Deep-Sea Research by Manned Submersibles

Marine scientists are learning how to use deep-diving manned submersibles effectively to study the sea floor.

J. R. Heirtzler and J. F. Grassle

Although three-quarters of the earth's surface is covered by seawater, an insignificant portion of it has been directly viewed by man. The oceans are so large and the investigators so few that general surveying techniques comprised a reasonable program in the past. In the last few years our general knowledge of the oceans has been rapidly filled in, the practical use of the seabed has emerged, and the law of the sea has begun to limit research on foreign continental shelves. As a result of these trends the scientific study of the deep-sea floor has become more immediate.

The history of submersibles is short and the record of their scientific utilization even shorter—less than two decades. They have been generally viewed by the public as vessels which are used in attempts to set depth records and whose crews execute rather ill-conceived scientific projects. This image is also held by much of the scientific community and has been difficult to dispel as the truly scientific use of submersibles has begun. The public also frequently draws parallels between manned submersibles and manned lunar spacecraft. They are similar in that they are crafts of similar size used in the exploration of unknown geologic terrains, but the resemblance hardly extends to cost.

The community of scientific submersible users has been relatively small, in contrast with the number who have used submersibles for industrial, not to mention military, purposes. About 350 scientific papers were written by scientific submersible users during the last quarter-century (*1*). Fifty percent of these papers were written by 12 percent of the authors. Nearly half of the articles were on marine biology, somewhat more than one-quarter on geology and geophysics. Nearly all of the dives referred to in these early papers were made on the continental shelves, where the water is not more than 200 meters deep.

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New Programs in the Deep Sea

In the deep sea the trend of research is somewhat different from that on the continental shelves. The purposes are different and the logistics are more complex. Again, it is the geologists, geophysicists, and biologists who are the major users.

Marine geologists are forming consortia for the intensive study of several mid-ocean ridge areas. This was done in the French American Mid-Ocean Undersea Study (FAMOUS) project on the Mid-Atlantic Ridge southwest of the Azores, and in the Cayman Trough project in the Caribbean (Fig. 1). Similar projects are in the planning stages for the East Pacific Rise ridge crest near the entrance to the Gulf of California; near the Siqueros fracture zone at 9°N, where the sea-floor spreading rate is exceptionally high; and at the Galápagos spreading center northeast of the Galápagos Islands. Dives are planned at these and other sites after they have been extensively surveyed with surface ships and deep-towed instrument packages. The primary objectives of these studies will be to examine in detail the unique volcanic and geophysical processes at these spreading centers and associated fracture zones. The fine scale of hydrothermal activity, distribution of metalliferous sediments, age relationships of sea-floor material, petrographic and magnetic characteristics, location of microseismicity, and so forth will be delineated.

In project FAMOUS, 47 dives were made to a depth of approximately 3000 m by the American submersible *Alvin* and the French submersibles *Archimède* and *Cyana* (*2*). These dives were undertaken in a coordinated fashion in 1974 after numerous surveys of the area during the previous 2 years by surface ships and deep-towed instruments. The submersibles were used to investigate fissures in the sea floor that were only a few meters wide but 100 or more meters long. Small volcanic hills a few tens of meters wide at the center of the rift valley were studied; these hills are believed to be situated in the Atlantic where new crust is being formed by sea-floor spreading. The scientists photographed small dykes in the vertical west wall of the inner rift valley. They localized areas of a few square meters in one fracture zone where hydrothermal action appears to be taking place. Numerous precisely located and oriented rock samples were collected for petrologic, chemical, and magnetic analyses. These and other observations have led to realistic explanations of how the ocean floor is being created and have had a major impact on our understanding of the oceanic basement and on the planning of projects such as the Deep Sea Drilling Project.

The FAMOUS data that bear on the local distribution of fish, sponges, and corals have not yet been analyzed (Fig. 2). The divers found water movements down the faces of cliffs and through fracture zones that are poorly understood. Visual observations of the location of various biological communities indicate a close relationship to physical oceanographic and geologic conditions.

The New England seamounts extend for 2000 kilometers from the East Coast of the United States. In 1968 two dives were made on Bear Seamount (*3*), which is closest to the coast, and we had our first direct look at the tops of others only within the last 2 years, when dives were made on seven others (*4*). The seamounts are extremely rugged and have several types of topographic features not previously seen on the sea floor. On Mytilus, one of the seamounts closer to the continent, dead coral that had lived in water no more than 100 m deep has been sampled from *Alvin* at a depth of 3000 m. These dives are our first brief look at an area nearly as large as the continental United States. The base of the seamounts and the great abyssal plains are so deep that they can be reached by only one submersible—the *Archimède*.

