Oceanic Islands of the World

The locations of islands and groups mentioned in this book are shown on the maps on the next three pages. In the past two decades, many of these names have changed, reflecting the shift of autonomy from distant continental powers to the islands themselves. Many atlases now in print still use the older names; newer reference works include both. On the following pages, most of the names are the familiar older ones, all of them are the names used in the book itself.
Finding Islands

Charles Darwin was one of the first scientists to learn the advantages of investigating oceanic islands. The scientific method in the laboratory is to isolate a sample of known properties and then observe the effects of systematic changes in pressure, temperature, or some other variable. Nature rarely conducts her experiments under such controlled conditions, but for some studies islands provide her closest approximation to a laboratory. Oceanic islands are small, young, isolated, simple, and subjected to a limited range of environmental factors. Thus, in nature's young, isolated laboratory of the Galapagos Islands, Darwin found the glimmerings of biological evolution. Likewise, the simplicity of several widely separated islands helped him to realize that their differences were largely a consequence of a single geological factor—subsidence.

Consider the continents. They are aggregates of every type of rock produced for billions of years, and most of their history is obscure. Their rocks have been deformed repeatedly, fractured, and warped up and down. They have been eroded and weathered by every type of changing climate, and older rocks are partially buried by thick sedimentary rock derived from them. The whole is obscured by every type of soil and by plants. Across the continents migrate animals and plants in constant flux. One can have little reason to hope that nature has conducted many controlled experiments on the continents. Consider the arsenic that modern chemistry has identified in Napoleon's hair. If he had died in Paris, his poisoners might have been anyone and their motives unknown. However, he died on St. Helena, a small, isolated, volcanic island in the South Atlantic, and all his food came from his British gaolers or his few friends.
Matao Island in the Society Island group—an isolated peak in a vast sea.

Some islands are merely continents in miniature, and they are difficult to understand for the same reasons. Among these are all the islands rising from the shallow waters of the continental shelf, islands such as Ireland and Newfoundland. Likewise, more isolated Japan, New Zealand, and many other islands have all the geologic characteristics of continents except size. Even the tiny Seychelles Islands in the Indian Ocean must be excluded from our story despite their tropic beaches and coconut palms. They are composed of a granite 700 million years old—both the type and the age of the rocks show that the Seychelles are a tiny fragment of drifting continent.

The remaining oceanic islands and their submarine counterparts, seamounts, are remarkably similar. They arise in deep water on normal oceanic crust. All of the thousands of islands, about 20,000 larger seamounts, and countless smaller ones grew as volcanoes composed of rocks of very similar types—at least to the nonspecialist. All have come into existence during the last few percent of the history of the earth. The older ones that grew high enough to become islands have now sunk beneath the waves. The only major variable affecting the present appearance of such islands is that some of them have been in tropic waters and remained there, so they are now capped with coral reefs in the form of atolls. With such a large and uniform population of islands, it is relatively easy to isolate the effects of single variables in nature's experiments. One can compare erosion in the
belt of the trade winds with erosion by polar ice. Likewise, one can compare the number of species that can drift across an oceanic gap of 100 miles with the number that can cross 1000 miles.

THE PROBLEM OF DISCOVERY

The plant and animal life of small isolated islands, like their geology, has intrigued scientists since it was first discovered. How could insect species typical of North America and Asia have reached the Hawaiian Islands? How could an odd creature like the dodo come to be on only one island in the world? Darwin studied the different finches on individual islands in the Galapagos, and Alfred Wallace studied the life of islands in general; between them they produced the theory of biological evolution. No theory ever generated more controversy, but, in more modest ways, almost all ideas about island life have been controversial.

How did plants and animals find and populate oceanic islands? The range of ideas on the subject is remarkable. At one extreme is the idea that most of the biota of islands consists of waifs who drifted there on air or water. At the other extreme is the idea that the islands are peaks of former continents, on which animals walked dry-shod carrying seeds with them. Moreover, it is not just the nonhuman discovery of islands that is controversial. Anthropologists have waxed hot about the Polynesian discovery and occupation of the islands of the central Pacific. It is well to remember that almost every island was successively found and populated by plants, animals, non-Europeans, and Europeans. As in most matters, the less information available, and the narrower the focus, the greater the range of speculation about causes of phenomena. Consequently it seems reasonable to consider what we know least about—the migrations of plants and animals—only after an analysis of the migration of humans. Likewise, it seems only reasonable to consider how Europeans found islands before thinking about how Polynesians did it. It might seem that we need go no further than the history of European voyages to understand how islands are discovered, but, regretfully, even that history is flawed. Imaginative scholarship has worked out when each Pacific island was found by Europeans. (That is the sort of date that appears in history books, the recorded date of the last discovery by any species.) However, data are scant about the total number of voyages, the efficiency of the discovery effort, and much else that would be useful for generalizations about discovery by other cultures and species. Thus, to obtain an adequate data set, we must go farther afield.
**Exploration for Oil**

Oceanic islands are small objects that generally occur in clusters separated by vast empty spaces. So are oil fields, and the history of discovery of oil fields is known in great detail, especially in the United States, because of legal requirements for disclosure. The significance of that history was first understood by M. King Hubbert, who developed a measure of effort for oil exploration—the total length of holes drilled with the objective of seeking new oil fields. (Holes that merely expanded known oil fields did not count.) He could estimate the volume of oil discovered each year and compare it with the drilling data. All the oil ultimately found in a field he credited to the year that the field was discovered. Hubbert found that the discoveries per unit effort had declined exponentially with time for more than 80 years. Assuming that history would repeat itself, he could determine the volume of undiscovered oil by simple extrapolation, and in 1957 he predicted a calamitous drop in oil discoveries in the United States. That prediction, properly interpreted, was correct.

In 1975, George Shurman and I applied Hubbert’s basic idea to the same problem, namely, how much oil remains to be discovered in the forty-eight contiguous United States, but our analysis can be extended to discovery in general.

We assumed that the chance of discovering an oil field by purely random drilling was simply the area of the oil field divided by the area being explored. For example, the total area of all known giant fields was 23,455 km² and the area of sedimentary basins being explored was 4,700,000 km². Therefore the chance of hitting a giant field with one hole was about 1/200. If most of the oil were in the biggest fields, purely random drilling would discover those fields first. Moreover, the probability of discovering a given area of oil field per unit effort would decline exponentially with time. Considering that, in fact, practically all the oil discovered in the forty-eight states was in giant fields and that the discoveries per unit effort had declined exponentially with time, it was apparent that the history of oil exploration could be modeled by Monte Carlo simulation of random drilling.

We programmed a computer to sample randomly the whole area of the contiguous states including all known oil fields. At the end of each unit of "drilling," (10⁹ feet, or 20,000 holes about a mile deep) we determined which fields had been "discovered." In this simple way, we made ten Monte Carlo simulations of the discovery of oil as it would have occurred by random drilling at the historic rate. When the actual history of discovery was plotted in comparison, it lay within the envelope of simulated histories. In brief, the exploration for oil had been no more successful than random drilling.
The computer was searching for area of oil fields, which is not exactly related to the volume of oil in fields. In fact, the simulated search did much better than industry in finding some types of fields—those with large area. The largest field by area or volume in the contiguous states is the East Texas field, which was discovered by industry in 1930. In nine of ten simulations, the computer found the field before that time. (Moreover, that giant field was not actually found by the geologists of organized oil companies but by a small-time wildcatter who was drilling on a hunch.) This could have been predicted without Monte Carlo modeling. The area of the field (f) is 567 km²; the area to be explored (A) is 4,700,000 km²; if the number (n) of holes drilled is 20,000, the probability of finding the field is

$$1 - \left(1 - \frac{f}{A}\right)^n = 0.91$$

by drilling at random. In fact, industry had already drilled 300,000 exploratory holes when the East Texas field was found. The probability of not finding the field with that number of random tries is $2 \times 10^{-16}$. The cause for this bad luck is not wholly understood, but it seems clear that, in organized exploration by Western civilization, doing as well as pure chance may be something of an achievement.

Some leaders in the oil industry were hardly surprised, although they had not had a quantitative evaluation of efficiency before. They already knew from their own unpublished analyses that they would have done better by drilling on a grid or even at random in some unexplored provinces. It is evident that geologists and geophysicists can identify the kinds of rocks and structures in which oil may accumulate, and they are efficient at finding small oil fields in known oil provinces—which are equivalent to island clusters. Apparently, the lack of efficiency in finding giant fields derives from an institutional persistence in drilling for oil in one of the possible types of oil-bearing structures when in fact the oil in a province is in another type. Thus, having found oil in anticlines, industry might drill one anticline after another in a province where the oil is in ancient coral reefs. It is rather like generals refighting the last war. Meanwhile, the naive computer is just as apt to drill the first exploratory hole in a reef as in an anticline.

The correspondence between the model of random drilling and the actual history of oil exploration seems to justify some general conclusions regarding exploration for oil fields or islands:
1. The largest objects tend to be discovered first.
2. There is an exponential decline in the probability of finding an object of a given size with a unit effort of searching.
3. Once the first object in a cluster has been discovered, the remainder are easier to find.
4. The ideas of explorers can greatly affect their chances of success.

EUROPEAN DISCOVERIES

As far as explorers are concerned, islands differ in one fundamental way from oil fields—they are capable of killing the unwary. Thus, the attitudes of sailors regarding uncharted waters are always mixed. In the late nineteenth century, navigational charts were full of chimerical islands because every possible hazard to navigation, however questionable the information suggesting its existence, went on the charts. As late as the 1960s, charts of the South Pacific were full of the notations “P.D.” for “position doubtful” and “E.D.” for “existence doubtful,” regarding rocks and shoals. The only prudent course for a captain was to avoid the site of any possible hazard. So it has always been, except for those few surveying and oceanographic ships whose job it is to deliberately seek and survey such hazards or disprove their existence. It took Western civilization about 1500 years to discover all the oceanic islands, and it appears that Captain Cook and his lieutenants were almost the only people in all that time who took their surveying job very seriously.

The probability that an island will be found by sailors depends on its site, its distance from a home port, the number of voyages from the port, the freedom of action and spirit of adventure of captains, the likelihood of ships’ being driven long distances by storms, and so on. All in all, it is not surprising that the largest oceanic volcano, Iceland, was the first to be discovered, in the fourth century A.D., by the Norsemen, who lived not far to the east. They colonized the island by the ninth century and roamed the northern seas—which contain few oceanic islands.

The next phase of discovery was in the fourteenth and fifteenth centuries, when Portuguese, Spanish, and other European explorers began to seek a sea route to the spice and silk of the East. Just as Columbus accidentally found the vast area of the Americas, so others sighted tiny oceanic islands or ran aground on them. In 1420 the Portuguese Zarco discovered the Madeira islands, for the last time, when storms drove him west from his exploration of the coast of Africa. A Genoese map of 1351 shows that contact had been made before—the islands are only 670 km west of Africa.
Global wind patterns that determine sailing courses and migration paths.

and the Straits of Gibraltar. The Azores, even farther west, were already known to the Carthaginians, who left coins, and Arabian geographers. They were discovered for the last time in 1432, when Van der Berg was driven on the islands by a storm. Although the Azores are in three widely separated groups, all nine islands were found and some even colonized by the Portuguese within twenty-five years. We may generalize that, like oil fields, once one of a cluster of high islands is found, the rest will be discovered quickly if there is any desire to do so. Among other reasons, each high island is commonly visible from the peaks of another in the cluster.

As the Europeans sailed farther south, further discoveries were made apparently for the first as well as the last time by man. These included the cluster of the Cape Verdes in 1456; the tiny, isolated, midocean islands of Ascension, in 1501, and St. Helena, in 1502. Clearly, the explorers were tacking far into the Atlantic to follow the latitudinally zoned winds. The Portuguese reached oceanic islands in the Indian Ocean soon after Mauri-
The cliffs of ironbound St. Helena.

...ius in 1505, and Reunion in 1513. All of the islands discovered to this time had several features in common. They were high volcanoes, active or dead, uninhabited, and wholly lacking gold, diamonds, or anything else offering quick profit. Some were ironbound by great cliffs but even these had a few protected anchorages and fresh water, so the islands had some use. Moreover, being high, they were visible from great distances and thus hardly hazardous to navigation.

So when Magellan entered the Pacific, in 1520, he had some knowledge of oceanic islands. We may pause to consider what else he knew and his situation. He knew about the trade winds. After beating his way through the straits that bear his name it could hardly have escaped his attention that he was in the wrong latitude to sail west. Not to mention that the known riches of the East were in the Northern Hemisphere. His ship was marginal for the voyage and his supplies were already low. Considering all these factors, his only logical course was to sail northwestward until he reached the tropics and the gentle, persistent easterlies of the trade winds. This he did.

The state of the science of navigation in Magellan’s time enabled him to determine latitude at sea, but not longitude. Indeed, in those days before surveying by triangulation, no one knew longitude very well on land, either. The course being steered and speed made good through the water could be measured, but wind and sea drift were always uncertain, and often hopelessly so after a series of storms. As a consequence, the
longitudinal positions of ships not infrequently were in error by hundreds of kilometers and occasionally by more than two thousand kilometers. Not until Captain Cook's time, in the late eighteenth century, were nautical chronometers accurate enough to permit determinations of longitude. Even two centuries after Cook, positioning errors of 15 km to 30 km were common in celestial navigation. Not until the invention of electronic and artificial satellite navigation in the 1960s and 1970s did a ship at last know where it was most of the time. Then, naturally, almost everything that had been discovered had to be relocated.

Explorers of the Pacific

Magellan made the first European discovery of a Pacific island on 24 January, 1521, but we do not know which one, for lack of a longitude. From its latitude and its description as a low island fringed with trees, we know it was an atoll in the northern Tuamotus, but whether Fangahina, Angatau, or Pukapuka is uncertain. (This ingenious method of identifying island discoveries by combining latitude and island description was developed by Andrew Sharp, and his chronology is used here.) Magellan saw no sign of inhabitants and could not anchor on the steep coral bottom, so he sailed on. He had found a small, low, surf-bound, valueless hazard to navigation. The last oceanic island in the main Pacific basin, the 267th, was discovered in 1859 by Captain N. C. Brooks of the Hawaiian barque Gambia, and for some time the uninhabited island took the name of the ship. Then it was renamed and in due course gave its new name to the most famous naval engagement of World War II, the Battle of Midway.

The whole period of discovery lasted 338 years. If we divide it into 50-year intervals, it is evident that there were two major phases of discovery. The first began with 32 discoveries before 1550 and tapered off to the interval 1651–1700, when only three islands were discovered. The second and greater phase began with 12 discoveries in 1701–1750 and peaked at 113 in 1751–1800. Two-thirds of all the islands were discovered in the century beginning with 1751. The variations in discovery rate were due to improvements in ships and navigation, concern with hazards, variations in the frequency of voyages, and changes in the motivation for voyaging. Of these the last apparently was dominant.

It appears that voyagers from 1521 to 1700 viewed Pacific atolls and volcanoes with more fear than hope. The famous explorers Quiros, Mendana, Schouten, and Le Maire all followed routes of easy sailing, west on the southeast trades and home either around the world or east on the westerly winds in high northern latitudes. Sir Francis Drake sailed across the Pacific from California, presumably on the northeast trades, and reported no islands at all. Thus he confirmed the wisdom of the Spanish
The voyages of that uniquely determined explorer Captain James Cook. Most so-called explorers followed the safe and easy highway in the South Pacific. The prudent Spanish merchants followed the safe loop in the North Pacific.

conquerors who, beginning in the late sixteenth century, sent galleons from Acapulco to Manila along 13°N latitude and back at 40°–60°N latitude. For centuries they sailed the same route because exploration had shown it to be safe. It was all as routine as the P&O sailings from England to India in the days of empire, although the best accommodations were not POSH but SOPH. Naturally, the Spaniards discovered few islands as they sailed in a vast loop around the unknown Hawaiian Islands.

With the dawn of the eighteenth century came a thirst for geographic knowledge, science, and, perhaps more important, a final hope for territorial expansion on a continent thought to lie in the South Pacific. The British troops who surrendered at Yorktown later in the century played a tune, “The World Turned Upside Down.” That is what theoretical geographers once thought would happen if the many continents in the Northern
Hemispheres were not balanced by equal continents to the south. Thus a new wave of explorers moved through the Pacific basin. Roggeveen with two ships found eleven islands from isolated Easter through the Tuamotus, Society and Samoan archipelagoes. Byron, Wallace, Carteret, and Bougainville followed with comparable discoveries. Unfortunately for territorial hopes, they more or less followed the same old explorers’ turnpike.

Enter the incomparable Captain James Cook, who made three voyages from 1768 to 1779, when he was killed in Hawaii. Even he followed the turnpike on his first voyage, but thereafter he followed logic and took the west winds to crisscross the South Pacific. In this he was preceded by Tasman, who sailed on the westerlies south of Australia in 1642 and (after the Maoris and the kiwis) discovered New Zealand. Cook came the same way, and between 1772 and 1775 he eliminated the possibility of a southern continent outside polar waters. He did a similar search of the North Pacific on his last voyage; he bisected the Acapulco-Manila loop and found the Hawaiian Islands.

In the central Pacific basin, Cook found and surveyed 30 islands. Through his unique influence and training, his lieutenants and their lieutenants, seemingly everyone associated with him, continued to explore. His lieutenant Clerke found the last two high Hawaiian Islands. A decade later, his former navigator, Captain Bligh, discovered two islands with HMS Bounty. When the mutiny occurred, Bligh and the loyal sailors were placed in an open boat. They then made the longest recorded voyage in such a boat, all the way to Batavia, seldom touching land for fear of the Melanesian cannibals, who even paddled out from shore to intercept them. In the midst of all these hardships and perils, Bligh discovered—and surveyed one side of—eleven islands in the Fiji and Banks groups. (Cook had once remarked that to survey an island he frequently had to expose his ship on a lee shore, which was contrary to all his training. He did so because the Admiralty had sent him out not to preserve his ship but to survey.) His chief mate, Lieutenant Fletcher Christian, discovered fertile Raratonga (and the Raratongans) with Bounty before reversing course and eventually burning the ship off the landing on isolated, uninhabited Pitcairn. To complete this log, Captains Edwards and Oliver, searching for the mutineers, discovered three more islands in the central Pacific and four more among the continental islands of the Solomons.

The Efficiency of European Exploration

The oceanic islands of the main Pacific Basin east of the island arcs comprise 184 atolls or rocks barely above sea level and 83 high islands, including elevated atolls. The distinction is made between high islands and low because height is what determines how far an island can be seen—its
"size," for the purpose of discovery. Thus, the history of discovery of the finite population of high and low islands in this circumscribed area may be compared to the better known history of the population of giant and small oil fields in the United States.

In the first phase of exploration, from 1500 to 1700, the number of islands discovered per 50 years systematically declined. Presumably this reflects both a decline in interest in the Pacific and the fact that its Spanish masters were content to conduct commerce along known, safe routes. As far as island discoveries go, therefore, the heroic first phase did not amount to much. Nothing of value was thought to exist in the main Pacific basin, so it was pointless to search for islands.

In the second phase, beginning in 1700, discoveries per fifty years averaged about four or five times the rate in the previous two centuries. However, within this phase, particularly from 1760 to 1860, there was hardly any systematic trend in the rate of discovery per decade until the 1830s, by which time almost all the islands had been discovered. Even if the discoveries by the unique Cook are eliminated, the rate varied randomly from 10 to 29 per decade for 70 years despite the almost complete exhaustion of the finite population of islands available for discovery. Random searching at a constant rate would have produced an exponential decline in the rate of discovery. If, indeed, random searching is an appropriate model for European exploration for Pacific islands, there must have been a balancing exponential increase either in the rate of exploration or in its efficiency.

It is easy enough to devise simple models of random searching and apply a Monte Carlo method to generate simulated histories of discovery. All that is necessary is to determine the size and position of the targets and then have a computer run straight lines or random sailing courses through the search area. Two models might be necessary because the size of the target varies with the objectives of the searcher. We define "finding" as seeing an island. A voyager who is trying to avoid islands discovers one only if it chances to come in sight. However, islands give many signs of their existence besides being visible. The orographic rain clouds that tower above high islands are often visible long before the island comes in sight. Likewise the milky blue-green color of a still-invisible atoll may be reflected on the clouds of the trade winds. Inasmuch as the temperature of a lagoon is higher than that of the surrounding water, the pattern of the little tropical clouds over the lagoon may also be revealing. Land birds, floating vegetation, seals, wave and swell patterns, even smell can indicate the nearby presence of land yet undiscovered. Thus, one computer program would sail straight on and the other would begin a box search until the discovery was made. The latter would be much more successful because, effectively, it would be seeking much bigger targets.

