Hawaiian Archipelago Formation

The Hawaiian Archipelago comprises eight so-called **main islands,** which make up over 99 percent of the chain's emergent land area, and about the same number of clusters of small, mostly uninhabited low landmasses of the **Northwestern Hawaiian Islands** (see chapter 23). As shown in Figure 3.1, all these large and small islands form a long, essentially straight alignment, extending from the southeast to the northwest for approximately 2,400 km (1,500 miles). The nearest landmass outside the chain is isolated Johnston Atoll, about 800 km (500 miles) to the south of the center of the chain, with no continent closer than about 3,200 km (2,000 miles) (Frontispiece; Figure 11.1).

The profile at the top of Figure 3.1 shows that the individual Hawaiian Islands (or, occasionally, a small group of closely situated ones) are merely the emergent summits of enormous mountains whose bases are in the neighborhood of 5,000 m (16,500 feet) below sea level. This is also true of the lava foundation of the numerous sandy islets, shoals, and submerged banks making up the Northwestern Hawaiian Islands. These mountains are all volcanic peaks, although only on the southernmost main island, the "Big Island" of Hawai'i, is one currently erupting.

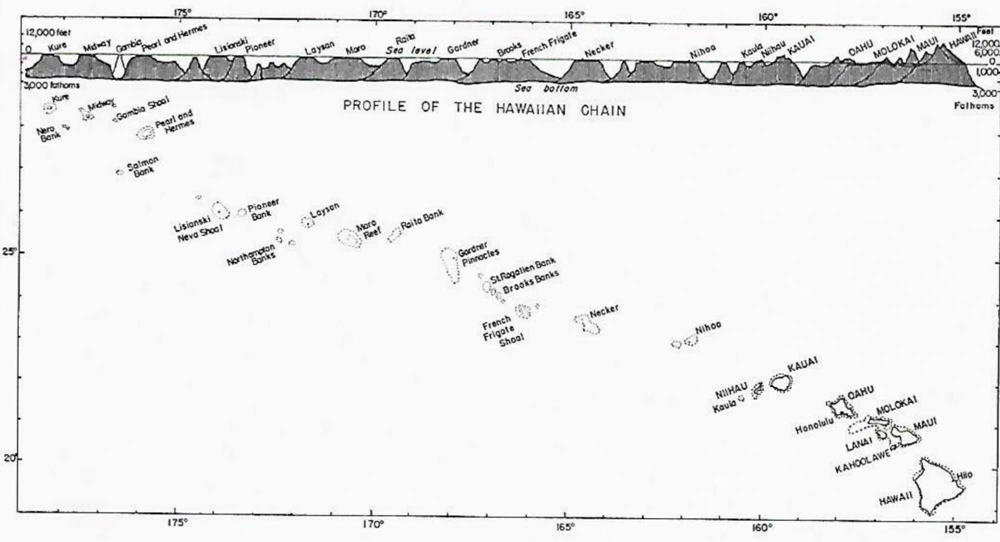

Figure 3.1. Islands, banks, reefs, and shoals of the Hawaiian chain. The vertical scale of the profile is exaggerated about twenty times. The distance from the center of Hawai'i to that of Kaua'i is approximately 515 km (320 miles). Dotted lines indicate the 180-m (595-foot) submarine contour around each island. (Unnumbered figure on p. 2 of E. H. Bryan Jr. [1954], used with permission of Bishop Museum Press.)

Table 3.1 lists the ages of the various islands; most of these ages were obtained using the potassium-argon radiometric procedure (see chapter 2). The islands become progressively and uniformly older as the chain is followed to the northwest, although the seafloor around each island is from 20 to 90 million years older than the island itself. The island age sequence as well as the discrepancies between island and seafloor ages will become clear in the following discussion.

HAWAIIAN HOT-SPOT VOLCANISM

Island-Chain Formation

The Hawaiian Islands were formed by the **Hawaiian hot spot,** currently centered at about the middle of the southeast coast of Hawai'i Island. Magma is emitted through a portion of the Pacific Plate that has taken about 20 million years to move northwest from its place of formation on the East Pacific Rise (see chapter 2). This newly extruded lava eventually builds up into a volcano that is steadily carried away from the hot spot as the plate moves toward its subduc-

Table 3.1. Radiometric ages of various Hawaiian islands. The ages (mostly obtained using the potassium-argon procedure) represent those of the oldest lava yet found on each island. The meaning and significance of the rejuvenation-lava ages are discussed in the text. A range of ages usually indicates testing of different major volcanoes on the same island. (Data primarily from Clague and Dalrymple [1987].)

Island	Age (in millions of years)
Hawai'i	0.00–0.60
Maui	1.00–1.75
	(rejuvenation lava <0.001–1.1)
Kaho'olawe	1.03
Lāna'i	1.60
Moloka'i	1.90–2.10
	(rejuvenation lava 0.4–0.5)
O'ahu	2.75–4.00
	(rejuvenation lava 0.006–0.8)
Kaua'i	5.25
	(rejuvenation lava 0.5–2.8)
Ni'ihau	5.55
	(rejuvenation lava 0.4–2.5)
Nihoa	7.50
Necker	10.7
La Pérouse Rock	12.4
Gardner Pinnacles	13.3
Laysan	20.2
Pearl and Hermes Reef	21.1
Midway Atoll	28.3

tion zone in the North Pacific (Figure 2.2). The stationary hot spot continues to extrude magma, but either the supply of this is sporadic or its flow to the surface of the plate is intermittently slowed or blocked. Thus, a line of discrete volcanic islands rather than a continuous ridge is produced.