Manned submersibles hold great potential for studying currents and sedimentation phenomena in canyons cutting the continental slope (*5*), disposal of wastes, and the distribution of manganese deposits.

The last decade has seen a major increase in our knowledge of deep-sea biology. Sampling techniques developed in the middle and late 1960's led to the discovery of a vast diversity of unanticipated life forms, raising fundamental questions about the evolution and maintenance of this diversity. Most of this work was done with instruments that reached the bottom at the end of a mile or more of steel cable. These techniques were adequate for outlining the major features of benthic community structure, but were insufficient to explain the functioning of these communities. Instead of snapshot views of the bottom at haphazard intervals, deep-sea biologists felt the need of repeated visits to fixed locations on the sea floor to conduct controlled experiments. Study of the dynamics of deep-sea communities required precise sampling at fixed times. A few years ago the "permanent bottom station" concept evolved with the establishment of three deepwater stations in the North Atlantic.

The first measurements of the dynamics of deep-sea communities were made at these stations from *Alvin*. Information on the rates of degradation of organic wastes, rates of the spread of material, and rates of recovery of deep-sea populations is relevant to an understanding of the impact of disturbances such as the waste dumping and deep-sea mining. Equipment designed to measure rates of microbial activity, recruitment, growth, metabolism, and community succession has been placed and retrieved at varying intervals, up to 26 months. The rates of these life processes in the deep sea are extremely low compared to those in shallow water.

Rates of microbial activity have been shown (*6*) to be 10 to 500 times lower in the deep sea than in shallow-water environments. *Alvin* has been used to sample bacterial populations in the sediment and the water column. The bacteria are incubated with isotopically labeled substrates for up to 15 months on the bottom. Solidified organic materials exposed for 15 months also show little evidence of microbial disintegration. Measurements of in situ community respiration (*7*) indicate rates two orders of magnitude lower than those measured in shallow-water environments.

Boxes of azoic sediment have been used to measure rates of colonization and growth of deep-sea infauna (*8*). Boxes have been brought back after 2 to 26 months at one of the three permanent bottom stations. Rates of recruitment and growth are extremely low compared to rates in shallow water. After 26 months on the bottom, the density of life is still an order of magnitude lower than in surrounding sediments and almost all of the animals are still juveniles. Of the few adults found after 26 months, all but two individuals belong to a single polychaete species normally uncommon in the deep sea.

In contrast, studies of wood panels placed at the three permanent bottom stations provide the exception to the generalization that life processes proceed at very low rates in the deep sea (*9*). In a period of 3 months the boards become riddled with dense populations of two species of wood borers, indicating rates of recruitment and growth closer to those measured in shallow-water environments. The wood habitat of these animals is normally an ephemeral resource in the deep sea, and the wood borers are opportunistic species adapted to survive in a short-lived habitat.

