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## THE DISTRIBUTION OF AGE DISPARITIES IN CONIFER CHARCOAL FROM ARCHAEOLOGICAL STRUCTURES AND APPLICATIONS FOR TREE-RING-RADIOCARBON DATING

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**ABSTRACT.** Age disparities between charcoal samples and their context are a well-known problem in archaeological chronometry, and even small offsets could affect the accuracy of high-precision wiggle-matched dates. In many cases of taphonomic or anthropogenic loss of the outermost rings, sapwood-based methods for estimating cutting dates are not always applicable, especially with charcoal. In these instances, wiggle-matched *terminus post quem* (TPQ) dates are often reconciled with subjective or ad hoc approaches. This study examines the distribution of age disparities caused by ring loss and other factors in a large dendroarchaeological dataset. Probability density functions describing the random distribution of age disparities are then fit to the empirical distributions. These functions are tested on an actual wiggle-matched non-cutting date from the literature to evaluate accuracy in a single case. Simulations are then presented to demonstrate how an age offset function can be applied in OxCal outlier models to yield accurate dating in archaeological sequences with short intervals between dated episodes, even if all samples are non-cutting dates.

**KEYWORDS:** cutting date, dendrochronology, old wood problem, TPQ, wiggle-matching.

### INTRODUCTION

Radiocarbon ( $^{14}\text{C}$ ) analysis of sequential tree-ring segments (wiggle-matching) provides a precise method for dating archaeological material in situations where low sample depth, growth complacency, or the lack of temporally overlapping master-dating series limits the application of ring-width based dendrochronological methods. Wiggle-matching refers to a Bayesian calibration procedure that fits a sequence of  $^{14}\text{C}$  dates separated by absolutely known time gaps to the shape of the  $^{14}\text{C}$  calibration curve (Bronk Ramsey et al. 2001). When applied to tree-ring series, this technique takes advantage of the fact that many temperate tree species grow in annual increments and thus their wood is an archive of historic interannual variability in atmospheric  $^{14}\text{C}$ . Unlike a dendrochronological date, which is a single calendar year, the date determined by a wiggle-match model will be in the form of a posterior density distribution. Nonetheless, a wiggle-matched date can be interpreted in a similar manner to a dendrochronologically determined date. For example, if the bark or waxy edge is present, the date of the outermost ring will represent the final year of growth—often referred to as a cutting date. If outer rings are missing, however, the dated ring represents a *terminus post quem* (TPQ) for the final year of growth—or a non-cutting date.

Wiggle-matching will likely continue to grow in importance in archaeological science as researchers increasingly turn to historical questions that resolve to temporal scales of a human generation or less (Bayliss 2009; Bayliss et al. 2020; Whittle et al. 2010). Recently, increases in data availability and statistical methods enable higher resolution dates based on annual sequences and create new opportunities for chronometric insight (van der Plicht et al. 2020). However, if the full potential of the method is to be realized, certain problematic aspects of dating archaeological wood must be dealt with. Charcoal samples

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from archaeological structures are often recovered as fragments and lack outermost rings. As discussed in more detail below, solutions to these problems require an indication of the sapwood-heartwood boundary which is problematic in charcoal. While normally avoided for single age determinations, charcoal fragments with many rings are valuable specimens for wiggle-matching. Dates on such material generally only provide a TPQ and the time gap, or disparity, between tree death and the age of the outermost dated ring must be assumed or inferred by other means, often subjectively.

The potential for age disparities between a wood sample and its archaeological context—sample in-built age or the “old wood problem”—is well described in archaeological chronometry, but methods to objectively correct for it are lacking. The use of dead wood is the classic source of sample in-built age, and current *chronometric hygiene* approaches for addressing sample in-built age in archaeological  $^{14}\text{C}$  studies have mostly focused on avoiding charcoal and detecting large age disparities in datasets. This is despite the fact that charcoal is by far the largest source of datable material directly linked to construction events at most archaeological structures, and material lacking outer rings is often the best or only available material for dendrochronological or  $^{14}\text{C}$  dating.

This study analyzes age disparities caused by ring loss and other factors in a dendroarchaeological dataset by calculating the difference between the tree-ring date of charcoal samples lacking a terminal growth ring (non-cutting dates) and the estimated age of their context determined from cutting date clusters. The study provides an objective method to correct non-cutting dates based on the empirical distribution of age disparities in a sample of tree-ring dated, short duration, contexts. Dendroarchaeological theory developed to deal explicitly with date disparities and interpret the large number of tree-ring dates obtained in the southwestern U.S. is adopted to identify the most likely age of contexts aggregated in this study. The interaction of sample characteristics such as tree taxon, tree age, taphonomy, and the cutting cluster itself are explored to determine if these factors are associated with different levels of age disparities. The characteristic age disparity of different sample groups is modeled with a log-normal distribution to produce a hypothetical ring-loss correction for wiggle-matched  $^{14}\text{C}$  dates. The age correction model is then evaluated with published data from a chronological study of monumental construction in Mexico. Finally, a simulated sequence with events at intervals of < 20 years dated by wiggle-matches with random age disparities are corrected with the age offset developed in this study. The results suggest that, if the probabilistic age disparity of samples can be modeled, wiggle-matched segments from charcoal lacking outer rings can still accurately date sequences with intervals at the scale of a human generation depending on the particularities of the samples and position on the calibration curve. This is important as archaeologists strive to reconstruct archaeological events—or ruptures in historical sequences—by reconstructing abrupt changes in structured practice (Beck et al. 2007; Bolender 2010). Theoretically, this could improve the vitality and realism of archaeological narratives, but theoretical assumptions about the temporality of the archaeological record has often outpaced the empirical reality (Bailey 1983; Clarke 1973; Lucas 2008; see also comments by Whittle in Beck et al. 2007: 853). In this sense, tools that can broaden the application of high-precision  $^{14}\text{C}$  dating techniques have great importance.

### **Age disparities in $^{14}\text{C}$ and dendrochronological dating**

Wood and charcoal from standing buildings, buried structures, and geologic deposits can be dated several ways including tree-ring width pattern matching and isotopic methods. However,

wood and charcoal frequently induce significant biases in chronometric analyses that result in age overestimation due to a disassociation between the last year of preserved xylem formation (the dated event) and the time at which the wood was incorporated into an archaeological or natural deposit (Haury 1935; Bannister 1962; Waterbolk 1971; Schiffer 1972; Pettitt et al. 2003; Blockley and Pinhasi 2011). A disparity between the dated event for a particular sample and the incorporation of the sample into systemic and archaeological contexts (*sensu* Schiffer 1972) emerge from three sources. (1) The procurement and use of dead wood, (2) the recycling of building material from older structures for fuel or construction purposes, and (3) the removal of the terminal growth layer by human tooling or taphonomic processes (Dean 1978). The scale of dating anomalies from the first two processes—*in-built age* from the use/reuse of relict wood—can be on the order of decades to centuries, or even millennia in exceptional cases (Schiffer 1986; Smiley 1998; Ahlstrom et al. 1991; Kennett et al. 2002; Allen and Huebert 2014; Cook and Comstock 2014). The third process—an age disparity resulting from *outermost ring loss*—generally results in anomalies on the order of years to decades (Graves 1991; Dean and Ravesloot 1993; Nash 1997). Stockpiling of timber has been recorded in some pre-industrial contexts and can be thought of as a special case of in-built age with the resulting age disparity being typically less than a decade (Dean 1981).

Significant dating anomalies have been attributed to in-built age across the globe, resulting in widespread rejection of legacy  $^{14}\text{C}$  dates based on wood charcoal particularly when samples are of uncertain species, tree-age, taphonomic status, and provenience (Spriggs 1989; Ashmore 1999; Pettitt et al. 2003; Blockley and Fitzpatrick 2006; David 2008; Nolan 2012; Hart and Nolan 2015). Some have argued that in-built age errors are less widespread and/or overestimated in the literature (Cook and Comstock 2014), and some data exist to support this for temperate regions (Kim et al. 2019). However, the overwhelming evidence for age disparities caused by in-built age has led to the avoidance of wood charcoal for  $^{14}\text{C}$  dating as standard practice for archaeologists in the 21st century (for example Price 2007:228; Renfrew and Bahn 2004:147). Instead, short-lived organisms or residues are strongly favored when matching a  $^{14}\text{C}$  dated event to a particular context or human activity (see Hart and Brumbach 2005; Taché and Hart 2013; Higham et al. 2014; Gilmore 2015). However, despite a preference for direct dates on short lived organisms, the prevalence of wood charcoal in both legacy datasets and new collections means that charcoal dates must be incorporated into  $^{14}\text{C}$  chronologies at some level. One can only date the material that is available, so whatever is selected should as closely as possible correspond to the archaeological event targeted for analysis (Hamilton and Krus 2018; Thompson and Krus 2018). To this end, Bayesian calibration tools allow analysts to objectively model the effects of in-built age on the timing and duration of past activities given all relevant information (for example Krus et al. 2015), and studies that have applied outlier detection models show that not all (or even a majority of) the charcoal samples are anomalous in stratified sequences (Martin et al. 2017). Even researchers with contrasting conclusions on the validity and reliability of wood charcoal dates agree that direct assays on wooden building material (e.g., support posts or ceiling beams) should provide a reliable estimate for wood procurement and construction (Cook and Comstock 2014; Hart and Nolan 2015). Therefore, dates on wooden and charred structural elements remain central evidence for archaeological chronologies.

