Project FAMOUS: Exploring the Mid-Atlantic Ridge

Jules Verne described an incredible journey to the center of the earth. Nearly as incredible to those involved has been the actual exploration of the huge rift valley that splits the undersea Mid-Atlantic Ridge into two mountain chains. Probing the sea floor at a depth of nearly 3 kilometers in the chasm the French call "the navel of the world," French and American oceanographers in tiny submersibles found a host of novel volcanic forms, a series of cracks and fissures in the seabed which in some cases were large enough to swallow the submersibles, and metallic deposits thought to be laid down by streams of hot water. The French-American Mid-Ocean Undersea Study (FAMOUS) provided a unique first-hand look at the eastern boundary of the crustal plate on which the North American continent rides, a site where new crust is being formed in the process now known as sea floor spreading.

FAMOUS was a major collaborative effort that bears no little resemblance to the Apollo program. There were in all 25 separate cruises to the target area, a region of ridge between 36° and 37°N, culminating last summer in a series of 42 dives by three submersibles.* Extensive maps of the sea floor topography were made preparatory to the dives, and the scientist-divers who were to descend in the vessels underwent training to prepare for their missions on the bottom. During dives the scientists in the submersibles followed a detailed mission plan, recording observations and collecting samples, while other members of the team monitored progress and the minute-to-minute location of the submersible from the surface. The resulting information includes more than 100,000 photographs of the seabed; a set of rock, sediment, and water samples from precisely known locations; and, not least, the impressions of the first field geologists to observe directly the faults and lava flows of the newly formed sea floor. In addition, cores were obtained by the Deep Sea Drilling Project (DSDP) from two drill holes not far from the exploration site.

The Mid-Atlantic Ridge is part of a worldwide submarine mountain system 65,000 kilometers in length and extending into every ocean. The ridges mark the trailing edges of the crustal plates that, in their movements, are the prime cause of crustal deformation, mountain building, and earthquakes. It is also one of the few places where, since the crust is relatively new and not yet buried by hundreds of meters of sediment, the basaltic crustal material itself is exposed in large quantities. Only in the North Atlantic, however, is the ridge so steep and cut by so deep a rift valley. Sections of the ridge are offset from each other by canyons transverse to the main valley and known as fracture zones, the sites of frequent earthquakes caused by friction between the receding North American and African plates. Project FAMOUS explored two sections of the central rift valley and two fracture zones.

One of the major accomplishments of the project was the technical feat itself. FAMOUS established—according to James Heirtzler of the Woods Hole Oceanographic Institution, head of the U.S. team—that "it is now relatively easy for oceanographic scientists to work at the bottom of a deep ocean" (see box). Another was the discovery that, as Tjeerd van Andel of Oregon State University put it, "the ocean floor is disturbingly different from what we had imagined" in its enormous variety of rock forms and chemistry, topography, and sediment content over very short distances. Uniformity of the ocean floor has generally been assumed in interpreting ship-based profiles and dredging hauls, and this assumption is now called seriously into question, van Andel believes.

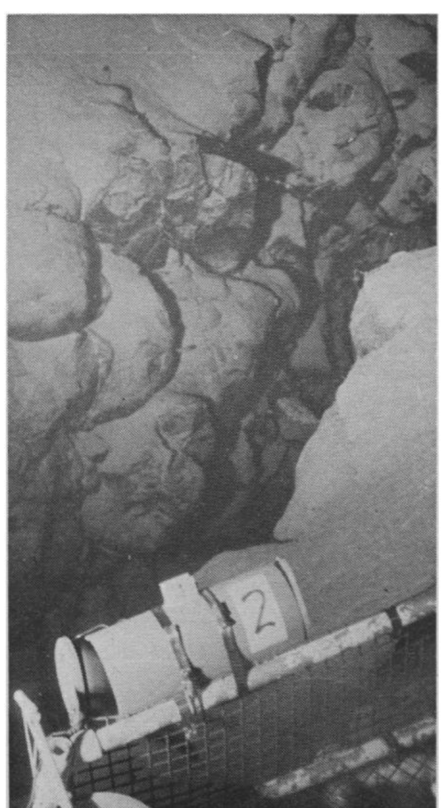

Fig. 1. A medium-sized fissure in the floor of the mid-Atlantic rift valley resulting from sea floor spreading. [Source: Woods Hole Oceanographic Institution]

