



In a heroic and sometimes contentious effort, researchers push to extend accurate radiocarbon dating back to 50,000 years ago

Radiocarbon Dating's Final Frontier

The 1994 discovery of France's Grotte Chauvet revolutionized ideas about symbolic expression in early modern humans. The breathtaking drawings of horses, lions, and bears that adorned the cave walls were executed with perspective and shading and rivaled the virtuosity of all other known cave art. But when were those drawings made? Early radiocarbon dates suggested 32,000 years ago, right after a major cold spell hit Europe. This implied that modern humans blossomed under frigid conditions while their Neandertal cousins were going extinct. But improved radiocarbon dating now suggests that the oldest paintings at Chauvet could be at least 36,000 years old. That's smack in the middle of a period of relative warmth and challenges speculation about modern humans' adaptability to a cold climate.

Getting the dating right is "crucial," says archaeologist Clive Gamble of the University of London's Royal Holloway campus. "It is not just a case of winning a trophy by being the oldest. The model up to now has been that mod-

ern humans could go anywhere and do anything, and ... it didn't matter what the climate was." Thanks to more accurate dating, says Gamble, "that model is now showing signs of cracking."

Indeed, as radiocarbon experts revise their estimates, all researchers working in the eventful period from about 50,000 to 25,000



Push 'em back. These fighting rhinos in France's Grotte Chauvet could be more than 4000 years older than originally thought.

years ago are facing an across-the-board realignment of dates. That's when both Neandertals and modern humans lived in Europe and when wildly fluctuating temperatures

culminated in the spread of glaciers across much of the Northern Hemisphere.

There's no question about the basic principles of the radiocarbon method: Plants and animals absorb trace amounts of radioactive carbon-14 (^{14}C) from CO_2 in the atmosphere while alive but cease to do so when they die. So the steady decay of ^{14}C in their tissues

ticks away over the years. But the amount of ^{14}C produced in the atmosphere varies with the sun's solar activity and fluctuations in Earth's magnetic field. This means that the radiocarbon clock can race ahead or seemingly stop for up to 5 centuries. As a result, raw radiocarbon dates sometimes diverge from real calendar years by hundreds or even thousands of years. Thus researchers must calibrate the clock to account for these fluctuations, and that can be a challenge. For example, the start of the Holocene, the period when the last ice age ended, is usually dated to 10,000 uncalibrated radiocarbon years ago.

But the radiocarbon clock stopped for several hundred years right at that point, so that the start of the Holocene—when agriculture began—can't be pinned down any more pre-

By land and by sea. Corals and foraminifers from the oceans, and trees from the land, are used to craft the radiocarbon calibration curve.

cisely than somewhere between 11,200 and 11,800 years ago (see graph). Because the best estimate of the calibration keeps changing, many scientists avoid reporting calendar years and simply cite “radiocarbon years” as a universal measuring stick when announcing new finds (see News of the Week story by Balter).

Yet recent progress in radiocarbon dating may finally give researchers the accuracy they seek. In 2004, after 25 years of painstaking labor, an international group of radiocarbon experts extended the calibration curve back to 26,000 years by using data from tree rings, corals, lake sediments, ice cores, and other sources to create a detailed record of ^{14}C variations over the millennia. The final frontier, which the group hopes to reach by the end of this decade, will be to push calibration to the 50,000-year mark; beyond that, there is too little residual ^{14}C to measure precisely.

Refinement of existing data, plus some promising new data sources, including ancient trees from the swamps of New Zealand, may help close the final gap. “These are very exciting times,” says nuclear physicist Johannes van der Plicht, director of the radiocarbon laboratory at the University of Groningen in the Netherlands. He adds that a final calibration curve “will answer so many questions in archaeology,” in large part because the 50,000-year limit coincides with a major migration of modern humans from Africa to Europe and Asia.

Earth scientists, many of whom use radiocarbon dating to study the movement of glaciers and ocean currents, are equally enthusiastic, in part because of the unprecedented climate variability that occurred between 30,000 and 50,000 years ago. Those who study sea-level fluctuations during and after the last ice age—data used to model patterns of global warming—rely “almost entirely” on radiocarbon dating, adds geophysicist Richard Peltier of the University of Toronto in Canada.