While in-built age has occupied the literature on archaeological  $^{14}\text{C}$  dating, date anomalies caused by outermost ring loss has concerned dendrochronologists to a greater degree. This is because in some cases it is possible to correct for ring loss by various means. In

dendrochronology, outer ring loss is inferred by the absence of features characteristic of a terminal growth layer such as: bark, beetle galleries, a contoured *waney edge* of the living trunk, or an outermost ring preserved around the complete circumference of a cross-section. The loss of outer rings was identified as a problem for associating the dated event with the event of human interest since the beginning of dendroarchaeology (Douglass 1935, 1939; Haury 1935). Most attempts to correct for ring loss focus on statistical methods for estimating the number of sapwood rings originally present. For example, oaks (*Quercus* spp.), and some conifer species have a predictable sapwood width that varies proportionally to the age of tree or the width of heartwood rings (Dean and Holstein 1980; Robinson and Ahlstrom 1980; Dean and Ravesloot 1993; Nash 1997; Haneca and Debonne 2012; Sohar et al. 2012; Bleicher et al. 2020). Sapwood estimation requires the presence of a regular and clearly identifiable heartwood-sapwood transition. Not all tree species have regular heart-sapwood transitions, and many times sapwood is not preserved at all. Data from the Laboratory of Tree-Ring Research at the University of Arizona, Tucson show that tree-ring samples from archaeological contexts are usually preserved in a charred state if not subjected to an arid or anoxic environment (Towner 2015). In conifers and many hardwoods, the sapwood-heartwood boundary is identified by a change in color of the xylem which pyrolysis completely obscures (Kabukcu 2018). Additionally, many buried archaeological samples lack all their original heartwood rings. For oaks these caveats are less limiting. Recent research suggests that the number of sapwood rings can be estimated from the mean width of only the outermost heartwood rings (Bleicher et al. 2020), and the presence of sapwood in oak charcoal can be inferred by the quantification of tyloses abundance (Dufraisse et al. 2018). These advances however, do not address the problem of missing rings in conifers which is the focus of the present study.

## MATERIAL AND METHODS

This study proposes that: (1) date disparities for conifer wood types subjected to deterioration in archaeological context have characteristic distributions, and that (2) statistical functions describing the expected age disparity for a sample, referred to here as an age offset function, can be used to correct TPQ dates from tree-ring specimens. The tree-ring date database used in the study consists of charred wood and charcoal recovered from buried proveniences at similar archaeological contexts from the southwestern U.S. A data summary from all archaeological contexts assembled in this study is available in Supplementary Materials (Supplement 1), as is the complete dataset of all non-cutting dates (Supplement 2). The age disparity between samples lacking the terminal growth ring and their dated context is calculated based on dendroarchaeological theory informing the interpretation of tree-ring date clusters. The significance of various factors on the calculated age disparity including tree species, tree age, sample condition, and the duration of tree procurement represented in the cutting date cluster, were assessed in a stepwise manner to partition subgroups of samples with distinct age offset distributions. Statistical functions were then fit to the distribution of age disparities from each sample subgroup. Key aspects of this analysis including stepwise partitioning, fitting of probability density functions, goodness-of-fit-tests, and figure plotting can be replicated using the R script provided in Supplementary Materials (Supplement 3). The advantage of using a parametric function to describe expected age disparity by sample groups is that it allows the easy correction of  $^{14}\text{C}$  dates in the calibration program OxCal. Practical examples of the application of the taphonomic age offset functions to wiggle-match calibration models are discussed below

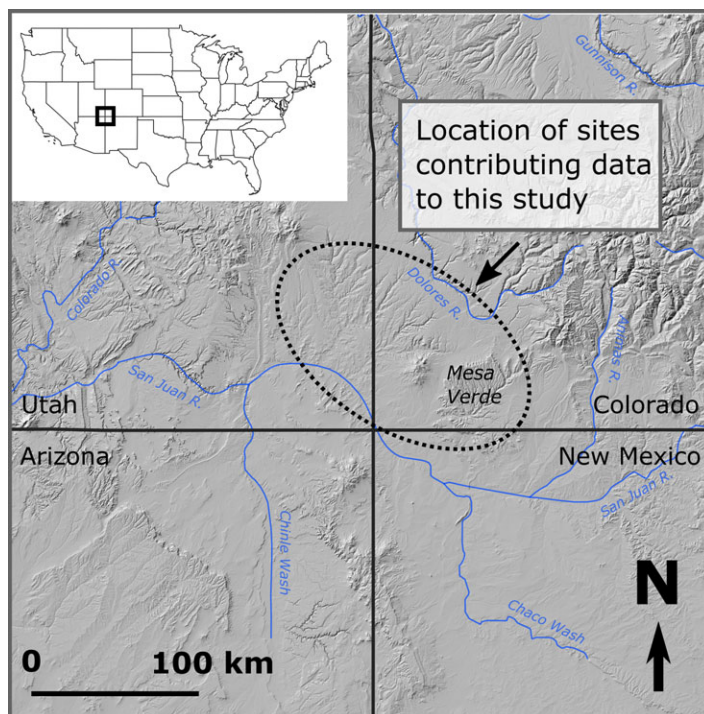


Figure 1 Location of the archaeological sites in the greater Mesa Verde region contributing dendrochronological dates to this study.

and are also provided in Supplementary Materials (Supplement 4 and Supplement 5A and Supplement 5B).

### Tree-Ring Data

A dataset of 703 cutting dates and 729 non-cutting dates from 85 contexts at 50 archaeological sites (see Supplement 1 for complete summary of dataset) from the Mesa Verde region of the southwestern U.S. was assembled from a database of tree-ring dates on file at the Laboratory of Tree-Ring Research at the University of Arizona (Figure 1). Archaeological sites well-known in the regional literature contribute tree-ring dates for the analysis including; 5LP2164 (Morris 25), 5MT23 (Grass Mesa), 5MT2108 (Lowry-Ackman Group), 5MT2831 (Morris 33), 5MT3868 (Duckfoot Site), 5MT4725 (McPhee Village), and MV1626 (Badger House Group) (see Adams 1983; Adler and Wilshusen 1990; Kohler and Higgins 2016; Kohler and Mathews 1988; Pierce 2005; Martin 1938; Morris 1937; Schachner 2010; Wilshusen 1986; Wilshusen and Blinman 1992; Wilshusen and Ortman 1999; Wilshusen and Van Dyke 2006; Wilshusen et al. 2012). As detailed in later sections, tree-ring specimens come from four conifer species, and the samples range in size from charcoal fragments to portions of large beams with intact cross-sections, and specimens contain from 28 to 383 growth rings with an average of 115. Dated timbers providing dates for this study were excavated from pit structures, jacal (wattle and daub), and masonry rooms dating from ca. AD 500–1200 and are culturally affiliated with the Basketmaker III (BMIII) though Pueblo III (PII) periods in regional history. The appearance of substantial

pit structures—or subterranean dwellings, communal buildings, and ritual structures (Cameron 1990; Kohler and Higgins 2016)—marks the onset of the BMIII period around AD 500 in the Mesa Verde area. Toward the end of the BMIII period, and into the Pueblo I (PI) period, pit architecture is supplemented by surface rooms made from jacal, and later by more permanent masonry structures, around ca. 1000 AD with pit structures assuming more ritual uses (McGuire and Schiffer 1983; Wilshusen 1989). At many PI sites in the region, all three types of architecture are present with evidence that each was in use simultaneously (Lightfoot 1992). The majority of contexts in this analysis—82 of 85 (96.4%)—date to the BMIII and PI periods, with only three (all probable kivas) dating to the PII or PIII periods. As a result of relatively short use lives of these structures and the unique destruction patterns favoring widespread preservation of wood charcoal, this sample presents an ideal scenario to interpret building events and age offsets from those events. 724 of the 729 (99.3%) non-cutting dates are from specimens preserved in a charred state. Because of their size and provenience, tree-ring specimens in this dataset are interpreted as structural remains (e.g., support posts and roof beams). However, there remains the possibility that some portion of the sample is derived from non-structural wooden artifacts introduced after construction, or rubbish accumulating after destruction. This could complicate the identification of cutting date clusters and adds noise to the empirical distribution of age offsets. To minimize these effects, steps are described below to both identify ideal contexts from cutting date clusters, and to accommodate the expected noise emerging from small quantities of slightly younger wood in the sample.

### Calculating Age Disparity

To calculate the time gap between a sample lacking a terminal growth ring and its predicted cutting date, an individual non-cutting date is subtracted from the estimated procurement year inferred from the modal value of a cluster of cutting dates from the same context. It has long been understood that clusters of tree-ring cutting dates represent building events, and that dates that diverge from these clusters represent cases of ring loss, beam re-use, or structure repair (Bannister 1962; Dean 1978; Haury 1935). Ahlstrom (1985; Ahlstrom et al. 1991) elaborated this concept and explained the importance of examining the shape of cutting date distributions. He and colleagues proposed that tight, well replicated, cutting date clusters—unimodal distributions, spanning only 1–2 years, with many dates—represent discreet tree procurement episodes uncomplicated by the various processes that could cause dating discrepancies (Ahlstrom et al. 1991: 637). Conversely, loose clusters—multi-modal distributions or distributions dispersed over decades—suggest sequential rebuilding and remodeling often associated with extended use or reoccupation of a dwelling (Ahlstrom 1985).