Lō'ihi

In 1980, an actively building submarine volcano was found about 30 km (19 miles) off the southeastern coast of Hawai'i Island and was named **Lō'ihi** (Figure 5.1). Because Lō'ihi is only about 45 km (28 miles) from Kīlauea Volcano, and both are so actively adding lava to this region, it is quite possible that the facing slopes of these two young volcanoes will coalesce

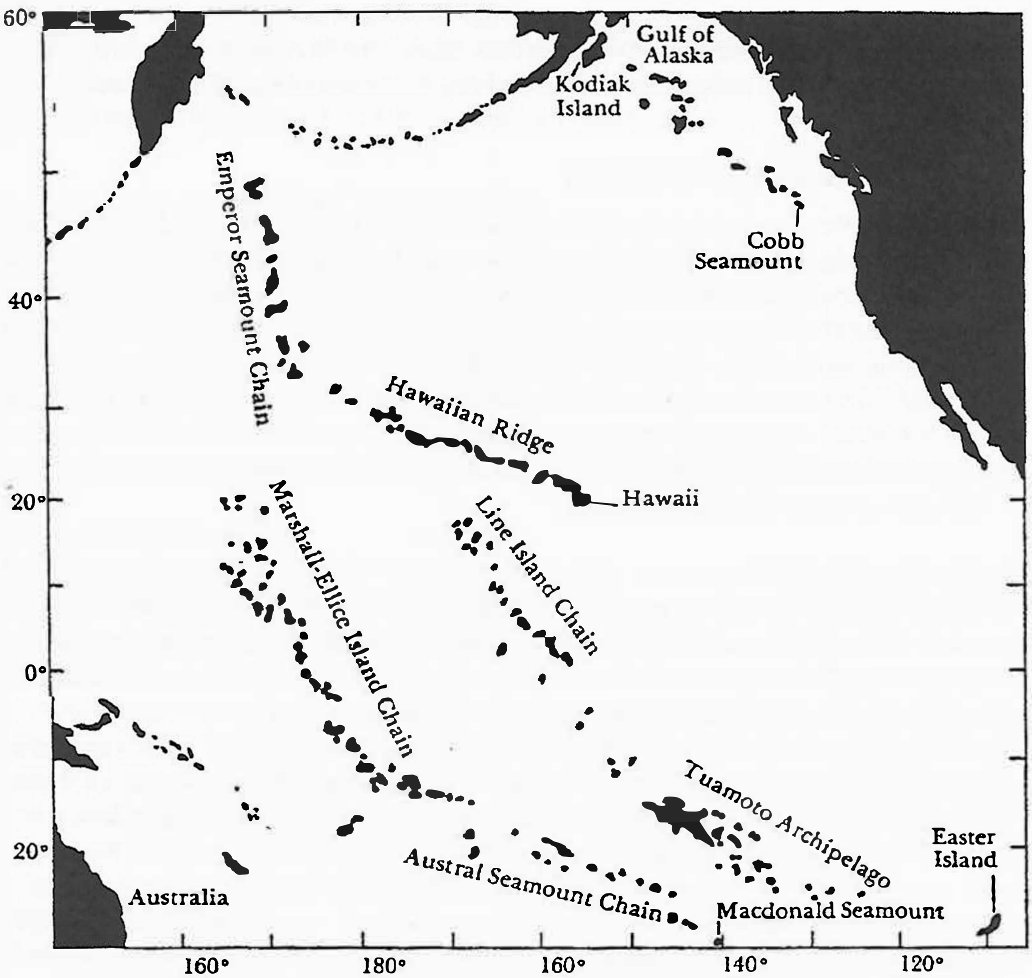

Figure 3.2. Island and seamount chains of the Pacific Plate. At the upper right of the figure, it is thought that the line of islands extending northwest and then north from the Cobb Seamount may also have been formed in the same manner as the central ocean-plate chains. (Fig. 10 of Dalrymple et al. [1973], used with permission of *American Scientist.*)

before Lō'ihi emerges above sea level. Lō'ihi would then form a sixth volcanic peak on Hawai'i rather than a separate island. Such submarine coalescence was probably the case with the other five volcanoes currently visible on Hawai'i, although the oldest (Kohala) could possibly have once constituted a distinct island.

Hot-Spot Conduits

The fact that Lō'ihi, Kīlauea, and neighboring Mauna Loa are all active at essentially the same time indicates that magma from a (presumed) single hot spot can simultaneously service more than one volcano. There could conceivably be some confluence of their magma conduits and thus intermixture of the magma supplying each volcano, although this has yet to be conclusively demonstrated. At any rate, each magma conduit initially leading directly vertically from the hot spot's opening in the ocean floor apparently remains open and capable of transmitting lava for perhaps a million years as it is being drawn out to the northwest by plate movement. Evidently, the magma in the conduit eventually cools enough to solidify, and the volcano to which the conduit leads becomes dormant and finally extinct. Before this happens, however, one or more newer conduits develop and provide magma to younger volcanoes located to the southeast.

EMPEROR SEAMOUNT CHAIN

Although only the islands from Hawai'i to Kure are shown in Figure 3.1, study of the North Pacific seafloor has shown that extending this so-called Hawaiian Ridge farther to the northwest are at least a half dozen submerged seamounts. From the northwesternmost of these a continuing line of still more seamounts undergoes a pronounced bend to the north, and these twenty-five or more similar structures form the **Emperor Seamount Chain** leading to the Pacific Plate subduction zone at the Aleutian Trench (Figure 3.2). The ages of lava dredged at selected seamounts of the ridge and chain progressively increase from about 30 million years just beyond Kure, through approximately 43 million years at the bend itself, to at least 75 or 80 million years near the Aleutian Trench.

Pacific Plate Rotation

Most investigators believe that the Emperor Seamounts represent earlier productions of the Hawaiian hot spot, with yet-older similarly submerged volcanic mountains already destroyed by progressive plate subduction. If this is correct, while a major portion of the Emperor Seamount chain was being developed, the location of the pivot point or rotational axis of the plate was such that they were transported in a rather northerly direction. A little over 40 million years ago, however, the plate axis shifted far northeast, from a little south of the tip of Baja California to just off the west coast of Greenland, so that the line described by all subsequently formed Hawaiian Islands extended in a northwesterly direction. It is not known for certain what caused the shift in rotational axis of the Pacific Plate, but it is suspected that the collision of the India portion of the Indian-Australian Plate with the Eurasian Plate (Figures 2.1, 2.2) somehow indirectly affected the directional movement of plates contiguous with one or both of them.