Yet the eagerly awaited calibration is complicated by dissent in the ranks. One U.S. scientist has bypassed the international working group and published his own calibration curve, to the annoyance of

Ribbons of time. The thickness of the curves shows that calibration of very old dates, based on deep-sea corals (*bottom graph*), is less precise than younger dates based on tree rings (*top*).

many colleagues, while a British archaeologist is using provisional calibration data—prematurely, in the view of some radiocarbon experts—as evidence that *Homo sapiens* spread across Europe more rapidly than previously thought. Both researchers argue that science can’t wait for an internationally agreed-upon calibration

curve. The question at issue, says archaeologist Sturt Manning of Cornell University, is “who actually owns time”: the experts working to calibrate radiocarbon, or the research community at large.

Science from the sewer

The radiocarbon revolution that gave such a huge boost to archaeology and other fields had somewhat inauspicious origins: the sewers of Baltimore, Maryland. In 1947, chemist Willard Libby and his colleagues demonstrated that

methane gas produced by

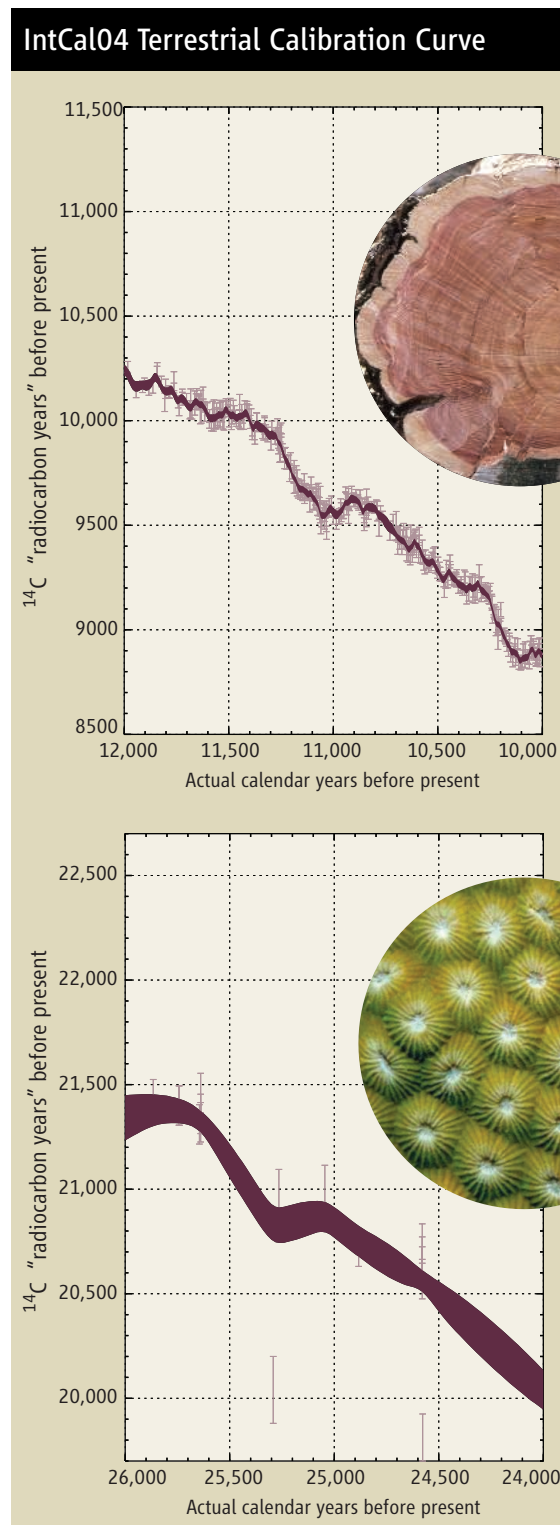
Baltimore’s Patapsco Sewage Plant contained trace amounts of radioactive ^{14}C , thus proving that living organisms harbored the isotope (*Science*, 30 May 1947, p. 576).

