The floor of the Pacific Ocean sinks around most of its margins, but new oceanic crust forms in the basin along the East Pacific Rise, an oceanic ridge.

to make new oceanic crust. Some geologists have compared this process to what would happen if two patches of ice on a lake were slowly moving apart with the water freezing as it welled up between them. Both pieces of ice would grow, but the gap between them would remain at a constant width.

**Molten Rock**

Underground molten rock is called magma; if it erupts, we call it lava. Some lava erupts quietly in the form of lava flows; the rest erupts explosively to make pyroclastic debris: bombs, cinders, and ash. All are volcanic rocks and typically consist of microscopic crystals, perhaps with a few large enough to be seen easily.

Some magma crystallizes and cools underground, forming intrusive rocks. These look quite different from volcanic rocks, although their compositions are the same. Intrusive rocks typically consist of crystal grains large enough to be seen without a magnifier.

As much as 40 percent of the garnet lherzolite in the area of the Hawaiian hot spot melts into basalt magma. The molten magma erupts within an area encompassing the three vigorously active volcanoes in Hawai‘i: Kilauea, Mauna Loa, and the Lo‘ihi Seamount, which has yet to grow above sea level. The greatest distance between those volcanic summits is about 50 miles, which approximates the diameter of the Hawaiian hot spot.
Basalt with vesicles, small cavities that form when gas bubbles are trapped in cooling lava.

One or 2 percent of the weight of the magma is gaseous, mainly steam, carbon dioxide, and sulfur dioxide. These gases enter the magma at great depth, where it is under high pressure. As the magma nears the surface, where the pressure is lower, the volcanic gases bubble out of solution the way gas bubbles out of uncorked soda pop. Escaping gases froth the magma, helping make it light enough to rise and causing it to fountain or explode when it reaches the surface. Most of the volcanic gases blow off during eruptions and do not become part of the volcanic rock. Gas trapped in the lava creates small bubbles called vesicles.

Magma rises because it is lighter than the rocks it rises through. Detailed studies of the earthquakes generated by rising magma show that a fresh batch of Hawaiian magma can erupt within a few weeks or months after it begins rising in the mantle. The molten rock normally pauses on the way up. Geologists call a reservoir of stored, waiting magma a magma chamber.

The most pronounced pause is a mile and a half or more below the surface, where the magma apparently loses buoyancy when its density matches the surrounding rock. A large volume of magma may collect in a magma chamber at that depth. The trigger for eruption may be the ascent of new magma into the chamber from below. As the chamber swells, its roof cracks, allowing gases at the top of the magma to expand and propel the molten rock to the surface.

Mauna Loa erupts such huge amounts of lava that geologists are convinced it must be tapping an enormous chamber of stored magma. They use instruments called tiltmeters to monitor the ebb and flow of molten rock through the magma chamber. Tiltmeters are extremely sensitive in measuring the slope of the ground. They show when the flanks of the volcano be-
come steeper as a magma chamber fills, then flatten as the magma erupts. It is almost as though the volcano were inhaling, then exhaling.

Erosion has exposed the interiors of extinct volcanoes on the older Hawaiian islands, so we can see how they grew. As expected, they consist largely of lava flows with lesser volumes of pyroclastic debris. They also contain intrusive rocks, mainly dikes, and some basalt sills. A dike is a steep fracture filled with intrusive basalt; a sill is a more or less horizontal layer of basalt intruded between the lava flows. Dikes and sills are especially abundant in volcano summits, but many dikes also cut across the flanks in narrow bands called rift zones. In some places, erosion exposes masses of intrusive rocks, old magma chambers that completely crystallized. Many of these are more or less globular masses of gabбро called bosses. Gabбро is chemically identical to basalt and consists of the same minerals, but in larger crystals.

Fissures are the most common type of volcanic vent in Hawaiian eruptions. They open ahead of rising magma, then break the surface as long cracks. First, super hot volcanic gas and steam jet from a new fissure, spraying out shards and globes of molten magma. Then, as the fissure widens, a torrent of lava pours out and may spread for miles downslope. After the eruption ends,
The opening of an eruptive fissure as a dike breaches the surface near the southern rim of Kilauea caldera. July 1974.

A fissure at Kilauea partly filled with lava that drained back into it in July 1974.
magma continues to fill the original fissure and crystallizes, becoming a dike. Most dikes exposed by erosion of older volcanoes are probably what remains of the natural plumbing that fed magma into fissure eruptions.

Some Hawaiian eruptions do not follow the typical pattern. Instead, unusually high concentrations of gas and steam may blast most of the magma out as black clouds of dusty ash or as heavier charcoal-sized cinder lumps. The cinders fall near the vent, building a cone, while the ash may drift far downwind. Cinders and ash are two examples of pyroclastic debris, a catchall term volcano specialists use to describe bits of lava exploded from a vent.

**Shield Volcanoes**

Hawaiian magmas are among the hottest on earth. Temperatures as high as 2,200 degrees Fahrenheit have been measured in molten lava at Kilauea. Other kinds of lava erupt from some mainland volcanoes at temperatures as low as 1,560 degrees.

The type of eruption and type of volcano depend on the composition of the magma, the temperature of the magma, and how much gas it contains. The high temperature of Hawaiian basalt magma, its chemical composition, and its gas content all favor eruption of very fluid lava that can travel for miles and spread out in flows rarely more than 30 feet thick.

A long series of such eruptions builds a gently sloping mound of thin lava flows around the vent. If such a mound is only a few miles across, geologists call it a lava shield. Much larger ones, tens of miles in diameter, are called shield volcanoes.

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*Basic types of volcanic landforms in the Hawaiian Islands.*
Cinder cones dot the top of Mauna Kea (foreground). Mauna Loa, in the background, is one of the world's largest shield volcanoes.

Mauna Loa and Kilauea on the Big Island are shield volcanoes on a gigantic scale. So gentle are their slopes, so broadly arching their summits, that visitors accustomed to the steep cones of mainland volcanoes find it difficult to grasp what they are seeing. Smaller lava shields that grew during single eruptions on the flanks of Mauna Loa and Kilauea include Mauna Iki and Mauna Ulu, in Hawaii Volcanoes National Park.

Section through a typical Hawaiian shield volcano.

1. Volcano; 2, rift zone; 3, summit caldera; 4, lava flows above sea level; 5, magma chamber; 6, submarine slide; 7, basalt rubble; 8, pillow basalts; 9, gabbro; and 10, magma chamber.
While the shield volcano stands above the hot spot it grows rapidly, perhaps erupting continuously for years. The volcano may pour out a cubic mile or more of fresh lava onto the slopes every century. The typical rock erupted during this early phase of activity is an extremely common type of basalt called tholeiite.

Like most other basalts, tholeiite is black, or nearly black; it commonly contains small, scattered crystals of yellowish green olivine. During the main stage of shield growth, tholeiite basalt tends to erupt frequently and gently, at least by volcanic standards. You can watch most of these eruptions at remarkably close range.

**Dying Volcanoes**

Eruptions become infrequent as the shield volcano starts the long journey away from the hot spot. Volcanic activity continues in sporadic, widely scattered eruptions around the summit, leaving the upper slopes of the volcano littered with cinder cones and rough lava flows. Meanwhile, weathering and streams convert the original volcanic landscape on the lower slopes of the mountain into an erosional landscape.