The orientation of at least two other isolated Pacific Plate island chains seems to support the theory of shift in rotational axis. These are the Tuamotu-Line Islands and the Austral-Marshall-Ellice Islands (Figure 3.2). Both are similar to the Hawaiian-Emperor chain in the existence of an active hot spot at the southeastern end and a linear arrangement of apparently successively older islands and seamounts stretching from southeast to northwest in the southern segment, but abruptly bending more to the north near their midpoint. Their bend, like the Hawaiian-Emperor one, is radiometrically dated at approximately 40 million years.

RATE OF PLATE MOVEMENT

Assuming the Hawaiian hot spot has remained essentially stationary during formation of the Hawaiian-Emperor chain, at least a rough idea of the rate of Pacific Plate movement can be obtained by dividing the distance between the hot spot and a particular included island or seamount by the age of the latter. For example, Midway Atoll is about 2,500 km (1,550 miles) from the hot spot, and its greatest radiometrically determined age is roughly 28 million years. The pertinent division yields a plate-movement rate of a little under 9 cm (3.6 inches) per year. The rates similarly obtained for approximately three dozen other islands and seamounts of the chain average 8.6 cm (3.4 inches) per year, with most of the rates falling within about 10 percent of that figure. These rates, however, must be regarded as absolute maximum ones because it is unlikely that in any case the oldest lava of each island was recovered for dating.

LAND–SEA LEVEL RELATIONSHIPS

Although present-day maps show that the main Hawaiian Islands comprise eight discrete major landmasses, rather slight differences in levels of land and sea can easily alter this number in the case of those islands separated by relatively shallow channels. Past changes in these levels apparently spanned the surprising range of 365 m (1,205 feet) above current sea level to about 1,000 m (3,300 feet) below. Such changes can occur if the absolute elevation of the land fluctuates while that of the ocean remains constant, or vice versa. Or the two elevations may simultaneously move in opposite directions to produce the greater differences in relative levels.

Vertical Land Movements

In **tectonic** change, only the land varies in elevation. One tectonic-change type may be due to thermal-expansion doming near a hot spot of the ancient ocean plate underlying an island and subsequent lowering of the island as the plate cools and thins while moving away from the area. A second type of tectonic change also of significance in the Hawaiian Islands is the initial depression and eventual reelevation of the ocean plate under the great weight of a large volcano, which first builds on it and then slowly erodes away. This latter tectonic phenomenon, in which the changing weight of an island is in equilibrium with the upward resisting force of the underlying ocean plate at any given time, is usually subclassified as an **isostatic** (Greek *"isos"* [equal] and *"statikos"* [causing to stand, or staying]) change.

Vertical Sea Movements

During **eustatic** (Greek *"eu"* [original] and *"statikos"*) changes, only the sea level fluctuates, as when the oceans rise during interglacial or melting periods of continental ice sheets and fall during glacial or accretion periods of the thick ice layers. To illustrate the potential magnitude of eustatic change, if all the present-day glaciers melted, it has been estimated that the ocean worldwide would rise 60 m (198 feet). And, because these continental ice sheets may have been close to three times as large during some of their previous dozen or so maxima of the past 1.8 million years, eustatic changes were undoubtedly substantially greater then.

Effects on the Hawaiian Islands

The Hawaiian Islands have certainly undergone the first type of tectonic movement as they subsided while being carried away from the hot spot, but to what degree—and exactly when—they have also been simultaneously affected by the isostatic type of tectonic change is still not fully determined. At any rate, the *average* tectonic lowering apparent for all the main islands is about 2 cm (0.8 inches) per 1,000 years. In regard to eustatic changes, there seems to be general agreement that relative changes of sea level around the main islands in the range of at least 75 m (248 feet) above to possibly 90 m (297 feet) or more below the current ocean level have occurred during the past 2 million years or so.

During this time period if sea level rose only about 30 m (99 feet) the eastern and western halves of Maui would have become separate islands. Conversely, with a sea level drop of only 80 m (263 feet), the current islands of Maui, Lāna'i, and Moloka'i would have been consolidated; a fall of another 60 m (198 feet) would have added Kaho'olawe to this landmass. At least the first three of these four islands have been unified as a single one (informally called **"Maui Nui"** [Big Maui] (Figure 3.3), about half the size of current Hawai'i Island, at least once and possibly several times during their existence. The ocean around the older islands of O'ahu,

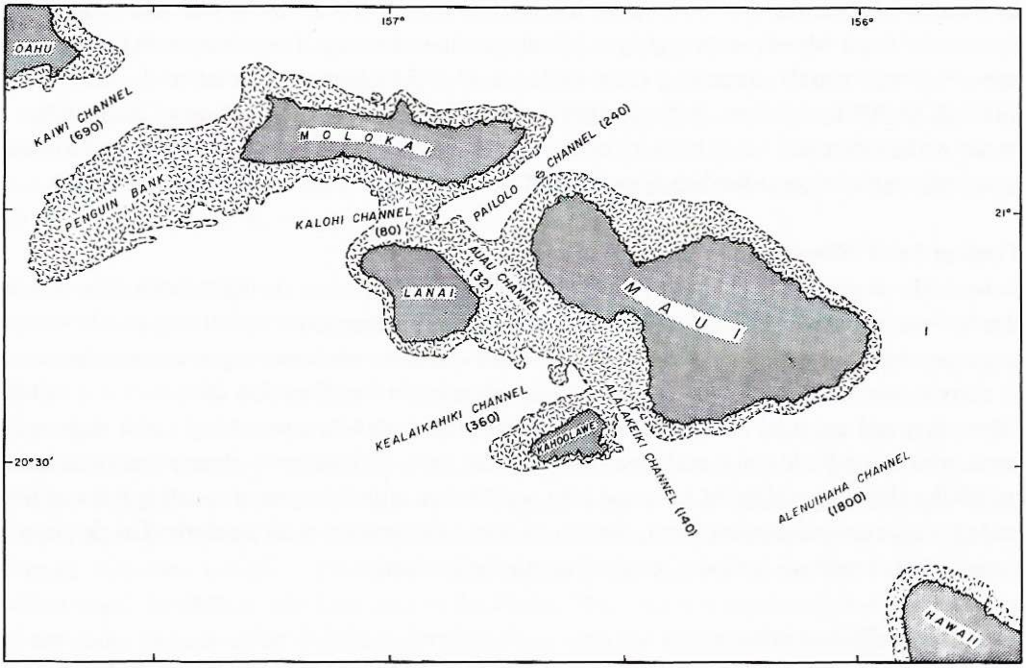

Figure 3.3. Approximate outline of Maui Nui (stippled area). This large ancient island was formed during the past 1 to 2 million years whenever relative sea level dropped at least 140 m (460 feet) below current height. The dashed line enclosing the stippled area is the 180-m (595-foot) submarine contour. Channel depths are in meters. (Fig. 20.1 of Macdonald et al. [1983], used with permission of Frank L. Peterson.)