On the other hand, methane from much older sources, such as petroleum deposits millions of years old, did not contain ^{14}C . From that point on, as Libby put it in his 1960 Nobel Lecture, “we [were] in the radiocarbon-dating business.”

The revolution’s early days were heady times. Libby wowed archaeologists when he accurately dated a number of samples whose ages were already known, including the 2750 B.C.E. coffin of the Egyptian pharaoh Zoser (*Science*, 23 December 1949, p. 678). Most

archaeologists, who had previously relied on relative dating methods based on pottery styles, inscriptions, and guesswork, were thrilled to finally have a method for absolute dating, although a few attacked the method when it contradicted their pet theories.

Some other dating methods, including thermoluminescence and uranium-series dating, overlap with the period covered by radiocarbon. But these techniques cannot be applied to bones, seeds, and other organic materials found in abundance on most archaeological sites. Yet as early as 1960, when Libby was



awarded the Nobel Prize for his work, dating experts realized that past fluctuations in ^{14}C levels were leading to erroneous and inconsistent results. Thus, although Libby had good luck with Zoser's coffin, radiocarbon dating of some earlier Egyptian artifacts contradicted dates from reliable historical sources. As the number of such troublesome discrepancies rose, it became clear that a calibration curve to correct for ^{14}C variations, based on an independent data source, would be needed.

Fortunately, just such a source was at hand: the sequences of annual tree rings, which dendrochronologists had been accumulating for decades. Long-lived trees such as the California bristlecone pine and European oaks and pines, which are often preserved in peat bogs, provide sections of ring width patterns that dendrochronologists use as bar codes to line up sequences of increasingly greater ages. By radiocarbon dating the rings, researchers began to construct calibration curves that could convert raw radiocarbon dates into real calendar years going back thousands of years.

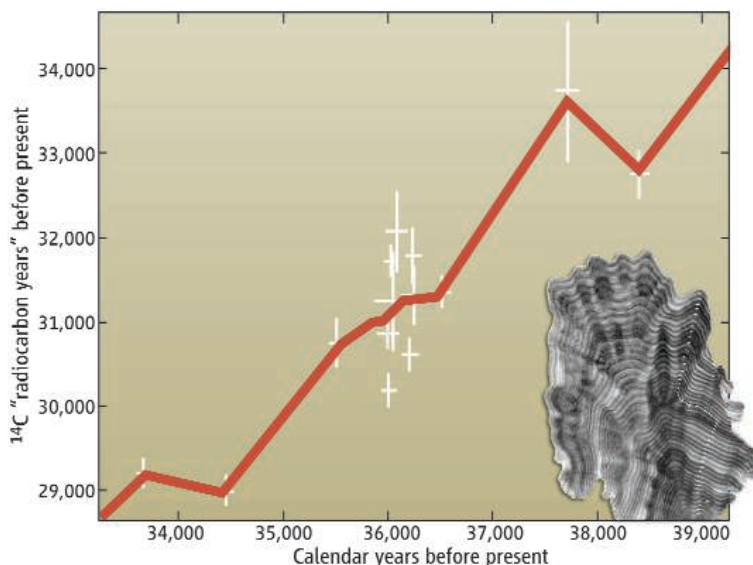
Since then, the story has been one of continuously improving accuracy, as researchers have worked to pin down the curve. Starting in the late 1970s, radiocarbon labs began using accelerator mass spectrometry to directly count ^{14}C atoms rather than estimating them indirectly; this allowed tiny samples such as small seeds and grains to be dated with much greater precision. And the early 1980s saw "a movement to have a consistent calibration," says Timothy Jull, head of the radiocarbon lab at the University of Arizona in Tucson and editor of the flagship journal *Radiocarbon*. An international group has since met regularly on the issue, and new curves have been published approximately every 6 years.

The most recent calibrations, unveiled in *Radiocarbon* in 2004, consist of three different curves: one to date marine samples and one each for terrestrial samples in the northern and southern hemispheres. The effort involved in each is tremendous. For example, IntCal04 is based in part on the overlapping alignment of many thousands of tree-ring segments from the Northern Hemisphere dating back to 12,400 years ago. "This is a phenomenal achievement," says

Richard Fairbanks, an isotope chemist at Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, and a former member of the IntCal04 group.

