuff. Bits of charcoal indicated occupation of at least one of these caves.

In trade wind weather it is easy to land on the low wave-cut bench on the south side of Lehua. The upper slopes are inaccessible from below, except where small valleys cut down through the cliffs that back all parts of the bench and form the shore wherever the bench is lacking. The cliffs back of the landing are from 30 to 60 feet high. Gulches on the inner side of West Horn permit ascent from the bench to the upper parts of Lehua, but it is probably impossible to land on this part of the wave-cut bench except in southerly weather.

On the west side of Kaula where it is possible to land in steady trade wind weather, the Lighthouse Service has constructed a rough trail of ascent from the fragment of wave-cut bench. Pins have been grouted into the rock and footholds cut in the tuff near the water line. A rough bench at about 100 feet elevation is reached by means of these pins for handholds and, for part of the way, by a heavy chain hanging down a gully in the tuff. The derrick and tank house of the lighthouse installation are on this bench (pl. 4, *B*). A substantial ladder leads from here to the upper slopes. In some weather it is possible to land on Kaula on the inner side of North Horn, whence a strenuous climb leads to the end of North Horn at nearly 300 feet elevation.

An automatic gas light of the U. S. Lighthouse Service was established on Lehua on April 24, 1931, and on Kaula on August 18, 1932. For a good many years before Lehua was transferred by the Territory of Hawaii to the federal government for a lighthouse reservation, it was leased from the Territory by the owners of the island of Niihau who, to a considerable extent, protected the sea birds that nest there, and also eradicated weeds which on migration might damage the grazing lands of Niihau.

Seen from a distance, Lehua and Kaula have unsymmetrical, conical outlines. From nearby, however, each is a crescentic ridge comprising the above water part of the rim of a tuff crater with steep slopes leading outward to the open ocean and inward to a bay. The original smooth slopes built by constructive volcanic action have been modified by the destructive work of winds, waves, and running water. The average slope of Lehua is about 30 degrees as determined by the method of Finsterwalder (20); if the bordering sea cliffs are excluded the average slope is about 27 degrees. The average slope of Kaula is about 36 degrees or 28 degrees if the sea cliffs are excluded. Corresponding figures for the outer slopes of Kaula are 38 degrees and 21 degrees; for the inner slopes, 33 and 38 degrees. Cliffs modify the values for the outer slopes more than for the inner slopes because the cliffs on the outer side are much higher. Inasmuch as the surface of each island is largely bare rock or only slightly weathered, it is possible to reach all parts of the islets except the cliffs and parts of the wave-cut bench below the cliffs. The steep slopes, however, make the going arduous and in places dangerous.

Lehua

According to the planimeter measurements of the drawing reproduced as figure 2, Lehua has an area of about 291 acres at sea level. With the remarkably great average slope of 30 degrees the total surface, if flattened out, would be about 15 percent (44 acres) greater. The arcuate crest line of Lehua is about 9,250 feet long. The greatest width (about 2,600 feet) lies along a line bearing N. 22° E. through the summit point, the elevation of which is given by the U. S. Geological Survey (Niihau topographic sheet) as 702 feet.

From the summit the crest line extends as two "horns" (fig. 2). West Horn (pl. 3, *A*) extends northward for 4,000 feet. It narrows rather abruptly to a width of about 600 feet and drops rapidly to a crest elevation of 250 feet. It is gashed on its inner or eastern side by several sharply incised, miniature canyons. One of these has cut completely through the ridge leaving a natural bridge or arch with a thickness of about 30 feet and a span of about 25 feet. East Horn of Lehua (pl. 1, *B*) extends eastward from the summit for about 1,750 feet, falling gently in elevation to about 500 feet. Thence it curves through northeast to north for 2,000 feet, with a drop in crest elevation of only 75 or 100 feet. The remaining 1,600 feet of the crest line includes a drop of from 400 feet to sea level. East Horn has a rather uniform width of about 1,500 feet. The tips of the two horns are about 2,900 feet apart, and the reentrant bay extends inward about 2,200 feet from the line joining the tips.

From the summit of Lehua a subsidiary crest line extends 1,650 feet S. 55° W. to the southwest corner of the islet. This subsidiary crest line, which offers the least arduous route to the summit from the south shore, is not part of the crater rim but is a break or topographic unconformity separating two surfaces of quite different origin. Southeast of it is the normal southward sloping depositional surface of the tuff cone. Northwest of it is a surface which has been cut across the bedding of the tuff by some sort of landsliding or faulting process.

Kaula

According to the planimeter measurements Kaula has an area at sea level of about 136 acres. As the average slope is about 36 degrees, the total surface area, if flattened out, would be about 24 percent (32 acres) greater. The summit elevation is about 540 feet.

The curving crest line of Kaula is about 5,500 feet long (fig. 3). The greatest width of the islet (about 1,650 feet) is along a line bearing about N. 78° E. through a point 150 feet south of the summit, which is 56 degrees different from the bearing of Lehua's greatest width. It seems appropriate to speak of a "North Horn" and a "South Horn" on Kaula. North Horn of Kaula extends northward for 2,500 feet from the summit. It drops rather quickly to about 400 feet elevation and then very gently to the 280 foot high cliff that truncates the end. It is similar in formation to West Horn of Lehua. Near the end of the outer side of North Horn is a remarkable sea cave (pl. 4, *C*). South Horn of Kaula extends first southward, then southeastward, and finally eastward for a total distance of about 3,000 feet (pl. 4, *A*). The crest line drops rather uniformly to the top of the terminal cliff, which is about 100 feet high.

The tips of the two horns of Kaula are about 3,200 feet apart, and the reentrant extends inward about 1,200 feet from the line joining the tips.

Kaula lies near the southeast end of a shoal (fig. 1) about 8 land miles long and about 4½ miles wide, bearing west-northwest.

Circularity

As a rapid glance at the maps (figs. 2, 3, 4) suggests that the rims of the craters, or the crest lines of the two islets, approximate arcs of circles, it seemed interesting to try to fit an arc of a true circle as closely as possible to each. The following results were obtained.

The crest line of Lehua is everywhere sharp and distinct. It includes the main curve following the crater rim and approximates an arc of a circle. A trial circle with a radius of about 2,025 feet was selected by inspection in the attempt to fit a circle to the crest line. The inevitable errors were dealt with mathematically, whereby the areas between the crest line and the trial circle were measured by planimeter. Some of these areas lay inside the circle and outside the crest line. These were added and compared with the sum of the areas of the other parts—those lying outside the circle but inside the crest line. In the first trial, the areas inside the circle exceeded those outside by 435,500 square feet, which indicated that the trial circle was too large. The excess of 435,500 square feet was distributed along the 9,250 feet of the crest line, which then gave about 47 square feet of excess area for each linear foot of crest line. Consequently, a circle of 47 feet less radius, or 1,978 feet seemed indicated. As it was impossible to plot very closely, a circle of about 1,975 feet radius was chosen with its center 2,180 feet N. 27° E. of the triangulation station at the summit. The crest line follows this circle closely through an arc of 259 degrees. The departure of crest line from arc averages less than 90 feet and nowhere is as much as 270 feet. The areas outside this second circle exceed those inside by only about 5,000 square feet (396,000 — 390,750 = 5,250 sq. ft.); or 0.57 square feet per lineal foot of crest line.

Similar trials for Kaula led to the selection of a circle with a radius of 1,750 feet, with its center 1,820 feet N. 86° E. of the summit. Such a circle departs on the average about 46 feet from the crest line throughout an arc of 169 degrees. The departure nowhere exceeds 97 feet. The areas outside this circle exceed those inside by 10,560 square feet, or 2.05 square feet per lineal foot of the arc.

