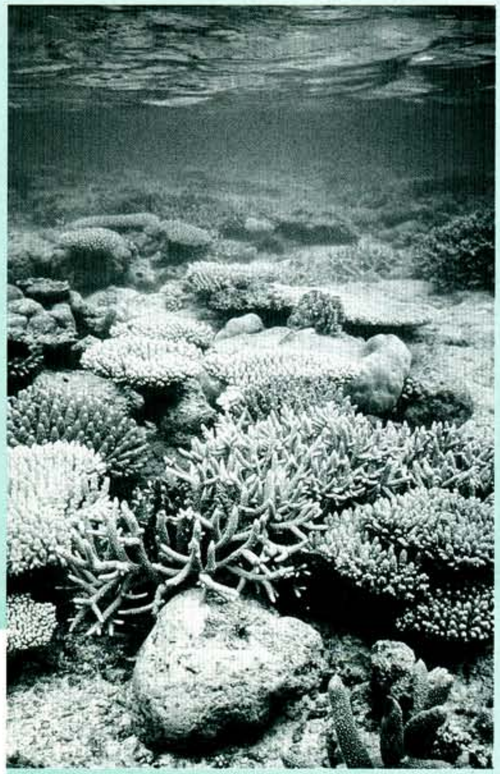
Research divers drilling cores on a large coral colony in Indonesia. Coral cores from the tropical Indo-Pacific provide unique and valuable information on the variability of climate over human timescales.

Within certain coral skeletons scientists are finding indicators of Earth's environmental history that may help explain not only how today's climate system works, but also how it changes over time.

Professor Christopher Charles of Scripps's Geosciences Research Division and his research team of paleoclimatologists are among a small group of oceanographers who, since the 1980s, have developed the use of corals to study past climates. They extract long, thin coral cores and interpret from them details of historic tropical ocean conditions in much the same way that tree rings are used to delineate ancient climate over the continents. When chemically analyzed, these coral samples reveal impressive details of ocean and climate parameters going back thousands of years—information inaccessible in any other manner.



"We have a biased perspective of climate change, because there are significant climate-related processes that occur on time scales extending well beyond human lifetimes, some even extend beyond cultural horizons," Charles explains.

Historical climate records from calibrated instruments cover just over 100 years, and reliable ocean readings only the last 50. Before