Until FAMOUS, there had been little success in bridging the gap between small-scale features of the ocean floor, as indicated by a single dredge sample or bottom photograph, and larger geologic features, because the samples and photographs could not be located more accurately than about 100 meters. With the submersibles used in exploring the rift valley, however, locations of samples were determined to within 10 meters or less, making possible the construction of traditional geologic maps, the first in the deep sea. Study of the photographs and samples are now yielding insight into at least three fundamental processes—sea floor spreading, formation of new crust, and hydrothermal emplacement of minerals.

The mid-ocean ridges are well known to be zones of divergence between two crustal plates. But there has been considerable debate as to whether accumulation of new material at the ridges helped to force the plates apart or not —whether sea floor spreading is an active or a passive process. Evidence that the plates are being pulled, not pushed apart comes from the more than 400 cracks and fissures the FAMOUS scientists identified within a 6-kilometer-square area. The U.S. submersible *Alvin* descended into one of the larger cracks, the presence of which, along with other indications of tensional forces in the crust, argues in favor of passive sea floor spreading.

The cracks, oriented mostly parallel to the ridge axis, ranged from hairline fractures near the center of the rift valley to gaping fissures 10 meters

* J. R. Heirtzler and X. Le Pichon, *Geology* 2 (No. 6), 273 (1974).

Submersibles: A Research Technology Whose Time Has Come?

Submersibles are not new. But their extensive use in oceanographic exploration of the sea floor is. As employed by Project FAMOUS, submersibles were the tip of an organizational and logistical iceberg that included perhaps the most extensive bathymetric mapping of the ocean floor ever done, a novel and extremely accurate navigation system, and a team approach to undersea exploration. The result is a new ability to apply the traditional techniques of field geology in the deep ocean, an ability that has made enthusiastic believers of the scientist-divers who participated in the project.

Three of the world's four deep research submersibles were used—the U.S. *Alvin* and the French *Archimede* and *Cyana* (Fig. 1). Each carried three persons and a multitude of instruments crammed into a metal sphere 2.1 meters across to depths between 2.1 and 2.9 kilometers. Divers in the *Alvin* spent about 4 to 6 hours on the bottom plus an additional 3 hours in the round trip from the surface, and some of the French dives lasted still longer. In all, the submersibles covered some 50, often tortuous, kilometers of seabed in a summer of diving.

Visibility on the bottom was about 10 to 15 meters. A sonar system enabled divers to detect objects beyond the range of the lights up to 300 meters. Despite training dives, most of the scientists reported that coping with a sense of strangeness fostered by the unusual volcanic forms and abrupt topography on the bottom and the demands of loading film in the dark and operating unfamiliar instruments took several dives to get used to. (*Alvin*'s crew consisted of two scientists and a pilot; the French craft carried one scientist and two pilots.) Nonetheless, the geological features that are visible on a small scale to the eye are not readily observable by other means, the scientist-divers claim. They found their ability to interpret photographs of the sea floor, for example, to be enormously improved after the diving experience.