The number of islands discovered in the Pacific in each fifty-year period from 1500 to 1900. Clearly by 1700 no one was looking for islands.
The problem in measuring the rate and efficiency of European exploration is that the total length of all Pacific voyages is unknown. Thus, there is nothing comparable to the total length of exploratory drilling for oil fields. Consequently, the actual efficiency of exploration—number of islands discovered per unit effort—cannot be determined for comparison with random searches.

What can be determined from Sharp's chronology of discovery is how many islands were found on each voyage that found any islands at all. Consequently, it is possible to see how this number varies per unit effort, even though the sample is very small compared with all the voyages that discovered nothing at all. An appropriate measure of success would then be the excess number of islands (that is, in excess of one) discovered per successful voyage per ship. Small though it is, the sample suggests that this number declined exponentially from 2.5 in the first fifty-year period to 0.5 in the last fifty-year period of the first phase of exploration. Considering that two-thirds of the islands were still undiscovered in 1700, it appears that either no one was looking for them or that the searches had bad luck comparable to that in the search for the giant East Texas oil field.

The more voluminous data for the period from 1760 to 1840 are quite consistent in suggesting that chance was a major factor in the discovery of
Pacific islands. Excluding Cook’s discoveries, the excess number of islands discovered per successful voyage per ship declined exponentially from 2.2 to 0.2 in each ten-year period, with only a gap from 1820 to 1830 to mar the picture. Even including Cook, whose searches were far from random, an exponential decline is apparent. It appears that in the second phase of Pacific exploration the actual rate of discovery per unit effort declined as it would have in a random search. Thus, if the rate per decade remained fairly constant, it must have been because the amount of searching, whether deliberate or random, increased exponentially.

In each phase of exploration, the high islands were found generally before the low ones. This is best seen in the last century of discovery. All but two of the high islands were found by 1800 and the last, Rimatara, by 1811. In contrast, most low islands were found in the 1820s than in any other decade in the two phases of exploration. Atolls continued to be found for 48 years after the last high island. It seems that, like the discoverers of oil fields, European and later American explorers found the big targets first.

The first high island to be discovered in the Pacific region of interest here was Ponape, 786 m high, in 1529. Ponape is one of three widely separated high islands among the abundant atolls and drowned atolls of the Caroline group. The atolls surrounding Ponape were discovered in 1529, 1568, 1773, and 1824. It is evident that atolls can easily escape notice. There are curious anomalies in the other direction. We may recall that Darwin on HMS Beagle missed seeing the nearby phosphate island of Makatea but saw Tahiti in the distance at dawn; yet Makatea, only 110 m high, was discovered in 1722 and Tahiti, 2228 m high, not until 1767. In general, the high islands of the eastern Pacific were discovered before the far more abundant and clustered high islands to the west. The Galapagos were the first group found; all twelve were discovered in 1535. The eastern islands along the return loop from Manila were discovered early, even the tiny but high spire of Alijos Rocks off Baja California was found in 1558. The only other group found in the sixteenth century were the southern Marquesas. Only eastern high islands were discovered in the seventeenth century, and the last two of these sparse eastern islands, Easter and Sala y Gomé, were found by 1722.

The Society and Samoan groups, if not all of their islands, were discovered before Captain Cook’s time, but thereafter most of the high islands were discovered by him and his lieutenants. After their time, little was left. The remote phosphate islands of Nauru and Ocean were almost the last, in 1798 and 1804 respectively. Curiously, on those islands was what the Spaniards and their successors despised of finding—a fortune in ore.
POLYNESIAN COLONIZATION

The Europeans who entered the Pacific for more than 300 years came from an unwashed, polluted, disease-ridden culture that had passed from the Bronze Age to the Iron Age several millennia earlier, a culture that had cannon, cathedrals, and the printing press. The people they found on the tiny isolated islands were clean, healthy, and generally friendly, and they seemed exceedingly handsome to sailors long at sea. Polynesians had a materially simple stone-age culture with only three domestic animals—the pig, cat, and the chicken. There were no wild mammals or reptiles to hunt or defend against. There were no machines, no wheels, no pottery—because atolls and volcanic islands lack clay. Food was abundant but the variety of fruits and vegetables limited. The sea provided a wide variety of limitless protein. These cultures had complex social structures with kings and nobles, property rights, warfare, and religion. Islanders built temples in the form of uncedented but sand-filled stone platforms. On some of the high islands, they ornamented the temples with large stone statues resembling the well-known ones on Easter Island. The statues were carved of volcanic tuff, easily worked with obsidian or pitchstone hand axes, so little technology was involved.

The first scientist to encounter Polynesian culture was Joseph Banks, who was with Cook on his first voyage. The future Sir Joseph would long be the President of the Royal Society, but on Tahiti he was a young man in paradise. He studied the botany, but his journals make it clear that he spent more time enjoying than analyzing the complaisant society of Tahiti. Scientists who later visited the islands began to devote themselves to the origin, history, and culture of the Polynesians. Evidence was derived from oral traditions, physical anthropology, serology, domestic plants and animals, artifacts, and analysis of cultural evolution. A very strong consensus among diverse specialists was that the Polynesians had come from southeast Asia, probably from what is now Indonesia. If so, they had peopled the Pacific by sailing into the trade winds. The magnitude of their achievement can be perceived from the number and desperation of the European attempts to deny that it happened.

A long European tradition proclaimed that in general one did not sail east into the trade winds. The European way to go east was to do so on the westerlies at high latitudes, but to do that was a comparatively difficult technical feat. Europeans and, later, Americans could not believe that a Stone-Age culture was capable of a large-scale migration by either route. Almost every conceivable alternative was proposed, and it seemed that the wilder the idea the greater its popularity. It was proposed, by a scientist, that the sailing simply had not taken place. A gigantic, Pacific-wide
The ecologically well-adjusted Polynesian culture as portrayed by John Webber, who was with Captain Cook on the third voyage.

continent had been submerged and what were now islands had once been its mountains. The Polynesians had walked on their migration and merely retreated to the peaks when submergence separated them. A drowned continent was a popular idea among biologists, particularly botanists, but few would have agreed that it had submerged while man was on earth. A nonscientific enthusiast gave the continent a name, “Mu,” and wrote several books comparing its history with that of the other imaginary sunken continent—Atlantis.

Some people allowed migration by ship, but surely not by a Stone-Age culture. It followed that the Polynesians were little more than the feral remnant of a high culture. But what high culture? Among the possibilities considered were a lost tribe of Jews, or of Aryans, or the mysterious but doubtless technologically mighty inhabitants of Mu. In yet another interpretation, the Polynesians themselves did migrate by sea, but this was not much of a technical achievement because it was done downwind on the trade winds from South America. Thor Heyeerdahl demonstrated that the voyage could be made on a properly provisioned raft that was towed across the near-shore currents. His account, *Kon-Tiki*, went through seven printings in its first year, 1950, and ultimately more than twenty-five printings.

The idea of a simulated Polynesian voyage from South America would not have surprised Sir Peter Buck, who in 1938 published the concept that there were real voyages. Buck, however, assumed that the voyagers had first sailed from Polynesia to South America. The return downwind would
then have been easy. Sir Peter Buck was a Maori, born Te Rangi Hiroa, who held a position as a Maori medical officer to pursue the origins of his people. Speaking a Polynesian dialect as his mother tongue, he made extensive use of interviews to obtain oral traditions, histories, and genealogies, some of which went back 92 generations. With Buck the pendulum at last swung. The title of his book *Vikings of the Sunrise* referred not to the antecedents of the Polynesians but their abilities as sailors and navigators. It went through two editions and additional printings and has become widely accepted, especially in Polynesia. He visualized fleets of double-hulled sailing canoes that set sail, according to plan, bearing hopeful emigrants and the provisions to support them. On the broad platforms between the twin hulls were the domestic animals, plants, and seeds to establish new settlements. The voyages counted on rain to supplement water, and upon fish to supplement food.

The great canoes were seen and illustrated by early European voyagers, so Buck’s interpretation of Polynesian history began on firm ground. He knew the South Pacific well and was scornful of the “nonsense” in print about the impossibility of sailing east in the latitude of the trade winds. The trades sometimes ceased and were replaced by westerly winds from time to time. He cited the experience of the pioneering Christian missionary John Williams, who sailed east from Samoa to the Cook Islands on a straight course without changing tack. In any event, sensible sailors preferred to explore by beating against prevailing winds because, if no new island was discovered, they could speed home to food and water. The only weak link in this appealing history of noble human achievement was the possibility that the island hopping was accidental. Perhaps the Polynesians populated new islands only when their sturdy canoes were driven who knows where by great storms. Buck cinched his analysis by pointing out that, although women swam, dove, fished and sailed, it was only within lagoons. They did not accompany men in fishing in the open sea where they could have been blown away. No women, no new colonies; it was as simple as that. If the women were at sea, it could only have been with the great colonizing fleets.

Sir Peter Buck had painted an attractive picture, consistent with mainstream science and based on a personal compilation of oral history in the 1930s. In 1956, Andrew Sharp pointed out that the picture was not consistent with earlier observations of Polynesian culture. Sharp observed that once the Europeans arrived they grossly changed Polynesian life. Polynesians on some islands were almost exterminated by European diseases. Cultures were rapidly corrupted, as they were all over the world, by the awesome European technology. The isolated Polynesian society was exposed to the world. For example, Captain Cook's Tahitian translator,
Omai, had spent two years in London before sailing on Cook’s third voyage. Even within the Pacific, Polynesians traveled with the Europeans and, moreover, could learn of many islands with which they had not necessarily been familiar. Thus the memories and, possibly, the traditions of Polynesians after the great discoveries of 1760–1780 were suspect.

It is prudent, therefore, to go back to European journals and logs of voyages to Polynesia before any significant changes occurred. The first scientific voyage was Cook’s on Endea¬mor in 1768–1771. Cook, Banks, and Solander were all curious and qualified observers, and the journals of the first two have something to say about Polynesian origins. Banks believed that the Polynesians had come from the west because of their language and their domestic plants and animals. Cook, the master mariner, saw not the slightest problem in accepting that the migration was against the trade winds. He found that the inhabitants of the Society Islands were familiar with islands “laying some 2 or 300 Leagues to the westward of them.” He assumed, in those days early in the second phase of European exploration, that island succeeded island to the west. Thus the inhabitants of the islands west of Tahiti would in turn know of the islands west of them, and so “we may trace them from Island to Island quite to the East Indies.”

By his third voyage (1776–1779), Cook had more data and a more complete hypothesis of Polynesian migration. Polynesia was divided into two main regions: western Polynesia, consisting of the Tonga, Samoa, and Fiji groups, and eastern Polynesia, which included the Society and Tuamotu islands. The Polynesians told the early explorers that deliberate voyages were made only within the two regions. How voyages were made between groups or to islands outside the groups was suggested by what Cook learned at Atiu, in what are now the Cook Islands. Omai, the interpreter, found three of his fellow Tahitians on Atiu, 1100 km from home. They were the survivors of a party of twenty who had expected to have a brief sail from Tahiti to Raiatea, barely over the horizon at sea level. Cook knew of many other accounts of accidental voyages such as one in 1696, when a large canoe was driven by storms from the Caroline Islands to the Philippines, 1800 km away. Men, women, children, and babies survived. Cook reasoned that such accidental long voyages by family and tribal groups attempting easy interisland trips will serve to explain, better than a thousand conjectures of speculative reasoners, . . . how the South Seas, may have been peopled; especially those islands that lie remote from any inhabited continent, or from each other.
In short, Cook proposed that the islands were peopled not by hypothetical great fleets of migrants but by an essentially random search, which was still going on.

Andrew Sharp fleshed out this skeleton of an idea with data from the time after Cook's death, on his third voyage. Accidental voyages were more frequent toward the west because of the normal trade winds. However, there were many also to the east during lulls in the trades or, more commonly, when gales or typhoons overwhelmed the normal weather. For example, a canoe-load of people from Manihiki in the Northern Cooks survived an accidental voyage of 1100 km to the southeast to Aitutaki in the Southern Cooks. Another important influence on the probability of long accidental voyages is the frequency of inter-island travel by groups of men and women. Sharp showed that family and group voyages to nearby islands were commonplace in the nineteenth century just as they are now. The population of one pair of islands moved en masse back and forth between them every few years; their use of the islands was rather like crop rotation. Other people would go off to visit family connections on nearby islands; or to colonize a less desirable and thus unoccupied area of a nearby island.

A question might be raised about the probability that a group of families would survive for weeks when they had supplies on board for only a day or two. The probability cannot be assessed; perhaps most of those swept away were drowned or died of exposure, hunger, and thirst. Nonetheless, successful storm-driven, accidental voyages may have been numerous enough to populate the islands. In any event, the ability of the ancient Polynesians to survive at sea defies the modern urban imagination.

Some faint idea of what can be done is provided by the little book Survival on Land and Sea, prepared for the U.S. Navy by the Ethnographic Board of the Smithsonian Institution. I have read my copy many times since I received it on board ship in 1944. After a few special sections about not drowning in a parachute and about surviving under burning oil from a ship, it presents a manual for staying alive in a life raft that would apply to anyone adrift. You can live for weeks without food and 8 to 12 days without water. A pint of water a day keeps you fit if you are not active. Moreover, fish hooks can be made from many materials, including wood, and fish line from cloth or rope. Small pelagic sharks collect under and around boats, and birds, flying fish, and squid may land aboard. Rain can be expected to provide water; and potable water, rather like oyster juice, can be squeezed or chewed from freshly caught fish. Exposure can be a problem; I would never abandon ship without a hat. However, awnings can be improvised and clothes minimized, so that perspiration is free to evaporate but the sun is still screened. Clothes should be dipped in
Dates of discovery of central Pacific islands by Polynesians (Europeans). The area of Polynesian settlement after 1000 A.D. is shown in color. North and east of New Guinea, Polynesian settlements coexisted with Melanesian cultures.

salt water to provide cooling by evaporation, although care should be taken not to be chilled.

With this kind of information, and determination, young men from the fields of Iowa and the streets of Chicago have survived for weeks in open boats and rafts. The Polynesians were as nautical a culture as ever existed, swimming like otters, sailing from infancy, and fishing for a living. They started on their inter-island cruises or inter-archipelago expeditions with just the sorts of gear, rigging, and sails that were most useful for long survival at sea. Even after destructive storms, enough voyagers could have survived to people the Pacific.

Thus, the random-voyage hypothesis seems entirely adequate to explain the peopling of the Pacific, although it has evoked a mixed response. A troubling aspect is that it seems to diminish the Polynesian achievement—in fact, it is not known that large-scale planned migrations did not occur. However it was accomplished, what was the chronology of Polynesian exploration and colonization?

The Polynesian culture apparently developed among people who migrated from Indonesia through Melanesia to the Samoa-Tonga region per-
Stone heads on Easter Island mark the easternmost occupation of Polynesian colonists. However, plants and mineral specimens indicate noncolonizing voyages on to South America.

haps 3000 years ago. Yet radiocarbon dating so far has not shown any occupation of the central South Pacific islands until the first millennium A.D. Presumably, human waifs were coming and going east with storms and home again with the trade winds. Given a seagoing people in western Polynesia for at least 1000 years, it seems impossible that they did not accidently learn of the islands farther east. Nonetheless they neither deliberately nor accidentally populated Tahiti or the other islands. Could it be that home in Tonga or Samoa was so ideal that every group of shipwrecked waifs merely built a new boat and sailed back on the trade winds?

Apparently, something changed, perhaps population pressure, and Polynesians occupied the incredibly distant Marquesas islands about 300 A.D. They were on Easter Island by 400 A.D. and throughout the Society, Tuamotu, Austral, and eastern Cook islands by perhaps 700 A.D. In 800 A.D. they probably were in Hawaii and a century later in New Zealand. The Polynesians also discovered, although they did not permanently occupy, numerous isolated islands—probably more than once. There are ancient ruins in the interior of some high islands in the Carolines, and an abandoned temple on Pitaaim. Skeletons, artifacts, and ruins are spread from the Line Islands to Henderson, which is southeast of Pitaaim. Polynesians not only reached the Galapagos but somehow made contact with South America, whence the sweet potato was brought to New Zealand.

In sum, Polynesians discovered and colonized the islands of the open South Pacific as well as Hawaii in about 600 years. They had gone everywhere from New Zealand to South America. It took Europeans with much better ships almost half as long just to find the islands, and they never
have colonized many of them. We have no way of knowing how much of
the colonization was deliberate and how much accidental, but regardless of
how the Polynesians peopled the Pacific, it seems to have been reasonably
efficient—pigs, chickens, and all. Considering that in exploration it is no
small achievement to do as well as pure chance, there is no way to dimin-
ish the greatest maritime feat in human history.

**POPULATION BY PLANTS AND ANIMALS**

A large number of biologists have studied island life in the past hundred
years, including many specialists in subjects that rarely overlap. Inevitably
there is a great diversity of apparently conflicting evidence and thus a
range of opinion on how plants and animals populated oceanic islands.
Even so, there is agreement on the one point that is most controversial
regarding human exploration: Plants and (non human) animals found the
islands accidentally, without intent, and entirely according to the laws of
chance. One might reason that chance would favor those with biologi-
cally more capable of dispersal, like the Europeans and Polynesians, who
were culturally prepared to discover oil fields and islands. We have seen
that such human discoveries may be inevitable even if there is a large
element of chance. Regarding other species, biologists also seem to have
achieved a consensus that organisms capable of long-distance dispersal are
more apt to be on an island than not.

On many other points, controversy continues. For example, faunal
affinities indicate that different organisms reached such islands as Hawaii
from different continents, but when and by what routes is less certain. In
the last chapter of this book, we shall view island life in the light of plate
tectonics and insular geology, which have some bearing on the history of
dispersal to islands. Here, however, we shall focus on the paths by which
colonizing plants and animals reached the islands. Many, perhaps all,
opportunities have enjoyed scientific support; these include migration across
former continents or former linear continental fragments called “land
bridges,” hopping along former island chains, and simple dispersal to the
islands as they are now distributed.

The hypothesis that ocean basins and continents were not permanent
had widespread support from the early nineteenth century until fairly re-
cently. Many of the most eminent geologists believed that dry land had
been where the ocean basins are now and that subsidence had merely
transformed one into the other. Thus, biologists could cite expert geologi-
cal opinion to explain the modern distribution of plants and animals. The
gistorical evidence that was explained by the hypothesis was of two types,
and by the late nineteenth century the facts were hardly in dispute. First, marine fossils and sedimentary rocks occur widely on continents, including what are now the peaks of the highest mountains. Clearly, the land that can be seen has once been the sea floor. It once seemed only reasonable that the sea floor, which could not be studied in such detail, might once have been land. Second, Paleozoic and early Mesozoic fossil assemblages of the Atlantic coasts of Africa and South America are very similar, and this is true of Northern Europe and North America as well. Furthermore, the sequences of sedimentary rocks on opposite sides of the Atlantic are also very similar, and the geological structures of the two coasts trend out to sea. It is obvious that at one time Africa and South America, for example, were connected by dry land.

To plant geographers, the idea of foundered continents was particularly attractive. J. D. Hooker, Darwin's friend and one of the earliest supporters of evolution, did not see how the "peculiar endemics" of insular floras could be explained by random dispersal over water. Moreover the insular floras reflected a "far more ancient vegetation than now prevails on the mother continents." All manner of problems about dispersal from continents to isolated islands were identified by botanists and other biologists as well. These problems posed no difficulties if the islands were merely peaks of foundered continents. All was explained by land distributions that had now vanished. On the other hand, all these problems were acute for a second group of biologists who believed that ocean basins and continents were not interchangeable. To be convincing, they would have to prove that long-range dispersal over water was not only possible but going on now.