Kaua'i, and Ni'ihau is deep enough to have prevented any similar coalitions among them during at least this period.

HAWAIIAN ISLAND LIFE HISTORY

The life-history sequence of a Hawaiian island from a deep submarine volcano to a drowned reef-topped island is depicted in Figure 3.4, but it must be emphasized that this is an idealized arrangement because some of the islands may not have undergone every one of the stages shown. The manner in which a single island can be formed from more than one volcano and attain its current physiographic characteristics is additionally illustrated by diagrams of O'ahu's geologic growth in Figure 3.5.

Deep Submarine Stage

Lō'ihi corresponds with the **Deep Submarine Stage** of Figure 3.4, *A*. It extends approximately 4,000 m (13,200 feet) above the ocean floor, with its summit currently about 950 m (3,135 feet) below sea level. The upward growth rate of a submarine volcano should be relatively rapid compared with that of a subaerial one because, upon contact with water under such high pressure, the extruded magma forms somewhat billowy or pillowlike dense lava masses that tend to pile up near the point of extrusion rather than flowing freely away. The exact growth rate of Lō'ihi has yet to be determined, but it probably at least equals that of the subaerial portions of Mauna Loa and Kīlauea, which average perhaps 1 to 2 cm (0.4 to 0.8 inches) per year. Thus, the newest Hawaiian volcano should appear above the sea in about 40,000 or 50,000 years, if not somewhat sooner.

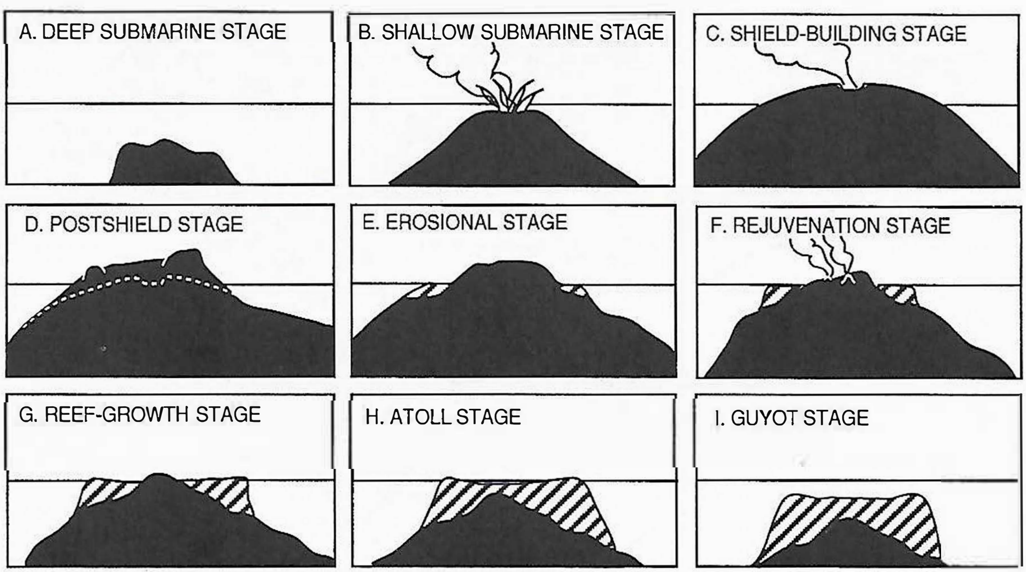

Figure 3.4. Idealized life history of a Hawaiian island. All of the stages except *B* are typified by the current islands and seamounts of the Hawaiian-Emperor chain. (Figure by Keith Krueger.)

Shallow Submarine Stage

When a submarine volcano has grown to within about 100 m (330 feet) of the ocean surface it enters the **Shallow Submarine Stage** (Figure 3.4, *B*). There is no Hawaiian volcano currently in this growth stage, but the well-studied activity of an Icelandic hot-spot volcano named Surtsey that reached sea level in the early 1960s may be used to illustrate it. As the summit nears the surface, the water pressure progressively decreases, so the steam and other gases in the magma can come out of solution. Seawater also contacts the extruding magma, producing enormous amounts of additional steam, and the combined pressure of the gases results in explosive eruptions. Contact of just-extruded lava with seawater fragments it into various-sized pieces, and great amounts of the sand-grain-sized ones are carried aloft by steam. This fine material then rains down from the steam clouds to pile up around the point of eruption, although initially most of it is washed away by waves soon after each eruptive episode.