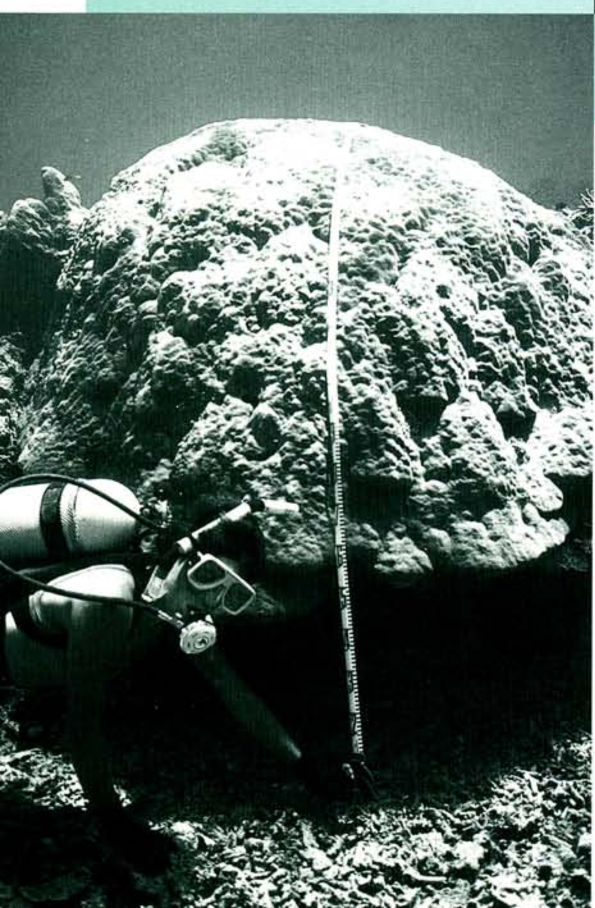
Coral Archives Reveal Climate History

BY CHUCK COLGAN

then, there are few data and sketchy accounts, so scientists turn to nature's archives of proxy records locked in living and fossilized materials, ice, rocks, and sediments in lakes and oceans. These indicators reveal episodes of abrupt climatic change and dramatic environmental consequences over millions of years, and significant events even within the past few thousand years, according to Charles.

About 15,000 years ago, at the end of last Ice Age, the ice sheets that covered the high latitudes of North America and Eurasia began to melt. During the following 8,000 years, about 12 million cubic miles (50 million cubic km) of glacial meltwater were introduced into the ocean, resulting in a sea-level rise of about 390 feet (118 m). The continents and oceans as we know them have existed since then. Today's climate developed only about 2,000 years ago.

Below, scientists search for corals large enough to yield evidence of past climate, such as this 200-year-old colony of the coral *Porites*. **Near right,** small cores are taken using a pneumatic drill. **Far right,** the diver uses a thin rod to dislodge cores, which are taken back to the laboratory for analysis. **Top right,** if a good climate signature is discovered, divers return with a larger hydraulic drill to take cores up to 16 feet (5 m) in length.



During the past two millennia, the geological archives suggest that global average atmospheric temperatures have been relatively stable, varying no more than 4°F (2°C). Today, with the addition of anthropogenic (man-made) greenhouse gases, such as carbon dioxide, methane, and ozone, which are expected to increase global warming—possibly by as much as 7°F (4°C)—during the next hundred years or so, there are many new questions about how the climate responds to change.

The tropical oceans play a central role in the global climate machine as regulators of heat and moisture exchange between massive areas of the sea surface and atmosphere. This interaction creates and fuels great ocean circulations and wind patterns that generate and push weather systems around the world. The largest observed variation in the global system is the El Niño/Southern Oscillation (ENSO) cycle. Part of the ENSO cycle produces widespread sea-surface warming of the entire tropical Pacific, which can change worldwide weather patterns, sometimes dramatically. Because corals grow close to the sea surface, they provide excellent records of tropical air and sea conditions.

"The advantage of the corals is they act as a long continuous monitor of sea-surface temperatures that extends for many hundreds of years, dramatically increasing the number of examples of decadal cycles of drought and rain, ENSOs, and other features, and you can begin to look for causes," Charles says.

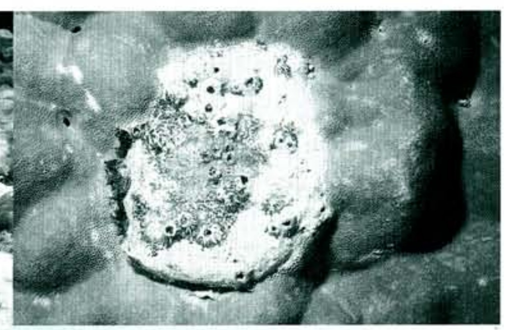
Charles and his group, which includes postdoctoral researcher Michael Moore, have visited several sites in the Pacific and Indian oceans to sample corals in the genus *Porites*. Over hundreds of

Left, once removed, core sections are sequentially labeled. **Below left,** coral-coring operations in north Sulawesi, Indonesia.

years colonies of these animals grow into massive, boulder-like shapes. Each colony is composed of millions of tiny polyps, which have a fleshy surface and a cup-shaped, hard skeleton base composed of calcium carbonate.

The scientists scuba dive into shallow reef waters and use an industrial-sized hydraulic drill to take cores ranging from one to four inches (2.5 to 10 cm) in diameter and up to 15 feet long (4.6 m). They are careful not to damage the surface of the coral colony during drilling. After extracting the core they install a concrete plug in the small hole, which is soon overgrown by the surrounding coral.

