Richards & Beck chose to illustrate this using the two Neanderthal samples from Vindija Cave, Croatia measured at Oxford. The resulting age ranges are in the order of 4000 years. Taking errors into account the resulting uncalibrated age ranges at 2σ are over 1500 years — enough to preclude any sophisticated use of the results. That the Vindija Neanderthals were *some* of the latest the earth ever saw remains true: I would push the data no further. This having been said, it is important to stress that it is not ^{14}C pre-treatment and measurement that is at fault: a "date" is data and can be "corrected" in the future. For this reason I would stress to museum curators that the dating of precious samples from this period is still valid; no one will benefit from abandoning sampling.

'We can only hope that as these crucial datasets increase we gain some probabilistic means of ascertaining the most likely portions of calibrated age ranges for samples. I suspect that this might eventually be employed for the Vi-207 result (OxA-8296) given that it straddles two peaks of the curve. We must also hope that developments in luminescence, U-Series and ESR will improve precision down to the levels enjoyed (if that is the right word) by ^{14}C. Until then we should heed the warning and cease to make scientifically unsupported statements about archaeological "contemporaneity". We are too used to thinking of revolutions as a good thing: they can be drastically unsettling too.'

Dramatic shifts in atmospheric radiocarbon during the last glacial period

DAVID A. RICHARDS & J. WARREN BECK*

Introduction

Radiocarbon measurements obtained from a stalagmite from a submerged cave of the Bahamas (Beck *et al.* 2001) demonstrate that atmospheric ^{14}C concentrations during the last glacial and deglacial periods were much greater and more variable than previously believed. At times, atmospheric concentrations reached levels higher than the 'bomb-pulse' spike that resulted from nuclear weapons testing during the 1950s and 1960s. Abrupt shifts in ^{14}C levels are also evident in this record, which have major implications for those requiring accurate chronological control for their studies. Interpretation of these results also presents a significant challenge to those investigating fundamental aspects of the Earth's dynamical system during the past 50,000 years. This record seemingly requires large shifts in atmospheric ^{14}C production rate (a function of variability in the Earth's geomagnetic field strength, solar activity, or galactic cosmic ray flux), as well as significant redistribution of ^{14}C between reservoirs of the carbon cycle.

Meticulous effort by numerous researchers has previously revealed secular variation of $\Delta^{14}C$ (effectively, the ratio of ^{14}C to stable ^{12}C relative to pre-industrial wood) by comparing radiocarbon ages with calendar ages of overlapping tree-ring sequences. For the period covered by tree-ring calibration (11,858 cal BP to present), there was a ~15% reduction of atmospheric ^{14}C concentration, principally attributed to a concomitant increase in the Earth's magnetic field strength. Periodic short-term changes of up to 5% are superimposed upon this general decline, which give rise to the 'wiggles' and 'plateaux' identified in calibration curves. The speleothem record, however, indicates that $\Delta^{14}C$ during the last glacial period was at times greater than twice pre-industrial levels and subject to abrupt shifts of at least 70%. Clearly, major efforts are now required to confirm the structure of $\Delta^{14}C$ variation observed therein, and identify causal mechanisms.

Initial radiocarbon calibration curves relied exclusively on tree-ring records (Stuiver *et al.* 1986; 1993), but more recently extension has been enabled by coupled thermal-ionisation mass-spectrometric (TIMS) ^{230}Th and AMS ^{14}C ages of fossil corals and AMS ^{14}C ages of annually varved ocean sediments. INTCAL98 is a compilation of such data and is recognized as the international standard calibration curve (Stuiver *et al.* 1998). It extends to 15585 cal BP in detail, but beyond this it has the form of a linear extrapolation based on a very limited number of coral results. Over the past 5 years there have been a number of attempts to improve upon this situation using alternative archives such as lacustrine carbonates, speleothems (e.g. stalactites, stalagmites), terrestrial macrofossils in varved lake sediments and deep-ocean foram

