Galápagos '79: Initial Findings of a Deep-Sea Biological Quest

by

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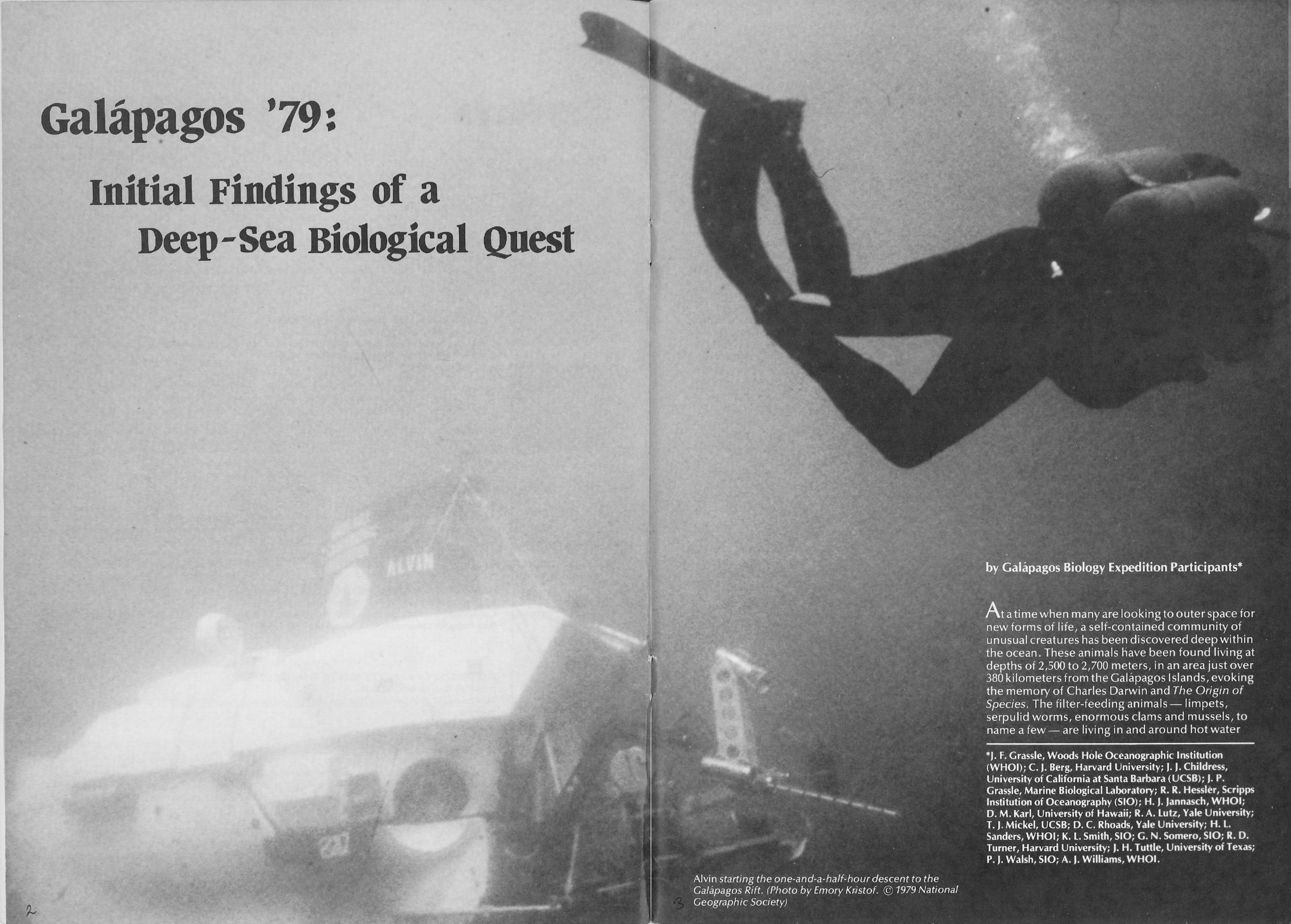

Alvin starting the one-and-a-half-hour descent to the Galápagos Rift. (Photo by Emory Kristof. © 1979 National Geographic Society)

by Galápagos Biology Expedition Participants*

At a time when many are looking to outer space for new forms of life, a self-contained community of unusual creatures has been discovered deep within the ocean. These animals have been found living at depths of 2,500 to 2,700 meters, in an area just over 380 kilometers from the Galápagos Islands, evoking the memory of Charles Darwin and *The Origin of Species*. The filter-feeding animals — limpets, serpulid worms, enormous clams and mussels, to name a few — are living in and around hot water

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Alvin pilot Dudley Foster talking to surface controller on the underwater telephone. The observer, Fred Grassle, holds the control box for the pumping system. (Photo by Al Giddings.

vents in what is known as the Galápagos Rift area, an active zone of sea-floor spreading (see *Oceanus,* Winter 1974). Most of the normally sparse life found at these depths live off particles that settle to the bottom from surface waters, where they have been created through the processes of photosynthesis and decomposition. These recently discovered animal colonies, however, are using as their ultimate food source the products of chemical synthesis — that is, the upwelling of minerals (mostly sulfur compounds) from the earth's molten interior that support a population of bacteria subsisting on hydrogen sulfide and carbon dioxide.