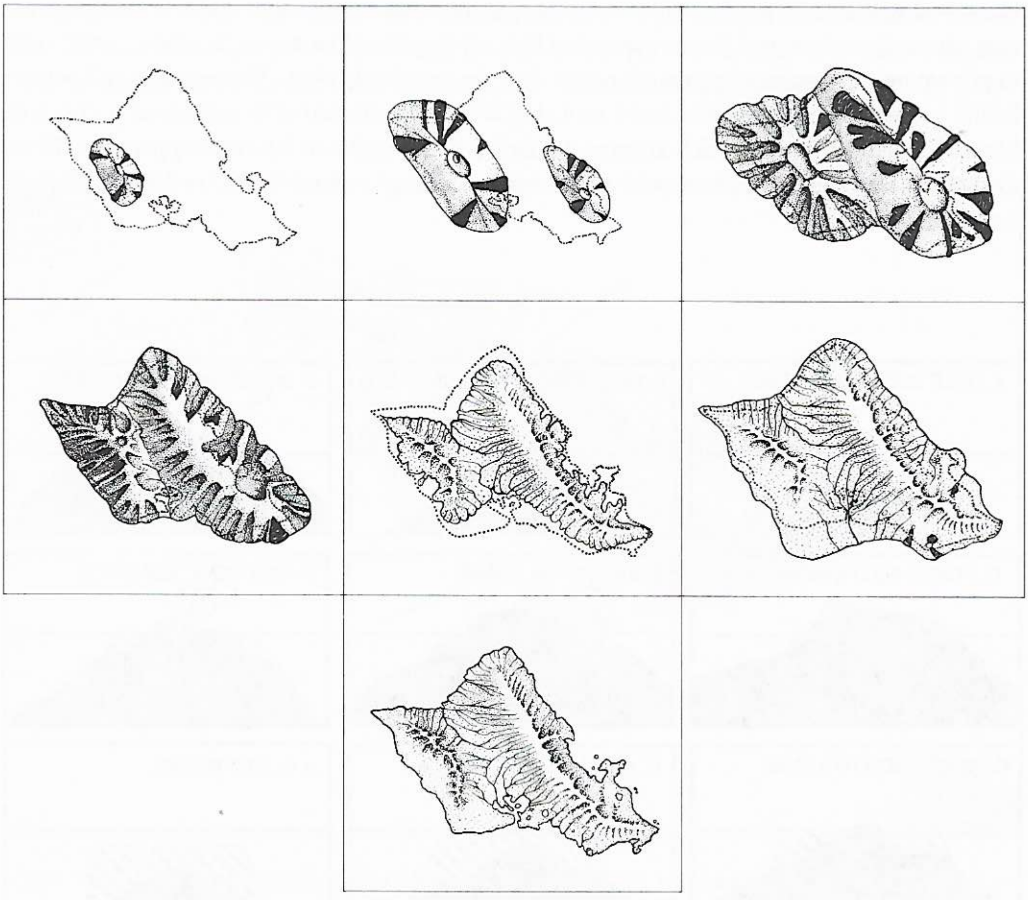

Figure 3.5. Formation of O'ahu Island. This series shows the development of a Hawaiian island from the coalescence of more than one volcano. (Adapted from unnumbered figures on pp. 6–7 of Carlquist [1980], used with permission of the National Tropical Botanical Garden.)

Shield-Building Stage

Finally, however, the summit region of the emerging volcano broadens and its center builds far enough above the sea to prevent freshly extruded lava from being reached by the waves. The typical low, rounded, subaerial (above-sea) portion of a shield volcano is then able to grow from the almost countless thin flows of very fluid lava (Plate 4.1). This initiates an extended **Shield-building Stage** (Figure 3.4, *C*), which is exemplified by Kīlauea and Mauna Loa. It is usually the period of most active eruption—and growth—of an emergent island, with well over 95 percent of the subaerial volume of the volcano being produced. As the volcano continues to grow from summit flows, lava also increasingly begins to issue from often-numerous secondary openings along rift zones radiating great distances from the summit (Figure 3.6).

Also, as the volcano's mass increases, it isostatically subsides by downward deformation of the underlying ocean floor. The growing Hawai'i Island, for example, is sinking at an aver-

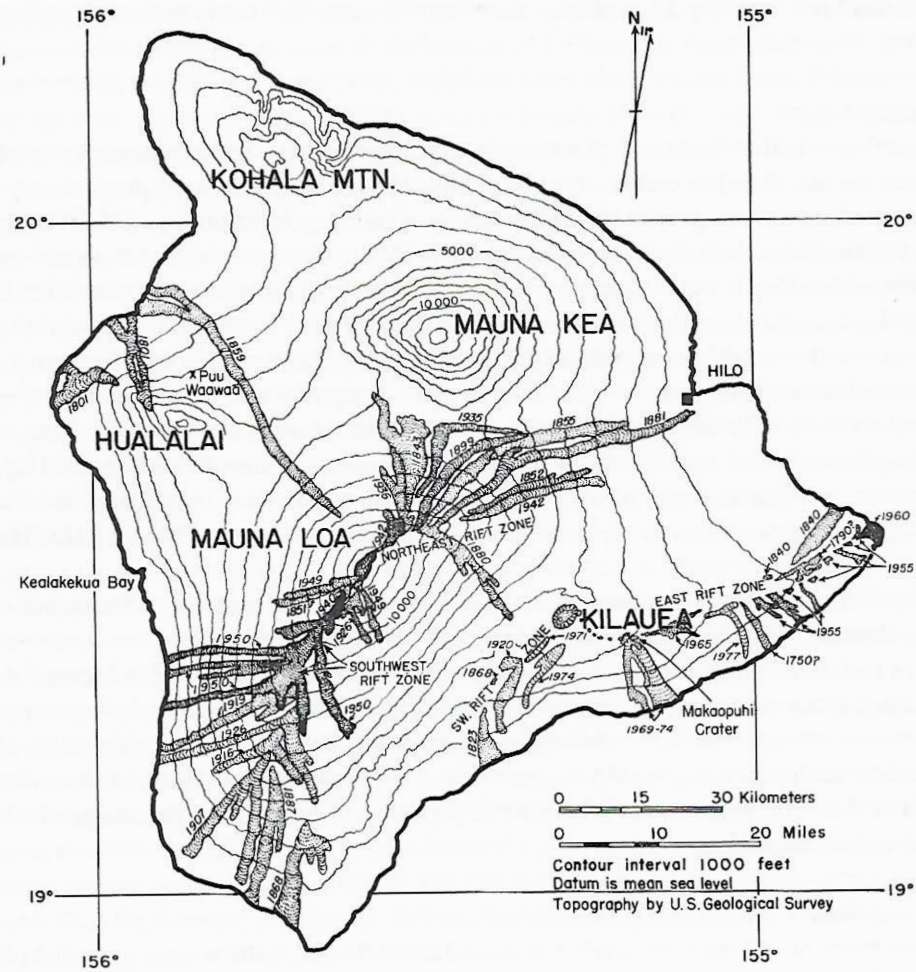

Figure 3.6. Topographic map of Hawai'i Island. Five major volcanoes making up the island are shown, as well as the locations and dates of lava flows occurring between about 1750 and 1977. (Fig. 3.2 of Macdonald et al. [1983], used with permission of Frank L. Peterson.)

age rate of about 0.35 cm (0.14 inches) yearly. In general, this subsidence progressively lessens substantially, but still continues (initially at perhaps 0.002 cm [0.008 inches] per year) after the volcanic island is carried slightly away from the mounded hot-spot area, as the moving ocean lithosphere itself continues to thin from its previous thermally induced thickness over the hot spot.