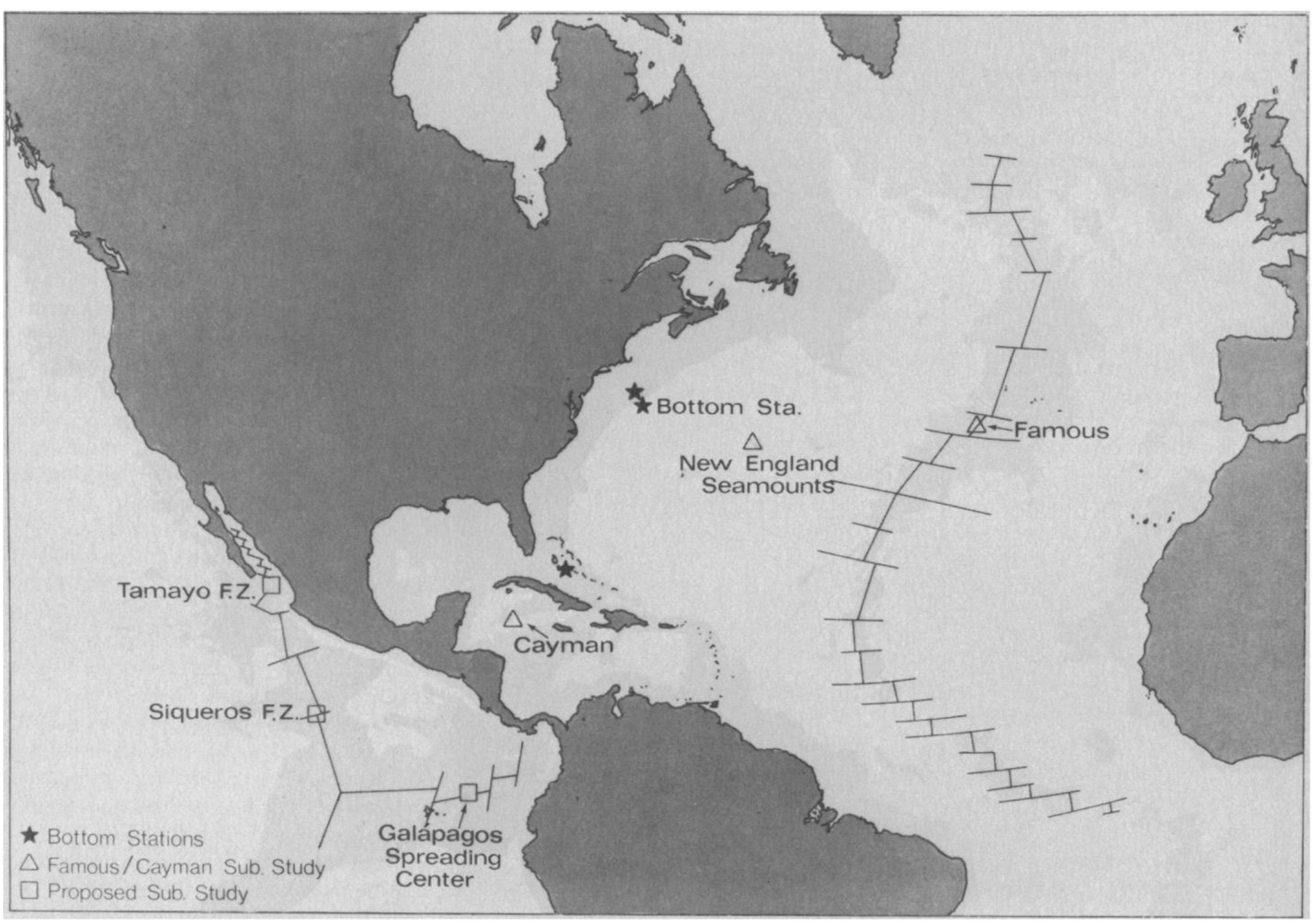

Fig. 1. Areas of major deep-sea studies by manned submersibles, including proposed study areas. The lightly shaded areas are less than 3.66 km in depth.

Submersibles Today

Surveys show that there are about 70 operational submersibles with a depth capability of 200 m or more (*10*). Nearly all of these are engaged in work for the petroleum or other industries off the continental shelves of the United States or in the North Sea, or in military research, and so cannot be classified as submersibles for scientific research.

There are ten submersibles that can operate at depths greater than 1.83 km (6000 feet) and half of these are from the United States (Table 1). Those operated by the U.S. Navy are occasionally made available for unclassified usage; *Deep Quest* is now effectively laid up, and only *Alvin* is scheduled in the same way as oceanographic research ships. The French submersibles scientists have worked closely with the Americans in recent years and have employed *Cyana*, which was recently modified to operate to 3000 m, and *Archimède*, which is the oldest vessel of the list but can dive the deepest. The International Hydrodynamics Company Ltd. of Vancouver has built a number of submersibles of the *Pisces* class. One is being used in the Beaufort Sea by the Canadian Department of the Environment and two in the Black Sea by the Soviet Academy of Sciences.

Table 1. Manned submersibles with an operating depth limit exceeding 1.83 km.

