6

AN INTRODUCTION TO WIGGLE-MATCH DATING AND AN EXAMINATION OF ITS POTENTIAL IMPACT ON CHRONOLOGICAL STUDIES IN THE SOUTHWEST

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It is accepted wisdom that short-lived organic remains such as seeds, pits, and grains from food-crops are the preferred materials for radiocarbon dating past human activities. They are the products of cultivation; they archive ^{14}C-levels from a single year (or more accurately a single growing season), so uncertainties stemming from organism lifespan are negligible. They are unlikely to be stored for more than a few years' time, minimizing the uncertainties associated with stockpiling, long-term storage, reuse, or inheritance. Food grains and seeds often provide the tightest link between sample radiocarbon content and the timing of events with which they appear to be associated. Moving down this hierarchy of preference is an expanding list of more complex samples: small-diameter twigs or roots, charcoal from twigs or roots, bones from domesticated herbivores, charcoal from hearth contexts, pottery residues, and so on. With each of these items, there is an increased chance of temporal disconnection between the life of the sample and the archaeological human activity under study.

Yet there are circumstances in which short-lived samples do not provide the best chance of obtaining a precise calendar date. If the event under consideration took place during a "plateau" or "wiggle" in the radiocarbon calibration curve, then the short life of the dated organism is less relevant. The characteristic shape of the calibration curve itself becomes dominant and determines, using the terminology of R. E. Taylor and O. Bar-Yosef (2014), the *effective precision* of the date. This precision can be disappointingly low if the duration of

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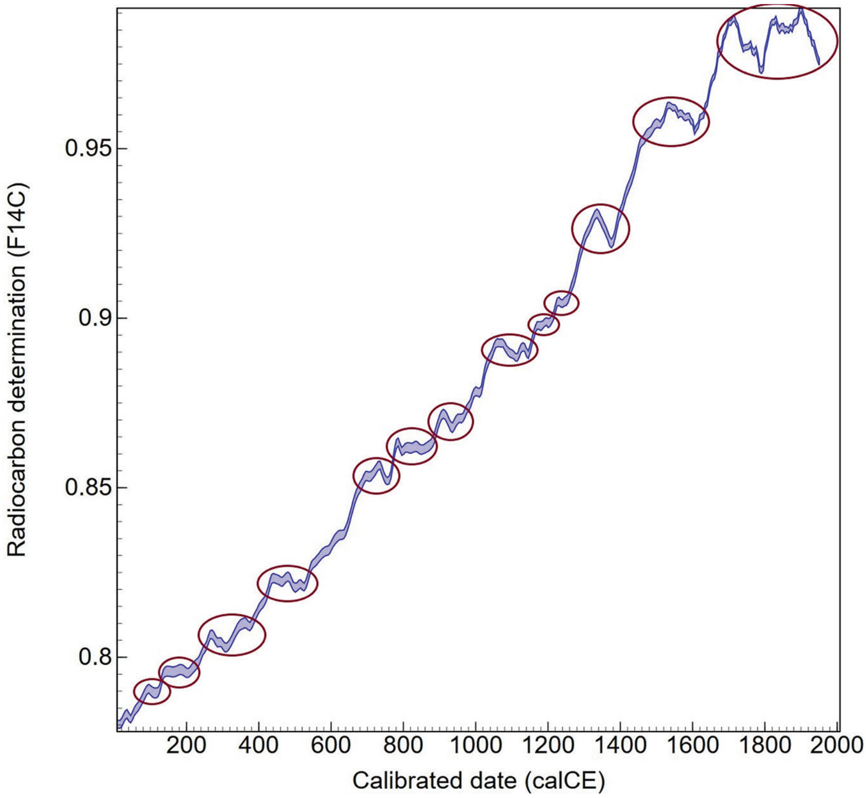


Figure 6.1. The most recent 2,000 years of the calibration curve IntCal13 (Reimer et al. 2013) plotted using OxCal 4.3 (Bronk Ramsey 2009). Calendar age is on the X-axis: older to more recent, left to right. Radiocarbon content, in Fraction Modern (F14C) appears on the Y-axis. Ovals surround plateaus and wiggles that render the *effective precision* of radiocarbon dates within them to greater than a century.

the plateau or wiggle spans centuries. Examination of the tree-ring based portion of the calibration curve IntCal13 (Reimer et al. 2013), reveals a multitude of plateaus and wiggles within the past 12,600 years. In the past 2,000 years alone (figure 6.1), plateaus and wiggles are so frequent that the default strategy of selecting short-lived samples makes far less sense than the accepted wisdom implies.

This chapter focuses upon the well-established technique known as radiocarbon *wiggle-matching*. Wiggle-matching is used to generate high-resolution radiocarbon dates for events that occur within calibration curve wiggles and plateaus, the very circumstances in which dating short-lived materials is suboptimal (Bronk Ramsey, van der Plicht, and Weninger 2001; Pearson 1986). The method is underutilized in Southwestern archaeology, yet it has advantages that make it well suited to solve dating problems encountered with frustrating frequency. The purpose of this chapter is to (re-)introduce wiggle-matching to archaeologists working in the region, explain the method, make its advantages and drawbacks explicit, and demonstrate aspects of its application within the context of a dating project being undertaken by the University of Arizona Accelerator Mass Spectrometry Laboratory and the National Park Service at Montezuma Castle National Monument. In so doing, this chapter pushes our methodological boundaries by reminding us that effective techniques are being used elsewhere in the world and can be applied to great effect here in the Southwest.

Wiggle-matching works across the tree-ring-based portion of the calibration curve. The method usually involves making several radiocarbon measurements per sample. It works best on wood specimens when bark is present, and when there are at least thirty years of growth represented so that the resulting wiggle-match date reveals the cutting or felling date of the tree. Thus, it is well suited to dating wooden posts and beams, and episodes of building construction or repair. The types of questions it can address are similar to those typically addressed by dendrochronology, yet an important characteristic of wiggle-matching is that it can be used on wood specimens not datable by dendrochronology, either due to complacency, species incompatibility, the presence of missing rings, or the addition of false rings. Wiggle-matching does not deliver the annual time resolution of a dendrochronological date, but it can match, and in some cases exceed, the precision of the best-calibrated, short-lived sample radiocarbon date.