The *Porites* cores clearly display annual growth bands, similar to those found in trees, which can be counted from the present surface



Near right, after coring, a small hole remains—here the size of a drinking glass. Living tissue is confined to the uppermost half inch (approximately 1cm) of the coral's structure. It is this layer that allows corals of the genus *Porites* to attain such great age by preventing the settlement of destructive boring clams and sponges.

Above, to prevent permanent damage to corals, divers fill the core hole with a concrete plug. After several years, the normal ecological succession of encrusting organisms has taken place, and live coral tissue grows over the plug.

layer to past ages. The banded layers alternate in density, such that more porous layers are formed by warmer summer water and denser layers by cooler winter water.

Back in the laboratory, the cores are x-rayed to image the growth bands, which then can be subdivided into seasons and even months. While measuring the relative thickness of layers within the bands distinguishes favorable and unfavorable ocean conditions for growth, the composition of individual layers holds even more quantitative climate data drawn from the chemistry of the ancient seawater.

"It's actually a step above the level of information you get with coral growth bands, because the chemistry is so much more quantitative of the physical processes," Charles notes. "Instead of dealing with complex laws of biology and ecology that dictate whether or not a coral is growing well, we are looking at very precise chemical measurements that depend entirely on the conditions of the seawater."

Using a mass spectrometer, the researchers measure the concentrations of stable isotopes and other geochemical tracers found in coral skeletons. The most significant is the ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O) in a sample, which is established by the conditions of the seawater when the coral was growing. The ratio depends mainly on water temperature—the warmer the water, the less ^{18}O in the skeleton. This measurement also can be used to determine past precipitation in regions of the tropics with heavy rainfall. Proportions of other elements, such as cadmium, barium, and calcium, reveal the distribution of nutrients to corals in the past ocean, a further indicator of sea-surface temperatures, ocean mixing, and circulation. Other aspects of coral chemistry, such as strontium, carbon-14, and uranium, are also useful tracers of oceanic processes.

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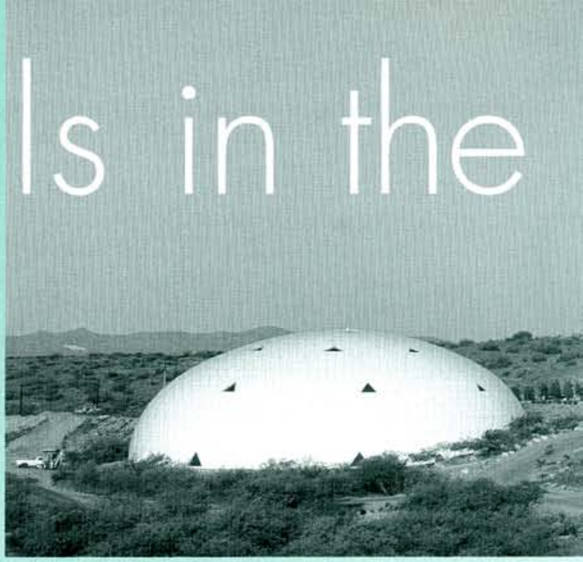
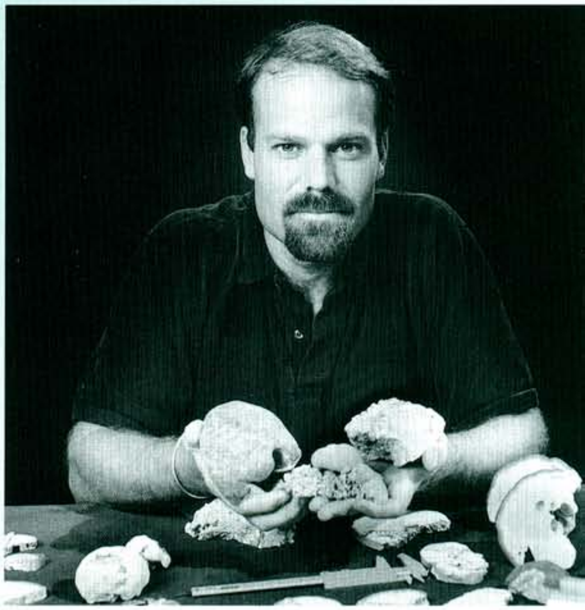
Corals in the