Submersible	Operator	Year of launch	Operating depth limit (km)	Payload (kg)	Length (m)	Manipulators	Viewports
United States							
Sea Cliff	U.S. Navy	1968	1.98	320	4.22	2	5
Turtle	U.S. Navy	1968	1.98	320	4.22	2	5
Deep Quest	Lockheed	1967	2.44	3200	12.2	2	2
Alvin	Woods Hole Oceanographic Institution	1964	3.66	680	7.02	1	5
Trieste II	U.S. Navy	1964	6.10	910	23.8	3	1
France							
Cyana	CNEXO	1970	3.0	200	5.80	1	2
Archimède	French Navy	1961	11.0	2720	21.0	3	3
Soviet Union							
Pisces VII	Soviet Academy of Sciences	1975	2.00	910	5.89	2	3
Pisces XI	Soviet Academy of Sciences	1976	2.00	910	5.89	2	3
Canada							
Pisces IV	Canadian Department of the Environment	1972	2.00	910	5.89	2	3

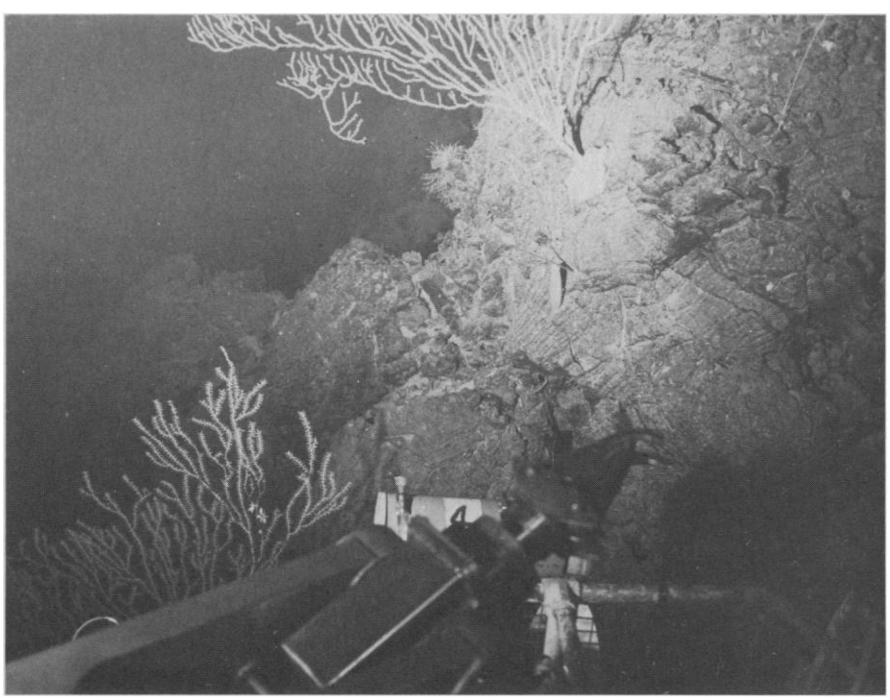

Fig. 2. Gorgonian corals growing on basaltic rocks of the Mid-Atlantic Ridge at a depth of 2700 m. A small vase-shaped siliceous sponge is located just below the upper gorgonian. The manipulator and tray of *Alvin* are in the lower part of this photograph.

Although it has been used little by the scientific community, the U.S. Navy's nuclear-powered submersible NR-1 has unique capabilities. Because its available power is virtually unlimited, the NR-1 can reach greater speeds and remain submerged longer than other research submersibles. It is able to illuminate very large areas of the seabed. It also has programmed track-following ability and other electronic marvels beyond the budget of the scientific research community.

The bulk of deep submersible research has been done by the *Alvin* in the United States and *Archimède* in France, although the *Cyana* has been very active recently. Each of these vessels requires a mother ship to assist in moving it to the dive location and for recharging energy sources, checking equipment, and housing diving personnel. *Alvin* and *Cyana* can be hoisted out of the water by the mother ship and put on deck after each dive.

The deeper-diving research submersibles vary in outward appearance (Fig. 3) but have similar capabilities. Personnel and instrumentation are generally housed in a metallic sphere about 2 m in diameter that contains one to five viewports. The inside is at atmospheric temperature and pressure, and there are no special suits or decompression requirements for its occupants. Two or three persons are accommodated, at least one of whom is a qualified submersibles pilot and the others scientists. The equipment consoles contain propulsion controls, navigation and communication equipment, interior environment monitors, controls for interior and exterior scientific instruments, and data loggers. The U.S. submersibles are built under rigid codes and certified by the Navy or the American Bureau of Shipping.

The high-pressure technology for submersible construction has been well understood for some time (*Trieste* penetrated to a depth of more than 10 km in 1960). Recent advances in submarine capabilities have resulted from the use of microminiaturization of electronic circuits and the general adaptation of existing techniques to the specific problems on which the submersible will be employed—especially navigational, photographic, and sampling methods.