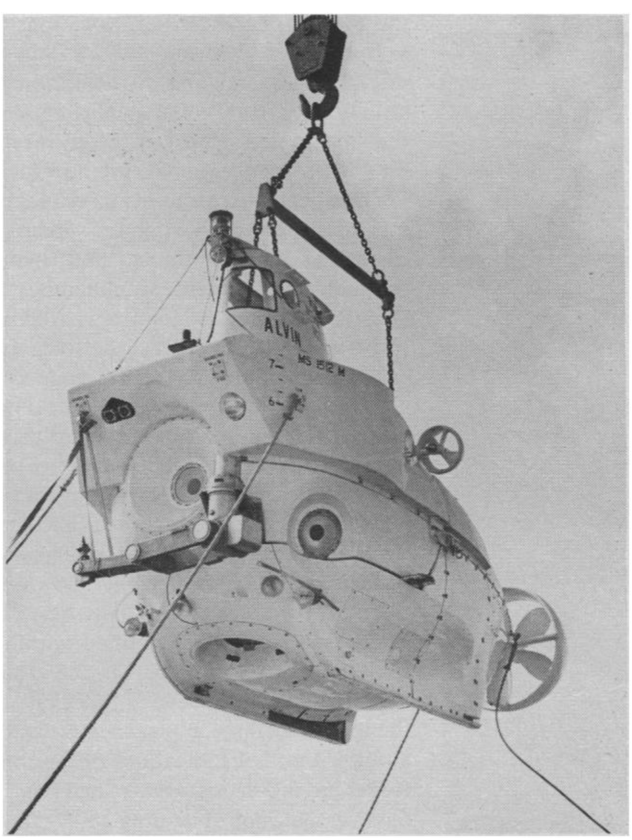

Fig. 1. The U.S. submersible *Alvin*, capable of carrying a crew of three to a depth of about 3.5 kilometers. [Source: National Science Foundation]

To tie the small-scale observations into a systematic exploration of the region required considerable preparation. In several cruises over the target area, the U.S. Navy made and released extremely detailed bathymetric charts that show depth contours as fine as 5 fathoms (about 10 meters) with an advanced military echo-sounding system. Since even ordinary echo-sounding gear is almost nonexistent on most university-operated research ships, the charts represented a remarkable resource that allowed dives to be carefully planned to study specific features.

Perhaps the most significant advance in submersible technology, however, was an improved navigation system used on *Alvin* that allowed minute-to-minute tracking of the submersible so that both the divers and the sea-surface observers could locate the ship and its movements on the charts with unparalleled accuracy. The system included three acoustical transponders anchored near the ocean floor, synchronized precision clocks on submersibles and surface ships, and a small computer. At preset intervals, a signal emitted by the sub was picked up and relayed by the transponders to the surface ship. Within seconds the computer analyzed time delays in the signals and triangulated among them to locate the submersible, allowing for the possibility that a transponder, hidden from the submersible by the hilly sea floor terrain, had picked up a delayed signal bounced off the sea surface. The system performed automatically and reliably, according to William M. Marquet of Woods Hole (it was "down" only 10 minutes in 17 dives), and provided the submersible's position—and hence the location of photographed features and bottom samples—to within 5 to 10 meters. The navigation system for the French submersibles was similar in many respects and had a nearly comparable accuracy.

Submersibles are not inexpensive to operate, although they do not cost much more than surface ships. And if, as some oceanographers contend, dredges and underwater cameras are reaching the limits of their effectiveness, then the submersible may indeed be about to come into its own, especially for detailed examination of an undersea site. Certainly they permit a new dimension in oceanographic research, that of the live observer in the deep ocean. Those who have been down to the bottom are convinced. James Moore of the U.S. Geological Survey talks of doing "true ocean geology." Jean Francheteau of the National Oceanographic Centre of Brittany says that "oceanography is at a turning point in regard to tools for examining the seafloor." The National Science Foundation would seem to agree, as it has, in effect, nationalized the *Alvin* to make it accessible to a broader range of researchers.—A.L.H.

across near the valley walls (Fig. 1). This progression in size suggests that the spreading process is continuous, according to Robert Ballard of Woods Hole. In contrast, the volcanism in evidence on the valley floor appears to be episodic and localized in occurrence. Indeed, the valley floor is so cracked and broken that outside of a central region many of the more delicate volcanic forms have been destroyed. The implication appears to be that tectonics (plate movements) is the overriding process along the mid-ocean ridge system, and not volcanism.

In addition to horizontal movements, the divers found evidence of vertical motions of the crust. The walls of the rift valley itself, for example, appear to have been lifted up (as high as 300 meters) from the valley floor rather than formed in place. The mountain chains that form the ridge itself are tectonically more complex than the rift valley and are not yet well understood.

