sand. Changes of climate concurrent with the glacial and interglacial epochs affected the rainfall and vegetation in critical areas. Lagoonal sediments were deposited in the Mana plain along the southwestern side of the island forming broad flats and leaving former sea cliffs abandoned inland by the sea. A geologic section across the island showing its present form, after the long epoch of erosion, is shown in figure X-14.

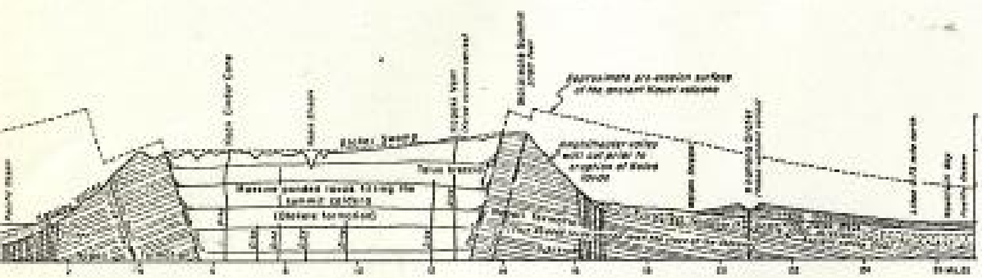
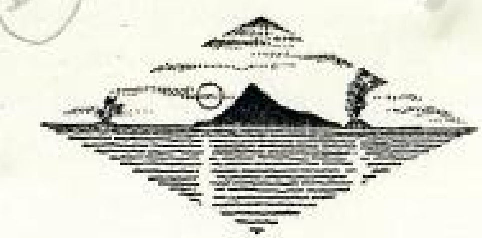


Figure X.14—NW-SE geologic section from the mouth of Kalalau Valley across the summit of Kauai to Nawiliwili Bay near Lihue. Many more dikes exist than are shown. Thickness of bedding in caldera is exaggerated. Vertical exaggeration about 2½ × horizontal scale.

Geology of the State of Hawaii
by Harold T. Stearns
Pacific Books
Palo Alto, CA
1966

266pp



11

ISLANDS OF NIIHAU AND LEHUA

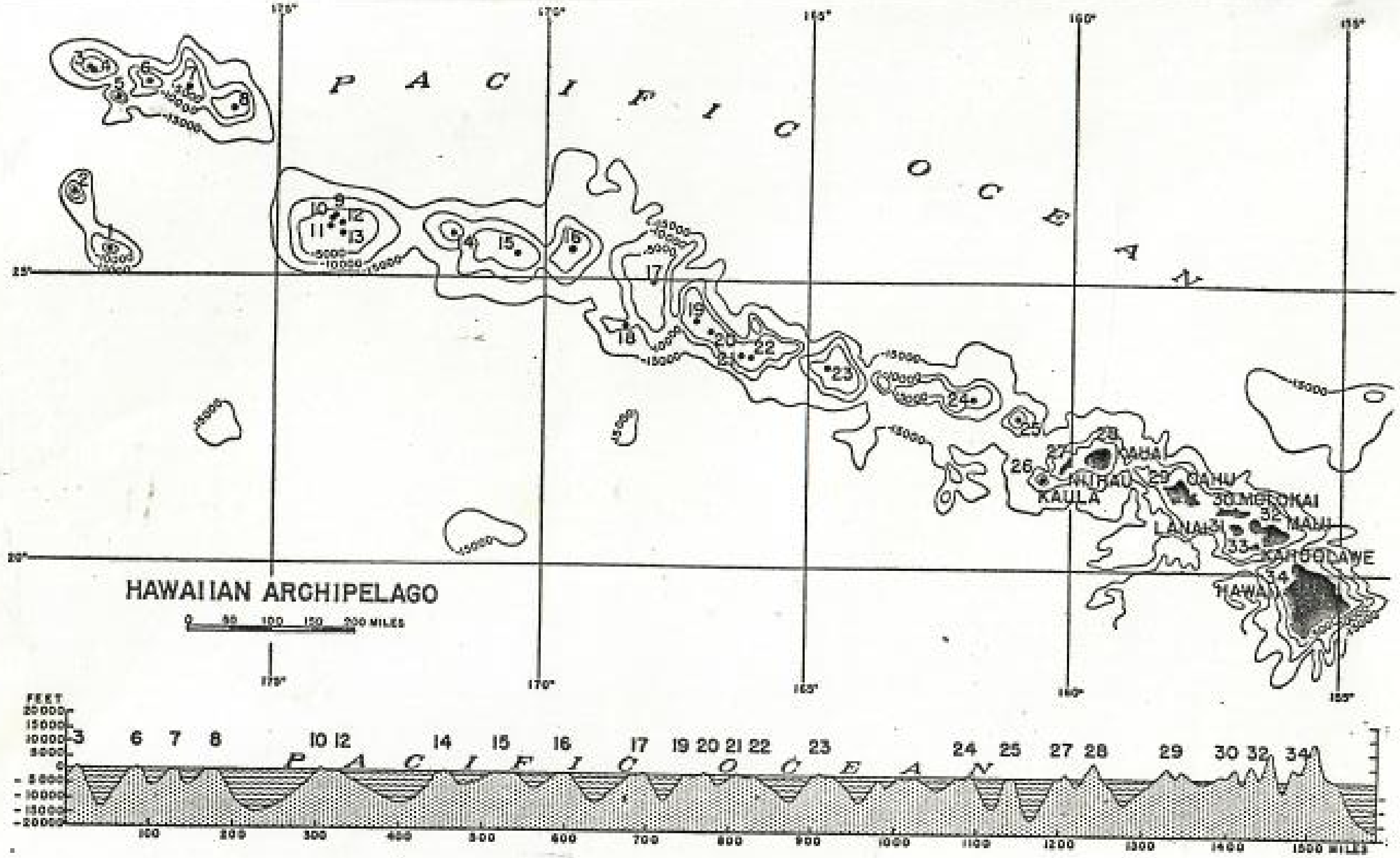
Geomorphology

Niihau lies 17½ miles southwest of Kauai. Its area is 72 square miles, and its highest point has an altitude of 1,281 feet. The population is 254, chiefly Hawaiians. The island is privately owned. The present form of the island is shown in figure XI-6.

Niihau has two major geomorphic provinces—the uplands, a remnant of a shield- or dome-shaped basaltic volcano; and the lowlands, a coastal plain averaging about 75 feet above sea level but containing numerous playa lakes only slightly above sea level (fig. XI-1).[98] Some of the ashes from Lehua Island, a tuff cone which lies a mile off the northern tip of Niihau, are found on the coastal plain of Niihau. Kaula Island, 22 miles southwest of Niihau, is a tuff cone crowning an independent submarine volcanic dome (fig. XI-2).[100] Its ashes were not found on Niihau.