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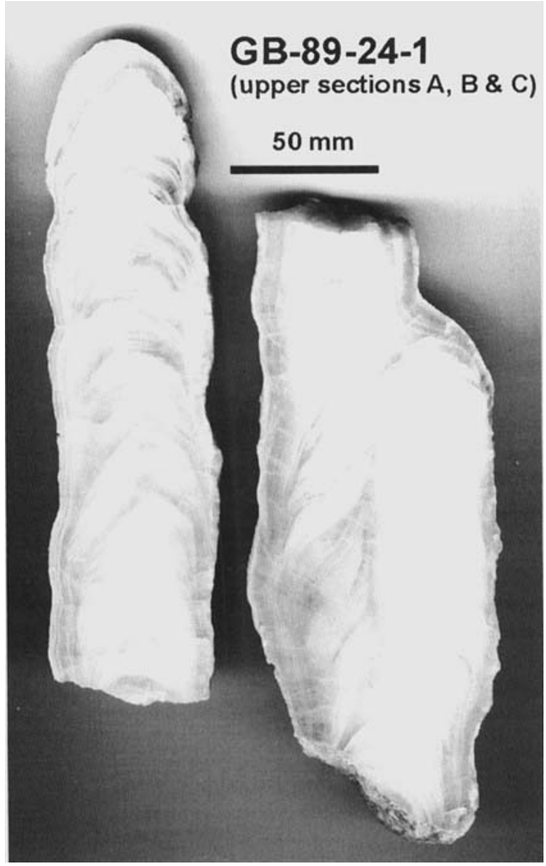
Cave diver in Blue Hole of the Bahamas. Note excellent preservation of submerged speleothems. GB-89-24-1 was found broken on the floor of the cave shown here and removed with the utmost care to preserve the unique underwater environment. (Photo courtesy Sarah Cunliffe.)



A stalagmite composed of dense, clear calcite that grew from 45,000 to 11,000 years ago. Continuous growth exhibited in this section, except for hiatus between 28,000 and 26,000 years when drip location moved. Total axial length of GB-89-24-1 is 620 mm (lower section not shown).

records correlated with ice-core records (see 'The 2000 Radiocarbon Varve/Comparison Issue' of *Radiocarbon* 43(1)). These new data confirm the fact that radiocarbon ages are consistently younger than the calendar age estimates but there remains a significant amount of scatter in the data.

Radiocarbon and uranium-series measurements in speleothems

Speleothems, especially stalagmites, have an advantage over most archives because they often grow more or less continuously, and can generally be accurately and precisely dated using TIMS ^{230}Th ages. Beck *et al.* (2001) obtained 278 AMS ^{14}C measurements from the axis of growth of a stalagmite that had been extensively dated from 45,000 to 11,000 years ago using independent TIMS ^{230}Th-^{234}U-^{238}U and ^{231}Pa-^{235}U methodology to establish a calendar age chronology (Edwards *et al.* 1986; 1997). Conventional ^{14}C data were corrected for a 'dead carbon fraction (DCF)', which is a secondary component of carbon from the overlying limestone and contains negligible ^{14}C . This is analogous to the marine reservoir correction that must be applied to ^{14}C ages of corals and foraminifera. DCF was shown to be essentially constant (~1450 years) for the period of overlap with the INTCAL98 record, in spite of being a period of dramatic climate change. This value for DCF was assumed to have this same value for the entire period of growth, but we nevertheless, include a conservative estimate of its uncertainty (±470 years, 2σ) to accommodate any minor changes in climate, recharge and drip-water routing that might affect the contribution of dead carbon.

A 'comparison' curve

Based on these results, we have produced a weighted smoothing spline with confidence

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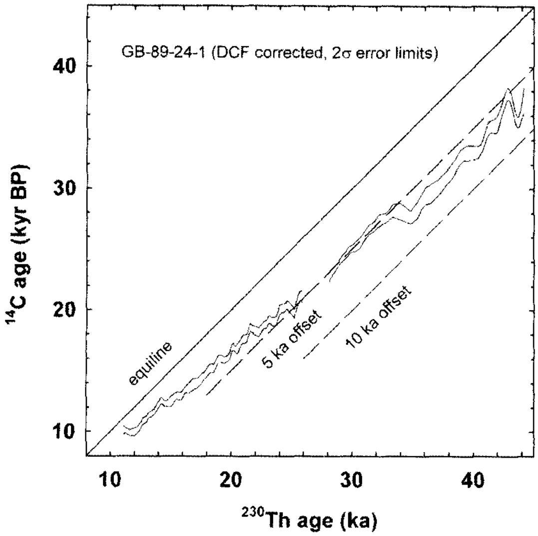

FIGURE 1. *Radiocarbon 'comparison' curve. Confidence bands (2σ) of a weighted smoothing spline fitted to ^{230}Th-derived calendar ages and ^{14}C ages (corrected for dead carbon fraction) of a speleothem from the Bahamas.*

bands fitted to the DCF-corrected ^{14}C ages and ^{230}Th-derived calendar ages (FIGURE 1). It is clear that radiocarbon ages were at all times younger than calendar ages during the period 45,000 to 11,000 years ago (we refrain from using cal BP for the timescale, which is based on ^{230}Th ages and not absolute). The largest difference is at radiocarbon ages of ~36,000 BP when there is an offset from ^{230}Th-derived calendar age by possibly 8000 years. More importantly, however, there is significant structure to the data, suggesting that there were sudden increases and decreases in ^{14}C . This has the effect of creating major plateaux and reversals, which will cause clusters of indistinguishable radiocarbon ages for material that was formed at different times over extended periods of up to 3000 years. The potential implications for the radiocarbon calibration are well illustrated by an 'unofficial' calibration of recent ^{14}C ages of hominid specimens from Vindija, a cave in Hrvatsko Zagorje, Croatia (Smith *et al.* 1999). Uncalibrated ^{14}C ages of the two most recent dated Neanderthals from the Eurasian region are significantly younger than their ^{230}Th-derived calendar age and, importantly, we find a large expansion in age uncertainty by at least an order of magnitude (TABLE 1).