The big volcanoes stop erupting tholeiitic basalt almost as soon as they begin to decline. A new type of lava appears, enriched mainly in the alkali element sodium. This lava comes in many varieties, with such names as hawaiite, mugearite, and ankaramite.

It is difficult, and in many cases impossible, to distinguish these lava types in the field. You generally need a chemical analysis, a good view of a thin section of the rock through a specialized petrographic microscope, and a lot of experience with basalt. Think of them all as alkalic basalt.
Typically, a Hawaiian volcano begins on the ocean floor, matures into an island shield volcano, then declines as the moving plate carries the island off the hot spot.
The vents that erupt alkalic basalts in the late stage of volcanism are near those that erupted olivine tholeiite during the main stage of activity. So it seems the late-stage alkalic magmas must follow the volcanic plumbing established during the preceding stage of shield growth.

The waning activity during the late stage leaves the upper slopes of the volcano littered with widely scattered cinder cones and lava flows. The big volcanoes stop erupting tholeiitic basalt as soon as they begin to decline. Their late-stage activity produces a variety of lavas, mainly basalt enriched in the alkali element sodium. These basalts come in many varieties with such names as hawaiite, mugearite, ankaramite, and nepheline. They all look very much like ordinary basalt. Think of them as alkalic basalt.

Years of laboratory research and intellectual gymnastics have not enabled geologists to imagine how tholeiitic basalt magma could turn into alkalic basalt. Nothing that could plausibly take place in a magma chamber would cause that change. Alkalic basalt magma must melt with that composition in the mantle. Geologists can imagine several more or less plausible scenarios to explain how it might happen. Most theories involve melting a smaller proportion of the lherzolite in the mantle, or melting it at depths greater than those at which tholeiitic basalt magma can melt.
Some of the late vents also erupt a lava called trachyte, consisting largely of feldspar, which is very rich in sodium. You can recognize trachyte by its pale gray color, which contrasts notably with that of ordinary black basalt. Many geologists believe trachyte magma develops during long storage in a slowly crystallizing alkalic basalt magma chamber, where the denser crystals of pyroxene and olivine settle, and the lighter crystals of feldspar float or stay behind. The result would be a layered magma chamber with trachyte at the top and basalt below.

The patient processes of erosion carve the quiet volcano into rugged terrain for tens of thousands of years after the last of the late eruptions. Then, on many aging Hawaiian islands, another round of volcanic activity begins. Geologists call this the rejuvenated stage of volcanism.

Eruptions in the rejuvenated stage appear to be unrelated to earlier eruptions. Individual vents are widely scattered across the volcano, and may lie in areas that never erupted. Many are near the coast; some are on the sea bed far offshore. Each seems to have its own plumbing to the lava source in the mantle. Evidently, the last batches of magma rise along new channels, perhaps because the old shield plumbing system has clogged. Eruptions in the rejuvenated stage create small lava shields, cinder and ash cones, and lava flows.

Rocks erupted during the rejuvenated stage of volcanic activity include some alkalic basalts like those that erupt during late-stage activity, along with others, called nephelinites, which are much more strongly enriched in sodium. Those may contain unusual minerals, like nepheline and melilite,
Air view of the east rift zone on Kilauea, with an eruption in progress at Pu‘u ‘Ō‘ō. Mauna Loa is in the background.
—U.S. Geological Survey, Jim Griggs photo

which resemble feldspar but contain larger amounts of sodium and smaller amounts of silicon.

**Xenoliths**

Any older fragment of rock incorporated in a lava flow or ash bed is called a xenolith. Many of them come from inside the volcano; some come from the mantle. Xenoliths from the mantle are found only in lavas erupted from volcanoes in the rejuvenated stage, never in the lavas erupted earlier. Many geologists believe the heavier xenoliths settle out of the magma chambers beneath and within the big shield volcanoes, as sediment settles in a lake. If so, then the xenoliths in the lavas erupted during rejuvenated activity may tell us that magma rises without pausing in magma chambers on the way up from the mantle.

**Rift Zones**

Immense mountains, these Hawaiian volcanoes. They rise from ocean floor as deep as 18,000 feet to a maximum elevation above sea level of 13,796 feet on Mauna Kea, a total of more than 31,000 feet. Hawaiian volcanoes are essentially huge piles of weak rock slowly spreading as they settle under their own weight. The spreading gradually opens narrow bands of fractures that permit magma to intrude far into the shield flanks, sometimes resulting in fissure eruptions tens of miles from a volcanic summit. Geologists call these fractured eruptive belts volcanic rift zones.

From the air, a rift zone looks like a long line of pyroclastic cones and lava shields trending straight down the slopes of the volcano. Because frequent
eruptions rapidly build up the rift zone, the flanks on either side of a rift zone typically are steeper than the slope along the line of the rift zone itself.

Most Hawaiian volcanoes have three prominent rift zones radiating like spokes from their summits. Where a young shield builds up against the slope of an older volcano, only two rift zones develop. They separate the shield’s stable side, next to the older volcano, from the side that slopes unsupported to the deep ocean floor. Kilauea is an good example; an older neighbor, Mauna Loa, buttressed its northern flank and determined the orientation of its two rift zones.

**Pyroclastic Cones**

During the main stage of volcanism, rift zone eruptions produce fissures and lava shields. Later, cinder cones appear. Cinder cones normally form during a single eruption lasting a few weeks or months, and they rarely grow to be higher than a thousand feet. Craters shaped like cups truncate their tops. Toward the close of activity, as the last gas escapes from the magma, the cone stops growing, and a lava flow may burst through the loose cinder at the base. The lava erupts there because the loose pile of cinder has no internal strength, the same way milk runs out at the base of a pile of corn flakes. The flow may raft off a whole section of the cinder cone as it pours away, leaving behind a horseshoe shaped rim.
Once it has gone out of business, a cinder cone normally never erupts again; most are single-shot eruptive features. The next outburst in the neighborhood will build a new cinder cone somewhere nearby.

In many cases, steam filters through the cinder cone for months or even years after the eruption has ended. The steam oxidizes the iron in the cinder, staining the cinder cone red with iron oxide. The result is a red cinder cone, a source of red road and garden gravel.

Lava bombs and blocks abound on cinder cones. Bombs are blobs of lava blasted out of vents. They become streamlined by the wind as they sail through the air. Blocks are jagged chunks of older rock that rushing volcanic gases rip from the throat of the volcano and throw out without streamlining. Bombs and blocks up to several feet in diameter are fairly common. Where they land on soft beds of ash or cinder, the layers sag under their weight.
Major types of volcanic deposits in Hawai'i. Pāhoehoe and 'a'a are two different kinds of lava from surface flows, one rough and the other smooth. Cinders, bombs, and blocks are explosively ejected lava fragments.

Steam is mainly what makes some volcanic eruptions explosive. Magma is likely to encounter shallow underground water if it rises into coastal areas during the rejuvenated stage of activity. The water boils into steam, which explodes in huge blasts, ejecting magma as a fine, hot mist mixed with chunks of older rock. The tiny mist particles are volcanic ash. They accumulate around the vent as an ash cone that is considerably broader than a cinder cone, generally with a shallow crater. Lē'ahi (Diamond Head) and some of its neighbors near Honolulu are good examples of ash cones.

Escaping gases sometimes inflate magma into a spongy froth called pumice, which is comparable to the head on a glass of beer. Many people recognize pumice as a porous, gray scrubbing stone so light that it floats, or almost floats. Hawaiian pumice differs from the mainland variety in being golden and very porous. Hawaiian pumice has so many vesicles, or gas bubbles, that they quickly connect; the pumice becomes waterlogged and sinks.