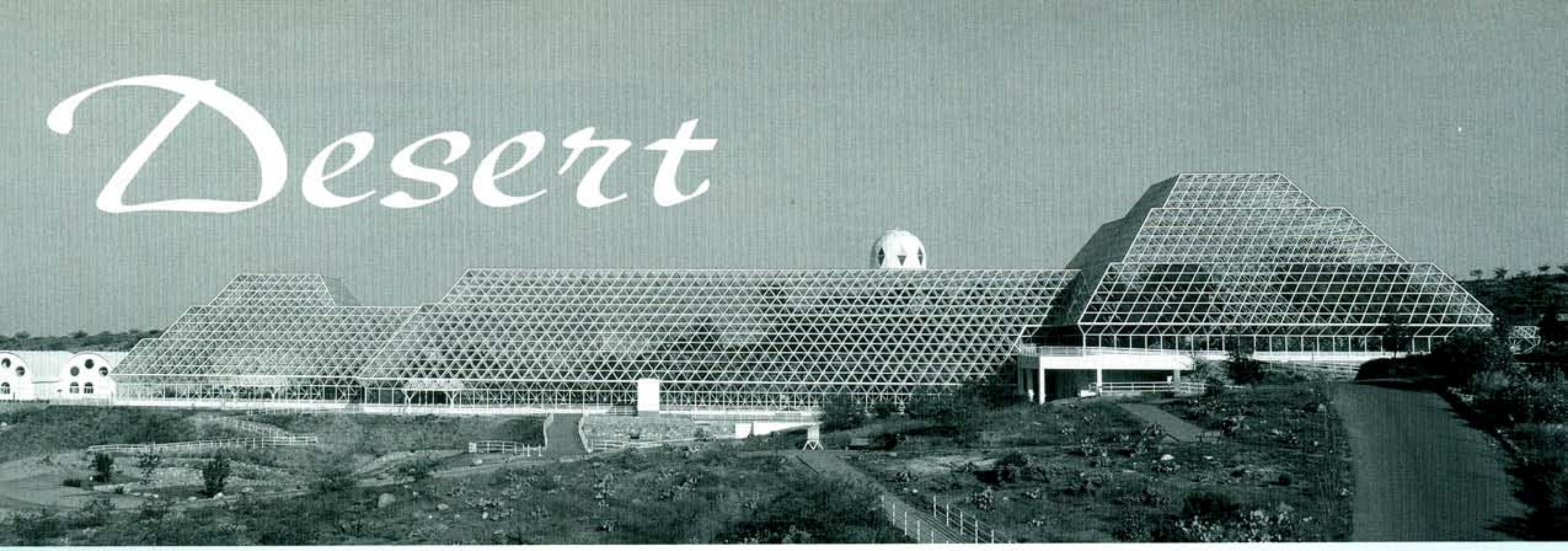
When paleoclimatologists analyze corals to infer past ocean conditions, they make assumptions about how corals store chemicals in their skeletons as they grow over years and centuries. But the scientists don't know if changes in the corals' metabolisms affect the recordings they find. No one has been able to make direct measurements of long-term coral growth—until now.



Scripps researcher Michael Moore examines sponges from the tropical Pacific and the Caribbean. Like corals, they secrete a calcium carbonate skeleton. The isotopic composition of sponge skeletons appears to be in equilibrium with seawater. This makes them valuable in tracking slight changes in seawater temperatures over the last few centuries.

Samples of *Astrosclera*, a slow-growing sponge, collected in south Sulawesi, Indonesia.

