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T.P. Guilderson, P.J. Reimer, and T.A. Brown

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Timing is Everything: The Boon and Bane of 14C Geochronology

T.P. Guilderson [1,2]
P.J. Reimer [1]
T.A. Brown[1]

[1]The University of California's LLNL Center for Accelerator Mass Spectrometry.
[2]Institute of Marine Science and Department of Ocean Sciences, University of CA – Santa Cruz.

There are underappreciated limitations of the conversion of ^{14}C-ages to the fixed, calendrical time-scale that bear directly upon our understanding of the dynamic climate system, or the relationship between the collapse of one civilization and it's neighbor's. In this paper we present a quantitative assessment of the limits of ^{14}C-geochronology and calibration onto the absolute calendrical time-scale over the Holocene. We take into account not only the inherent limitations of the ^{14}C-calendar calibration curve, but also analytical uncertainties.

The ages derived from the radiocarbon (^{14}C) method (1,2) are the basis for chronological control over the last ~50ka in many paleoclimatological, geophysical, and archaeological studies. Natural radiocarbon is formed predominantly in the stratosphere by the interaction of cosmic ray produced (secondary) neutrons with 14-nitrogen. The newly formed ^{14}C is oxidized and mixed into the troposphere. The ^{14}C production rate is governed by geomagnetic shielding, background galactic ray flux, and the solar wind (3). Variable ^{14}C production and partitioning of ^{14}C between the atmosphere, terrestrial biosphere, and oceanic carbon reservoirs invalidates a fundamental tenet of decay-based isotope geochronology: the initial $^{14}C/^{12}C$ ratio is not constant with time nor throughout the Earth's reservoirs. Depending on the depositional environment and material being analyzed additional corrections may be required: e.g., oceanic reservoir (4), lacustrine hard (5) and soft (6) – water effects. Non-constant atmospheric $^{14}C/^{12}C$ through time requires that ^{14}C ages be "calibrated" to obtain ages on an absolute time-scale (7). For decades the radiocarbon community has recognized this need and has adopted an international standard for calibration, most recently IntCal98 (8). The backbone of IntCal98 is made-up of several millennia-long tree-ring chronologies providing an annual, nearly absolute time frame, which has been rigorously tested by internal and external replication of overlapping sections. Independent measurements in recent years have yielded largely compatible results. The older section of the IntCal98 curve is based upon marine data and contains additional assumptions (e.g., assumed constant reservoir age offset) and uncertainty required to predict atmospheric ^{14}C concentration. The tree-ring section of the calibration curve is immune to the vagaries of variable reservoir age and hard/soft water effects that can impact data-sets derived from other materials. The tree-ring data are the standard by which other calibration type data-sets are judged.

To illustrate the strengths and weaknesses of ^{14}C geochronology in attempting to determine precise calendar year ages from individual ^{14}C dates, we use the IntCal98 ^{14}C-calendar calibration data-set (8) and focus on the tree-ring section of the calibration curve

which extends from modern times to ~11,800 years calendar BP. The ^{14}C-errors of the respective tree-ring sections are superior to routine dating due to higher precision and multiple measurements. Between 0-8,000 yrs BP the error is often better than ±20 years, and except for a few brief intervals it is ≤ 30yrs over the 11,800 years. We have linearly interpolated IntCal98 at 20 (calendar) year intervals and determined ^{14}C dates corresponding to the calendar ages. The resampled ^{14}C ages were then calibrated using Calib v4.4 (4) using a nominal ±40 year ^{14}C uncertainty. A second calibration was performed using a constant ±15 year uncertainty.

The resulting calibrated data are plotted [Figure 1a] to show their respective calibrated age range uncertainties as a function of calendar age. This plot is similar to the "time-warp" plots of Stuiver and Reimer (4), with the difference being that the time-warp plots were used to elucidate the fundamental limitations of the calibration curve, and did not incorporate the effects of real-world/routine ^{14}C-age measurement error for a given calendar age. This synthetic application is equivalent to ^{14}C dating of terrestrial macrofossils that exclusively derive their carbon from the atmosphere.