Volcanic pumice cones usually form downwind of a vent and may grow several hundred feet high. Mixed lava and pumice cones may grow even higher.

Where ash or pumice cones develop from eruption of trachyte magma, a dome may form. A dome is a huge lava mound that grows from a vent after the magma has blown off most of its gas, allowing the remaining molten rock to ooze out. Domes can completely fill the crater of a pyroclastic cone. While not common in Hawai'i, trachyte domes do make a few prominent landmarks.

Another kind of cone sometimes forms when molten basalt lava pours into the ocean, exploding into billowing clouds of steam and debris. The
A volcanic bomb about 2 feet across on Haleakalā, Maui.

Volcanic blocks strewn across a slope inside the basin atop Haleakalā, Maui.
expanding steam can rip the lava into millions of black, glassy cinders, which pile up in mounds called littoral cones. Unlike other types of pyroclastic cones, these lie far from the eruptive vent, at the end of a lava flow. Many littoral cones lack well-defined craters; waves rapidly wash them away.

Craters

Volcanic craters come in many varieties, from different origins. Some open explosively during pyroclastic eruptions; others form as the volcanic surface quietly subsides into an emptying magma chamber. Most craters are distinctive enough that you can recognize their type and know how they formed.

Explosion craters, the kind that form during pyroclastic eruptions, are generally shaped like a cup sitting on top of a pile of pyroclastic debris. Craters on cinder cones are rarely more than a few hundred feet across; those on ash cones may approach a diameter of a half mile.

Subsidence craters and calderas open where the surface subsides as magma drains from beneath. Typically, they have vertical walls and sloping bottoms filled with rubble, or flat floors where lava has ponded. Repeated collapse produces compound subsidence craters. For example, Halemaʻumaʻu, the
Keanakāko'i is a pit crater near the summit of Kilauea. This photograph from July 19, 1974, shows lava pouring into Keanakāko'i Crater and simultaneously erupting from a fissure at the base of the far wall.

Traditional home of Pele, the Hawaiian fire goddess, is a large pit crater in Kilauea caldera. Small subsidence craters are called pit craters; those larger than a mile or so across are called calderas. Most Hawaiian shield volcanoes have calderas at their summits.

During the main stage of shield growth, molten lava may erupt from a vent for months, or even years. It may pool in the vent, creating a lava lake. The chilled crust atop the molten lake continuously breaks and reforms in response to the convective circulation underneath. You can watch many of the phenomena of plate tectonics modeled in miniature in the restless crusts of lava lakes.

Kilauea caldera is a large compound crater that opened as the summit of Kilauea Volcano subsided.
Lava lakes also form where flows pour into pit craters. A lava lake several hundred feet deep may take decades to solidify, like the one that formed in Kilauea Iki Crater on the Big Island in 1959. But the crust will be strong enough to support the weight of a person in a few days.

**Lava Surfaces**

Hawaiians long ago distinguished between two types of basalt lava flows: ‘Aʻā lava has a craggy surface of jagged basalt blocks full of gas bubbles. It is almost impossible to walk across it without shredding your boots. Pāhoehoe lava has a billowy surface, ropy in places, looking almost smooth enough to be soft. Pāhoehoe surfaces on steep slopes typically assume the look of en- trails. Pāhoehoe flows may also have large hummocks, called tumuli, that form where escaping gases heaved up plates of solidified lava. Fresh pāhoehoe lava has a paper-thin, shiny black glass crust that reflects light in iridescent colors.

Despite their differences in appearance, pāhoehoe and ‘aʻā lavas have the same chemical composition. In fact, both kinds of lava occasionally appear on different parts of the same flow.

Temperature is one of the more important factors that determines whether molten lava will develop an ‘aʻā or pāhoehoe. Hot basalt lava, very fluid, solidifies as pāhoehoe. Cooler lava, more pasty and stiff, tears itself apart through its own forward motion, creating rubbly ‘aʻā.
Pāhoehoe lava engulfed a school bus near Kalapana on Kilauea in 1991.

Flowing lava does not heed stop signs. Between 1983 and 1985, when this photo was taken, 'aʿā flows repeatedly entered Royal Gardens subdivision on Kilauea. —U.S. Geological Survey, Jim Griggs photo
The gas content of the magma also helps determine what kind of surface will develop. Gas makes the lava fluid, helping it to develop a pāhoehoe surface. Friction with the ground beneath causes shearing within the moving flow, especially if the lava is spilling rapidly down a steep slope. High shear situations with low gas content favor formation of 'aʻā; low shear, with high gas content, favors formation of pāhoehoe.

Tongues of fluid pāhoehoe lava pour downhill in lobes no more than a few feet thick. As a hard crust forms on the lobe, the lava within flows out from under it, leaving a hollow tube. These develop one after the other, and overlap one another, so the flow of a single eruption may consist of a heap of thin, irregular layers, many of them hollow. Thin bands of reddened rubble generally separate them. Where separate pāhoehoe flows are stacked, they
merge in such an intricately layered heap that it is difficult to tell them apart. A typical pāhoehoe flow is less than 10 feet thick.

In contrast, more viscous 'a'a flows generally have a solid core, with thick red zones of rubbly basalt above and below. As the fluid interior of the flow advances, it carries rubble on the surface, rolling it over the front of the flow, then covering it. You can imagine it laying down its own tread as it crawls along. The individual flows are distinct. Typically, they are 10 to 30 feet thick.

Spectacular structures may form at volcanic vents. Many blobs of lava coughed out of a vent all at once are called spatter. Spatter piles up and forms ramparts, which stand like walls next to eruptive fissures. A towering lava fountain along a fissure may build a spatter cone several tens of feet high.

When lava pours into the ocean or a deep pool along a river, the water quenches the surface, forming a skin that swells up as molten rock accumulates underneath. The skin bursts, feeding a bulb of hot lava that in turn
grows its own skin, swells, and bursts. Over and over this process repeats, until the entire flow may appear to be a heap of rock bulbs. When you see them exposed in a cliff or roadcut, they look like a pile of pillows.

A single lava pillow usually is no more than a few feet in diameter. Chips of glassy lava and black sand shed from the growing pillow fill the spaces between it and its neighbors. Steam percolating through this debris may oxidize the iron in the basalt, staining it red.

In roadcuts, cliffs, and stream banks, you may see another feature typical of lava. The thick cores of ‘a’a flows show neat palisades of vertical rock columns. Geologists have understood for more than a century that the columns express a pattern of shrinkage fractures in the rock. Some people who have watched lava flows in action report seeing those fractures form as the rock crystallizes, while it is still hot. Most of the shrinkage takes place in the transition from molten lava to solid rock. The further shrinkage that accompanies cooling is relatively minor, but it doubtless opens the fractures a bit wider.

Seen from above, the pattern of shrinkage cracks looks like the pattern of fractures you see in sun-cracked mud, or in crazed porcelain. The fractures outline polygons that have four to seven sides, most commonly five. Try counting the number of sides on basalt columns exposed in a roadcut or cliff.

Shrinkage cracks form perpendicular to the surfaces where the lava is losing heat. On most lava flows, those are the upper and lower surfaces, so the columns are vertical. If lava fills an old valley, the columns make a flaring pattern as they meet the valley walls at right angles. If magma fills a fissure to make a dike, the shrinkage cracks open at right angles to the walls, and the columns lie horizontally, like stacked firewood.