The distribution of cutting and non-cutting dates from Pit structure 4 at the Duckfoot site (5MT3868) is an exemplar of this concept. Duckfoot is a PI hamlet that was nearly completely excavated in the 1980s providing archaeologists a high-quality dataset for interpreting construction sequences and depositional processes (Cameron 1990; Lightfoot 1992; Varien and Potter 1997). At Pit structure 4, all cutting dates are within 6 years of one another with a strong mode indicating construction in the year 872 or 873 AD with a short occupation and a modest amount of remodeling prior to 875 AD. When plotted by the date of the outermost ring, the rapidly declining and flat left tail of non-cutting dates suggests that ring loss accounts for most of the discrepancies from the mode of cutting dates (Figure 2). An extremely early outlier non-cutting date (about 180 years earlier than the mode) is observed in this distribution and could be caused by a combination of dead

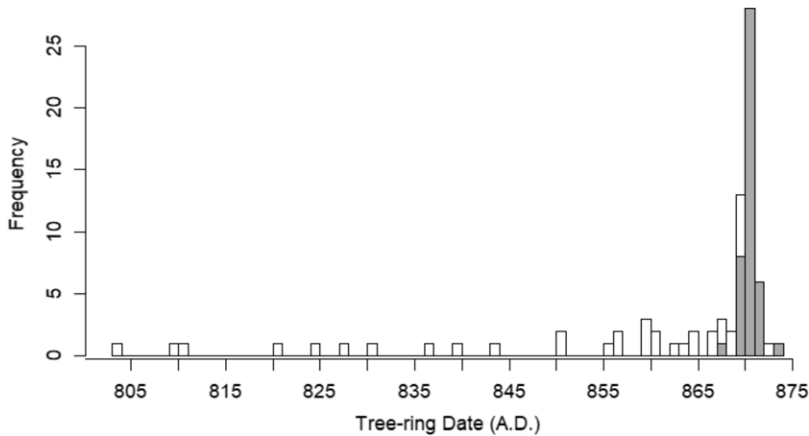


Figure 2 Distribution of tree-ring dates from Pit structure 4 at the Duckfoot site. The tight symmetrical distribution of cutting dates (gray bars) around AD 872 suggest construction of the site in 872 or before the growing season of 873 with modest additions of wood construction material in the structure in the few years after. The long, rapidly declining tail of non-cutting dates (white-bars) is a predictable outcome of random taphonomic ring-loss in an assemblage of cutting dates from a single short-term construction event. A single non-cutting date was recorded at AD 689 but was truncated from the distribution for the sake of clarity.

wood use, recycling, and significant ring loss (Lightfoot 1992). Pit structure 4 at Duckfoot then, provides an archetypal model for interpreting age disparities in assemblages of charcoal non-cutting dates. Non-cutting dates randomly grouped within decades prior to a cutting date cluster probably represent ring loss, and to a lesser extent beam stockpiling and recycling, while larger time gaps represent in-built age occurring due to other processes such as intergenerational beam recycling, dead wood use, and/or severe taphonomic degradation of the outer rings.

In the date cluster concept, the single most likely year for a construction date corresponds to the peak density or mode of a distribution of cutting dates assuming that the distribution of dates is unimodal. To calculate this value in the study, a gaussian kernel was fitted to cutting dates from all individual contexts to locate short-term building events with a single well-defined mode like the example from Duckfoot in Figure 2. Contexts with cutting dates ranges > 30 years and multiple modes were eliminated from the sample, and the true construction date ( $d_c$ ) for each context was assigned based on the maximum kernel density of the cutting date distribution. The age offset between the construction date and samples missing their outermost rings ( $d_n$ ) is simply:  $d_c - d_n$ . Where the larger the value, the greater the number of years that a non-cutting date is older than the modal construction date of its context. Negative age offsets (e.g., non-cutting dates younger than cutting date cluster) are possible due to remodeling after construction or the introduction of furniture and other non-structural artifacts that post-date construction. Based on the theory for cutting date cluster interpretation presented above, and the fact that this analysis excludes diffuse cutting date clusters from the sample, the working hypothesis for this study is that negative age offsets will be a rare occurrence. Regardless of this, the application of a probabilistic ring-loss correction does not depend heavily on the complete absence of negative age offsets in the empirical distribution (see “Statistical Methods and Date Calibration” section).

### Sample Partitioning

Sub-setting the dataset into different groups and performing significance tests across categories helps this study understand which factors affect the distribution of age disparities. The goal of this process is to objectively isolate discreet age offset functions based on readily characterized specimen attributes that can be tested in different contexts. This section discusses the factors upon which the sample was partitioned, and expectations for how such factors affect the data.

Taxonomy and taphonomy could interact to produce variability in age disparities. While interspecific wood properties impact the character of charcoal fragmentation (Chrzazvez et al. 2014), the coarse fraction (>2–4 mm) of charcoal assemblages tend to vary independently from species and reflect underlying species abundances (Chabal 1992; Théry-Parisot et al. 2010). This suggests that outer rings of dendrochronological samples should fragment independently of taxon—and therefore taxon should not influence the abundance of cutting dates or the distribution of non-cutting dates in the sample. As a check on this assumption the assemblage was partitioned into two sub-groups: pines/fir and juniper. The sample is composed mainly of junipers (*Juniperus* spp. Probably *J. scopulorum*) (67%) with Douglass fir (*Pseudotsuga menziesii*) comprising a minority of the sample (7%). The remainder of the sample are pines, with pinyon pine (*Pinus edulis* or *monophylla*) most numerous (20%) compared to ponderosa pine (*Pinus ponderosa*) (6%).

The taphonomic status of samples was classified based on recorded attributes. For example, the outer rings of fragmented specimens might be less likely to be recovered compared to intact cross-sections. If so, the shape of the distribution of age disparities in these two groups might vary significantly with fragments having a longer tail or larger central values. Typically, specimens in the database are classified as either cores, cross-sections, partial cross-sections, or fragments with wood, charred wood, and charcoal usually distinguished. For this study, specimens in the data set were partitioned into two groups, fragments and cross-sections, the latter group including samples marked as either cross-sections or partial cross-sections.

The age of specimens could also produce different age disparities independent of other factors. Ring widths of southwestern conifers often exhibit a characteristic negative growth trend, where average ring widths decrease to an asymptotic value as the tree ages. The expectation is that when the outside portions of ring segments are eroded, combusted, or biologically degraded, specimens from older trees—with narrower ring widths on their outer portions—are likely to lose more years from their ring record compared to younger trees. A pronounced nonlinear trend is not always evident, but visual examination of ring width plots from Rocky Mountain juniper (Dean 1995), ponderosa pine (Dean 1994), and two needle pinyon pine (Woodhouse et al. 2006) from the northern Colorado Plateau show that when it does occur, the growth phase characterized by large ring width increments occurs during the first 25 to 50 years. For segregating the data, ring segments longer than 50 years are considered “old” trees while segments shorter than 50 years are classified as “young” trees. Tree age was approximated by subtracting the outermost and innermost ring dates of each segment. For samples with pith or near pith rings, this age will be close to the true age of the tree, whereas for samples lacking pith or rings characteristic of being near pith this age represents the minimum tree age. A total of 102 tree-ring dates in the dataset had fewer than 50 rings and so were classified into the young tree group (14%) while 627 tree-ring segments had more than 50 years and so were classified into the older tree group (86%). Growth trends are affected by climate, stem height, competition, and site



productivity (Fritts 1976), and a single value describing a tree's growth status cannot capture the true variability in the sample. While a global method for age categorization based on an approximate age cutoff is admittedly simplistic, a method of age categorization must be adopted to initiate an exploration of the role of tree age on ring loss patterns in archaeological charcoal specimens. Because of the size of the data set, this analysis cannot retroactively measure each ring series and judge tree growth status from the actual ring width patterns. If the results motivate additional questions about the role of tree age on ring loss, then studies can more thoroughly investigate the topic. It is also noted that severe ring loss potentially complicates this (or any conceivable) age classification system. For example, a specimen originally containing hundreds of rings that is now observed to have less than fifty rings in its archaeological context will be misclassified. Such a specimen will rightly have a large age offset, but contrary to the expectation outlined above. If this is a widespread issue, then it would be expected that tree-age would be eliminated as a significant factor for predicting age disparities in charcoal.

Finally, the span of the date cluster (e.g., the range of cutting dates from a single context) was also evaluated for its effect on the distribution of age offsets. Intuitively, one would suspect that the distribution of non-cutting date age disparities would be more difficult to model with a parametric function in contexts where possible construction dates span many years as opposed to one or two years. This is simply because if there are multiple likely construction years there is less correspondence between the maximum kernel density (a single year) of the cutting date distribution and the offsets from the timing of the different construction episodes. It seems reasonable that spans of five years or less constitute a short duration building event and that the mode of such a cutting date distribution would be a reasonable approximation of the true timing of construction, especially for  $^{14}\text{C}$  dated contexts. It was already mentioned that the sample excluded all contexts with cutting date spans more than a human generation or about 30 years. However, it is not clear if narrower—but still somewhat diffuse—cutting date spans would significantly impact the distribution of age offsets in the tree-ring dates. To evaluate this, the sample was partitioned into two groups: contexts spanning 0–5 years and 6–30 years, where the span is simply the difference between the maximum and minimum cutting date, and so a span of zero years indicates that all cutting dates are the same year.