Desert



Biosphere 2, near Tucson, Arizona, is a unique facility used as a laboratory for studying the effects of climate change on different ecosystems.

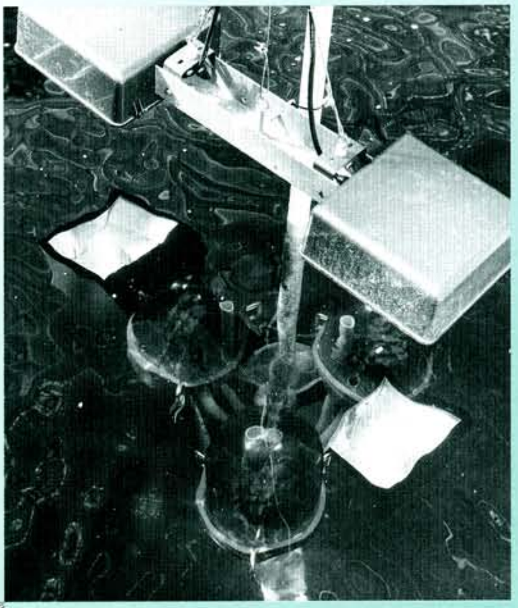
Michael Moore, a Scripps postdoctoral researcher, has transported living *Porites* coral colonies from Hawaii into the million-gallon tropical ocean at Biosphere 2 in Arizona for a unique growth experiment.

"Biosphere 2 is a great laboratory because its environments are large and stable, and yet can be precisely controlled and monitored," Moore explains. "The corals will be subjected to high and low light levels as well as high and low nutrient levels in an effort to accelerate or slow their metabolism."

The advantage at Biosphere 2 is that Moore will be able to adjust various environmental conditions, such as temperature, salinity, and oxygen isotope concentrations, while slowly manipulating the health of the corals. For the next five years, he will sample the corals and analyze their composition in a lab at Scripps.

Moore hopes to determine if the corals' calcium carbonate skeletons incorporate oxygen isotopes from seawater at the same rate under all extremes of nature, such as El Niño warming and ice-age cooling.

An additional test will gauge the sensitivity of a very slow-growing tropical sponge, called *Astrosclera,* as a paleothermometer. It is a mushroom-sized creature with a calcium carbonate skeleton. Unlike corals it does not contain symbiotic algae, so Moore suggests it may yield more accurate recordings of past tropical seawater temperatures because its growth may be less affected by other ocean conditions.

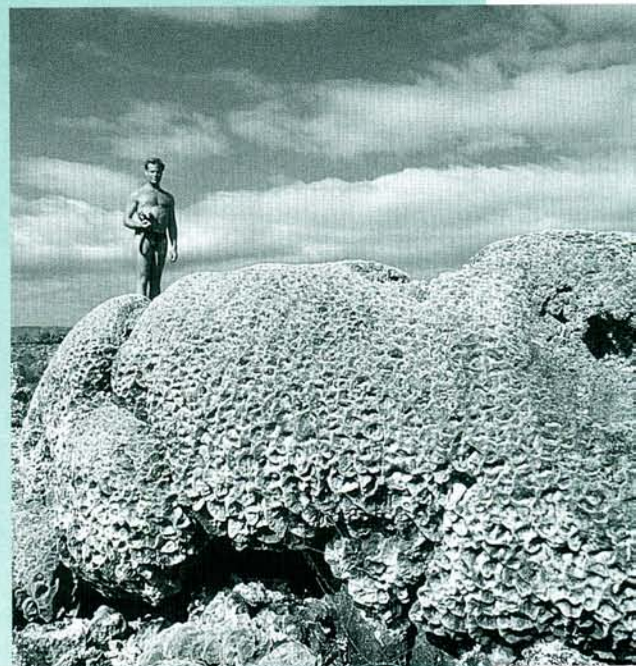


Above, Michael Moore's Ocean Paleo Temperature Experiment (OPTEx). To better understand the reliability of trace metals and oxygen isotopes as tracers of climate, Moore will culture colonies of *Porites* in Biosphere 2 for the next five years. The apparatus supports several corals near the water's surface, while special lights simulate tropical conditions.