**Lava Channels and Tubes**

As the margins of a lava flow cool and harden, they confine the molten lava to a narrow channel. The centralized stream may become further confined as surges of liquid lava overtop the channel banks and chill into levees.
During periods of vigorous flow, big pieces may break off the walls of the lava levees and roll along in the stream of molten lava. The pieces grow larger as smooth coats of fluid lava chill around them, forming lava balls. You can see rounded lava balls scattered across the surfaces of many flows.

The channel at the center of a flow may also form a crust where the molten rock chills against the air. As molten lava beneath continues to flow and drains out from under the crust, it leaves behind a hollow in the flow—a lava tube. Some lava tubes are large enough that a person can walk through them, and some lava tubes are miles long. Most are very shallow, but some older tubes partly buried by younger flows extend deep into the ground.

The roof of a lava tube is an excellent insulator. Measurements taken at Kilauea show the lava temperature dropped only a few degrees between the
A common type of lava tube forms when the top surface of a lava flow cools and hardens. When the lava flow stops, a hollow tube remains.

point where it entered a roofed channel at Kūpiaianaha, an active vent in the east rift zone, and the point where it emerged at Kalapana, 7 miles away. The insulating effect of lava tubes enables pāhoehoe lava to flow much farther than it would if it were exposed to cooling air. Without lava tubes, the shield volcanoes of Hawai‘i would be steeper than they are, and would form much smaller islands.

When molten lava pours into a forest, the moist wood of the larger trees chills it around their trunks. If the flow level recedes, a pillar of hardened lava may remain standing; the trunk usually burns, leaving a hollow pillar. Geologists call such cylindrical monuments lava trees. If the flow level does not recede, a large tree trunk enclosed in lava may simply leave a vertical shaft called a tree mold. Hundreds of lava trees and tree molds adorn the surface of many pāhoehoe lava flows.

Age Dating

The vast bulk of the volcanic geology in Hawai‘i began forming before people started recording history in the Islands. Geologists are like historians, but they usually cannot rely on eyewitness accounts to tell them when events happened. Instead, they depend on techniques that measure the natural decay of ancient radioactive materials. Perhaps the best-known technique involves carbon-14.

The chain of reasoning that leads to radiocarbon dates begins with the cosmic rays that constantly bombard the earth’s atmosphere. They convert
A lava tree or a tree mold will form after molten lava surrounds a tree.

Some of the nitrogen in the upper atmosphere is carbon-14, which promptly reacts with oxygen to make carbon-14 dioxide. The cosmic bombardment maintains a constant level of carbon-14 dioxide in the atmosphere. Plants use it to build tissues, and animals eat plants, so every living thing contains carbon-14 dioxide at the same concentration as the atmosphere.

After living things die, they no longer absorb carbon-14 dioxide, and the amount in their tissues decays radioactively, turning back into nitrogen. The radioactive decay continues at a constant rate, so it is possible to determine how long ago an organism died by measuring how much carbon-14 is in the tissues.

Geologists studying volcanic rocks look for charcoal in volcanic ash or beneath a lava flow. If it appears that it was charred in the eruption, they can measure the carbon to obtain a radiocarbon date. This method works to an age of about 40,000 years. Several other more complex dating techniques work on older rocks, but not particularly well in the range between 40,000 and approximately 500,000 years. Older rocks are less trouble. The materials responding best to those methods are basalt or volcanic ash that is absolutely fresh, neither altered nor weathered.

**Sinking Islands**

As soon as they begin to grow, Hawaiian volcanoes begin to sink. The Pacific plate floats on the asthenosphere like ice on a lake. If you put a weight on ice, it depresses it into the water. Likewise, as a big volcano grows above the Hawaiian hot spot, it depresses the plate into the mantle. The volcano sinks until it is in floating equilibrium on the mantle, the same way a chunk
of wood sinks until the water can support its weight. Geologists call the flotation of the earth’s lithosphere isostasy and refer to the slow subsidence of the Hawaiian volcanoes as isostatic sinking.

The Hawaiian Deep is a moat around the youngest Hawaiian islands, about 1,500 feet deeper than the surrounding ocean floor. It sank as the weight of the islands depressed the lithosphere. Both the ice and the lithosphere adjust to the added weight by flexing upward around the depression. The rise around the Hawaiian Deep is called the Hawaiian Arch.

After big volcanoes pass beyond the shield-building stage, they may lose as much as two-thirds of their elevation to isostatic sinking. The Big Island

Giant cliffs, or pali, mark the headwalls of slumps on the southern flank of Kilauea. The weak southern flank of the volcano is sliding into the ocean.
is the youngest of the Hawaiian Islands, still growing and sinking faster than any of the others; the tide gauge at Hilo shows that the coast there is sinking about 1 to 2 inches every ten years. O‘ahu, an old island, long ago reached floating equilibrium with the mantle; tide gauges there show little sign of subsidence.

Even the islands that are in floating equilibrium are still sinking, although extremely slowly. They sink because the Pacific plate loses heat as it moves away from the east Pacific oceanic ridge. The ocean floor where they stand becomes denser as it cools, so it and the islands that stand on it float lower on the mantle.

**Island Collapse**

As Hawaiian volcanoes spread out and sink in response to the pull of gravity, huge land masses detach along rift zones and slide into the ocean. Some of them move slowly and enter the ocean in a thoroughly dignified, if ponderous, manner. Others plunge suddenly into the depths, with enough momentum to spread the slide dump more than 100 miles across the ocean floor. The largest of these landslides take place when a volcano grows to maximum size. They come around, on average, only once every 300,000 or 400,000 years.

Giant Hawaiian slides form because of the weak debris, thousands of feet thick, that makes up the submarine portions of all the islands. This is the

![Image: The northwestern flank of Kaua'i, a shield volcano, collapsed into the ocean and created an enormous sea cliff that has eroded into the spectacular Na Pali Coast. This view is from the Kalalau Trail, which precipitously hugs the coast for 10 miles.](image)
The dark areas are huge underwater landslides in the Hawaiian chain. Some of them have carried away a third of an island’s landmass.

Steam-shattered product of countless lava flows that have poured into the ocean. As an island grows, fresh solid lava covers up this sediment pile, weighing it down. Ultimately, the landmass grows so large that the weak material underneath gives way. A volcano swelling with magma may trigger landsliding by making the slopes of the island too steep.

Some landslides extend all the way to the ridge-crest rift zones and summits of volcanoes. Molten rock and fractures make these areas weak, creating natural break points for land separation. A third or more of an island can sink beneath the waves in a single slide.

Low sea cliff along the coast of Hawaii Volcanoes National Park. Nā`ūlu sea arch is the result of wave erosion along fractures in the lava.
Giant landslides leave long cliffs where their headwalls cut the flanks of the volcanoes. Some of those cliffs are high on the slopes of the islands. Others rise thousands of feet out of the surf. All erode into spectacularly rugged terrain. Every main Hawaiian island has at least one coast where a towering cliff faces the ocean. Rocks exposed in many of those cliffs are full of vertical dikes, the filled fissures of defunct rift zones.

Small shoreline cliffs rising 10 to 50 feet above sea level are more common than the giant slide scarps. They are ordinary sea cliffs that develop as waves pull blocks of rock away from their bases. Then the undermined cliff collapses, dumping debris into the surf. Heavy seas sweep the rubble away, clearing the base of the sea cliff for more wave attack. As successive collapses drive the cliff landward, it leaves in its wake a gently sloping bedrock surface, the wave-cut bench.