A BRIEF REVIEW OF THE RADIOCARBON CALIBRATION CURVE

When J. R. Arnold and W. F. Libby introduced the radiocarbon method in 1949, they showed a "curve of knowns," consisting of six measurements that reflected a theorized exponential decrease in radiocarbon content in progressively older samples (Arnold and Libby 1949). The radiocarbon content of each sample was predicted by its age, the elegantly simple first-order decay equation, and an assumption that atmospheric radiocarbon levels in the past were identical to the present.

This picture of an orderly radiocarbon decrease with age proved incorrect. In 1958, H. de Vries (1958) documented reversals in radiocarbon content around AD 1700, and by 1961, enough data had been collected from known-age tree-ring measurements that M. Stuiver (1961) postulated a correlation between periods of low sunspot activity and high atmospheric radiocarbon levels. In 1965, Hans Suess (1965) published 150 measurements on known-age wood from the past 2,000 years, a data density high enough for him to postulate that short-term (approximately 100-year-long) variations in atmospheric radiocarbon levels were linked to changes in cosmic ray intensity. As data accumulated, it became clear that de Vries's reversal was not an anomaly but a phenomenon repeated many times in the past. Libby's original assumption that atmospheric radiocarbon levels in the past were identical with the present was no longer tenable. Radiocarbon content could not be directly converted into calendar age using a simple mathematical equation. In order to correct for inaccuracies, the atmospheric radiocarbon content of the past had to be empirically determined. This need spawned decades of work that culminated in a series of increasingly long and more data-dense calibration curves. The first comprehensive curve was published in 1986 (Pearson and Stuiver 1986; Stuiver and Pearson 1986), with expanded versions coming out in 1993, 1998, 2004, 2009, and 2013. The current curve IntCal13 (Reimer et al. 2013) extends 50,000 years into the past. The most recent 13,900 years were generated from high-precision radiocarbon dates on dendrochronologically dated tree-rings. This portion of the curve is predominantly comprised of measurements on blocks of wood containing 20, 10, 5, or 3 rings each. Only for the last 500 years is the curve constructed at annual resolution. An updated version, IntCal20, is imminent.

WHY ARE THERE WIGGLES?

Cosmic ray bombardment of the earth's upper atmosphere alters ^{14}N to become ^{14}C. The balance between production, removal, and radioactive decay determines atmospheric ^{14}C levels. Although each of these processes are involved, it is production rate variations, rather than perturbations in the cycling rates that transfer carbon between the atmosphere and various linked carbon pools, that are most likely responsible for the wiggles in the calibration curve (Burr 2013). Cosmic rays—that is, hydrogen nuclei, helium nuclei, and free protons—come from our sun and sources outside our solar system. They interact with the earth's atmospheric gases to produce energetic neutrons. These neutrons collide with atmospheric nitrogen nuclei and produce ^{14}C. The flux of cosmic ray particles at the space-upper atmosphere interface is influenced by both the earth's magnetic field and the sun's magnetic field. The strength of these fields varies over time in both periodic and stochastic manners. Solar variations are dominant, and a consequence of multiple phenomena. These multiple interactions modulate the cosmic ray flux striking the upper atmosphere in a complex way, altering radiocarbon production rate, and ultimately changing in atmospheric radiocarbon levels over time.

During periods when the ^{14}C production rate is high, the slope of the calibration curve is positive, and more recently formed rings contained higher radiocarbon levels than those that preceded them. When the production rate falls, the slope is shallow or even negative. At these times, year-to-year changes in atmospheric radiocarbon levels are nonexistent or even decreasing, so more recently formed rings contain the same or less radiocarbon than those in preceding years.

CALIBRATION CURVE SLOPE DETERMINES THE PRECISION OF A CALIBRATED DATE

The slope of the calibration curve hugely influences the precision of a calibrated radiocarbon date. Organisms that lived during periods of rapid change—that is, steeply positive or negative portions of the curve—can be dated with higher precision than those that lived during periods of slow or no change. If one is trying to date an event that occurred during such a plateau, all the advantages of short-lived samples are negated. The best precision achievable is a date range that spans the duration of the plateau (figure 6.2). Wiggles are just as destructive to precision as plateaus. Radiocarbon measurements on short-lived organisms that lived during wiggles end up generating multiple calendar date ranges.

Fortunately, extensive plateaus in the calibration curve are relatively rare. More typically they are shorter, lasting a century or so, or wiggles of similar duration. Combinations of plateaus and wiggles occur as well, attesting to the multiple and independent processes that alter radiocarbon production rates.