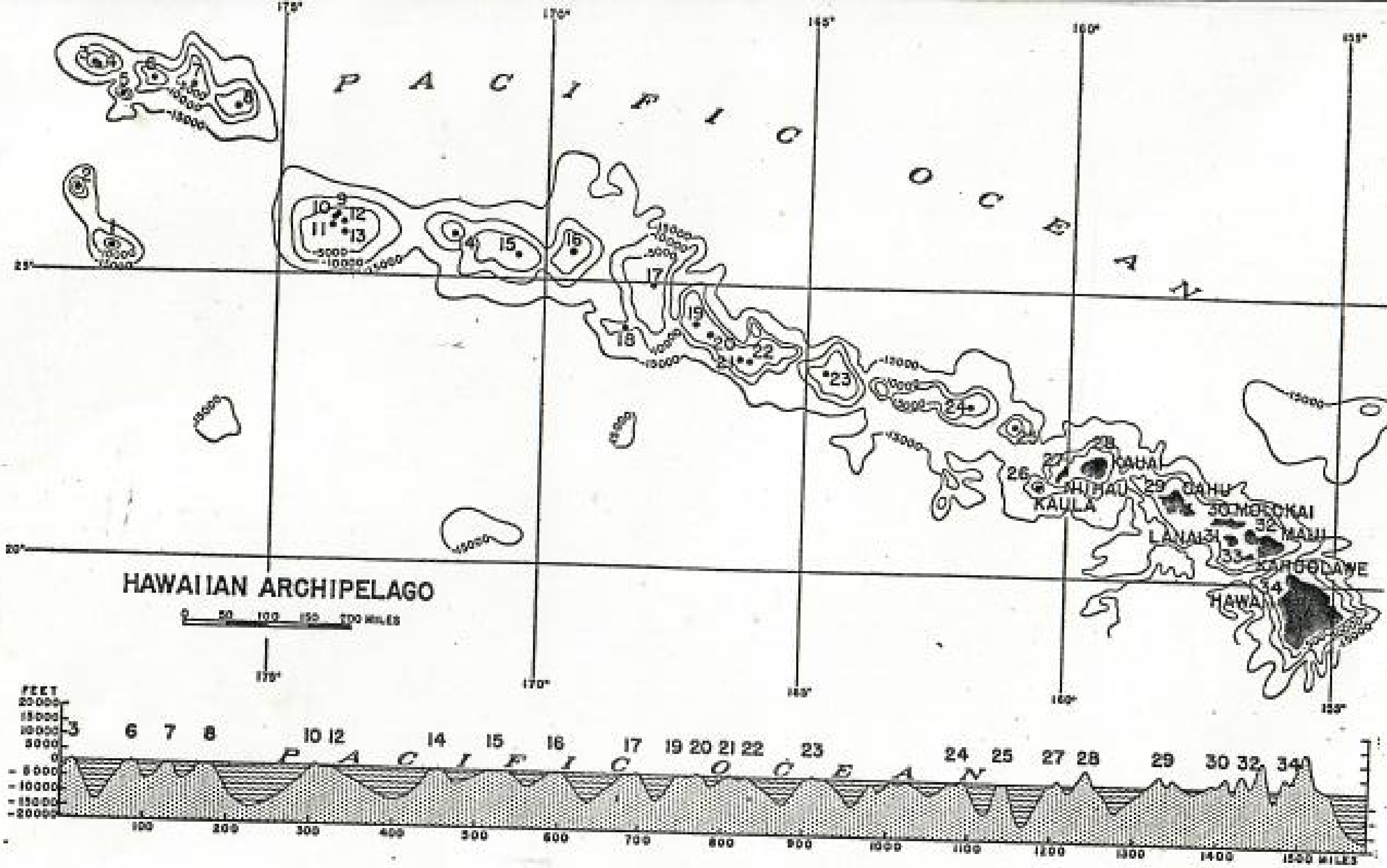
The uplands are the dissected remnant of an ancient volcano and are covered with about 5 feet of red soil which is underlain by 20 to 50 feet of partly decomposed basalt. Dikes exposed in the interstream divides indicate that the original dome surfaces have been worn down about 100 feet, probably prior to the 1,200-foot submergence of the islands. Niihau extended about 6 miles farther east than it does now in relation to present sea level. Like the other volcanoes, it probably had a caldera (fig. XI-3), and at some time, it may have been connected to Kauai, as the channel between them is only 2,550 feet deep. Niihau rises 13,000 feet above the ocean floor to the north and south.

The lowlands have a complex origin. Surrounding Niihau are a submarine shelf 300 feet below sea level and 1 to 2 miles wide and a



Explanation of Figure 1-2.

1. Unnamed shoal; 2. Bensaleux Reef; 3. Kure or Ocean Island; 4. Green Island; 5. Nero Bank; 6. Midway Islands; 7. Gambia Shoal; 8. Pearl and Hermes Reef; 9. Lisianski Island; 10. Fisher Reef; 11. Minor Reef; 12. Neva Shoal; 13. Springbank Reef; 14. Laysan Island; 15. Maro* (Dowsett) Reef; 16. Raita Bank; 17. Gardner Pinnacles; 18. Two Brothers Reef; 19. St. Rogatien Bank; 20. Brooks Banks; 21. La Pérouse Pinnacle; 22. French Frigate Shoal; 23. Necker Island; 24. Nihoa; 25. Unnamed shoal; 26. Kaula; 27. Niihau; 28. Kauai; 29. Oahu; 30. Molokai; 31. Lanai; 32. Maui; 33. Kahoolawe; 34. Hawaii.



Explanation of Figure I-2.