Constructional Forms

Constructional surfaces, made by the accumulation of rock, are represented on Lehua and Kaula solely by tuff-built surfaces which follow the upper surface of the sloping beds, such as the smooth parts of the outer slopes of each islet, where falling ash found lodgment on the sloping surface of earlier fallen ash (pl. 3, *B*). There are other constructive surfaces on the inner slopes of these islets where thin veneers of ash found lodgment. In some places on the inner slopes either ash never fell or has since fallen into the bay. There are small areas of inward sloping tuff surfaces on the inner side of East Horn on Lehua (pl. 1, *B*).

Landslide Surfaces

On the west face of Lehua (pl. 1, *A*) the arching beds of tuff are cut off abruptly. It is believed that these arches never extended farther seaward but that support from underneath had been eliminated by earlier downfaulting so that ash found no permanent lodgment and slid off into the sea. Thus the supported parts of the tuff beds have remained to make these astounding arches. On the upper parts of the inner slopes of Lehua (pl 1, *B*) the edges of many parallel beds of tuff are revealed which have been cut off by landsliding or by lack of lodgment of ash. On Kaula a great joint surface, trending N. 50° E., bounds the southwest side of a reentrant from which a block of tuff has evidently fallen into the sea (pl. 4, *B*).

Wind-cut Surfaces

Wind has produced no major changes on either Kaula or Lehua, but on both it has cut intricate and fantastic details of the rock sculpturing. By abrading weak bits of surface rock wherever they may be, the wind has produced such pits as those shown in plate 2, *B*.

Stream-cut Surfaces

Because the areas of Lehua and Kaula are small and the surface slopes steep and mostly bare of vegetation, the streams are small and strictly ephemeral. The low elevation makes it probable that the annual rainfall is scant, perhaps about 20 inches. Consequently the work accomplished by running water is slight. The only factor favoring active stream work is steepness which gives the streams high velocity. On both islets the outer and the inner slopes have been trenched by radial streams. The largest trench on Kaula heads about 550 feet S. 8° W. of the summit and is about 750 feet long. It is some 30 feet wide and 20 feet deep for much of its length. Lehua is far less trenched than Kaula (pl. 3, *B*).

On the south side of Lehua, the dips of the tuff beds near the shore are decidedly less (20±°) than those higher up (33±), so that there is a flattening of the slope. Chance irregularities have brought together in one place the flow of several shallow radial streams and diverted them into channels parallel to the shore. These streams have cut gullies from 10 to 20 feet deep. Several such peripheral valleys are indicated by reentrants in the contour lines of the Lehua map (fig. 2).

Wave-cut Surfaces

In general the northeast and east sides of the Hawaiian islands are the most attacked by waves because most exposed to the trade winds. The southerly sides are usually protected, but during the southerly (*Kona*) storms they may undergo very vigorous wave attack for short periods. Lehua is protected from southerly storms by Niihau

and from easterly storms by the broad mass of Kauai, the nearest point of which is only 18 miles away. Kaula is fully exposed. Almost the entire 7,000 foot shore line of the inner curve of Lehua has a wave-cut bench or terrace ranging in height from 5 to 10 feet and in width from 0 to 30 feet (fig. 4, *b*; pls. 1, *B* and 3, *A*) as estimated from points above. About nine tenths of the 4,400 feet of the inner curve of Kaula have similar bench from 10 to 80 feet wide and from 4 to 8 feet high, as estimated from a motor boat at close range (pl. 4, *A*).

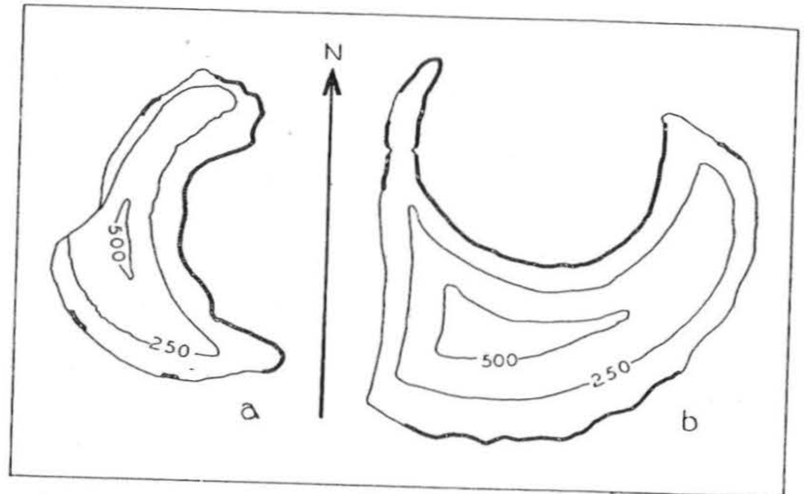


Figure 4.—Sketch maps of (a) Kaula and (b) Lehua. The heavy lines indicate parts of the shores with wave-cut bench and the light lines, parts where cliffs plunge directly into the ocean.

Less accurate observations were made on the outer curves of these two crescent-shaped islands. However, there is a similar bench along half or two thirds of the west shore of Lehua, which is some 4,800 feet long. The bench along the northern part of the east shore and the southeast shore is poorly developed and fragmentary for 5,250 feet from the tip of East Horn. From the southwest corner of Lehua eastward for 3,500 feet along the south shore the bench is splendidly developed with an elevation of 2 to 4 feet above sea level. Its width reaches a maximum of about 100 feet. (See pls. 2, *A* and 3, *B*.) In fact, the bench is well developed on all sides of Lehua except that most exposed to the prevailing winds (fig. 4, *b*). The outer shore of Kaula has very little bench. The best fragment, lying southwest of the summit, is about 150 feet long, 0 to 20 feet wide, and 4 to 6 feet above sea level (fig. 4, *a*). The bench is well developed along the whole length of the inner curve.

It has recently been suggested by Johnson (12, 13, 14) that the classical explanation of exposed wave-cut surfaces, as due to the emergence of submarine benches cut at an earlier time of relatively higher sea level, is erroneous and that they are actually the work of storm waves at present sea level. In other words, Johnson holds that these are not old features being destroyed, but that they are modern features being enlarged.

If the bench is the work of present day storm waves it should be best developed on those parts of the shore line which are most exposed to storm waves and least developed on the sheltered shore lines. If, on the other hand, the bench is an old feature now undergoing destruction it should have survived most on the sheltered shore lines and least on the exposed shore lines. On both islets the bench is nearly or quite continuous on the inner curves but largely lacking on the outer curves. On both, the inner faces have the gentler but far more persistent attack of the trade wind waves. However, as the inner curve is a bay it tends to dissipate the energy of the waves. On Lehua the amount of wave energy crossing 2,900 linear feet (the distance between the two horns) is spread over 7,000 feet of the inner shore line. On Kaula the energy of 3,200 feet of waves is distributed over 4,400 feet of shore line, as pointed out by Davis (7). Thus the energy of wave attack on the inner curve of Lehua is diluted to 41 percent ($2900/7000 \times 100 = 41\%$) and on Kaula, to 73 percent ($3200/4400 \times 100 = 73\%$). This dilution is qualitatively obvious to observers on either islet during trade wind weather; the impact of the waves is not excessive. Thus the sides exposed to trade wind waves are not violently attacked. The sides exposed to the occasional violent southerly storms have suffered more. It therefore appears that storm waves destroy rather than create the bench.

The inner shore lines of Kaula and Lehua are very similar—the benches are much alike—but the outer or southerly exposed shore lines contrast strongly. Kaula, with no protecting island to the south, has very little bench on its southerly shore. Lehua, which is partly protected from southerly storm waves by Niihau, has a wide bench.

So again, storm waves seem to be destroyers rather than creators of these benches.