The pioneer in the second group of biologists was Charles Darwin, whose reasoning derived from his hypothesis on the origin of atolls. He had proposed that the coral atolls were reefs built on the tops of isolated submarine volcanic edifices. If the bases of the volcanoes had once been connected by dry land, as parts of a continent, the coral would have grown up like the Great Barrier Reef off Australia, only the Pacific reefs would have been even more extensive. Furthermore, with very few exceptions, the only rocks found on islands in deep ocean basins are volcanics, such as basalt, and coral limestone. If the islands were peaks of foundered continents, they should be like the peaks of unfoundered continents. Many should have outcrops of Paleozoic or Mesozoic fossiliferous sedimentary rocks like the Alps or Himalayas, or granite and metamorphic rocks like the Sierra Nevada. Darwin said that they did not, and if everyone had accepted his conclusion, the foundered-continent hypothesis might have been abandoned. However, as Darwin himself noted, the Seychelles Islands, rising from the deep Indian Ocean, are in fact coarse granite. More-
over, many of the pioneering geologists who followed the discoverers of islands seem to have had very bad luck in sampling and describing rocks. On many islands they found what were interpreted as metamorphic and igneous rocks more like continental granite than oceanic basalt. How they did this on what are now obviously youthful volcanoes rising from oceanic crust is mystifying to nonpetrologist. However, the samples were few and the interpretations made in good faith, so as late as 1950, Darwin’s conclusion was based on evidence that was widely perceived as equivocal.

After Darwin’s ideas were published, the Challenger expedition found that the deep sea floor is covered with red clay and globigerina ooze. A. R. Wallace pointed out in his book Island Life, published in 1880, that rocks made of such materials do not exist on continents, and this suggested that continents and ocean basins are permanent. When Wallace had sent his first, brief manuscript outlining the theory of evolution by natural selection to Darwin, he had believed the founded-continent hypothesis. This was hardly surprising, because much of his field work was in the Indonesian islands, which are in fact continental in composition and arise from a shallow continental shelf. In times of lowered sea level, animals could migrate about with dry paws. Darwin wrote to Wallace that he agreed with everything that Wallace proposed except for the populating of islands in the deep sea. On that point Darwin would defend his own views “to the death.” Wallace soon appreciated the difference between continental and oceanic islands and supported Darwin, but other scientists did neither.

Further evidence for the permanence of continents came not from the tiny oceanic islands but, like the Challenger data, from the broad, deep sea. Geophysicists would show that continents and oceanic crust are too different for one to be changed into the other. By about 1900, O. Hecker had made enough measurements to show that the Atlantic, Indian, and Pacific ocean basins are as close to isostatic equilibrium as the continents are—both types of crust float buoyantly on denser material below. Thus, the ocean basins, which ride much lower than the continents, must be made of much denser rock. In the 1950s, Russell Raitt and Maurice Ewing, among others, began to measure cross sections of the oceanic crust from ships by explosion seismology. They discovered that the standard oceanic crust is much thinner than the standard continental crust and that crust of intermediate thickness is very rare. The result of half a century of geophysics at sea was a complete confirmation of Darwin’s conclusion that ocean basins are not founded continents. What then of the compelling evidence that Africa and South America had once had a land connection? Alfred Wegener had explained it all in 1913 by continental drift. The stratigraphic and paleontological evidence of trans-Atlantic linkages was undisputed, but it now had no bearing on the dispersion of animals and plants to oceanic islands.
If Darwin did not immediately convince everyone about the populating of islands, it was not for lack of his usual valiant try. He conducted a lengthy series of experiments to determine how long seeds and plants would float in sea water and still be fertile. Ripe hazel nuts, he found, sank immediately but if dried first they would float 90 days and still germinate. Dried asparagus with berries floated 85 days, and so on. He also amassed an enormous collection of observations of plant and animal dispersal. Coconuts drift across oceans, and West Indian beans regularly beach on Scotland. Birds cross oceans and carry fertile seeds in their crops. A blob of mud from a partridge’s leg contained the seeds of 82 plants of five species. These experiments and observations proved that a surprising range of plants and animals could survive long-distance transportation by air or sea and reproduce on islands.

Darwin did not show that breeding pairs or genetically diverse groups of mammals or reptiles could populate islands. But there are no mammals and few reptiles on oceanic islands, except for those that were brought by people. Indeed, a correct explanation of the origin of insular populations must include a filter that eliminates species incapable of long-range migration, and that is one of the virtues of the waif hypothesis.

Among the last common island organisms to be proved capable of distant dispersal were insects. Even on the Hawaiian Islands, with their large human population, there was no way to detect an insect that had just been blown in from California. J. L. Cressey solved the problem in the 1930s by towing a large fine-mesh net behind an airplane near the islands. It was like the discovery of plankton in the sea a century earlier. Insects and spiders are abundant even high in the air, and the species represent groups in the same proportions as those of the insect faunas of oceanic islands.
Plate Tectonics and Islands

The scientific study of oceanic islands began two centuries ago, but several new factors have made them more inviting objects of study. First, almost all volcanic islands have now been dated. Therefore the rates of such phenomena as erosion or subsidence can be measured, whereas before they were speculative. Second, geological history as a whole has benefitted from intensified study with new tools during recent decades. In earlier times, each new fact either tended to undermine old hypotheses or stood alone. Now, the theories of continental drift and plate tectonics provide a framework that becomes stronger as each new fact is riveted into place. Third, widespread observations can be quantitatively related by plate tectonics. Tectonic plates are rigid, so all points on a plate remain in the same configuration as the plate drifts about. Thus, if the speed and direction of drift of a few points or islands can be established, the drift of all others on the same plate can be calculated. A few very careful observations, although scattered, are enough to add a new accuracy and unity to geologic history.

TECTORNIC PLATES

The crust of the earth is a spherical shell of rock that consists of a few rigid plates. There are only eleven giant ones at present, and many smaller; two of the giants seem to be in the process of splitting up. These tectonic plates drift about continually, shifting position and jostling each other. Consequently, the boundaries between them are marked by earthquakes. In-
The tectonic plates of the world. Spreading centers are shown in orange, subduction zones in blue. Black lines are transform faults.

indeed, one way to define a plate is "a region of the crust lacking earthquakes but ringed by them." If we look at a world map of earthquake epicenters, two things are striking. Almost all the quakes are along the lines of plate boundaries, and few of these lines correspond to the boundaries between continents and ocean basins. Clearly, the forces that move tectonic plates are so mighty that they can hardly tell the difference be-
between high continents and the deep sea floor. Coastal Southern California, for example, is on the Pacific plate and is drifting northwest with the rest of the plate toward Siberia. Eastern California, in contrast, is attached to the North American plate, which extends east to the center of the Atlantic Ocean. Eastern California, with its plate, is drifting slowly to the southwest.
Magnetic anomalies along the Reykjanes Ridge, southwest of Iceland. Colors show areas of magnetic reversal relative to the present orientation. In about 12 Ma, the plates on either side of the ridge have spread about 200 km.

**Spreading Centers**

Plates are created by solidification of passively upwelling magma, which fills in the cracks where plates drift apart. The cracks are called spreading centers, and they are characterized by tensional earthquakes (caused by stretching), which are confined to shallow depths because the hot crust in these places is too weak for stresses to accumulate any deeper. When a spreading center first forms, it may open a crack in either a continent or the sea floor. Such a crack gradually opened between what are now Africa and South America roughly 200 million years ago. Those continents are far apart now, but the seismically active crack still exists at the crest of the Mid-Atlantic Ridge. That ridge is one of a class of great topographic features called, for convenience, "midocean" ridges even though some are nowhere near the middle of an ocean, and the Pacific has sometimes contained two or more of them. Midocean ridges are typically a few kilometers high above the deep ocean floor and, with their sloping flanks, a thousand kilometers wide.

The magnetic field of the earth reverses polarity at intervals on the order of a hundred thousand to a million years. When lava cools, some of
the minerals in it act as tiny magnets and orient themselves in the direction of the magnetic field. The spreading crack on the crest of a midocean ridge is frequently filled with lava, which then cools, splits, fills, splits, and so on. Thus the cold rocks of the ridge contain a fairly permanent record, like a magnetic tape recording, of the reversals of the earth's magnetic field through geological time. Indeed, the whole ridge is like a stereo tape recording with magnetic patterns on each flank that are commonly mirror images of each other. The pattern of normal (like now) and reversed magnetic orientations (anomalies) has been dated by comparing rocks of known age on land with those on the sea floor. Inasmuch as most of the magnetic anomalies of the ocean basins have been mapped by ships, the age of most of the vast, deep sea floor is known. Using the width of dated magnetic anomalies, it is possible to measure how rapidly the midocean ridge crest where they were created was spreading apart—even though it was 100 million years ago.

Subduction Zones
The size of the earth has been quite constant for billions of years. Consequently, when a spreading center produces an area of new crust, an equal area of old crust must be removed from the earth's surface somewhere. The opening of the whole Atlantic Ocean basin, for example, resulted in the loss of an equivalent area, mainly in the Pacific. The regions where tectonic plates drift together and crust is lost are mostly subduction zones. In such a zone, one plate plunges beneath the other, usually at an angle between 30° and 45°, and goes on down for hundreds of kilometers into the mantle. The plate that plunges is almost always oceanic crust, because continental crust is more buoyant. The path of the plunging plate can be traced by the earthquakes that are generated. Under Japan, for example, where the Pacific plate plunges beneath the Eurasian plate, the earthquakes are shallow; under the Sea of Japan, farther west, the quakes are deeper; and under easternmost Siberia, they are deepest. Typically, subduction zones have the largest and most damaging earthquakes in the world because the rocks there are old, cold, and able to accumulate large strains before breaking.

The great compressive forces in subduction zones deform the crust into deep oceanic trenches and high continental mountains such as the Alps and Himalayas. The reheating of the plunging oceanic crust and sediment causes magma to liquefy at depth. It rises to the surface to form lines of beautiful volcanoes like the Cascade Mountains of Oregon and Washington and including the most beautifully symmetrical of all—Fujiyama in Japan. Like sea-floor spreading, subduction can take place within continents or ocean basins, but in fact it takes place mainly at the
boundaries between continents and oceans. The Pacific, unlike the Atlantic, is ringed by subduction zones and the line of fire of active volcanoes. The reason is not that the zones develop at the edges of continents; as at spreading centers, the forces that move plates are much too great to be influenced by the type of crust. What happens is that the buoyant continents drift to subduction zones and stay there like rafts at the edge of a whirlpool in a river.

**Transform Faults**

The crest of the Mid-Atlantic Ridge is not straight; it is offset just like the Atlantic coasts of Africa and South America and for the same reason. The offset is an abrupt step, and it is caused by *transform faults*, which, like spreading centers and subduction zones, are one of the three basic elements of plate tectonics. A transform fault is, as the name implies, merely a fault, a cut in the earth's crust, running between the other two kinds of tectonic elements. Most transform faults offset the crests of midocean ridges; a few run between a ridge and a subduction zone; even fewer run from one subduction zone to another. The earthquakes on ridge-ridge transforms are quite shallow (1 km to 5 km deep) because the crust there is young and weak. However, where transform faults cut older crust, earthquakes may be 10 km to 20 km deep.

The most famous transform fault is the San Andreas fault, which transects California and destroyed much of San Francisco in 1906. It is of
the most common type, a ridge-ridge transform; thus, its notoriety derives not from unusual geology but from the concentration of people and buildings around it. The San Andreas runs between two “mid-ocean” ridges, one of which actually extends into Mexico and the other of which is only a short distance off Northern California. The southern one is the great East Pacific Rise, which extends from the South Pacific to the mouth of the Gulf of California. This gulf has been created in its present form during the last few million years by the drift of the Pacific plate away from the North American plate. The sea floor of the gulf is broken into a number of short ridges and long ridge-ridge transform faults. The San Andreas fault is one of them; it emerges from the northern end of the gulf and extends into California. Then it passes 100 km or so east of Los Angeles and right through the western part of San Francisco before trending out to sea near Cape Mendocino. The fault ends at the Gorda Ridge, but the plate boundary continues on past Alaska and Japan and ultimately back to the South Pacific. The San Andreas fault, causing centimeters of offset every year, may seem enormous to Californians, but it is only a minor part of the truly enormous perimeter of the Pacific plate.

The faulting along submarine ridge-ridge transforms produces a distinctive topography with long, narrow mountains and deep troughs, high volcanoes and great cliffs. The active faulting that generates earthquakes takes place only between spreading centers. However, the distinctive topography is preserved and drifts away from the ridge crest with the growing plates on both sides. The resulting mountain ranges, called fracture zones, are typically from 10 to 100 km wide and may be thousands of kilometers long. If the water in the ocean were removed, the great fracture zones would be readily visible even from the moon and seem so straight and evenly spaced as to appear artificial.

AGING AND SUBSIDENCE OF PLATES

The earth’s rigid surface layer, or lithosphere, is almost wholly in buoyant equilibrium, or isostasy. Because the lithosphere effectively floats on a weak plastic layer, or asthenosphere, its elevation is related to its density. High mountains are composed of rocks of low density, and the deep sea floor is composed of rocks of high density. The crest of a mid-ocean ridge rises high above the deep sea floor because the young crust created at the spreading center is hot. As the crust drifts away, it cools by conduction to the cold sea floor; it grows denser, so it subsides to form the sloping flanks of the ridge. Cross-sectional profiles of ridges show that their flanks are concave upward between the high crest
An echo-sounding profile across the Mid-Atlantic Ridge shows endless hills and mountains superimposed on broad concave slopes.

\[ d_t = d_0 + Kt^{1/2} \]

where \( d_0 \) = initial depth (2500–2600 m) 
\( d_t \) = depth (in meters) at time \( t \) (in Ma) 
\( K \) = a constant (320–360 m)

In short, the depth increases with the square root of time. The average initial depth and the constant \( K \) are still being determined within a narrow range. The heat flow and other properties of plates also vary with \( t^{1/2} \), and all these variations can be explained by simple physical models. Thus, it is possible to calculate the expected depth of the sea floor if its age is known. Likewise, the subsidence history of a plate, its depth at any time in the past, can be calculated. The ability to make these calculations has greatly improved understanding of the elevation and subsidence of islands.

Oceanic crust older than 60 Ma is not known to subside according to the same time relation as younger crust. It has been suggested that heat from the interior of the earth has conducted through the whole plate by that age, so there is no further cooling. The matter is controversial at present, and it is not possible to calculate the thermal history of very old oceanic crust.

**Thickness and Strength of Plates**

Isostasy is commonly achieved by local support. For example, a continent or a mountain range may be considered to be floating, buoyed up by the liquid asthenosphere directly below it. However, some support is regional, distributed in the area around a mountain. The phenomenon can be visualized in terms of a skater on thin ice. The skater is a load on the ice. If he breaks through and is buoyant, his weight is locally supported. How
ever, if the ice supports him without breaking, it is pushed downward in a
dimple. Although it is not so obvious, the ice is also arched upward in a
ring around the dimple—the skater’s weight is regionally supported.

Oceanic islands are loads on the lithosphere, and some are supported
locally and some regionally. It depends on the age and thickness of the
lithosphere when a growing volcano exerts a load.

The top of a plate is the sea floor, whose temperature is about 0°C.
The bottom of the plate can be defined in various ways. For example, the
top of the asthenosphere, which is in many places about 100 km below the
top of the lithosphere, may be taken as the plate’s lower boundary, or it
can simply be defined as an isotherm—commonly, 1200°C. (The accre-
ting edge of a plate is at a spreading center, where magma is injected at
temperatures between 1000°C and 1200°C. Thus, the temperature of a
drifting plate is about 1200°C at the side and bottom when the plate is
being created.) In any event, the thickness of a plate ranges from 0 km to
100 km, and it increases with age.

The thickness ($Z$) of a plate down to the 1200°C isotherm varies with
age as follows:

$$Z = 9.4t^{1/2} \text{ km}$$

Thus it thickens rapidly at first but is only about 30 km after 10 Ma, and it
does not reach 100 km for more than 100 Ma. The elastic thickness is the
thickness of the upper layer of the lithosphere that gives regional support
to loads. The elastic thickness also varies with $t^{1/2}$, but the constant is
much less than 9.4. Although some uncertainty still exists, it appears that
the elastic thickness is no more than 10 km at 10 Ma, and may not exceed
40 km at any age. In any event, it is established that large volcanic islands
on very young crust, like Iceland or the Galapagos Islands, are locally
supported. On the other hand, even large islands like Hawaii do not break
through old lithosphere and achieve local support. Instead, the litho-
sphere deforms like unbroken thin ice, and Hawaii rises from a deep that is
ringed by a broad, low arch. Smaller volcanic seamounts and islands have
similar but subtler effects on the lithosphere, depending on its age.
Midplate Swells

Although most of the sea floor is at a depth appropriate for its age, in some places it is anomalously shallow. The most noteworthy of these places are midplate swells, more or less circular or oval areas 500 km to 1000 km in diameter that are commonly 1000 m to 1500 m too shallow in the center. Midplate swells normally underlie volcanic islands; examples are the swells from which rise the Hawaiian, Marquesas, Society, and Samoan islands, in the Pacific, and the Cape Verde Islands, in the Atlantic. Indeed, most active volcanoes within plates are on swells and thus, presumably, most dead volcanoes were on swells when they were active. This speculation is confirmed by the relief of guyots, drowned ancient volcanic islands that were eroded down to sea level before they sank beneath the waves. The relief of a truncated island is the distance from the nearby deep sea floor to sea level. This relief is preserved if the truncated island sinks below the sea surface (when it stops being eroded), and thus the relief of a guyot indicates the local water depth when it was truncated by waves. Many guyots have a relief of 3000 m to 4000 m, indicating that they were truncated in water depths found only near the crest of midocean ridges or on midplate swells. It can be established that many guyots are much younger than the crust from which they rise; therefore, if they also have low relief, they were active on midplate swells rather than midocean ridges.

If the date of active volcanism of a guyot is known, and it was truncated rapidly, the date of truncation is known and thus the local water depth at that time. It will be shown later that the duration of truncation depends on the size of an island. However, for guyots with small summit platforms, truncation takes only a few million years, which is often within the margin of error for determining the date of active volcanism. Given the age of a guyot and the present depth of its summit, its average rate of subsidence can be calculated. In many circumstances, the guyot's relief can be taken to be the initial depth of the midplate swell on which the guyot grew. This information can be used to test hypotheses regarding the origin and history of midplate swells.

Three origins have been proposed for midplate swells: rising mantle convection that arches the lithosphere, addition of low-density material to a plate, causing it to rise isostatically, and thermal rejuvenation. The last hypothesis was proposed by Robert Detrick and the late Thomas Crouth in 1973. I had noted in 1969 that drilling of atolls in the Marshall Islands in the central Pacific showed that they were sinking at the same rate as younger lithosphere. Detrick and Crouth observed that many midplate swells have the depth of standard lithosphere with an age of 25 Ma. From
the drilling of atolls and the shape of the Hawaiian swell, they calculated that swells subside like 25-Ma lithosphere. They then reached the bold but logical conclusion, in 1978, that the lithosphere of swells has been *thermally rejuvenated*—thinned by heating from below and elevated by isostasy.

Marcia McNutt and I confirmed the value of thermal rejuvenation as an explanation for midplate swells in 1982. We had examined 33 isolated oceanic volcanoes, including twelve guyots. The volcanoes ranged in age from active to 90 Ma and were on lithosphere from 3 Ma to 163 Ma old. The depth of the lithosphere when volcanism ended was less than the standard depth for lithosphere of that age, so the volcanoes were or are active while on midplate swells. A plot of the depth of the swells when volcanism ended versus the age of the lithosphere at that time shows that lithosphere less than 12 Ma old had been uplifted to a depth of 2500 m to 2600 m—the same depth as the crest of midocean ridges. Older lithosphere had been uplifted to a depth that depended on its age. The relation can be expressed easily in terms of thermal rejuvenation—older lithosphere is commonly rejuvenated by about one third of its age. It is not rejuvenation by the fabled Fountain of Youth, but many a sixty-year-old would be happy to be forty again.

The midplate swells under our twelve guyots and the atolls of Enewetak and Midway sink at rates that depend on the age of the lithosphere—the younger the lithosphere, the faster the swells subside. But whatever the age, they subside faster than normal lithosphere of the same age. Once again, the relation can be expressed easily in terms of thermal rejuvenation—regardless of its age, the uplifted lithosphere subsides as though it had the age of normal sea floor with the same depth. A midocean ridge flank with an age of 15 Ma has a standard depth of about 4000 m. Older, deep lithosphere that is uplifted to 4000 m on a midplate swell subsides as though it were 15 Ma old.