With time, periodic withdrawals of magma underlying the volcanic summit area cause its center to sink, after which lava rimming the depression may also sink in concentric rings, forming stairlike "step faults." This subsidence forms a broad caldera, such as that currently present on both Kīlauea and Mauna Loa. A caldera may never develop on some Island volcanoes, and the caldera of others can apparently disappear through lava filling, only to redevelop elsewhere in the summit area. Caldera formation may possibly begin much earlier than the Shield-building Stage, however, because very recent submarine photography reveals that Lō'ihi already has one or more large summit depressions. Calderas crowning Island volcanoes are usually quite impressive structures; that of Kīlauea is 3 km (1.9 miles) wide and 4 km (2.5 miles) long, and Mauna Loa's is 2.5 by 5 km (1.6 by 3.1 miles). The step faulting in both of these is quite obvious.

Postshield Stage

After perhaps a half million years of active subaerial growth, however, an Island volcano enters what may be considered its senescent period, during which eruptions become progressively less frequent and any caldera present slowly disappears, signifying the beginning of the **Postshield Stage** (Figure 3.4, *D*). The magma extruded gradually changes to a more viscous and dense type that, after filling in the caldera, continues to build up until the summit area itself has been extended noticeably above the now-buried caldera rim. The total amount of lava produced during this entire Postshield Stage is slight, however, probably amounting to only between 1 and 3 percent of the total subaerial volume of the volcano. The production of fair numbers of symmetrical cratered cinder cones both near the volcano's summit and scattered over its flanks (but not along the earlier rift zones) is frequently typical of postshield time. Mauna Kea on Hawai'i provides an excellent example of the Postshield Stage, and the numerous good-sized cinder cones are a conspicuous feature of its current summit and upper slopes (Plate 7.1). Hualālai of the same island has probably at least entered this stage.

Beginning at perhaps some point in the preceding Shield-building Stage, however, and continuing through at least the Postshield Stage, substantial parts of a volcano—sometimes as much as half of the subaerial volume—are periodically lost, as also depicted in Figure 3.4, *D*. Such diminutions are caused by truly giant earth slumps in which the ocean-facing slopes of the mountain massively slide into the sea, sometimes at avalanche speed (see chapter 5). Such dislocations are presumably usually triggered by a combination of swelling of the volcanic summit or flanks through magma injection and gravitational force on the continually thickening and unbuttressed slopes.

Erosional Stage

From the moment an Island volcano first appeared above the sea, water erosion as well as physical and chemical weathering have acted to wear down each new building lava flow. The net gain, however, only shifts to a net loss caused by these various destructive forces toward the end of the Postshield Stage. In the ensuing **Erosional Stage** (Figure 3.4, *E*), during which it has been estimated that the subaerial height of an Island volcano may sometimes be erosionally reduced at the geologically rapid rate of about 8 cm (3.2 inches) every 1,000 years, the volcanic slopes quickly begin to be deeply furrowed by stream channels.

Formation of soil through physical and chemical weathering of older lava (see chapter 5) also proceeds at a relatively swift pace. Erosion as well as extensive soil slumping and rock avalanches continue to move material to the lowlands, and in many places this erosion results in the formation of giant valleys (Plate 8.1). Also, especially during periods of heightened sea level, the ocean inexorably wears away at the volcano's lower flanks and levels off broad coastal areas while producing steep sea cliffs (Figure 6.5, Plate 6.1). Kohala Volcano (Figure 3.6) on northwestern Hawai'i is in the Erosional Stage.

The enormous depressed summit area of Maui's Haleakalā is often called a "crater," but, in reality, this developed its current form only during and after the Erosional Stage. Some geologists think the volcanic summit covering the ultimately filled caldera may originally have reached some 1,000 m (3,300 feet) higher than the mountain's current 3,055 m (10,082 feet), but others feel it was never significantly higher than at present. At any rate, eventual meeting of the heads of the two great stream-eroded valleys of Ke'anae and Kaupō during the Erosional Stage removed the caldera fill and cover, which left a new deep summit basin. Subsequent volcanic episodes beginning about 100,000 years ago largely filled this with lava flows and ash, and also produced the cinder cones now dotting the current basin floor.

Rejuvenation Stage

The islands of Maui, Moloka'i, O'ahu, Kaua'i, and Ni'ihau have all experienced eruptions during or after the late Erosional Stage, with one on million-year-old East Maui's Haleakalā occurring in historic time. Those of O'ahu's Ko'olau Volcano occurred between about 2.0 and 2.7 million years after the volcano first appeared above water, and those of Wai'ale'ale on Kaua'i at least 5.0 million years after emergence. Thus, even though an island may be as many as 5 million years old, it can still experience at least localized volcanic activity in the **Rejuvenation Stage** (Figure 3.4, *F;* sometimes called Posterosional Eruption Stage). This means that all main island volcanoes of at least Erosional-Stage age must be considered only dormant rather than extinct, including those of Lāna'i and Kaho'olawe, although these latter two have apparently never experienced Rejuvenation-Stage eruptions.

Incidentally, although subaerial eruptions of this stage on Maui, Moloka'i, O'ahu, Kaua'i, and Ni'ihau are geologically well documented, published reports of historic submarine eruptions between these islands, as well as farther northwest of Ni'ihau, are either in error or still subject to scientific confirmation. In one case, a reputed 1956 submarine eruption in the channel between O'ahu and Kaua'i was said to have produced masses of floating pumice and clouds of "sulfurous fumes." Upon testing, however, the recovered pumice proved to be from an earlier distant eruption off the Mexican coast. A little farther up the chain, what may have been a submarine eruption was said to have been witnessed a year earlier by passengers and crew of an airliner passing over a locality about 90 km (56 miles) east of 10.7-million-year-old Necker Island. Thus far, however, no physical evidence has come to light that either confirms or refutes this claim.