### **Statistical Methods and Date Calibration**

The empirical distributions of age disparities compiled in this study were modeled with a variety of probability density functions with the best fitting function selected to represent the age offset for that class of specimens. Candidate functions were fit to empirical distributions of age disparities with the `fitdistr()` function of the R package “`fitdistrplus`” (Delignette-Muller et al. 2015). Multiple functions including the exponential, log-normal, gamma, and Weibull distributions were examined as candidates for describing the empirical data generating functions. Parameter fitting was accomplished by maximum likelihood estimation, or in some cases, by minimizing the Anderson-Darling distance to maximize the goodness-of-fit of the tails (Delignette-Muller et al. 2015: Table 2). The fit of candidate models was compared using the Akaike Information Criterion (AIC) and one-sample Kolmogorov-Smirnov (K-S) tests. AIC is a tool for model selection that estimates the discrepancy between data and fitted models penalized for the number of parameters (Akaike 1974). When comparing models fitted to the same data, the most parsimonious model with the highest mean log-likelihood will have a lower AIC score and will be

avored as a description of the data (Sakamoto et al. 1986). The K-S test is a widely used non-parametric test comparing continuous distributions (Conover 1998). In the one sample K-S test, the null hypothesis is that the function generating the observed data is described by a candidate distribution (Venables and Ripley 2009). The K-S test is used in this paper not for direct model comparison but rather to verify that the probability of the null hypothesis ( $p_0$ ) is above the minimum level for acceptance/rejection ( $\alpha = 0.05$ ). AIC was calculated with the AIC() function and the K-S test was performed using the ks.test() function in R.

Mann-Whitney tests were applied to the distribution of age offsets in the partitioned Groups in step-wise fashion to test the null hypothesis that the age offsets in a particular pair of subgroups were identical. Partitions showing insignificant differences (null hypothesis with  $> 0.05$  probability) were eliminated and the combined dataset with remaining partitions were subjected to the next test until only significant partitions remained. The Mann-Whitney test was performed by a two sample Wilcoxon test with the R function wilcox.test().

To evaluate the accuracy of the hypothetical age offset functions,  $^{14}\text{C}$  wiggle matches calibrated against IntCal20 (Reimer et al. 2020) in OxCal 4.4 (Bronk Ramsey 2009) were corrected for age disparity by adding the age offset to the modeled outermost ring date (see Supplement 4):

$$\text{wm} + \text{offset} - \text{range\_shift}$$

where `wm` is a `D_Sequence()` model and `offset` denotes a generalized distribution function (Bronk Ramsey et al. 2001; Bronk Ramsey 2020). The term `range_shift` denotes a small negative value added back to the age offset to correct for the probability of negative (or younger than the modal cutting date) age disparities in the distribution. Due to the presence of a smaller number of negative values in the empirical distribution of age disparities, a positive range shift had to be applied to the distribution prior to fitting density functions such as the log-normal. The range shift was accomplished by adding the absolute value of the minimum age offset plus one. Reversing the sign of the range shift and adding it back to the predicted values of the age offset function produces correctly scaled age offsets. The goal of the study was to describe typical age offsets due to ring loss and other factors and the presence of negative values—and the necessity of a range shift to correct for this—adds noise to the resulting age offset functions. The simple fix for this would be to eliminate contexts with negative age disparities. However, this would have consequences for the size of the dataset and resulting statistical power of the analysis. The approach of this study—allowing negative age disparities—trades some noise in the function for robustness. It is predicted that with a more perfect dataset the resulting age offset functions would have tighter modal values but would be substantially similar in terms of the range and shape of the functions produced with the noisier data.

In addition to applying the age offset to a single wiggle-matched date, this study undertook a simulation to evaluate whether existing tools in OxCal—specifically the `Outlier_Model()` function—could be utilized to correct for expected age disparities caused by outer ring loss. For this, an age offset function determined in this study was used in place of the exponential function typically recommended to model age disparities caused by in-built age for old charcoal samples (see Dee and Bronk Ramsey 2014). For example:

`Outlier_Model (“ring loss”,U(0,10)-LnN(1,0.1),U(0,1),“t”);`

Note that “U(0,10)” in the above CQL2 code for the outlier model describes the range shift function detailed above, and the parameters of the log normal function LnN() given above are for illustration only, and in actual usage depend on the fitted parameters of the appropriate density function.

A sequence of five building events each separated by 18 years (an 18-year *tempo*) is simulated in this study with three non-cutting dates in each of the sequential phases for a total of 15 dates. Eighteen years was chosen as the interval between simulated events because it corresponds to hypothetical intervals proposed for monumental additions in the Cahokia area (Pauketat et al. 2017) and is also on the shorter end of a human generation length. In this way, the simulation explores how taphonomic ring-loss and ring-loss correction might affect archaeological reconstructions of historically relevant question at human scale. Each event in the hypothetical sequence is modeled from three simulated D\_Sequence() models in a single phase. The sequence is modeled with no cutting dates and the test evaluates whether the outlier tool with an appropriate model and parameters can reconstruct the true dates and tempo of the simulated events. Each D\_Sequence() consisted of five R\_Simulate() dates in a 40 year long sequence with a Gap() of nine years (see Supplement 5A). The simulated target date for the outermost ring in all the D\_Sequence() models for the first phase is AD 1050, with the next four following in sequence at 1068, 1086, 1104, and 1122 (Supplement 5A). To produce age disparities, a random number of years was subtracted from each wiggle-match model with the number drawn from the appropriate age offset subgroup. The simulated sequence was calibrated with and without an outlier model to evaluate how an appropriately parameterized outlier function corrects for age disparities expected from ring loss (see Supplement 5B). The simulation was repeated for five iterations, and results are summarized as the pooled mean and standard deviations of the three D\_Sequence() models in each phase.

## RESULTS AND DISCUSSION

Age offsets for all non-cutting dates ( $n = 729$ ) are distributed from -12 to 583 years with modal age disparity between 0-5 years (Figure 3). Based on the AIC test, a log-normal function is the most informative model for the empirical distribution of the total un-partitioned dataset, but the fitted function ( $\mu = 3.54$ ,  $\sigma^2 = 0.72$ ) is nonetheless an unlikely candidate for the data generating function of the un-partitioned data based on the K-S test ( $D = 0.08$ ,  $p_0 = 0.003$ ). Examining Figure 3 it appears that the candidate function underestimates the density of very high age disparities and underestimates the density of very small age disparities. This supports the assumption that additional factors influence the distribution of age offsets in the sample.

### Significance of sample characteristics on age disparity

Tree taxa and the span of cutting dates are insignificant factors in the analysis of age offsets. The null hypothesis that age offsets in juniper ( $n = 488$ ) and pine/fir ( $n = 241$ ) are equivalent is supported by Mann-Whitney tests in seven of the eight possible groups (Table 1). This does not suggest that other taxonomic divisions (for example conifers vs hardwoods) would not result in significant differences in age offsets in other cases, only that dividing the all-conifer sample in this study yielded no consistent benefit compared to other categorical divisions. Age offset is also not consistently related to the span of the date cluster either. The null hypothesis, that the distribution of non-cutting dates from contexts with diffuse cutting date clusters (cutting date

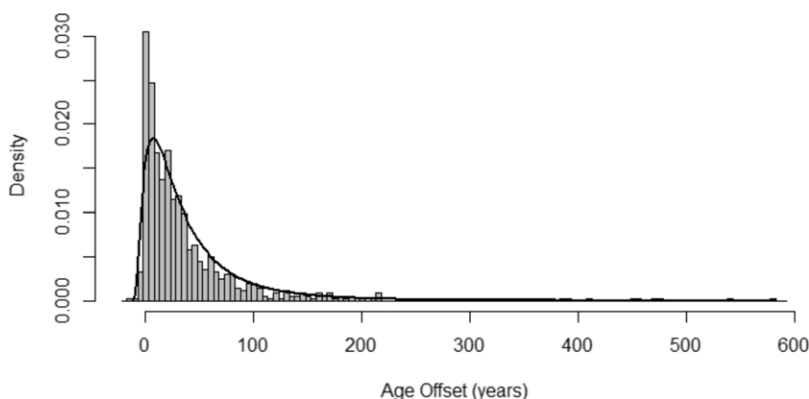


Figure 3 Histogram of the distribution of all age disparities in the sample. The black line shows the density distribution of a log-normal function ( $\log(\mu) = 3.54$ ,  $\log(\sigma) = 0.72$ ) fit to the distribution. The probability from the K-S test that the two distributions are identical is small enough to reject this model as an acceptable estimate for the data generating function ( $p_0 = 0.003$ ).

spans of 6-30 years) ( $n = 545$ ) is identical to tight clusters ( $\leq 5$  years) ( $n = 184$ ) cannot be rejected in any pairing when taxa is disregarded.