**DRIFTING PLATES**

The fact that tectonic plates are rigid might seem entirely obvious because solid rock, such as Gibraltar, is the very image of rigidity. However, it is all a matter of scale and the duration of stressing. If the whole earth is shocked almost instantaneously by a great earthquake, it rings like a rigid bell at low frequencies appropriate for its size. On the other hand, geologists have known for a century that the very slow application of pressure to heated rock can cause it to deform like toothpaste or soft clay. The solid,
spherical cobbles of an ancient beach can be drawn into elongate shapes like pencils by the process of metamorphism. Thus, dealing as they do with millions and billions of years, geologists tend to think of the earth not as rigid but as yielding and plastic.

Moreover, a famous scientific paper in 1937 had demonstrated that it was impossible to lift up a large area of continental crust. (It had a striking cartoon of a giant crane lifting up the earth’s crust, 30 km thick, under the state of Texas.) The solid crust proved to be too weak to be lifted at the edges without sagging in the middle. Consequently, it was a considerable surprise to geologists and geophysicists when it was proved that enormous tectonic plates are rigid. Not in the vertical direction—plates do bob up and down locally by small amounts to maintain isostasy, and they cannot be lifted any more than Texas can—but horizontally, they are inflexible.

The rigidity of the plates was demonstrated by appeal to a theorem of the mathematician Leonhard Euler. This states that if one rigid shell moves over another without changing direction, two diametrically opposite points must remain fixed. These points are called Euler poles. The motion of any point on the moving shell may be considered as a rotation around an axis that connects the Euler poles. Relative to the inner shell, points on the moving shell traverse circular arcs centered on the Euler poles. If a tectonic plate is rigid, it can be considered a fragment of a spherical shell (the lithosphere) moving over an inner shell (the earth’s mantle). Then its movements must conform to Euler’s theorem.

If the Euler poles were, by coincidence, the poles of rotation of the earth, the circular arcs would exactly coincide with the parallels of latitude. In fact, they rarely do, so one must visualize Euler latitudes measured from the actual location of the Euler poles. The motion of a whole rigid plate can be described accurately only by an angular velocity around an Euler pole. The velocity of a given point, however, may be expressed usefully as a linear rate, usually as millimeters per year. This rate varies with Euler latitude from zero at the poles to a maximum at the Euler equator. The highest spreading rate known is 170 mm/yr, in the southeastern Pacific, but it may have been faster in Cretaceous time.

A point on the side of a drifting rigid plate, like all other points, must follow a circular arc, and thus the transform fault boundaries at the sides of plates must lie on circular arcs. The crust of the North Pacific was demonstrated to be a rigid plate—by analysis of the motion on the faults that bound it—by Dan McKenzie and Robert Parker in 1967. From California to Alaska to Japan, all the faults plotted along circles centered on an Euler pole near Greenland. Jason Morgan, also in 1967, showed that transform faults and fracture zones between plates lie along circular arcs around an Euler pole. Morgan also showed that, in the Atlantic, the widths of ma...
A hypothetical mid-ocean ridge superimposed on the Pacific Ocean. Because rigid plates drift apart in accord with Euler’s Theorem, the angular velocities are constant at different Euler latitudes, but the linear rates of relative motion are greatest at the Euler equator and least at the Euler pole.

Magnetic anomalies and thus the rates of spreading vary with the Euler latitude in exact correspondence with Euler’s theorem.

**Relative and Absolute Drifting**
Angular rotations around an Euler pole define the motion of one plate relative to another. The local spreading rate indicates how fast two plates are moving apart, but it implies nothing about their motion relative to the earth’s rotational poles or equator. Two plates can spread apart, for example, even though both are drifting west, if their rates of drift are different. If plate tectonics is to be useful in reconstructing geological history, it would be desirable to tie plate motion into a normal geographic framework. It is fairly easy to relate plate motion to the equator or poles because both the earth’s magnetic field and its climatic zones leave traces in the geological record. Latitude, for example, determines the dip angle of the
magnetic field, and the dip is recorded by the orientation of magnetic minerals, not only in volcanic rocks, but also in some kinds of sediment. Likewise, the global wind system influences the location of deserts and the orientation of sand dunes and plumes of volcanic ash.

Latitude is always relatively easy; longitude is the problem. The ancient Greeks could measure differences in latitude, but it was not until the eighteenth century A.D. that the invention of the chronometer permitted the determination of longitude. The difference in difficulty is easy to understand. The earth has a natural north and south pole and equator because it is spinning. Likewise, it is easy for a sailor to measure latitude from the position of the sun and stars relative to the horizon. In contrast, longitude is purely an arbitrary convenience for sailors and geographers. At one time, different western European nations made maps with a zero longitude through their national capitals. The present global acceptance of a zero longitude through the astronomical observatory at Greenwich, England, is a rather recent development. How, then, is there any hope of finding indicators of longitude in the geological record? Surprisingly enough, such indicators have been found. For the history of their discovery, it is necessary, as in most things related to oceanic islands, to go back to Charles Darwin on his five-year voyage on H.M.S. Beagle.

Volcanic Age Sequences

Darwin reached Tahiti in November 1835—still eleven months from home. The American geologist James Dwight Dana followed in 1839 on the multiship U.S. Exploring Expedition. Although the naturalist Sir Joseph Banks had seen the Pacific islands much earlier with Captain Cook, Darwin and Dana were the first geologists to do so. Darwin, it should be noted, considered himself at that time to be primarily a geologist. Between them, the two geologists discovered the orientation and age sequence of the Pacific islands that would enable Jason Morgan 130 years later to determine paleolongitudes. Darwin's theory of the origin of atolls will be discussed at length in Chapter 7. Briefly, he conceived that volcanic islands subside and that, in coral seas, the subsidence transforms the peaks that fringe the volcanoes into barrier reefs and later into atolls. Thus, different types of islands represent stages of development. With less certainty, islands can be compared, and an atoll can be taken to be older than an extinct volcano with a barrier reef. Darwin, however, ventured no such comparisons.

Darwin did not publish his theory in detail until his book The Structure and Distribution of Coral Reefs came out in 1842. However, he obviously talked about it long before then because Dana read about it in a newspaper in Sydney, Australia, in 1839. Dana was electrified by the
theory, because he had already come to similar ideas—and he was still in a position to test them on the Exploring Expedition. It was he who would be able to correlate the relative age of islands with their distribution.

From Sydney, the U.S. Exploring Expedition sailed on to the volcanic islands in Samoa and Hawaii. Three months in the latter group gave Dana a remarkable insight. Nothing could be more obvious to a geologist than an age sequence in the Hawaiian Islands. Flying in from the south, one first sees the smooth cap of the gigantic active volcanoes of the island of Hawaii. Then past Maui to Oahu and Kauai, the islands are ever more deeply eroded into knife-edge ridges and enormous valleys. Assuming only an equal intensity of erosion, the age sequence is manifest. Dana deduced all this at a time when few scientists even believed that valleys are eroded by the streams that run through them. Dana concluded that depth of erosion “is therefore a mark of time and affords evidence of the most decisive character.” Darwin, in the same circumstances, might not have drawn any such conclusion because he thought that most valleys had been eroded by ocean waves. However, his views were derived from field trips in the complex continental rocks of home.

Dana was cautious in extrapolating from what he knew, namely that the order of extinction of volcanoes was Kauai, west Oahu, west Maui, east Oahu, northwest Hawaii, southeast Maui, and southeast Hawaii. His relative order of extinction of pairs of volcanoes on individual islands was completely correct, because he could see where erosion had exposed the overlap of the younger volcano on the older. The erosional age sequence

Different stages of erosion on the young island of Hawaii (left) and the older island of Molokai (right).
from island to island differed slightly from the sequence of extinction of individual volcanoes, but Dana thought that perhaps this was so only because minor, local volcanism continued long after a great pulse of rapid activity built the vast bulk of the shield volcanoes. Dana's ideas on the commencement of eruptions were limited because "no facts can be pointed to which render it even probable that Hawaii is of more recent origin than Kauai, although more recent in its latest eruptions." He thought that eruptions might have commenced in early Paleozoic time—perhaps 400 Ma ago. Dana, the discoverer, seems to have been one of the few scientists to make any distinction between the sequences of origin and extinction of volcanic archipelagoes.

Dana had personally visited the major volcanic archipelagoes of the Pacific and, like any scientist who works with nautical charts for years at sea, he knew that the islands had the same west-northwest trend. Thus, after his analysis of the Hawaiian group, he was prepared to opine that the Society Islands were "first extinct at the northwest end." Dana did not know of the active volcanoes at the southeastern end of the Society Islands because they have not yet grown above the sea surface. However, Mehetia, the island between Tahiti and the active seamounts, has had recent lava flows. Farther to the northwest are a series of deeply eroded islands beginning with Tahiti. The most notable feature of the islands is that the lagoons grow broader as one sails to the northwest. At the north ern end of the archipelago, the central volcano disappears, and all that remains is an atoll—a lagoon circled by a reef. Dana's age progression in the Society Islands thus was a side-by-side display of what Darwin visualized as the stages, one above another, in the subsidence of individual islands.

In the Hawaiian Islands, there were reef-circled pinnacles northwest of Kauai, and beyond them were atolls. The age sequences in the Society and Hawaiian islands were in the same direction. Dana found a third sequence from active volcano to atoll in the Samoan group, but it was in the opposite direction. Dana sent Darwin a copy of his Geology of the U.S. Exploring Expedition when it was published, in 1849. Darwin responded "last night I ascended the peaks of Tahiti with you . . . " The whole scientific world was aware of the remarkable age progression of the Pacific islands.

The discovery of Midway atoll, in 1859, was the last to be made on the surface of the sea. However, the vast floor of the sea between the sparse islands was unknown. It remained so until the end of World War II, when advances in anti-submarine warfare yielded superior echo sounders. The 1950s became a golden age of deep-sea exploration, and geologists once again addressed the questions about oceanic islands that had been
raised a century before. The Dana age progression was a central fact of island geology, and it might have been expected to dominate hypotheses regarding the origin of Pacific islands, but it did not. The ideal of the explorers in the 1950s was Harry Hess, who had discovered the guyots (predicted by Darwin) during the war. Perhaps the reason the Dana progression was ignored at first was because Hess had ignored it in his explanation of the origin of the Hawaiian Islands. He proposed that fissures and tension cracks had opened along a great “transcurrent” fault—one of a class of faults that are typically straight and have only horizontal motion. Inasmuch as the whole length of such a fault is active at once (on a geological time scale), an age progression would hardly be expected and none was mentioned.

As sea-floor exploration progressed in the 1950s, the islands tended to be ignored because so many large undersea volcanoes were discovered. These were of two general types: flat-topped guyots, which were drowned ancient islands, and pointed-topped seamounts, which had never been truncated by waves. The guyots were assumed to be geologically old, at least old enough to grow 4 km to 5 km up from the sea floor, be truncated, and sink to various depths. Moreover, some were dredged and proved to be roughly 100 Ma old. Many of the seamounts and guyots were in lineations trending northwest—like Dana’s island chains with age progressions. However, some groups, such as the Emperor Seamounts, had a distinctively different trend that was almost due north. This was particularly intriguing because the purely submarine Emperor trend was clearly an extension of the Hawaiian trend with a connection at a “bend” or “elbow.” Moreover, the Hawaiian trend itself seemed to continue even beyond Midway atoll. Evidently, another stage of submergence carried even atolls beneath the waves.

The discovery of the Emperor-Hawaii bend might have made it clear that the lineations were produced by some process that acted sequentially and could change directions. However, these facts were clouded by other discoveries. Some groups of guyots, such as the Mid-Pacific Mountains, were in clusters rather than lineations. Some lineations seemed to overlap rather than meet at a bend. Most confusing of all, in many places, atolls, barrier reefs, high islands, and guyots were all mixed together. The reality of the age progression seemed highly questionable.

In 1957 L. J. Chubb made a considerable advance by simply ignoring the sea-floor discoveries. First he showed that almost all the high islands in the Pacific have west-northwesterly trends. Not just the ones noted by Dana, but four other groups as well. But atolls are relatively senile chains of islands, and Chubb showed that they have a different trend that is more northwesterly. He would have included most of the submarine volcanoes
in his generalization that the "direction of earth-movements" had changed gradually during geological time from NNW to NW to WNW.

**Hot Spots**

The nature of these "earth-movements" was proposed by J. Tuzo Wilson in 1963. Harry Hess and Robert Dietz had already proposed that the oceanic crust is created at the crest of midocean ridges and spreads to each side. But Hess called his hypothesis "geopoetry," and Dietz viewed his seminal paper as a "pot boiler"; few people took sea-floor spreading seriously in 1963. Wilson did. He proposed that the sea floor spreads because it is carried along by convection currents that rise from deep in the mantle in thin sheets, flow horizontally beneath the crust, and then return to the mantle in thin sheets. That left a motionless core in each convection cell. Wilson visualized in this core a fixed source of lava, which would rise to build volcanoes. The horizontal convective flow would carry volcanoes away from the source, and the result would be a linear age progression of volcanoes.

But the reality of the age progressions still had to be confirmed. In 1964, Ian McDougall (and later, Brent Dalrymple and others) began to publish the ages of insular volcanic rocks. Dana had been sure only of the sequence in which the volcanoes became inactive. The isotope geochemists showed that each giant island in the Pacific was produced in only a million years or so, and, although there was minor volcanism later, the Dana progression indeed gave the sequence of island formation.

In 1972, Jason Morgan, one of the inventors of plate tectonics, applied it to the problem of the lineations of islands. He showed that the island lineations of the Pacific plot as circular arcs around an Euler pole and that the spacing of islands in the age progressions depends on the Euler latitude. However, the islands do not indicate relative motion between rigid plates but relative motion between one rigid plate and a framework of lava sources called hot spots, in the mantle. If the mantle itself is considered motionless and hot spots do not move around in it, Morgan had tied the past motion of plates into the present geographical framework.

Lines of volcanoes have come to be called hot-spot tracks, and they have been studied intensely all over the world. The tracks on different plates can be compared from a knowledge of the relative motion between plates. It appears that hot spots do indeed lie in a fairly rigid framework imbedded in the mantle. So-called "absolute motion" of plates is relative to this framework. Individual hot spots persist for 10 Ma to 100 Ma or

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The Emperor Quots and the Hawaiian Islands are a single chain of volcanoes formed as the Pacific plate drifted over the Hawaiian hot spot. Presumably, the volcanoes at the bend were active when the plate changed direction.
In this northward view of an imaginary, simplified ocean basin, two plates spread apart at a mid-ocean ridge, which is offset by a large transform fault in the middle distance.

The shiny black lava produced at the spreading ridge is quickly covered by sediment, white from the calcium carbonate shells of dead protozoans, that rains down from the surface layers of the ocean. As the drifting plates cool and thicken, they subside. In water more than about four kilometers deep, calcium carbonate dissolves and the accumulating sediment is a rich brown color.

Both plates happen also to be moving due north, at right angles to the spreading movement. The overall direction of drift can be seen in the lines of volcanoes formed as the plates drift over hot spots fixed in the earth's mantle.

The volcanos rising from the hot spot in the foreground are in tropical waters. Like the older, dead volcanos that arose from this hot spot, it is destined to acquire coral reefs and become an atoll as it drifts off the midplate swell over the hot spot. The other hot spots are in cooler waters. Unprotected by coral, these volcanos are quickly plowed off by erosion and sink beneath the sea in gravity.

At left and right, the oceanic plates plunge into the mantle at subduction trenches. Melted material from the plunging plates rises to form lines of volcanoes parallel to the trenches.
V-shaped submarine ridges of the South Atlantic. Many such ridges were once islands.

more, and, if they drift, it is by no more than a few millimeters per year. Their characteristics indicate that they consist of long, narrow plumes of magma rising from the hot lower mantle. These fixed plumes penetrate the lithosphere and rapidly build volcanoes, which become extinct when drifting separates them from the source area.

Morgan's analysis included the origin of the Emperor-Hawaii bend. Inasmuch as the hot spots are fixed, the Pacific plate simply changed its direction of motion without interrupting the production of volcanoes. From other hot-spot tracks of the same age as the Emperor trend, an older Euler pole was established and with it the motion of all such tracks for about 80 Ma in the Pacific.

**Hot-spot Tracks and Plate Boundaries**

Hot-spot tracks were first discovered in the interior of a drifting plate. However, plate boundaries also drift. What happens when a spreading center or a transform fault passes over a hot spot? Iceland sits astride the Mid-Atlantic Ridge, which is spreading apart slowly. Voluminous flows from numerous volcanoes keep the opening rift filled, but what if volcanism ceased? The island would split and the separate halves would drift away on their respective plates. Exactly this phenomenon has occurred
many times. In the South Atlantic, for example, are two submarine volcanic ridges making a V, with the base on the crest of the Mid-Atlantic Ridge. The V was generated because the mid-ocean ridge crest was over a hot spot but each flanking plate was drifting north as well as spreading east or west. The American plate, in short, drifted northwest, and the African plate drifted northeast. Very detailed studies of spreading centers by means of research submersibles have found tiny volcanoes that have split apart. Likewise, regional mapping discloses pairs of volcanoes that are symmetrical around a spreading center. Thus, this phenomenon of splitting volcanoes is a commonplace—as might be expected, considering the coincidence of spreading and volcanism that is required to generate the oceanic crust.

A rarer phenomenon is the drifting of an active transform fault over a hot spot, but examples may exist. Visualize what would happen if an east-west ridge-ridge transform fault were to drift toward the north over the Hawaiian hot spot. The present line of volcanoes on the western plate would continue to drift toward the northwest and still point toward the hot spot. However, the volcanoes that were subsequently built on the eastern plate would drift toward the northeast away from the hot spot. The volcanoes would form a fragmented V with two sections missing. Something of the sort apparently happened in both the South Atlantic and the South Pacific but the geological histories are not yet firmly established. In any event, the simplicity of the theory of plate tectonics makes it possible to predict the consequences of the intersection of a plate boundary and a hot spot.
Sea Level

The coastal zone of an island is the locus of a wide range of distinctive phenomena that may be preserved in the geological record. To pick the most obvious examples, coral reefs grow only in shallow water and waves attack only the shoreline. In contrast, the biological and geological zones above and below sea level are much less sharply defined. Thus the indicators of sea level provide the best hope of unraveling the history of vertical movements of islands. Islands are dip-sticks that record the changing distances from the sea floor to the sea surface. Unfortunately, the record locally is the same if the sea floor goes down or the sea surface goes up, and the history of sea level changes is not necessarily informative about causes.

With regard to the vertical movement of islands relative to sea level, three factors are known to be geologically important, namely, cooling of tectonic plates, global fluctuations of sea level, and isostatic compensation for loading and unloading. Probably, local relative sea level is also affected by such factors as mantle convection and changes in rotation of the earth, but, if so, the effects have not been identified for certain in the geological record.

We have already considered the most important factor that influences the long-term vertical motion of islands. They stand on a lithosphere that is sinking at a rate determined by its age or its thermally rejuvenated age. Lithospheric cooling can pull an island down 1000 m in less than 10 Ma and 2500 m in 60 Ma. No other known or suspected effect is as large, so, in the absence of contrary evidence, it can always be assumed that an island is sinking relative to sea level. However, the rate of thermal subsidence decreases rapidly from 36 centimeters per thousand years to a com-
mon value of about a tenth of that, and other phenomena cause smaller but much more rapid fluctuations in relative sea level. Consequently, in the short term, an island may emerge or may submerge more rapidly than expected from thermal subsidence. Nonetheless, the effects of thermal subsidence are firmly established, and any deviation from the expected rate is in itself an anomaly that needs explanation. The factor of thermal subsidence, in short, is reasonably well isolated.

The second known factor is global change in sea level. Such a change is called eustatic, meaning that the whole sea surface fluctuates by the same amount. The causes and characteristics of eustatic changes will be discussed in this chapter.

The third known factor is isostatic compensation, which acts in response to something else. If thermal subsidence tends to pull an island under water, the additional volume of displaced water will tend to buoy it up—thus reducing the expected change in relative sea level. If a eustatic drop in sea level tends to elevate an island, the lessening of buoyancy will tend to pull the island down—thus also reducing the expected change in relative sea level. Fortunately, the effects of isostatic compensation in many circumstances are qualitatively well known and can even be calculated with confidence. In sum, the most uncertain factor affecting the apparent vertical movement of islands is the eustatic shift of sea level.