Hawaiian Rejuvenation-Stage eruptions usually consist of temporally and spatially limited episodes of isolated volcanic activity occurring on the heavily eroded lower slopes of old volcanoes. Their locations almost never show any relationship to the orientation of earlier volcanic rift zones. These eruptions often produce highly visible Island structures such as cinder cones, but in most cases do not significantly alter the overall shape of the original volcano. Apparently, although the hot-spot conduit to an island may have long ago been effectively plugged, some pockets of magma deep within various parts of a volcano remain molten for millions of years. These magmatic remnants occasionally come in contact with underground fresh- or saltwater, apparently either by rising toward the surface or more likely through subsidence of the island. The resulting eruptions are often quite explosive, and such an occurrence in a populated area today could cause considerable damage and possible loss of life.

On O‘ahu, these sporadic late eruptions began about 0.8 million years ago (Table 3.1, rejuvenation lava dates), with the most recent one possibly occurring as few as 6,000 years ago. Cratered cones resulting primarily from ash and cinder eruptions, such as Diamond Head, Punchbowl, and a number of others (Figure 5.5), were formed during this stage, but other Rejuvenation-Stage activity on both O‘ahu and other islands occasionally included substantial flows of quite fluid lava.

Reef-Growth Stage

In Figure 3.4, although the **Reef-growth Stage** *(G)* is placed after the Erosional and Rejuvenation Stages, it was proceeding simultaneously with them. Whenever the nearshore waters were free from destructive lava flows, extensive coral-algal growth (see chapter 11) encircling an island had been building a **fringing reef.** The portion of this reef closer to the shore, however, especially in areas where shallow water extends out considerable distances and seawater circulation is limited, may be retarded in growth by both freshwater runoff and the sediment it carries. The coral farther out along the seaward perimeter, though, grows more rapidly because of its proximity to clearer, freely circulating ocean water with more oxygen and nutrients. This latter coral forms a **barrier reef,** which often essentially reaches sea level, in contrast to the shoreward fringing-reef "floor," which may be from 3 to 30 m (9.9 to 99 feet) or more below the ocean surface. Around the main islands a barrier reef is best developed in O‘ahu's Kāne‘ohe Bay, about 3 km (1.9 miles) offshore. In the Northwestern Hawaiian Islands, at least Nihoa and Necker with their limited amount of volcanic land still above sea level probably qualify for the Reef-growth Stage.

Atoll Stage

During the entire time a northwesterly moving Hawaiian island has been sinking as it moved off the thermally domed area at the hot spot, the surrounding coral-algal reef has been simultaneously growing upward; this growth is as much as 1.5 cm (0.6 inches) or more per year under the relatively favorable water temperatures and other conditions prevailing at the latitude of Hawai‘i Island. This is more than enough to allow the living reef to maintain its upper level a little below the ocean surface as the sinking continues. As the island drifts farther north into colder water, reef growth progressively slows, but the reef has already attained a considerable thickness over the original volcanic base. For example, drilling at two localities on Midway Atoll revealed reef thicknesses of 155 and 378 m (512 and 1,247 feet).

When the last lava prominence of the island disappears beneath the sea through subsidence and subaerial erosion, it becomes covered with reef growth and the island enters the **Atoll Stage** (Figure 3.4, *H*). In place of the planed-down former summit area, there is now—ideally—only a shallow central reef basin with the higher peripheral barrier reef dropping off steeply into the surrounding ocean depths. The enclosed **lagoon** thus formed most often averages about 10 m (33 feet) in depth, with its deepest portions usually extending down no more than approximately 100 m (330 feet). Its geographic extent, however, is usually vast because its perimeter was originally determined by the shoreline shape of the island in its maximum growth stage. Such extensive shallow lagoon areas are also variously known as "banks," "reefs," or "shoals." Important **reef passages** allowing entrance of vessels into the calmer lagoon water are gaps and channels in the barrier and fringing reefs formed long before when watercourses of the volcanic island discharged substantial streams of sediment-laden fresh water into the immediate area, inhibiting reef growth.

In many instances, enough wave-broken reef fragments accumulate on higher segments of the barrier reef to build up slightly above the ocean surface. Still more coral-algal debris, along with sand and occasionally driftwood, then continue to increase the size and elevation of this incipient islet, and ocean birds as well as migratory shorebirds begin to use it for nesting or roosting. Plant seeds washed ashore or brought in by the birds begin to grow, and soon a small, vegetated sandy island has been formed. All of the islands thus developed, together with the lagoon around which they are arranged, make up an **atoll.** ("Atoll" is the term used for such an island-lagoon arrangement by Maldive Islanders of the Indian Ocean; this term quite possibly is the only Maldivian word to be used worldwide.) In other parts of Polynesia, where atolls are more prevalent than in Hawai'i, the atoll islands are called *motu,* of which the Hawaiian word *moku* (used for a district, island, section, fragment, or other delimited land entity) is a cognate. Hawaiian atolls—although seldom as symmetrical as in the idealized description given here—are represented by French Frigate Shoals, Maro Reef, Laysan and Lisianski Atolls, and Pearl and Hermes Reef, as well as Midway and Kure (Plate 3.1) Atolls, all in the Northwestern Chain (see chapter 23).

As long as at least a small volcanic part of an island remains above the sea, it is often informally termed a **"high island,"** to distinguish it from a sandy atoll *motu* or **"low island."** In regard to the locations of atolls worldwide, because the reef-building species of coral and many calcareous algae are warm-water organisms, atolls can only be formed from those oceanic-plate volcanoes situated in tropical or near-tropical waters. As a result of this temperature restraint, the current distribution of atolls is limited as follows: one in the open Atlantic Ocean, about twenty-five in the Caribbean, seventy-five in the Indian Ocean, and perhaps more than three hundred in the Pacific.