Dropping date cluster span and taxa as significant factors focuses the analysis on the state of preservation and tree age. Both factors appear to have significant effects on the distribution of age disparities of non-cutting dates. The null hypothesis that age offsets of fragmented specimens ( $n = 569$ ) are identical to cross-sections ( $n = 160$ ) is rejected in groups of both older ( $> 50$  rings) and younger ( $\leq 50$  rings) tree specimens. Likewise, the null hypothesis that age offsets of older tree specimens ( $n = 627$ ) are identical to younger trees ( $n = 102$ ) is rejected for both fragmented and intact specimens (Table 1). The simple classification of taphonomic state and tree age captures significant variability in the predicted age disparity. Specimens with fewer remnant rings are associated with probabilistically smaller age disparities, just as fragmented specimens are associated with probabilistically larger age disparities. A 73 percent increase in modeled mean age disparity is observed with fragmentation and an 83 percent increase in mean age disparity is associated with tree age. These effects work in concert to produce increasing levels of age disparity as predicted at the outset.

The results of subdividing the dataset support the intuitive assumption that greater levels of mechanical destruction correlate to increased ring loss, and that the characteristic growth trend of conifers causes a loss of more rings from the outsides of older trees compared to younger trees. This translates to ranked predicted age offset ordered from lowest to highest: intact specimens from younger trees (Group 1,  $n = 13$ ), fragmented specimens from younger trees (Group 2,  $n = 89$ ), intact specimens from older trees (Group 3,  $n = 147$ ), and fragmented specimens from older trees (Group 4,  $n = 480$ ).

Box plots of the distribution of age offsets in each group (Figure 4) and the parameters of the fitted probability density functions also support the predicted ranks for age offset associated with each Group (Table 2). In all cases there is a rapid non-linear decline in the frequency of age offsets from low values (0–5 years) (Figure 5), and a log-normal distribution is the best fitting

Table 1 Effects of event duration, specimen fragmentation, and tree age on the distribution of age disparities in different sample partitions determined by Mann-Whitney (two-sample Wilcoxon) tests.

	Test statistic	p-value
<i>Null Hypothesis: Juniper = Pine/Fir</i>		
Cross categories		
Single year x younger trees x cross-sections		Insufficient sample size
Intragenerational x younger trees x cross-sections	1	0.377
Single year x younger trees x fragments	20	0.47
Intragenerational x younger trees x fragments	340	0.88
Single year x older trees x cross-sections	44	0.41
Intragenerational x older trees x cross-sections	971	<b>0.02</b>
Single year x older trees x fragments	1826	0.82
Intragenerational x older trees x fragments	7562	0.99
<i>Null Hypothesis: Intragenerational cluster = Single year cluster</i>		
Younger trees x cross-sections	15	0.79
Younger trees x fragments	1080	0.06
Older trees x cross-sections	1342	0.57
Older trees x fragments	22881	0.33
<i>Null Hypothesis: Fragmented = Cross-sections</i>		
Younger trees	856	<b>&lt;0.01</b>
Older trees	38840	<b>0.03</b>
<i>Null Hypothesis: Older trees = Younger trees</i>		
Cross-sections	1509	<b>&lt;0.01</b>
Fragments	28522	<b>&lt;0.01</b>

model to describe the distribution of age offsets in all Groups. The goodness-of-fit between the empirical distribution of age disparities and the fitted log-normal functions for all groups is above the level of rejection. However, it is interesting to note that the goodness-of-fit for Group 4 ( $p_0 = 0.07$ ), though still above the threshold of rejection, is low. Group 4 is the largest sample size of the partitions, and like the unpartitioned data there may be latent factors affecting the distribution. Visual examination of the empirical distribution of Group 4 age disparities and the fitted function (Figure 5) suggests that the candidate function is still an adequate approximation for the purpose of this study. These results suggest that multiple factors can affect the probability of age disparity caused ring loss or in-built age of charcoal samples, and if analysts seek more accurate statistical representations of outlier  $^{14}\text{C}$  dates of wood or charcoal then consideration of these factors is necessary.

### The Accuracy of Age Offset Functions

Adding an age offset function from this study to a degraded wiggle-matched ring series from a real archaeological context helps validate the results of model fitting with independent data. The study of Turkon et al. (2018) provides such an example, where wiggle-matched cutting

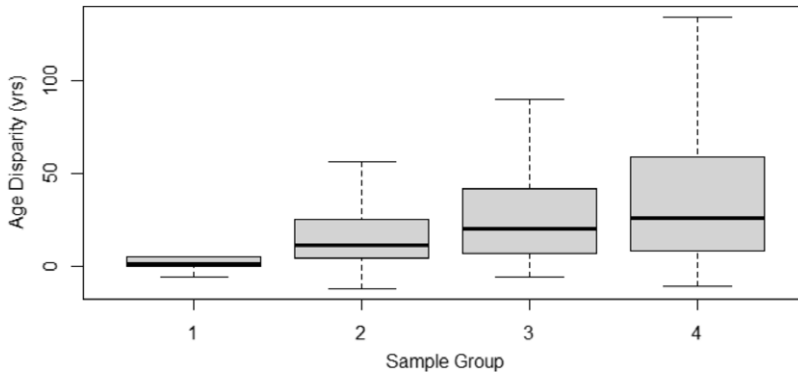


Figure 4 Box plot showing the change in the distribution of age disparities with each sample Group discussed in the text. As predicted, age disparity increases from Group 1 (cross-sections from younger trees) to Group 4 (fragmented specimens from older trees). The reasons for this relationship are discussed in the text. Large outlier values in Group 2 and 4 are omitted for clarity.

dates provided a chronology of monumental construction at La Quemada Cuartel and Los Pillarios archaeological sites in Zacatecas, Mexico. These sites were important local monumental and political centers in the Malapaso Valley on the northern frontier of Classical Mesoamerican civilization during the first Millennium AD (Turkon et al. 2018:105–106). In their study, tree-ring series were cross-matched into a relative chronology and then anchored in time with sequential  $^{14}\text{C}$  dates. One context dated by the investigators consisted of roof fall in a temple complex at Los Pillarios that, based on two wiggle-matched cutting dates and its relationship to La Quemada Cuartel, they interpret as dating to ca. AD 770 (p. 117). However, one sample from this context (PIL 15) lacked the terminal growth ring or any indication of the waxy edge and predated the other cutting dates from Los Pillarios by more than 60 years. According to the authors, this date is still congruent with the AD 770 hypothesis based on archaeological context. For this test case, an estimated cutting date was obtained by adding the age offset function for the appropriate group—parameterized according to Table 2—to the TPQ date of a hypothetical wiggle-matched ring series in OxCal (see Supplement 4).

Sample PIL 15 from Los Pillarios is a fragmented specimen containing more than 70 rings (Turkon et al. 2018: 111) which places the sample into Group 4. Seven sequential  $^{14}\text{C}$  dates from PIL 15 (Turkon et al. 2018: Table 3) were recalibrated against IntCal20 (Reimer et al. 2020) and yielded a modeled date of 706 AD ( $\mu \pm 5$  ( $\sigma$ )), an age which is virtually identical to the original report. Applying the age offset function derived from Group 4 specimens yields a cutting date corrected for ring loss between 702 and 850 AD (95.4% posterior density), and probably 711–764 AD (68.2% posterior density) (Figure 6). The mean cutting date estimate corrected for ring loss is 756 AD  $\pm 47$  ( $1\sigma$ ), and agrees with the authors' interpretation based on the archaeological evidence and other high-precision  $^{14}\text{C}$  ages that PIL15 dates a context that was built around 770 AD. This supports the conclusion that the modeling process in this study yielded a realistic estimate of age offset in non-cutting dates from fragmented and charred tree-ring specimens.

Table 2 Summary of the continuous probability functions describing the age offsets of each Group. Statistical fit is p-value of the K-S test used to estimate the probability that the candidate function is representative of the empirical data generating function.

Group	Sample size	Range of date disparities		Log-normal model parameters		Mean age offset	Statistical fit	
		Min	Max	$\mu$	$\sigma^2$		K-S p-value	$R^2$
1. Younger trees x cross-sections	13	-6	42	2.25	0.93	9.5	0.57	0.85
2. Younger trees x fragments	89	-12	369	3.24	0.64	25.5	0.13	0.55
3. Older trees x cross-sections	147	-6	188	3.29	0.93	26.8	0.82	0.90
4. Older trees x fragments	480	-11	583	3.62	0.79	37.3	0.07	0.92

