the way." To get the head far enough into the magnet so that it is in the homogeneous portion of the field, the shoulders have to go in too. As John Schenck, also of General Electric, says, "If you get a magnet that you could do the head in, you could do the heart."

Currently, Oxford Research Systems has plans for a very large magnet having a 60-centimeter bore and weighing four tons. This will accommodate a moderately sized human thorax. Tests with the instrument will begin in a few months at a number of places, including Oxford, Philadelphia, and Massachusetts General Hospital in Boston.

The cost of the instruments is currently high, but not prohibitive if further clinical trials bear out the promise of the early work. According to Chance, the instrument built by his group cost about a quarter of a million dollars. The smaller Oxford instrument lists at close to a half million dollars and the larger one can be picked up for about three-quarters of a million. This puts their costs in the same range as that of x-ray CAT (computer-assisted tomography) scanners.

Incidentally, phosphorus NMR, which produces biochemical information, could be considered more as a complement to than as a competitor of the x-ray methods, which produce images of body structure. Still, if phosphorus NMR techniques can ever be combined with the imaging methods already developed for proton NMR (*Science*, 17 October 1980, p. 302), it may be possible to obtain two- or three-dimensional images of human tissues and organs that incorporate both biochemical and structural information.—JEAN L. MARX

Staggered Antarctic Ice Formation Supported

If the West Antarctic ice sheet formed as late as 9 million years ago, it may have been the trigger for dramatic ocean changes

Antarctica was not always the continent of ice. According to conventional thinking, little glaciation occurred there until about 16 million years ago. By 13 million years ago, about as much ice had accumulated as is seen today. Oceanographers from the University of Georgia recently found new evidence* for the formation of a relatively small but crucial chunk of ice, the West Antarctic ice sheet, no more than 9 million years ago. Using their more precise dating, they link that glaciation with many of the dramatic chemical and physical changes known to have occurred in the ocean at about the same time.

Paul Ciesielski, Michael Ledbetter, and Brooks Ellwood of the University of Georgia do not base their dating of the West Antarctic glaciation on the usual gauge of the volume of glacial ice—changes in the oxygen isotopic composition of the ocean. They contend that the West Antarctic ice sheet could not have had much effect on the isotopic composition of seawater, in part because of the small volume of ice involved. Instead of isotopic effects, the Georgia group looked for physical effects that glaciation would have caused, especially on the sediments surrounding Antarctica.

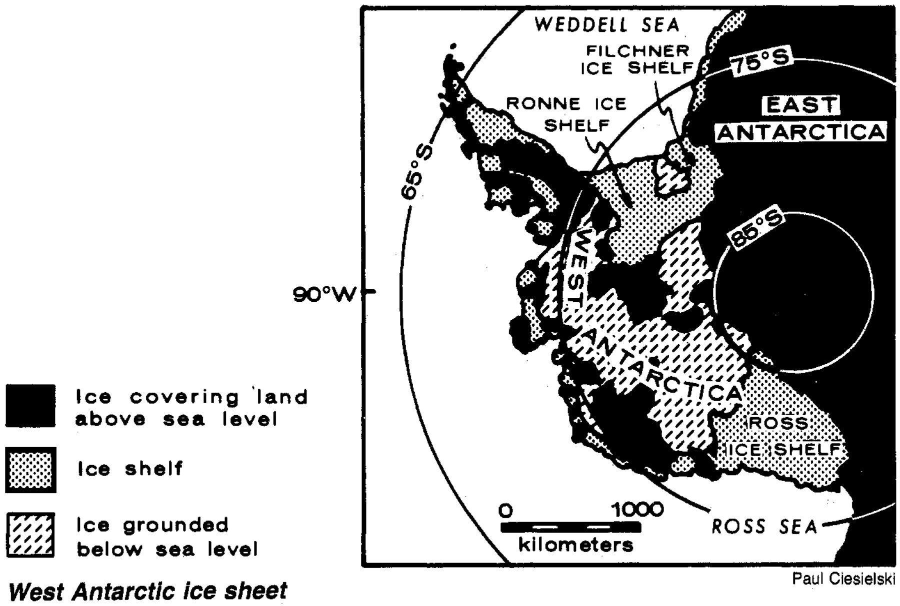
Among other effects, extensive West Antarctic ice seems to have cut off a plentiful supply of sediment to the Ross Sea, which flanks West Antarctica proper. Ciesielski and Margaret Savage, also at Georgia, found that prior to 10 million years ago sediment, which was apparently ground off the continent by glaciers, piled up in the Ross Sea at the rate of 100 meters per million years or more. More recently, a typical rate there has been no higher than a few meters per million years. The explanation of the high rates, they say, must be that up until 10 million years ago melting glaciers were dumping their heavy loads of sediment directly into an ice-free Ross Sea. Then, the ice extended to form a floating ice shelf that not only eliminated much of the sediment supply but also, by about 5 to 6 million years ago, scraped away some of the bottom sediments. That erosion can also be seen in the sediments. David Drewry of the University of Cambridge and John Mercer of Ohio State University independently have argued for an ice-free Ross Sea prior to 5 or 6 million years ago. Their hypotheses were based in part on earlier studies with less precisely dated samples.