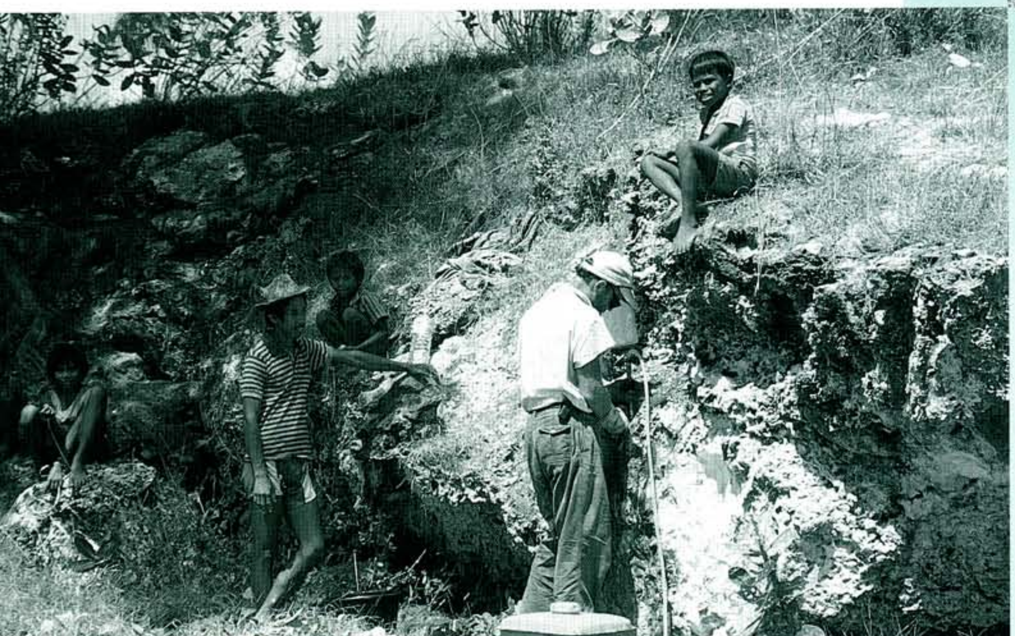
Left, the million gallon (3.7 million liter) tropical reef tank inside Biosphere 2.

Charles's most recent studies focus on coral cores taken last year at the Seychelles, an island group in the southwestern equatorial Indian Ocean. He is looking for climatic links between monsoon events there and ENSO cycles within the past few hundred years by comparing these cores to Pacific cores. Results show strong correlations between sea-surface temperatures in both oceans over the past 150 years, suggesting consistent linkage, even during Pacific El Niño warming events. Exactly what drives this climatic connection between such distant locations remains a complicated and significant question, especially because monsoons have such an important impact on precipitation and agriculture over east Africa and throughout southern Asia.

In other studies, attempts are being made to relate tropical oceans to some puzzling aspects of ice ages, such as periods of dramatic warming and variations in ice sheet growth that are indicated in proxy records derived from recently bored deep-ice cores. The longstanding view is that during ice ages tropical oceans were relatively warm and unchanging. Now Charles and others are finding indications of periodic ocean temperature cooling in tropical corals that relate to ice cycles, and that such shifts occurred abruptly over a few decades.



Volcanic activity in the Galápagos Islands in 1953 lifted an entire living coral reef out of the water, including this large colony.



Moore samples a large fossil coral colony from a 35,000-year-old uplifted reef terrace in Sumba, Indonesia. Scientists examine the geologic record in order to determine how Earth's climate has changed.