Beyond the limits of the dendrochronology record, however, radiocarbon experts have had to rely on other, considerably less precise sources of data. Between 12,400 and 26,000 years ago, the IntCal04 curve is based on two types of marine deposits: foraminifers (single-celled organisms that secrete calcium carbonate) from the Cariaco Basin of northern Venezuela up to 14,700 years ago (*Science*, 9 January 2004, p. 202), and several fossil coral records, including samples collected by Fairbanks and colleagues from the Atlantic and Pacific oceans, that cover this entire period.

The new curve also introduces statistical methods to reduce uncertainties. Researchers applied a complex probabilistic approach called Bayesian statistics to make educated estimates of what the calibration curve should



Going it alone. Richard Fairbanks's curve, based on corals (inset), extends the radiocarbon calibration to critical periods in human evolution.

look like. When each data point was weighted according to how certain researchers were about it, "a more robust estimate of the curve resulted," says Caitlin Buck, an archaeological statistician at the University of Sheffield in the U.K. and member of the IntCal group. Statistics can also improve the dates at specific sites, as in the case of the volcanic eruption of the Greek island of Thera, which destroyed a Minoan town and was recently dated to about 1600 B.C.E.—at least 100 years earlier than other estimates (*Science*, 28 April, p. 508).

The field's progress can be viewed graphically, points out Cornell's Manning.

The calibration curve is actually a ribbon rather than a line (see graphs, p. 1561), in which the width of the ribbon represents the remaining uncertainties in translating radiocarbon dates to calendar years. "If you plot all the calibration curves over the last 20 years, you will find that the ribbon is getting much narrower," Manning says.

All the way back?

Encouraged by their recent successes, radiocarbon researchers now have their eyes on the bigger prize of the 50,000-year limit. Indeed, when the IntCal group began work on the 2004 curve, it had high hopes of extending it back to this final barrier. Yet it was not to be. Although the marine data sets were reasonably consistent with each other up to 26,000 years ago, after that they began to scatter and diverge, in some cases by up to several millennia. Geochronologist Paula Reimer of Queen's University in Belfast, Northern Ireland, who coordinates the working group, says that the differences—among the raw data as well as among the researchers—were just too great: "We had four or five people, all of whom thought their records were right." So the group settled for publishing in *Radiocarbon* a comparison of the data sets earlier than 26,000 years, which they ironically called "NotCal"—meaning, Reimer and other members say, that it was *not* intended to be used as a calibration curve.

But archaeologist Paul Mellars of the University of Cambridge in the U.K. used the published data to essentially do just that. Mellars was eager to get the most accurate dates for possibly contemporaneous Neanderthal and modern human sites in Europe. So he used the midpoint of the differing "NotCal" curves to approximately calibrate the radiocarbon ages of 19 hominid sites ranging from Israel in the East to Spain in the West. Using this best-guess method, Mellars found that modern humans had not only spread across Europe faster than previously thought, but that they had overlapped with Neanderthals during a shorter interval: only about 6000 years rather than 10,000 years in Europe as a whole, and as little as 1000 years in some parts of the continent. Mellars concluded in the 23 February 2006 issue of *Nature* that Neanderthals must

have “succumbed much more rapidly to competition” from modern humans than many had assumed.

But Reimer and others say Mellars should not have used the NotCal data as he did. “It is dangerous to draw too fine conclusions using these data sets,” says Reimer, because they have not been finalized and the divergences between them have yet to be reconciled. Other researchers have started asking van der Plicht whether they can use the “Mellars curve” for calibration. “This is a bad thing,” says van der Plicht.

Mellars insists that archaeologists can’t wait for a final calibration curve. “Are we all really expected to keep studies of modern human origins on hold for the next 5 years, until they decide they’ve finally got the calibration act together?” he asks. The working group, he argues, “has hijacked the term ‘calibration’ to mean an absolutely agreed, rubber stamped, legalistic, signed, sealed, and delivered curve.” And even when the experts agree on a curve, Mellars says, it will not be “final and absolute” but “simply the best estimate from the data at the time.”