The level surface of the bench has been determined by some leveling control, and sea level is the only conceivable one. The bench surface in most places cuts across the beds of tuff though in some places the bench follows the bedding of the tuff where a weaker layer has been stripped from a stronger layer. The usual beveling of the tuff beds by the bench is well shown along the south shore of Lehua (pl. 2, *A*). Here the beds strike east-west (parallel to the shore) and dip south (seaward) about 15 degrees.

The upper surface of the bench is in general very smooth, though grooved a little where weaker beds have been more abraded. The seaward edge of the bench is a plunging cliff, rather frayed out in detail. From the way in which waves strike the edge of the bench it appears that it is now being destroyed by wave attack. The behavior of waves approaching shores with steep underwater slopes is as follows:

As the trough of a wave approaches the bench the water drops and recedes; the succeeding crest, as it approaches, is oversteepened and seems to be tripped up by the receding water of the trough, so that it slides down the incline of the wave front and delivers most of its blow at the base of the plunging cliff, thus tending to undercut the cliff and drive it back. After delivering its blow at the base of the cliff the foamy water surges upward along the cliff and a little froth may fall forward onto the bench. Wave attack on the seaward margin of the bench is helped appreciably by the borings of sea urchins. They cling to the rocks in some way and, by their jaws, or their movable spines, or both, wear small pits and grooves in the tuff. (See pl. 1, *C*.)

Wherever waves cut a bench, they must of necessity also make a cave or a cliff at the back of the bench. At first a reentrant notch or shallow cave is cut. This may be deepened locally, especially if the rocks are of varied resistance, and a rather deep cave formed. Caves at sea level are the deepest of the reentrant notches (pls. 2, *A*; 3, *B*; 4, *C*) particularly where the attack has been localized along weak beds or structures. At a cave on Kaula (pl. 4, *C*) the wave attack has been localized through the weakening by weathering of an older series of tuffs below an unconformity. The broad cave on Lehua (pls. 2, *A* and 3, *B*) is due to localization of wave attack by a weakly cemented bed or group of beds of tuff. On West Horn of Lehua a cave has been developed into an arch or natural bridge due to the narrowness of the ridge and the process of weathering along a major joint.

Cliffs on both islands are prominent features (pls. 1, *B*; 2, *A*; 3, *A*; 3, *B*; 4). Those along the inner curve of Lehua range from 40 to 100 feet high, and those along the outer curve, from 30 to 200 feet. On Kaula the range is 50 to 100 feet on the inner curve and 100 to 160 feet on the outer curve; on the west side where a great joint block has fallen out, the cliffs reach 350 feet (pl. 4, *B*).

Several of the small islets near the north end of Niihau are composed of evenly bedded tuffs that dip very slightly southward. Their flat upper surfaces appear to be original depositional surfaces, but they might conceivably be remnants of a bench cut along a resistant bed when sea level was higher than it is now. These islets are bordered by plunging cliffs, which are now being cut back by wave erosion.

STRUCTURE

Kauai, Niihau, and Kaula

Kauai, Niihau, and Kaula well illustrate the general principles that volcanic centers tend to lie along straight lines and that the spacing between them tends to be uniform. Strong erosion has removed the original summit crater of Kauai, but for the present discussion it is assumed to have been near Waialeale. Downfaulting and wave erosion have removed the original summit crater of Niihau, but it was probably a few miles east of Pueo Point, at the south end of the east coast of Niihau. The original summit crater of the Kaula dome is assumed to have been about the center of the shoal outlined by the 100-fathom line. (See fig. 1.)

A straight line joining Waialeale to the center of the Kaula shoal is 74 land miles long and bears S. 69° W. Pueo Point is 3 miles, N. 57° W., from the middle point of this line. The original summit crater of Niihau is probably as close or closer to the middle point.

Soundings 40 miles or more from the shores of the Hawaiian islands are about 2,500 fathoms, and indicate the depth of the sea bottom platform on which the Hawaiian volcanic structure is superposed. The 1,000 fathom line surrounds Kauai, Niihau, and Kaula in one closed curve, which is separate from the 1,000 fathom line around Oahu. Thus the 1,000 fathom line indicates that these three islands are closely related in origin and are manifestations of a line of weakness bearing N. 69° E., and crossing at an angle of about 40 degrees the general trend of the Hawaiian islands, which is about N. 70° W. The submarine saddle between Kauai and Oahu probably is crossed by the 1,600-fathom but not by the 1,700-fathom contour line.

The spacings between Kaula and Niihau and between Niihau and Kauai are about 37 miles, which is considerably greater than the 22 to 25 miles which Friedlaender (9) gives for the average in the Hawaiian islands. If a 900-fathom contour line were drawn it would probably connect Kaula to Niihau, for the deepest sounding between them is 877 fathoms. Similarly, a 500-fathom contour line would connect Niihau to Kauai.

Kaula and Its Shoal

As shown in figure 1, Kaula lies near the southeast end of an irregular, oblong-shaped shoal outlined by the 100-fathom line, about 8 land miles long on the west-northwest axis, and 4½ miles wide. About 27 square miles are enclosed by the 100-fathom line, which probably outlines a wave-truncated lava dome and the surrounding bank built of its detritus. The lava dome presumably had a sea level horizontal section some 3 by 6 miles and a height of approximately a thousand feet. On Kauai and Oahu there are tuff cones and craters which are much younger than the lavas forming the bulk of these islands, and which were not erupted until great valleys had been cut. A like length of time would have permitted the complete truncation of the much smaller lava pile of Kaula. Kaula appears to be a secondary tuff structure built on a wave-cut platform rather than on a stream-eroded surface. A single sounding of 5 fathoms rises from the general 35-fathom level at a point about 3 miles N. 60° W. of Kaula and may be either another secondary structure which did not reach sea level or a residual not removed in the planation of the shoal. The bottom at this point is reported as "rock" on the chart. The general depth of 35 fathoms on the shoal surrounding Kaula is perhaps due to wave planation during a low stand of sea level in one or more of the Pleistocene glacial stages.

Among the blocks embedded in the tuff of Kaula are many fragments of reef rock, which would indicate that the shoal had been populated by lime-secreting plants and animals prior to the eruption of the ash. Most of the blocks of basalt in the Kaula tuff are angular and preserve the shapes that they had when torn from the conduit walls by the uprushing gas-charged magma. Some of them, however, are well rounded like beach or stream pebbles. These probably preserve shapes given them by battering and abrasion by wave work on the shoal. Thus, it may be concluded that the Kaula shoal formerly had a more or less continuous mantle of beach boulders, and that, at some time, it carried more or less reef.

Lehua and Niihau

Lehua lies some 9 miles north-northwest of the supposed position of the original summit crater of Niihau, to which it bears the structural relationship of a secondary tuff crater. Mr. John McCombs, Engineer of the Bishop Estate, reports that Cape Kawaihoa at the south end of Niihau and the hill known as "Kaeo", near the middle of Niihau, are also secondary tuff structures. Lehua Channel, between Lehua and Niihau, is only 3,800 feet wide and some 7 fathoms deep. Tuff from Lehua has made a number of tiny islets close to the north shore of Niihau. According to McCombs, tuff, for which Lehua seems to be the only source, extends several miles south along the west shore of Niihau.

