of creating a reservoir at a modest depth and temperature. The cost has been modest as well, about $40 million. The next step could be a pilot plant that would generate electricity from 220°C rock at 6 kilometers.

The recent American attempt to go from a shallow system to a large, hot loop powerful enough to drive a commercially viable electric generator has failed. A half dozen vertical fractures connecting the lower inclined sections of the first two wells were projected to yield 35 megawatts of thermal power. The holes reached the intended 200°+ temperatures, but the small fracture systems opened between the holes limited output to one-quarter of the intended power. To date, $150 million in U.S. federal funds have gone toward hot dry rock research at Fenton Hill plus a total of $30 million from Japan and West Germany.

The next step at Fenton Hill would be a 1-year flow test to determine just what the reservoir can do over the long term. Before that, extensive damage to EE-2 must be repaired. During a hydrofracturing operation in December 1983, an overworked flange gave way, which eventually created a towering geyser that spewed 10 million liters of hot water during the next 36 hours.

This failure created the worst-case conditions that the expert panel had warned about. EE-2's ruptured casing and other problems have just been sidestepped by sidetracking the hole starting above the problem areas. The long-term flow test now depends on the fiscal year 1988 budget, which is still being worked out in Congress.

Hot dry rock has proved to be a recalcitrant, even devious foe, demanding greater respect and subtlety of design than pioneers in the field imagined. Still, interest is growing. Other programs are under way at sites in Japan, the Alsace region of France with European Community and West German funding, Sweden, and the Soviet Union. What may help as well is a new perspective. "We believe that hot dry rock has a future," says Batchelor, "but you have to look at it strictly in the long term. It is wholly unrealistic that a novel technology could compete with 1984 power plants," as post-energy crisis politics seemed to be demanding. Industry involvement is probably necessary, too, if hot dry rock is to meet its potential in the 21st century, says Batchelor. ■

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ADDITIONAL READING

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Coral Bleaching Threatens Atlantic Reefs

Unexplained changes are occurring in some of the most productive ecosystems on the planet, the Caribbean coral reefs

BENEATH the clear, still waters of the Caribbean something is amiss. From the Florida Keys to St. Croix, the rich brown reef-building corals have turned a startling, snowy white, an indication of environmental stress. The severity of this "bleaching" episode, as it is called, cannot yet be assessed, but many Caribbean researchers fear it could profoundly disrupt the ecology of the Atlantic coral reefs—some of the richest, most productive ecosystems on the planet. Earlier this month Senator Lowell Weicker (R–CT), a strong supporter of oceanographic research, held a hearing to try to assess the extent of the problem and likely causes.

Bleaching occurs when corals expel the symbiotic algae that reside within the corals' soft tissues. In exchange for nutrients, these photosynthetic algae provide energy and oxygen, thereby boosting the rate at which corals grow and secrete their calcium carbonate skeleton that makes up the stony framework of the reef.

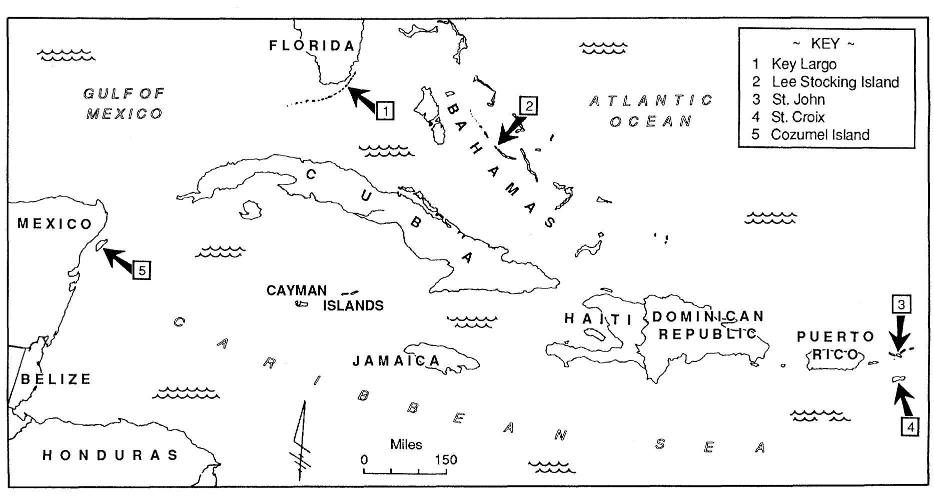
For some unknown reason, in response to environmental stress, corals expel the algae, known as zooxanthellae, which leaves the corals weakened and may lead to death. It is called bleaching because without the brown algae, the denuded corals are white.

