Refining the Radiocarbon Time Scale

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At the end of the Permian, Earth's continents were assembled into one giant supercontinent, Pangaea, which would have affected climate differently from today's dispersed continents (*5*). The physiological capabilities of marine organisms at the end of the Permian were different from those of the organisms that dominate today's oceans (*6*). Plankton with calcium carbonate skeletons had not yet evolved, and the extent (and hence the calcium carbonate buffering capacity) of seafloors covered in carbonate sediments was therefore more restricted than in modern oceans (*5*).

Despite these differences between then and now, this ancient global warming interval can provide insights that are relevant to our understanding of the future global warming ocean. In particular, the effects of increased temperature, oxygen minimum zone development, and ocean acidification on different components of the marine fauna can be better understood. A goal of future research should be to discern which environments fared better, and which worse, during this time of heightened environmental stress. Of particular interest is the nature of linkages between benthic and pelagic ecosystems and how they were affected by increased temperatures, anoxia, and high sulfide levels, as well as linkages between marine and terrestrial environments.

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ATMOSPHERIC SCIENCE

Refining the Radiocarbon Time Scale

A highly resolved lake sediment record is set to improve the accuracy of calibrated radiocarbon dates between 12,600 and 50,000 years ago.

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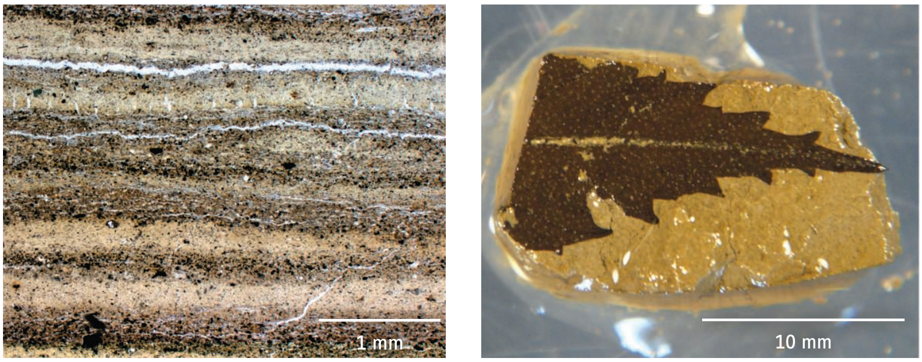
The annually formed layers of sediment from Lake Suigetsu have the potential to reveal information about environmental change in Japan over the past ~50,000 years with chronological precision as good as, or better than, the Greenland ice cores (*1*). Such precision is invaluable for synchronizing records and evaluating leads and lags in the global climate system. Perhaps even more important, the fragile leaves and seeds hidden within these layers (see the figure) provide a record of past atmospheric concentration of ^{14}C, the radioactive isotope of carbon. As reported by Bronk Ramsey *et al*. on page 370 of this issue (*2*), this record stretches back over the full length of the radiocarbon age scale. The results are invaluable for improving the accuracy with which radiocarbon dates can be converted to the calendar time scale.

Radiocarbon (^{14}C) is one of the main dating methods in archaeology and Earth science for the late Quaternary period back to ~50,000 years ago. The method is based on the predictable radioactive decay of ^{14}C, which forms when neutrons generated from cosmic ray bombardment collide with nitrogen in the upper atmosphere. However, the ^{14}C concentration in the atmosphere is not constant, because varying amounts of cosmic rays reach the atmosphere and carbon storage and release from the ocean and biosphere change with time. To estimate the true age of an unknown sample, its radiocarbon age must be corrected for these changes.

To ensure that radiocarbon dates are corrected consistently, scientists have been building internationally recognized calibration curves for many decades. The latest such curve, IntCal09, covers the whole radiocarbon age scale to ~50,000 years ago (*3*).

IntCal09 relies heavily on tree rings, which are ideal for building a correction (or calibration) curve, because the year of growth of the ring can be determined precisely, provided that the tree section to be measured can be matched to a master chronology. The oldest securely dated master chronology goes back to 12,593 calendar years before the present (cal B.P., where "present" is set as 1950 A.D.). For calibration beyond this date, IntCal09 had to rely on ^{14}C measurements of corals and the tiny shells of planktonic organisms found in marine sediments (*3*).

However, using the marine data to calibrate the atmospheric radiocarbon record is not straightforward. There is an apparent radiocarbon age difference of ~400 years on average between an organism living in the surface ocean and one living on land at the same time. This discrepancy arises because the ocean is a large carbon reservoir that responds more slowly than the atmosphere to changes in ^{14}C production. The deep ocean also contains car-



Radiocarbon correction beyond tree rings. Bronk Ramsey *et al*.'s atmospheric ^{14}C record, derived from measurements on terrestrial macrofossils (right) from the laminated sediments (left) of Lake Suigetsu, will help to improve the IntCal calibration curve used to estimate the true age of radiocarbon dated samples.