Dramatic sea cliffs can form along volcanically active shorelines in a manner akin to the giant landslides mentioned earlier. As lava pours into the ocean, steam explosions and crashing waves pulverize the advancing flow, shedding vast amounts of black sand, spatter, and other fragments, which tumbles into the water. Eventually, the advancing lava overrides this debris, adding new land to the island. Periodic surges of lava cause the debris underneath to slide, collapsing the front of the flow. Geologists call this process bench collapse, and it is responsible for developing much of the low cliff on the southern coast of Kilauea.

*Development of a sea cliff from bench collapse as a lava flow adds new land to an island. The stippled area shows sediment shed from the front of the flow as it builds out to sea.*
Soils

In addition to isostasy and landsliding, ordinary weathering and erosion by flowing water help bring the islands back to the sea.

All rocks are fractured, most of them in regular patterns. Water seeps into the fractures and reacts with the rock, converting it into soil. Water attacks angular chunks of rock from two directions at edges, three directions at corners. So, an angular chunk of rock becomes rounded as the edges and corners weather more rapidly than the flat faces.

A good many Hawaiian soils enclose rounded residuals of the original rock; we call these residual stones. If the soil erodes, the residual stones lag behind to litter the surface. Many large rocks in Hawaiian streambeds became rounded not through stream transport but as residual stones.

Rocks weather into soil through a variety of physical and chemical processes that depend on climate. In Hawai‘i, most of those processes work faster on the wet windward sides of the islands than on their dry leeward sides. Flows that erupted 200 years ago on the dry, leeward side of the Big Island still look almost perfectly fresh and support few plants. Flows that erupted only a few decades ago on the wet, windward side of the Big Island wear a coat of gray lichens and support a scattered growth of small shrubs and trees.

The chemical reactions between water and the silicate minerals in basalt contribute most to converting rock into soil. Basically, the silicate minerals turn into various types of clay, while most of their calcium, magnesium,
sodium, potassium, phosphate, and much of their silica go into solution. The silicate minerals swell as they turn into clay and no longer fit tightly together. The rock breaks apart the same way a wall would break down if the bricks in it were to swell, some more than others.

In wet regions, the rain washes the constituents out of the soil, leaving behind a residue consisting mainly of a clay called kaolinite, mixed in varying proportions with aluminum oxide and iron oxide, which stains it all red or yellow. The final result is a soil called laterite, the typical soil of the wet tropics. Because laterite does not contain the soluble fertilizer nutrients calcium, magnesium, potassium, and phosphate, it is extremely infertile. It is difficult to fertilize laterite because the kaolinite clay does not retain fertilizer nutrients; they wash out readily, as the original nutrients did. Native jungle vegetation thrives on laterite because those plants are adapted to the infertility. They gain most of their nutrients from decaying litter on the forest floor.

The proportion of iron oxide, aluminum oxide, and kaolinite clay in laterite soil largely depends on the composition of the original bedrock. If the bedrock is rich in iron and poor in aluminum, the soil will consist mainly of iron oxide. If the bedrock is rich in aluminum and poor in iron, the laterite will consist mainly of aluminum oxide. Laterite that is extremely rich in aluminum and nearly without iron is bauxite, the only ore of aluminum. The Hawaiian trachytes consist mainly of feldspar minerals, which contain a lot
of aluminum and no iron. Where trachytes are exposed on the wet sides of the islands, they weather into bauxite.

Some experts argue that mining Hawaiian bauxite could actually improve agricultural productivity by stripping off the most infertile top layers of the soil. They contend that the more fertile subsoil would support better crops. Many laterite soils are ten feet deep and more, so it is reasonable to argue that plenty would remain after the top is stripped off. But few people are ready to accept the idea that such mining would improve the appearance of the Hawaiian landscape or would qualify as the best use of its precious land.

**Fluted Cliffs and Amphitheater Valleys**

Besides the beautiful beaches and active volcanoes, one of the most striking aspects of the Hawaiian landscape is towering, fluted cliffs, including the famous Pali on O‘ahu. The wet northeastern sides of the Hawaiian islands all feature cliffs or pali, most of which originated as giant landslide scars. They are awesomely high and steep, their surfaces fluted with immense vertical grooves that look as if a monster had raked them with a set of giant claws. In fact, fluted cliffs covered with vegetation exist on most rugged tropical islands.

The fluted pattern reflects a unique aspect of tropical weathering and erosion. The warm water of the tropics dissolves rock more effectively than does rain in temperate climates. A comparison of soil and rock compositions shows that less than half the atoms in a typical sample of basalt remain after it is weathered into laterite soil. Many of the dissolved atoms enter the groundwater; some enter streams; all end up in the sea.

On a steep cliff face, naturally acidic rainwater clings to shady surfaces longer than it does to sunny, windy ones, where it readily evaporates. In time, the shady areas dissolve, leaving wide, deep pockets and gullies, while the sunny areas form ridges. The pattern smooths out into regular fluting, since the smaller ridges and gullies hidden in the shadow of the larger ridges remain moist and dissolve completely, leaving only the larger ridges and gullies behind.

In addition to fluting in cliffsides, spectacularly broad amphitheaters have formed at the heads of some large valleys, with long, thin waterfalls cascading down steep slopes. Other tropical settings have similar amphitheater-headed valleys, but not in more temperate climates. The Hawaiian valley walls are so steep that they can barely hold soil. The ridges between valleys are narrow, with knife-edge crests. Deep sediment deposits fill the valley floors.

The streams draining the Hawaiian islands are generally clear. They carry so little sediment that they seem unlikely to be entirely responsible for forming those huge valleys. They must have had some help. As with the fluted cliffs, rock dissolution must play an important role in forming the amphitheaters.
The unique amphitheater shape of most valleys in Hawai‘i may be because most of the rainfall and moisture helping to dissolve them accumulates high on mountain slopes. When the upper end of a valley grows more rapidly than the lower part, it eventually will develop into an amphitheater.

Ancient volcanic calderas also play a role in the formation of some of Hawai‘i’s most spectacular amphitheater valleys. Lavas altered and softened by hot gases while eruptions were still active make up the old calderas. Streams erode such soft rock easily, hollowing out the calderas into wide erosional bowls sometimes several thousand feet deep.

Frequent minor landsliding is another major erosional process on the wet sides of the Hawaiian islands. Deep soils developed on steep slopes of weak volcanic rocks are likely to slide, filling a valley floor. The extremely sharp ridge crests characteristic of the windward slopes are typical of tropical landscapes, where nearly continuous landsliding is an important process.

With all this steep topography, waterfalls abound. Even small streams are interrupted by delightful little falls and cascades. This is mainly because some rocks erode more easily than others. Volcanic ash erodes quickly, as do buried soils and the rubble zones above and below ‘a‘ā flows. Dikes and the massive cores of ‘a‘ā flows resist erosion and become the lips of waterfalls.

Running water uses abrasive particles of sediment to carve bedrock in the same way a sandblaster uses sand. Neither water nor wind alone can carve rock. The clear streams draining the wet sides of the islands are poorly equipped to carve solid masses of rock. When did you last see a postcard with a picture of a muddy waterfall?

Drowned Valleys and Tsunami

Streams carve valleys into the island as it sinks. Seawater floods the lower valley floor, and streams, landslides, and lava flows fill it, making a broad flatland framed between high canyon walls. You can mentally reconstruct the valleys’ original depth by projecting the slopes of the valley walls downward to where they meet below the surface. In most cases, the sediment fill turns out to be hundreds of feet deep.