The exploration of sea-floor spreading centers that gave rise to the present discoveries began in 1974 with dives by submersibles on the Mid-Atlantic Ridge. Later, the Cayman Trough near Cuba was explored. But it was not until early in 1977 that the existence of these unusual colonies of marine animals became known. At that time, a third major geological expedition, part of the International Decade of Ocean Exploration sponsored by the National Science Foundation, departed for the Galápagos Rift area, some 380 kilometers northwest of the islands and 1,000 kilometers west of Ecuador.

Since the initial discovery of the unusual forms of life was made by geologists and chemists (see *Oceanus,* Vol. 20, Number 3, Summer 1977), a team of biologists joined the next Galápagos Rift expedition (January 14 to February 26 of this year). The objectives of the biology program — there also was integrated geology and chemistry work going on — were to study the distribution and structure of the communities; to learn how the newly discovered animals adapt to their unusual chemical and thermal regime; and to determine if a self-sustaining group of microorganisms was responsible for the concentration of life at the hydrothermal vents. Included were studies of microorganisms; the growth, distribution, and life histories of organisms comprising the unusual hot springs communities; genetics; biochemistry; and in situ and laboratory physiological studies of mussels and crabs.

Our detailed observations of the behavior and habits of organisms at the Galápagos vents were made possible through use of a new television system developed specially for the cruise. A CCD (charged coupled device) camera was developed by the Radio Corporation of America in conjunction with the National Geographic Society (which sent a photography team to participate in the expedition), and Robert Ballard, a geologist and engineer at Woods Hole Oceanographic Institution. The camera, instead of having a regular Vidicon television tube, houses a solid state system that allows it to be miniaturized. It is about 20 centimeters long and can be equipped with a macrolens that permits zoom capability, recording images on a 2.5-centimeter tape.

Another advance in underwater technology connected with the expedition concerned Angus (Acoustically navigated underwater system). Angus is an unmanned two-ton sled that is towed across the bottom terrain. It can take some 3,000 colored pictures of the bottom in a 15- to 16-hour period. Previously it had been towed at about 3.6 meters from the bottom, giving pictures of a relatively small area. With a new lighting system, Angus can "fly" at about 18 meters from the bottom, increasing the picture range by a factor of seven. It can now provide pictures covering a half acre — or 1,765 square meters — in one frame. This system was used to search for the vents — a patch of bottom 50 meters in diameter, 380 kilometers from land.

The Biology Program

The biology team was assigned 10 dives out of a total of 30 on the expedition. Participating vessels included the submersible *Alvin,* operated by Woods Hole Oceanographic Institution; the submarine's mother ship, the *R/V Lulu*; and the *R/V Gilliss,* owned by the U.S. Navy and operated by the University of Miami. J. Frederick Grassle, an Associate Scientist in the Biology Department at Woods Hole Oceanographic Institution, was the chief scientist for the biology portion of the cruise, heading a group of scientists from Harvard University, Scripps Institution of Oceanography, Yale University, the University of California at Santa Barbara, the University of Texas, the University of Hawaii, the Marine Biological Laboratory, and Woods Hole Oceanographic Institution. Ballard led the geology program and John Edmond of the Massachusetts Institute of Technology led the geochemistry study.

Typically, *Alvin's* front basket was cluttered with a vast array of gear that included a stereo camera with thermistor probe, insulated containers, a slurp gun, sterile microbial samplers, two kinds of in situ microbiology experiments, scrapers, corers, exclusion cages, fish traps, amphipod traps, larvae traps, plankton nets, collecting plates for studying colonization, two kinds of current meters, a recording thermistor string, and in situ respirometers. A new pumping system was devised for obtaining water samples and filtered samples of varying particle size. The filter samples will be used for studies of microorganisms and particulate organic material.

