record of the dialogue with the imagined computer system. What they end up with, says Demers, is a document that is a far better description of the computations than ever existed before.

Demers says he was skeptical when Wilson first proposed writing and documenting a FORTRAN program in this way. But now, he realizes, Wilson "is clearly right." Others agree. R. Miles Waugh, the manager of computer applications at Philip Morris plans to send a group to Cornell to learn to write programs in this new way. The GIBBS method, Waugh remarks, provides, "a rapid translation of scientific knowledge into computerese. It interprets the scientist's need the first time through." The project itself, he says, "is a fifth-generation kind of thing."

Wilson himself is anxious for others to try similar projects. "One of the things that is needed is more GIBBS-type collaborations" he says. "This is as hard as building an operating system. I make no promises that the GIBBS project by itself will solve the computer language problem, but to have more chance of success we need more projects in competition with it."—GINA KOLATA

# Ice Cap of 30 Million Years Ago Detected

*The oxygen isotopes of marine sediments are providing strong indirect evidence of an Antarctic ice cap twice as ancient as the present one*

Paleoceanographers are finding strong indications of a major ice sheet that covered Antarctica 30 million years ago, 15 million years earlier than an ice cap had been generally supposed to exist. If it later melted away before the present ice cap formed, as now seems likely, then the icing over of the entire Antarctic continent was not a one-time, irreversible step toward the present global ice age. Significant amounts of early glacial ice would also mean that sea level changes due to the waxing and waning of an ice cap extended farther into the past, affecting such processes as biological evolution, climate, and the accumulation of marine sediments. Some researchers are now unwilling to rule out even older ice caps at times when the globe was much warmer than it is today.

Researchers have been endeavoring to decipher the geologic history of Antarctic ice under some severe limitations. The present ice has not left geologists working on the continent much to look at. What little rock that is left exposed does contain hints of ice older than 15 million years. This early ice seems to have been massive enough to cover volcanoes now standing well above the present ice and to override the Transantarctic Mountains and shape the presently ice-free Dry Valleys (*Science*, 28 May 1982, p. 973). That convinced some geologists, but not many paleoceanographers, that substantial ice existed sometime before the traditional date for ice-cap formation. The latter had already set 15 million years as the earliest time of significant ice during the past 250 million years.

Paleoceanographers have worked under their own limitations, ones that are beginning to be circumvented. Their main tool has been the oxygen isotope composition of the carbonate skeletons of microorganisms, called forams, preserved in deep-sea sediments. The lighter of the two stable isotopes, oxygen-16, tends to accumulate preferentially in glacial ice. When ice enriched with oxygen-16 forms on Antarctica, the heavier isotope, oxygen-18, tends to be left behind in the ocean where it increases in abundance relative to the lighter isotope. Forams record the relative proportions of each isotope in seawater when they form their carbonate skeletons. The more ice on the land, the heavier the carbonate isotopes of their skeletons. The problem has been that this effect of ice volume on the oxygen isotope composition of forams adds to the effect of seawater temperature. The chilling of seawater mimics the growth of ice.

> Old and new data are being more assertively interpreted in terms of ice volume changes

On the basis of scanty observations, most paleoceanographers had until now assumed that the variations in oxygen isotope composition before 15 million years ago could be ascribed solely to ocean temperature variations. Three groups of researchers studying foram microfossils at three different sites now have isotopic evidence that temperature changes alone probably could not have caused the observed variations. Kenneth Miller and Richard Fairbanks of Lamont-Doherty Geological Observatory studied foram microfossils at two Deep-Sea Drilling Project sites in the western North Atlantic (*1*). Lloyd Keigwin of Woods Hole Oceanographic Institution and Gerta Keller of the U.S. Geological Survey (USGS) in Menlo Park (*2*) and Miller and Ellen Thomas of Scripps Institution of Oceanography (*3*) studied separate sites in the equatorial Pacific.