In due time, the sinking of the island carries so much of the valley below sea level that its upper reaches can no longer supply enough sediment to fill the floor. Maps of the underwater topography of the Hawaiian islands show many canyons that have completely drowned.

The sinking stream valleys of Hawai‘i are potentially treacherous places to live because of the funnelling effect they have on giant sea waves called tsunami. Most tsunami start when sudden movement on a fault shifts a large area of the ocean floor vertically, to the accompaniment of an earthquake. The movement of the seabed displaces a large volume of water and forms a wave that races across the ocean at speeds of several hundred miles per hour,
As a volcanic island sinks, the valleys fill with stream sediment. The result is a broad valley with a flat floor.

depending on the depth of the water. Such waves pose no problem to ships at sea, where crews do not notice their passing. But they slow down and build to monstrous heights when they approach land and enter shallow water, especially in bays and inlets.

Earthquake waves travel much faster than waves at sea, and seismograph stations monitor them constantly. Scientists can provide information on tsunami location and size hours before the water waves arrive. Earthquake waves travel about as far in a minute as a tsunami does in an hour. So a seismograph record of a distant earthquake on the ocean bottom can provide ample warning of a possible tsunami.

When seismograph stations issue a tsunami watch, Civil Defense personnel in Hawai‘i prepare for action. In many cases, no tsunami develops, possibly because the fault movement shifted an area of the ocean floor horizontally. Only vertical displacements cause tsunamis. If a wave actually forms near the quake epicenter, the watch is upgraded to a warning, and sirens along the coasts in Hawai‘i will sound, alerting people to evacuate. You can see these sirens, bright yellow horns or groups of dark green “doughnuts” on telephone poles, near many beaches.

A tsunami may arrive like a rapidly rising tide or like a rapidly falling tide. They have been compared to the sea flowing onshore like a broad river. In either case, very high and very low water levels occur at intervals of about 10 to 15 minutes. People have made the costly mistake of rushing out to catch the fish that lie exposed when a tsunami suddenly uncovers large expanses of the sea floor; the water level soon rises much higher than it was before it dropped. It is equally costly to stop running for high ground after surviving
the first crest; the next several waves will probably rise even higher. After an hour or two, the tsunami ends with a series of progressively smaller waves.

Although earthquakes account for most tsunami that strike Hawai‘i, the biggest waves arise from giant landslides suddenly dumping large chunks of a volcano into the ocean. Although none have been in historic time, geologic evidence gives some idea of their size: Geologists have discovered loose blocks of reef limestone 1,070 feet up the slopes of Lāna‘i. These blocks were torn loose by a tsunami coming from the south about 100,000 to 105,000 years ago. Lāna‘i stood higher then than it does today, so the wave may have risen even higher. The same tsunami probably stripped all the soil off the island of Kaho‘olawe below a present elevation of 800 feet.

The effects of another monster tsunami in Hawaiian waters would be catastrophic beyond imagining, considering that the tsunami that wiped out downtown Hilo in 1946 was only about 20 feet high. It seems likely that most of the people who live in the coastal lowlands would drown—more than 95 percent of the population of the state. Such a wave would come with little or no warning because it would originate in local waters. Fortunately, monster tsunamis are so infrequent that there is no practical reason to worry about them.

Wind, Waves, and Beaches

Ordinary waves take their energy from the wind, then expend it in doing the work of shaping the coast. The prevailing northeasterly trade winds consistently drive the heaviest waves against the northeast coasts of the Hawaiian Islands, though storms far out at sea raise heavy swells that may come in from any direction.

Most people expect to see waves come straight in from the ocean, regardless of which way the wind may be blowing, or how the coast twists and turns. How do the approaching waves conform themselves to the outline of the shore?

Basically, they feel the bottom before they reach the land. When a wave enters shallow water, it slows down as it begins to drag on the bottom. Meanwhile, any part of the wave that may still be in deep water races ahead until it gets into shallow water, where it too begins to slow down. Imagine a wave approaching a coast obliquely: It will pivot like a line of marchers as one end slows in shallow water while the end still in deep water lunges forward.

Occasionally, waves approach the beach exactly head on, at a right angle. They then arrange the beach sand into a row of scallops with sharp points projecting into the surf, called beach cusps. The waves sort coarser sand into the cusps and leave finer sand in the low areas between them. Beach cusps last only as long as the wind is constant; when the wind shifts, the waves quickly erase them as they again wash onto the beach at a slight angle.

Anyone who has tried to snatch a choice seashell out of the waves quickly finds out what happens when the waves approach at a slight angle, as they
The beach at Wainiha, on the north shore of Kaua’i, continues across the mouth of the bay as a bar.

normally do. You try to grab the shell out of the incoming swash, only to miss it and see the backwash carry it out into the foaming water. When the next wave brings it back almost in reach, you have to walk a few feet down the beach to make the next grab. If you miss several times, you find you have moved a considerable distance down the beach. The wash of every incoming wave sweeps the shell obliquely onto the beach, and then the momentum of the moving water carries it farther down the beach in the backwash.

Every particle of sand on the beach is also moving down the coast. You can think of the beach as a river of sand flowing along the shore. On some days, the waves move the sand one way, on other days, the other way. Most beaches have a prevailing wave direction.

People commonly build walls, called groins, across the beach to trap the moving sand. Groins generally work very well. A row of groins converts a smooth, narrow beach into a much larger beach with a map outline something like the teeth on a ripsaw. However, the sand trapped on the growing beach never reaches its natural destination. If you look downshore from a set of groins, you will almost certainly find the beach there eroding, because the groins are starving it of the normal supply of sand.

Although breakwaters and piers do not look like formidable barriers, they trap sand as efficiently as groins, and also cause beach erosion farther downshore. Sand grains do not move under their own power—waves move them. Anything that interferes with the waves will affect sand movement.
Anything that traps sand in one place will starve the beach somewhere farther down the line, causing beach erosion. Communities on some Hawaiian coasts import sand to maintain their beaches.

Whether a beach consists of sand, pebbles, or cobbles depends partly on the size of particles available and partly on the size of the waves moving them. In big storms, and on the windward sides of the islands, waves winnow out the small particles, leaving only cobbles and boulders on the beach. Sandy beaches are more abundant on the leeward sides, where waves are smaller. On all Hawaiian beaches, the smaller waves of calmer seasons carry sand onto the beach, burying the big rocks until large waves in the next heavy storm uncover them again. It is a long-standing pattern: Waves store the sand offshore during heavy weather, then spread it across the beach when the weather improves.
In 1991, lava from Kilauea buried this famous black sand beach at Kaimū.

On the youngest Hawaiian shores the beaches are made of black sand. When molten lava enters the ocean, steam explosions blast the liquid rock into fine sand particles. Each grain is a jagged piece of volcanic glass. Waves and currents sweep the sand along the shore, where it collects in sheltered coves to make black sand beaches. The sand supply is not constant, so black sand beaches tend to wash away after a few centuries. Lava flows recently buried the most famous Hawaiian black sand beach, along the south shore of Kilauea Volcano on the Big Island, while creating new ones nearby.

Where surf and currents erode fresh beds of volcanic ash, they separate grains of olivine from the lighter grains of other minerals. The olivine grains concentrate into green sand beaches that also contain black pyroxene.