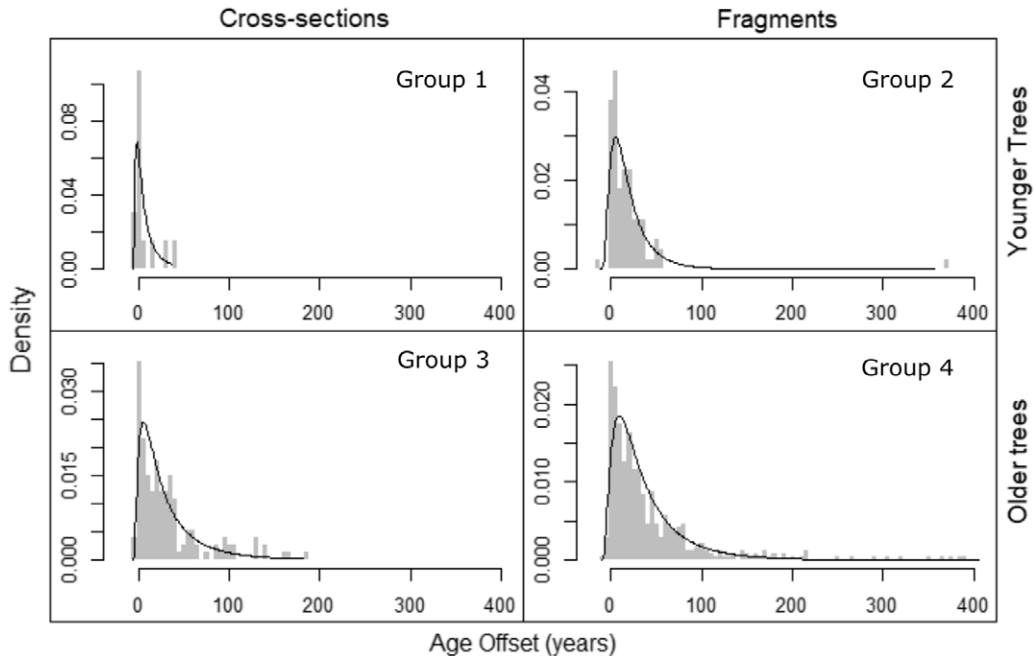


Figure 5 Distribution of age disparities in the four sample groups. Lines show the log-normal function fit to each group with parameters and goodness-of-fit given in Table 2.

### Age Offset Functions in Archaeological Sequences

As can be seen from the empirical distributions of dating disparities (Figures 3 and 5), ring loss can span decades to centuries in some samples. This means that stratigraphic date inversions can be generated by ring loss alone in short duration sequences and is a potential problem for archaeologists seeking to answer questions about the tempo of historical events, particularly if the recurrence interval is on the order of years. For example, an archaeological debate about the nature of recurring construction events could involve tempos ranging from annual to generational spans and can only be resolved with high-resolution dates in a reliable sequence. The Mississippian region of North America provides such a case where the evolving rearrangement of space within sacred precincts, punctuated by repetitive additions, is commonly observed in the archaeological record (Lindauer and Blitz 1997:176). Researchers have proposed various scenarios for monumental additions and renewal activity with tempos ranging from annual to multi decadal (Anderson 1994:127; Hally 1996; Pauketat 2002; Alt and Pauketat 2017).

In a simulation, introducing random age disparities into wiggle-match models (based on Group 2 specimens) in hypothetical sequences produced date inversions that would be problematic in the absence of an appropriate outlier model (Figure 7). This is observed in the low agreement index for the uncorrected sequence averaged for the five iterations ( $A_{\text{model}} = 17$ ) compared to the sequence corrected for age offset ( $A_{\text{model}} = 87$ ). Dates from the sequence corrected using the age offset parameters for Group 2 specimens (Table 2) are less precise but more accurate than dates from the uncorrected simulated sequences (Table 3). Reconstructed event dates in the



Table 3 Comparison of simulated age disparities in wiggle-match dated phases calibrated as is and with an outlier model to correct for predicted age offset.

Target	Uncorrected	Corrected
$A_{\text{model}}$	17	87
Event @ 1050	1019 ± 11	1050 ± 12
Interval (18 yr)	5 ± 11	24 ± 13
Event @ 1068	1035 ± 3	1067 ± 10
Interval (18 yr)	3 ± 1	6 ± 5
Event @ 1086	1054 ± 4	1085 ± 11
Interval (18 yr)	4 ± 3	8 ± 7
Event @ 1104	1077 ± 6	1107 ± 11
Interval (18 yr)	6 ± 6	6 ± 5
Event @ 1122	1097 ± 15	1126 ± 14

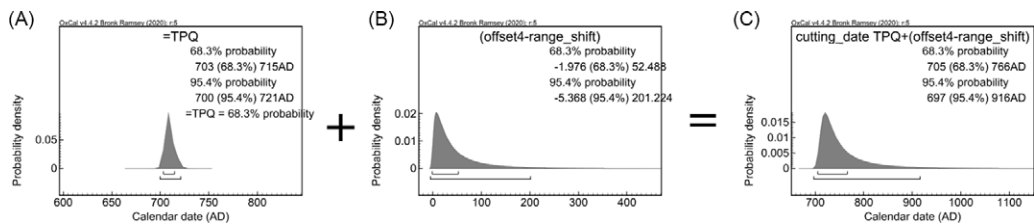


Figure 6 Schematic for the age-offset correction for Group 4 samples applied to a single non-cutting wiggle-matched date from the Los Pillarios archaeological site (data from Turkon et al. 2018). The TPQ distribution (Panel A) is the posterior distribution of the outermost ring from the wiggle-match model. Panel B shows the age-offset correction which consists of the function derived from the distribution of age disparities in Group 4 samples with the range shift to account for negative values in the log-normal function (see “Methods and Materials” section for explanation). The estimated posterior density for the true cutting date for the sample is shown in Panel C.

uncorrected sequence are inaccurate in three of the four phases while the corrected sequences accurately reconstruct the “true” event date for each phase. The uncorrected sequence underestimates the true time span between phases in two of the four intervals averaged across the five iterations, whereas the corrected sequence accurately reconstructs the true interval between each phase. Importantly, the corrected age model reconstructs the true interval between phases with enough precision in three of the four cases to distinguish events occurring on a generational or sub-generational tempo (approximately 25 years) from events occurring at a longer tempo.

Experimentation with this simulation revealed that three  $D_{\text{Sequence}}()$  ages per phase is near the limit of accuracy and precision demonstrated above. While removing one date from up to two phases does not markedly impact the results, using only two dates for all five phases does erode the degree to which event dates and the tempo of events can be accurately reconstructed in the simulation. Because the precision of wiggle-matches should vary with series length and position on the calibration curve (Bayliss et al. 2020), studies seeking to apply this method for correcting TPQ dates for ring loss are advised to simulate effects in their situation.

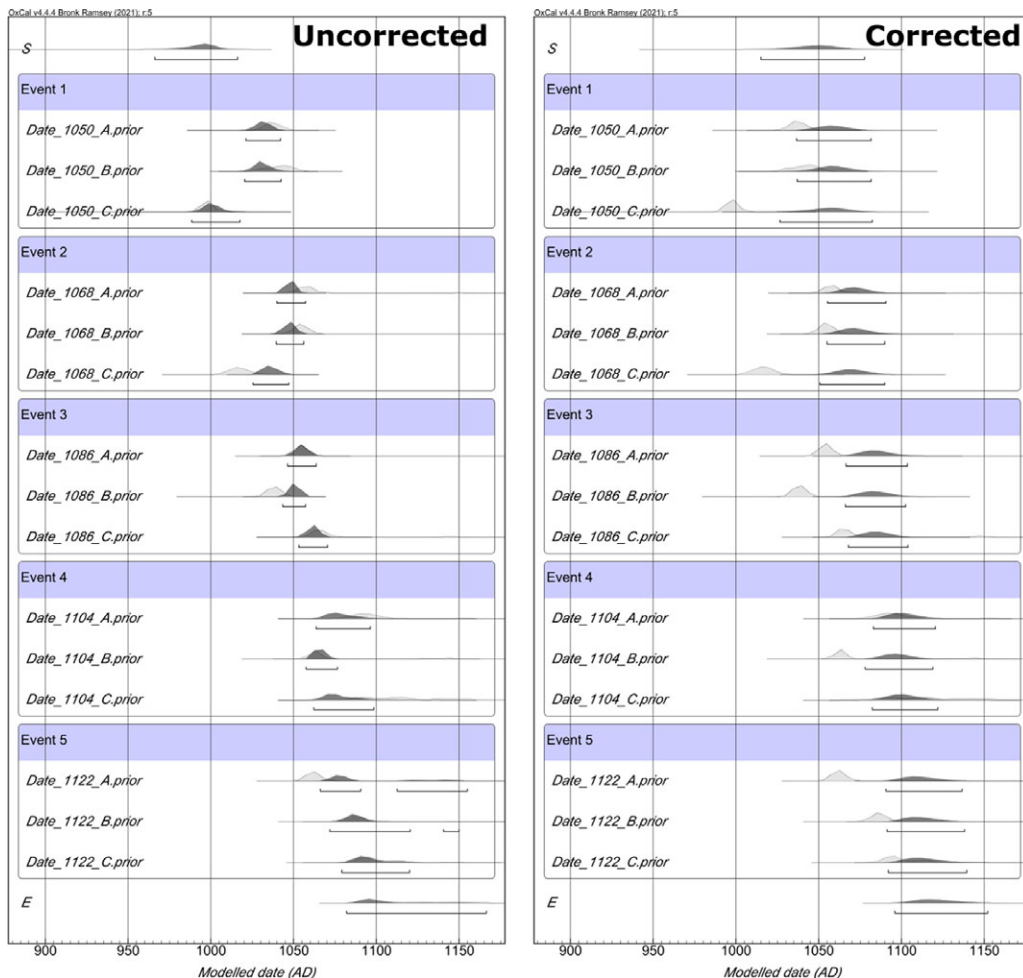


Figure 7 Simulation of two identical sequences composed of five phases of simulated dates in wiggle-match models. All of the simulated wiggle-matches are non-cutting dates with age disparities randomly drawn from the distribution of Group 2 samples. The uncorrected sequence (left) has poor agreement due to multiple stratigraphic inversions caused by ring loss. The sequence on the right was corrected by the application of an outlier model parameterized with the log-normal function shown in Table 2. The corrected sequence has acceptable agreement and accurately reproduces both the true age of each simulated phase as well as the tempo of the events represented by each hypothetical phase.