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CREDITS: (LEFT) GORDON SCHLOLAUT/HELMHOLTZ CENTRE POTSDAM-GFZ GERMAN RESEARCH CENTRE FOR GEOSCIENCES, GERMANY; (RIGHT) RICHARD STAFF/OXFORD RADIOCARBON ACCELERATOR UNIT/UNIVERSITY OF OXFORD, UK

bon that has become depleted in ^{14}C through radioactive decay since it was entrained into the global circulation. Eventually, deep water upwells and mixes with the surface ocean, leaving it depleted in ^{14}C relative to the atmosphere. Because changes in ocean circulation can result in variable upwelling of this deep water, the ^{14}C record in marine organisms is attenuated and offset from the atmosphere by an amount that changes with time and location. To use the marine records in the terrestrial calibration curve for periods before the tree rings, the offset must be estimated, increasing the uncertainty of the calibration.

A direct atmospheric ^{14}C record like that from Lake Suigetsu can be used to decrease the uncertainty in the calibration curve. It will also be invaluable for capturing higher-frequency oscillations in atmospheric ^{14}C, which are not resolved in the IntCal09 curve for the time period before the tree rings. For stratigraphical series of radiocarbon ages—such as those used to date the earliest pottery from the Xianrendong Cave, China, to 20,000 years ago (*4*)—matching the radiocarbon dates from sediment layers to these oscillations will improve age estimates.

However, laminations in lake sediments are seldom, if ever, perfect. In the dark clay sediments of Lake Suigetsu, white layers are formed by the deposition of silica cases of algae (diatoms) in spring and summer; each layer is counted as 1 year (*5*). However, not all layers are preserved, and, in some cases, two diatom layers may be produced in a single year. Counting the layers thus has an associated uncertainty, which accumulates with depth. Bronk Ramsey *et al*. circumvent this problem to an extent by matching the ^{14}C of uranium-thorium–dated stalagmites from the Bahamas (*6*) and China (*7*) to the Suigetsu ^{14}C record, thereby reducing the uncertainty on the Suigetsu time scale.

The IntCal09 calibration curve assumes a constant atmospheric-surface ocean age offset (*R*) to estimate the atmospheric ^{14}C levels from the marine calibration records, which were selected from regions where ocean currents are believed to have been stable over the past 12,000 years. Through comparison with the Lake Suigetsu record, Bronk Ramsey *et al*. show that for these oceanographically stable regions, *R* was larger ~20,000 years ago than during the past 12,000 years, but not to the extent estimated by some authors (*8*, *9*). This estimated variation in *R* will provide more realistic values for the marine data in the calibration curves.

Earth's geomagnetic field shields against cosmic rays, which produce ^{14}C and other isotopes such as ^{10}Be in the atmosphere. About 40,000 years ago, a substantial decrease of the geomagnetic field strength, the Laschamp event, nearly doubled the production rate of ^{10}Be (*10*) and would have had a similar effect on ^{14}C. The ^{14}C production spike is attenuated in the IntCal09 marine records due to the large carbon reservoir. This has led to debates about whether radiocarbon calibration for atmospheric samples would be invalid for this time period (*11*, *12*). In the Suigetsu record, the Laschamp effect is within 2 standard deviations of the IntCal09 calibration curve. Given radiocarbon measurement uncertainties of hundreds to even a few thousand years in this time period, the Laschamp effect will have minimal effect on calibration.

The Lake Suigetsu ^{14}C record reported by Bronk Ramsey *et al*. does not have sufficient data density to provide a stand-alone calibration curve, but it will substantially augment and improve the atmospheric radiocarbon calibration curve. Work is in progress to update the IntCal calibration curve, which will include the Lake Suigetsu data. The resulting improvement in the accuracy of calibrated radiocarbon dates will greatly affect studies of past climate and environmental change and human response to these changes.

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CIRCADIAN RHYTHMS

Circadian Surprise—It's Not All About Transcription

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Posttranscriptional regulation plays a substantial role in controlling the mammalian circadian clockwork.

The integral role of the circadian clock in numerous aspects of health has prompted extensive study of the molecular architecture of clock networks. Understanding how the clock controls downstream processes has widespread clinical impacts, as it affects many diseases and biological processes including immune responses, metabolism, and aging (*1*–*3*). The primary molecular components of the mammalian oscillator and a detailed understanding of the regulatory interactions among them have been well characterized (*4*, *5*). However, one critical question remains unanswered: How do the cogs of this clock translate the rhythmic regulatory relationship among themselves into the plethora of outputs that are under circadian control? On pages 349 and 379 of this issue, Koike *et al*. (*6*) and Morf *et al*. (*7*) investigate this problem from opposite ends of the spectrum—a genome-wide discovery approach and the functional characterization of a specific factor, respectively—yet they converge to emphasize the importance of posttranscriptional regulation of messenger RNA (mRNA) levels on the clock.

Although a few specific connections have been identified (*8*–*10*), the direct global orchestration that occurs between transcriptional loops of the clock and the myriad of circadian-regulated phenotypic responses has been elusive. Koike *et al*. mapped in both time and genome-space the targets of many transcriptional components of the mammalian circadian clock. As they compared the regulation of these targets to their expression by RNA sequencing, the authors found a surprising disconnect between the nascent transcripts and the amounts of steady-state mRNA. This

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