Isolated instances of bleaching commonly occur in response to heavy rains, pollutants, decreased salinity, or other local stresses. But never before has bleaching occurred almost simultaneously across such a wide swath of the Caribbean, researchers say.

An even more extensive bleaching episode—followed by mass mortality—swept through the tropical eastern Pacific in 1983, brought on, it is believed, by the unusually warm 1982–83 El Niño, the strongest in a century. Reefs off the coasts of Costa Rica, Ecuador, Panama, Colombia, and the Galápagos Islands were devastated.

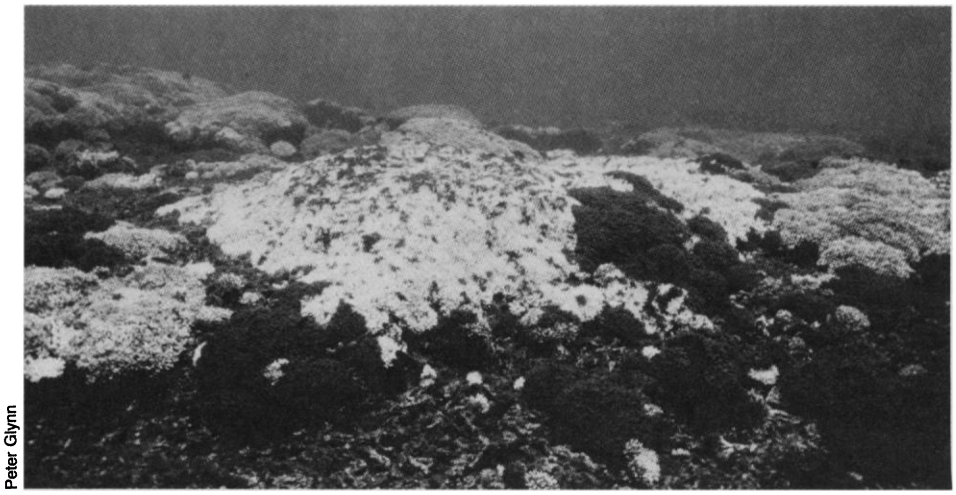
What caused the Caribbean bleaching is not known, but suspicions center around elevated water temperatures there, too. Nor is it clear what this bleaching episode portends. The bleaching, most of which was detected just last month, seems to be spreading both in geographic scope and in intensity, according to E. H. Williams of the University of Puerto Rico. Some of the corals are beginning to die, but it is too soon to tell whether the bleaching is a precursor to mass mortality, as it was in the Pacific, or whether the corals are likely to recover. If corals die and stop laying down their calcium skeleton, reef growth halts and reefs themselves are more vulnerable to erosion and physical devastation.

It seems to have started in mid-July in the



Warm waters? *Elevated water temperature is the prime suspect in this massive coral bleaching, which has spread throughout the Caribbean basin.*

Florida Keys and off the coast of Colombia. The corals in shallow water at Looe Key were the first to discolor, but it soon spread to deeper corals, Walter Jaap of the Florida Department of Natural Resources told the Senate. In Key Largo the reefs began to discolor at the end of August. Judith Lang of the University of Texas was in Colombia in mid-July, where she first observed bleached coral off of Islas del Rosario. By mid-August 14 species were affected. But it was not until late August or early September that marine researchers realized they were dealing with a phenomenon affecting the entire Caribbean basin, ranging from Florida to Jamaica and as far east as St. John and St. Croix. Numerous coral species are bleached, as are other algae-associated animals like sponges and sea anenomes, from shallow waters to depths of 40 meters or more.


Peter Glynn

Uva Island reef, Panama, 1983. *The 1982–83 El Niño devastated reefs in the tropical Pacific. Here, bleached corals appear among dead corals overgrown with algae.*

The Bahamas appear to be particularly hard hit. In the Exuma Cays there, Robert Wicklund of the Caribbean Marine Research Center in Florida observed massive bleaching off Lee Stocking Island in October. Along a 20-mile stretch of the Exumas, some 10 species of corals are affected down to a depth of 73 meters, Wicklund reports. So far, however, evidence comes mainly from observations from marine researchers and divers alike. At the University of Puerto Rico, Williams is trying to document the true extent and timing of the bleaching.