Gilliss was delayed in Panama and arrived late at the diving site, which meant that the first two dives in *Alvin* had to be made without the results from the Angus sled and a network of navigational transponders. The first dive was made in a region of hydrothermally deposited sediment mounds 20 kilometers south of the ridge axis. These structures are so common that precise navigation was not needed to locate them. High water temperatures were detected at the crest of the mounds where thick crusts of manganese and iron oxides are formed (Corliss, and others, 1979). Later examination of box core samples taken on and around the mounds indicated a rich infaunal community on the slopes and areas surrounding the mounds. The rarely seen flower-like xenophyophorian protozoan is common in the sediment of this area.

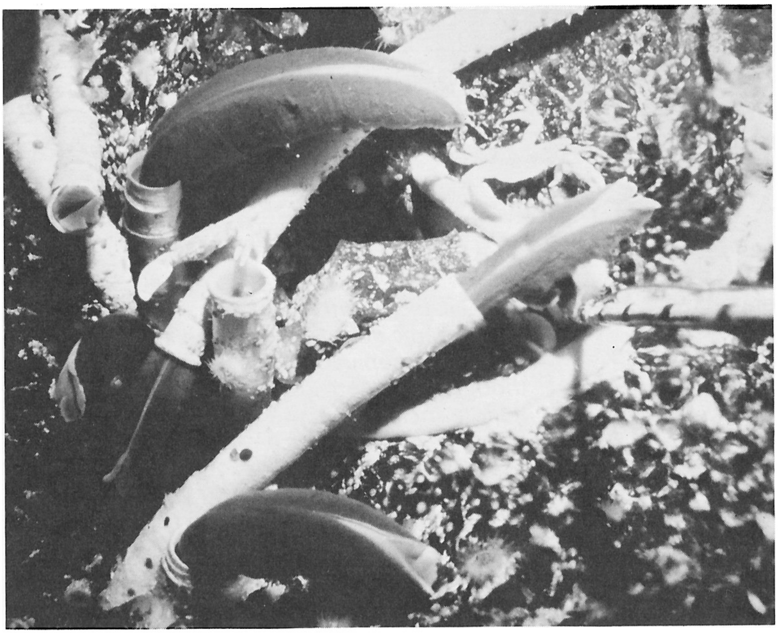
On the second dive to the general area of hydrothermal vents, white webs of worms, dubbed "spaghetti," and occasional large dead clams were observed. These were similar to the specimens collected on the 1977 expedition. The specially designed slurp gun vacuumed the spaghetti off the rocks. Later, on deck, we finally solved the mystery of their identity: they were enteropneusts, worm-like relatives of the early ancestors of vertebrates, normally found living in sediments. Yellowish balls suspended just above the bottom — previously called "dandelions" by geochemists — also were collected with the slurp gun, but fragmented in surface waters. An intact specimen was collected on a later dive. It is a benthic siphonophore (a relative of the Portuguese man-of-war) belonging to the family Rhodaliidae. Although members of this group were first collected during the Challenger Expedition (1872-76), they have seldom been collected whole and have been assumed to occur in the water column above the bottom. By the end of the second dive, two promising vent sites had been located from Angus film processed on board the *Gilliss.*

On the third dive, an active vent with live communities was located near Clambake I (an area explored on the 1977 dives) and named Mussel Bed. The major portion of the dive was spent placing testing equipment on the bottom, including slides for studies of microbial colonization. In addition,

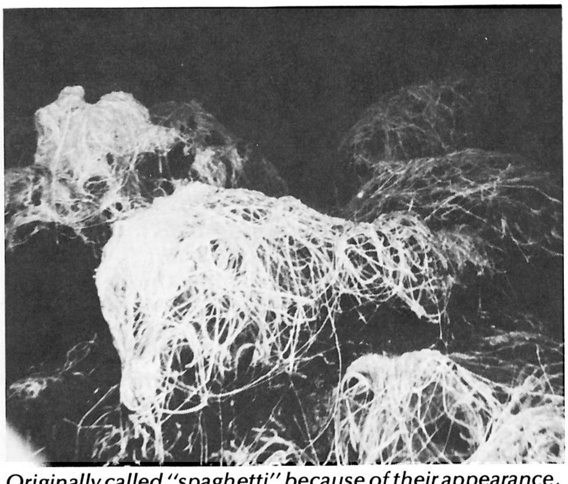
Larger Colonies of Life Found

The Galápagos Rift is part of a global mid-oceánic ridge system in which the crust of the earth is separating as a result of what are thought to be convective processes. Similar regions include the Mid-Atlantic Ridge and the East Pacific Rise; the latter is an area south of the Gulf of California and west of Puerto Vallarta, Mexico. In late April and early May of this year, a joint French-American-Mexican expedition to the Rise reported further interesting discoveries, including chimney-like volcanic vents where water temperatures may exceed 300 degrees Celsius (570 degrees Fahrenheit).