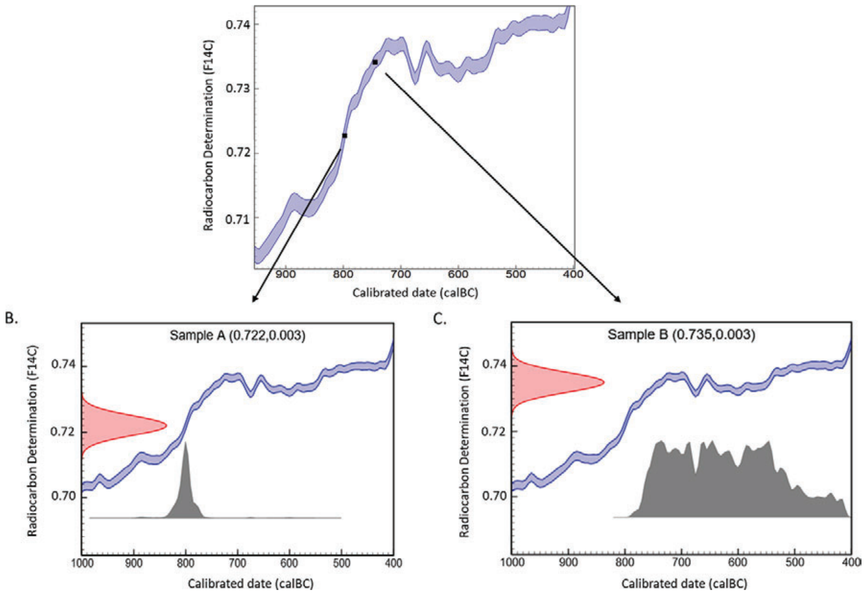


Figure 6.2. Calibration curve slope determines calibrated date precision. (A) Two hypothetical events are indicated as small squares; one occurred at 800 BC, within a period of rapidly changing atmospheric radiocarbon levels, and another at 740 BC, at the beginning of a period of unstable and then slowly decreasing levels. Calibration plots for hypothetical radiocarbon samples derived from short-lived plants that grew during each event are presented in (B) and (C). Radiocarbon content measurements (presented here as Fraction Modern, F14C) are calculated from multiple rounds of measurement. These rounds are summarized numerically for each sample as a mean and standard deviation listed in each plot's title (e.g., Sample A = 0.722 ± 0.003 F14C) and shown graphically as a bell-shaped distribution projecting off the Y-axis. The calibration curve transforms radiocarbon content measurements into calendar date ranges depicted as "mountainscapes" sitting above the X-axis. These mountainscapes can either be simple, as in figure 6.2B, or complex, as in 6.2C, depending upon the shape of the calibration curve where the radiocarbon content measurements intersect it. The likelihood that a particular calendar date is correct is indicated by the height of the curve above it, and so the mountainscapes are referred to as "probability density functions." The plot in figure 6.2B. calibrates sample A, formed in 800 BC. Its radiocarbon content is transformed into a calendar date range that spans 840 BC to 765 BC, only seventy-five years at 95 percent confidence. Figure 6.2C shows the calibrated radiocarbon date from short-lived sample B, associated with the 740 BC event. Its 95 percent confidence range spans 770 BC to 430 BC, *340 years!* The important point is that the measurement precisions of both Sample A and Sample B are identical (±0.003 F14C), yet the spans of their calibrated dates differ widely. Credit: plots generated with IntCal13 (Reimer et al. 2013) and plotted using OxCal 4.3 (Bronk Ramsey 2009).

WIGGLE-MATCHING

Wiggle-matching addresses the challenges of trying to date events that occurred within plateaus and wiggles in the calibration curve. It typically uses wood or charcoal specimens with cutting dates somehow associated with the event of interest. The specimens usually need to contain several decades of visible annual rings. The innermost ring, as well as several other rings are sampled, carefully noting the ring counts between sampling points. Wiggle-matching works

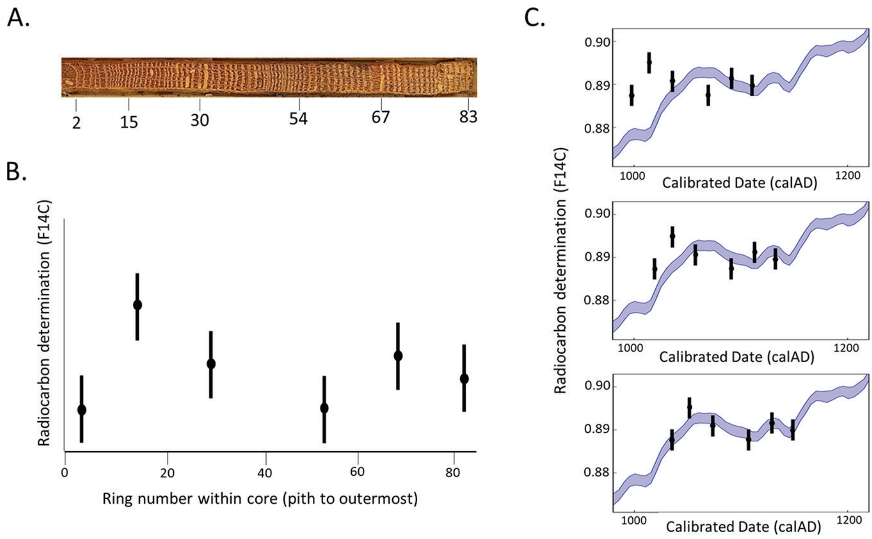


Figure 6.3. An illustration of wiggle-matching by eye: (A) a core whose outermost annual ring is the event of interest is sampled at six locations, and the ring number of each samples is noted. (B) Radiocarbon measurements of the six samples plotted versus ring number. (C) After matching the scales of the axes of plot B with the calibration curve, the dataset is shifted along the IntCal13 curve to determine a position of best fit, shown here in the lower right-hand plot. The position of best fit can be determined graphically, algebraically by a least squares calculations combined with Chi-squared testing, or using Bayesian statistical methods. Credit: plots generated using IntCal13 (Reimer et al. 2013) and plotted using OxCal 4.3 (Bronk Ramsey 2009).

because trees incorporate atmospheric carbon in their tissues, and the annual cycles of tissue formation are visibly evident as tree rings. Thus, rings archive annual variations in atmospheric radiocarbon levels. The ordered series of radiocarbon measurements from a sequence of tree rings, plotted according to ring number, should re-create a portion of the calibration curve. If that portion contains enough structure such that it only matches the master calibration curve at a unique position, the lifespan of the sample can be fixed in calendar time. The real objective is to constrain the position of the outermost ring as tightly as possible in the calendar time, regardless of whether it formed within a plateau. The random oscillations in the calibration curve that stymie short-lived sample calibrations actually facilitate the determination of precise wiggle-match dates.

The innermost ring should always be measured to investigate the possibility that it predates the plateau or wiggle. A high-resolution date from it could be directly transferred to the cutting date simply by ring counting and in a sense make further sampling unnecessary. More typically, a sample at or close to the outermost ring is measured, as well as several samples in between as funding permits. Sampling may be done iteratively and in a more directed manner once an approximate position has been established. A conceptual illustration of the method is depicted in figure 6.3.

There are several methods by which wiggle-matching can be accomplished. Graphical methods, as shown in figure 6.3, and least squares fitting (Pearson

1986), will indicate a position of best fit, but neither quantifies the statistical uncertainty of the match. Chi-squared testing and Bayesian methods have significant advantages in that they do quantify the matching uncertainty (Bronk Ramsey, van der Plicht, and Weninger 2001). In this chapter, only Bayesian wiggle-matching will be discussed further. The tools for it are available as part of the open source OxCal software package, which is used widely for radiocarbon date calibration and Bayesian modeling of radiocarbon dates. The wiggle-match functions are easy to use and take little time to master. They do not require an understanding of the mathematical and statistical calculations; the software takes care of that. They do require conceptual understanding, however.