The cause of the Caribbean bleaching is equally mysterious, but through a process of elimination, elevated water temperatures are emerging as the most likely suspect. Corals and zooxanthellae live in a delicate equilibrium, and any one of a number of stresses—including excessive ultraviolet light, decreased salinity, and increased sedimentation—can trigger corals to expel their resident algae. Why they do this not entirely clear. The most likely explanation, says Lang, is that stress interrupts photosynthesis, and the algae become an energetic drain.

Because of the sudden onslaught of bleaching over such a widely scattered area, a water-borne pathogen can be ruled out, says Christopher D'Elia, director of the biological oceanography program at the National Science Foundation, though an airborne pathogen remains a possibility. Similarly, it is unlikely that pollution could cause such widespread devastation.

That leaves water temperature, which D'Elia says was "anomalously warm" last summer. Corals thrive in waters of between about 18° and about 28° or 29°C. They usually expel their zooxanthellae above 30°C, although thermal tolerance seems to vary by species and geographical location.

Temperature records are scanty, which is part of the problem. John Ogden, director of the West Indies Laboratory at Fairleigh Dickinson University in the Virgin Islands, is using National Weather Service satellite maps to try to determine just how hot the water really was last summer. He is finding "pockets of uncommonly hot water," about 32°C, at the time bleaching was occurring. "I'm not saying hot water did it, but it certainly is the most likely cause."

The fit is not perfect though, he and others admit. "The curious thing is that as we went deeper on the reef at Lee Stocking Island, a higher percentage of corals in a greater number of species were bleached, down to about 30 meters," says Lang. One possible explanation, she says, is that the corals in shallow waters have adapted to periodic bouts of higher temperatures while those at greater depth have not. Ultimately, the answer may lie in a combination of stresses—once weakened by temperature extremes, corals are more susceptible to disease and other insults.

What might have caused the suspected temperature rise is anyone's guess. Speculation ranges widely from reduced cloud cover to global climate change. One possibility, says Ogden, is some oceanographic event in the Atlantic "of the El Niño variety." A more likely explanation, he thinks, is that when the trade winds dropped this year, some very hot, hypersaline water masses developed in insulated bays and then sank through lighter, cooler water and flowed out of the bays and over the reefs. "I like that explanation for some of the microscale events," Ogden says. "But I don't think it accounts for everything. Let's face it, we don't know much about it."

The ultimate effect of this episode on the ecosystem will depend on the geographic extent of bleaching and whether the affected corals die or recover. "With the event in the Pacific, it was some months before the corals actually died. They were bleached but it was not immediately obvious that there would be massive mortality," says Lang. "I would be more comfortable if we knew how warm the water had been. If we knew it was well over 30° for several months, I would think the corals would die. If it was 29°, I would think they would recover."

Peter Glynn of the University of Miami is not optimistic about Caribbean recovery. He has been tracking the recovery of the reefs off Costa Rica, Panama, and the Galápagos Islands that were devastated by the 1983 El Niño. "All three are showing minimal recovery, if any, and that is 4 to 5 years after the disturbance." Moreover, he says, the reefs off the Galápagos that were killed by the bleaching are now eroding at a rate of 2.5 to 5 centimeters a year. Usually the limestone structure remains after the corals have died, providing a substrate for future coral colonization. But in this case the reefs were invaded by sea urchins, which are grinding them down to sand as they look for food. Judging by what happened in the Pacific, Glynn expects the corals in the Caribbean to begin dying in numbers within a few weeks.

Ogden is more optimistic. "El Niño happens over and over again, pouring hot water all over the Galápagos and Ecuador. And the corals recover," he says."My personal belief is that this bleaching in the Caribbean is a transient, ephemeral phenomenon. There is a good likelihood that the corals in the Caribbean will recover."

But the answer will not be known for at least several months. By that time, researchers may be beginning to sift through records of wind speed, suspended sediments, salinity, cloud cover, and temperature to try to understand what caused the unprecedented bleaching in the Caribbean. ■

LESLIE ROBERTS