The eruptions from the volcanic structures have carpeted the region with deposits of copper, iron, zinc, cobalt, lead, silver, and cadmium – often combined with sulfur. It is believed to be the first time such mineral deposits have been found in the open ocean. In addition, the scientists – diving in the research submarine Alvin, *operated by Woods Hole Oceanographic Institution – discovered new colonies of life covering areas more than twice the size of the Galápagos Rift communities. The participating American scientists on this expedition were from Woods Hole and Scripps Institution of Oceanography.*



Vestimentiferan worms with brilliant red plumes extend from tough flexible tubes. Limpets and anemones are common, and a single crab is visible. (Photo by R. R. Hessler)



Originally called "spaghetti" because of their appearance, these worms have been identified as enteropneusts. (Photo by J. J. Childress)

mussels were sampled and vent water filtered. With so many tasks to accomplish, our studies were limited to Mussel Bed and the Garden of Eden area (also explored in '77) 3 kilometers to the east. Meanwhile, collections and photographs were made by the geologists in a new area called Rose Garden, which was named after dense beds of red-tipped vestimentiferan worms living in white tubes up to 3 meters long.

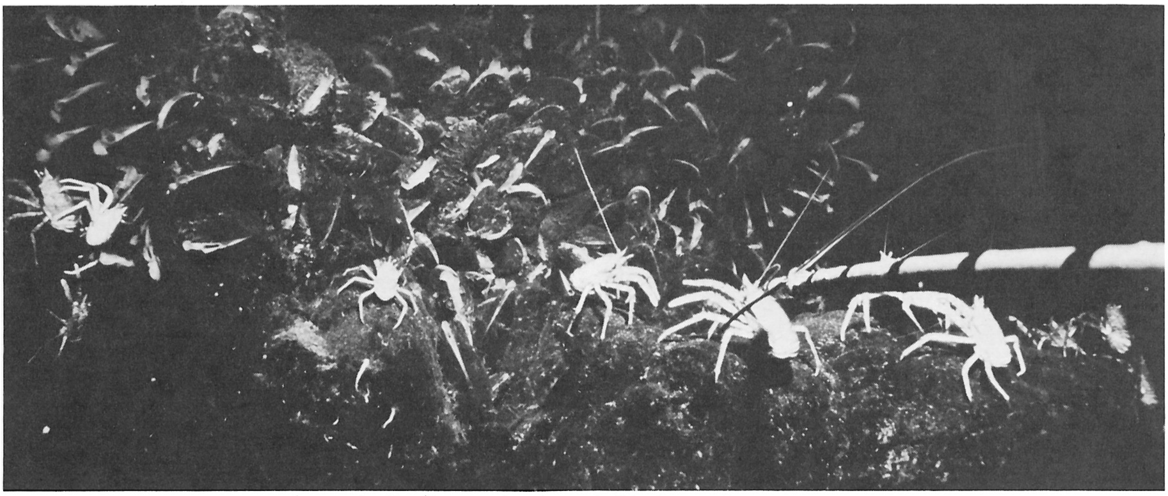
The stereo camera, mounted on a mechanical manipulator outside *Alvin,* was used to study the distribution of organisms with respect to temperature. A temperature probe gave a distance reference and provided a continuous recording of temperature on a data log inside the submersible. Detailed photogrammetric analysis of these stereo photos will enable us to accurately measure size and distance in three dimensions.

By using the slurp gun and carefully picking animals from clumps of mussels and rocks, numerous smaller animals were obtained, many of which promise to be as interesting as the larger specimens collected. One, a small shrimp-like Leptostracan crustacean, has comb-like structures at the end of its eyestalks where eyes would normally be. This sort of eyestalk modification has never been observed in other crustaceans. The combs are probably used to scrape microorganisms (food) from the hard rock and mussel surfaces.

Collecting and observing large numbers of animals was necessary to answer some of the questions posed by these new discoveries. For example: To what extent is each area an island? How do rates of growth and metabolism there compare to other areas of the deep sea, where relatively low rates have been recorded (see *Oceanus,* Vol. 21, Number 1, Winter)? How do temperature, pressure, and food supply relate to metabolic rates?

Live brachyuran crabs were recovered from the vents, and a number were kept alive for almost three months after the expedition. Studies of their metabolic rates at different temperatures and pressures indicate they need pressures of at least 125 atmospheres to survive and are killed at about 400 atmospheres. Their metabolic rates appear to be somewhat lower than those of shallow-living crabs at comparable temperatures. The Galápagos crabs are able to remove oxygen from water at very low partial pressures, so they probably rely largely on aerobic (oxygen-dependent) metabolism in the vent waters. The upper temperature limit for the crabs is greater than 22 degrees Celsius at in situ pressures.