WIGGLE-MATCHING USING BAYES'S METHOD IN OXCAL

Bayesian methods are often described using a formal terminology that is opaque to nonstatisticians, but what they actually describe are modes of reasoning familiar to us all. A. Bayliss (2007) explains it thus: "We analyse the new data we have collected about a problem ('the standardized likelihoods') in the context of our existing experience and knowledge about that problem (our 'prior beliefs'). This enables us to arrive at a new understanding of the problem which incorporates both our existing understanding of the problem and our new data ('our posterior belief')." Expressing this in formal terms, the probabilities of related observations (called the posterior probability) are conditional on their probability prior to making any observation (Puga, Krzywinski, and Altman 2015). Since a calibrated radiocarbon age is given as a probability density distribution, a posterior distribution can be calculated that takes into account prior information known about the sample; specifically, its temporal placement either in relative or absolute years (Bronk Ramsey 2009). For wiggle-matching, knowledge of the number of years on the tree-ring sample between multiple radiocarbon measurements condition each posterior age distribution (Bronk Ramsey, van der Plicht, and Weninger 2001). The overlap, or agreement, between the posterior density distribution, and initial probability distribution (the standardized likelihood) approximates the goodness of fit for the wiggle-matched sequence (Bronk Ramsey, van der Plicht, and Weninger 2001).

Figure 6.4 shows a wiggle-match based on three measurements from a wood sample containing fifty-six rings, whose cutting date was associated with the 740 BC event described in figure 6.2. Radiocarbon measurements were obtained from the 1st, 29th and 56th rings. The wiggle-matching was carried out using the OxCal software (Bronk Ramsey 2009) and IntCal13 (Reimer et al. 2013).

Within the "Tools" menu there is a tab "Models," and within that a menu item "Tree-ring sequence" (figure 6.4A). To construct a wiggle-match, four parameters are specified per sample: sample name; radiocarbon date (^{14}C yr BP); uncertainty (^{14}C yr BP), and the gap in years between this sample and the next. These parameters were entered into the yellow field, in this case using the comma separator. The data must be ordered from oldest to youngest. A final gap can be specified if the outermost sample is not the outermost ring of the tree. Modeling is initiated by hitting "run" under the File tab. Wiggle-match results are presented by

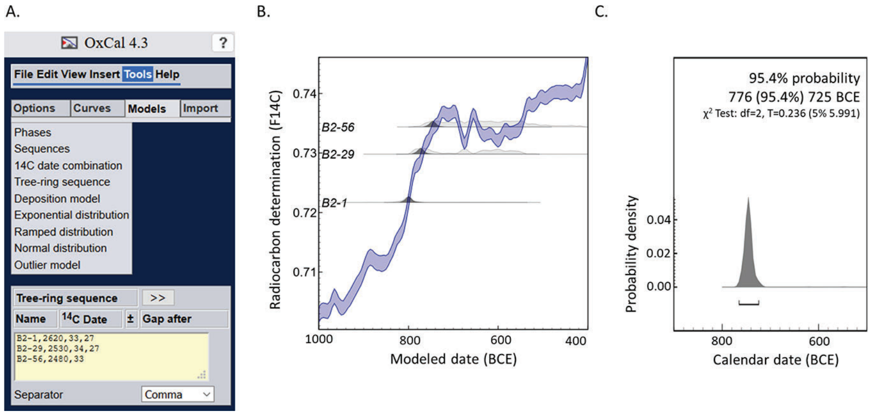


Figure 6.4. Wiggle-matching using OxCal. (A) A screen shot showing menus and the data entry box in yellow. “sample name,” “^{14}C date,” “uncertainty” and “gap after” are typed in, separated by a comma, and pressing the “>>” button, enters data into the wiggle-matching model. Hitting “run” under the “File” tab starts the calculations. (B) A “Curve Plot,” one of the output options. OxCal graphs the probability density function of the individual measurements before wiggle-matching in light gray and the post wiggle-matching probability density function in black. This view makes it clear that sample B2-1 is constraining the wiggle-match. The before and after probability density functions are virtually identical, whereas for rings 29 and 56, wiggle-matching makes the probability density functions dramatically shorter. (C) A “single plot” output, showing the probability density function for the cutting date of the wood. Single plots for each sample are available by toggling through the output files. Credit: plots generated using IntCal13 (Reimer et al. 2013) and plotted using OxCal 4.3 (Bronk Ramsey 2009).

the software in a number of ways: in tables, in graphical representations, and as raw data.

The statistical result of most interest is usually the modeled date range of the outermost ring (figure 6.4C). The best case would be that this modeled date range brackets the actual cutting date and is narrower than the radiocarbon date range obtained from a measurement of just the outermost ring alone. In truth, neither of these gains are guaranteed (see Bayliss et al. 2015). Wiggle-matching might not achieve anything. Effectiveness is assessed by comparison of the calendar age ranges of individual samples before and after wiggle-matching. Graphic depictions show before and after probability density functions of individual samples superimposed. A particularly useful graphical representation of the data is the “Curve Plot,” in which the probability density distributions from before and after the wiggle-match analysis are superimposed on each other, *and* on the calibration curve in positions corresponding to each sample’s radiocarbon content (figure 6.4B). This view is helpful for identifying the rings that constrain the wiggle-match and for making decisions about whether additional sampling might further refine the results.

The wiggle-match shown in figure 6.4B contrasts with the example presented in figure 6.2C. Both samples were associated with the 740 BC event; however, the wiggle-match modeled date range of the outermost ring spanned only 41 years at 95 percent probability, whereas the date range achieved by radiocarbon dating the outermost ring alone spanned centuries. Its brief life coincided with the beginning of a long period of unchanging atmospheric radiocarbon levels. The wiggle-match model improved the 95 percent probable date range because the earliest rings of B2 were formed before the plateau.

WIGGLE-MATCHING VERSUS DENDROCHRONOLOGY

The objective of wiggle-matching is usually identical to the objective of dendrochronology, namely, to determine the time of felling, or death date, of a tree. With both methods the target event may not match the event of archaeological concern or importance. Therefore, all of the interpretive complexity inherent in dendrochronological dating applies to wiggle-match calibration. Behavioral and sometimes taphonomic processes can result in estimated felling dates that are older than the construction date (Baillie 1996; Dean 1978). Shaping of timbers during construction and the erosion of the outsides of timbers over time may remove outside rings; the use of dead wood, stockpiling timber, or the recycling of timbers from earlier structures can bias age estimates toward older dates.

