Deep Sea Drilling: A Giant Step in Geological Research

Advances made in the last decade of sea-floor exploration add up to a conceptual revolution in the earth sciences. In the process of filling in "the blue area" on the map, geologists and geophysicists have enormously increased the amount of information available to them and have converted such once doubtful ideas as continental drift and the Ur continent Gondwanaland into widely accepted concepts. Although a variety of techniques including both seismic surveys of subbottom, reflecting strata and paleomagnetic measurements have contributed to the exploration of the sea floor, the climax of this effort has been the Deep Sea Drilling campaign of the ship *Glomar Challenger* operated by Scripps Institute of Oceanography at La Jolla for a consortium of universities and research institutes with funding from the National Science Foundation.

The *Challenger*, now entering its third year of sea-floor drilling, is manned by teams of scientists from several countries representing many universities and institutions, each team conducting shipboard research for a 2-month period. The examination and interpretation of the samples require the work of several different specialties, and the interaction of paleontologists, geologists, geophysicists, and oceanographers underlines the uniquely interdisciplinary nature of the Deep Sea Drilling project.

In the basic procedure holes are drilled up to 3300 feet into the sea floor in water as deep as 20,000 feet, with technology borrowed from the petroleum industry. The cores recovered are subjected to shipboard inspection and laboratory work, including paleontological dating, x-ray examination, and measurement of natural radiation. Afterward more detailed investigation is carried out at a variety of shore laboratories. The cores, which are available to any scientist, are stored at two repositories: Pacific cores at Scripps Institute and Atlantic cores at Columbia's Lamont-Doherty Geophysical Observatory.

Since operations began in August 1968, more than 30,000 feet of sediment and hard rock core have been recovered from 219 holes at 154 drilling sites by the end of the 13th cruise leg. Of these, five legs were concentrated in the North and South Atlantic, five in the Pacific, two in the Gulf of Mexico and the Caribbean, and, most recently, one in the Mediterranean.

The sedimentary record represented by each core contains a geologic history that can be tied in with the biologic history from the fossils included in the core (the major divisions of geologic history and their approximate dates are given in Table 1). The completeness of this oceanic record contrasts with shore-based evidence, which must often be pieced together from many sources, and it provides a base line against which to calibrate seismic and magnetic data on the sea floor. Perhaps the primary fact of this oceanic record is the relative youth of the oceanic crust, apparently Jurassic or younger, compared to the much more ancient continental crust.

Sea-Floor Spreading

One of the main objectives of the Deep Sea Drilling project was to test the hypothesis of sea-floor spreading. Geologists had for many years suggested the existence of an ancient supercontinent (Gondwanaland) because of similarities in geologic structures on widely separated continents. In 1958 Bruce Heezen of Columbia University suggested that continents drift by sea-floor spreading when he noted that the epicenters of earthquakes lined up with the rift valleys of the midocean ridges. The spreading hypothesis as it has evolved is based on the assumption that oceanic crust is continuously created by the upwelling of material from the mantle at the midocean ridge and that it is destroyed in the oceanic trenches by incorporation into the mantle or by partial incorporation into mountain belts. More recently, theories of spreading have been elaborated in terms of plate tectonics. These theories postulate that the sea floor is composed of rigid crustal blocks, and that major deformations occur only at the edges or boundaries of the plates.

Early but indirect evidence for sea-floor spreading was provided by the study of the magnetic anomalies known to be associated with the midocean ridges. F. J. Vine and D. H. Matthews proposed in 1963 that the pattern of alternating positive and negative anomalies found on either side of the ridge arose when the prevailing direction of the earth's magnetic field was frozen into the cooling basalt during the formation of new crust at the ridge, and was then carried out to either side as the sea floor spread. To many, however, the evidence for spreading was unconvincing.

Results from the Deep Sea Drilling program have now provided direct evidence for continental drift by sea-floor spreading, thus confirming to some degree the picture developed by the plate tectonic theorists from magnetic data; but the evidence gathered so far also indicates that the crustal motion is more complicated than had been previously supposed.

The substantiating evidence for sea-floor spreading now seems very convincing. On Leg 3 in the South Atlantic, for example, the ages of the oldest sediments immediately above the underlying basaltic crust ranged from 11 to 67 million years, with the age of the crust from each hole being proportional to its distance from the axis of the Mid-Atlantic Ridge. Similar results were obtained in the North Atlantic and the Pacific. Spreading in all cases seems to be symmetrical about the midocean ridges at nearly constant rates of 1.2 centimeters per year in the North Atlantic, 2.0 cm/year in the South Atlantic, and 12.0 cm/year in the Pacific, at least over the last 70 million years. These spreading rates agree remarkably well with those obtained from the magnetic measurements; however, the oldest crust yet found in the North Atlantic, just off the continental rise, is about 160 million years old. This age implies that the rate of spreading in Mesozoic times was perhaps twice that at present.

Three-Dimensional Motion

However, complicating the sea-floor spreading picture is the evidence that there has been substantial vertical motion of the ocean crust as well. A suggestion of vertical motion is implicit in the spreading hypothesis both because of the sinking in the trenches, and because of the relative height of the midocean ridges—as much as 3000 meters in elevation from flank to crest —so that significant flank subsidence was to be expected. Nonetheless, the extent and, in some cases, the rapidity of the vertical motion has come as a surprise to many.