Deciphering paleoclimate from corals is currently limited because there are not many cores that cover long time scales, and these have been taken from just a few locations. Finding and coring pristine segments covering more than a couple of centuries is difficult.

Recently, corals have become the tools of choice for understanding climate variability during the past 10,000 years. Federal funding for coral paleoclimate research is growing steadily, and Charles and Moore have support from the National Science Foundation to collect at several unsampled tropical locations during the next two years, which will greatly improve the available data sets.

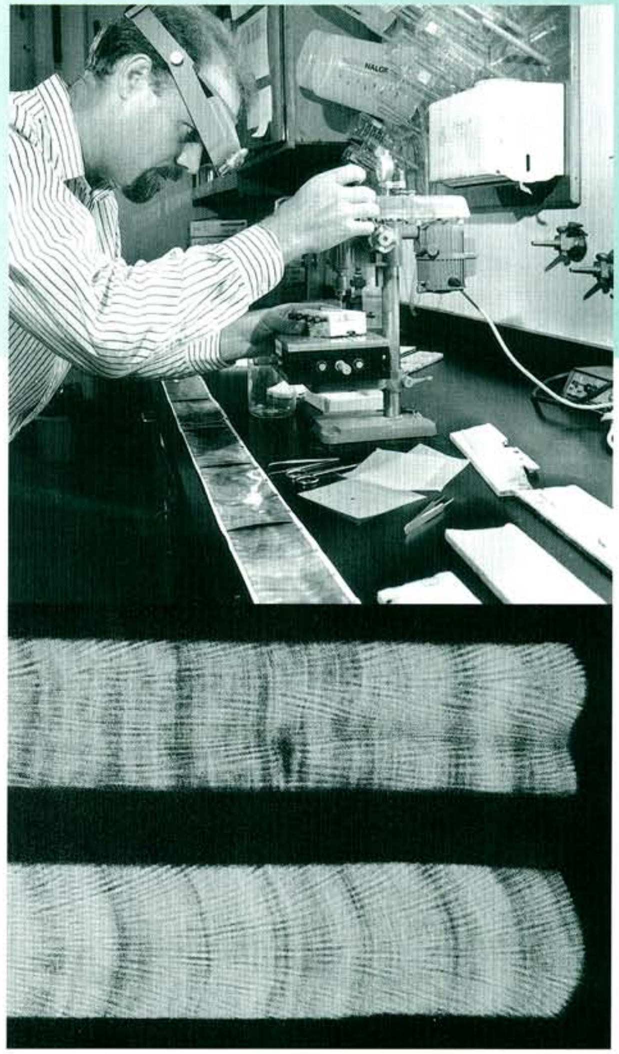
"One central question we're trying to answer is whether past extremes are similar to or different from today's extremes of temperature and climate," Charles said. "Having information on how fast climate changes naturally and what the limits have been is a relevant aspect of understanding greenhouse warming."

Charles is quick to point out that in all of nature's proxy records, some going back tens of millions of years, there is evidence that even cataclysmic climate episodes are eventually balanced by a return to more normal conditions. So potential anthropogenically induced global change effects are not likely to make Earth uninhabitable for humans, but there are questions of how fast change may occur, to what extremes, and how human societies can adapt without widespread hardships.

Unraveling the complexities of past, present, and future climate factors is a challenge, but Charles finds some aspects easier to tolerate than others.

"For those of us in the business of reconstructing Earth's climatic history, it is comforting to think that the secrets of the ice ages may be divulged in a place where, afterwards, one could sip drinks from a coconut," he quips.

Top, Michael Moore uses a small drill to collect samples of *Astrosclera* skeleton. A microsampler stage allows samples to be taken at very small increments. **Bottom,** corals, like trees, have annual rings that create a precise record of age. This image of a coral slab shows high- and low-density bands for each year of growth.



Scripps researcher Christopher Charles loads coral samples into an automated gas-source mass spectrometer. This instrument makes precise measurements of stable isotope ratios, providing data on past ocean temperatures.