The accuracy of Bayesian wiggle-matching implemented in OxCal has been validated with dendrochronologically dated tree-ring series in multiple studies for both annual and averaged calibration curves (Galimberti, Ramsey, and Manning 2004; Tyers et al. 2009). Wiggle-matching cannot provide the annual resolution of dendrochronology. However, in best-case scenarios, wiggle-matches generate uncertainties smaller than best-case single sample radiocarbon dates. Precison of plus or minus a decade are possible but must be tempered. Laboratory comparison exercises demonstrate offsets between laboratories on the order of a decade at one standard deviation, so claims of such high precision should be viewed skeptically (Hogg et al. 2012; Scott et al. 2007). Moreover, A. Bayliss et al. (2017) undertook a wiggle-matching study in the context of dating timbers from Medieval buildings in England, where legal and financial considerations place particular demands on dating accuracy. They examined short sequence (~30 yrs) wiggle-matching on known-age building timbers, and showed that half of the time, wiggle-match 95 percent confidence intervals did not bracket the true date of the timber. It is important to keep these limitations in mind in spite of the seductive promise the method offers for substantial improvements in precision over what can be achieved with short-lived samples.

ADVANTAGES BEYOND DENDROCHRONOLOGY

There are two aspects of wiggle-matching that allow its application in circumstances where dendrochronology cannot be applied: (1) wiggle-matching can be used on complacent trees that otherwise cannot be tree-ring dated, and (2) wiggle-matching is tolerant of missing and/or false rings in a manner that dendrochronology is not. The first aspect is significant. Trees suitable for dendrochronological dating are said to be "sensitive." They tend to live in habitat fringes, under conditions where they are frequently stressed by lack of water or low temperatures. Frequent stresses cause the greatest variation in ring widths, and this variation is the raw data of dendrochronology. However, sensitive trees are only a subset of what is available for harvest. Much more abundant are "complacent trees," those growing in resource-rich environments. These show limited year-to-year variations in ring widths and are not well suited to dendrochronology. But complacency has no effect on wiggle-matching. What is important for wiggle-matching is simply that the tree produces visible annual rings and the ring sequence spans a uniquely shaped portion of the calibration curve. Consequently, the pool of wiggle-match datable wood should be larger than the pool datable by dendrochronology (see Nash, chapter 3 in this volume). This feature may prove advantageous given the much more restricted pool that a timber-containing archaeological structure presents.

Another aspect is that dendrochronology has naturally introduced a geographical bias toward archaeological sites within environments that contain dendrochronologically datable wood (see Nash, chapter 3 in this volume). Wiggle-matching may counter such biases by expanding the number of datable sites to include lowland and riparian environments where wood resources are abundant and trees within them complacent.

In dendrochronology, a ring is said to be "missing" if lateral growth did not extend uniformly down the stem to the sampled radius. Tree-rings containing intra-annual bands of thickening cells are said to be "false rings," which in some species can be difficult to distinguish from true annual ring boundaries. Both situations—missing and false rings—can be identified and corrected for with adequate cross dating and replication in dendrochronological studies using living trees but are sometimes intractable in archaeological applications because of the necessarily restricted pool of potential samples. Wiggle-matching can likely tolerate missing or false rings in a manner that dendrochronology simply cannot. The uncertainties inherent in radiocarbon measurements are likely to be much larger, in many cases, than those arising from inaccuracies in ring counting. More work needs to be done to quantify the effect of these anomalies on the accuracy of a wiggle-match date, but this tolerance could expand the list of datable tree species beyond those considered suitable for dendrochronology. That said, it is important to emphasize that wiggle-matching nevertheless requires that rings represent annual growth. For example, recent work by Y. Ehrlich, L. Regev, E. and Boaretto (2018) demonstrated ring counts in Mediterranean olive (*Olea europaea*) are not annual and cast doubt upon a previously published wiggle-match date from an olive branch associated with the Minoan eruption of the Santorini volcano (Friedrich et al. 2006).

MONTEZUMA CASTLE, VERDE VALLEY, ARIZONA

We have been working at Montezuma Castle, an archaeological site (AZ O:5:14 [ASM]) and national monument located in the Verde Valley of central Arizona. Our focus has been the twenty-room, five-story cliff dwelling constructed within a limestone alcove looking down on Beaver Creek (figure 6.5). The creek is a perennially flowing tributary of the Verde River and is part of a lush riparian corridor that contains some of the last extant Fremont cottonwood–Goodding

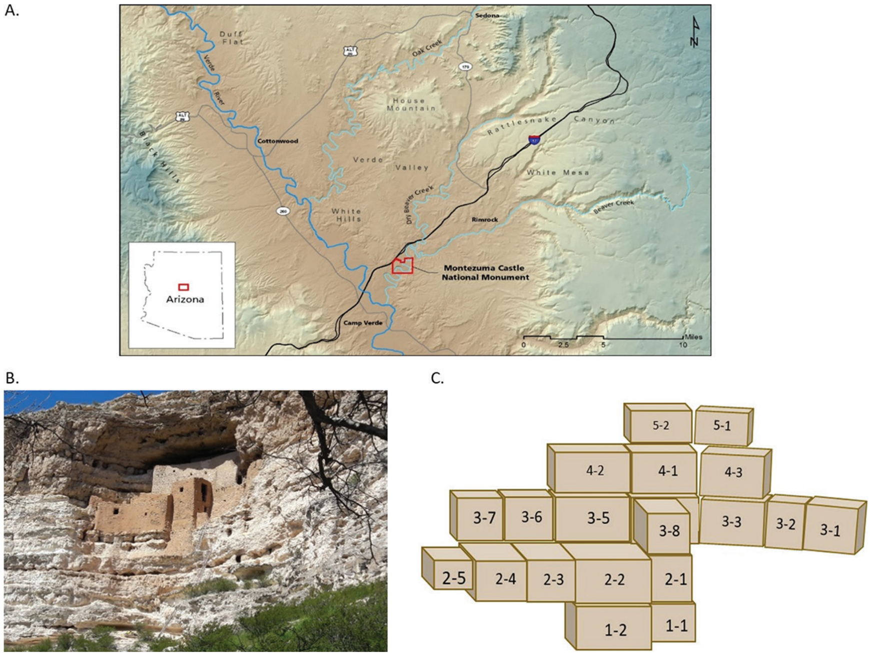


Figure 6.5. (A) Site Location (from Guebard 2016); (B) Montezuma Castle cliff dwelling (photo: N. Kessler); and (C) a schematic of the structure using the room numbering scheme of Wells and Anderson (1988). Credits: (A) Map from NPS; (B) Photograph, G. Hodgins 2018; (C) schematic G. Hodgins.

willow forests in the American Southwest (Stromberg 1993). The Southern Sinagua built the cliff dwelling and artifacts found at the site date to the Honanki and Tuzigoot phases (AD 1125–1400) (Breternitz 1960; Colton 1946). Studies suggest that the cliff dwelling was abandoned by the late fourteenth century (Guebard 2015, 2016).