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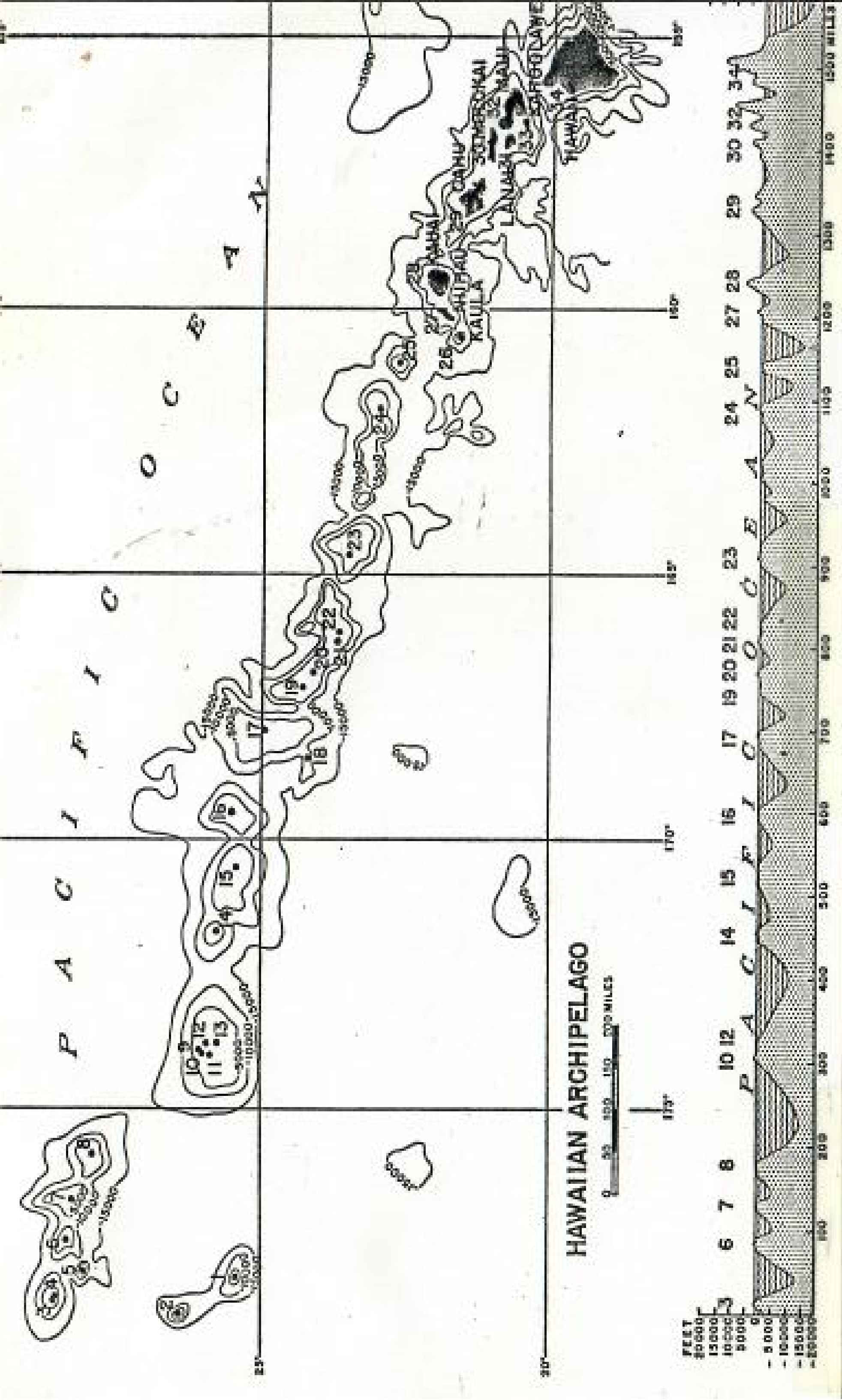

Figure 1-2—Map and profile of the Hawaiian Archipelago showing submarine contours in feet. (Explanation of numbers on facing page.)

The northeastern sides of the mountains are usually wettest because of the prevailing wind. Maximum precipitation occurs between altitudes of 2,000 and 6,000 feet depending upon the form and height of each island. Above 6,000 feet the precipitation decreases, making high peaks semiarid. As the winds descend the lee slopes, they become warmer, drying winds, causing arid and semiarid climates on the leeward sides of the islands. On the island of Hawaii, however, where the mountains are sufficiently high to pierce the layer of trade winds, eddies result in prevailing southwest winds on the lee side so that the climate in the leeward districts is fairly wet. The annual rainfall ranges from 10 inches or less on the lee coasts to about 450 inches in the wettest belts. In one year 624 inches of rain was recorded on the summit of Kauai at an altitude of 5,170 feet.

It is difficult to grasp the immensity of the oceans of the earth until one flies over them and sees the Hawaiian Islands as tiny green specks floating in a vast blue sea. The oceans cover 71 per cent of the earth's surface and sea water averages 2¼ miles in depth over 139 million square miles. If all the salts in the sea were withdrawn and piled upon the continents, it would cover the land with white crystals to a depth of 500 feet.[21]

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Explanation of Figure 1-2.

1. Unnamed shoal; 2. Bensaleux Reef; 3. Kure or Ocean Island; 4. Green Island; 5. Nero Bank; 6. Midway Islands; 7. Gambia Shoal; 8. Pearl and Hermes Reef; 9. Lisianski Island; 10. Fisher Reef; 11. Minor Reef; 12. Neva Shoal; 13. Springbank Reef; 14. Laysan Island; 15. Maro* (Dowsett) Reef; 16. Raita Bank; 17. Gardner Pinnacles; 18. Two Brothers Reef; 19. St. Rogatien Bank; 20. Brooks Banks; 21. La Pérouse Pinnacle; 22. French Frigate Shoal; 23. Necker Island; 24. Nihoa; 25. Unnamed shoal; 26. Kaula; 27. Niihau; 28. Kauai; 29. Oahu; 30. Molokai; 31. Lanai; 32. Maui; 33. Kahoolawe; 34. Hawaii.