The date of the formation of the Ross ice shelf is important, Ciesielski says, because the West Antarctic ice sheet could not have formed without that ice shelf. Unlike the lofty East Antarctic ice sheet, much of the ice in the west lies up to 2000 meters below sea level between what would otherwise be islands in a West Antarctic sea. According to some glaciologists, the West Antarctic ice sheet could not have thickened to its 4000-meter depth without ice shelves in the Ross and Weddell seas to buttress the ice sheet and prevent it from flowing laterally under its own weight.

As a second check on the time of ice shelf formation, the Georgia group attempted to more precisely date the appearance of a particular type of sedimentation. They looked for the rock debris carried away from Antarctica by icebergs and dropped on the sea floor as the icebergs melted. Close to the continent at 59°S, ice-rafted debris, which can range from sand to cobble size, first appeared 12 to 13 million years ago, they say. But it did not extend to lower latitudes (about 50°S) until after 10 million years ago, the pebble-sized dropstones not arriving until after 8 million years ago. Because only the large, tabular icebergs calved by ice shelves could survive in those warmer waters, the ice shelves—and thus the West Antarctic ice sheet—could not have formed until after about 9 million years ago, as estimated from the Ross Sea and other cores.

A third date comes from another continent. Although the geological traces of the West Antarctic ice sheet's creation remain buried beneath thousands of meters of ice, researchers can put their hands on the geological record of glacial activity in neighboring South America. Mercer has pointed out that the climate of the southern tip of South America should be closely linked to that of West Antarctica by the prevailing winds and currents. He found that the earliest glacial deposits in South America are between 5.4 and 7.2 million years old. Thus, the Georgia group reasons, the West Antarctic ice sheet must have formed by then.

**Marine Geology*, in press.



West Antarctic ice sheet

The solid black areas in West Antarctica roughly represent the "West Antarctic Islands" that would have existed before ice covered them and filled the surrounding sea.

Although researchers have for some time suspected a delayed formation of the West Antarctic ice sheet, the timing of these three indicators of glaciation, and thus the strength of the whole argument, had remained uncertain. Part of the problem was the marine sedimentary record. Ideally, sediments accumulate layer upon layer, like the pages of a book. Unfortunately, both natural processes and human activities can disturb that perfect chronological ordering and muddle the sedimentary record.