In a normal operating dive a deep-sea submersible will stay submerged for 6 to 10 hours and may be on the bottom for 3 to 7 hours in water 3 km deep. (The rate of ascent and descent is about 2 km/

hour.) It can move over the bottom at a speed of 1 to 2 knots and so may cover a path of a few kilometers if it moves steadily.

It is routinely possible to locate the submersible to within 10 m in water a few kilometers deep by the use of acoustic transponders. The vessel's orientation, depth, altitude, and so forth are logged every few seconds. Improved configurations of running lights, strobe lights, and television lights have been developed. By precise placement of the submersible and use of the mechanical arm, small-scale biological and geological features can be sampled with various scoops, tube corers, pry bars, drills, water bottles, nets, and traps. An external tray may contain these or deployable instruments such as time-lapse cameras, temperature probes, current meters, seismometers, and the like (Fig. 4). By locally marking or perturbing the environment it is possible to find the site again, and experiments can be conducted on the bottom.

In operation, the research submersible differs from the usual oceanographic ship in a number of ways.

1) It has a somewhat different set of instruments. Especially heavy reliance is placed on photographic techniques, visual observations, and acoustic devices.

2) For surveys it operates in a faster mode during cruising. Three coordinates of translation and one of orientation must be kept in mind and these can change from second to second during cruising. Scientific notes are kept with a tape recorder rather than a note pad; knowing how to make a quick sketch is, however, a distinct advantage.

3) A close interaction between pilot and scientist is required. The pilot must be included as a participating member of the scientific team, although he may have no extensive knowledge of the project or may not be a scientist by formal training. Only he can position the craft to do the scientific job, and he does not have time for lengthy discussion about it. In turn, the scientist may be of some assistance in routine checks when the pilot is busy.

4) Most submersibles work within a tight energy budget. Each different propulsion motor, light, and instrument has a different rate of power consumption. Use of each limits the use of the others and affects the length of time the submersible can stay on the sea floor. The scientist must be aware of the compromises that will be required.

Because of these unique aspects of submersible operation, it is helpful for scientists to make a familiarization dive before their main diving operation. These may be made during engineering tests or during some other scientist's research dives.

Manned Submersibles and Unmanned Instrument Packages

There are a number of unmanned instruments, especially of the geological-geophysical type, that would appear to do the same jobs a submersible does. Some are advanced surface instruments such as the U.S. Navy's narrow-beam multichannel echo sounding system (SONARRAY, from sonar array) and the British surface side scan system (GLORIA). Some instruments can be dropped to the sea floor and be made to pop up on command or at a set time (seismometers, current meters, and so forth). There are several deep-towed instruments, some of which, such as the Scripps Deep-Tow, are quite elaborate with multiple sensors and accurate navigation. These instruments have graphic and quantitative data output and fre-

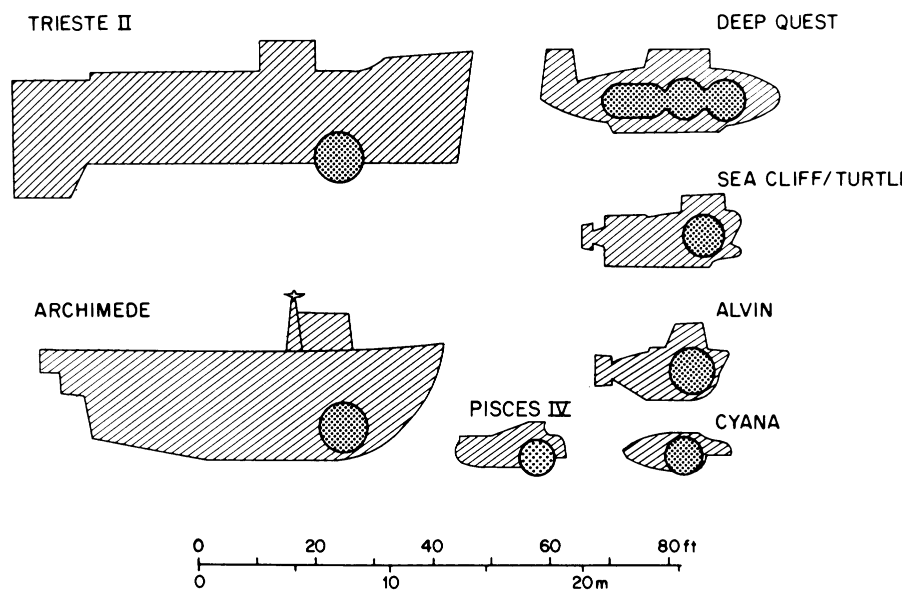

Fig. 3. Profiles of submersibles with operating depths exceeding 1.83 km.