**RELATIVE CHANGES**

The position of sea level varies every second because of waves, tides, and longer-term oscillations. Thus, a useful "level" can be established only by averaging measurements over a year or more; this has been done with tide gauges in hundreds of places for as long as two centuries. Annual mean values are accurate to a millimeter, and with such accuracies and periods of observation it has been shown that many tide gauges have moved relative to a mean sea surface.

For periods longer than a century or two, it is necessary to use "tide gauges" derived from historical or geological rather than physical observations. The discovery of the ruins of a Greek temple in water five meters deep would be historical evidence of a local change in relative sea level. Such evidence is rarely accurate to more than a few meters; for example, the temple has subsided at least 5 m but may have gone down much more if its base was above sea level initially.
The important geological indicators of changes in sea level are of two types, biological and erosional-depositional. There are many organisms that live only within a few meters of sea level, but by far the most important for our purposes are reef corals. Elevated coral reefs are found widely on the unstable islands of subduction zones and rarely elsewhere. They are certain indicators of elevation, and they can be dated by isotope geochemistry. Unfortunately, coral reefs are not such accurate physiographic indicators of submergence, because they are usually capable of growing up to fill the gap to sea level. However, as Darwin pointed out, coral reefs are alive and some die when they are submerged. Moreover, drilled reefs give stratigraphic evidence of submergence. Layers of reef rock have been deposited one on another for as much as forty million years.

The other important geological indicators of sea level are wave-cut benches and terraces and the sea cliffs that rise above them. Waves are remarkably effective in eroding even the hardest rock. Growing volcanic islands in the sea are terraced and cliffed between eruptions. In softer sedimentary rock or the sand and mud of the coastal zone, wave erosion is even faster. Thus it may be assumed that any stand of sea level will be recorded by wave erosion within a few meters of sea level. Moreover, waves and currents build beaches, lagoons, and offshore bars, and these may also be preserved as indicators of sea level or, at least, shallow water. These erosional and depositional indicators of sea level are widely observed at tens and hundreds of meters above and below sea level. Thus,
even though they are not as accurate as tide gauges, they are accurate enough to be useful.

A problem with coral reefs, wave-cut terraces, and beach deposits is that they are commonly destroyed or buried in a geologically brief time. Oceanic islands themselves do not persist very long, either, so the reefs and benches may endure as long enough to indicate uplift. However, after only a few million years, elevated reefs, for example, may be so modified by solution and erosion as to be unreliable indicators of the amount of uplift.

As it happens, the indicators of sea level are preserved when oceanic islands are submerged rather than uplifted, but not enough atolls and guyots have been drilled to demonstrate a consistent geological history. In contrast, the continental margins have been explored extensively in the search for oil. The geological history of a continental margin, unlike that of an oceanic island, is vastly complicated by deposition of sediment eroded from the adjacent continent. Nonetheless, hundreds of holes have revealed the geological history of the points where they are drilled, and the structure of the wide areas between holes has been tied to them by a technique called seismic stratigraphy. Rocks are relatively transparent to low-frequency energy, such as the vibrations produced by explosions, and thus it is possible to map the boundaries between layers of different kinds of rock just as a higher-frequency echo sounder can map the boundary between the sea and its floor. The seismic reflectors can be identified where they intersect the holes.

Exploration has been so intense in many places that relative changes in sea level have been identified. The stratigraphic indicators of these changes consist of patterns of onlap and offlap of coastal and marine sediments, and erosional gaps when there was no deposition. As sea level rises, the shoreline moves inland and beach sands and other coastal sediments lap onto the land. Behind them, marine deposits thicken if they build up to maintain a constant water depth. When sea level falls, the coastal and marine sediments are exposed to erosion, and a temporal gap in the stratigraphic record is created. This simple picture is complicated by the flux of sediment into and out of the region. Nevertheless, the method has been highly successful, although the cause of the fluctuations that it has identified remains controversial.

**Local and Regional Warping**

Historical and geological indicators of fluctuations in sea level are widespread, and the causes of those fluctuations have been sought for centu-
The Temple of Serapis near Naples.

The uplift of Scandinavia (in meters) since the ice cap melted.

ries. The famous Greek temple of Serapis near Naples, for example, was studied by Darwin's mentor, Sir Charles Lyell. Boring by marine molluscs prove that it has been partly submerged more than once. However, the evidence for similar vertical movements is lacking elsewhere in the area, so the cause is local. It is, we now know, the swelling and detumescence of a nearby volcanic region. Likewise, the uplift of Scandinavia was long ago obvious because ancient seaports became unusually shallow, then emerged, and gradually became elevated above a receding shoreline. This uplift extended from Denmark to the northern tip of Norway and from the Atlantic to eastern Finland. Nonetheless, it was a local phenomenon with a local cause. During the ice ages of the past million years, the whole region that now has elevated shorelines was covered by a continental ice cap centered in the northern end of what is now the Gulf of Bothnia. The load of the ice on the continental crust made a dish-shaped depression surrounded by a peripheral bulge. When the ice began to melt, the warped rocks began to resume their original shape. At the shrinking periphery of the ice, the sea cut terraces and left dateable marine fossils. By correlating terraces of the same age, it is possible to map the amount and rate of uplift of the deglaciated region. The center has been uplifted 500 m, and the amount of uplift is progressively less toward the edges of the former ice.
cap. Moreover, exactly the same evidence of differential, regional uplift can be obtained with tide gauges. Near Copenhagen, the sea floor is rising at 3 cm per century; at Stockholm the rise is 50 cm per century, and at the northern end of the Gulf of Bothnia it is 110 cm per century. All these phenomena are also observed in North America, where there was another ice cap.

The most conspicuous evidence for historical changes in sea level is all associated with local or regional causes, but geologists have tended to seek global causes for more ancient uplifted terraces and reefs. Thus, the abundant evidence of elevated shorelines on Pacific islands has been attributed to several eustatic changes in sea level. In fact, most if not all are caused by the warping of converging tectonic plates or by local loading by young volcanoes (as explained in Chapter 8). The apparent lack of evidence for higher eustatic sea levels in ancient times is a puzzle, because the melting of existing glaciers would produce it, and the glaciers have not always existed. However, when glaciers were much more extensive, sea level was lower and left clear evidence to prove it.

**EUSTATIC CHANGES**

The many factors that affect sea level are of three types, namely, changes in the density of sea water, changes in its mass, and changes in the shape of the sea basin. As to the first type, tide-gauge records indicate regional changes in sea level that vary with the seasons. In Hawaii, for example, summer heating and expansion of surface waters causes sea level to be 18 cm higher in the early fall than in the spring. Reasonable historical variations in heating, salinity, and air pressure can cause other regional or even hemispheric heating variations as great as 20 cm. Variations due to this cause during geological time may be larger; heating the whole ocean by 10°C would raise sea level by about 6 m, and the sea certainly has been much warmer than it is now. Changes in sea level from variations in density alone are not large compared with other causes, but they occur constantly and it must be assumed that, in addition to the rapid movement of waves and tides, sea level itself is fluctuating hemispherically or globally on a time scale of months or years.

The second cause of change in sea level is variation in the mass of the sea. Changes in density are minor, so changes in mass can be equated to changes in volume. These can occur by the transfer of water between the sea and the interior of the earth, the atmosphere, rivers and lakes, ground-
Distribution of terrestrial water \(\left(10^9 \text{ km}^3\right)\)

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mantle</td>
<td>4,600,000</td>
</tr>
<tr>
<td>Ocean</td>
<td>1,350</td>
</tr>
<tr>
<td>Groundwater</td>
<td>200</td>
</tr>
<tr>
<td>Ice (at present)</td>
<td>30</td>
</tr>
<tr>
<td>Ice (at glacial maximum)</td>
<td>90</td>
</tr>
<tr>
<td>Rivers and lakes</td>
<td>0.5</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.01</td>
</tr>
</tbody>
</table>

No other planet has an ocean, and there is no reason to believe that the earth had one in the early days when, like the other planets and the moon, it was still being bombarded by meteorites. Instead, it is generally accepted that the ocean has evolved gradually by outgassing from the mantle. The number in the table is based on the ordinary assumption that the mantle has the composition of stony meteorites; if so, it clearly is an adequate source for all surface water. What is not agreed upon is the rate at which the ocean grew. Geological evidence indicates that the salinity of the ocean has not varied enough to produce major biological or sedimentary changes. This argues for a relatively constant rate of growth. For present purposes we are concerned only with the last 100 Ma, because there are no older oceanic islands, or even guyots. In that time, growth of the ocean at a constant rate, say, 0.1 cm per thousand years, would have raised sea level by 100 m. It is uncertain that any such rise took place; even if it did, it would have few geological effects. It would not drown the continents because their level is adjusted by isostasy to such slow and persistent changes in sea level. It would not affect the erosion of islands or the life of coral reefs because it is much too gradual. The only effect of any consequences with regard to islands is that ancient guyots might be 100 m deeper than otherwise expected. No such effect is observed. On the contrary, as we shall find, ancient guyots are anomalously shallow. If there has been any significant increase in the volume of the ocean in the past hundred million years, the effect on sea level has been completely masked by other effects.

Turning to other sources and sinks of seawater, it is evident that the atmosphere, lakes, and rivers do not, and moreover cannot, store enough water to have any important effect on sea level. There is an extremely rapid flux of water to and from the ocean through the air and rivers but the volume is insignificant. The relation is just the opposite for groundwater buried in ancient sedimentary rocks. That volume is significant but the flux, caused by erosion and deposition, is extremely slow, so probably it, too has not affected sea level in the geological period of interest.

That leaves ice. If the Antarctic and Greenland ice caps were to melt, sea level would rise about 50 m even after isostatic adjustment. (That is one of the reasons to be concerned about global heating through excessive burning of fossil fuels and the greenhouse effect.) The continental glaciers repeatedly were much more extensive in Pleistocene time than now, and it is estimated that sea level was lowered 150 m to 200 m several times. The
rates and geological consequences of these extremely important fluctuations in sea level will shortly be discussed. Suffice it to say for the moment that fluctuations at such rates and on such a scale have not been typical of most of geological time.

The third cause of change in sea level is variation in the shape of the ocean basins. For example, the growth of submarine volcanoes and deposition of marine sediment elevate sea level. Geologists used to assume that these effects were cumulative and, indeed, it was initially proposed that geysers are deep because eons of slow sedimentation had gradually raised sea level. However, the discovery of plate tectonics eliminated that assumption. The sea floor is relatively young, and all the older marine volcanoes and sediment have been swept onto the continents or down into the mantle. It is now reasonable to assume that for each lava flow or grain of sand that enters the ocean, one is lost by subduction in trenches, so sea level is unaffected by these processes.

A global balance of evaporation and precipitation may also be assumed to leave sea level unaffected, but occasionally there may be an imbalance because of a change in the shape of the ocean basins. This occurred about 5.5 Ma ago, when the Mediterranean region was tectonically isolated from the Atlantic. The global average rate of evaporation is about a meter per year and, in the Mediterranean basin, that was not balanced by rain and rivers. In a geological trice, much of the Mediterranean became a salt-encrusted desert and the rivers were cutting enormous canyons down what had been (and would again be) the continental slope. The evaporated water of the Mediterranean Sea had to be transferred to the world ocean and thereby raise sea level, but, at most, the rise was only 10 m. That rise disappeared in a geological instant when the Atlantic spilled over the Straits of Gibraltar in a gigantic waterfall. Isolation of ocean basins appears to be rare, but it can cause rapid eustatic changes in sea level.

The only other known way to alter the volume of an ocean basin significantly is by a change in the volume of mid-ocean ridges. This may occur by a change in the length of spreading centers or in the rate of spreading. Ridge crests are constantly being shortened by subduction and lengthened by propagation. Inasmuch as the crests are shallow and displace water, these variations affect sea level. Unfortunately, the effects are difficult or impossible to quantify because subducted ridges cannot even be counted let alone measured.

In contrast, the effects of a change in spreading rate can be calculated with confidence. For the purposes of illustration, consider the consequences if the spreading rate became infinite. The ocean basins would all
be about 2500 m deep and the continents would be deeply flooded. Clearly, a more probable increase in spreading rate would also flood the continental margins and, from the relation of sea-floor depth to age, the amount of flooding could be calculated. As it happens, the continental margins about 100 Ma ago were flooded, and the cause is believed to be accelerated sea-floor spreading.

The Past 35,000 Years

Fluctuations in sea level during the past 35,000 years are relatively easy to determine, because fossil shorelines are abundant and they can be dated by the radiocarbon content of shells and wood. The fluctuations differed from place to place because of noneustatic effects. However, global eustatic effects are clear. Sea level from 35,000 to 30,000 years ago was near the present level. By 16,000 years ago, it was 130 m lower because of the growth of glaciers. About 14,000 years ago, sea level began to rise rapidly, but it slowed 7000 years ago and has been relatively constant for the last 5000 years. Reginald Daly, who first realized the effects of glacial-eustatic fluctuations on islands, thought sea level had been about 5 m higher than now in relatively recent time. There is a narrow bench and a nip in sea cliffs at that height on some islands, but it is not now thought to be due to eustatic change.

The maximum rate of eustatic change was about 1000 cm per thousand years for periods of 5000 to 10,000 years. Except possibly for the
A wave-cut bench and nip in a sea cliff in the Gambier Islands. The bench is about one meter above the present mean sea level.

Evaporation and flooding of the Mediterranean basin, these glacial-eustatic fluctuations are by far the fastest known. They are roughly 1000 times faster than fluctuations caused by variations in the speed of sea-floor spreading. They are 30 to 50 times faster than the thermal subsidence of the sea floor. Thus it can be assumed that, whenever there are large continental ice caps, glacial-eustatic fluctuations will wholly dominate the movement of sea level relative to an island.

The principal effects of rapid fluctuations of sea level on islands depend on the efficiency of wave erosion and the life of coral reefs. With regard to waves, the entire depth of the ocean is affected by wave motions such as tsunamis and tides. However, the abyssal motion is capable of no more than stirring sediment. Almost all wave energy of geological interest is expended by the breaking of surface waves at the shoreline in depths of less than 10 m. During a long still-stand of sea level, waves should cut a gently sloping rocky terrace on which wave energy is lost to sediment transport and friction. Thus, the most important effect of rapid fluctuations in sea level is to expose a coastal band to the shallow depths of vigorous abrasion by waves. Most continental and insular shelves are less than 130 m deep, and consequently the shoreline has swept across them twice in the last 35,000 years.

Coral reefs can grow so rapidly that they should always be as high as the highest stand of sea level. If there had been a eustatic sea level 5 m
higher than at present, all atolls should now rise that high, but they do not. On the other hand, all atolls were coral islands 130 m high 16,000 years ago. Many atolls that are presently drowned also were then exposed, to lesser heights. Just what then happened to the reefs is conjectural and will be discussed after consideration of repeated glacial-eustatic fluctuations in Pleistocene time.

The Past Million Years

Continental ice caps have developed and vanished several times in the history of the earth, so their existence at present is not proof of secular cooling. Nonetheless, a trend toward the growth of ice caps has continued now for 30 million years. Some ice has existed in Antarctica during that entire period, and the eastern ice sheet developed by 16 Ma ago. The western Antarctic ice sheet followed 5.5 Ma ago. In the Northern Hemisphere, glaciers began about 2.4 Ma ago, and during the last million years or so continental ice caps formed repeatedly. It appears that the fluctuations are strongly influenced by periodic variations in the earth's tilt and precession, which, in turn, influence solar heating at the earth's surface. Inasmuch as the astronomical factors are well known, it appears possible to date glacial fluctuations when other methods are lacking.

In New Guinea, the repeated eustatic rise and fall of sea level combined with the steady uplift of the shoreline to create a giant staircase of dead reefs.
The influence of astronomical cycles on eustatic changes in sea level has been confirmed by dating elevated coral reefs on Barbados and New Guinea. Both these islands have been uplifted gradually, as a consequence of the horizontal compression in subduction zones, and the reefs resemble giant staircases. Both the tops and faces of the individual reefs in each sequence have been dated and found to correspond to the schedule of astronomical fluctuations of insolation. It is necessary to make only the simplifying assumption that the uplift has been at a constant rate in order to generate a complete history of sea level for the last 140,000 years. This type of study indicates that sea level was a few meters higher than now about 125,000 years ago but has since been lower until recently. In the interval, it fluctuated up and down by 40 m to 60 m six times. Every time sea level went down, a reef died and was gradually elevated to become the bottom step in the staircase. Meanwhile, when sea level again rose rapidly compared with the elevation of the land, a new reef grew upward and in turn died to become a new bottom step.

Glaciers leave obvious evidence of their existence, but the record on land is complicated by the fact that younger glaciers may override the traces of older ones. From this continental record, geologists concluded that there were four glacial and interglacial periods in Pleistocene time, about the past million years. However the astronomically determined periods of low insolation were far more frequent, and the waxing and waning of glaciers probably was correspondingly variable. For present purposes, it may be assumed that sea level fluctuated by significant amounts scores of times. Likewise, reefs and atolls were repeatedly exposed and elevated by more than 100 m and perhaps as much as 200 m.

What happened to the atolls when they were elevated? The answer is still uncertain, perhaps because there were large local variations. At present it is apparent that some uplifted coral reefs are being dissolved at or just above sea level. Thus, the uplifted atolls of Pleistocene time might have been dissolved away and replaced by a new reef whenever sea level again rose. This hypothesis is supported by the correlation between rainfall and the depths of atoll lagoons. Rain can slowly dissolve elevated reefs, and the depth to which an elevated atoll was dissolved thus might vary with rainfall. The broad, relatively flat floor of the central lagoon of an atoll presumably rests on or above the level of the surface of solution when the atoll was elevated. Atoll lagoons range in depth from 0 m to 150 m, and tropical rainfall in the open ocean ranges from 40 cm to 520 cm per year. Thus, there is great variability, and it is striking that lagoon depth within many island groups varies systematically with rainfall. However, there is no systematic variation from one group to another. The deepest
Lagoon in the Ellis Islands, for example, is about the same depth as the shallowest one in the Maldives although the Ellis group has the greater rainfall. Thus, factors other than rainfall must be very important in the history of elevated atolls.

The best kind of information available about the effects of swelling sea level on atolls comes from drilling, but it is regrettably sparse. The Pleistocene reefs of three atolls, Eniwetak, Bikini, and Mururoa, have been drilled in connection with nuclear tests. The stratigraphy may be summarized as follows:

- 0 m–10 m  coral less than 6000 years old
- Erosional unconformity
- 10 m–20 m  coral 120,000 to 150,000 years old
- Erosional unconformity
- 20 m–50 m  coral more than 500,000 years old
- Erosional unconformity
- 50 m–82 m  undated coral
- Erosional unconformity

The reefs apparently had a consistent history, although data are scant and generalizations may be risky. During the past 6000 years, 6 m to 10 m of coral has grown upward during a period of relatively stable sea level. Between 120,000 and 6000 years ago, when sea level was lower than now,
although fluctuating, the reef was eroded. Between 150,000 and 120,000 years ago, when sea level was high, from 10 m to 12 m of coral built up. Before that was a period of erosion beginning more than 500,000 years ago. The earlier events are obscure, but there were two more cycles of alternating erosion and deposition, giving a total of four. The history indicates several facts about the relationship between these atolls and sea level. First, coral accumulated only during high stands of sea level. Second, intervals of erosion were much longer than those of accumulation. Third, coral 120,000 years old is at only about 10 m and thus it was not dissolved very deeply, if at all, when sea level was at its lowest. Nor, during the last 500,000 years, has solution extended below 20 m.

The sparse but high-quality data from drilling suggest that not very much happened to elevated atolls. Presumably the same minor amount of solution has taken place on existing elevated atolls, but no major erosion. The drilling data also suggest a rise in sea level relative to the atolls. In New Guinea, the gradual elevation of the sloping land and fluctuation of the sea produce one reef beside another. In the main ocean basins, the gradual submergence of the sea floor and fluctuation of the sea produce one reef on top of another, with periods of erosion in between.