More than 100 mussels were collected from each of two areas for studies of genetic differentiation between populations at the vents. Analysis of enzyme variants will determine the differences between vent populations. In addition to the studies of mussels on the surface, rates of oxygen uptake were compared using respirometers



Galatheid crabs perched on the top of pillow lavas. The dense field of mussels, some with their siphons out, are close to the source of hot water. (Photo by R. R. Hessler)

in situ. By comparing respiration in mussels living at 2 degrees Celsius in the central and peripheral areas of the vents, it may be possible to determine how food supply relates to metabolic rate.

Many shells of the large white clam were found around dead vents. Living specimens, meanwhile, were observed nestled among the large mussels surrounding live vents, but they were never abundant. Of the material collected thus far, the size of the clams ranges from 130 to 264 millimeters in length. The anatomy of the large clam places it in the family Vesicomyidae, genus *Calyptogena*. Unlike most bivalves, it has red blood and a meaty odor. These features have not yet been analyzed. Karl Turekian and colleagues at Yale University have used thorium-228/radium-228 activity ratios to estimate the age of a 22-centimeter-long clam to be less than 10 years.

The very abundant mussels clustered in the vicinity of active vents were hosts for polynoid polychaetes. At some vents almost all mussels contained polychaete symbionts in the mantle cavity, whereas at other vents they were rarely found. Like their shallow-water counterparts, the mussels are capable of forming lustrous pearls (a few small ones were found).

From studies of the larval shell morphology on juvenile specimens, it appears that these animals have a long planktonic larval life. Abyssal currents may transport the larval stage hundreds of kilometers. Since the hot water supply is not likely to be constant, a long-lived dispersal stage would be needed to locate new sources of water. The mussels are thought to be a new genus in the family Mytilidae.

The large red vestimentiferan worms mentioned earlier were collected on the eighth dive. Smaller relatives were discovered several years ago during dives with the submersible *Deepstar 400* at 1,125 meters off California. These were assigned to the phylum Pogonophora (Webb, 1969). More recent studies indicate that these should be classified as a major taxon distinct from the Pogonophora (Van der Land and Norrevang, 1977). Forty-five to 76-centimeter specimens were collected in 1977 in the Galápagos Rift area. The specimens from the 1979 expedition are larger, with tubes as long as 2.4 to 3 meters. The largest animal collected had a tube more than 2.4 meters long and a body length, after preservation, of 1.5 meters, with a diameter measuring about 5 centimeters. Juvenile specimens less than 15 centimeters in length clustered around the base of the large tube also were recovered. The creature has a brilliant red tip, the color deriving from oxygenated hemoglobin in the blood. The animals have no gut and are thought to live on dissolved organic material in the water.

For reasons not clearly understood, each species occurs at a different distance from the vents. The pillow lava formations farthest from the vents are largely barren, with occasional corals, anemones, or sea cucumbers. As the vent is approached, crabs, enteropneusts, and dandelions appear — the enteropneusts found draped on rocks at the edge of the zone and the dandelions in protected low spots closer to the vents. The clam beds, mussels, serpulid worms, and large numbers of small anemones are located at intermediate distances. Although the distribution of mussels and crabs extends into the supply of warm water, most of the animals are living at the ambient water temperature of 2 degrees Celsius. The tops of pillow lava formations adjacent to the vents are covered with serpulid worms, their feathery plumes enabling them to filter particles from the water. Galatheid crabs — the females carrying large numbers of eggs — are common on the tops of pillow lava formations. These relatively active animals crawled into the frame of *Alvin* and many were "collected" when the submersible surfaced.

The vestimentiferan worms live only in the supply of warm water — ranging in number from a dense field spread along a 50-meter fissure at Rose Garden to only two or three small individuals in the narrow vent openings at Mussel Bed. The rock walls of the vents are densely covered by a species of light-colored, filter-feeding limpet, which also is found scattered along the tubes of the vestimentiferan worms. The warm-water flow from the vents is the preferred place for a pink brotulid fish, often seen with its head nestled down in the vent, where it probably feeds.

The Collection of Microorganisms

"Milky-bluish" water flows from the most active hydrothermal vents, suggesting that bacterial oxidation of hydrogen sulfide to elementary sulfur and sulfate could produce the basic food source for the entire community in the form of bacterial cells. Chemosynthetic bacteria use the energy from this chemical oxidation for the fixation of carbon dioxide into organic matter, similar to the way photosynthetic organisms use sunlight as their energy source. Other compounds that can be chemosynthetically oxidized are elementary sulfur and thiosulfate, as well as hydrogen, ammonia, nitrite, iron, and manganese. Iron and manganese crusts are prevalent in the vent area, indicating that the oxidation of materials other than sulfur compounds may contribute to the amount of carbon dioxide fixed.