Crater Rim Structure of Lehua and Kaula

Lehua and Kaula have similar origins and therefore have similar, though not identical, structures. Each has been built by explosive volcanic action in which the proportion of gaseous to liquid matter is great. The excessive amounts of gas in their swift uprush break the lava into small particles, which are carried high into the air and which solidify before finishing their descent. Thus such an eruption is a sort of rain of ash or lava particles. The trade winds drift the ash so that there is more accumulation on the leeward side of the vent than on the windward side. In such eruptions the wind also sorts the ash, causing the finer ash particles to drift farther while the coarser fall back near the vent. Varying wind strength and intermittent eruptions both cause variations in the coarseness of the ash falling at any given point and thus give a bedded or layered character to the ash. Bedded in with the ash are blocks of older lavas and other older rocks torn from the walls of the conduit. Sooner or later after the eruption the ash may become cemented to form tuff. On both Lehua and Kaula there were several eruptions so that cones with craters were formed (fig. 5, *b*). However the inner slopes of the craters were so steep that most of the ash falling back (fig. 5, *c*) could not find lodgment above sea level and slid down into the sea-filled

center of the crater. Inasmuch as these islets are distinctly asymmetrical, due to strong wind drifting, the craters have always been open to the sea and waves have entered and removed the ash. There are only thin veneers of small extent on the inner slopes of both Lehua and Kaula (pls. 1, *B*, and 4, *A*).

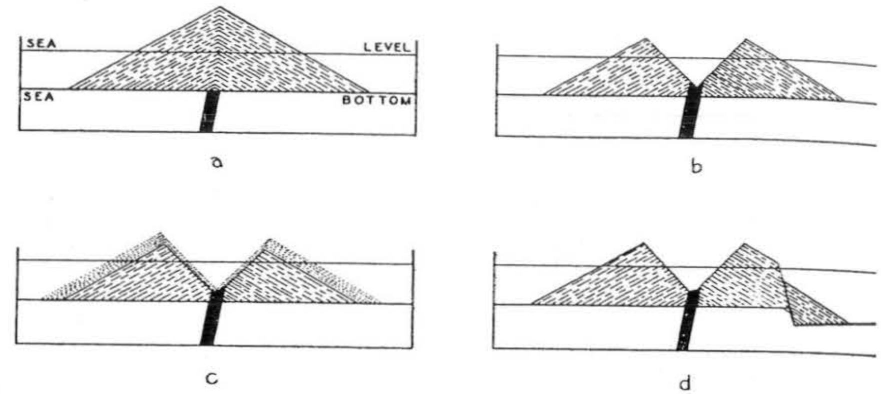


Figure 5.—Diagrammatic structure sections of various kinds of pyroclastic cones: *a*, craterless cone formed by the accumulation of ash after a single eruption; *b*, cone with crater blown out by successive eruptions; *c*, depositional anticline or arched structure of bedding formed by ash falling back on both inner and outer slopes of cone; *d*, straight cliff formed by faulting, with slope too steep to allow ash to settle, thus breaking the continuity of the tuff beds.

Structure of Lehua

Lehua is composed of three series of tuff beds. The series which forms the summit of the island and which therefore may be called the "Summit Tuff" has the greatest volume. The Summit Tuff also forms the crest and outer and inner slopes except for small areas. The end of East Horn and the part of West Horn near the "arch" are composed of a younger series of tuff beds, the "Post-Summit Tuff". Parts of the south shore near the landing expose the older "Pre-Summit Tuff" beneath the Summit Tuff.

The various small islets close to the north shore of Niihau are formed of horizontal beds of tuff undoubtedly derived from Lehua as no other possible source is visible. As the Summit Tuff is the most abundant on Lehua it seems likely that the same tuffs would extend farthest and that these islets are of the Summit Tuff series.

The Pre-Summit tuffs are exposed at a number of places in the wave-cut cliff of the south shore of Lehua. After their deposition they were slightly gullied by streams to depths of 2 to 5 feet and widths of 4 to 12 feet. Eventually the gullies were filled in by the unconformable beds of the Summit Tuff series.

The Post-Summit Tuffs on the end of East Horn lie on and are parallel to a surface which cuts diagonally across this tip of the island. It is obviously not a stream-cut surface, but is presumably due to the slipping off of a block of Summit Tuff that had been undermined by wave erosion. The Post-Summit Tuff of West Horn does not extend to the extreme end of the horn but fills in a broad, westward sloping trough in the Summit Tuffs. (See pl. 3, *A*.) For some unascertained reason the Summit Tuff at this point seems always to have been weak. Earlier in its history considerable slumping took place making the trough which is now filled with Post-Summit Tuff. More recently it has suffered excessive erosion by wave attack from one or both sides of the horn which has been pierced to make a curious arch. The opening of the arch is due to the removal of the locally weak Summit Tuff. The bridge or top of the arch is of the stronger Post-Summit Tuff, which has persisted despite the withdrawal of the support formerly furnished by the underlying Summit Tuff.

The south part of the west side of Lehua exposes a great series of superposed, grandly arching beds of Summit Tuff (Pl. 1, *A*). This face of the islet, broadly regarded, is a slightly concave surface cutting steeply across the depositional anticline with beds sloping both ways from the axis of the crater rim. This steep face trends about N. 16° E. and continues some distance southward under water from the southwest corner of Lehua. The cliff face is not smooth in detail but is deeply gouged by troughs which follow the bedding of the tuff rather than the steepest slope, as do normal stream-cut gullies. This great, steep, west face of Lehua might be regarded either as a fault scarp or as a wave-cut cliff. The under-water, southward extension is difficult to explain on the hypothesis of wave erosion, but a fault would cut the submarine as well as the subaerial parts of the Lehua tuff heap. Therefore it is believed that this straight surface is the result of faulting.

The question next arises as to whether the fault is older or younger than the Summit Tuff which is exposed in it. If younger than the tuff, the fault should have exposed a surface down which

streams would rush at times of sufficient rainfall, following courses perpendicular to the shore line and cutting gullies that follow the steepest slope. However, the gullies do not follow the steepest slope but diverge greatly to follow weak beds of tuff. If faulting had occurred prior to the eruption of the Summit Tuff, a rather straight cliff would have been made, facing westward and overlooking a downsunken block. Both the higher, eastern block and the lower, western block would be composed of Pre-Summit Tuff. On the renewal of volcanic activity the Summit Tuff would fall on both blocks, but more abundantly on the nearer, higher, eastern block. Some of the tuff would find permanent lodgment on the eastern block, but that west of a surface sloping upward at about 35 degrees from the edge of the block would be beyond the angle of repose and would slide down into the deeper water to the west, as suggested in figure 5, *d*. Thus in a section at right angles to the fault line the continuity of the tuff beds would be broken. Parallel to the fault line, however, there would be arched beds if the vent were opposite the fault and not too far away. If the vent were farther away the beds might dip one way or the other instead of in both directions parallel to the fault line. As the trade wind crosses this fault obliquely it has a southerly component of motion parallel to the fault. Therefore more ash would be drifted to the south slope making the beds thicker south of the anticlinal axis than north of it.

The tuff that found permanent lodgment on the higher block would become hardened first, and it is believed quickly on the surface where air and water find most ready access. On the edges of the tuff beds thus exposed above the fault there would be a selection of certain beds for greater hardening and of others for less, depending upon their texture and composition. In the course of time abrasion by wind and by running water would carve most deeply into the less hardened beds regardless of their attitude. The resulting furrows or gullies would not necessarily follow the steepest gradient but would follow the weakest beds.

Such a process has never been observed; it would involve centuries of time. This explanation is, therefore, admittedly largely deductive, but it correlates (1) the straightness of the west shore of Lehua, (2) the gullying following bedding instead of gradient, (3) the view that hardening of ash to tuff occurs soon after deposition, and (4) the view that the hardening is at first surficial.

The tuffs of Lehua are traversed by numerous minor joints for which no regular system of position could be ascertained. There are in addition a number of major vertical joints, most of which are approximately radial in trend. About 12 of the joints are surmounted by mounds 2 to 6 feet high where they cross the crest line of East Horn (pl. 1, *B*). Presumably the joints, by giving air and water better access, have permitted greater hardening of the tuff adjacent to them. The mounds are in turn due to the greater hardness of the tuff. Yet the joints also create regions of weakness which have been eroded out as narrow gashes found along joints that are surmounted by mounds as well as along moundless joints.