The calibrated age range waxes and wanes as a consequence of variations in the atmospheric $^{14}C/^{12}C$ ratio. The average 1σ calibrated age range for the calibration quality (±15 year) data post 11,800 cal BP is 140 years (min. 4yrs, max. 511yrs) and is 180 years (min. 30yrs, max. 529yrs) for the nominal ±40 year data. The low minimum calibrated age ranges for the calibration quality data are due to single year calibration data from 0BP to 500BP. Recurrent features in the calibration curve are periods when the atmospheric $^{14}C/^{12}C$ ratio falls at a rate equal to that of ^{14}C decay, resulting in "age-plateaux". A recent example is the "Golden Age of Greece" 546BC-404BC which occurs at a radiocarbon plateau (~2,450 ^{14}C yr BP) that extends for nearly 350 years [Figure 1b]. An older example would be the two ^{14}C plateaux associated with the Younger Dryas chronozone which have made it extremely difficult to determine absolute synchroneity of climate change during this time period. Moreover, and regardless of the rate of change of atmospheric $^{14}C/^{12}C$, the calibrated age may not be unique (7). In very few instances (<2%) the calibrated age range equates to the ^{14}C analytical error. This effectively translates to an often under appreciated shortcoming of many paleoclimate time-series: it is very difficult to independently determine absolute phasing at the centennial level. Indeed, far too frequently the interpretations of leads, lags, or absolute synchronicity of paleoclimate records are not supported by the ^{14}C chronology.

Through much of the Holocene increased precision will buy a 20-50% reduction in the 1σ calibrated age range, at least on high quality terrestrial samples. For example, if we explicitly accept the GISP-2 ice-core chronology of the "8200 year event" (9) we can determine this to be 7,410 ^{14}C years BP. Calibration of a "date" of 7,410±40 results in a one-sigma probability distribution of 8,173-8,325 cal BP whereas the same date calibrated with ±15 year uncertainties results in a calibrated age of 8,167-8,284 cal BP. The calibrated age ranges are a result of the near 1:1 relation between ^{14}C years and calendar years between 7,800-8,800 cal BP with a small ~100 year plateau between 8,300 and 8,200 cal BP.

More precise ^{14}C-based chronologies could help discern the temporal relationship between abrupt climate change and societal response. With higher precision, samples from the collapse of the Akkadian Empire at ~3800 ^{14}C yrs BP (10) could be calibrated to 4,149-4,231 cal BP versus 4,093-4,241 cal BP from normal precision dates. Such increased precision could be used to elucidate the phasing of the abandonment of city-states in northern versus southern Mesopotamia and perhaps distinguish between direct climatic versus societal effects. In contrast, additional precision would not necessarily assist in determining the climate and societal relationship during the Terminal Classic Collapse of the Mayan civilization (11). While the end of the Terminal Classic Collapse at ~1000 ^{14}C yrs BP (1000AD, 12) can be calibrated to 1003-1027AD, if we define the collapse as initiating at 800AD (~1190 ^{14}C years BP) then approximately the same calibrated age range, 780-890AD, is derived from ±40 year or ±15 year dates.

To the consternation of many, problems and difficulties still exist in deriving an accurate ^{14}C-calendar calibration curve prior to the last deglaciation. Extant data sets of varying pedigrees that span marine isotope stage 2 and 3 exist, with no two data sets establishing a firm consensus (13). At most, only one of the "comparison" data-sets might be correct. Any individual calibration-type data set in this interval will require validation and confirmation, ostensibly from a direct record of atmospheric $^{14}C/^{12}C$. Buried trees from alluvial and lacustrine deposits in sufficient quantity to cross-date hold our best hope to provide a detailed and precise calibration curve. Substantial improvement in the pre-last glacial maximum calendar calibration using sub-fossil trees are likely to take advantage of long-lived Huon Pine (*Lagarostrobos franklinii*) and New Zealand Kauri *(Agathis australis)*.

In general, a productive chronological approach is to derive a first pass, gross-^{14}C stratigraphy and then, where possible, to refine the chronology with a higher density of dates and replication taking advantage of intervals where extra analytical precision will be the most helpful. To this end, the paleo and archeological communities need to become more familiar with the calibration curve and its inherent limits by simulating ^{14}C ages and calibrations. Improved calibration precision can also be gained in situations where "wiggle-matching" a sequence of dates is possible, such as tree-rings, or where stratigraphic information can be included in a Bayesian analysis. However, in most instances it is not possible to "wiggle match" ^{14}C-ages to the calibration curve. Notwithstanding these considerations, we need to remind ourselves of the depositional history and context of the samples that we are using, and their impact on our ability to answer the questions that we are asking.