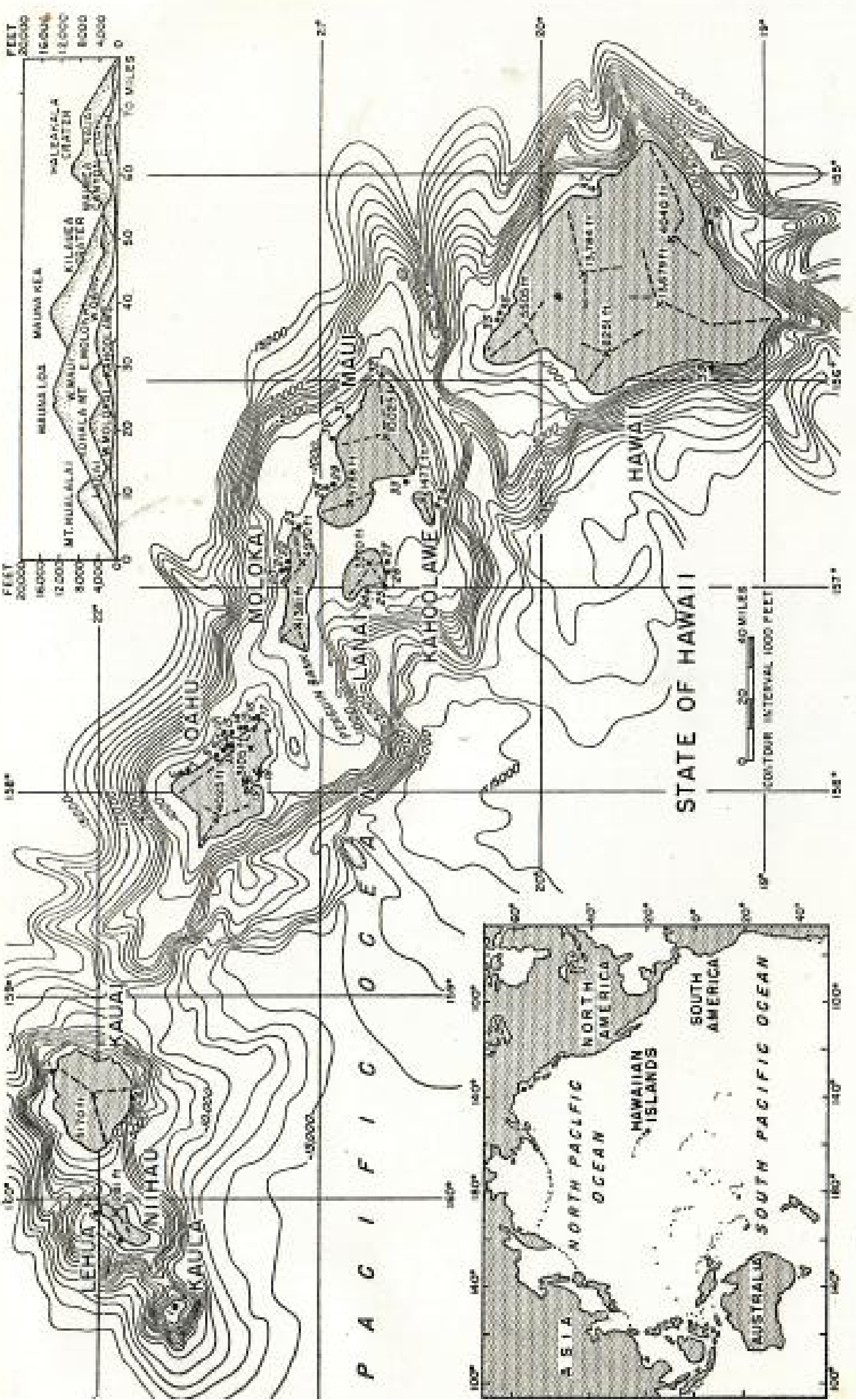

Figure I.1—Map of the larger islands of Hawaii, their known rift zones, generalized submarine contours in feet, and principal islets. (Explanation of numbers on facing page.)

TABLE 1

AREA, ALTITUDE, MAXIMUM DIMENSIONS, POPULATION, AND PRINCIPAL CITY OF EACH OF THE LARGER ISLANDS

Island	Area (sq. mi.)	Altitude (feet)	Maximum distance (miles) North-south	Maximum distance (miles) East-west	Population*	Principal city
Hawaii	4,030	13,784	87.3	75.3	61,332	Hilo
Maui	728	10,025	25.0	38.4	35,717	Wailuku
Oahu	604	4,025	40.0	26.0	500,409	Honolulu
Kauai	555	5,170	24.5	29.9	27,922	Lihue
Molokai	260	4,970	10.1	37.0	5,023	Kaunakakai
Lanai	141	3,370	13.3	13.0	2,115	Lanai City
Niihau	72	1,281	9.7	9.0	254	None
Kahoolawe	45	1,472	6.4	10.9	0	None
Total	6,435	.....	....	....	632,772	....

* According to U.S. Census, 1960.

days at a time. Relatively low islands such as Kahoolawe and Lanai are sheltered from the trade winds by other islands and consequently are very dry. In windy seasons ribbon-shaped dust clouds from these two islands commonly extend many miles over the ocean.

Both the trade and southerly winds bring rain to the islands. The heavy storms usually come from the south. During some storms as much as 24 inches of rain in four hours has been recorded. Rainfall exceeding 20 inches in 24 hours has been recorded in several places. During the 24 hours following the evening of January 24, 1956, a rain gage on Kilauea Plantation, Kauai recorded nearly 40 inches of rainfall, of which 6 inches fell in a single half hour. It shattered all previous records of maximum rainfall in the Hawaiian Islands and may be close to the heaviest known world rainfall.[116]

←――――――

Explanation of Figure I-1.

The submarine contours are generalized. Lower inset map shows position of the Hawaiian Archipelago in the Pacific Ocean, and upper inset shows profiles of the volcanic peaks of the main islands. The islets are 1. Kaula; 2. Kuakamoku; 3. Lehua; 4. Kalanipuao; 5. Mokuneae; 6. Mokuauia; 7. Kukuihoolua; 8. Mokolii; 9. Kapapa; 10. Kekepa; 11. Moku o Loe; 12. Moku Manu; 13. Mokolea; 14. Papoia; 15. Mokulua; 16. Manana; 17. Kaohikaipu; 18. Mokuoeo; 19. Ford Island; 20. Mokapu; 21. Okala; 22. Mokohola; 23. Mokuhooniki; 24. Nanahoa; 25. Moku Naio; 26. Poopoo; 27. Puupehe; 28. Mokeehia; 29. Hulu; 30. Papanui o Kane; 31. Keopuka; 32. Alau; 33. Molokini; 34. Puu Koae; 35. Mokupuku; 36. Paoakalani; 37. Cocoanut Island; 38. Mokuokahailani; 39. Keaoi.