Why are pre-Holocene atmospheric ^{14}C variations so large?

Beck *et al.* (2001) investigated possible causal mechanisms for the dramatic changes in ^{14}C content in the atmosphere evident in the speleothem record. It would appear on the basis of modelled cosmogenic nuclide production rates and a simple-box model of the carbon cycle that the record cannot be totally explained by changes in the Earth's magnetic field intensity or the solar electromagnetic field. Changes in the ocean, the Earth's largest reservoir of carbon, must also be invoked. Switches in the mode of ocean circulation and, hence, distribution of ^{14}C in the carbon cycle are required to enable such abrupt and high magnitude shifts. It is clear that the glacial ocean must have behaved in a different manner to that observed today.

Conclusions

Regardless of the causes of these fluctuations, the implications for calibration of the radiocarbon timescale are large, especially for the period prior to *c.* 30,000 cal BP. If the speleothem record presented here can be corroborated with other records, it implies that the older part of the radiocarbon timescale is populated by a number of plateaux and even age reversals. This will make utilization of the radiocarbon for dating purposes more challenging, but it may explain some instances of previously observed

sample	sample no.	conventional ^{14}C age (yr BP)*	^{230}Th-derived calendar age (yr BP)†
Vindija G1 (Vi-207)	OxA-8296	29,080±400	37,550–34,850; 34650–33,050
Vindija G1 (Vi-208)	OxA-8295	28,020±360	36,150–31,850

* From Smith *et al.* (1999)

† Based on results using OxCal 3.5 (Bronk Ramsey 1995) and the spline fit illustrated in FIGURE 1.

TABLE 1. *Radiocarbon dates and preliminary calendar ages of Vindija G_1 (Vi) human remains.*

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age reversals and compressed time periods in the archaeological and geological record. Until such time as corroborative records become available, we consider our spline to be a 'comparison' curve in line with recommendations by van der Plicht (2001), and do not recommend use of our data for calibration purposes until confirmation of the timing and magnitude of variation is confirmed by independent data. Our record does, nevertheless, suggest that there are many more surprises in store for us in this rapidly developing field.

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PAUL PETTITT kindly introduces the significance of a second note on recent developments in ^{14}C dating:

'One of the major limitations of ^{14}C dating is the unreliability of measurements on the bones in which collagen preservation is low, either through diagenesis or combustion. Certainly, as Aertz *et al.* suggest with their dating of "burnt collagen" from burials at Sanaigmhor Warren, Islay, measurements on this organic fraction are usually underestimates. Assuming that the team have undertaken a good number of measurements on samples that they can cross-check with independent means of ascertaining the age of the samples, whether by dating of associated charcoal or through *ceramic* style, this new development, facilitating the measurement of carbon in structural carbonate at the Groningen Centre for Isotope Research, is a major breakthrough in measurement methods.

'Because carbonate preservation in these samples is low, i.e. around 10%, the sample size required for this technique, ~1·5 g, is large by AMS standards. Presumably though, this will present no problems with samples of cremated bone which are of limited anatomical and palaeopathological value, and as the authors suggest even particulate bone can be used, thus allowing the preservation of more intact bones from cremation deposits. In any case, sample size is certainly outweighed by the advantages of being able to date a large sample set previously unavailable for dating with any degree of confidence. This is very good news — for later prehistorians in particular, and a welcome example of how ^{14}C dating continues to be developed in internationally respected laboratories.'

Radiocarbon dates on cremated bone from Sanaigmhor Warren, Islay

A.T. AERTS, A.L. BRINDLEY, J.N. LANTING & J. VAN DER PLICHT*

One of the most interesting and immediately useful developments in radiocarbon dating for archaeologists in recent years has been the discovery that cremated bone can be easily and very successfully dated. That it might be possible was recognized in late 1998 and tested extensively in the following 12 months. It is now abundantly clear that cremated bone provides a highly reliable material for radiocarbon dating (Lanting *et al.* in press)

Bone consists of long chains of proteins (collagen) in which particles of poorly crystallized inorganic material are embedded. The inorganic material is primarily a calcium phosphate with an apatite-like structure ('bio-apatite'). A unique feature of this bio-apatite is that it includes some carbonate ions by substituting phosphate ions

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