The shimmering water approximately one meter above the vents contained 10^5 to 10^6 bacterial cells per milliliter as measured by direct counts with an epifluorescence microscope. These counts indicate a high bacterial output at the vents, considering that there is strong mixing with ambient water in this stratum as revealed by temperature fluctuations. The cells in these water samples (Figure 1) displayed morphological uniformity, as well as a relatively low fraction of amorphous material, both of which were unexpected. Dense clumps (mostly 12 to 100 microns in diameter) of bacterial cells were common (Figure 2).

Scanning electron microscope studies of a number of different surfaces collected near the vents disclosed some unusual forms of organisms (Figure 3). Pieces of mussel surface were rusty brown in appearance. Instead of a deposit of amorphous material, dense layers of cells or nodule-like structures were found, some apparently heavily encrusted with metal oxides (unidentified at this time). A network of filamentous structures appears to relate to prosthecate (stalked) bacteria.

Some 200 isolates of sulfur oxidizers are now under investigation. Their growth on a large variety of different enrichment media indicates an unusual diversity of metabolic types. Depending on their specific oxidation products, the growth media after incubation varies in pH from 5.1 to 8.6. Most strains prefer reduced concentrations of oxygen. Many grow well in the absence of an added nitrogen source, but only one strain has been found to

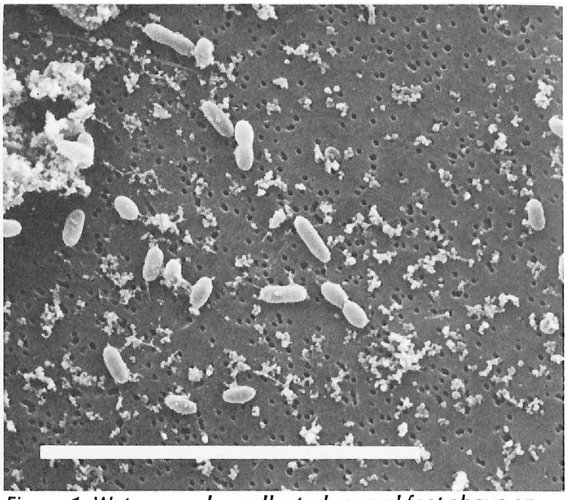


Figure 1. Water samples collected several feet above an active vent on a Nucleopore filter (pore size 0.22 micron). Bacterial cells of rather uniform appearance show division stages, indicating active growth. Magnification 5,000x (bar=10 microns).

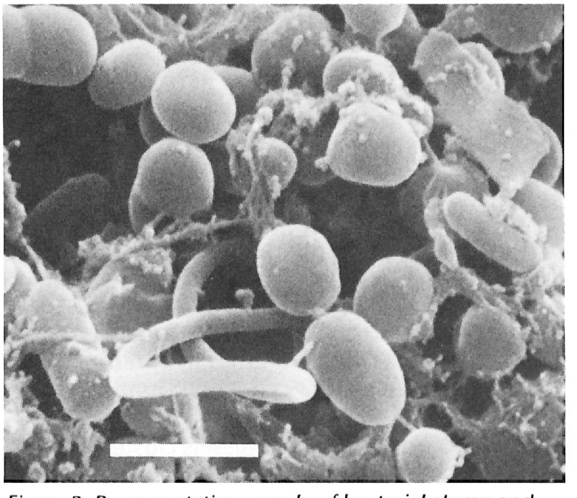


Figure 2. Representative sample of bacterial clump and amorphous matter, probably elemental sulfur. Magnification 20,000x (bar=1 micron).

exhibit enzymatic nitrogen fixation. Spirilla strains that can oxidize thiosulfate but prefer an organic substrate have been cultured. Anaerobic bacteria, which grow in the absence of oxygen and reduce sulfur compounds, also have been found. Prosthecate bacteria are in the process of being isolated. A free-living spirochaete (an elongated, spirally twisted, unicellular bacteria that moved by the contraction of flagella-like filaments) has been isolated.