All of these researchers agree that about 29 million years ago the isotopic composition of seawater was so heavy that, if the traditional assumption of an ice-free world were made, deep ocean water would have to have been as cold or colder than it is today. That is just a couple of degrees above 0°C. One calculation would make deep seawater as cold as −0.2°C. The reasonable alternative to ice-cold seawater in a supposedly ice-free world, everyone seems to agree, is seawater that was slightly less frigid and a significant volume of ice, presumably in Antarctica. Estimates of the actual ice volume run from one-third to one-half the present volume of the Antarctic ice cap. That much water removed from the ocean and stored as ice would have lowered sea level about 40 meters. Eighteen thousand years ago, when both Antarctic and Northern Hemisphere ice sheets had reached their maximum size, mean sea level fell to at least 100 meters lower than today.

Now that early ice has a certain measure of respectability, old and new data are being more assertively interpreted in terms of ice volume changes. In 1980, Keigwin pointed out that about 36 million years ago oxygen isotopes in both bottom- and surface-dwelling forams became slightly heavier. They were not so heavy as to require unreasonable bottom temperatures, but both surface and bottom values varying by the same amount and in the same direction would be an unlikely result of climate change. A withdrawal of light isotopes to an ice cap, among other possibilities, could explain the concerted change, Keigwin suggested; temperature changes could account for the rest. This concerted variation of isotope compositions is now taken as support for an even earlier ice cap of about the same size as the one that existed 30 million years ago. From additional, unpublished work on samples from their North Atlantic sites, Miller and Fairbanks suspect that a significant ice cap also existed about 24 million years ago.

The details of the history of this ice—especially how far back it goes—remain highly uncertain. James Kennett of the University of Rhode Island, who had favored little or no ice earlier than 15 million years ago, still sees strong evidence from both the ocean and the land that all Antarctic ice disappeared before today's ice cap formed 15 million years ago. Other researchers accept this as a reasonable possibility. And, says Kennett, it is "hard to believe" on the basis of various evidence from the land and the oceans that it was cold enough earlier than about 38 million years ago to allow any ice. Not every one is yet willing to go that far. Since 1980, Robley Matthews of Brown University and Richard Poore of the USGS in Menlo Park have argued on the basis of oxygen isotope compositions that there are no data in hand that would allow the presumption of an ice-free world any time in the past 100 million years (*4*).

Rather than depend on the appearance in the isotope record of unreasonable deep-sea temperatures, Matthews and Poore contend that an ice-free world before 15 million years ago creates unreasonable tropical sea-surface temperatures. Intensive marine studies under the CLIMAP project in the mid-1970's suggested, they say, that even 18,000 years ago, when at least twice the present volume of ice existed, the temperature of tropical surface waters was about the same as it is today. Assuming that the tropics have always behaved that way, they take any variation in the isotope composition of surface-dwelling tropical forams as a sign of an ice volume effect uncontaminated by any temperature effects. Observations become increasingly more meager with increasing age, but Matthews sees no evidence of an ice-free world until 100 million years ago.