Fairbanks is equally impatient. Last year, he and his co-workers decided to strike out on their own rather than wait for the consensus curve. In the September 2005 issue of *Quaternary Science Reviews (QSR)*, the team published its own version of a calibration curve spanning the entire period from 50,000 years ago to today, based on its dating of fossil corals from the Atlantic and Pacific oceans. The team dated the corals using both radiocarbon and uranium-thorium dating. And the authors made it clear that they intended their curve to be used as a “stand-alone” radiocarbon calibration, arguing that their screening criteria for coral data were more rigorous than those of other coral data sets as well as the Cariaco Basin foraminifers.

The more than 20 members of the IntCal04 working group, however, did not take this affront lying down. In the April 2006 issue of *QSR*, they contended in a letter that the Fairbanks paper was “extremely misleading” about the efforts of other groups and argued that stand-alone curves would lead to “confusion” among archaeologists and other researchers who had to use them. “The question is whether we maintain a common calibration curve or have



Tall order. Researchers hope ancient kauri trees buried in New Zealand swamps may extend tree-ring records back to at least 50,000 years ago.

different calibrations, as we did in the past,” says Jull. And Reimer maintains that the Fairbanks curve does not sufficiently take into account uncertainties from using a marine data set to estimate a terrestrial curve, because the oceans contain less ^{14}C than the atmosphere and researchers must try to correct for the difference.

Fairbanks, however, defends his decision to go it alone. “There is a critical need to have at least the skeleton of a precise and accurate radiocarbon calibration curve spanning the useful limits of radiocarbon dating now,” he says. “No international commission will stop scientific progress under the guise of consensus science.” Fairbanks adds that the IntCal04 group relied heavily on his team’s coral data to extend its curve to 26,000 years. And he notes that he apparently has a growing number of customers. When his calibration Web site* debuted in August 2005, it received 900 visitors per month; by July 2006, it was getting about 1900. “Rick’s curve is simply the most objective, because it involves the fewest assumptions,” says

* www.radiocarbon.LDEO.columbia.edu

Christopher Charles of the Scripps Institution of Oceanography in San Diego, California, who used Fairbanks’s curve to date deep-sea sediments and counts himself among the satisfied customers. Archaeologist John Hoffecker of the University of Colorado, Boulder, whose team recently used the Fairbanks curve to calibrate dates earlier than 40,000 years ago at the site of Kostenki in Russia, says that despite the controversy he was “reassured by Fairbanks’s reputation.”

Despite this acrimonious debate, however, there are signs that the community—and at least some of the data—might now be pulling together. At last April’s 19th International ^{14}C Conference in Oxford, U.K., earth scientist Konrad Hughen of Woods Hole Oceanographic Institution in Massachusetts, leader of the Cariaco Basin team, presented revised data that seemed to close much of the gap with Fairbanks’s coral dates. “They are now getting very close,” says Manning, although Fairbanks points out that “Hughen’s Cariaco Basin data set shifted closer to our coral data ... and not the other way around.”

And whereas the European tree-ring record goes back only 12,400 years, a paper presented at Oxford by Chris Turney of the University of Wollongong in Australia suggests that such records may be pushed back even to the 50,000-year limit. Turney and colleagues have been radiocarbon-dating fossil kauri trees—which can live up to 1000 years—from swamps in New Zealand. The dates stretch back 55,000 years and hold out the promise of a new terrestrial calibration source that could help reconcile some of the uncertainties in the marine records. “This would resolve a lot of issues,” Reimer says, “although it will take a lot of work.” Nevertheless, radiocarbon experts are optimistic that the 50,000-year barrier will soon be reached. “I foresee that in 10 years it will all be solved,” says van der Plicht.

If so, the revolutionary promise that Libby and his colleagues first glimpsed in the sewers of Baltimore may soon become reality. And we may end up with a much better idea of when and why the creators of the Grotte Chauvet’s glorious artworks came to France—and what the weather was really like when they ventured outside.

—MICHAEL BALTER