**Tertiary and Cretaceous Sea Level**

The Tertiary Period, extending from about 65 Ma to 1 Ma ago, had important fluctuations in sea level, according to the interpretation of the seismic stratigraphy of continental margins by Peter Vail and colleagues. They believe that sea level was generally higher than now for the first half of Tertiary time and that the most important single event was a rapid drop in Oligocene time, about 30 Ma ago. The onlaps and offlaps of the stratigraphic record may indicate both changes in sea level and changes in rate of subsidence of continental margins. In any event, the actual amount of these relative changes is conjectural. Nonetheless, it appears probable that fluctuations in sea level during Tertiary time occasionally exposed atolls and the insular shelves of volcanic islands to erosion. These do not seem like favorable conditions for the growth of atolls, but, curiously enough, most if not all existing atolls are of Tertiary age.

The geological history of sea level in Cretaceous time, from 135 Ma to 65 Ma ago, is notable for a rise that caused broad shallow seas to spread even to the interiors of continents. Seismic stratigraphy indicates few fluctuations in this gradual rise. Consequently the islands of Cretaceous time were rarely elevated and exposed to accelerated erosion. Instead, they were ordinarily submerged rather rapidly by the combination of ther-
nal subsidence and a rise in sea level. These circumstances presumably would have been highly favorable for reef organisms of Tertiary time, but they were not for Cretaceous reef builders. Certainly the Cretaceous reefs did not ordinarily, if ever, grow up to become the platforms of Tertiary atolls. Instead they died and went down with the numerous Cretaceous islands that became the guyots of the western Pacific.
Islands Without Coral

We have followed the growth of solitary volcanoes from the deep sea floor up into the air to form islands. In the reverse process, they are eroded by stream and wave and eventually are pulled back underwater by thermal subsidence. We may visualize four stages in the life of a volcanic island in water free of coral. A brief period ($10^5$ years) of submarine growth, a longer ($10^6$ years) period of both subaerial growth and erosion, then from $10^6$ to $10^7$ years of subaerial erosion, and from $10^7$ to $10^8$ years of increasingly deep submergence until the volcano reaches a subduction zone.

During the second stage, volcanism normally overwhelms erosion and is able to build great peaks with smooth slopes like those of Mauna Loa and the Galapagos Islands. Even in this phase, however, erosion may locally be dominant, and the volcano may have to rebuild its slopes repeatedly. Soon after the initial shield-building phase ends, erosion is uncontested, but even then it is much more intense in some places than in others. After prolonged erosion, a minor phase of eruption may occur and it typically fills valleys and buries sea cliffs with thick flows that resist erosion more than the rocks formed earlier. Thus the stage of volcanic life with interacting volcanism and erosion is highly complex in detail.

EROSION

The erosion of volcanic islands is influenced by the mineralogy, lithology, and physical properties of their rocks, their size, shape, height, and geographical position, and the intensity and distribution of the winds, clouds, and waves around them. It is only because the islands have so many fea-
tures in common that the effects of individual variables can be identified. Thus it is that a protective shield of coral is of paramount importance, and, on these grounds, this chapter is separated from the next. With regard to other variables, individual islands are perceptibly more cliffed by waves on the windward side of prevailing seas than on the lee. Likewise, the rate of river erosion is perceptibly faster on the windward side than on the lee and varies perceptibly with elevation—as does rainfall. As to the relation between wave and river erosion, it often depends on the size of an island. Rivers act on the area of an island, which varies as the square of the radius for a circular island. In contrast, waves act only upon the perimeter, which varies only with the radius. Thus, the relative importance of wave erosion decreases with the size of the island—at least while the island is high. If an island persists long enough for rivers to reduce the interior to a low plane, river erosion becomes very slow and wave erosion again becomes dominant.

Weathering

Surface rocks are physically and chemically altered to soil by a complex process called weathering, which varies mainly with mineralogy, temperature, and the balance between rainfall and evaporation. Although all exposed rock surfaces are subject to weathering, the soils in any given place generally are derived from primary weathering somewhere else. This is particularly true of the soils that have nurtured civilizations. These are largely transported by winds and rivers to the plains where they are farmed. Even the soils of islands as remote as Hawaii have a minor content of fine quartz and mica grains blown from the continents. However, most weathering products on islands are indigenous and therefore highly sensitive to local conditions.

In high latitudes and on very high peaks of tropical islands, freezing and thawing may occur in a daily cycle. Ice expands in cracks and is capable of splitting rock into fragments of all sizes. This process has carpeted the crests of Mauna Loa and Mauna Kea, but no lower Hawaiian peaks, with small angular fragments between the higher outcrops from which they are derived. However, mechanical weathering of this sort is minor compared with chemical weathering.

Volcanic islands are composed almost wholly of glass and fine-grained minerals that are more vulnerable to chemical weathering than most continental rocks. The island minerals and their glasses are dominantly olivine, pyroxine, and plagioclase; the more resistant minerals orthoclase and, particularly, quartz are rare or absent. The island rocks react with carbonic and humic acids in rain and groundwater to form both soluble and insoluble decomposition products, but hardly anything remains of the
original rock. This is in marked contrast with the weathering of granite, for example, which produces large quantities of sand-sized grains of quartz and feldspar. The quartz grains persist for times on the order of $10^6$ or $10^7$ years, first as sand and then as sedimentary and metamorphic rocks.

The carbonate compounds resulting from weathering of island basalt are soluble and are carried away by flowing streams or groundwater. Other weathering products include clays, largely kaolinite, silica, and oxides of iron and aluminum. The common red coloring of island soils is the iron oxide hematite. Rarely, the aluminum oxide, bauxite, is concentrated in deposits large enough to be of possible economic interest. Usually the deposits are in areas of very high rainfall, where aluminum oxide is leached from the top layers of the soil. Bauxite is creamy white to pale brown in color; if exposed by erosion, it stands out against the dark red soil. The white color may account for occasional reports of uplifted coral in the high and inaccessible interior mountains of some islands. James Dwight Dana tried to find such a coral reef reported to be in the interior of Tahiti.

Volcanic islands weather into large volumes of soluble carbonates and easily transportable clay but hardly any sand—the very material that makes beaches and river beds. The rivers commonly are paved with rounded cobbles that continue to weather. Black sand is found in small volume on the beaches of active volcanoes, but these sands weather rapidly. The clay and iron and aluminum oxides form soils that are famous for plantations of pineapple and sugar cane. Thus, the weathering products are not all immediately lost to the island. However, island slopes are steep, rainfall high, and erosion rapid, so the soils, from a geological viewpoint, are merely perched briefly on the island before they are carried down to sea level. There they may be deposited as mud in valleys or, as we shall see, continue down to the deep sea.

**Glaciers**

Glaciation on the 3500-meter peak of Mauna Kea left subtle traces in the form of parallel scratches on rock and also thin moraines of till. Presumably, inactive insular peaks of comparable height have commonly been the site of glaciers even in the tropics. The Balleny Islands, at 66°S latitude in the Pacific, show the effects of high latitude. The islands are less than 1000 m high, but they are almost covered with ice fields and glaciers. Young Island is the largest in area, being about 30 km long and 8 km wide. In a few places, rocky sea cliffs 200 m high are exposed, but the whole interior and much of the coast is covered with glacial ice. Sea cliffs of ice are 100 m to 300 m high.

Bouvet is a small active volcanic island on the crest of the Mid-Atlantic Ridge not far north of Antarctica. Little else is known about it because
ice tongues extend to the sea from the interior "plateau," which appears to be a crater filled—temporarily—with ice. Presumably, glaciated active volcanoes are common in very high latitudes.

By far the best known glaciated active volcanic island is Iceland. Although it is only 1000 m to 2000 m high, it is located between 64°N and 66°N latitudes, so it is sprinkled with enormous glaciers. The largest, Vatnajökull, has an area of more than 10⁶ km². Iceland lies on the intersection of the Mid-Atlantic spreading center and a hot spot, so volcanism is widespread and intense. Occasionally, volcanoes erupt under the glaciers and produce some of the most spectacular natural events known. Entire lakes are melted within glaciers; when they break through one side of the ice, catastrophic floods occur. One in historical times briefly discharged water upon the surrounding countryside at twenty times the rate of the Amazon River.

Glaciers erode rock rapidly, and alpine glaciers produce great relief such as the Matterhorn and Yosemite Valley. Thus it may be assumed that, when and if insular glaciers melt, spectacular relief is exposed to more normal erosion by wave and stream. However, no such conspicuously eroded volcanic islands are known. In part, this reflects the curious fact that few islands of the right height exist in the intermediate latitudes.
where glaciation might have occurred in Pleistocene time but not now. In part, it may be due to the relative brevity of glacial epochs and the brief existence of volcanic islands.

Even though no examples have been identified, we can speculate on what happens to ancient volcanic islands in high latitudes in glacial periods. Consider Young Island, in the Balleny Islands. At present it is almost entirely covered with glaciers, which protect it from wave erosion but which, presumably, are themselves eroding the interior into spectacular mountains and valleys. The ice has depressed the pre-existing island, which may now be entirely below sea level. What happens if snow continues to accumulate rapidly and thicken the ice, which is only slowly melted by a polar sea? Thermal subsidence of the oceanic lithosphere always tends to pull any island down. Is it possible that when a climatic change or a warmer ocean current eventually melts the ice, the island would be too deep to return to the surface by isostatic rebound? If so, there may be drowned ancient islands in very high latitudes that have never been planed off by waves. Some insular matterhorn may remain to be discovered deep under the polar seas. Certainly, fantastically eroded mountains are ensnared in coral that protected them as they subsided in warm water. Perhaps ice has played a similar role.

Waves

Waves and swells clearly are very effective in eroding the shores of volcanic islands. Typically, small islands are “iron bound,” meaning that they are circled by towering cliffs with great waves breaking at the base. The cliffs must be seen to be appreciated; at Tristan da Cunha, in the South Atlantic, they are 300 m to 1000 m high and nearly vertical for hundreds of meters. For comparison, the Eiffel Tower is about 300 m high. On small and intermediate-sized islands, waves commonly are more effective eroders than streams, so valleys are left hanging and streams enter the sea as waterfalls. On larger islands, streams carve large valleys, and waves are focused on headlands between them. The precipitous narrow ridges between valleys and the great cliffs at the headlands isolate many valleys on exposed coasts of older islands. Such are the circumstances of the Napali coast of Kauai.

Some historical lava flows that reached the shoreline have already been clipped by waves, so the erosion is demonstrably rapid on a small scale. To measure what can happen on a larger scale and for a longer period, we can turn to Prince Edward Island. It is a small elliptical island, about 5 km by 10 km, that lies at 46°37′S latitude in the southwestern Indian Ocean. Its location in the “roaring forties” exposes it to strong and
frequent gales, which bring great swells, essentially without interruption, from the west and southwest. About 215,000 years ago, brief volcanism built a broad, gently sloping shield that rose 500 m above sea level. The island is too low and small for much rainfall, so stream erosion has been negligible. However, the great swells truncated the western side of the island to below sea level and carved a cliff 500 m high. About 15,000 years ago, minor volcanism on the insular shelf at the base of the cliffs rebuilt part of the shelf above sea level, but the original shape of the volcanic shield can be reconstructed from a detailed topographic map of the island and surrounding sea floor. The average thickness of rock removed was 172 m, and a shelf 2 km to 3 km wide was cut. It is difficult to make a direct comparison, but the rate of erosion is about the same as in the extreme conditions of the Himalaya Mountains, where, on average, a layer of rock a meter thick is removed every thousand years.

Pitcairn Island, the haven for the mutineers of the Bounty, is smaller and older than Prince Edward but not so intensely eroded because it lies in the more equable waters of the subtropical central Pacific. It is 2 km wide by 4 km long, 347 m high, and 450,000 to 930,000 years old. Rainfall averages 200 cm/yr, but stream erosion is negligible because the rocks are permeable. In contrast, the island is ringed by cliffs and there is only one
landing—where the mutineers unloaded and burned the *Bounty*. In some places, the cliffs are less than 50 m high, less than a twenty-story building, but 200 m is common. Even so, the cliffs do not compare with those at Prince Edward.

It might be thought that the cliffs of Pitcairn are lower because the island is older than Prince Edward and has sunk along with the sea floor. This idea can be examined by studying the depth of the insular shelf break, which is the outer edge of the gently sloping terrace cut into the original volcano at the same time as the steep cliffs. The terrace is sloping, rather than level, because of Pleistocene and earlier fluctuations in sea level. Numerous samples indicate that most insular shelves are mostly bare rock, and the slope of the volcano flanks below the shelf break has not been oversteepened by sedimentary deposits. Thus it appears that the depth of the shelf break is a reasonable measure of the subsidence of an island. The depth of the shelf break of 43 noncoral islands ranging in age from active volcanoes to 20 Ma shows no systematic trend. Yet in 5, 10, and 20 Ma, young sea floor sinks 700 m to 1500 m; older sea floor sinks more slowly, but even crust 40 Ma old sinks hundreds of meters in 20 Ma. We come to the conclusion that even though the sea floor sinks because of cooling, the islands that are free of coral do not sink. (It will be shown in the next chapter that islands ringed by coral sink rapidly.)

Although there is no correlation between an island’s age and the depth of the shelf break, there is an excellent correlation between age and shelf width. This is most readily seen in the Canary Islands, which drift only very slowly because they are near the pole of rotation of the African plate. Thus, the Canary hot spot has been producing large volcanoes for at least 18 Ma, and they overlap to form the existing islands. Tenerife is a triangular island with a large central active volcano, which does not spread to the coast. Most of the coastal rocks are only 0.7 Ma to 1.9 Ma old, but sections of two isolated corners are much older. Wave erosion has been most intense on the northeast corner. There the relation between age and shelf width is consistent, as the table on this page shows. The shelf also changes abruptly in width at the boundary between rocks of different age on the southwestern, leeward side.

If the ages and shelf widths of eight isolated Atlantic islands and eleven major sectors of the Canary Islands are compared, the simplest interpretation of the observations is that waves have widened the shelves by 0.6 km/7Ma to 0.7 km/7Ma for at least 16 Ma. A similar analysis for the relatively reefless Hawaiian and Marquesas islands indicates widening by 1.1 km/7Ma to 1.7 km/7Ma for 7 Ma to 7 Ma. If all dated volcanic islands, including active volcanoes, are considered together, the relation between shelf width and age does not appear linear. Many islands, such as Prince

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Width (km)</th>
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<td>0.7–1.4</td>
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<td>5–7</td>
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<td>15.7</td>
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Edward, that are less than a million years old have shelves 2 km to 3 km wide so initial erosion appears to be particularly rapid. This seems reasonable in that waves lose their power to erode when they lose energy by friction with a widening shelf. However, the age-width data are relatively scattered for older islands, which suggests that various other factors become increasingly important.

One such factor is certainly the intensity of swell, as can be seen by comparing different sides of the same island. For example, east of Australia is Lord Howe Island, a later haven of the refugee descendants of the Bounty mutineers. It is a small island rising from a broad shelf but not from the middle of it. The island is 14 km from the shelf edge on the weather side and only 5 km from the edge on the lee side. Youthful Ascension Island, in the Atlantic, shows a similar relation, with a weather shelf 3.5 km wide and a lee shelf only 1 km wide. Much older (19 Ma) Gomera Island in the Canaries shows a greater gap: weather side 9 km wide, lee side 3 km wide. It is interesting to consider the wave-cut platform that will remain when one of these islands is at last eroded away and sinks to become a guyot. The truncated top of the guyot will not be flat, nor will it be a right cone sloping uniformly from the perimeter to a point center. Instead, it will be a cone with the apex of the center and closer to the former weather side of the island. Thus, in favorable circumstances, it may be possible to determine the direction of the dominant swell that truncated a guyot that has drifted into an entirely different latitude since it was an island.
Rivers

The principal factors that influence the erosion of a volcanic island by rivers are the permeability of rock, the shape and slope of the island, and the quantity and distribution of rainfall. Permeability is important because fresh lava flows are highly permeable, and rainfall may simply penetrate to become groundwater instead of flowing off as surface streams. Most permeable are flow surfaces, where gas bubbles accumulate, so the thin flows of the shield-building stage are particularly permeable. As time passes, weathering produces relatively impermeable clay soils at the surface, and deposition of minerals from groundwater tends to fill openings and reduce porosity and permeability. Thus it is that the ratio of surface runoff to groundwater flow gradually increases in accord with the age sequence in the Hawaiian Islands, from 0.8 in the young island of Hawaii to 3.8 in the old island of Kauai. The only exception is Oahu, where groundwater flow exceeds runoff.

The residence time of Oahu groundwater is decades to centuries, so the volume of groundwater is enormously greater than the amount of surface water. In fact, almost any oceanic island, high volcano or atoll, contains a vast reservoir of fresh water. Islands are so permeable that
The Ghyben-Herzberg lens of freshwater (light blue) under an oceanic island rests on denser saltwater (dark blue) that permeates the base of the island.

Seawater saturates them and moves with the tides, although with some time lag. In the absence of rain, the seawater within an island is at sea level. However, rainwater percolates through the island and floods on the seawater in what is called a Ghyben-Herzberg lens. The lens of fresh groundwater forms because flowing groundwater has a slope, from the interior to the coast, that is inversely related to permeability. Because of hydrostatic balance, the lens is biconvex. Like the island itself, the groundwater has a root; for normal densities of fresh water (1.0) and seawater (1.025), the root is about 40 times as thick below sea level as the water it supports is above sea level.

Volcanic islands generally are circular or elliptical cones or domes, and it is easy to visualize the influence of their shape upon erosion by imagining simple circular cones that lie in seas without waves and on which rain falls uniformly. The consequent rivers that develop on a cone are radial because the slopes of the cone are radial. The side slopes of the river valleys tend to be relatively constant but the longitudinal slopes are steeper in the headwaters than at the shoreline. Thus the valleys of the radial streams are funnel shaped; they are narrow and shallow at the shoreline and spread into great, deep amphitheaters in the interior. At the shoreline, the rivers are more widely spaced than in the interior, and between them the conical volcanic slopes appear relatively unmodified; these are such distinctive features as to have a special name—planites.

The planites have a triangular plan because, as time passes, the widening valleys converge in the interior and are separated only by knife-edges, steep-walled ridges. These ridges become so narrow that, in such places as Moorea and the Marquesas Islands, there are great natural windows that cut through them. Farther in the interior, the amphitheaters overlap, and the whole interior of an island may be gabled while the peripheral planites are relatively intact. The formation of an erosional caldera by this process has been so rapid that it has removed the central peak of Tahiti Ili, the southern peninsula of Tahiti, which is only 0.4 Ma old. The center of the older main cone of Tahiti (0.5 Ma to 0.9 Ma old) is
Left: The relatively uneroded planese between deep gullies are preferred locations for human settlement on Reunion. Right: A satellite view of Reunion shows the radial pattern of erosion and the gutted interior of the island.

Also an erosional caldera. If erosion by waves is added to this picture, the planese headlands are clipped between the rivers. Consequently, the coastal apices of the triangular valleys are also removed, and the coastal valleys have more parallel sides.

All the simple phenomena described above have been observed, but the fluvial erosion of some volcanoes is more complex because rainfall is not uniformly distributed. Several effects are important in the distribution of rainfall. One is orographic. A moving air mass encounters a mountain, is forced upward and cooled. The dew point drops, and rain or snow falls on the mountain crest. In the Canary Islands, winds come from many directions and 120 cm of rain a year falls on the 2000-meter central peak of Gran Canaria Island, but only 20 cm falls along the shore. However, the pattern can be different if almost all of the rain comes from one direction, as it does in the Hawaiian Islands. There the northeast trade
winds are laden with water up to about 2000 m and they flow in complex patterns around and over the high islands. Circular, relatively low-lying Kauai is entirely within the humid air mass and the rainfall is closely related to elevation, ranging up to 1100 cm/yr at the peak, in a pattern comparable to that of Gran Canaria. Hawaii is much higher than Kauai and the rain-filled clouds pass around the peaks, so most of the shoreline is in a soggy belt with 250 cm/yr to 750 cm/yr of rain, while the peaks are deserts with only 40 cm/yr. The morphological effects are not very great on the slopes of the active or very young volcanoes, because the rain penetrates to become groundwater and new lava flows fill incipient valleys. However, the northern tip of the island is Kohala Mountain, which has been extinct for 400,000 years. It is about 2700 m high and elongate northwest-southeast and therefore perpendicular to the trade winds. Rainfall somewhat east of the peak has a high of 320 cm/yr and it is about 220 cm/yr on the windward coast. On the lee coast, it is only about 25 cm/yr. The dissection of the once smooth volcano has an almost uncanny correlation with the rainfall. Directly under the most intense rainfall are the headwaters of three great valleys. To the northwest on the weather coast, where rainfall is much less intense, are many small gullies. In contrast, the leeward desert is virtually undissected.