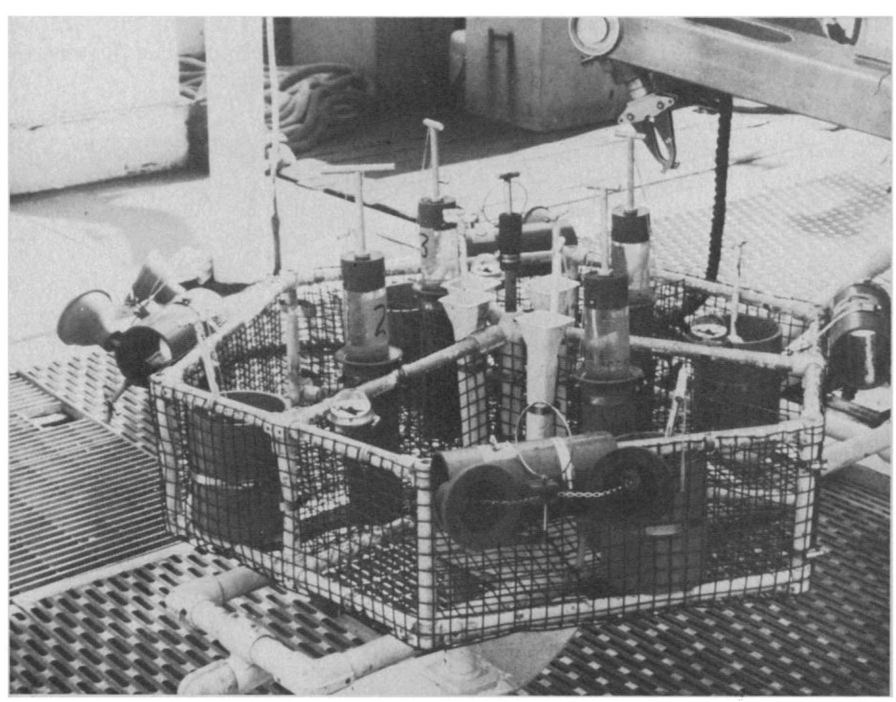

Fig. 4. Tray for carrying instruments and samples on front of submersible. Cylindrical water-collecting tubes are attached around the periphery. The T-bar handles are attached to transparent plastic coring tubes, bags for scooping sediments, and pry bars. The tray rotates like a lazy Susan about a central axis to bring parts of it within the pilot's field of view.

quently have more appeal than submersibles, which sometimes yield only photographic or subjective data. In addition, a small transponder package (ANGUS, from acoustically navigated geologic underseas survey) can be attached to almost any instrument on the end of a cable to determine where it is at all times. With all these instruments, what is the advantage of using a manned submersible?

Compared to a person using remote sensing, the diver gets a clearer impression of the interrelationships of the environmental components. Also, he can perform many operations more precisely than his colleague on the surface. He can (i) see and sense several things in real time and move his observational platform exactly to check his initial impressions and observations; (ii) put instruments and sampling devices onto and into the bottom with minimal disturbance of the sediment; (iii) conduct experiments requiring complex manipulations and precise sampling; (iv) sample areas such as rift valleys, seamounts, and submarine canyons where the bottom topography is such that no standard gear can be operated effectively; (v) precisely sample small-scale features such as sediment forms, rocks, or individual organisms (Fig. 5); (vi) provide continuity of observation for behavioral studies and fine-scale surveys; (vii) conduct experiments at time intervals of a year or more by repeated visits; and (viii) sample from specific layers in the water column (for example, layers of high turbidity, dense zooplankton populations, or bottom chemical gradients).

The submersible has been utilized to do all of these things within the last few years. There have also been programs that effectively employ submersibles and unmanned instruments together in the same geographic area. It should soon be possible to use the same crew of technicians to operate manned and unmanned instruments from the same platform at different times of day as navigational data and equipment handling techniques become more standardized.