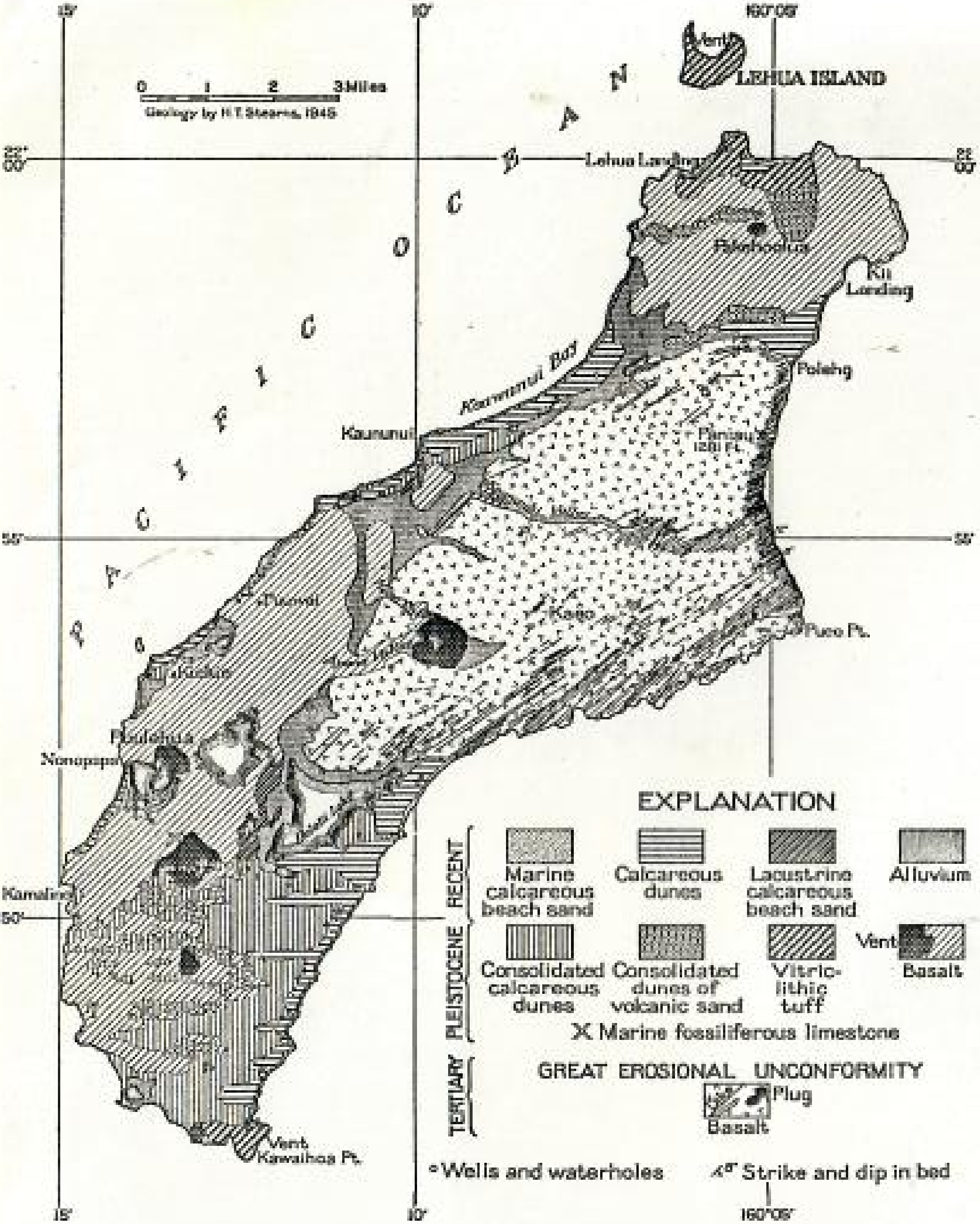

Figure XI.1—Geologic map of the island of Niihau. The Pleistocene basalts are the Kiekie volcanic series and the Tertiary basalts are the Paniau volcanic series.

narrower shelf 60 feet below sea level. Several tuff and lava cones erupted through the broad shelf and have built it above sea level to form the coastal plain (fig. XI-5). During the minus 60-foot stand of the sea much sand was blown inland, especially on the southeastern coast, to form dunes 150 feet high. These dunes became cemented with the subsequent rise in sea level. Marine limestones were found up to 100 feet above sea level.

Geology of Niihau

General character and age of the rocks.—The highlands of Niihau, and presumably also the basement of the dome, are built chiefly of thin lava flows poured out rapidly from a dome-shaped shield volcano. The flows are predominantly olivine basalt and basalt. They include both aa and pahoehoe types. No soils, and only a few thin vitric and vitric-lithic tuff beds, are interstratified with the flows in the part of the cone above sea level. Numerous dikes, half a foot to 17 feet thick, cut the dome remnant. Most of them trend northeast-southwest. Cinder cones are absent. Faulting has disturbed the beds in the heart of the dike complex. The Paniau volcanic series are the volcanic rocks composing the remnant of the ancient shield volcano of Niihau (fig. XI-1).

The Kiekie volcanic series, of Pleistocene age, form the coastal plain of Niihau. In contrast to the thin-bedded lavas in the ancient dome remnant, the later lavas of the plain are massive and nearly horizontal, and consist chiefly of pahoehoe. Except at Kawaewae cone the lavas welled out quietly, forming small secondary lava domes without cinders and with only a little spatter. The Lehua Island and Kawaihoa cones erupted violently, spreading ash far and wide, because sea water entered their vents. The exposed parts of their cones are subaerially-deposited consolidated ash. The cones of the Kiekie volcanic series trend slightly west of north, in contrast to the northeast-trending rifts of the Paniau volcanic series.

The sedimentary rocks are composed of older and younger alluvium, calcareous beach and dune sand, playa deposits, and dunes of cemented ash. Small outcrops of highly fossiliferous emerged reef exist in three places. Recent cemented calcareous beach deposits, commonly called beach rock, lie along some of the coast.

The age of the Kiekie volcanic series is determined by its relation to the shore lines of probable Pleistocene age. All the lavas on the coastal plain are older than the minus 60-foot stand of the sea, which appears to be correlative with the Illinoian stage of glaciation. Most of the

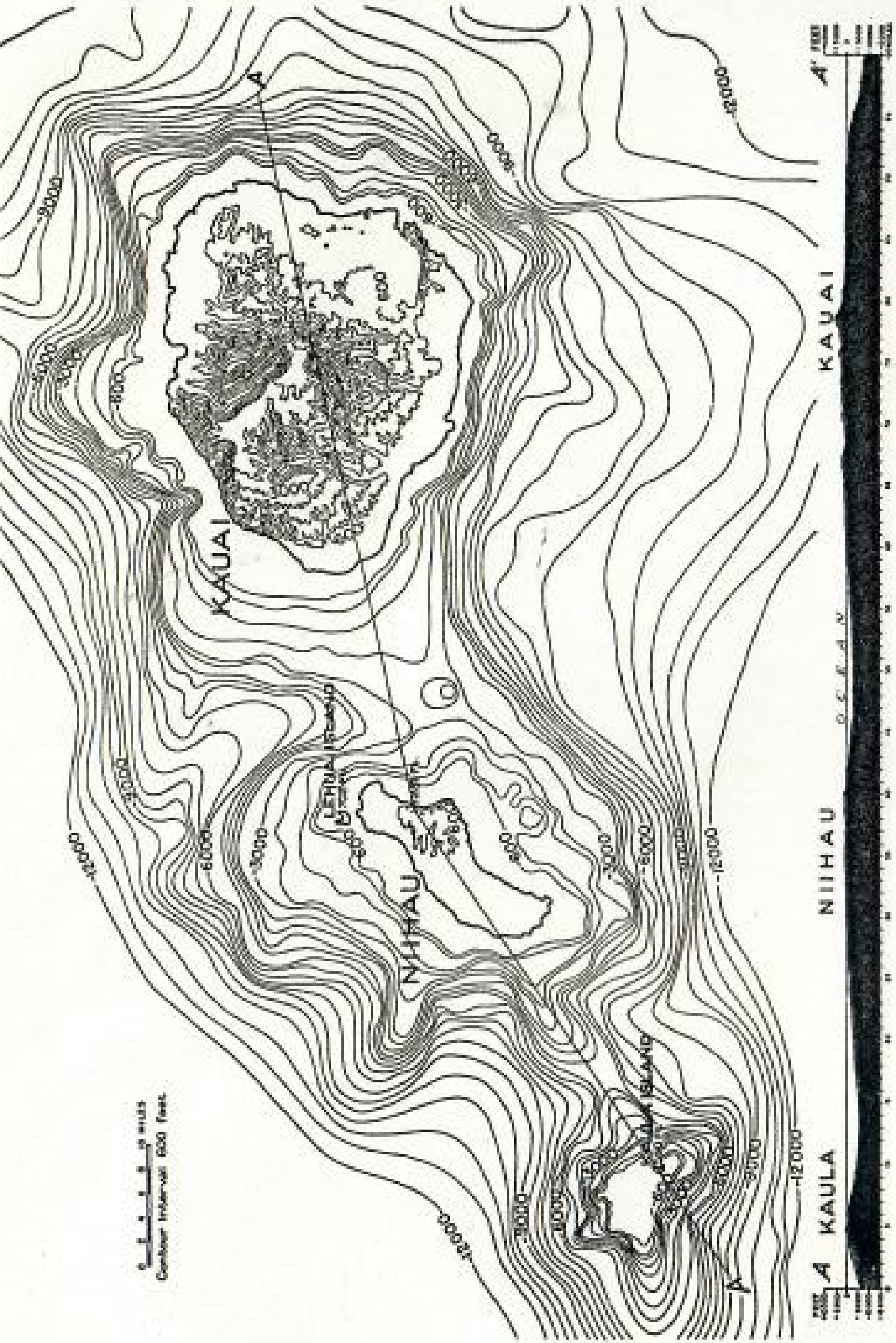

Figure XI.2—Map of Niihau and Kauai showing submarine contours and profile along the line A-A'.

lithified dunes were formed during the minus 60-foot stand of the sea. Emerged reef of the plus 100-foot stand of the sea lies on Kawaihoa cone, and Kawaewae cone was cliffed by seas higher than the 100-foot stand. The lava forming the northern part of the coastal plain is probably of late Pleistocene age, as there is no evidence on it of the 100-foot stand of the sea, and the rocks are only slightly decomposed. In contrast, the rest of the lavas forming the plain are rotted to a depth of several feet. They are all older than the plus 100-foot stand of the sea, which appears to have occurred during the Yarmouth interglacial stage. The older lavas on the plain are tentatively assigned to the early (?) and middle Pleistocene.