It takes little imagination, now that the potassium-argon ages of the islands are known, to see a close correlation between age and the degree of
dissection, after allowances for patterns of rainfall. However, Chester K. Wentworth in 1927 performed the much more difficult feat of calculating the age of the islands from the degree of dissection alone. Wentworth reconstructed the original shapes and volumes of the Hawaiian volcanoes and compared them with the present volumes, as determined with a planimeter and topographic maps. Dividing the eroded volume by area, he obtained an average depth of erosion that may be compared with the ages as now known: Hawaii 8.7 m (active), Kohala 13.6 m (0.4 Ma), Maui 40 m (1.0 Ma), Molokai 70 m (1.6 Ma), Oahu 100 m (2.7 Ma), and Kauai 127 m (4.4 Ma). A smooth concave-upward curve correlates age and depth of erosion to 1.6 Ma. I have recalculated the average rate of erosion for Kauai using much more detailed maps than those available to Wentworth. The depth of erosion on Kauai appears to average 271 m, which gives a smooth, concave-upward curve for at least 4.4 Ma. If, instead, the rate of erosion is calculated it appears to decline in accord with standard observations in continental geomorphology. Comparing windward sides of high islands, the average rate has declined from 280 m/Ma
for young Kohala to 40 m/My in older Oahu. In contrast, the rate on the leeward side of high islands and all sides of low islands is only 2 m/My to 6 m/My and hardly varies at all with age. The average rates of fluvial erosion of these islands can be compared directly with that of the Himalayas, which is about 1000 m/My. It is evident that the spectacular relief of volcanic islands is not a consequence of rapid erosion but of the peculiar conical shape and structure of the volcanoes.

In order for Wentworth to convert his erosion data to rates and thereby determine the age of the islands, he needed a historical determination of an erosion rate. This he found on the island of Lanai. The kiawe tree had been introduced to Hawaii in 1837, and the trunks of older trees were buried to a depth of as much as a meter on the narrow coastal plain. Knowing the volume and age of sediment and the area of the source region, Wentworth determined an erosion rate. From it, he obtained an age of Kohala of 225,000 years and of Kauai of 2,090,000 years. These are in just the right proportion but are half the ages measured by modern isotopic methods forty years later. Wentworth’s measurements were soon criticized and then largely ignored for decades, despite the fact that they could have been very useful if accepted.

**Marine Dispersal of Sediment**

The solid rock of volcanoes is converted by weathering to soluble carbonates and silica that disappear into the ocean. Much of the clay likewise is dispersed, but in suspension instead of solution. However, a minor residue of mud, sand, and gravel passes on to the insular shelves. Where is it finally deposited? Seismic profiles of the bottom beneath the sediment indicate that sediment does not form thick deposits on the shelf or the deeper slopes. This confirms the thousands of notations on older nautical charts that record rocky bottom around islands. A detailed survey around Oahu in 1974, for example, showed that sediment on the shelf was mostly less than 10 m thick. The only exceptions were small accumulations along the bases of drowned sea cliffs and river valleys. It appears from the distribution that the sediment is merely being transported along the bottom toward the deep sea rather than accumulating in place on the shelf. However, the picture, as always, is clouded by Pleistocene changes in sea level. Perhaps it is more significant that sediment does not accumulate on the deep flanks of islands. The fraction that is not dissolved or carried away in suspension apparently is mainly transported to the deep sea bottom beyond the submarine slopes of the islands. There, in fact, it is readily detected because it forms an apron and buries the surrounding abyssal hills. Deep-
sea cores show graded bedding and other evidences that the sediment flows rapidly from shallow water to deep in the form of turbidity currents. In sum, hardly any of the products of weathering and fluviatile and wave erosion remain on the volcano from which they are derived.

Isostatic Uplift in Response to Erosion

Two lines of evidence indicate that islands in cool waters do not subside. One of these is that the depth of the shelf break does not increase with age but the width of insular shelves does. The only explanation seems to be that the shelves, and thus the islands, remain at about the same level and are progressively eroded away by waves.

The second line of evidence is that, in the interiors of some islands, rock formations are exposed that appear to have been deposited under water. The evidence at La Palma in the Canary Islands is particularly convincing: the formation includes pillow lavas, breccias containing fragments of pillows, and hyaloclastites. A slaggy lava formation on St. Helena also appears to be submarine in origin. The exposure of these once submarine rocks has involved local tectonic elevation and tilting. However, the point of interest here is that submarine rocks are not necessarily buried deep under the subaerial lava flows of an island that has subsided because of loading and also cooling of the deep sea floor. On the contrary, the submarine pedestal of the center of some islands has remained near sea level, and even been uplifted and exposed by erosion.

If these interpretations are correct, an anomaly appears. The deep sea floor sinks, barrier reefs and atolls sink, guyots sink, but volcanic islands that are free of coral do not sink. The only distinctions of such islands is that they alone are exposed to wave erosion and lose their weathering and erosional products to the ocean and the deep sea floor. Thus, it appears that these islands stay at sea level because of isostatic rebound as they are eroded away. Likewise, it appears that the persistence of islands depends on their size. They endure until they are eroded away. Then they sink at the same rate as the cooling lithosphere on which they rest.

SUBMERGENCE

In general, thermal subsidence is balanced by erosion-isostasy, but in some circumstances it may only be slowed. For example, the thermal subsidence
of very young lithosphere may be too fast to be balanced by the uplift of a small low island that is not eroded by streams. A combination of wave erosion and subsidence may produce either a series of narrow terraces separated by cliffs, or, less likely, a smooth but relatively steeply sloping shelf. There are few places where the existence of such topography can be confirmed. The only small, isolated volcano known to have grown upward fast enough to be an island next to a midocean ridge crest is now the submerged Cobb Bank off Washington. It is 1.5 Ma old and lies on crust 3 Ma old, so it was active on crust less than 1.5 Ma old. Cobb has submerged terraces at two general levels, 823 m to 1189 m and 183 m to 200 m, as well as a broad summit platform at 82 m and a single central pinnacle rising to 34 m. It appears that a simple, small conical island was notched by waves and almost truncated as it rapidly subsided. Rounded cobbles on the terraces support the interpretation that they were once beaches. Thus Cobb Bank has the morphology predicted for a small island on very young crust.

Pinnacles, Rocks, and Banks
In the slowly drifting parts of the Atlantic, high volcanic islands persist for long periods because of renewed volcanism. Either sources of magma drift with the islands, or, more probably, relatively fixed hot spots can be tapped from some distance. In contrast, islands on the rapidly drifting Pacific plate ordinarily have only one major shield-building phase and one minor phase a few million years later. Hardly any volcanic islands in the Pacific are more than 10 Ma old and most are less than 5 Ma. Thus, it appears that, without repeated volcanism, even large islands are eroded to near sea level in 5 Ma to 10 Ma. What then remain are pinnacles, rocks, and banks with elevations of about 300 m to −200 m. The pinnacles and rocks are feathery spires rising almost vertically 50 m to 300 m above the sea. Most are isolated, although some are flanked by a separate smaller rock or two. They rise from extensive and relatively flat rocky platforms and clearly are the last erosional remnants of once extensive islands. Banks, in nautical terms, are defined as features that do not break the surface and are less than 200 m deep. Some of them, such as Cobb Bank, preserve a small central spire that somehow escaped final truncation by waves. Most, however, are relatively smooth, showing that truncation was complete.

Banks are in the euphotic zone, and biological productivity tends to be high, but fine-grained organic remains generally are stirred by waves
Ball's Pyramid, not far from Lord Howe's Island, is the last subaerial remnant of an eroded oceanic island.

...and swept away by currents. Thus, most of the surface of a bank is bare rock. Once below the depth of vigorous erosion, the mass of a bank remains constant and there is no isostatic rebound to counter thermal subsidence. If sea level were constant, all banks thus would have a simple subsidence history. However, sea level fluctuates; with every large eustatic lowering, banks are reexposed and erosion-isostasy acts again. Consequently, the actual history of banks is longer and more complex. Still, thermal subsidence is persistent, and banks that do not drift into coral seas sink eventually beyond 200 m depth and the range of eustatic fluctuations. The average time that a bank exists depends on the age or thermally rejuvenated age of the underlying lithosphere. If an island existed for 10 Ma before it was truncated to a bank, the lithosphere is at least 10 Ma old. Lithosphere of that age subsides through the depth range of banks in only 3 Ma to 4 Ma. However, a bank on lithosphere 100 Ma old may persist for 8 Ma to 12 Ma before it sinks below 200 m and, by definition, becomes a guyot. In that case, the bank is in the depth range for eustatic change in sea level for a longer period. Thus it is hardly surprising that...
fossils derived from shallow banks are common in deep-sea drilling cores in the Pacific, nor that they were deposited at times of lowered sea levels.

**Guyots**

The banks that at last escape below 200 m become guyots by definition, but except in depth and name they are unchanged at first. Thereafter, in the average lifespan of 10⁹ years, little can happen to a guyot to change its appearance. Gravel has been dropped on summit platforms by Pleistocene icebergs in the Gulf of Alaska and on the Emperor Guyots, but the deposit appears to be thin and uniform. In exactly the right circumstances, however, the platform shape is modified. In the South Pacific, many guyots sank to depths of hundreds of meters before they drifted north into the warm seas that would permit coral to convert them to atolls. Some of these guyots have drifted farther north under the zone of high productivity in equatorial surface waters. Consequently, their summit platforms are covered with hundreds of meters of layered pelagic sediment. This smooth pelagic cap is thickest in the middle of the platform and slopes toward the edge. The mere existence of a thick cap indicates that a guyot in the Northern Hemisphere was created in the Southern. By sampling the cap, the time when the guyot crossed the equator can be determined as well.

The only other thing that happens to guyots is that some bob up and down in addition to their normal thermal subsidence. This bobbing amounts to hundreds of meters in tens of millions of years. Some upward and downward motion may be due to distortions of the lithosphere by convection currents in the mantle; if so, they have not been detected. In contrast, it appears probable that guyots are elevated as they override the Tahitian midplate swell and presumably others. Certainly, volcanic islands and guyots develop on or near the crest of the East Pacific Rise. The guyots on the rise flanks east of the Tahitian swell should have sunk with the lithosphere and thus be at depths of 1500 m to 2000 m by the time they reach the swell. However, the guyots on the swell are all at depths of less than 1000 m.

Guyots must also be uplifted near subduction zones as the lithosphere curves upward, because of its rigidity, before it plunges into the mantle. This can be shown to occur for atolls, as will be discussed in Chapter 9, but it is difficult to document for guyots. However, the age sequence of the Pratt-Welker guyots in the Gulf of Alaska is quite well known, and the
guyot on the outer swell of the Aleutian Trench is shallower than it should be for its age. Presumably, it has been uplifted. There are also guyots in the trenches of the western Pacific, and some of them have been pulled down thousands of meters along with the sea floor. What then happens in subduction zones will be left hanging (until Chapter 9) while we return to the open ocean.
Charles Darwin had never seen an atoll when he conceived of a hypothesis for their origin. However, he was on a surveying ship, H.M.S. Beagle, surrounded by charts and descriptions of different types of islands, and that was enough. There were already explanations for atolls, because explorer’s descriptions of great rings of wave-girt coral around calm lagoons in the deep Pacific had captured the interest of stay-at-home scientists. Darwin’s mentor, Charles Lyell, had proposed that what he called “lagoon islands” were “nothing more than the crests of submarine volcanoes having the rims and bottoms of their craters overgrown by coral.” Other hypotheses, then and after, were equally ad hoc. Darwin’s hypothesis, in contrast, was a powerful synthesis that explained many phenomena previously thought to be unrelated. Darwin began by noting that there were only three types of oceanic islands, namely, volcanic, coral, and combinations of the two. He simply proposed that there was only one sequence of development of all oceanic islands. Volcanoes grow up from the sea floor to form high islands and then die. Coral grows in the shallow water fringing the shoreline. The volcano subsides and the coral grows upward, leaving a gap between a barrier reef and a central volcanic island. The subsidence continues until the volcanic island disappears and nothing remains but an atoll.

The hypothesis in itself was attractive for its simplicity and its synthesising power, but Darwin did not leave it at that. He set out to confront all the critical points in the hypothesis with data already available. It appears that, by the time he had developed the idea, the formation of an empty lagoon encircled by coral seemed rather obvious—if volcanoes subside. He
therefore concentrated on the proof of subsidence. This he derived from proving the following:

1. Corals do not live below a certain depth (d).
2. Coral reefs may be thicker than d.
3. Coral reefs can grow upward fast enough to remain in shallow water as the underlying sea floor subsides.

As to the depth at which corals grow, he had made observations using a sounding line with a bell-shaped weight full of wax to which loose bottom samples adhered or which showed the shape of hard bottom. Above 36 m, he found coral; below, sand. He visualized the boundary as one determined by a variable environment and cited observations, by others, of deeper coral. However, nothing supported the existence of living coral below 56 m.

Concerning the thickness of reefs, the island of Mangaia, east of (and uplifted by the load of) Tahiti, is an uplifted atoll about 110 m high. Other atolls were uplifted enough to expose coral more than 56 m thick. Clearly they had subsided before they were elevated.

As to the rate of growth of coral, the general belief in Darwin's time was that corals grow extremely slowly, because some in the Red Sea were believed to be unchanged since the time of the pharaohs. Moreover, the depth of the living coral near the entry to Tahiti harbor had not changed from 4.5 m in 67 years of sounding by British ships. Darwin reasoned that the subject had not "hitherto been considered under a right point of view." A coral reef is alive, and like all living things its growth is controlled in part by the environment. The proper question is not how rapidly a reef grows in unfavorable conditions, but how rapidly it can grow in favorable ones, as when an island subsides. He was able to cite experiments and accurately timed observations of fouling of ship bottoms. They showed that coral can grow 360 mm/yr and possibly 1560 mm/yr, although Darwin himself doubted the latter number. In any event, he believed that coral would have no difficulty in keeping up with subsidence due to any geological cause known to him. However, he did not know about the speed of Pleistocene changes in sea level.

Darwin's hypothesis was published in 1842 and was generally acclaimed for decades as a triumph of scientific logic. The great Lyell discarded his own hypothesis and supported that of his protege. Darwin had become famous as a consequence of his correspondence and his readable books about his experiences on the Beagle. His hypothesis not only had
Top to bottom: Moorea, Bora Bora (both in the Society Islands), and Avarua (in the Tuamotus) represent successive stages in the transformation of a subsiding volcanic island into a coral atoll.
great appeal in itself, but was based on the personal observation of the most qualified scientist in the world. If possible, acceptance of the hypothesis was even stronger and more widespread after 1872, when Dana published his book Corals and Coral Islands. After reading the newspaper account of Darwin’s ideas in Sydney in 1839, he had sailed to the Fiji Islands and there seen “similar facts on a still grander scale and of more diversified character.” Dana remarked that he was more positive than Darwin about the subsidence hypothesis. Moreover, Dana showed that features of islands that he had observed, but that were unknown to Darwin, could have been predicted from the basic hypothesis. Thus, the two leading observers of islands on early nineteenth-century scientific expeditions were in complete agreement.

Critics of Darwin’s Hypothesis

However, new types of observations are the commonplace of science, and, in the second half of the century, the Challenger Expedition set out to explore not the islands but the sea between them. John Murray, the only geologist, found that the skeletons of the calcareous microorganisms that lived in surface waters accumulated on the deep sea floor at depths from about 2500 m to 4500 m but were absent at greater depths. He and his colleagues concluded that the skeletons dissolved in the cold deep water. Drawing on his expertise in deep-sea sedimentation, Murray rejected the subsidence hypothesis in April 1880. Atolls were formed because sediment accumulated on undersea mountains and eventually produced shallow banks. When a bank was shallow enough, corals attached themselves and grew up to sea level. Solution of the coral skeletons in very shallow water produced a central lagoon, although the very favorable environment at the edge of the bank preserved a ring of living coral.

Darwin himself had considered that atolls might develop on great banks of sediment, but he rejected the possibility of such banks in the pure blue waters of the central Pacific. He does not seem to have considered the possibility of sediment accumulating on the peak of a high submarine volcano, as it appears that Murray did. Darwin knew from soundings by Beagle around islands that shallow submarine banks usually are swept free of pelagic sediment by waves and currents. In any event, Murray seemed to have a point. Why should all oceanic volcanoes grow high enough to be islands? Indeed, even the widely spaced soundings of Challenger showed that the sea floor had submarine mountains of some sort.

Regrettably, Murray’s logic failed, and he believed that if atolls could form as he proposed, then Darwin’s subsidence hypothesis was wrong.
Many weaknesses in Murray's hypothesis were soon identified and, in any event, it did not eliminate Darwin's ideas or give an alternative explanation for Darwin's and Dana's evidence of subsidence. At best, it appeared to identify a minor variation on Darwin's theme. Nonetheless, Alexander Agassiz, another oceanographer, almost immediately supported it and rejected subsidence. So did Edward Forbes, in his book about his work at Keeling Atoll, published in 1885. H. B. Guppy studied that same atoll and agreed with Forbes in 1888; he also mapped the reefs of the Solomon Islands and concluded in 1884 that barrier reefs could build up from gently sloping shelves without subsidence.

Somehow, perhaps because of the great fanfare regarding the Challenger Expedition, Murray's idea caught on from the beginning, just as Darwin's had when Beagle returned. Darwin wrote to Alexander Agassiz in May 1881 to ask for his opinion on "Mr. Murray's views." He himself was in no way committed to anything except whatever hypothesis best explained the scientific facts. "If I am wrong, the sooner I am knocked on the head and annihilated so much the better." Darwin wished that some "doubly rich millionaire" would pay for borings of Pacific and Indian atolls to obtain cores down to "500 or 600 feet."

After Murray's ideas gained widespread support, a test by drilling seemed even more desirable. In 1890, Professor W. J. Sollas in England began to correspond with Professor Stuart Anderson at the University of Sydney. Anderson was to try to borrow a drilling rig from the Australian Government. Sollas whipped up support for the project and proposed it formally at a meeting of the British Association for the Advancement of Science in 1893. A committee of distinguished scientists was immediately appointed to proceed with the project. Eventually it would include a number of British geologists as well as John Murray and Francis Darwin, the son of Charles, apparently to balance matters. In 1894, £10 was allotted by the Royal Society for the annual expenses of the committee. In 1895, the Pacific atoll of Funafuti was selected for drilling. It was one of the atolls closest to the drilling rig, which was already available in Sydney.

In 1896, the Royal Society obtained a grant of £600 from the Treasury and the use of H.M.S. Penguin from the Admiralty. Sollas was appointed leader of the small scientific party. The formal objective was to investigate the depth and structure of a coral reef. If the drilling encountered a rock other than coral limestone, Sollas could "use his discretion." Darwin's supporters wanted the possibility of reaching a volcanic platform to be acknowledged. Off Sollas went, only to learn the great difficulties of drilling in reef limestone full of frangible and hard limestone with occasional caverns and cavities. Sollas tried drilling at the lagoon margin but could not spud into the loose sand. After Herculean efforts, he managed to
penetrate 105 feet at a site on the seaward edge of the island. The section was all limestone and dolomite and included both coral fragments and the foraminiferal tests that make up the sand on lagoon beaches.

Francis Darwin was a physicist and astronomer, and perhaps it was at his suggestion that a magnetic survey was made of the atoll. Inclination and declination were measured along the ring of islands circling the lagoon. The bathymetry of the lagoon was being surveyed by boat, and a raft was constructed to provide a relatively stable, and iron-free, platform for magnetic observations. The point of the survey was that coral limestone and the platform of pelagic mud proposed by Murray would contain no magnetic minerals and thus mapping would merely show the uniform magnetic field of the Earth at that spot. On the other hand, the basaltic rock of volcanoes does contain magnetic minerals. If Charles Darwin was right, the platform under the coral had the fantastically eroded shape of a modern volcanic island surrounded by a barrier reef. Thus, a magnetic map at the surface of the atoll would be influenced by the variable distance to the basalt not too far below. In fact, the magnetic survey showed that the field was not smooth; instead, there were large “disturbances” localized on the east and west sides of the atoll. It was proposed that any subsequent drilling might be directed toward the magnetic highs with the hope of reaching the material causing the disturbances.