On somewhat older Hawaiian shores, streams wash black basalt and red oxidized cinder to the coast. The basalt sand grains make beaches ranging from black to pale gray. The cinder may collect to form red sand beaches.

Coral reefs flourish along the oldest coasts, on islands that are no longer sinking very fast. Waves pound the reefs and break them into fine grains of beige to yellow calcareous reef sand, which collects on the shore to make the most stable, and most famous, beaches in Hawai‘i.

Layers of cemented sand sloping up onto a beach from the waterline are beach rock. It differs from reef rock, which doesn’t have such layers.

Seawater is slightly alkaline and does not dissolve calcite, the major mineral in reef sand. But beach sand above sea level is exposed to the rain, which is slightly acidic. Rainwater dissolves calcite from each grain of sand it wets. As
the solution of calcite and rainwater soaks deep into the sand, it precipitates calcite in the spaces between grains, cementing them together. The high beach becomes solid beach rock.

When sea level drops, wind and rain quickly erode exposed beaches. Beach rock is much more resistant than loose sand and may remain intact long after the surrounding sand has disappeared. Stony remnants of ancient beaches are common on all the older Hawaiian islands. Eroded beach rock shows many sloping layers. Each is a past beach face buried as the beach acquired more sand. The layers slope toward the ancient shore.

**Coral Reefs and Sand Dunes**

Beach rock typically overlies wave-cut benches in basalt, and in some places it overlies reef rock. The kinds of coral that build reefs live only in water consistently above 65 degrees. Many corals live in association with algae that require sunlight, so the water must also be clear and shallow. Other kinds of algae and many kinds of animals living on the reefs contribute to their development.

Corals are animals related to anemones and jellyfish. They live partly by snatching microscopic animals from the passing water and partly on the largesse of the algae that live in their tissues. The algae are photosynthetic plants that take in carbon dioxide, use the carbon in building their tissues, and release free oxygen. The coral use the oxygen for their own metabolism,
and consume some of the algae. The algae, in turn, use the carbon dioxide the coral produces, and benefit from the shelter it provides.

Individual coral animals, or polyps, look like minute anemones, with tiny tentacles that wave in the water. Some of the tentacles are stingers. The polyps live in colonies where each little tentacled organism sprouts from a continuous membrane of coral flesh. They take dissolved calcium from seawater, combine it with some of the carbon dioxide they produce in their metabolism, and deposit it as calcite, the basic mineral matter of the reef. If you look closely at a piece of reef coral, you can see the little dimples in which the individual polyps nestled.

Corals spread locally by budding new polyps from the continuous membrane of tissue; they spread more widely by shedding enormous numbers of eggs into the passing seawater. The eggs develop into larvae, which drift in the water until the time comes for them to develop into polyps. Then they settle on whatever hard base they may encounter, where they attempt to start a new colony. The chances that any individual larva will survive all the hazards of the ocean are almost vanishingly small. This means that it takes a long time for reef corals to start on new volcanic islands. Even after 5 million years, Kaua‘i has few very large reefs.

Established reefs face many hazards. Storm waves and tsunami may break them up or spread sand or mud across the coral, suffocating it. Agricultural chemicals washing into the ocean can kill coral, and so can sewage, which nourishes a smothering bloom of algae. Parrot fish use their heavy beaks to scrape calcareous algae from corals. Their incessant rasping produces large amounts of fine sand. Worms, sponges, starfish, sea urchins, and boring clams all bore holes in coral reefs.

The most devastating of the many hazards threatening coral reefs may be the changes in sea level that accompany the coming and going of ice ages. Sea level slowly drops as glaciers grow during an ice age, leaving the old reefs high and forcing the reef zone offshore to the new coast. Ice ages end suddenly, and sea level rises rapidly as the glaciers melt. The meltwater quickly submerges reefs beyond the depths at which corals and their associated algae can live. These fossil reefs, including some that grew during previous ice ages, girdle the submerged slopes of most Hawaiian islands.

Corals are highly competitive animals, so different species dominate in different localities in a reef. They come in shades of white, pink, yellow, brown, blue, purple, or black, but all fade to the white of bare calcite after the polyps die. Corals also come in many shapes, some massive, others rounded or branched like antlers. Sea fans look like flattened trees and grow in a rainbow of colors, and lettuce corals look like crinkled leaves. Mushroom corals are shaped like the cap of a broad mushroom several inches across, with many thin ridges radiating spokelike from a central stem. Corals growing in shallow
Hawaiian coral reefs support abundant sea life.

Water tend to be massive and rounded; those growing in deeper water, below the reach of waves, are more delicate and branching.

To the extent that the waves beat on coral reefs, they spare the main shorelines sheltered behind the reef. Without the barrier of the offshore reefs, waves would wash much of the beautiful sand in Hawai‘i off the beaches.

Visitors to Hawai‘i comment on the beautiful turquoise water. You see this color only in the shallow water beyond the coral reefs, and only when the sun shines. Two or three factors seem to have the most important effect in creating turquoise water: In the shallow water behind a coral reef, bright sunlight easily illuminates the white sand eroded from the reef. It reflects from billions of tiny particles of sediment and organisms suspended in the water,
creating shades of turquoise. In deeper water, less light reflects off the bottom and the waves do not stir up sediment, so the water appears darker. Thus the different shades of color depend on the light, the depth of the water, and the amount of suspended sediment.

The sediment supply present in beaches and reef lagoons is truly enormous. It contributes to the formation of sand dunes as well. Some people associate sand dunes with deserts. In fact, sand dunes are just as closely associated with beaches in all climates, whether wet or dry.

Waves wash sand onto the upper beach at high tide or during heavy storms. When the upper beach dries in the sun, the sea breeze blows sand off it and into coastal dunes behind the beach. The dunes blow inland until they are beyond the reach of the ocean’s strong salt spray, when plants can grow and stabilize them.

It is a marvel that sand dunes exist at all. Why does the wind sweep the sand into neat piles, instead of scattering it across the countryside? Imagine what would happen if the wind were blowing sand across an asphalt parking lot where you had laid a small blanket. The sand would catch on the blanket because it is soft; the grains bounce onto it, but not off. As a pile of sand accumulated on the blanket, it would catch more sand for the same reason that the blanket did, because it is soft. For a sand dune, softness is the essence of existence.
Changing sea levels complicate the life of sand dunes. When sea level drops, as in an ice age, coral reefs are exposed to the air and die. Wind sweeps across them, blowing large volumes of sand inland to build big dune fields. Then, when sea level rises again, the ocean floods the old reefs, greatly reducing the supply of sand. Plants then cover and stabilize the dunes.

Just as beach rock forms when infiltrating rainwater cements sand grains with calcite, calcareous sand dunes also turn into rock. Sand dunes typically are much thicker than beach deposits, so calcite cement generally penetrates only a little way into a dune, leaving the center soft. The outer rind of cemented sand blocks further penetration of rainwater.

Where erosion opens the interiors of old dunes, you may see many thin layers of hardened sand intersecting one another in an intricate pattern. Each layer is a former surface of a dune. Shifting wind causes dunes to slope one way, then another, accounting for the differently angled layering. Geologists call the overall pattern crossbedding.

As isostasy and plate drift continue, the volcanic bedrock of each aging Hawaiian island sinks into the sands of its own surrounding reefs and beaches, leaving behind a coral atoll—an echo of a vanished island. Ultimately the shifting sea floor carries the reef into such cool northern water that it dies and sinks. Each work of the hot spot, tens of millions of years old, disappears into the Pacific.
cern about a potential global greenhouse effect. They have recently begun monitoring ozone loss.