Structure of Kaula

The structure of Kaula is more simple than that of Lehua. The tuffs almost universally strike parallel to the surface of the ground, both on the outer and inner slopes. On part of North Horn the crest is smoothly rounded and the beds are nearly horizontal. Toward the bay the beds dip slightly inward until a maximum of about 5 degrees is reached at the brink of the steep inner slope. Outward from the crest the outward dips increase to about 25 degrees and then decrease to about 20 degrees at the brink of the outer cliffs. Most of the crest, however, is sharp and separates the very steep inner slopes, on which edges of tuff beds crop out, from the gentler, outer slopes, which are largely dip slopes. Locally the edges of the tuff beds on the inner slopes are mantled by thin veneers of tuff dipping very steeply toward the bay.

The structure of the middle part of the outer face of North Horn on Kaula and its squarely cut off end is different from that of the rest of the island. Here an unconformity separates the main series of tuff beds from an older series. The older beds seem to have formed a rather flat-topped islet much of which is now buried. The east and south flanks slope eastward and southward, respectively, at about 45 degrees and have been covered by younger tuffs, the lowest beds of which are rather jumbled but which are overlaid by normally arranged tuff beds. Both these boundaries of the islet of old tuff are places of weakness into which caves have been eroded. The weakness is presumably due to the weathering of the older tuff prior to the deposition of the younger tuff. The cave on the end of North Horn is shallow, but the one on the west side is a spectacular cave into which a whale boat may be rowed for a hundred feet or more (pl. 4, *C*). The mouth of the cave appears to be about 50 feet wide at sea level and 50 feet high above sea level. As seen from a motor boat off the cave's mouth, the water inside appears to be 4 fathoms or more deep.

The older tuff beds are also exposed in a triangular area, 400 feet long at the water's edge and 125 feet high, extending north from the pronounced reentrant on the west side of Kaula. These beds dip southward about 20 degrees. The outcrop is cut off at its northern end by an unconformity that dips about 40 degrees northward. These unconformities crop out on nearly vertical cliffs.

LITHOLOGY

Tuffs

The tuffs of Lehua and Kaula are in general very similar. The included blocks of older rocks, however, differ considerably.

All the tuffs are medium gray when fresh and weather to various shades of brown by the formation of hydrous oxides of iron. As the surfaces are in general well weathered and have scant vegetation, both islets are dominantly a brown color, except for the wave-cut bench and sea cliffs which have the color of fresh tuff. Here and there are white coatings and seams of calcareous matter. Considerable areas on Kaula and smaller areas on Lehua look whitewashed by the excrement of numerous sea birds.

Where small depressions have accumulated soil, derived from disintegrated tuff, it is possible to collect fairly representative material. From one such place on Lehua there were identified palagonitized glass, dark gray, stony basalt, and small grains of olivine. No grains of feldspar, augite, or magnetite were found, nor was magnetite detected by the use of a strong horseshoe magnet.

A similar soil sample from Kaula, collected by Mr. Frederick A. Edgecomb, was sifted and the various grades examined, the coarser with the naked eye or hand-lens and the finer with a binocular microscope.

All the grains were angular. Most of the coarsest grains (5+ mm) were fresh or altered volcanic glass, fine-grained basalt, and fragments of bird bones, along with a few bits of olivine. A count of 669 grains between 0.5 and 2.0 mm gave about 13 percent magnetite, 10 percent olivine, 10 percent bone, 1 percent augite and 66 percent undetermined. It was thought that the undetermined grains were largely basalt and glass. In the finest material only magnetite and olivine were identified. It is not surprising that little augite and no feldspar were identified although these are the chief constituents of the Hawaiian basalts, for they are softer and lighter than the magnetite and olivine, and therefore suffer more wear and are more easily blown or washed away. Moreover the good cleavage of augite and feldspar favor their destruction. The residue, however, suffices to show that the parent material was basaltic in composition.

Further studies of the constituents of the tuffs were made on three crushed samples from Lehua and on six from Kaula. Thin sections were studied for the three Lehua specimens and five of the Kaula specimens.

Olivine was found in all nine specimens, but it was not abundant in any of them. In three there were megascopic grains of olivine. The color ranged from pale yellow to pale green. Limonite rims were fairly common, as were inclusions of magnetite. Some of the olivine grains were themselves inclusions in basalt or in glass, but others were free and probably were ejected as discrete crystals.

Magnetite was separated in small amounts from seven of the eight crushed samples that were tried out with a strong horseshoe magnet. The magnet also pulled out grains of glass, basalt, and olivine which presumably contained inclusions of magnetite. In the thin sections opaque grains, which were undoubtedly mostly magnetite, were seen not only as inclusions, but also as independent grains. All were very small.

Augite was detected in only two of the specimens, and only in the thin sections. It is the usual pale Hawaiian augite. In the section of one specimen it was found in intersertal relation to plagioclase laths in a basalt lapillus. In the other there was a single, independent augite grain.

Plagioclase feldspar with the narrow parallel lamellae of albite twinning was noted only in the specimen with the intersertal augite. No grain was so oriented as to give usable extinction angles.

Non-mineral grains included basalt, glass, and palagonite. Basalt lapilli of various types were found in all the specimens. In the basalt grains plagioclase, augite, olivine, and magnetite were identified. A few basalt grains contained enough magnetite to be moved by the horseshoe magnet. Where the basalt grains are over one or two millimeters in size and are abundant they give the hand specimen a mottled or speckled appearance. Some beds consist chiefly of basalt lapilli.

Basalt glass was found in all the specimens. To the naked eye or under a hand-lens the glass is black, but in thin section it is olive brown, gray brown, dark brown and cloudy with tiny inclusions, pale green or pale olive green. Most of the glass is continuous but some glass grains are vesicular. Inclusions of magnetite and of olivine are not uncommon. Many of the smaller grains are fully palagonitized. Some of the larger grains are fresh throughout, but most are altered to either palagonite or limonite at their rims.

Palagonite was found in all of the specimens, but in varying amounts. It gives the weathered rock its general rusty brown tone. The individual grains are yellow brown, brown, or red brown as seen megascopically. In thin section the palagonite is yellow or yellow-orange. Palagonite has fully replaced the smaller grains of glass, but the larger grains preserve fresh centers inside of palagonite rims.

Calcite is the most common of the secondary minerals, and was found by HCl test in five of the nine specimens. Fillings of vesicles in one specimen

show the high birefringence and cleavage of calcite. Calcite also occurs as fillings of small interstices between grains, and as veins and seams up to 10 mm thick. In three specimens there was noted a mineral occurring as radiating, acicular aggregates. The index is less than that of Canada balsam, the birefringence is low, the extinction is parallel, and the elongation is negative. Some of this is clear and some is milk-white.

One tuff specimen from Kaula had on its surface a number of very perfect though tiny crystals of halite presumably derived from the evaporation of salt spray.

Induration of the Tuff

Three lines of evidence indicate that some time elapsed between the fall of ash and its consolidation into tuff.

1. Depressions made in ash beds by the impact of large bombs or blocks when they fall are common on Lehua and Kaula as shown in such miniature quaquaversal synclines or basins, called "bomb sags" by Wentworth (19), as appear on cliffs and valley sides. In many of these, part or all of the indenting block remains. On dip slopes, due to the differential erosion of the quaquaversally indipping tuffs, they appear as concentric, annular ridges and grooves. Such structures could not be made in firm tuff which yields to the impact of the falling block by fracturing rather than by a sort of flowage. The depressions therefore imply that the ash remains unconsolidated until at least a few beds have fallen.