In order that real-time decisions be made in an effective way, proper predive surveys must be made. The submersibles scientist should know the general characteristics of the area in which he is working. The SONARRAY echo sounding system, in particular, makes an ideal companion to a diving operation because it can resolve features about 10 m in size in water depths of 3 km. The distance of 10 m is about as far as observers can see in clear water.

Costs and Management

Of the U.S. deep submersibles that are expected to remain in operation in the near future, *Sea Cliff*, *Turtle*, and *Trieste II* are scheduled and operated by the Navy's Submarine Development Group One in San Diego. The *Alvin* is operated by a technical group based at the Woods Hole Oceanographic Institution but scheduled by an interinstitutional group called the University National-Oceanographic Laboratory System (UNOLS). Proposals for use of *Alvin* are received from the research community and reviewed by the UNOLS committee each year. This group evaluates the appropriateness of work for the submersible and sets scientific priorities.

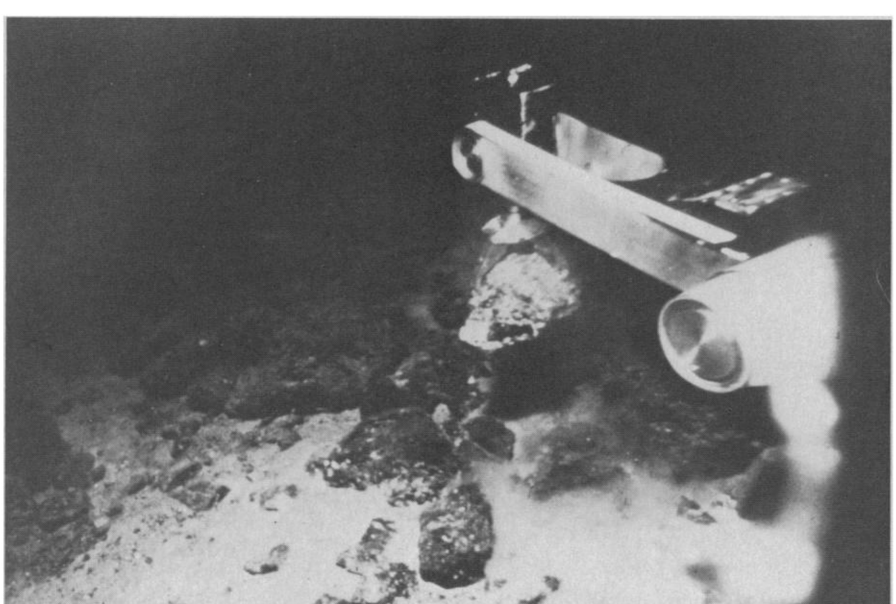

Fig. 5. The manipulator collecting an oriented rock sample.

In marine science costs are usually divided into scientific and operational categories. The operational costs for *Alvin*, its mother ship, and its supportive crew will be about $1.2 million in 1976—about those for a conventional large oceanographic ship. In 1975 and 1976 the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration supplied operating costs through an interagency agreement. To these costs must be added the cost of an escort ship if operations take place more than a specified distance from certain support facilities (which is frequently the case) and the cost of the science program on submersible, mother ship, and escort ship. *Alvin*'s schedule for 1976 shows that she made about 80 dives during about 180 operating days. This is slightly lower than the number of operating days for oceanographic ships that have about the same yearly costs.

Alvin is best suited for detailed work in areas where preparatory work has been done. Such areas should be where great transit time is not required and an escort ship is either not required or can be profitably utilized in a supportive scientific role. Recent and planned programs for *Alvin* meet these requirements. A circuit following favorable weather from the U.S. West Coast, to the Galápagos-Panama area, to the Caribbean-Bahama area, to the U.S. East Coast and to a winter overhaul is under consideration for a future schedule.

The funding of oceanographic work from surface ships is in itself a complex process involving coordination of funding for ship support, funding for science support, and scheduling of ship operations. It is not uncommon for notification of science support to be received within a few weeks of the initiation of work in a distant part of the world. The funding procedure is even more complex for submersible research since submersible operating support is often determined with a few months lead time, and prediving surveys and escort ships must be scheduled many months or years before. The management of the funding and the scheduling is probably unnecessarily cumbersome and provides as many challenges as the scientific problems themselves.

