not fit the Bardeen-Cooper-Schrieffer mold. First came the "heavy fermion" metals, which contain rare earth or actinide ions with local magnetic moments that are only weakly coupled to the conducting electrons. There are many reasons to believe that superconductivity in these metals is unconventional, but their intrinsic complexity has so far prevented a definitive determination of their electronic nature (*5*). Next came the high-temperature cuprates, in which the relative motion of the paired electrons has a d-wave structure ($l = 2$). However, cuprates have many additional anomalies that do not fit into a generalized Bardeen-Cooper-Schrieffer theory (*6*).

A decade ago, Maeno *et al.* (*7*) succeeded in growing perfect crystals of Sr$_2$RuO$_4$ and found that they were superconducting at low temperatures. Above the superconducting transition temperature, the material behaves as a standard metal, but there are clear signs that the motion of the electrons is strongly correlated at all temperatures, similar to ^{3}He atoms, which move in this way to avoid each other both in the superfluid and the normal liquid. This observation quickly led to speculation that the superconducting state of Sr$_2$RuO$_4$ would also be p wave ($l = 1$) (*8*). This type of relative motion has consequences for the spin state of the pairs. Basic quantum mechanics for fermions requires the spins of electrons pairs with odd angular momentum to be parallel—that is, to form spin-triplet pairs, rather than the spin-singlet pairs in conventional and cuprate superconductors. Subsequent studies of the magnetic properties of Sr$_2$RuO$_4$ pointed to triplet pairing, and much supporting evidence has accumulated since then (*9*).

The final confirmation requires that the internal p-wave structure of the pairs be tested in a quantum interference experiment. The way to do this was outlined by Geshkenbein *et al.* (*10*) almost two decades ago. They proposed to modify the standard superconducting quantum interference device (SQUID), which consists of a ring with weak links in the left and right arms. A weak link (called a Josephson junction) can be made by inserting a narrow insulating barrier. Quantum tunneling of the electron pairs through the barrier is usually maximized when their phases on either side are equal. However, Geshkenbein *et al.* (*10*) pointed out that, in the case of p-wave superconductivity, a suitably chosen geometry would add an extra phase shift to the tunneling amplitude of one of the two Josephson junctions. The interference pattern of a SQUID is observed by measuring the dependence of the maximum supercurrent through the device as the total magnetic flux flowing through the ring is varied. The extra phase shift is easily recognized as a displacement of the interference pattern.

In their experiments, Nelson *et al.* (*1*), chose a geometry in which half of the ring is a conventional s-wave superconductor, which is joined to opposite ends of a Sr$_2$RuO$_4$ sample. As illustrated in the figure, tunneling between s- and p-wave superconductors requires interconversion between spin-singlet and spin-triplet pairs. The observation of the added phase shift by Nelson *et al.* is the final piece of evidence that confirms the close analogy between the metallic superconductor Sr$_2$RuO$_4$ and superfluid ^{3}He.

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OCEAN SCIENCE

Deep Ocean Overturning—Then and Now

Jess F. Adkins and Claudia Pasquero

The deep ocean contains nearly all the mass, thermal inertia, and carbon in the ocean-atmosphere system. The rate at which it overturns can therefore have a profound effect on climate. Measurements of the radiocarbon (^{14}C) distribution in the deep sea suggest that the modern ocean overturns once every ~1000 years. Radiocarbon is an accurate tracer of this process because it is created in the upper atmosphere by cosmic rays and can only enter the ocean through absorption of CO$_2$ gas at the ocean surface. When the surface water sinks to the deep ocean, it is isolated from the radiocarbon source, and its radiocarbon content decays with its characteristic half-life of 5730 years. Today, there is more radiocarbon in the deep Atlantic Ocean (as a result of deep-water formation in the North Atlantic) than in the Pacific Ocean. We say that the Pacific is "older" or less well "ventilated" than the Atlantic.

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A foraminiferan of the kind used in (*1*) to determine the age of mid-depth waters.

CREDIT: DEE BERGER / PHOTO RESEARCHERS, INC.

But what about the past ocean, especially at the time of the Last Glacial Maximum, about 20,000 years ago, when large ice sheets covered most of Canada? The calcium carbonate shells of foraminifera (see the first figure) in deep-ocean sediments from this time record the chemistry of the water in which they grew. But here we run into a problem. We cannot use radiocarbon in bottom-dwelling foraminifera as a tracer of water mass age, because their radiocarbon values record the sum of the ages of the sediment and of the water in which they lived. Without an independent chronometer for sediment age, we are stuck with one measurement and two unknowns. However, we can still measure the radiocarbon difference between old samples, as long as we know that they formed at the same time in the past.

This trick is used by Broecker *et al.*, on page 1169 of this issue (*1*), to estimate the radiocarbon age of the equatorial deep Pacific at a depth of 2 km during the Last Glacial Maximum. The authors compare the age difference between surface-dwelling and bottom-dwelling foraminifera both today and at the Last Glacial Maximum. They find that the surface-to-deep age difference was the same, or a little larger, in the past.