The dome remnant was deeply eroded prior to the extrusion of the Kiekie volcanic series, and its rocks are now partly decomposed to a depth of 50 feet on the interstream ridges. The 300-foot submarine shelf, which is well developed on the dome remnant, is believed to be of Pleistocene age. The rocks of the Paniau volcanic series in the dome remnant above sea level are tentatively assigned on this basis to the Pliocene epoch. It is probable that building of the dome from the ocean floor began in middle Tertiary time.

The rock units are summarized in the following table and their distribution in figure XI-1.

TABLE 16

Stratigraphic Rock Units on the Island of Niihau

Age	Rock assemblage	
	Sedimentary rocks	Volcanic rocks
Recent	Younger alluvium, playa deposits, and unconsolidated calcareous beach and dune sand	
Pleistocene	Lithified calcareous dunes, emerged marine limestone, dunes of volcanic sand, and older alluvium	Olivine basalts and vitric-lithic tuff of the Kiekie volcanic series
Great erosional unconformity		
Tertiary		Basalt and correlative dikes and plugs of the Paniau volcanic series

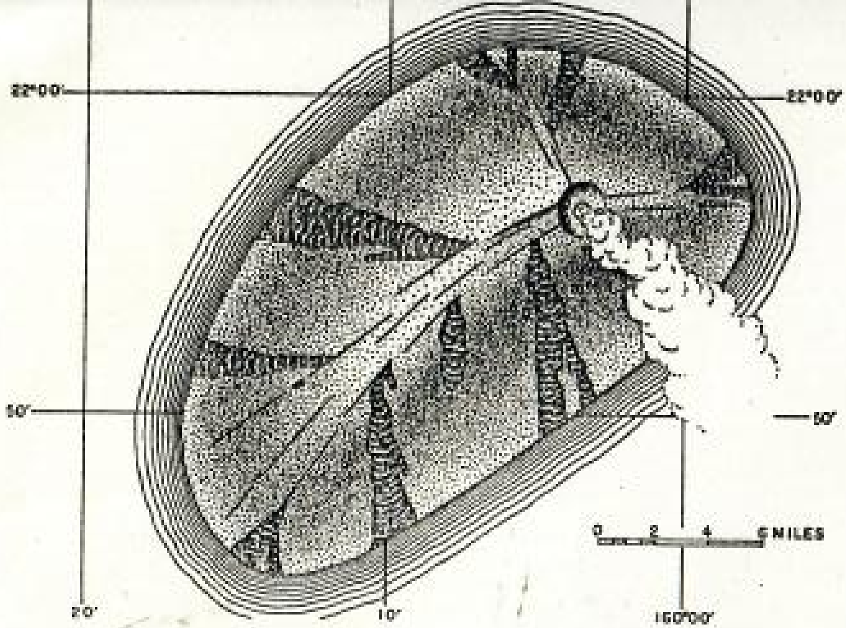

Figure XI.3—Niihau after completion of the primitive basalt dome and formation of the caldera.

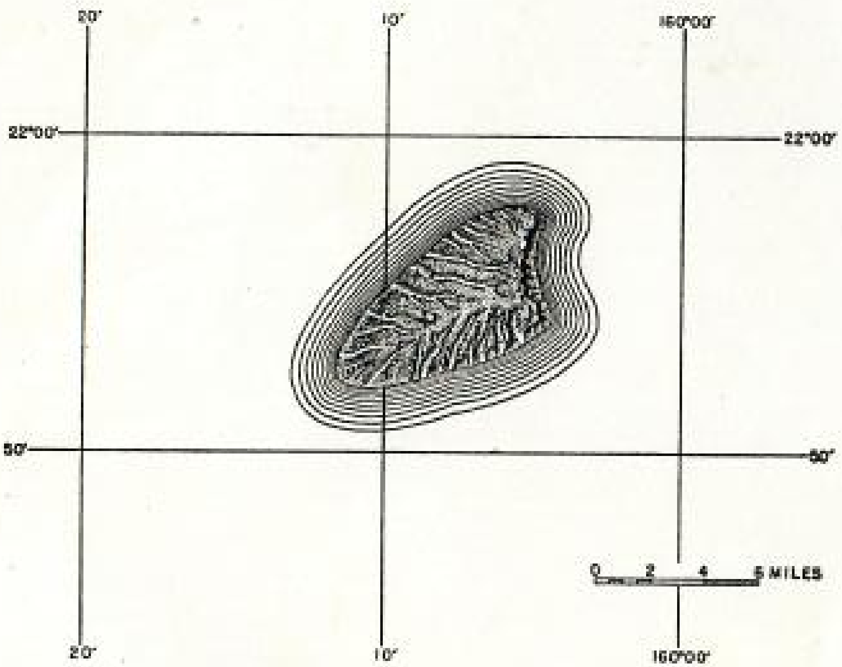

Figure XI.4—Niihau after a period of erosion and the partial submergence of the primitive basalt dome.

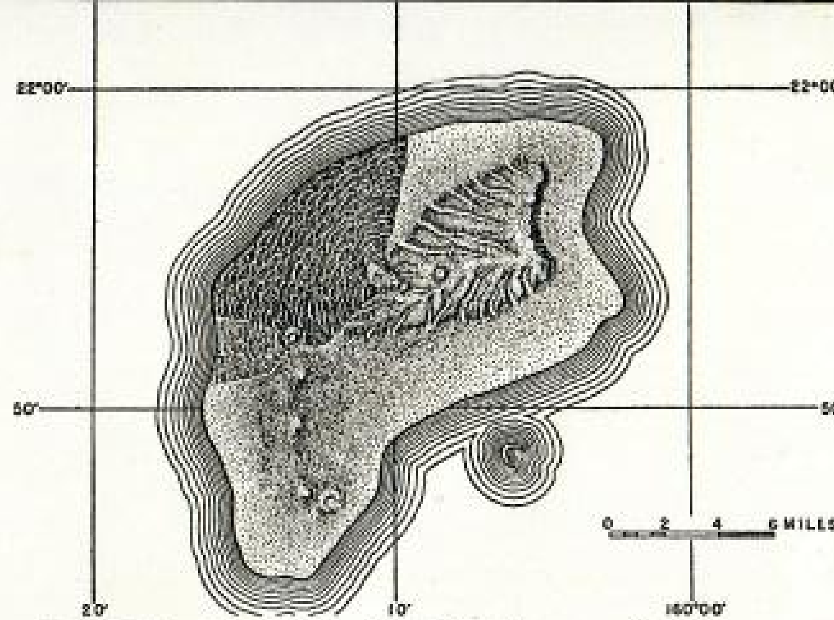

Figure XI.5—Niihau during the middle Pleistocene, when the sea was lowered by the removal of water to form the continental glaciers. Several secondary volcanic eruptions have occurred.