The critical depth of 500 feet hoped for by Darwin had not been reached, so the test was deemed unsatisfactory. In 1897, a second expedition drilled to 698 feet, but the continuing bathymetric surveys of the atoll were interpreted as indicating that the basement platform was only a little deeper. The Royal Society launched a third and last expedition in 1898. It was led by Professor T. W. David; by that time the whole endeavor must have seemed routine and even a bit of a lark, because Mrs. David came along. Lark or not, the atoll was successfully drilled and partly cored to 1114 feet; it was composed of reef and lagoon limestone from top to bottom. Sixty years later, British geophysicists would show that the volcanic basement was below 3000 feet.

After all that effort, the nicely balanced, scientifically neutral committee issued a monograph in 1904 summarizing the field observations. As to their meaning, “Into the controversies about the development of coral reefs, those who have been concerned in the preparation of this volume have not attempted to enter.” One of the committee members, Archibald Geikie, had already written in 1903 that Darwin’s “simple and luminous” hypothesis was generally accepted by geologists, but in fact it was not. The views of another committee member, Murray, were unswayed by the drilling. Many others argued that the holes were drilled in reef talus that had
buried the side of the atoll. Consequently, a basement platform under the lagoon might be quite shallow and composed of any material. The magnetic survey was ignored.

The principal competitors to Darwin's ideas after the Funafuti drilling can all be grouped under what came to be called the "antecedent platform theory." The basic problem of the idea was to account for the existence of hundreds of shallow banks at just the right depth for coral in the tropics. Darwin would have required an equal number of equally shallow banks in temperate zones before being satisfied, but only one of the advocates of this so-called theory—Reginald Daly—was a great generalizer.

Alexander Agassiz, the indefatigable observer of coral reefs and great friend of Murray, offered one version of the theory in 1899. He observed that the fringing-barrier reef on the northeast coast of Tahiti had basalt pinnacles projecting through it. Clearly, he thought, it rested on a largely truncated insular shelf. In this he was correct—the headland cliffs that remain next to the shelf are still visible. He observed that storm waves cross incomplete reefs in some places and attack the rocky shore. He saw no reason why this erosion should not continue until the whole island was truncated. The powerful scouring action of great waves would carry the erosional debris out through the narrow reef passes or over the reef itself. Moreover, the scouring would not stop at sea level but would erode solid basalt down to lagoon depths, despite the encircling reef. All these extraordinary phenomena were proposed to escape any taint of subsidence in the disappearance of volcanic islands.

The idea of wave erosion within a lagoon did not find widespread acceptance. However, the erosive powers of waves on coasts not protected by reefs was beyond question. Thus, several scientists proposed that reef coral did not colonize the volcanic islands that formed atoll platforms until after they were truncated to shallow banks. Just why corals now fringe and encircle volcanic islands but did not when the atoll platforms were truncated posed some problems. A brilliant, although incorrect solution was advanced in 1910 by Reginald Daly. He had been thinking about the marine effects of Pleistocene glaciation and realized that the surface waters would be chilled as well as lowered by a hundred meters or so. There was no way to measure the lowering accurately at that time, but the approximate volume of continental glaciers could be estimated. He began his analysis of the origin of atolls with the observation that the lagoons of the larger atolls have a uniform depth of 70 m to 90 m. How he could have been led to such an inaccurate observation is inexplicable—the depths, ignoring pinnacles, of large atolls actually range from 20 to 90 meters. In any event, he concluded that such uniformity could not be a consequence
of sedimentation and, by elimination, must reflect erosion. The cold ice-age waters must have killed or weakened the tropical reef builders and thereby exposed all coasts to erosion. The future atolls were all planed off by waves during periods of lowered sea level. Then the earth warmed, the corals thrived, and all existing atolls grew upward with sea level as the glaciers melted. Barrier reefs grew up from the outer edges of insular shelves of islands that were only partially truncated.

Daly's glacial-control hypothesis was questioned by his colleague at Harvard, William Morris Davis, who supported Darwin's views. It was universally recognized that Daly had identified an important geological factor that had previously been neglected, but those who believed in antecedent platforms continued to seek causes other than glacial control. One group of eminent observers of coral reefs noted that many reefs are elevated. They proposed that antecedent platforms of differing initial depths could all approach sea level from below. Inactive volcanic seamounts, for example, might be elevated to shallow depths where reef corals would colonize them and grow rapidly to sea level. Meanwhile, elevation would continue without interruption and the reefs would die and appear as they do today. Moreover, the seamount might have a coating of limestone from deep-sea sediments as proposed by Murray. If so, the thin reef coral would be lodged on older and possibly thicker limestone that was not of coral origin.

In 1887, Guppy came to the conclusion that reefs, including atolls, were characteristic of regions of elevation instead of subsidence. The atolls simply had not time to rise above sea level. Alexander Agassiz made the same proposal early in this century. In the 1930s, the leading American geological experts on living and recent reefs were J. Edward Hoffmeister and Harry S. Ladd. They had spent three field seasons on the islands in the South Pacific. They found little to support either subsidence or glacial control of reefs. They observed that some uplifted coral reefs rested on foundations of non-coraliferous limestone. They also noted that some so-called elevated atolls had actually been flat banks of limestone before uplift and that the lagoon-like central basin was caused by subsaerial solution. They concluded that atolls developed on antecedent platforms having various origins, including uplift—but not subsidence. Guppy worked in the Solomon Islands, Agassiz around Fiji, and Hoffmeister and Ladd from Fiji to Tonga. In modern terms, they were all in tectonically active subduction zones. No wonder they saw evidence of uplift; but, unknown to them, most of the atolls were on the aseismic, passive, subsiding plates of the Pacific and Indian Oceans.
Confirmation

The origin of atolls seemed perfectly clear in 1842, but even Darwin had not explained everything, so a century later no firm consensus was possible without drilling. Funafuti had been drilled to more than 300 meters, and the Japanese penetrated more than 400 meters on the island of Kita-Daito-Jima, but nothing but limestone was encountered, and the results were viewed as inconclusive regarding the origin of atolls. After World War II, the necessary doubly-rich patron for drilling appeared in the form of the United States Government. First, the Navy wanted to explode an atomic bomb in shallow water to see what happened to ships. That was done at Bikini Atoll in 1950. Next, the first thermonuclear device was exploded at Eniwetok (now Enewetak) in 1952. An enlightened scientific program was carried out in the Marshall Islands in connection with these tests. Drilling and geophysical mapping of the test atolls seemed particularly advisable. At Enewetak, the explosion was to be on an unprecedented scale and there was concern that the test island or even the whole atoll might slump into deep water. As we have seen in Chapter 5, enormous insular slumps certainly occur. The actual effect was to blast the test island into dust and produce marvelous sunsets for local oceanographers for some months.

Bikini was drilled to 775 m, encountering only reef and associated limestone in a normal stratigraphic sequence from middle Tertiary upwards. Darwin’s hypothesis was the only one compatible with the observations. Seismic refraction studies of the atoll showed that about 1300 m of coral rested on an irregular basement surface of material with the same seismic properties as the insular shelf of Hawaiian volcanoes. However, the basement material was not drilled, nor had more than 500 m of the base of the reef. Two holes at Enewetak were drilled to 2307 m and 2530 meters, where they sampled the irregular surface of basalt on which the atoll began to grow in Eocene time.

By 1965, Midway Atoll also had been drilled and the thickness of coral measured by explosion seismology at Enewetak, Funafuti, Kwajalein, Nukufetau, and Midway. The coral was 800 m to 1600 m thick at all the atolls but Midway, and in those that were drilled the top of the Miocene was only about 200 meters deep. The measured relief of the volcanic basement was 100 m to 600 m deep, and it was as irregular as the magnetic survey at Funafuti had suggested in the previous century.

The results of this great effort wholly confirmed Darwin’s hypothesis. The coral was 800 m to 1400 m thick, was deposited in shallow water, and
rested on submerged volcanoes with irregular, presumably eroded summits. Meanwhile, ever more proofs and corollaries appeared. For example, guyots were discovered in temperate waters, as Darwin and Dana predicted from their hypothesis of the origin of atolls. Now their argument could be inverted: if drowned ancient islands exist in cool waters, where are they in tropic waters unless they are covered by the coral of atolls? An elaboration of the basic hypothesis was also demonstrated in that erosional horizons were found by drilling. Thus the atolls did not always subside faster than sea level fluctuated. Indeed, the presence of fossils of land snails that live only on high islands (and uplifted atolls) suggested substantial relative uplift. Daly's fluctuating sea level had indeed played a major role in the Pleistocene history of atolls. But whether the earlier high islands were exposed to increased erosion by a major temporary drop in sea level and planed off by waves will not be known without further drilling. Meanwhile, it is possible that the apparent elevation was real and that individual atolls were raised by overriding midplate swells or by midplate flexing (described in the next chapter).

A curious misconception arose because of the discovery of guyots almost simultaneously with the drilling in the Marshall Islands. Indeed, Bikini atoll clearly rises from beside a guyot platform. It was assumed that the smooth, almost level, erosional surface of the guyot extended under and formed the base for the atoll structure. Thus, while stating that Darwin was confirmed, the geologists were substantially denying the whole logic of his synthesis. Their interpretation became widely accepted and even now a widespread impression exists that atolls rise from the wave-truncated platforms of guyots rather than, as Darwin said, from mountains eroded by rivers and protected from waves. This misconception should have been dispelled by subsequent drilling and seismic reflection studies, which showed an irregular basement under the coral, but it persists. Thus, it may be worthwhile to try to imagine some way that an atoll can form on a truncated volcanic platform. Clearly, the platform must be truncated in coral-free waters and then drift into or be invaded by a water mass populated by coral. The problem is that a wave-cut bank is almost at the maximum depth for lodgement of reef corals, and it continues to subside as it ages. Thus, to form an atoll on a guyot, it is necessary to elevate the guyot into very shallow water. This very probably occurs from time to time on midplate swells. Even now, some of the shallow guyots southwest of Tahiti may be moving up to where they can become coral banks before they sink again as growing atolls. Compared with Darwin's hypothesis, this seems to be a difficult way to produce atolls, but at least a few can indeed form on the antecedent summit platforms of guyots.
Evidence for subsidence of islands with barrier reefs

<table>
<thead>
<tr>
<th>Island</th>
<th>Age (Ma)</th>
<th>Cliff height (m)</th>
<th>Mountain height (m)</th>
<th>Coral thickness (m)</th>
<th>Embayment</th>
<th>Outlying volcanic islands</th>
<th>Cliffs</th>
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<tr>
<td>Tahiti-iti</td>
<td>0.4</td>
<td>300</td>
<td>1315</td>
<td></td>
<td>Filled bays</td>
<td>No</td>
<td>Widespread</td>
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<tr>
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<td>0.5–1.2</td>
<td>60–150</td>
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<td>Moorea</td>
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<td>60–150</td>
<td>1207</td>
<td>280–340</td>
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<td>Huahine</td>
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<td>15</td>
<td>1035</td>
<td>320–340</td>
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<td>723</td>
<td>200–360</td>
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<td>Mangareva</td>
<td>5.2–7.2</td>
<td>425</td>
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<td>Povate</td>
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<td>786</td>
<td>600–800</td>
<td></td>
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<td>440</td>
<td>1060–1100</td>
<td></td>
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**Erosion and Deposition**

The erosional history of volcanic islands in warm tropical waters can readily be determined from examining the twelve with barrier reefs that have been dated and thus can be put in an age sequence (see the table on this page). The young volcanoes (0.4 Ma to 1.2 Ma old) have sea cliffs up to 300 m high and are gutted by headward erosion of streams and the formation of central calderas by erosion. Despite the rapid erosion, mountains remain that are as much as 2200 m high. There are no outlying small islands, because the submarine flanks are simple and steep. A reef circles much of the islands, but in some places it is fringing the shore and elsewhere separated from it by a lagoon. At the mouths of some of the principal rivers, erosional debris builds a delta on and kills the reef. Elsewhere, the rivers merely empty into the lagoon.
Moorea, west of Tahiti, is 1.5 Ma to 1.6 Ma old. The sea cliffs are 60 m to 150 m high although widespread, and the gutted interior has a peak 1200 m high. There are no outlying volcanic islands. The river mouths are embayed, indicating subsidence unmatched by deposition.

Five islands are 2.0 Ma to 4.0 Ma old. Only two have sea cliffs, and they are 15 m high. Most of the mountains are no higher than 600 m to
700 m. The valleys are almost all embayed, and there are outlying islands formed as small peaks become isolated from the main island.

There are four widely scattered barrier-reef islands 5.4 Ma to 14.0 Ma old. None have sea cliffs. The main mountains are 400 m to 800 m high; the valleys are embayed; and outlying islands are numerous. Indeed, the oldest, Truk, is sometimes called an "almost atoll," because it is a collection of small steep-sided peaks in a vast lagoon.

All in all, we can hardly ask for more positive geomorphological evidence of the gradual subsidence of an initially cliffed and deeply eroded group of islands.

None of the barrier reefs have been drilled or surveyed with geophysical techniques. Thus, to estimate the rate of subsidence it is necessary again to appeal to geomorphology. The key is that reefs have steeper seaward slopes than the submarine slopes on which they lie. From topographic and bathymetric maps, the shape of the volcanic slope under the reef can usually be determined and the thickness of the reef then estimated. The method was used by J. D. Dana and W. M. Davis, mostly by extrapolating planar slopes beneath the sea. Detailed charts of the sea floor near most reefs can now be used to extrapolate submarine slopes upward. This has been done for eight of the twelve dated islands with barrier reefs. The thickness of coral estimated in this way increases from about 50 m and 340 m for an island with an age of 1.5 Ma to 1.6 Ma, to between 600 m and 1000 m for two islands aged 5.2 and 8.0 Ma, to about 1100 m for 14-Ma Truk. The data thus are consistent with gradual subsidence. It should be noted that very similar thicknesses would result if the reefs merely grew sideways into deeper water without any subsidence. Lateral growth certainly takes place on some reefs, as Darwin showed, but it seems unlikely that it is important. Among other reasons, the islands apparently subside roughly 300 m to eliminate the sea cliffs and hundreds of meters to embay the valleys and isolate the small peaks.

If we accept the reef thickness as a measure of subsidence, the rates of subsidence of the islands can be compared with those expected from cooling of the lithosphere. The islands subside as fast as if they had been built on lithosphere with a thermal age of no more than 3 Ma, despite the fact that the actual age of the underlying lithosphere is early Cenozoic or Mesozoic. Some of the subsidence might be attributed to the added mass of the reefs, but the reef structure is very open and the aggregate density is too small to have much effect. Thus, most of the subsidence apparently is thermal and the rates indicate that the lithosphere has been thermally rejuvenated on midplate swells.

The subsidence of islands with coral appears to be entirely different
from the subsidence of those without. Indeed, it would be very surprising if they were the same. A volcanic island in cool water is eroded away by weathering, wave, and river, and almost all the erosion products are carried away from even the submarine base of the volcano. Thus, isostasy keeps the island at sea level until it is truncated. Then it sinks with the cooling sea floor, but by that time even initially very young crust has aged 5 Ma to 10 Ma and is not sinking so fast. In contrast, a reef-girt island is protected from waves, and the widening lagoon captures erosion products that are not in solution. Thus, isostasy does not keep the island at sea level, and it sinks immediately with the sea floor, which may be very young thermally.

**Drowned Atolls and Banks**

When he was on the Beagle, Darwin considered himself primarily a geologist, but, of course, he thought as a naturalist and always had the competition and the death of organisms in the back of his mind. He observed that submerged banks with flat tops and raised edges were dispersed among atolls in some regions. A notable one is Great Chagos Bank, in the central Indian Ocean. The bank is roughly 150 km in diameter. The interior is a "level muddy flats" somewhat less than 100 m deep, surrounded by long submerged banks, about 30 m deep, made of coral sand but very little live coral. The deep banks in turn are surrounded by a series of long narrow banks, at a depth of 10 m to 20 m, which form the rim of the whole great feature. This rim is composed of dead reef limestone with a thin layer of sand but scarcely any live coral. In short, Great Chagos Bank appears to be a dead and submerged atoll, despite the presence of nearby atolls and even of some thriving coral pinnacles within the great drowned lagoon. Why should a reef not die? Darwin wrote, "it cannot be expected that during the round of change to which earth, air, and water are exposed, the reef-building polypiters should keep alive for perpetuity in any one place." Particularly if oceanic islands subside.

Since Darwin's time, scientists have become more specialized and geologists generally have had difficulty in understanding how atolls could be drowned. The problem is not trivial. There are 261 atolls in deep-ocean basins and scattered among them are 116 banks, 10 m to 20 m deep, that are suitable sites for atolls and many of which have the morphology of drowned atolls. Moreover, many atolls, particularly in a few regions, are incomplete rings, and some are only single small islands on the edge of extensive banks. In sum, almost a third of the potential sites for atolls are
unoccupied, so it appears that atoll mortality has been high in recent geological time.

The cause of the high mortality may be related to the one important fact about atolls that Darwin did not know. Only 12,000 years ago, atolls were all islands 100 m to 150 m high because sea level was low. At that time, all the exposed coral was dead but, presumably, patches of live coral formed a fringe around the shoreline of most islands. Then sea level began
to rise at rates of 6 mm/yr to 10 mm/yr. Darwin had showed that small patches of coral in optimum conditions can grow 360 mm/yr, but he lacked data for whole reefs. Estimates by Harry Ladd in 1961 put the overall rate of reef growth at less than 14 mm/yr. Even so, this rate could have kept up with rising sea levels. Nonetheless, about a third of oceanic reefs did not, or have not yet, caught up with sea level, so conditions must have been less than optimum for reef growth. Such conditions are observed in the passes through the reefs of thriving modern atolls. In general, the passes do not fill in because of the relatively variable salinity, temperature, and sediment load of the waters that flow in and out in tidal cycles.

The factors that controlled reef growth are uncertain, particularly where atolls and shallow banks are intermixed. However, most drowned atolls are in regions that are relatively free of healthy ones. Such regions are in the western Caroline Islands, the South China Sea, and the Melanesian region north and west of Fiji. In the last of these regions, some drowned atolls have been dredged and their substructure determined by explosion seismology. They are thick reefs that had been atolls for tens of millions of years, but now there is no sign of them at the surface. Except for a scattering of non-reef-forming corals, the drowned atolls are dead. Indeed, no live coral pinnacles such as exist on Great Chagos Bank rise from the great flat “lagoons.” It is perfectly safe to proceed at cruising speed over seemingly endless rocky bottom only 20 m below the hull. However, if the oceanographer loses his nerve in the middle of one of these banks, it can take half a day at prudent speeds for maneuvering over a reef to finally reach deep water.

One modern characteristic of the regions with drowned atolls is that the rainfall is unusually high. Tropical rainfall is highly variable with latitude, and atolls experience rainfall ranging from 1000 mm/yr to 5000 mm/yr. However, most atolls are exposed to less than 2500 mm of rain per year. In contrast, drowned atolls are concentrated in regions with 2500 mm/yr to 4000 mm/yr of rain, so low salinity may be one of the factors that prevent drowned atolls from growing to the surface.

**Coral-Capped Guyots**

Thermal subsidence is constantly pulling the drowned atolls downward and presumably some of them will eventually become submerged deep enough to be guyots. Certainly, as Darwin surmised, there are dead, deeply drowned atolls. The first of these discovered in the central Pacific was appropriately named Darwin Guyot in 1974. It has a fossil reef fauna, the morphology of an atoll, and a minimum depth of 1250 m. Other
guyots that are presumably drowned atolls have not been sampled. How-
ever, seismic reflection profiles across some guyots in and north of the
tropical Pacific show mountainous basement topography buried by more or
less layered rock with a relatively flat upper surface. This rock can hardly
be anything but a coral reef that was deposited over a subsiding volcanic
island. Thus, Darwin is wholly confirmed. Atolls may die and sink be-
neath the waves.