2. Few of the indenting blocks are broken. In many days field work on these and other tuff structures in Hawaii, I have noted but few indenting blocks that were themselves fractured. These exceptions were probably almost ready to fall to pieces and needed only a small blow, such as loose ash might give, in order to shatter. Non-shattering of the falling blocks, like indentation of the ash, implies looseness of the ash for a time after falling.

3. A third critical point is the presence of crenulated beds of tuff. At various places on Lehua the crests of these miniature folds trend parallel to the strike of the beds. The distance from crest to crest is 5 to 9 inches, and the height of the folds, 1 to 2 inches. In some places the crenulation is restricted to a single bed of tuff not more than 2 inches thick. At one place (pl. 2, *B*) crenulation is seen clearly in three or four thin zones which are separated by less well crenulated or even somewhat jumbled beds. It would appear that when the ash had been slightly consolidated it slipped down slope a little on more rigid beds beneath. The sliding bed must have had some cohesive strength, otherwise it would merely have been badly jumbled. From the crenulations it may be concluded that induration is a process that takes some time and goes on by degrees.[2] Unconsolidated beds would jumble on sliding,

[2] In 1927 I observed that the lapilli at Pompeii erupted by Vesuvius in 79 A. D. are less well cemented than are the tuffs of Lehua and Kaula which are probably older. In answer to a query written for me by Mr. William A. Lessa, Dr. Alessandro Malladra, Director of the Royal Vesuvian Observatory, informed me that the material erupted by Monte Nuovo in 1538 is not perfectly cemented and is more friable than the material at Pompeii. Dr. Harry S. Ladd informed me that shortly after the eruption of Falcon Island, Tonga, in 1927, landing was very difficult because the ash was entirely loose and slid badly. Pompeii, Monte Nuovo, and Falcon Island show increasing induration with age suggesting that induration is progressive. However it is dangerous to collate data from such widely separated places; Falcon Island has been built up by eruptions and destroyed by waves several times, while Monte Nuovo and Pompeii are situated away from wave attack.

and fully consolidated beds would not slide at all. Only beds that were partly consolidated could develop such folds. It may further be concluded that this partial induration occurs soon after the ash has fallen, for if the sliding were delayed it should involve a thick ash bed rather than one of only a few inches.

Induration of ash to tuff seems to be to some extent surficial though by no means exclusively so. Evidence of this is the gouging out of certain tuff layers on the west side of Lehua (pl. 1, *A*). Here it appears that once the edge of a bed outcropping on the steep slope has been removed it is easy for wind and occasional running water to gouge out more of the same bed. Other beds that preserve the case-hardened surface are thus protected and persist. Of course, it is also partly due to differential resistance throughout the beds that some are gouged out and others stand up. Another phenomenon suggesting that induration is in part a surface or shallow process is found at the mounds on East Horn of Lehua (pl. 1, *B*). The mounds are due to greater resistance localized along joints. The explanation is suggested that early in their history the joints permitted air and moisture to get into the ash and to harden it near the joint surfaces. Later, however, some of these and many other joints have permitted air and water to enter to perform destructive work, such as enlarging the joints.

Miscellaneous Features of the Tuff

Search was made for molds of trunks and branches of trees in the tuff just above the unconformities on Lehua. Such molds are very abundant in the unconformity between the two sets of tuff in the Salt Lake Crater region, Oahu, and imply the development of considerable soil and the establishment of vegetation in the time between the two eruptive episodes. No such molds were found on Lehua, which indicates that in its earlier stages Lehua was probably at least as barren as it is now. No molds were visible at the distance from which Kaula's unconformity was seen, but a close examination could not be made. The tuff below each of the unconformities on Lehua appears just as little weathered as that above. The tuff below the unconformity on Kaula has been somewhat weathered so that it has weakened and favored cave excavation.

Blocks

On Lehua rock types noted among the blocks in all three series of tuffs include both porphyritic and non-porphyritic basalts of various shades of gray. Feldspar was the only mineral noted as making phenocrysts. Some blocks were presumably originally parts of dikes or sills, for they were without gas vesicles. More, however, are vesicular; in some the vesicles are nearly spherical as in pahoehoe flows, and in others more or less stretched out as is common in aa flows. Neither frothy pahoehoe nor basaltic glass was seen in Lehua blocks.

Near the base of the Post-Summit tuff on West Horn of Lehua are a number of blocks of reef rock. No reef rock blocks were seen in the Pre-Summit tuffs and only a single one in the Summit series. Such blocks imply that the conduit passed through a layer of reef rock. It therefore appears that the region of Lehua bore no reef till after the eruption of the Summit Tuff, which may have shoaled the crater enough so that the depth was favorable for corals and associated organisms.

The largest block of basalt noted on Lehua has a maximum diameter of about 4 feet. Another block measures about 3½ by 3 by 2½ feet and has a volume of about 13.5 cubic feet and a weight of some 2,100 pounds. The commonly noticed blocks range in size from a hen's egg up to a man's head. However there are many blocks ranging in size from a pea to a walnut which are not conspicuous in the tuff.

The blocks in the tuffs of Kaula show a greater lithologic variety than in those on Lehua. They include many of reef rock, a few of coarse calcareous sandstone, and a few of broken molluscan shells. Many of the blocks are composed almost entirely of olivine, having a coarse granular texture and a skinlike coating of fine-grained basaltic lava. The largest has a diameter of 9 inches. A few blocks have phenocrysts of olivine in a stony basaltic ground mass. Neither feldspar nor augite was noted as forming phenocrysts. Non-porphyritic basalts are common among the blocks and range widely in vesicularity, but none are "frothy". A few blocks are glassy in texture and have fair-sized vesicles with drusy crystalline linings. One block with several red garnets embedded in a stony, basaltic matrix and another block with minute biotite phenocrysts in a similar matrix suggest that at least some of the blocks came from great depths. The rather common blocks composed of aggregates of olivine grains are also very likely from great depths. Volcanic blocks of other lithologic types are presumably of shallower origin.

Most of the blocks on Kaula are angular, revealing the shapes they had when torn from the walls of the volcanic conduit. A few, however, are well rounded as if they came from a stream bed or a boulder beach. Presumably these were rounded by wave action on the shoal during its cutting, and were torn from about the same horizon as the blocks of reef rock and calcareous sandstone.

Cause of the Pyroclastic Eruptions

In Hawaii pyroclastic rocks made by violently explosive volcanic action may be due to the evolution of great quantities of steam when water and hot magma or lava come in contact with one another or to an unusually high inherent gas content of the magma. The contact of water and heated rock may result from the access of ground water to a deeply receded magma column or from the entrance of a lava flow into the ocean or a stream. On Lehua and Kaula the eruptions were not caused by access of water to a lowered magma column for such an eruption gives almost exclusively stony ejecta. The pyroclastics of both islets include a great quantity of glass and of palagonite.

It is conceivable that liquid lava emerged from submarine vents on the north flank of Niihau or on the wave-planed Kaula shoal and generated great volumes of superheated steam, which rent the lava asunder and hurled the fragments high into the air to fall back and build the craters.[3] If made by this process the tuffs would contain few if any xenoliths. But the numerous blocks included in the tuffs on both islets are certainly the analogues of xenoliths. The inclusion among the blocks of rock that presumably originated in great depths (garnet and biotite bearing basalts and the granitoid textured olivine nodules) implies the existence at great depths of energy enough to tear loose such fragments.

It is probable that the pyroclastics had their source in a magma of initially high gas content and therefore also of high mobility. Inasmuch as the gas is supposed to have been inherent in the magma when it formed, it would be available at the right time and at the right place to give enough velocity and enough kinetic energy to tear away blocks of rock from the conduit walls to make the analogues of xenoliths.

It appears that in the Hawaiian volcanoes the magmas supplying the usual quiet lava flows rise so gently that they do not have enough kinetic energy to rend fragments from the conduit walls. Hence the usual lack of xenoliths in Hawaiian lava flows.