## CONCLUSIONS

The purpose of modeling age disparities of non-cutting tree-ring dates was to develop a correction for wiggle-matched  $^{14}\text{C}$  sequences from charcoal lacking terminal growth rings and any indication regarding the original width of sapwood. Two significant factors for predicting the span of age offset between inferred construction events and non-cutting dates were isolated. Both fragmentation of ring segments and tree age increase the probabilistic age offset, with tree age having a slightly greater effect. The statistical functions fit to the distribution of age disparities are characterized by a rapidly decreasing probability from modal values around 0 to 5 years, with a mean age offset ranging from 10 to 40 years

depending on the type of specimen. Age offset corrected cutting dates necessarily have more uncertainty than wiggle-matched non-cutting TPQ dates. However, because age disparities of non-cutting dates can span multiple decades or centuries, a correct estimation of age offset in samples lacking outer rings enables a more accurate modeled date when the precision of wiggle-matches are only a fraction of the potential disparity. By accounting for age disparities, an analyst can estimate the true target of tree-ring dating in a wiggle-match calibration model, the year of tree death, within a margin of error. The applied case study supports the accuracy of the age offset function. In this example, the age offset correction yielded a realistic cutting date for the archaeological context in question, a date that is supported with independent archaeological and chronometric evidence. The simulation presented in this paper suggests that in cases where no cutting dates are available, outlier models with an appropriate age offset function can accurately reconstruct events at generational tempos. These results show that accurate and precise  $^{14}\text{C}$  dated events can be reconstructed from sequences of non-cutting dates when a realistic model of age disparities can be estimated.

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## SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit <https://doi.org/10.1017/RDC.2021.109>

## REFERENCES

- Adams EC. 1983. The architectural analogue to Hopi social organization and room use and implications for prehistoric northern southwestern culture. *American Antiquity* 48(1):44–61.
- Adler MA, Wilshusen RH. 1990. Large-scale integrative facilities in tribal societies: cross-cultural and southwestern US examples. *World Archaeology* 22(2):133–146.
- Ahlstrom RVN. 1985. The interpretation of archaeological tree-ring dates [PhD dissertation]. Tucson (AZ): University of Arizona.
- Ahlstrom RVN, Dean JS, Robinson WJ. 1991. Evaluating tree-ring interpretations at Walpi Pueblo, Arizona. *American Antiquity* 56(4):628–644. doi: [10.2307/281541](https://doi.org/10.2307/281541).
- Akaike H. 1974. A new look at the statistical model identification. *IEEE Transactions on Automatic Control* 19(6): 716–723.
- Allen MS, Huebert JM. 2014. Short-lived plant materials long-lived trees and Polynesian  $^{14}\text{C}$  dating: Considerations for  $^{14}\text{C}$  sample selection and documentation. *Radiocarbon* 56(1):257–276.
- Alt SM, Pauketat TR. 2017. The elements of Cahokian shrine complexes and basis of Mississippian religion. In: *Religion and politics in the ancient Americas*. New York: Routledge. p. 51–74.
- Anderson DG. 1994. *The Savannah River chiefdoms: political change in the late prehistoric Southeast*. Tuscaloosa (AL): University of Alabama Press.
- Ashmore PJ. 1999. Radiocarbon dating: avoiding errors by avoiding mixed samples. *Antiquity* 73(279):124.
- Bailey GN. 1983. Concepts of time in Quaternary prehistory. *Annual Review of Anthropology* 12(1):165–192.
- Bannister B. 1962. The interpretation of tree-ring dates. *American Antiquity* 508–514.
- Bayliss A. 2009. Rolling out revolution: using radiocarbon dating in archaeology. *Radiocarbon* 51(1):123–147.
- Bayliss A, Marshall P, Dee MW, Friedrich M, Heaton TJ, Wacker L. 2020. IntCal20 tree rings: an archaeological SWOT Analysis. *Radiocarbon* 62(4):1045–1078. doi: [10.1017/RDC.2020.77](https://doi.org/10.1017/RDC.2020.77).

- Beck Jr RA, Bolender DJ, Brown JA, Earle TK. 2007. Eventful archaeology: the place of space in structural transformation. *Current Anthropology* 48(6):833–860.
- Bleicher N, Walder F, Gut U, Bolliger M. 2020. The Zurich method for sapwood estimation. *Dendrochronologia* 64:125776.
- Blockley SPE, Pinhasi R. 2011. A revised chronology for the adoption of agriculture in the Southern Levant and the role of Lateglacial climatic change. *Quaternary Science Reviews* 30(1–2):98–108.
- Bolender D. J. 2010. Toward and eventful archaeology. In: *Eventful archaeologies: new approaches to social transformation in the archaeological record* (pp. 3–14). New York: SUNY Press.
- Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–360. doi: [10.1017/S0033822200033865](https://doi.org/10.1017/S0033822200033865).
- Bronk Ramsey C. 2020. OxCal 4.4 Manual Web Interface Build Number 130. Retrieved December 15, 2020 from [https://c14.arch.ox.ac.uk/oxcalhelp/hlp\\_contents.html](https://c14.arch.ox.ac.uk/oxcalhelp/hlp_contents.html)
- Bronk Ramsey C, van der Plicht JH, Weninger B. 2001. “Wiggle Matching” radiocarbon dates. *Radiocarbon* 43(2A):381–389. doi: [10.1017/S0033822200038248](https://doi.org/10.1017/S0033822200038248).
- Cameron CM. 1990. Pit structure abandonment in the Four Corners region of the American Southwest: Late Basketmaker III and Pueblo I periods. *Journal of Field Archaeology* 17(1):27–37.
- Chabal L. 1992. La représentativité paléo-écologique des charbons de bois archéologiques issus du bois de feu. *Bulletin de La Société Botanique de France. Actualités Botaniques* 139(2–4):213–236.
- Chrzazvez J, Théry-Parisot I, Fiorucci G, Terral J-F, Thibaut B. 2014. Impact of post-depositional processes on charcoal fragmentation and archaeobotanical implications: experimental approach combining charcoal analysis and biomechanics. *Journal of Archaeological Science* 44:30–42.
- Clarke D. 1973. Archaeology: the loss of innocence. *Antiquity* 47(185):6.
- Conover WJ. 1998. *Practical nonparametric statistics*. Vol. 350. New York: John Wiley & Sons.
- Cook RA, Comstock AR. 2014. Evaluating the old wood problem in a temperate climate: a Fort Ancient case study. *American Antiquity* 79(4):763–775.
- David B. 2008. Rethinking cultural chronologies and past landscape engagement in the Kopi region Gulf Province Papua New Guinea. *The Holocene* 18(3):463–479.
- Dean JS. 1978. Independent dating in archaeological analysis. *Advances in Archaeological Method and Theory* 1:223–255.
- Dean JS. 1981. *Chronological analysis of Tsegi Phase sites in northeastern Arizona*. 2nd printing. Tucson (AZ): The University of Arizona Press.
- Dean JS. 1994. Ditch Canyon—PIPO - ITRDB NM021. Retrieved from National Centers for Environmental Information NESDIS NOAA U.S. Department of Commerce website: <https://www.ncdc.noaa.gov/paleo-search/study/3073?siteId=15542>.
- Dean JS. 1995. Dead Juniper Wash—JUSP - ITRDB AZ103. Retrieved from National Centers for Environmental Information NESDIS NOAA U.S. Department of Commerce website: <https://www.ncdc.noaa.gov/paleo-search/study/3069?siteId=15539>.
- Dean JS, Ravesloot JC. 1993. The chronology of cultural interaction in the Gran Chichimeca. In: Woosley AI, Ravesloot JC, editors. *Culture and contact: Charles C. Di Peso's Gran Chichimeca*. Albuquerque: University of New Mexico Press.
- Dee MW, Bronk Ramsey C. 2014. High-p[recision bayesian modeling of samples susceptible to inbuilt age. *Radiocarbon* 56(1):83–94. doi: [10.2458/56.16685](https://doi.org/10.2458/56.16685).
- Delignette-Muller ML, Dutang C, et al. 2015. *fitdistrplus: An R package for fitting distributions*. *Journal of Statistical Software* 64(4):1–34.
- Douglass AE. 1935. *Dating Pueblo Bonito and other ruins of the Southwest*. Washington D.C.: National Geographic Society.
- Douglass AE. 1939. Notes on beam dating by sap-heart contact. *Tree-Ring Bulletin* 3(6):1–6.
- Dufraisse A, Coubray S, Girardclos O, Dupin A, Lemoine M. 2018. Contribution of tyloses quantification in earlywood oak vessels to archaeological charcoal analyses: estimation of a minimum age and influences of physiological and environmental factors. *Quaternary International* 463:250–257.
- Fitzpatrick SM. 2006. A critical approach to dating in the Caribbean: using chronometric hygiene to evaluate chronological control and prehistoric settlement. *Latin American Antiquity* 17(4):389–418.
- Fritts HC. 1976. *Tree-rings and climate*. 1st ed. London: Academic Press.
- Gilmore ZI. 2015. Direct radiocarbon dating of Spanish moss (*Tillandsia usneoides*) from early fiber-tempered pottery in the southeastern US. *Journal of Archaeological Science* 58:1–8.
- Graves MW. 1991. Estimating ring loss on tree-ring specimens from east-central Arizona: implications for prehistoric pueblo growth at Grasshopper Ruin. *Journal of Quantitative Anthropology* 3:83–115.
- Hally DJ. 1996. Mound construction and the instability of Mississippian chiefdoms. In: *Chiefly politics*. Gainesville (FL): University of Florida Press. p. 92–127.
- Hamilton WD, Krus AM. 2018. The myths and realities of Bayesian chronological modeling revealed. *American Antiquity* 83(2):187–203.