A second process along the mid-ocean ridge system is the formation of new oceanic crust, which seems to occur by the extrusion or eruption of molten basalt. When hot magma is quenched by seawater, so-called pillow basalts are formed. Pillow basalts are the most common type of rock on the earth's surface, yet because much of it lies on the sea floor covered in most places with sediments, it is among the least well known. Several new forms of pillow lava—some with bizarre shapes—were discovered in the course of the submersible dives (Fig. 2). The divers also charted eruptive sites and lava flows in a detailed study of formation mechanisms. They found a series of small sea mounts along the center of the rift valley to be sites of geologically very recent volcanic activity, but they found no evidence of ongoing eruptions. In the section of the rift valley explored by FAMOUS, at least, the volcanic activity appeared to the divers to be not only episodic but largely confined to a narrow central strip of up to 1 kilometer in width. Most of the new oceanic crust appears to be formed, at the surface, by eruptions of the chain of small volcanoes. The narrowness of the injection region emphasizes the sharpness of geologic boundaries in the rift valley, where a submersible can traverse from the North American plate to the African plate in a single dive, in contrast to the broader, more gradual geologic boundaries often found on continents.

Fig. 2. Pillow basalts on the floor of mid-Atlantic rift valley. The freshness of these recently erupted volcanic forms, many of which are still covered with a fragile glassy material, makes the rift valley a mecca for volcanologists. [Source: Woods Hole Oceanographic Institution]

Studies of 50 samples of fresh pillow basalts brought back from the rift valley show systematic variations in the chemistry and petrology of the rocks across the valley floor. According to James Moore of the Geological Survey in Menlo Park, California, basalts in the center of the valley are more primitive, are richer in olivine, and formed at a higher temperature than those sampled near either side. Both kinds have been found on the ocean floor before. In the rift valley, however, the change from one to another occurs over a distance of 1.5 kilometers—a phenomenon that may be related to properties of the magma chamber that separates the two crustal plates. The vertical temperature gradient in the valley floor is so high, 30°C per 100 meters, that the magma chamber is thought to be less than 2 kilometers beneath the sea floor. Various models of the chamber and of the magmatic processes by which new crust is formed are now being considered by the investigators.

A third process is that of mineral emplacement on the sea floor. In one of the fracture zones transverse to the main rift valley, the French team found two sites at which minerals, primarily iron and manganese, had been deposited on the bottom by hydrothermal activity. Both deposits were located in a tectonically active zone of the fault (known as a transform fault) that runs along the submarine valley floor—a zone where the crust was strongly sheared and the sediments showed signs of recent movements. Their geothermal origin was indicated by the vent holes, elongated fissures from which the metal-bearing hot water presumably issued, associated with each deposit. Temperature measurements near the vents showed no anomalies, however, indicating that the vents were not active during the study period. But the crust in the area was about 1 million years old and showed no signs of recent volcanic activity. Thus the deposits constitute the first unambiguous evidence of oceanic hydrothermal activity, apart from the Red Sea, according to Jean Francheteau of the National Oceanographic Center of Brittany, in Brest.

Oceanographers have long suspected that seawater, percolating down in cracks, plays an important role in dissipating heat from the crust. Mineral extraction might then occur as the water leached iron and other metals from the basalt and deposited them elsewhere. The FAMOUS results tend to support this view, although the lack of copper, cobalt, nickel, and other metals in the deposits remains something of a mystery. Moreover the discovery of hydrothermal activity in a fracture zone where the crust is highly sheared but not in the rift valley may mean, Francheteau indicates, that mineral emplacement in the oceanic crust occurs preferentially in such fracture zones. If this hypothesis is correct, the task of finding such deposits will be greatly simplified. In any event, the discovery is a major step toward a concrete version of a widely assumed but rarely specified relation between tectonic processes and mineral emplacement.

Still other results will undoubtedly emerge as the wealth of data gathered by the submersible dives is analyzed further. If nothing else, the exposure of a growing number of observational oceanographers to the ocean floor itself is bound to increase respect for its variability and to improve understanding of sea-bottom processes. And the characterization of mid-ocean ridges as tectonically passive features has already provided theoreticians with a major constraint on their efforts to explain how the earth's crustal plates move. If the success of FAMOUS is any measure, then the exploration by submersible of other ocean ridges, which is now being planned, and ultimately of the oceanic trenches themselves should prove well worthwhile.

—ALLEN L. HAMMOND