PALEOCLIMATE

A Better Radiocarbon Clock

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An accurate chronometer that covers the past 50,000 years is a fundamental tool for geology and archaeology. For example, some prehistorians believe that Neanderthals overlapped chronologically with modern humans, whereas others claim that they predated modern humans by several millennia. Accurate dating is essential to understand this crucial time in human evolution. Accurate dating is also of paramount importance in fields such as geophysics, geochemistry, and paleoclimatology.

The main chronometer for this time range is radiocarbon (^{14}C), but its use is not free of perils. This is because the atmospheric $^{14}C/^{12}C$ ratio—the starting point of the radiocarbon clock—varies over time. To obtain accurate dates, these fluctuations must be accounted for with a calibration curve. Fossil trees have been used to produce a high-resolution tree-ring calibration, which has been extended with data from layered sediments and tropical corals. The latest "official" calibration curve, INTCAL04, was recently ratified during the 18th International Radiocarbon Conference in Wellington, New Zealand (*1*). It refines the previous INTCAL98 curve (*2*), but stops at 26,000 calendar years before 1950 A.D. ("before present" or B.P.) (*3*), a period beyond which no consensus was reached.

Several groups have tried to extend this curve from 26,000 to 50,000 calendar years B.P. The records used for this purpose include annually laminated sediments (varves) from Lake Suigetsu in Japan (*4*, *5*), corals from the uplifted terraces of New Guinea (*6*), sediments of the former Lake Lisan in Israel (*7*), carbonate deposits from a submerged cave of the Bahamas (*8*), and deep-sea sediments whose stratigraphy can be tied to the Greenland Summit ice cores (*9*). The latter method is based on correlating a known paleoclimatic event dated by ^{14}C—such as transient warmings and massive glacial surges that occurred abruptly over periods of decades—with its equivalent in another record (such as a Greenland ice core) that has been dated with techniques other than radiocarbon.

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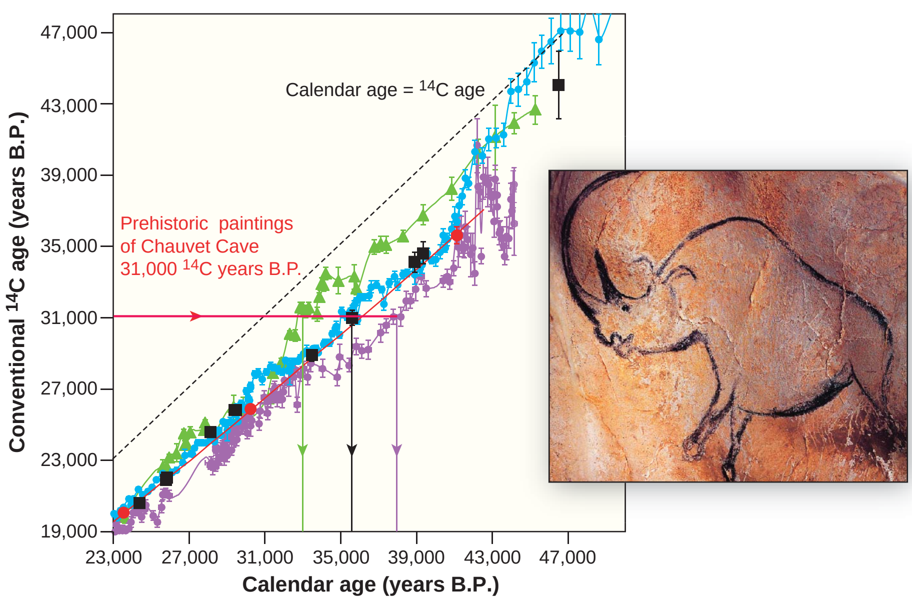
Despite these efforts, it remains difficult to calibrate periods older than 22,000 ^{14}C years B.P., because residual concentrations of ^{14}C in such samples are extremely low (a few percent of the concentration found in modern samples). In addition, old samples have often been altered by geochemical processes. In particular, most corals that grew before the sea-level minimum at 21,000 calendar years B.P. suffered intense meteoric alteration, precluding their use for ^{14}C calibration. The only two published reconstructions with satisfactory analytical precision and low overall data scatter are the Lake Suigetsu record (*4*, *5*) and the Bahamian speleothem (speleothems are cave carbonates such as stalagmites, stalagmites, and flowstones) (*8*). However, these two records strongly disagree. Hence, at least one of them provides an inaccurate picture of the true calibration curve (see the figure).