Preliminary measurements of in situ carbon dioxide fixation indicate much higher bacterial activities compared with previous measurements at other marine oxic/anoxic interfaces. The analysis of ATP (adenosine triphosphate) as an indirect measure of active bacterial biomass showed values two to four times higher than in local productive surface waters, and a hundred to a thousand times

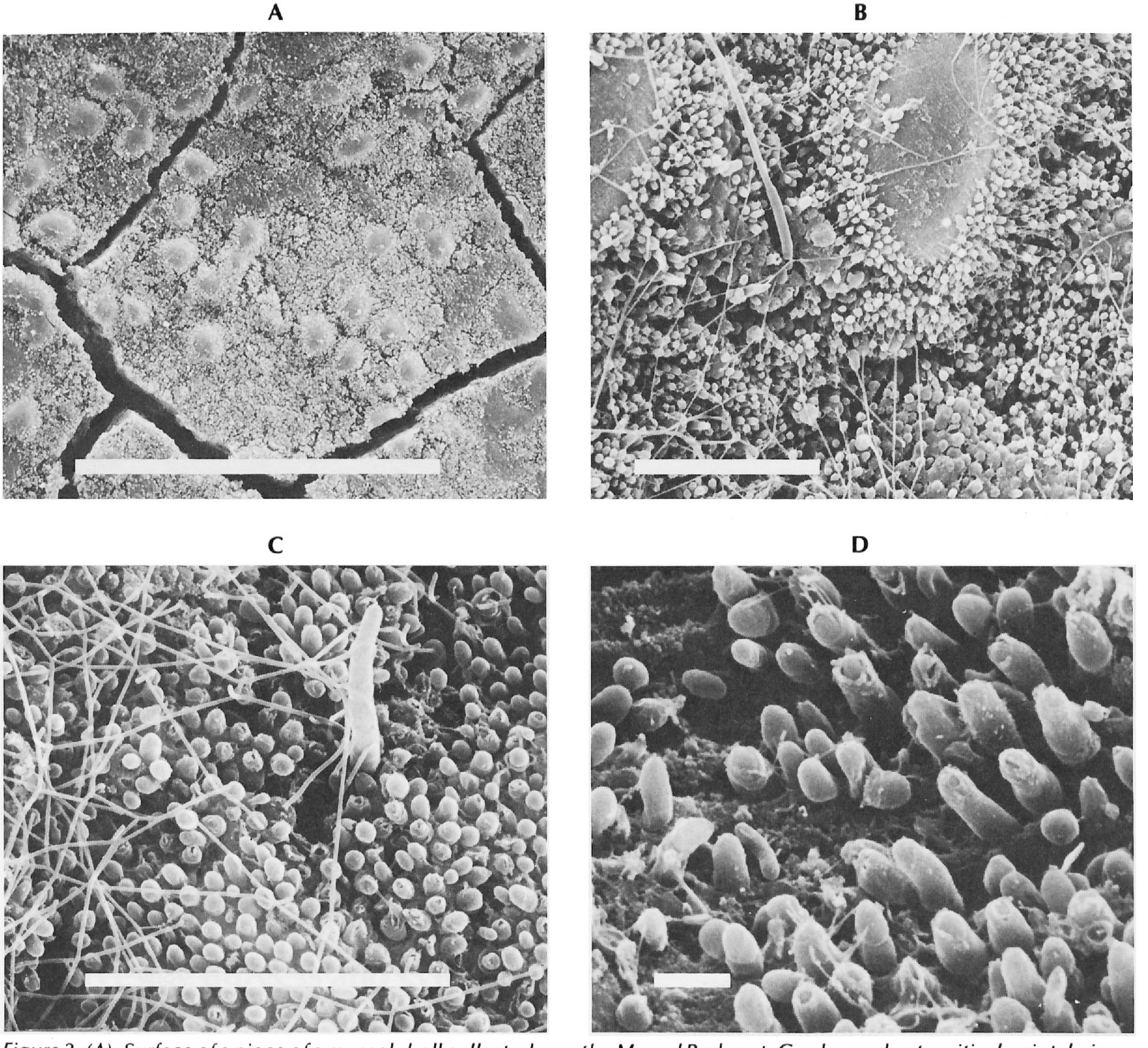


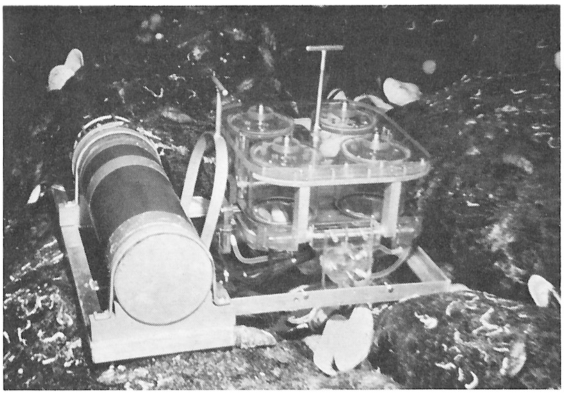
Figure 3. (A): Surface of a piece of a mussel shell collected near the Mussel Bed vent. Cracks are due to critical point drying during preparation of the specimen. Magnification 500x (bar=100 microns). (B) and (C): same preparation; network of stalks from prosthecate-like bacteria and sessile forms, apparently related to heavy mineral deposits. Magnification 2,500 and 5,000x, respectively (bar=10 microns). (D): closeup of attached and some non-attached forms, some of which appear to have an outer coating. Magnification 10,000x (bar=1 micron).