Two workshops were held in mid-1976 on the scientific use of submersibles. At one, held on the West Coast of the United States, a series of geological dives was planned, and at the other, on the East Coast, the focus was on biological, chemical, and geologic processes at bottom stations. About 25 scientists were at each and they proposed multidisciplinary projects for the next 1 to 2 years. These are the first of planned annual workshops to broaden participation in submersible research and make advance planning.

Conclusions

Manned submersibles are being utilized for detailed studies of the deep-sea floor to extend the coverage provided by oceanographic ships. After a slow start, the marine scientific community is learning how to utilize these submersibles effectively and economically to undertake biological and geological studies. In a departure from more traditional oceanographic procedures, series of complementary cruises are being undertaken by multi-institutional groups to study problems of the deep-sea floor. Submersibles now appear to occupy a permanent place in the list of necessary oceanographic facilities.

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NEWS AND COMMENT

Psychosurgery: National Commission Issues Surprisingly Favorable Report

They drilled the holes in my forehead. They cut the nerves over my right eye, and my legs stopped paining immediately. And I told him [the surgeon]. He said, "All right, now we'll take care of your back." And he cut the other nerve. In five days I was walking out. That's how great it was. I had no more pain in my back and leg, and I haven't had any since. Right there on the operating table, first the leg and then the back. I felt just terrific.—T.R., a psychosurgery patient.

Every year for the past 5 to 10 years, an estimated 400 psychiatric patients in this country have had psychosurgery. T.R. (quoted above) was one of them. In 1974, he was operated on in a last-ditch effort to relieve the severe depression and intractable pain that had disabled him for a dozen years, ever since he fell off a ladder and injured his back. During the intervening years, this 43-year-old man had tried everything else medicine had to offer. He took drugs, he had back surgery, and he underwent more than 150 courses of electroshock therapy. By the time he turned to psychosurgery, T.R. was a very desperate man.

T.R.'s case is one of many that are described in studies that were conducted during the past year for the National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research, which has just released a report* approving psychosurgery in carefully defined circumstances. The commission, which previously has recommended guidelines governing research on fetuses (*Science*, 17 October 1975) and prisoners, was created by Congress in 1974 to be the voice of and for the people in controversial areas of scientific experimentation (*Science*, 2 August 1974). At the time, psychosurgery was one of those controversial areas that was very much on Congress's mind.

Several years ago, a trio of physicians started quite a flap when they suggested that psychosurgery might be useful in taming the violent, including the leaders of the civil rights riots of the late 1960's. Their notion was not exactly greeted with enthusiasm. Then, in 1972, a Washington, D.C., psychiatrist named Peter R. Breggin launched what seemed like a one-man crusade against psychosurgery with articles with titles such as "The return of lobotomy and psychosurgery," published first in the *Congressional Record*. Partly at Breggin's urging, former Senator J. Glenn Beall (R–Md.) proposed that the bill establishing the commission be amended to ban all psychosurgery in the United States. In its stead, he accepted a provision that mandated that the commission conduct an investigation of psychosurgery in the United States and recommend policies defining under what, "if any," circumstances it should be allowed. There was a strong bias in Congress against such brain operations. And it is probably fair to say that several, perhaps most, of the 11 members of the commission approached their study of psychosurgery with a negative bias.

Therefore, it came as something of a surprise when the commission adopted its report that "encourages" the Secretary of Health, Education, and Welfare to support research on psychosurgery and that, in general, treats psychosurgery benignly. Asked by *Science* what it was that influenced the commission favorably, its chairman, J. Kenneth Ryan of Harvard Medical School, replied, "We looked at the data and saw they did not support our prejudices. I, for one, did not expect to come out in favor of psychosurgery. But we saw that some very sick people had been helped by it, and that it did not destroy their intelligence or rob them of feelings. Their marriages were intact. They were able to work. The operation shouldn't be banned."

In saying this, Ryan and the other commissioners are by no means endorsing the clearly destructive prefrontal lobotomies that were performed on an estimated 40,000 to 50,000 mental patients 25 years ago. (As one commission staffer put it, "We all agree that the prefrontal lobotomy was a bust.") What they are approving is study of the newer forms of contemporary surgery in which only small, selective areas of brain tissue are destroyed.

The data that so impressed the com-

*For information about the availability of the commission's report and supporting documents, write to the commission at 125 Westwood Building, 5333 West Bard Avenue, Bethesda, Maryland 20016.