During the conference in Wellington, the INTCAL working group presented a calibration envelope that reaches ages older than 26,000 calendar years. This work in progress, called COMPARE04, includes most of the aforementioned data, together with new results based on uranium-thorium dating of corals and speleothems.

New results based on the stratigraphy of ocean sediments were also presented during the conference. Most notable is the work by Hughen *et al.* (*10*), reported on page 202 of this issue. These authors have studied sediments from the Cariaco Basin off Venezuela, corresponding to the glacial period. By using the stratigraphic method mentioned above, Hughen *et al.* have been able to extend their previous calibration curve, which was based on the same sediments that are annually laminated after 14,500 calendar years B.P. (*11*). As presented in Wellington and to be published elsewhere (*12*), an ongoing effort by our group to document the calibration curve is based on a deep-sea core collected from the Iberian Margin. This core is close enough to Greenland to ensure unambiguous stratigraphic links between paleotemperature indicators, but sufficiently far



Extending the radiocarbon record. ^{14}C ages versus calendar ages beyond the range of INTCAL98, which stops at 24,000 calendar years B.P. (*2*). Red dots: data from Barbados, Mururoa, and New Guinea corals (*15*); green triangles: Lake Suigetsu varves (*4*, *5*); purple dots: Bahamian speleothems (*8*); black squares: ^{14}C data of the Iberian Margin core MD952042 (*12*); light blue dots: ^{14}C data of Cariaco Basin Ocean Drilling Program core (*10*). The last two data sets are based on the stratigraphic method with calendar chronology tuned to a Greenland Summit ice core (Greenland Ice Sheet Project 2). Red curve: second-order polynomial fitted to the coral data (*15*). Radiometric errors for ^{14}C and U-Th are shown at the 1σ level. (**Inset**) Rhinoceros painting in the Chauvet Cave, dated at ~31,000 ^{14}C years B.P. (red horizontal arrow) based on charcoal analyses (*13*). Vertical arrows correspond to three different solutions for the calibrated age.

CREDIT: FRENCH CULTURE MINISTRY/DRAC RHONES ALPES from the northern North Atlantic, where ^{14}C reservoir ages of surface waters varied strongly during the last glacial and deglacial periods (that is, before 10,000 calendar years B.P.).

The new results based on the stratigraphic method can be used successfully to calibrate ^{14}C ages (see the figure). Between 33,000 and 41,000 calendar years B.P., whereas previous records disagree by up to 5000 calendar years, the new data sets agree within the errors. This confirms the reliability of the stratigraphic method applied to these two distant and very different marine environments. The correct calibration curve thus probably runs between the Lake Suigetsu and Bahamian speleothem data sets.

These new results have important implications for archaeology. Consider the prehistoric paintings in the Chauvet Cave of southern France, which were created at about 31,000 ^{14}C years B.P. (*13*) (red horizontal arrow in the figure). According to the new stratigraphic data (*10*, *12*) and other results presented in Wellington, the calibrated age is almost 36,000 calendar years B.P. (black vertical arrow). The earlier Bahamian speleothem data yield ~38,000 calendar years B.P. (purple vertical arrow) and the Lake Suigetsu record gives ~33,000 calendar years B.P. (green vertical arrow), dates that are respectively too old and too young.