The cliff dwelling contains well-preserved plastered walls, doors, and windows. Intact wooden roofs/floors contain a large number of timbers and incorporate grass, sedge, and yucca. Despite superb preservation, archaeologists have struggled to determine the age of the structure and its construction sequence.

The majority of the 160 timbers surviving at Montezuma Castle cliff dwelling are preserved as posts, vigas (primary beams), *latillas* (secondary beams), and door and window lintels. Approximately 90 percent of structural wood consists of Arizona sycamore (*Platanus wrightii*), Arizona ash (*Fraxinus velutina*), and Arizona alder (*Alnus oblongifolia*) (Blanchette and Held 2010). Dendrochronology was first attempted by Florence Hawley in 1933. She collected ten samples, but only one core, taken from an imported and peculiarly placed ponderosa pine (*Pinus ponderosa*) support post, provided a somewhat speculative cutting date (Florence Hawley, unpublished notes and skeleton plots in LTRR archives). Coring campaigns in 1988 and 2011 yielded twenty-eight more cores from juniper (*Juniperus sp*.), cottonwood (*Populus fremontii*), Arizona sycamore, Douglas fir (*Pseudotsuga menziesii*), and ponderosa pine, but none provided cutting dates.

Most of the wood is from species that grow within the Beaver Creek riparian corridor, where moisture is not a limiting growth factor. The trees show little variation in ring width.

S. J. Wells and K. M. Anderson (1988) carried out detailed measurements, cataloged features of the structure, and proposed a room-construction sequence. They believed that initial construction started on the third level, roughly rooms 3-1 to 3-6, then grew upward with addition of levels four and five. Next, a westward expansion enclosed natural alcoves into rooms 2-4 and 2-5, added 3-7, and constructed room 1-2 on the bottom level. The addition of rooms 2-2 and 2-3 followed this, and the final construction phase added the column of rooms 1-1, 2-1, 3-8 to the front of the structure.

In 2012, L. V. Nordby undertook a detailed study that focused upon construction joints, wall abutments, doorways, hatchways, and other details (Nordby 2015). Like S. J. Wells and K. M. Anderson (1988), Nordby (2012) hypothesized the dwelling began with the construction of rooms on level 3, but he suggested construction next expanded downwards, adding level 1 and 2 room blocks, and then room 3-8. Levels 4 and 5 followed, with the final addition of room 2-5.

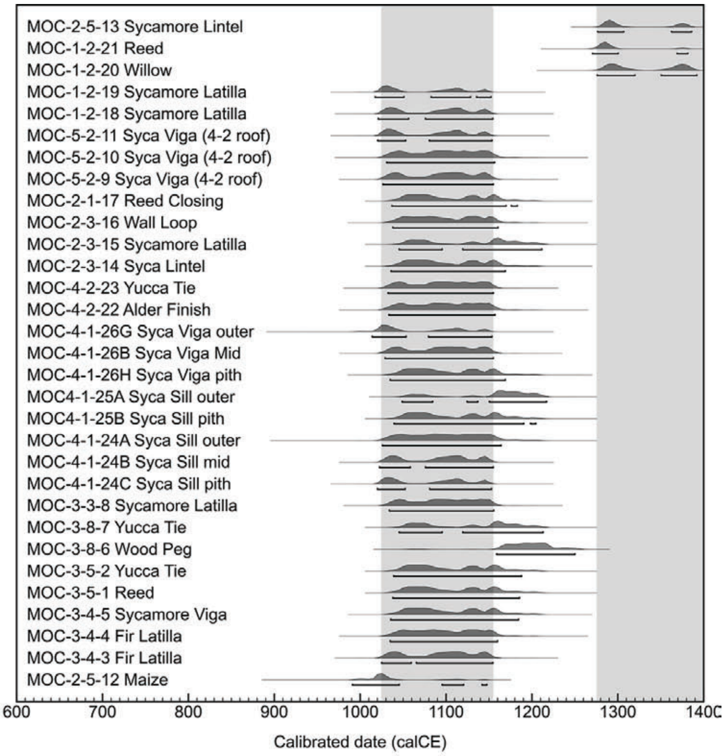
The presence of sealed hatchways indicates episodes of remodeling. Charred roof beams and ceiling/floor damage from a large boulder fall attest to past damage and subsequent maintenance and repairs that could have introduced wood from later times. Routine replacement of damaged or weakened beams and wood reuse likely occurred.