[3] A depth of 40 fathoms would produce a pressure of 108 lbs./in², which would raise the boiling point of water to about 332° F. The resulting steam would have considerable superheat which would cause it to expand violently when it rose to higher levels where the pressure was less.

GEOLOGIC HISTORY

Lehua

The chief events known in the geologic history of Lehua are as follows:

1. Construction of the dome of Niihau by the successive outpourings of many lava flows, the earlier solely submarine, the later largely subaerial.

2. Eruption from a vent on the northern submarine slopes of Niihau of a series of ash beds (Pre-Summit Tuffs) to form for the first time the islet of Lehua.

3. Erosion of this first Lehua to smaller size. Waves must have done most of the eroding, but the only evidence preserved is that of stream-cut gullies on the south shore.

4. Downfaulting of a part of Lehua on the west side of a line bearing about N. 16° E.

5. Eruption from the same vent of a second series of ash beds (Summit Tuffs) to form a far larger island, much like the present Lehua. The total arc was probably of about 275 degrees, leaving about 85 degrees open to the sea on the north. Slumping or landsliding of ash over the fault scarp caused the curious arches on the west side of Lehua.

6a. Reduction of this island by stream and wave erosion, but particularly by the landsliding into the sea of the tip of East Horn and a part of West Horn.

6b. Contemporaneously with this reduction there was some reef growth in the bay between the horns, that is, over the dormant volcanic vent.

7. Eruption from the same vent of a third series of ash beds (Post-Summit Tuffs) which found lodgment in restricted areas, on each horn.

8. Erosion to a slight extent by running water and wind, but strong erosion of a bench and cliff by waves working from a sea level between 10 and 20 feet higher than the present sea level.

9. Lowering of sea level by 10 to 20 feet, so that the wave-cut bench emerged.

10. The present epoch of erosion, moderately by wind and running water but chiefly by waves which are destroying the emerged bench and making a new one below present sea level. The ends of the horns are particularly exposed, and since their construction, East Horn has been cut back about 200 feet and West Horn perhaps 300 feet. From its one time maximum sea level area of 370 acres, Lehua has been reduced to 291 acres (about 79 percent).

KAULA

The geologic histories of Kaula and Lehua include some similar events but also some that are unlike. The chief events in the history of Kaula are as follows:

1. Outpouring on sea bottom of lava whereby a lava dome was built, which it is believed extended 1,000 feet or so above sea level with sea level axes of 3 and 6 miles and an area of some 14 square miles.
2. Beveling by wave erosion, with some help from running water and wind, producing a shoal of some 27 square miles inclusive of the marginal zone of detritus.
3. Growth of a reef on this shoal. (Perhaps not until after event no. 4).
4. Eruption of an older series of ash beds, which now are exposed only in inaccessible parts of North Horn. (It is believed, but not definitely known, that these ash beds contain fragments of the reef.)
5. Erosion, largely by waves, of the tuff made by the induration of the older series of ash beds.
6. Eruption of the younger series of ash beds making a crescentic ridge along about 223 degrees of arc, leaving about 137 degrees open to the sea on the east.
7. Sliding off along a joint surface of a considerable part of the outer slope of North Horn, making a reentrant angle.
8. Slight erosion by running water and wind: strong erosion of a bench and cliff by waves working from a sea level between 10 and 20 feet higher than the present sea level.
9. Lowering of sea level by 10 to 20 feet so that the wave cut bench emerged, simultaneously on Lehua and Kaula.
10. The present epoch of erosion, moderately by wind and running water but chiefly by waves which have destroyed nearly all of the wave cut bench on the exposed outer curve. South Horn has been cut back about 425 feet since its construction and North Horn, about 1,000 feet. The total area at sea level has been reduced from the original 197 acres to 136 acres (about 69 percent).

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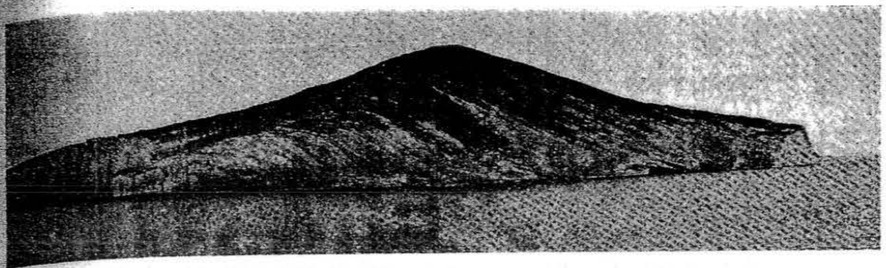

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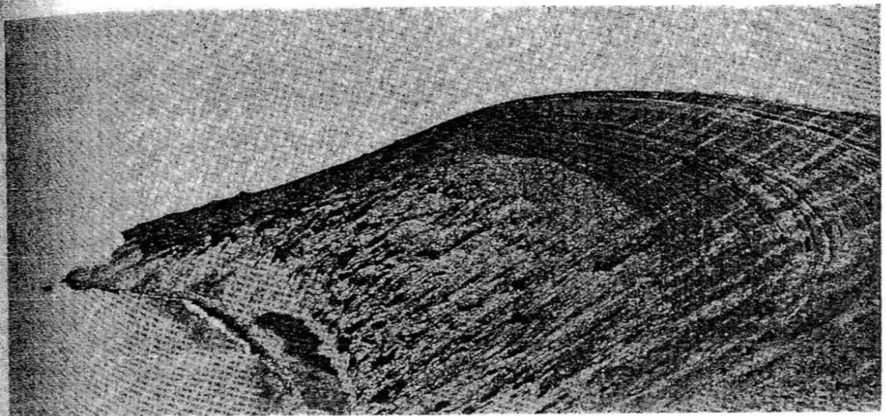

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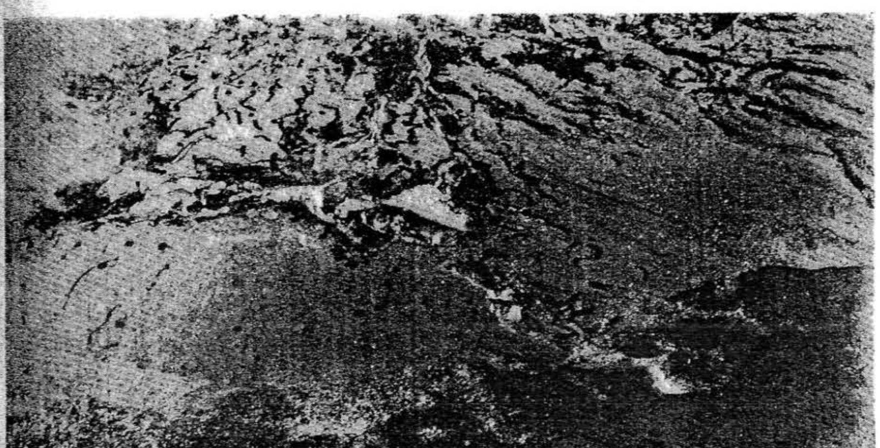
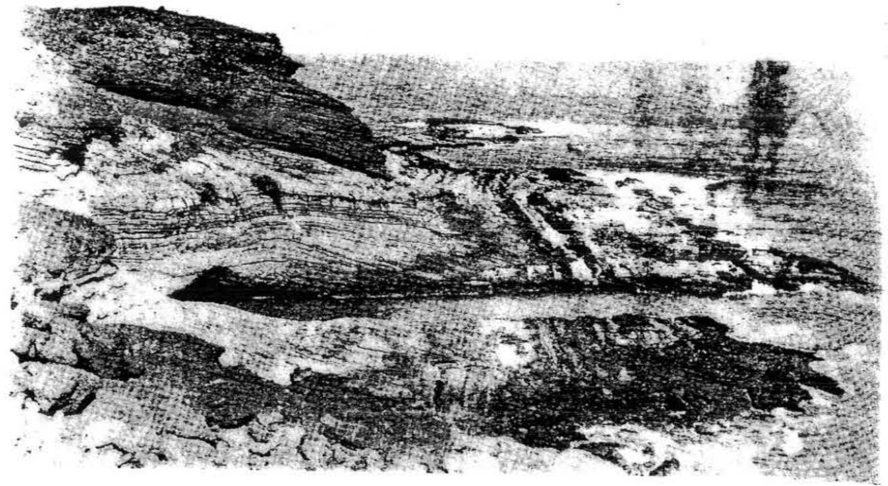


C

PLATE 1.—Lehua: *A*, panorama of southern part of the west side showing depositional anticline of tuff beds; *B*, inner side of East Horn seen from the summit, showing wave-cut bench, uniform bedding of the upper slopes, and mounds on the crest line; *C*, tuff on wave-cut bench of south shore channeled and pitted by sea urchins.