The new radiocarbon results also have wide implications for geochemistry and geophysics. For example, the observed differences between the ^{14}C and true ages reflect deviations of the atmospheric $^{14}C/^{12}C$ ratio, the long-term trend of which is modulated by the geomagnetic field. A well-known magnetic excursion, the Laschamp event, dated by Ar-Ar at ~41,000 calendar years B.P. (*14*), resulted in an abrupt increase of cosmogenic nuclide production (such as ^{14}C, ^{10}Be, ^{36}Cl, and ^{41}Ca). The new data from the Cariaco Basin (*10*) and the Iberian Margin (*12*), together with previous coral data (*15*), indicate that the atmospheric $^{14}C/^{12}C$ ratio reached a maximum of about 700 per mil above the modern one at ~39,000 to 41,000 calendar years B.P. Taking into account a millennium-scale phase shift linked to the carbon cycle, the calendar age for the Laschamp event is thus ~40,000 to 42,000 calendar years B.P. This is fully compatible with recent determinations, in the very same Iberian Margin core, of a ^{10}Be maximum (*16*) and a magnetic paleointensity minimum (*17*) at ~41,000 to 42,000 calendar years B.P. Further independent confirmation of this calibration point comes from ^{10}Be and ^{36}Cl concentration maxima in ice sections dated at ~41,000 calendar years B.P. in the Greenland Summit ice cores (*18*, *19*).

Significant progress is expected in the near future from the stratigraphic method for two main reasons. First, the recently drilled NorthGRIP ice core (*20*) will soon provide improved accuracy and precision for the calendar time scale up to 50,000 calendar years B.P., which is the backbone of the stratigraphic method. Second, additional data will allow researchers to verify and complement the emerging agreement observed between several data sets beyond 26,000 calendar years B.P. (see the figure). In the framework of the international IMAGES program, the research vessel *Marion Dufresne* has recently drilled several new sediment cores from the Iberian Margin and Cariaco Basin. This should increase the ^{14}C data base and permit measurement of other interesting parameters such as ^{10}Be concentrations and magnetic paleointensity. The hope is that a complete calibration curve, reaching back to 50,000 calendar years B.P., will be presented during the next International Radiocarbon Conference in Oxford, UK, in 2006.

References and Notes

1. 18th International Radiocarbon Conference, 1 to 5 September 2003, Wellington, New Zealand. A series of papers by the INTCAL Working Group led by Paula Reimer from the Lawrence Livermore National Laboratory will be published in *Radiocarbon*, providing full technical details on INTCAL04 and COMPARE04.
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NEUROSCIENCE

Calcium and CREST for Healthy Dendrites

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Neurons use their spectacular dendritic trees to receive and integrate information from thousands of input neurons. How are these elaborate branching structures built during development? Both intrinsic genetic programs and extrinsic signals are thought to shape the dendritic trees of particular classes of neurons (see the figure) (*1*). Intrinsic factors could be general or class-specific transcription factors that are switched on during neuronal development. These transcription factors may regulate additional molecules such as cell surface receptors that bind to growth and guidance cues. Extrinsic signals include these growth and guidance cues and later may take the form of neuronal activity during the formation of synapses between neurons (synaptogenesis) (*2*). In theory, extrinsic signals could act locally on cytoskeletal dynamics, directly changing the arborization pattern of dendrites. They could also act globally by regulating transcription and thereby driving the production of new proteins. Ghosh and colleagues have shown that dendritic growth of cortical neurons in culture is stimulated by Ca^{2+}-induced transcription (*3*). Now, on page 197 of this issue, they take their work a step further with their identification of CREST (Ca^{2+}-responsive transactivator) as an essential component of the activity-dependent transcriptional response that stimulates dendritic growth (*4*).

Many long-lasting effects of electrical activity on neuronal development and function depend on Ca^{2+}-regulated transcription (*5*). To identify new Ca^{2+}-responsive transcriptional activators, Aizawa *et al.* (*4*) used an interesting expression cloning strategy. Taking advantage of the fact that many transcription factors have separable DNA binding and activation domains, they fused cDNAs from a library made from rat developing brain with the DNA binding domain of the yeast Gal4

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