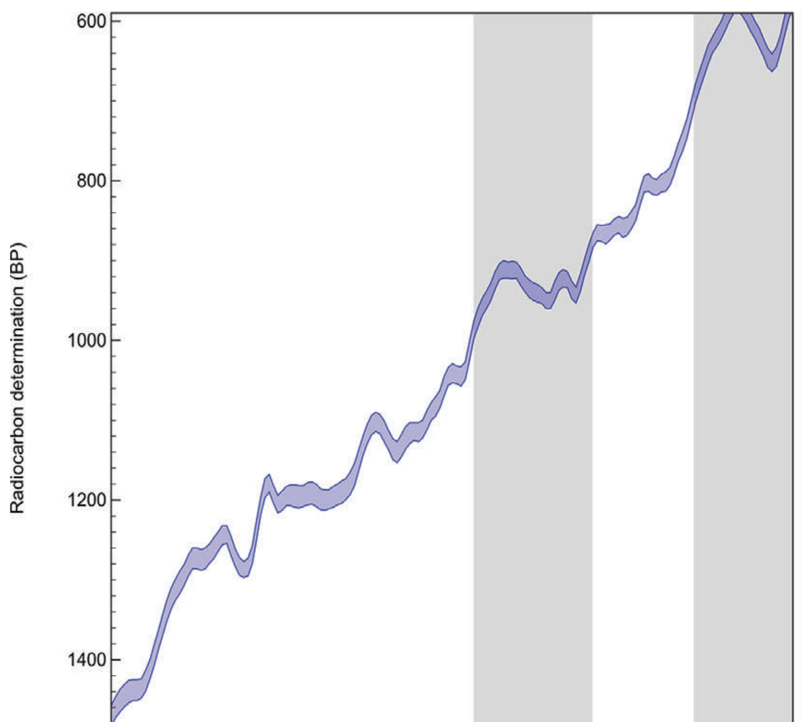
T. C. Windes and W. H. Doleman (2015), working with National Park Service archaeologist Matthew Guebard, attempted to test these models and provide an absolute chronology using radiocarbon dating. Thirty-six short-lived organic remains (grasses, sedges, and shavings of outermost wood from beams) were sampled throughout the structure and dated. Unfortunately, this dataset proved difficult to interpret as the dates ranged from the third to the fourteenth centuries CE, a far wider time span than seemed archaeologically possible. Moreover, some of the oldest dates on roof grasses predated the beams with which they were sitting by centuries. Dates from within rooms and between rooms were so scattered that construction sequence modeling was impossible.

In 2017, the University of Arizona AMS Laboratory undertook a second radiocarbon dating study. We obtained new, short-lived samples from various rooms in the structure, using a sampling strategy similar to that used previously. In addition, we decided to investigate whether wiggle-matching might improve the resolution of dates in the structure. To that end, we focused on dating a single room, 4-1. From room 4-1 we obtained three core samples, one from a sycamore viga, and two from sycamore sills embedded in a floor-level opening against the back wall of room 4-1.

The Arizona AMS dates on short-lived seeds and surface wood clustered within two date ranges, the majority between 1020 CE to 1165 CE and a few between 1275 CE to 1400 CE (figure 6.6). No anomalously old dates were evident; this is likely a consequence of the thorough cleaning protocols used at our laboratory (see Lange et al. 2019). The radiocarbon dates clustered because the

Figure 6.6. University of Arizona AMS dates from Montezuma Castle. The sample IDs encode structure-level-room-sample number information (i.e., MOC-3-8-7) according to the level-room system of Wells and Anderson (1988). All of the samples are from short-lived materials, or shavings of outermost wood from timbers, with the exception of three core samples 4-1-24, 4-1-25, and 4-1-26, obtained from room 4-1. The calibration curve spanning this timeframe is at bottom.





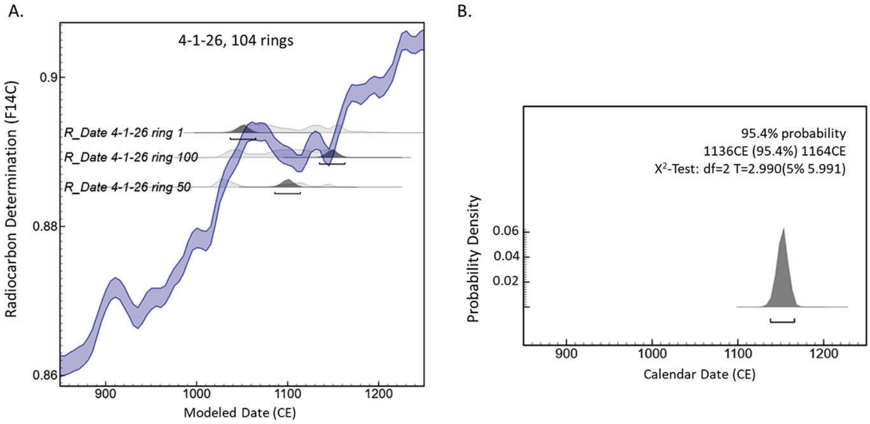


Figure 6.7. Bayesian Wiggle-match for a roof beam 26 from Room 4-1. The wiggle-match generated a modeled date range of 1136 CE to 1164 CE at 95 percent confidence. Credit: plots generated using IntCal13 (Reimer et al. 2013) and plotted using OxCal 4.3 (Bronk Ramsey 2009).

construction and occupation of the cliff dwelling occurred during two plateaus or wiggles in the calibration curve. This coincidence reduced the chronological resolution afforded by radiocarbon dating short-lived samples from the site.

A core from a sycamore viga (roof beam) in room 4-1 that contained 104 rings (sample 4-1-26) was dissected to provide an innermost, numerical middle, and outermost ring. All three were radiocarbon dated and the sequence of measurements wiggled-matched using Bayesian statistical methods available in OxCal v4.3 (figure 6.7). The radiocarbon measurements of the sequence of rings followed the dip in the calibration curve between 1050 CE and 1150 CE. The wiggle-match identified a single, narrowly defined date range for the final ring the sequence of 1136 CE to 1164 CE at 95 percent probability. This date range was substantially narrower than the calibrated date ranges for the individual rings in the core and the calibrated dates of eighteen of the short-lived organic remains from the structure.

We also obtained cores from two other timbers in the same room: 4-1-24 and 4-1-25. These timbers are only partially exposed, but it is possible they are roof elements of room 3-4 immediately below.

The wiggle-match from the 38-ring core 4-1-24 (figures 6.8A and 6.8B) produced a modeled date range of 1089 CE to 1153 CE. The wiggle-match agrees closely with the modeled date of 4-1-26 but does not provide the same resolution. The wiggle-match for 4-1-25 (figures 6.8C and 6.8D), the 7-ring core, was even more poorly resolved. It indicated three possible cutting dates. Both wiggle-matches are shown here because they illustrate the risks and tradeoffs in trying to sample shorter length cores: multiple possible solutions can arise. Without resolving which peaks in the probability density functions shown in figures 6.8C and 6.8D are correct, the wiggle-matches are not much of an improvement over the resolution that could be obtained from single measurements on short-lived samples.