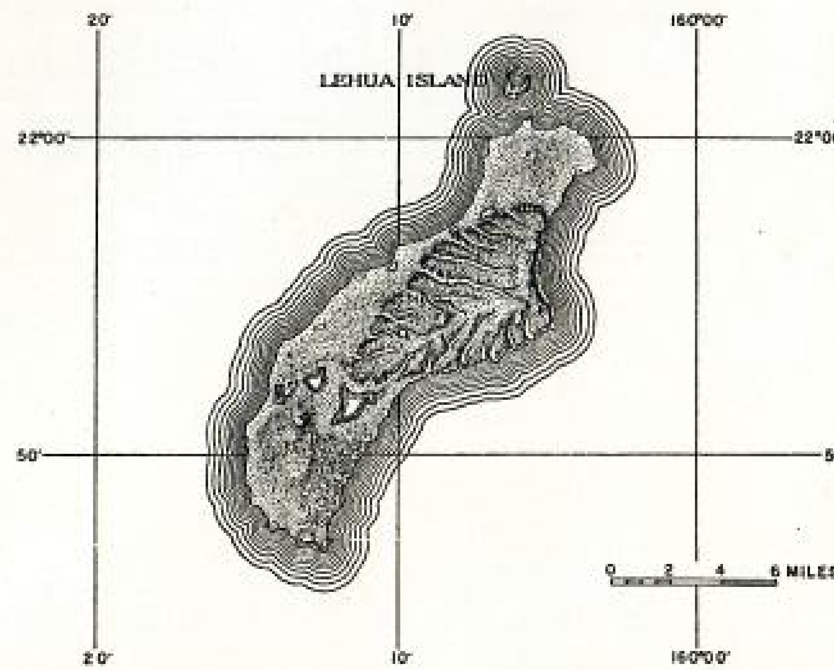

Figure XI.6—Present form of Niihau showing dunes and playa lakes in southern end of island.

Great erosional unconformity.—The rocks in the Paniau volcanic series are separated from all other rocks by a profound erosional unconformity. The Tertiary shield volcano underwent a long period of weathering, when streams cut canyons into its carapace, and the sea made cliffed headlands of the interstream divides. The Pleistocene basalts in Apana and Haao valleys rest against steep valley walls. All rocks on the coastal plain lie against cliffs or talus fans. The talus fans that extend below sea level apparently are subaerial in origin, and they indicate that the island stood relatively higher at the time they were formed. This greater altitude would have resulted in greater rainfall on the island and an accelerated rate of weathering and stream erosion.

Lehua Island

Lehua Island,[109] about 1 mile long, nearly ½ mile wide, and 702 feet high, is composed of subaerial tuff. The vent lay in the sea on the north side of the islet, and a strong north wind was blowing during the eruption, as shown by the pronounced asymmetry of the cone and deposits of ash as much as 8 miles to the south. The tuff above sea level in Lehua Island is 702 feet thick, and it extends an unknown depth below sea level. It is more than 15 feet thick on the tip of Niihau opposite Lehua Island. Much of the ash from the eruption must have fallen into the sea. The tuff is black and upon weathering turns to a tan powdery soil, which makes it easily differentiated from the red soils on the basalts. The tuff contains much glass and many fragments of vitreous basalt derived from the exploding magma. Some beds are breccias and contain many large angular fragments. There appear to be remnants of a wave-cut bench at least 30 feet above sea level on the southern shore of Lehua Island, but it was not examined on the ground.

Ash on Niihau.—Following the explosions on Lehua Island, ash mantled most of Niihau, as remnants of Lehua tuff are found as far south as Puulehua. The ash is a foot thick on the summit ridge 1 mile northwest of Pueo Point. The few small patches shown in figure XI-1 are by no means all of the ash covered areas; many of the grass-covered flats in the upland country probably are covered with a foot or more of ash. Large quantities were carried down the main stream valleys to the coastal plain, as shown by 6 feet of ash from Lehua Island near the mouth of Keanauhi Valley, 7 miles southwest of Lehua Island. The whole northern part of the coastal plain now mapped as lava was covered with 5 to 15 feet of the ash. It still remains in most of the low places, but to map the area as ash-covered would obscure the Pleistocene basalt dome. Following the deposition of the ash in this area, the winds piled it into dunes which have since become lithified. Two of these dune ridges were large enough to justify mapping.

The ash dunes extend into the sea at the western coast, where a wide marine bench has been cut into them; hence, it is concluded that the eruption occurred during the Waipio (minus 60-foot) stand of the sea in Illinoian(?) time. The vent must, however, have opened below sea level, as the explosion was the violent hydromagmatic type.

Geologic History of Niihau and Lehua Islands

1. Building of a dome-shaped island about 2,500 feet above present sea level and about 13,000 feet above the adjacent ocean floor, by the outpouring of basalt flows from a shield volcano with its eruptive center about two miles east of Niihau and from a strongly developed rift zone extending southwestward from the center (fig. XI-3). By analogy with other Hawaiian domes, a caldera probably indented the summit as shown in figure XI-3. The eastern rim of the caldera may have been lower than the western, as the eastern side was destroyed by subsequent erosion more rapidly than the western side.

2. Cessation of volcanism and establishment of a stream pattern.

3. Long period during which high marine cliffs were formed on the eastern and southeastern coasts and lower ones on all other coasts. Streams cut canyons in the dome. Weathering formed deep red soil on the inter-stream divides.

4. Gradual submergence of the island by a large but unknown amount, in common with the other islands of the archipelago (fig. XI-4). The island probably reached stability by the end of the Pliocene or during the early Pleistocene.

5. During the Pleistocene there occurred many shifts in sea level, from about 250 feet above to at least 300 feet below present level. A shelf 0.5 to 1.5 miles wide was cut 300 feet below present sea level, indicating long halts of the sea at that level. Reefs grew during rising seas.

6. Concurrent with the shifting seas of the Pleistocene, volcanism was renewed and lava and tuff built the submarine shelf above sea level. Buried cones are known to lie below sea level (fig. XI-5).

7. During the 100-foot stand of the sea the northern part of the coastal plain was still under water and Lehua Island had not yet erupted.

8. During the minus 60-foot stand of the sea sand blowing inland built extensive calcareous dunes, and a narrow shelf was formed around the island. A lava dome built the northern part of the coastal plain above sea level and Lehua Island was formed by a submarine explosion. Ash from Lehua Island fell over most of Niihau and soon thereafter was blown into dunes on the northern plain.