A major problem has been the way that the Deep-Sea Drilling Project's drill ship *Glomar Challenger* has been recovering sediment samples. Although eminently successful at retrieving cores of sediment hundreds of meters long from beneath the ocean floor, *Challenger*'s rotary drilling rig, borrowed from the oil industry, usually twists and distorts the soft, muddy sediment. That smears the details of the sequential ordering, greatly reducing one's ability to separate in time one event from another. Researchers can recover undisturbed cores by dropping a piston corer, a weighted pipe at the end of a wire, into the bottom. But piston corers usually penetrate less than 20 meters, not enough to reach the sediment deposited during Antarctic ice formation. The Georgia group minimized that problem by using piston cores taken from the Maurice Ewing Bank east of the tip of South America. There, strong currents have stripped away several million years worth of sediment, bringing the sediments of interest within the reach of the piston corer.

Researchers are excited about a new coring technique that combines the long reach of rotary drilling and the delicate touch of piston coring—the hydraulic piston corer (HPC). Also operated from *Challenger*, the HPC repeatedly drives itself into the sediment, each time recovering a length of undisturbed core from deeper in the same hole. The Georgia study included HPC cores from sites 512 and 514 in the extreme southwest Atlantic.

Even with an HPC core, knowing the age of a particular event, such as the first appearance of ice-rafted debris, is not a simple matter, especially at high latitudes. A length of core representing a million years of sedimentation may be shortened by deep-sea erosion, or it may be either shortened or lengthened by changes in the rate of sediment accumulation. Biostratigraphers keep tabs on this variability by tracking the evolutionary comings and goings of particular species of microscopic plants and animals, whose distinctive skeletal remains form much of the sediments.

The problem for paleoceanographers studying the sediments of the cold high latitudes, where many of the changes of the last 65 million years in the ocean and in climate are sharpest, is that the biostratigraphers have tied their time scale to the microfossils preserved in European sedimentary rocks. Those are warm-water species that are sparse or absent in the cold waters near Antarctica.

Because the biological time scale by itself is inadequate at high latitudes, paleoceanographers have combined it with a time scale recorded around the globe in nonbiogenic particles of the sediment. When a grain of a magnetic mineral, such as magnetite, settles on the ocean bottom, it may align with the earth's prevailing magnetic field, like a compass. But that field reverses direction from time to time, leaving alternating layers of sediment magnetized in opposite directions. Although only a few of the magnetic grains align, the direction of their lingering magnetic field can be detected in cores in the laboratory, if the direction has not been disturbed during core recovery. The pattern through time of alternating magnetic field directions has been dated by independent means, but the paleomagnetic time scale, like the biostratigraphic time scale, is susceptible to the distortions of erosion and sedimentation rate changes. Used together, however, the two time scales allow greater resolution than when either is used alone. With this approach, the Georgia group was able to piece together a composite sedimentary record for the southern high latitudes from fragments of the record 5 to 12 million years old.

From that more precisely dated record, Ciesielski, Ledbetter, and Ellwood have also deduced that the formation of the West Antarctic ice sheet gave the world ocean the final shove that brought it to a state similar to that seen today. Before that event, they say, a more limited amount of cold, surface seawater sank at high latitudes to flow through the deep ocean. Because sea ice contains less salt than the seawater from which it is formed, the formation of the ice sheet added salt to the already cold, dense surface water. Thus, a larger volume of water became dense enough to sink into the depths. The result, they say, was an abrupt increase in the volume and velocity of abyssal currents and a drop in abyssal temperatures. Some of the deep-sea erosion of that time may have resulted from these accelerated currents, they say.

Numerous other changes buffeted the world ocean 5 to 8 million years ago, but it remains uncertain how many of them may be directly linked to the formation of the West Antarctic ice sheet, Ciesielski says. Among the possibilities are the increased dissolution of carbonate sediments, the increased deposition of siliceous sediments, and a shift in the carbon isotopic composition of seawater. At least one dramatic event, the lowering of sea level 50 meters or more about 5.5 million years ago, cannot possibly be linked to the West Antarctic ice sheet, he says. The ice sheet contains too little ice to account for the removal of that much water from the ocean.

—RICHARD A. KERR