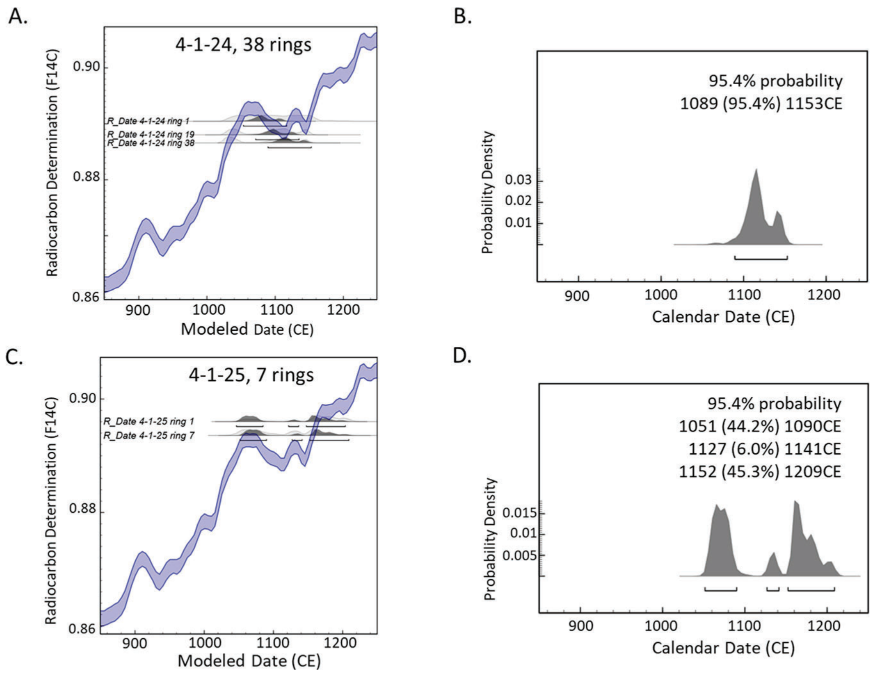


Figure 6.8. Bayesian Wiggle-matches for two shorter-lived timbers from Room 4-1. Wiggle-matching three radiocarbon measurements from a 38-ring core (4-1-24), A., generated a possible date range in close agreement with 4-1-26, B., the wiggle-match for the shortest, 4-1-25, C., resulted in multiple modeled date ranges, with some overlap to the other beams, D. Credit: plots generated using IntCal13 (Reimer et al. 2013), and plotted using OxCal 4.3 (Bronk Ramsey 2009).

Both core 4-1-24 and 4-1-25 identified potential modeled date ranges that overlapped with the cutting date of the viga 4-1-26. It is a reasonable argument that the secure cutting date of 4-1-26 should be used to clarify the ambiguities in cutting dates of the sill timbers, and it is possible to do this statistically. The probability density functions shown in figure 6.7B, and figures 6.8B and 6.8D, can be used in a Bayesian model to quantify the most likely modeled date ranges for all three. For the purpose of this chapter, such modeling is unnecessary.

The majority of the 160 timbers surviving at Montezuma Castle cliff dwelling are small-diameter latilla that are only a few decades old. These characteristics limit opportunities for wiggle-matching in spite of the abundance of wood found throughout the dwelling. If this is a general trend in lowland archaeological structures in the Southwest, the opportunities for wiggle-match dating might not be as abundant as we hoped.

When modeling the construction chronology of a structure such as Montezuma Castle, in which much of the sequence of construction is implied within the architecture, a small number of high-resolution dates may have a larger influence on the chronology of the whole structure. For this reason, we are targeting timbers in rooms within the central spine: rooms 1-2, 2-1, 3-4, and 4-1. These rooms have the highest concentrations of wood, the largest-diameter timbers, and in the models of both Wells and Anderson (1988) and Nordby (2015) are likely foundational architectural structures.

A close examination of the curve plots in figures 6.7 and 6.8 reveals several of the tree-ring measurements used for the wiggle-match do not sit directly on the calibration curve. Bronk Ramsey, van der Plicht, and Weninger (2001) point out that a partial explanation for this discrepancy stems from the fact that the calibration curve was constructed from measurements on multiyear blocks of wood, which have dampened any year-to-year fluctuations in atmospheric radiocarbon levels. The wiggle-match samples are annual and so will capture rapid fluctuations. Bronk Ramsey, van der Plicht, and Weninger (2001) suggest that this mismatch in time resolution would not significantly affect wiggle-match accuracy but would affect the *agreement index* of the model. The agreement index describes how closely the modeled date range overlaps with the premodeled date ranges. Indeed, tree-ring measurements used in wiggle-matching models might be expected to plot off the calibration curve. As annually resolved calibration datasets emerge, it will be interesting to see how they affect wiggle-matching precision and accuracy. The new calibration curves will contain more signals but also more noise.

CONCLUSIONS

Different sample types and sampling strategies are required for radiocarbon dating in different time periods. Short-lived samples are adequate within steep portions of the calibration curve. Longer-lived wood samples, however, containing annual or near-annual rings, are better for dating events that occurred within calibration curve plateaus.

There are many similarities between dendrochronology and radiocarbon wiggle-match dating. The precision and resolution of the former will always be better than the latter, and one should critically examine the data when wiggle-match dating precision approaches plus or minus a decade or lower.

An important distinction between the two methods is that wiggle-match dating can be applied to complacent trees that are undatable by dendrochronology. Chronological studies of archaeological sites within regions dominated by complacent forests, thus undatable by dendrochronology, *and* poorly dated by conventional radiocarbon dating methods because they fall within plateaus in the calibration curve, might be well served by wiggle-match dating.

Work in progress at Montezuma Castle National Monument has shown that wiggle-match dating can indeed improve radiocarbon date resolution over what can be achieved with short-lived samples. Although there is an abundance of well-preserved in situ wood within the monument, many of the structural wood timbers were found to be from fast-growing trees that are likely contain too few growth rings to provide a meaningful wiggle-match.

Wiggle-matching is an inherently empirical exercise. It is nearly impossible to make specific statements about the requirements necessary for a successful wiggle-match. Past atmospheric radiocarbon levels vary in such a random way that parameters such as minimum life span; tolerance of false or missing rings; or the required number, spacing, or position of additional sampling points must be determined by doing. Fortunately, relatively few measurements are required to indicate whether, for a particular case, the strategy will pay off. When it does, the benefit of one or two high-resolution dates positioned inside the chronological black box that a plateau represents becomes abundantly clear.

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