This result is somewhat surprising. In a paper published earlier this year in *Science*, Hughen *et al.* came to a different conclusion (*2*) (see the second figure). The authors documented the history of the atmosphere's radiocarbon content over the past 50,000 years. The atmosphere provides an indirect record of the ocean overturning rate, because its radiocarbon budget is very sensitive to how much CO$_2$ it exchanges with

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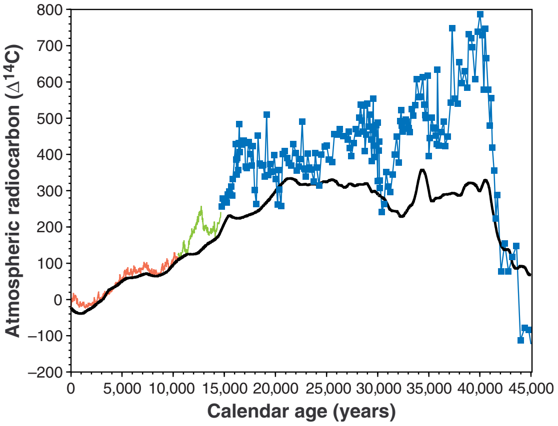

Atmospheric radiocarbon content over the past 45,000 years. Data from tree rings [red line (*11*)] and from foraminifera from the Cariaco Basin [green line (*12*) and blue points (*2*)] are compared to modeled production rate variations (*2*) (black line). Deviations between the data and the model reflect changes in the exchange of carbon between active reservoirs relative to today. The two most important processes for the largest deviations are changes in carbonate sedimentation and in the ocean overturning rate. The data suggest that, assuming constant carbonate flux, the glacial ocean overturned more slowly than it does today.

the deep ocean. Land biota and soils also take up radiocarbon, but export to the deep sea is by far the largest sink for modern atmospheric radiocarbon. If this sink were reduced, the atmospheric radiocarbon content would rise, and rise fast. If a new steady state were reached, and the production rate remained constant, the partitioning of radiocarbon between the atmosphere and deep ocean would shift toward higher atmospheric $^{14}C/^{12}C$ ($\Delta^{14}C$) ratios. This is exactly what Hughen *et al.* found for 11,500 to 13,000 years ago (see the second figure, green line) (*2*).

But there are several important other factors to consider. The production rate of radiocarbon is not constant. Radiocarbon production can be tracked through time by measuring the abundance of other radioactive isotopes produced by cosmic rays, such as ^{10}Be and ^{36}Cl, in ice cores (*3*); these isotopes are not affected by carbon sinks. It turns out that radiocarbon production was higher in the past (see the second figure, black line). But the measured $\Delta^{14}C$ at the Last Glacial Maximum was even higher (see the second figure, blue symbols). Hence, the ocean overturning must have been slower. However, Broecker *et al.* show with a simple calculation that the implied increase in the radiocarbon age of the deep ocean is much larger than their measured age difference from the foraminifera.

How can these disparate results be reconciled? One possibility is that the carbon cycle was fundamentally different at the Last Glacial Maximum. Changes in the burial rate of carbonate sediments can affect atmospheric radiocarbon, because these sediments remove radiocarbon from the system. Another option is that the waters below 2-km depth were much older than those measured by Broecker *et al.* There is not much data, but two papers have found very radiocarbon-depleted waters in the deepest parts of the ocean at the Last Glacial Maximum (*4*, *5*). Clearly we need water column profiles of radiocarbon for the Last Glacial Maximum from both the Atlantic and the Pacific.

Finally, it is possible that 19,000 years ago—the age of some of the data used by Broecker *et al.*—the system was not in a steady state. The atmospheric record in the figure shows that large swings in $\Delta^{14}C$ occurred regularly during the last glacial period. Such swings did not occur over the past 10,000 years of relatively constant climate, during which the radiocarbon cycle was in a steady state. Ice core records in Greenland show that no equivalent period occurred during the last glacial period.

Moreover, the small but growing number of deep radiocarbon values from the Last Glacial Maximum (*1*, *4*, *5*) provides insights into what drives the strength of the overturning circulation: Contrary to a widely held belief, the circulation rate is not driven by surface density gradients in the north-south direction. This conclusion agrees with recent theoretical arguments (*6*–*8*). For example, Huang has shown that a modeled increase in the density of high-latitude waters did not directly result in an increased rate of deep-water formation (*8*). In fact, a large meridional surface density gradient induces a strong vertical stratification, which inhibits the return of deep water to the surface and weakens circulation.

Observational data from the paleoclimate record support this theory. The ocean interior was more highly stratified at the Last Glacial Maximum than it is in the modern ocean (*9*), but the circulation was not much stronger, and was possibly slower, than it is today. More data are needed to determine whether the strength of the overturning circulation depends on winds and tidal energy (*7*, *8*, *10*), rather than on surface warming/cooling or evaporation/precipitation budgets at the surface. The growing paleoceanographic data set shows great promise to answer this question.

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EVOLUTION

Genomic Databases and the Tree of Life

Keith A. Crandall and Jennifer E. Buhay

Although we have not yet counted the total number of species on our planet, biologists in the field of systematics are eagerly assembling the Tree of Life (*1*, *2*). The Tree of Life aims to define the phylogenetic relationships of all organisms on Earth. On page 1172 of this issue, Driskell *et al.* (*3*) propose an intriguing computational method for assembling this phylogenetic tree.

These investigators probed the phylogenetic potential of ~300,000 protein sequences sampled from the GenBank and Swiss-Prot genetic databases. From these data, they generated "supermatrices" and then supertrees. Supermatrices are extremely large data sets of amino acid or nucleotide sequences (columns in the matrix) for many different taxa (rows in the matrix). Driskell *et al.* constructed a supermatrix of 185,000 protein sequences for more than 16,000 green plant taxa and one of 120,000 sequences for nearly 7500 metazoan taxa. This compares with a typical systematics study of, on a good day, four to six partial gene sequences for 100 or so taxa. Thus, the potential data enrichment that comes with carefully mining genetic databases is terrific. However, this enrichment comes at a cost. Traditional phylogenetic studies sequence

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