The trail to Mauna Loa's summit begins at the parking lot where the public road ends. It leads 3 miles past the Observatory, straight uphill to the stark rim of Mokuʻaaweoweo caldera, one of the most desolate landscapes you will ever see. It is worth walking a few hundred yards up the slope to see the diversion barriers that protect the observatory from lava flows. These are the first such structures in the United States.

Mauna Kea Summit Road

Saddle Road–Summit of Mauna Kea

15 miles

The Mauna Kea Summit Road winds very steeply past cinder cones and across late-stage flows of the south rift zone to 9,200 feet, where it levels off at Halepōhaku and the Ellison B. Onizuka Astronomical Complex. The drive is too much for some cars, and for some drivers. Zero your odometer at the intersection with the Saddle Road.

Two prominent cinder cones appear on the eastern skyline about 5.5 miles from the Saddle Road. Puʻu Kole, which erupted 4,500 years ago, appears to be the younger. In the foreground is an alkalic basalt flow that erupted about 5,300 years ago from the low mound about half a mile up the slope.

The road passes through the breached, horseshoe-shaped crater of Puʻu Kalepeamoa. The ridge west of the road is the eastern rim of the crater, where the trade winds piled cinder high to one side. The cinder contains many fragments of older rock, including black gabbro and green dunite.

The visitor center at Halepōhaku is on a smooth blanket of ash and cinder that looks perfectly fresh. Beyond Halepōhaku, the road climbs nearly 2,000 feet up a steep and cindery slope in a series of five switchbacks. At the top it skirts the eastern base of a prominent cinder cone, Puʻu Keoneheheʻe. Look southeast for a deep pit crater, one of the few that still exist on Mauna Kea. The road then enters glaciated terrain.

The Glaciers of Mauna Kea

The glacial deposits on top of Mauna Kea consist of till, deposited directly from glacial ice, and outwash, deposited from glacial meltwater. "Drift" refers to till and outwash together.

Glacial outwash on Mauna Kea typically consists of light-gray silt, sand, and gravel in neat layers. Outwash deposits in deeper canyons high on the mountainside also contain thick beds of chaotically mixed conglomerate.
Geologists interpret these deposits as flood dumps, perhaps the result of eruptions beneath Mauna Kea's former ice cap. If so, then at least six such subglacial eruptions took place. You can see an example of the more ordinary kind of outwash on the floor of the small valley near Pu‘u Keonehehe‘e, at mile 10.5.

Mauna Kea till is pale gray. It contains angular fragments of all sizes, randomly mixed. The glacial till and outwash deposits on Mauna Kea record four episodes of glaciation. The deposits include the Pōhakuloa drift laid down 150,000 to 100,000 years ago, the Waihou drift accumulated between 100,000 and 55,000 years ago, and the Makanaka drift deposited from 55,000 to 20,000 years ago. Except perhaps for the Pōhakuloa drift, each of these episodes corresponds to the Wisconsinan ice age of North America, which lasted from about 125,000 until about 11,000 years ago.

Most of the till along the road is the Makanaka drift. Scattered pale gray till drapes the dark gray or brown slopes of cinder cones farther up the slope. Glaciers eroded some of these cones almost beyond recognition.

Watch at mile 11.6 for scattered piles of basalt rubble. Ancient Hawaiians left them as they quarried the glassy lava to secure raw material making adzes. Federal and state laws strictly protect such sites.

Pu‘u Wai‘au is about a mile farther northwest. Steam and hot water percolating through the cone near the end of its eruption altered the cinder, creating the light-colored patches. The alteration products include clay, which makes the rock impermeable, thus increasing runoff from rain and melting snow. So the flanks of Pu‘u Wai‘au have more gullies than the more permeable flanks of neighboring, unaltered cones. Northwest of Pu‘u Wai‘au is Pu‘u Poli‘ahu, another noticeably altered cinder cone.
The Flow That Erupted under a Glacier

At mile 12.1, the summit cone of Mauna Kea, Pu‘u Wēkiu, comes into view, with observatory domes perched near the top. For the next mile or so, the road follows a basalt flow that erupted from Pu‘u Wēkiu. In many places, long tracks of parallel lines and mosaic zones of fracturing mark its surface. These suggest that the lava flowed beneath the ice, melting it and wedging its way along. The overlying ice created the peculiar fractures as it quenched the flow. Then it dragged the particles of grit across the lava, polishing its surface and etching long grooves and scratches.

Lake Wai‘au

A small parking area at mile 12.5 marks the beginning of a dirt path that leads half a mile west into the pass between two cinder cones, Pu‘u Wai‘au to the south and Pu‘u Hau Kea to the north. The path leads up the slope from the steep, lobate edge of a lava flow that erupted from Pu‘u Hau Kea 40,000 years ago. The peculiar fracture patterns along the edge of the flow suggest that the cooling lava banked up against ice.

A few hundred yards beyond the pass lies Lake Wai‘au, at the bottom of Pu‘u Wai‘au crater. It is one of the few natural bodies of fresh water in the Islands and, at 13,160 feet, is the highest lake in Hawai‘i. The cinder piled high along the southern rim of the crater tells of strong winds from the north as the cinder cone grew. An extinct rock glacier occupies the crater just south of the lake. You can recognize this mixture of rock, once imbedded in ice and flowing toward the lake, as a pad of hummocky, light gray debris.

If the bottom of Lake Wai‘au were unaltered cinder, it would not hold water. But the floor of the crater contains beds of impermeable clay weathered from ash that erupted from Mauna Kea 3,300 years ago. Circulating hot water and steam may have helped by altering the cinder beneath the ash. Lake Wai‘au occasionally overflows through the notch in the western rim of the crater.

The embankment of rough lava along the north side of Lake Wai‘au is part of the flow that erupted from Pu‘u Hau Kea. It poured across the low northern rim of the crater, then stopped. The cavernous voids, mosaic fractures, and lava pillows suggest that it stopped against ice. Look for many inclusions of dark and coarsely granular gabbro and green dunite, which consists mainly of olivine.

When light is low on the cindery slopes, you can also look for coarse fragments of cinder aligned in neat, evenly spaced rows a few inches apart, all stretching downslope. These cover many acres of the subarctic summit region of Mauna Kea. Just how they form is a mystery. Some geologists suggest that seasonal freezing and thawing of water in the shallow ground somehow sorts the cinder into neat rows.
Mauna Kea Summit

The road ends at the rim of Pu‘u Wēkiu. Spindly bombs and blocks embedded in cinder beds are exposed in roadcuts along the way. The summit is on the high eastern rim of Pu‘u Wēkiu crater, about 600 feet southeast of the parking area. A dozen astronomical observatories are a striking addition to summit scenery. Public tours of the observatories are offered occasionally. The night sky viewed from the summit of Mauna Kea is magnificent.

The view south from the parking area reveals the beveled summit of Mauna Loa, Moku‘aweoweo caldera. To the southwest, you can see Hualālai, and to the north, Kohala. The misty blue profile of Haleakalā, on Maui, rises out of the ocean beyond. At sunset, the afternoon clouds that generally hide the Hāmākua and Hilo sides of Mauna Kea provide a striking base for an optical effect that looks like a huge, pyramidal shadow cast by Mauna Kea.

A volcanic bomb embedded in cinder near the summit of Mauna Kea.