Guyot Stage

As a Hawaiian atoll continues its northwestward movement, ocean-water temperature steadily decreases, until the water becomes too cold (below approximately 20°C [68°F]) for reef growth to keep up with atoll subsidence. The usual reef wave-erosion rate of between 0.1 and 0.2 cm (0.04 and 0.08 inches) per year also continues, and the entire atoll sinks progressively farther beneath the surface. When the highest portion of the drowning atoll's reef reaches the critical lower limit of sufficient light for photosynthesis, the coral-algal growth finally ceases.

In terms of biological processes, this particular point of cessation of reef growth is a specific physiological one, rather than a fixed geographical one. That is, if the ocean warms through geologic time, the latitude where coral-algal growth stops moves correspondingly north; if the ocean cools, the pertinent latitude moves south (or the reverse of these directions in the Southern Hemisphere). This physiological boundary is so important in determining the eventual

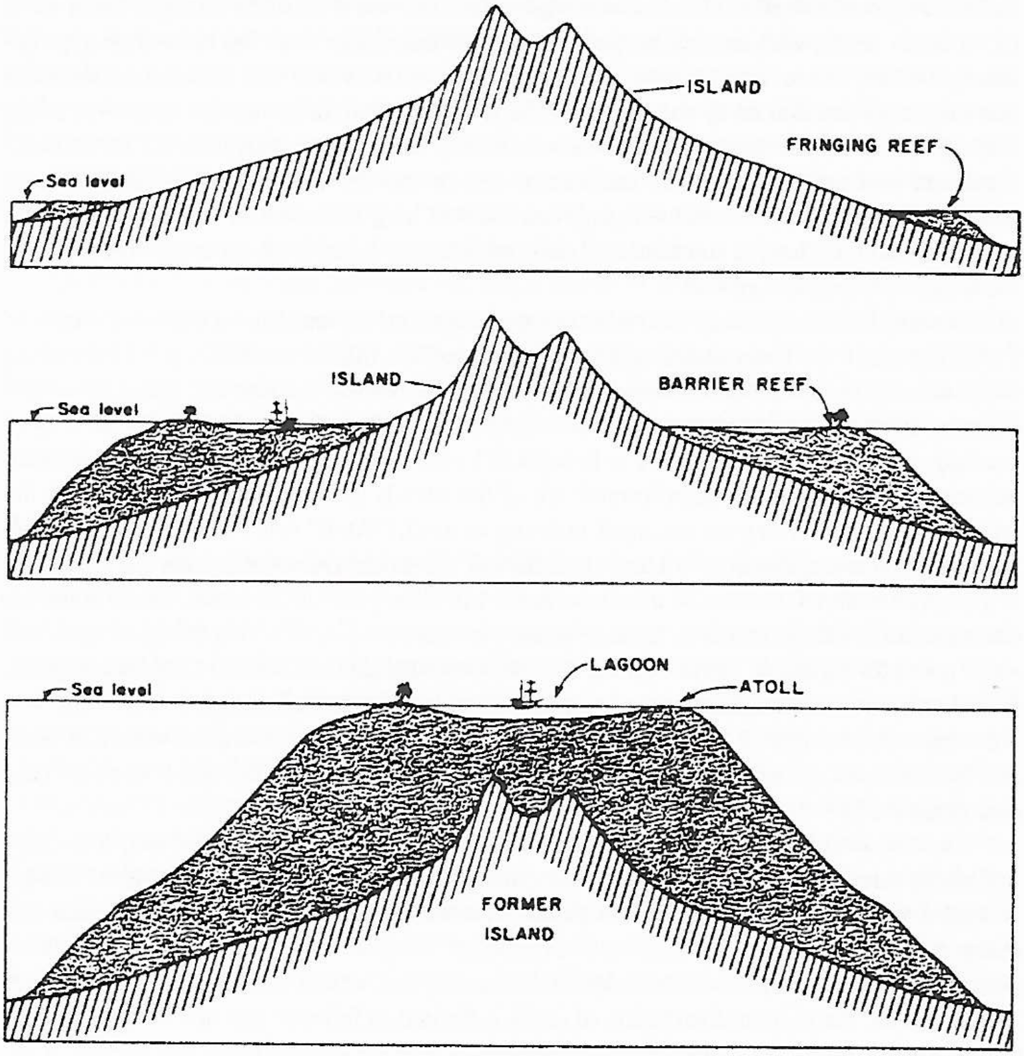

Figure 3.7. Progressive stages in atoll formation. The development of such a structure from a subsiding volcanic island and its surrounding coral-algal reef was correctly interpreted by Charles Darwin in 1839. (Slightly modified from Fig. 14.19 of Macdonald et al. [1983], used with permission of Frank L. Peterson.)

drowning of ocean-plate islands after the Atoll Stage that it has been given a special name: the **Darwin Point,** in recognition of Charles Darwin's important contribution in first envisioning the formation mechanics of atolls (Figure 3.7).

Moving past the Darwin Point, the drowned former atoll becomes a flat-topped seamount or **guyot** (Figure 3.4, *I;* named [indirectly] for Arnold H. Guyot, a nineteenth-century Swiss-American geologist and geographer). The current location of the Darwin Point is somewhere between the northernmost atoll, Kure, and the youngest guyot of substantial size, Hancock Seamount, less than 100 km (62 miles) to the northwest. Occasional seamounts are peaked rather than truncated, but these presumably represent submarine volcanoes that never reached the ocean surface before becoming extinct. There are almost three dozen guyots and peaked seamounts making up the northernmost part of the Hawaiian-Emperor Chain. This **Guyot Stage** represents the last change in the shape of a Hawaiian island until it melts upon subduction, and the Meiji Seamount is the one now poised on the brink of the Aleutian Trench just before being lost.

SUGGESTED REFERENCES

Burke and Wilson 1976; Carson and Clague 1995; Clague 1998; Clague and Dalrymple 1987, 1989; Dalrymple et al. 1973; Decker and Decker 1997; Decker et al. (eds.) 1987; Macdonald et al. 1983; Moore et al. 1994; Walker 1990.

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