higher than in a control sample taken at some distance from the vents. This observation — along with the high bacterial content of the vent water, the extraordinary metabolic diversity, and the carbon dioxide fixation by pure cultures — appears to confirm that bacterial chemosynthesis, largely through oxidation of hydrogen sulfide, is the basic food source for the vent community (Rau and Hedges, 1979). The major bacterial production probably takes place within subsurface "growth chambers," with a large percentage becoming diluted by ambient water before reaching consumers. Because of the complexity of the vents, it will be difficult to obtain a realistic quantification of bacterial production and efficiency.

The Work Is Just Beginning

The hydrothermal vents contain a combination of unusual factors, such as elevated temperatures (animals in the vents experience 10- to 15-degree Celsius temperatures, and occasionally higher ones), high pressures, and a unique chemical environment that supports a rich concentration of active sulfur bacteria. Growth and metabolic rates are high compared with other deep-sea regions. In contrast to other deep-sea habitats, the changeable environment and rich food supply favor species with rapid growth and a relatively short life span. The large areas containing dead clams may indicate the ephemeral nature of the food supply. At least some species have long-lived planktonic larvae, which enable them to colonize other areas along the ridge axis.

Despite the unusual composition of the communities, initial findings suggest that diversity — the number of species in a given population — is low. Although the communities are not directly comparable, this finding differs from the large number of species that are found in individual sediment samples in the deep sea.

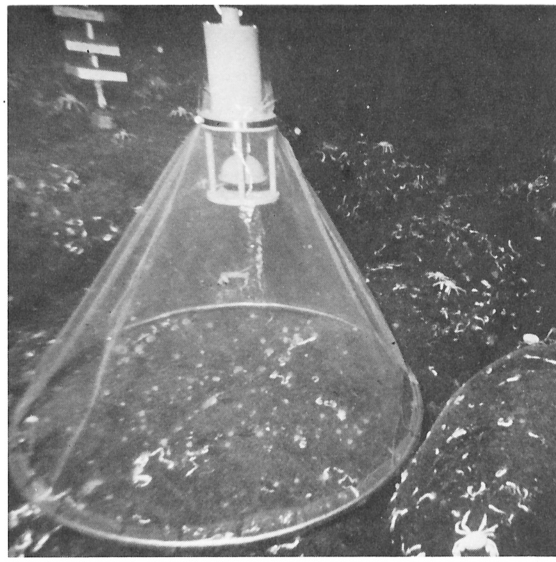


Respirometer used to measure oxygen uptake of mussels in situ. (Photo by R. D. Turner)

The vent food chains appear to be relatively simple, with the bulk of the organisms dependent on bacteria for food by taking up released dissolved organic material, filtering particles out of the water, or scraping material off hard surfaces. Less understood are the secondary consumers, such as scavengers and predators. The most obvious members of this group are rattail fish, an undetermined species of crab, and small amphipods — all attracted to bait.

The vent areas are more extensive than first believed. The individual concentrations of animals are part of a larger community that may extend for hundreds of miles along the axial ridge of the Galápagos Rift. The discoveries of large colonies of animals along the East Pacific Rise lend support to this view.

The greater part of the work from the Galápagos '79 expedition has only started. The biological work still to be done includes: photogrammetry; analyzing proteins for genetic information; studying the thermodynamic properties of enzymes; sorting out the numerous strains of bacteria; sectioning tissues for studies of reproduction; determining gut contents; and performing a variety of morphological studies.



Trap to catch larvae released from the bottom. Panels in background are for studies of larval settlement. (Photo by H. L. Sanders)

Another biological expedition to the Galápagos is scheduled for this November. More organisms will be collected, and a number of long-term experiments will be picked up that were placed on the bottom in January. It is expected that the experimental plates and glass slides will be colonized by rich growths of organisms, which will allow a comparison of growth rates with other areas of the deep sea. Thus these hydrothermal vents at major oceanic spreading centers will considerably advance our knowledge of deep-sea processes, but may also provide us with perplexing questions that will take some time to answer.

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