9. The sea rose about 85 feet, drowning the seaward parts of the dunes. Vegetation spread over the rest and cementation occurred. Playa lakes formed in depressions in the lowlands.

10. The sea fell 20 feet and formed benches and beaches 5 feet above present sea level, probably halting at 12 feet.

11. The sea fell 5 feet with a possible halt at 2 feet before regressing to about 300 feet below present sea level.

12. Rise of the sea from the glacial low stand of about 300 feet to present sea level when modern beaches and dunes formed (fig. XI-6).

13. Feral goats in historic time ate so much of the vegetation that much of the deep red soil on the uplands, formed during the million years or more since the cessation of volcanism there, was washed into the lowlands, filling up Hawaiian fish ponds and many of the playas. Extinction of the goats and the introduction of kiawe, haole koa, and other desert plants are slowly reclaiming the eroded areas of the island.

12

LEEWARD ISLANDS AND OFFSHORE ISLETS

Leeward Islands

Extending northwestward from Niihau are 26 islets, reefs, and shoals known as the Leeward Islands. They mark the summits of submarine volcanoes (fig. I-2). West of Gardner Island (fig. I-2, no. 17), only low coral islands are found, whereas to the east many are remnants of basaltic cones. The numbers in the following classified list refer to the numbers in figure I-2. For further data see bibliography numbers 20, 41, 59, 105 and 154.

Kaula is a secondary tuff cone built on a reef platform;[100] whereas the other volcanic islands are probably eroded remnants of primary volcanic domes. The rocks are composed of andesine, picrite, olivine, and nepheline basalts.[154] Andesine basalt is rare. The one specimen of nepheline basalt was collected on Necker Island from a dike which may have been the feeder to a secondary flow; but from the published description, this basalt appears to contain anemousite feldspar. If so, the lava probably belongs to the andesitic phase. A pilot observed a submarine eruption between Necker and Nihoa Islands on August 20, 1955.[83]

Coralline algae are the principal constituent of the living and emerged reefs. At Midway and probably at some of the nearby islands, the reefs contain an appreciable number of barnacles. The emerged reef on Midway stands 5 feet above sea level and indicates a late, apparently world wide, emergence of this amount.[137] Test holes on

TABLE 17

ALTITUDES OF LEEWARD ISLANDS

		Height (feet)
	Volcanic Islands	
17.	Gardner (basalt flows and dikes)	190
21.	La Pérouse Pinnacle in French Frigate Atoll (basalt flows)	122
23.	Necker (basalt flows and dikes)	277
24.	Nihoa (basalt flows and dikes)	910
26.	Kaula (tuff)	550
	Emerged Coral Atolls or Near Atolls [a]	
3.	Kure or Ocean (name of atoll)	—
4.	Green (sand island inside of Kure atoll)	20
6.	Midway	43
8.	Pearl and Hermes	12
9.	Lisianski	44
14.	Laysan	56
	Coral Atolls or Near Atolls	
1.	Unnamed	Breakers
2.	Bensaleux	Do
10.	Fisher	Do
11.	Minor	Do
15.	Maro (Dowsett)	Do
18.	Two Brothers	7
22.	French Frigate (excluding La Pérouse Pinnacle)	10
	Shoals (Probably Submerged Atolls)	
5.	Nero	−492
7.	Gambia	− 84
12.	Neva	− 18
13.	Springbank	−108
16.	Raita	− 54
19.	St. Rogatien	− 72
20.	Brooks	− 84
25.	Unnamed	−192

[a] The height given is measured to the top of sand dunes and does not indicate amount of emergence. The highest emerged reef known is only about 5 feet. The literature does not clearly state the evidence of emergence except for Midway and Pearl and Hermes Islands.

Midway indicate that the reef caps a deeply eroded basaltic volcano which subsided beneath the ocean prior to the middle Miocene. Radiogenic ages[51a] indicate Niihoa Island to be 7.5±.4 and Necker Island to be 11.3±.6 million years old. Thus the Leeward Islands predate considerably the visible part of the main Hawaiian Islands. A gravity survey for several of the Leeward Islands has been completed. No indication was found of any systematic change from southeast to northwest in Bouguer anomaly values.[32a]

Offshore Islets

Thirty-nine islets shown in figure I-1 lie close to the main islands. Islets numbered 1, 2, 3, 12. 16, 23, and 33 are secondary tuff cones of late Pleistocene or Recent age. Those numbered 4, 5, 8, 20, 21, 22, 24, 25, 26, 28, 29, 30, 31, 34, 35, 36, 37, 38, and 39 are remnants of lava flows isolated from the main islands by marine erosion. Islets 11 and 15 are part of the dike complex of the Koolau Volcano; 7, 9, and 10 are lithified dunes of the Waipio terrace stage; 17, 27, and 32 are remnants of cinder cones; 13 is the remnant of a secondary nepheline basalt flow or crater fill; 19 is composed of reef limestone, Salt Lake tuff, and earthy sediments; 6 and 14 are emerged reef limestone; and 18 is of unconsolidated sand and has been enlarged by dredged material.

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172. In July 1965, J. C. Belshé made several electromagnetic traverses across

Tuscaloosa Seamount, the largest of the so-called landslide blocks, and found a single dipole. The fathometer readings indicate a depression on the summit 3½ miles across and 300 feet deep, possibly a caldera. A core sample taken from this seamount under 9,500 feet of water, was examined by the writer and found to be fresh, bedded basaltic tuff containing foraminifera and rich in lime. One fragment was coated with a thin layer of manganese. These data appear to confirm Hamilton's interpretation that the seamounts are late submarine cones, but the presence of visicular fragments in the tuff requires great submergence.
173. Examination of cores from the Midway holes was possible through the courtesy of Harry Ladd. The writer is responsible for the following simplified logs. The hole on Sand Island, 17 ft. above sea level and 568 ft. deep penetrated reef limestone 0–426 ft.; foraminiferal limestone, marls, conglomerates, and red and green montmorillonite clays 426–520 ft.; weathered basalt 520–538 ft.; and basaltic bedrock 538–568 ft. A hole at the edge of the living barrier reef 10 feet above sea level penetrated reef limestone, lagoonal muds and foraminiferal limestone 0–1131 ft.; silts, sands, conglomerates, breccias, and other volcanic material, much of it weathered, 1131–1250 ft.; cobble conglomerate 1250–1265 ft.; weathered basaltic bedrock grading downward into fresh lava flows 1265–1654 ft. Miocene foraminifera have been identified in these holes by W. Storrs Cole.
174. T. K. Chamberlain (oral communication December 1965) explored the Waianae coast of Oahu in 1965 in a submarine with glass portholes. He saw stepped terraces on which were potholes filled with round boulders obviously left there in the geologic past when the sea was cutting into the terraces. A high steep cliff drops off the edge of the −300-foot shelf to a depth of more than 500 feet. Continuous bathymetric measurements indicate two higher shelves with their nick points at −230 to −250 feet and at −140 to −150 feet. The present day beach sand drifts slowly downward across these shelves and is lost in the deep water.