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12. This simple exercise utilizes the dendro-portion of the IntCal98 calibration curve which is constructed entirely of northern hemisphere trees. It should be noted that the seasonal migration of the inter-tropical convergence zone will yield a mixture of northern hemisphere and southern hemisphere air in the tropics including portions of Latin America (14). The northern-southern hemisphere difference averages 41±14 years between 1850-950AD but varies from ~8 to ~80 years for any given decade (15).

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Figure 1a. Calibrated age range as a function of calendar age and ^{14}C one-sigma error. The blue "snakes" are calculated using the higher-precision errors whereas the yellow "snakes" are calculated using a canonical ±40 year 1-sigma error for each ^{14}C age. The age ranges are plotted against true calendar (dendro) age and are calculated by subtracting the youngest acceptable (one-sigma) age from the distribution of possible calendar age ranges.

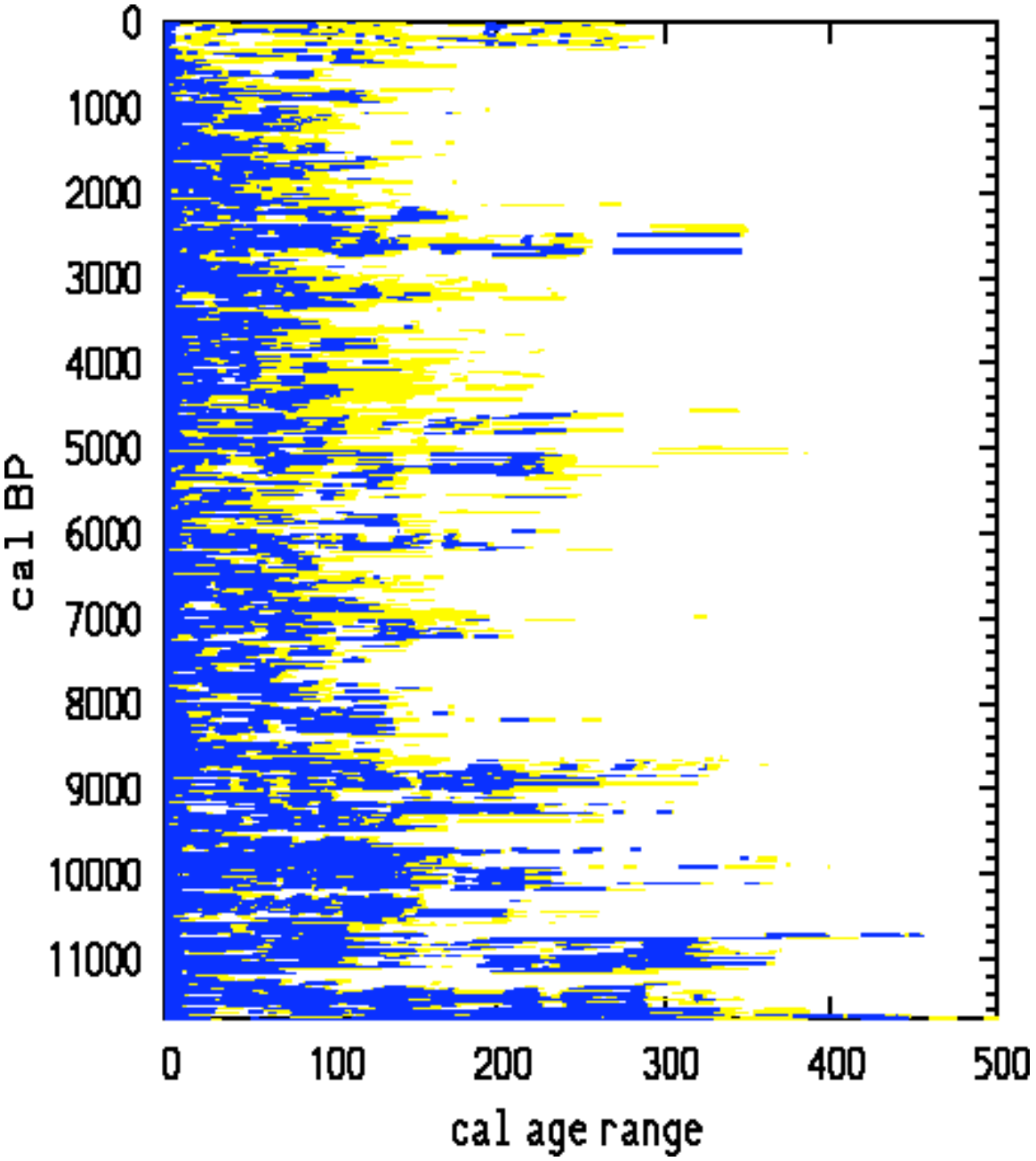
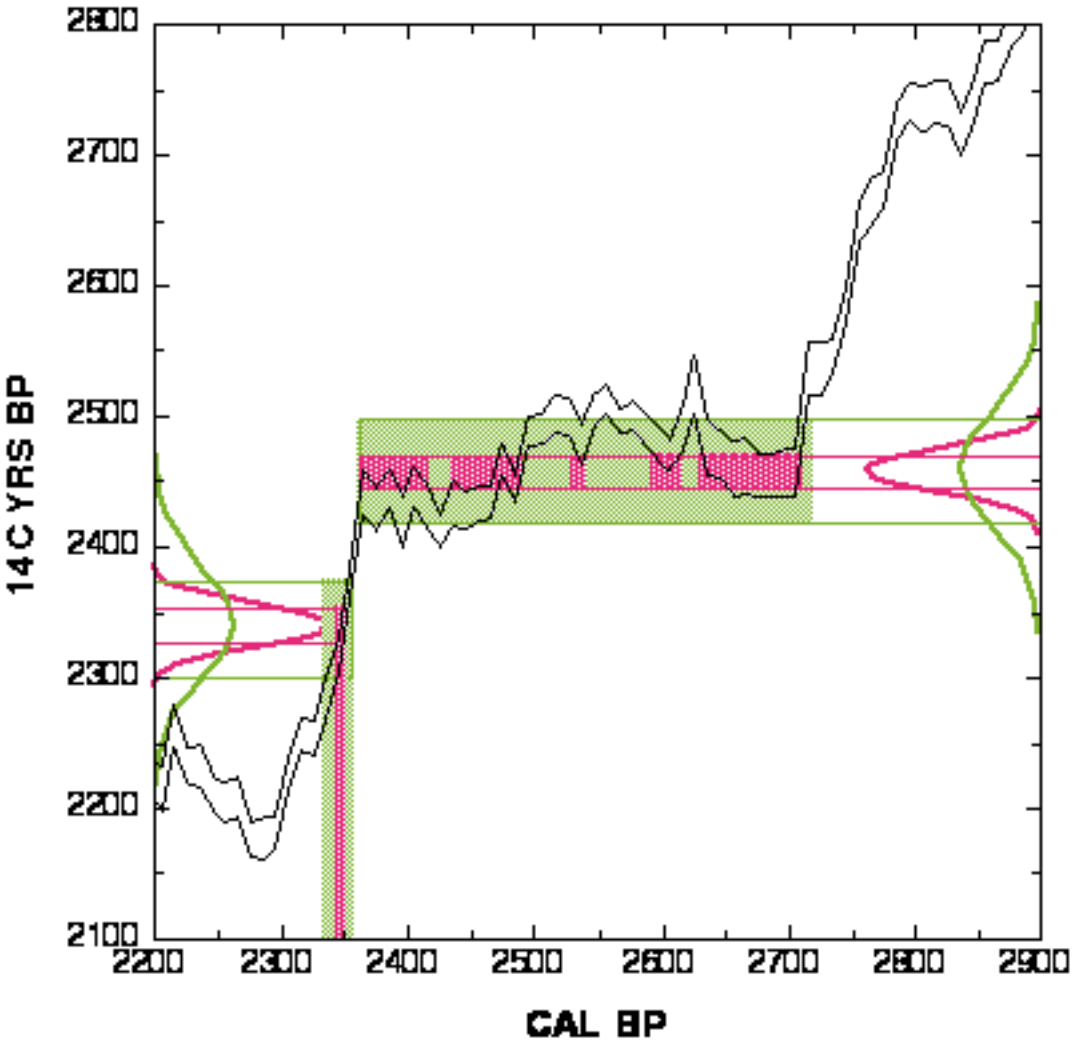
Figure 1b. Comparison of hypothetical normal and higher precision ^{14}C-dates in relation to the ^{14}C-calendar calibration curve 2200-2900 cal BP. The gaussian curves are the respective ^{14}C-age distributions for two dates of 2340 and 2460 ^{14}C years BP at normal (±40 year; green) and better (±15 year; magenta) precision. For visual clarity and illustrative purposes the pattern fills are the respective one-sigma intercept regions. It would be more correct to use the probability distribution function results, which for example would yield four age ranges for the 2460±40 year result, not the visually simplified one age range. The calibrated intercepts are translated to the calendar year axis for the 2340 ^{14}C year BP date.