

CALIBRATION INTRODUCTION

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There are 2 fundamental assumptions in radiocarbon dating, which were known early in the method development to be approximations, and which lead directly to the need to calibrate ^{14}C dates:

1. The rate of formation of ^{14}C in the upper atmosphere has been constant over the entire applied ^{14}C dating timescale (approximately the last 65,000 yr).
2. The ^{14}C activity of the atmosphere has been in equilibrium with the biosphere and ocean over the applied timescale.

Perhaps the most fundamental assumption is that the relative isotopic abundance of carbon atoms in a particular reservoir (e.g. the atmosphere) has remained constant. Even in the early days, this assumption was challenged by discrepancies reported between the measured ^{14}C ages and the known calendar dates (dendro-dates) of relatively modern wood samples (de Vries 1959) and further evidence continued to accumulate. The most comprehensive evidence of these variations was due to the considerable effort of some of the giants of ^{14}C dating, who made direct measurements of ^{14}C concentrations in tree rings (Suess 1965; Stuiver and Suess 1966; Damon 1982; Pearson and Baillie 1983). The explanations for the observed variations were both short- and long-term variations in the ^{14}C production rate due to solar sunspot activity and geomagnetic modulation. It then followed naturally that variations in production rate will influence the ^{14}C activity of the atmosphere and hence the biosphere and ocean. Changes in ocean circulation and carbon storage were also implicated in altering the ^{14}C activity of the atmosphere (Stuiver et al. 1991; Denton and Hendy 1994; Broecker 1997). For example, the rate of formation of deep water in the North Atlantic has been postulated to have significantly decreased during the Younger Dryas, resulting in a buildup of ^{14}C in the atmosphere (Fairbanks 1989; Bard et al. 1990; Edwards et al. 1993).

In addition to these entirely natural variations, since the late 19th century there have been 2 known anthropogenic effects resulting in variations in the atmosphere. The first is due to the combustion of fossil fuels (the *Industrial* or *Suess effect*; diluting the ^{14}C activity) and the second, nuclear weapons testing (the *Bomb* or *Nuclear effect*; enhancing the ^{14}C activity).

All might then seem lost in this variation, yet ^{14}C dating as an applied technique has flourished through the development of calibration tools and through detailed study of the fluctuations of ^{14}C . Indeed, the fluctuations themselves are of considerable interest to geophysicists and climate scientists.

Calibration of ^{14}C measurements requires knowledge of the levels of atmospheric ^{14}C in the past. This has come from ^{14}C measurements made on long series of known-age material, including tree rings, corals, and varved sediments of marine origin, etc., and the evidence continues to expand. The bulk of the evidence, from the archive with the longest history of study, has been from dendrochronologically dated trees. For many years, this archive was the only basis of the calibration tables and

curves where the ^{14}C age of the tree rings was listed or plotted against the absolute age (normally in decadal or bidecadal spans). Progressively since the 1980s, results have been added to the dendro-based calibration curve, extending the timescale and improving the precision (including single-ring results). But, as the availability of dendro-dated tree rings has become more and more limited in the timescales of interest, researchers have moved to other archives, including corals and varved marine sediments, extending the timescale back further (Stuiver et al. 1998). A number of special issues of the journal *Radiocarbon* (Volumes 28, 35, 40, and 46) have provided a compendium (and best knowledge at the time) of the calibration data. The most recent of these included the IntCal04 and Marine04 curves (Hughen et al. 2004; Reimer et al. 2004), which extended to 26 kyr BP using a new approach to calibration curve construction that accounted for the uncertainty in both the ^{14}C and calendar ages (Buck and Blackwell 2004). Since that time, a number of data sets have been used to provide calendar age estimates beyond 26 kyr BP, but there is not yet a ratified calibration curve available (Fairbanks et al. 2005; Hughen et al. 2006). The IntCal Working Group continues to work on the development of a ratified update, although there remain some issues concerning the applicability of many of the available archives for providing calibration data relevant for marine and terrestrial calibration (van der Plicht et al. 2004).

As the available data for calibration increased in volume and improved in quality, there have been significant changes to the actual calibration method being used, moving from the very simple curve intersection approach to the much more complex probabilistic approach (often Bayesian). At the same time, there have been major developments in the calibration software. Nowadays, there are a number of calibration programs available for terrestrial samples; the most widely used being CALIB, BCal, and OxCal, which are easily downloadable from the web or run on-line, as well as a number of special purpose programs such as BPeat, BChron, and CaliBomb.

Calibration remains an important practical and scientific issue, even though from those early days, the failure of the key assumptions might have seemed likely to doom the dating method to oblivion. Major challenges remain in pushing back the time limits over which we are able to calibrate and in applying the results to marine samples. Our need to calibrate our ^{14}C dates comes from the fluctuations in the ^{14}C levels in the atmosphere, but that too now is seen as a feature of scientific relevance and importance in its own right. We learn about our Sun and geomagnetic field modulation; we have the opportunity to study the interactions between the main carbon reservoirs (using ^{14}C as a natural tracer) have a chronometer used in many areas of science.

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