Evidence for vertical motion comes from the types of sediments found. Away from the spread of land-derived mud and sand, calcium carbonate dominates the deposits of sediments formed in shallow water. In deeper water, there is very little calcium carbonate in the sediment, because the calcareous material is dissolved at higher pressure and lower temperature. The sediment below this depth, known as the zone of carbonate compensation, is usually a red-brown residual clay.

The record, either calcareous or clay, is formed at the time of sedimentation and thereafter preserved as new layers are deposited on top. In many of the cores, the older and deeper sediments contain calcareous material, whereas more recent material was deposited at deeper depths, and has ended up as clay. It therefore seems that the crustal plates have indeed subsided, in agreement with the spreading hypothesis.

The drilling data also give evidence of more general subsidence and uplift in several parts of the ocean basins. In the South Atlantic the midocean ridge itself has apparently undergone major changes in elevation, subsiding for a period in the middle Miocene, then recovering. These changes seem to be associated with short-term changes in the rate of spreading, with slower spreading corresponding to the depressed height of the ridge crest. In the far northern Atlantic there is evidence of small continental fragments which had apparently become separated from the continents during the sea-floor spreading process and which then foundered rapidly.

The findings of vertical motions, while confirming the sea-floor spreading hypothesis, have caused a reassessment of the three-dimensional character of the plate movements and have provided a more complicated history to be unraveled. Theoretical treatments of plate tectonics do not at present incorporate such complexities.

Sedimentary Processes

One of the most surprising finds from the Deep Sea Drilling project has been the discovery of a widespread layer of Eocene chert in the North Atlantic sediments. Chert, or flint, had previously been found in marine samples, but its unexpected abundance indicates that about 70 million years ago the bottom water chemistry in the North Atlantic favored the deposition of opaline skeletons of microorganisms. These skeletons are usually lost by solution, but in this case their silica has been redistributed in the sediments to form the chert layers.

Table 1. Geologic time scale.

Period	Epoch	Age (m.y.)
	Cenozoic Era	
Quaternary		0–2
Tertiary	Pliocene	2–11
	Miocene	11–25
	Oligocene	25–40
	Eocene	40–60
	Paleocene	60–70
	Mesozoic Era	
Cretaceous		70–135
Jurassic		135–180
Triassic		180–225
	Paleozoic Era	225–600
	Precambrian Era	> 600

When drilling began, the chert layers were identified with some of the seismic horizons. But although horizons have been mapped over much of the ocean basins in apparently continuous patterns, further drilling has established that the seismic horizons are more complicated than was first thought. Apparently a horizon need not be exactly parallel to either time lines or rock strata, and its precise interpretation awaits a better understanding of sedimentary processes and properties.

Study of the chert layer and other evidence in the drilling cores will help to increase knowledge about sedimentary processes, and to increase understanding of sedimentary rocks found on land as well. These rocks may have been formed from sea water but were later washed by fresh water and disturbed by other events, so that the history by which they acquired their properties is not easily untangled. The simpler history in the oceanic sediments brought up in the cores will facilitate study of how water is squeezed out and how the sediments are turned into rock. Although these studies are just beginning, the widely held earlier view that sediments found on land must have been deposited in shallow water has been overturned in part by the more detailed information about deep water sediments from drilling cores and by the recognition of these sediments in mountain belts around the world.

Additional Findings

Other discoveries have also been made by the Deep Sea Drilling project. In the far western Pacific, Leg 6 found evidence of a large area of Jurassic crust, a remnant of the Mesozoic ancestor of the present ocean bottom. Directly adjacent to this ancient crust, Leg 6 found relatively new crust, only 30 to 40 million years in age, separated only by the Mariana trench. Similar apparently young crust was also found by Leg 6 and Leg 7 behind the island arc of the Caroline basin. At present there is no clear indication as to how this newer crust was formed and whether the processes that operate are similar to or distinct from those which formed the neighboring main basin.

The most recent results from the drilling program have helped to clarify the history of the Mediterranean area. The cores recovered contained rock salt and other minerals foreign to a marine environment in a layer of sediments devoid of fossils and dating from the late Miocene. It is believed that the Mediterranean was cut off from the Atlantic about 5 to 10 million years ago; extreme evaporation apparently concentrated the salt brine, thereby killing all life and precipitating the rock salt. Later movements again opened the sea to the Atlantic.

Evidence of crustal blocks of older material upheaved onto very recent sediments was also found in the Mediterranean. The data suggest compressive motions implying that Europe and Africa are now moving together again.

Although the mission of the *Challenger* has been a scientific one, it has discovered hydrocarbon deposits which may come to be of economic value. One of the diapiric structures in the Gulf of Mexico was drilled and found to contain oil and gas, a significant finding in that it was the first time that hydrocarbons had been found in deep sea conditions.

The Deep Sea Drilling program has helped to resolve a number of geological questions while raising many new ones. The thousands of feet of core recovered provide the opportunity for a more complete understanding of both detailed sedimentary processes and the broad outline of the earth's history. Undoubtedly new surprises will appear as technological advances make possible deeper penetration into the crustal material and as sea-floor exploration is extended into new regions, such as Antarctic waters.—ALLEN L. HAMMOND