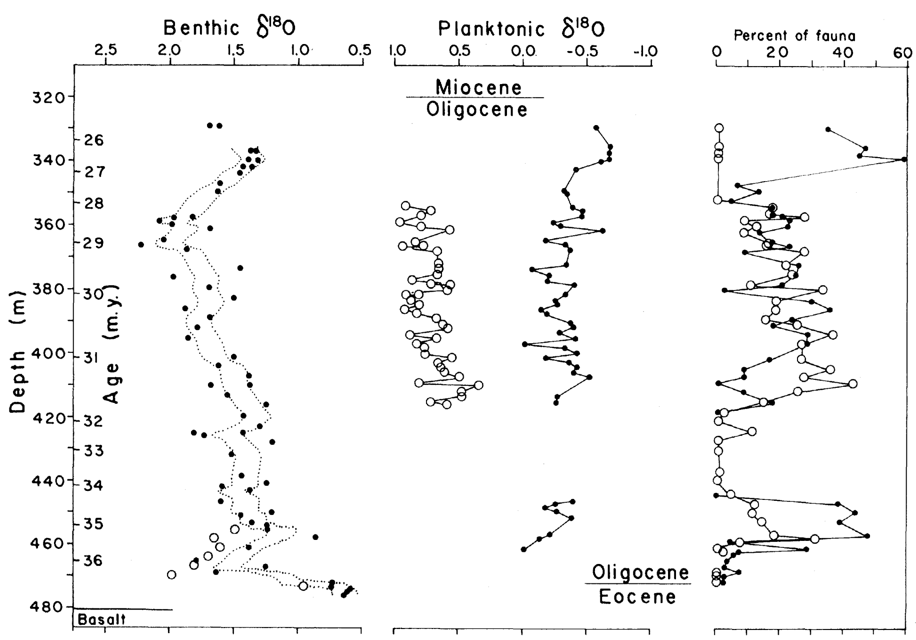
In further support of ice in earlier, warmer times, Matthews and Poore cite the work of Peter Vail and his group at Exxon Production and Research Company, Houston (*Science*, 25 July 1980, p. 483). In 1977, Vail presented a curve of changing sea level as determined from the three-dimensional arrangement of sediment layers on the continental shelves and slopes. The Vail curve is no longer interpreted strictly in terms of sea level change and controversy still surrounds the true causes of its various ups and downs, but many researchers believe that the more rapid shifts in the curve have something to do with sea level change. Miller associates the three peaks in the Vail curve between 38 and 24 million years ago with the highest rate of fall of sea level, related presumably to the formation of ice as indicated by the synchronous isotopic changes. Such shifts in the Vail curve appear frequently throughout its 600-million-year length.

Although some researchers believe that Matthews and Poore were right about this early ice for the wrong reasons, the new evidence supporting the existence of substantial ice 30 million years ago gives credence to the questions about climate change that their arguments raised. The world is much colder now than the ice-free world of 100 million years ago (*Science*, 17 February, p. 677); what in particular during this long cooling triggered ice-cap formation, the hallmark of an ice age?

According to one view prevalent among paleoceanographers, the climate deterioration of the past 50 million years seemed to be paced by the increasing isolation of Antarctica from tropical heat sources. Australia and then South America drifted away and allowed the cold circum-Antarctic current to encircle the continent. Presumably, once this current presented enough of a barrier to heat transfer, the ice cap formed. If an ice cap formed much earlier than supposed or formed more than once, there must be at least another factor in the triggering mechanism.

Another presumption among paleoceanographers about the long transition between a warm and a cold climate has been that, once a climate threshold—such as the chilling of the deep sea 38 million years ago or the formation of the Antarctic ice cap 15 million years ago—had been crossed, there was no going back. It now appears that there may be nothing inherently permanent about an Antarctic ice cap during the transition from a warm climate to a colder one; its existence may not necessarily reinforce the climatic processes that created it and thus ensure its survival.

—RICHARD A. KERR




**Traces of ancient ice caps**

*These plots of oxygen isotope composition ($\delta^{18}O$) against age (or depth in a sediment core) reveal a distinct maximum about 29 million years ago in bottom-dwelling (benthic) forams that is interpreted as evidence of a significant ice cap. The abrupt rise at 36.5 million years, together with other data, suggests an ice cap at that time as well. Closed and open circles represent different species. The dotted lines represent a band 0.2 per mil wide centered on a three-point running average. Reproduced from (2).*

### References

1. K. G. Miller and R. G. Fairbanks, *Nature (London)* **306**, 250 (1983); unpublished results.
2. L. Keigwin and G. Keller, *Geology* **12**, 16 (1984).
3. K. G. Miller and E. Thomas, *Init. Rep. Deep-Sea Drill. Proj. Leg 85*, in press.
4. R. K. Matthews and R. Z. Poore, *Geology* **8**, 501 (1980); R. K. Matthews, *Am. Assoc. Pet. Geol. Mem. 36*, in press.