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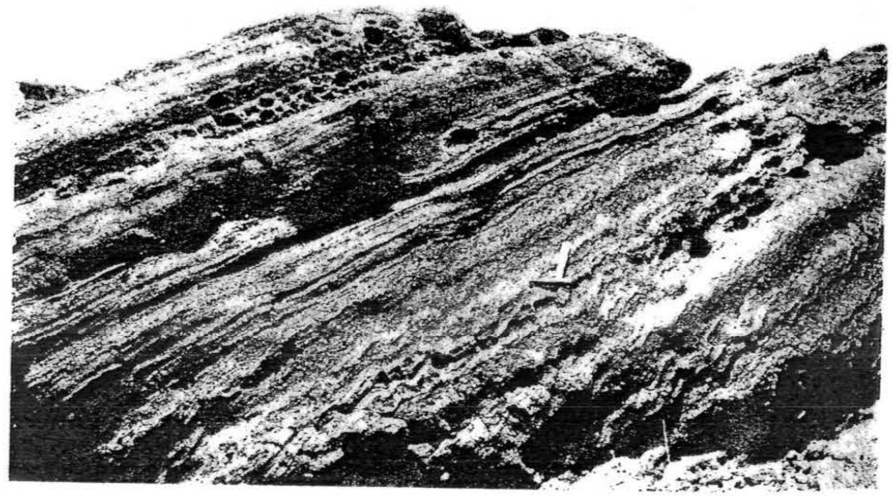

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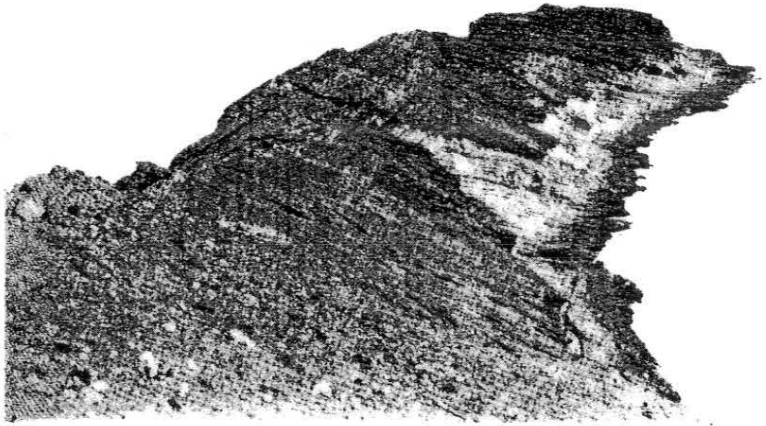
PLATE 2.—Lehua: *A*, wave-cut cliffs, bench beveling tuff beds, and cave on south shore; *B*, detail of tuff, showing wind-etched cavities near the top and crenulated beds of tuff near the bottom. (Photographs by E. L. Caum.)



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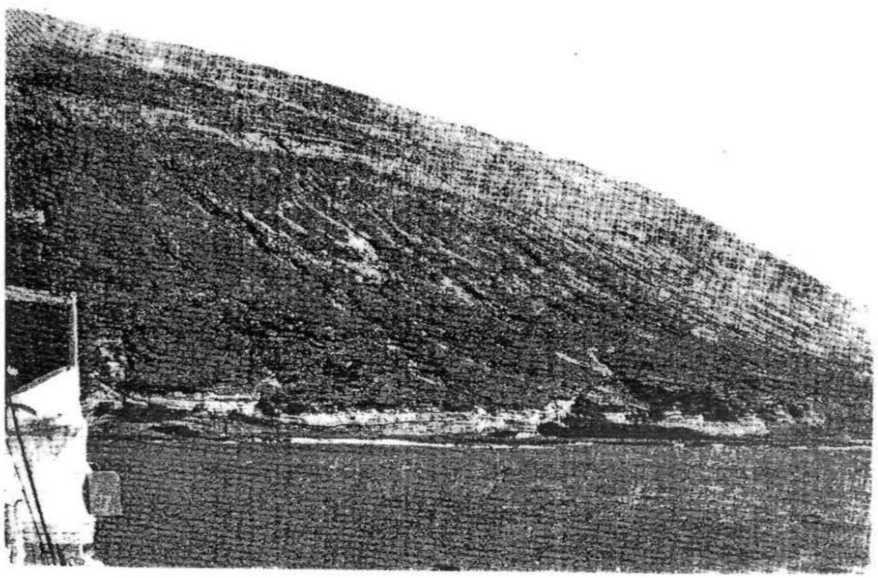

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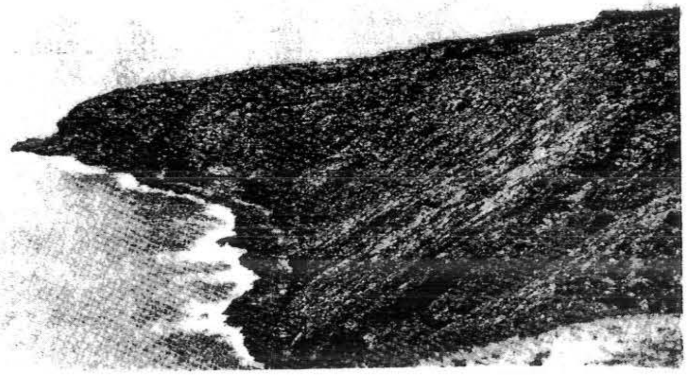
Plate 3.—Lehua: *A*, general view of West Horn showing the unconformity between the "Summit" and "Post-Summit" tuffs; *B*, south slope of Lehua from the channel; note the radial gullies, wave-cut cliffs, bench, caves, and remnants of tuff beds; landings are made at the extreme right of the view (photograph by E. L. Caum).



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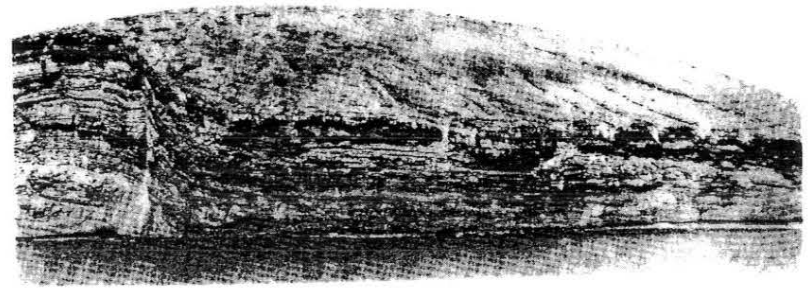

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Plate 4.—Kaula: *A*, inner side of South Horn; *B*, southwest outer shore showing a block, bounded by joints, which has fallen out; *C*, cave and unconformity at the north end of the outer side of North Horn.