- Haneca K, Debonne V. 2012. Precise tree-ring dating of building activities despite the absence of bark: a case-study on medieval church roofs in Damme Belgium. *Dendrochronologia* 30(1):23–34.
- Hart JP, Brumbach HJ. 2005. Cooking residues AMS dates and the Middle-to-Late-Woodland transition in central New York. *Northeast Anthropology* 69:1–34.
- Hart JP, Nolan KC. 2015. Comment on Cook and Comstock's "Evaluating the Old Wood Problem in a Temperate Climate: A Fort Ancient Case Study." *American Antiquity* 80(3):610–612.
- Haury EW. 1935. Tree rings. The archaeologist's time-piece. *American Antiquity* 1(2):98–108.
- Higham T, Douka K, Wood R, Ramsey CB, Brock F, Basell L, et al. 2014. The timing and spatiotemporal patterning of Neanderthal disappearance. *Nature* 512(7514):306–309.
- Holstein E. 1980. *Mitteuropäische Eichenchronologie: Trierer dendrochronologische Forschungen zur Archäologie und Kunstgeschichte*. Mainz am Rhein: Philipp von Zabern.
- Kabuku C. 2018. Wood charcoal analysis in archaeology. In: Pişkin E, Marciniak A, Bartkowiak M, editors. *Environmental archaeology: current theoretical and methodological approaches*. Cham, Switzerland: Springer International Publishing. doi: [10.1007/978-3-319-75082-8\\_7](https://doi.org/10.1007/978-3-319-75082-8_7). p. 133–154.
- Kennett DJ, Ingram BL, Southon JR, Wise K. 2002. Differences in  $^{14}\text{C}$  age between stratigraphically associated charcoal and marine shell from the Archaic period site of Kilometer 4 southern Peru: old wood or old water? *Radiocarbon* 44(1):53–58.
- Kim J, Wright DK, Hwang J, Kim J, Oh Y. 2019. The old wood effect revisited: A comparison of radiocarbon dates of wood charcoal and short-lived taxa from Korea. *Archaeological and Anthropological Sciences* 11(7): 3435–3448.
- Kohler TA, Higgins R. 2016. Quantifying household inequality in early Pueblo villages. *Current Anthropology* 57(5):690–697.
- Kohler TA, Matthews MH. 1988. Long-term Anasazi land use and forest reduction: a case study from southwest Colorado. *American Antiquity* 53(3):537–564.
- Krus AM, Cook R, Hamilton WD. 2015. Bayesian chronological modeling of SunWatch a fort ancient village in Dayton, Ohio. *Radiocarbon* 57(5):965–977.
- Lightfoot RR. 1992. Architecture and tree-ring dating at the Duckfoot site in southwestern Colorado. *Kiva* 57(3):213–236.
- Lindauer O, Blitz JH. 1997. Higher ground: the archaeology of North American platform mounds. *Journal of Archaeological Research* 5(2):169–207.
- Lucas G. 2008. Time and archaeological event. *Cambridge Archaeological Journal* 18(1):59.
- Martin EP, Coltrain JB, Coddling BF. 2017. Revisiting Hogup Cave Utah: insights from new radiocarbon dates and stratigraphic analysis. *American Antiquity* 82(2):301–324.
- Martin PS. 1938. *Archaeological Work in the Ackmen-Lowry Area Southwestern Colorado 1937*. Chicago: Field Museum of Natural History.
- McGuire RH, Schiffer MB. 1983. A theory of architectural design. *Journal of Anthropological Archaeology* 2(3):277–303.
- Morris EH. 1937. *Archaeological studies in the La Plata District southwestern Colorado and northwestern New Mexico*. Washington D.C.: Carnegie Institution of Washington.
- Nash SE. 1997. A cutting-date estimation technique for ponderosa pine and Douglas fir wood specimens. *American Antiquity* 62(2):260–272.
- Nolan KC. 2012. Temporal hygiene: problems in cultural chronology of the Late Prehistoric Period of the Middle Ohio River Valley. *Southeastern Archaeology* 31(2):185–206.
- Pauketat TR. 2002. A fourth-generation synthesis of Cahokia and Mississippianization. *Midcontinental Journal of Archaeology* 27(2):149–170.
- Pauketat TR, Alt SM, Kruchten JD. 2017. The Emerald Acropolis: elevating the moon and water in the rise of Cahokia. *Antiquity* 91(355):207–222.
- Pettitt PB, Davies W, Gamble CS, Richards MB. 2003. Palaeolithic radiocarbon chronology: quantifying our confidence beyond two half-lives. *Journal of Archaeological Science* 30(12):1685–1693.
- Pierce C. 2005. The development of corrugated pottery in southwestern Colorado. *Kiva* 71(1):79–100.
- Price TD. 2007. *Principles of archaeology*. Boston: McGraw-Hill.
- Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, et al. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62(4): 725–757. doi: [10.1017/RDC.2020.41](https://doi.org/10.1017/RDC.2020.41).
- Renfrew C, Bahn P. 2004. *Archaeology: theories methods and practice*. London: Thames and Hudson.
- Robinson WJ, Ahlstrom RVN. 1980. Re-evaluation of using heartwood to estimate sapwood. Report submitted to Taylor Museum Colorado Springs Fine Arts Center. Laboratory of Tree-Ring Research, University of Arizona.
- Sakamoto Y, Ishiguro M, Kitagawa G. 1986. *Akaike information criterion statistics*. Dordrecht, Netherlands: D. Reidel.
- Schachner G. 2010. Corporate group formation and differentiation in early Puebloan villages of the American Southwest. *American Antiquity* 75(3):473–496.

- Schiffer MB. 1972. Archaeological context and systemic context. *American Antiquity* 37(2) 156–165.
- Schiffer MB. 1986. Radiocarbon dating and the “old wood” problem: the case of the Hohokam chronology. *Journal of Archaeological Science* 13(1):13–30.
- Smiley FE. 1998. Old wood: assessing age overestimation. In: *Archaeological chronometry: radiocarbon and tree-ring models and applications from Black Mesa, Arizona*. Occasional Paper: Vol. 16. Carbondale (IL): Southern Illinois University at Carbondale. p. 49–64.
- Sohar K, Adomas V, Läänelaid A. 2012. Sapwood estimates of pedunculate oak (*Quercus robur* L.) in eastern Baltic. *Dendrochronologia* 30:49–56.
- Spriggs M. 1989. The dating of the Island Southeast Asian Neolithic: an attempt at chronometric hygiene and linguistic correlation. *Antiquity* 63(240):587–613.
- Taché K, Hart JP. 2013. Chronometric hygiene of radiocarbon databases for early durable cooking vessel technologies in northeastern North America. *American Antiquity* 78(2):359–372.
- Théry-Parisot I, Chabal L, Chrzavzez J. 2010. Anthracology and taphonomy from wood gathering to charcoal analysis. A review of the taphonomic processes modifying charcoal assemblages in archaeological contexts. *Palaeogeography Palaeoclimatology Palaeoecology* 291(1–2):142–153.
- Thompson VD, Krus AM. 2018. Contemplating the history and future of radiocarbon dating in the American Southeast. *Southeastern Archaeology* 37(1):1–11.
- Towner RH. 2015. Collecting and caring for tree-ring samples in the Southwest. *Advances in Archaeological Practice* 3(4):397–406. doi: [10.7183/2326-3768.3.4.397](https://doi.org/10.7183/2326-3768.3.4.397).
- Turkon P, Manning SW, Griggs C, Ramírez MAS, Nelson BA, Padilla CT, Wild EM. 2018. Applications of dendrochronology in north-western Mexico. *Latin American Antiquity* 29(1):102–121.
- van der Plicht J, Bronk Ramsey C, Heaton TJ, Scott EM, Talamo S. 2020. Recent developments in calibration for archaeological and environmental samples. *Radiocarbon* 62(4):1095–1117.
- Varién MD, Potter JM. 1997. Unpacking the discard equation: simulating the accumulation of artifacts in the archaeological record. *American Antiquity* 62(2):194–213.
- Venables WN, Ripley BD. 2009. *Modern applied statistics with S*. 4th edition. New York: Springer.
- Waterbolk HT. 1971. Working with radiocarbon dates. *Proceedings of the Prehistoric Society* 37(2):15–33. Cambridge University Press.
- Whittle A, Bayliss A, Healy F. 2010. Event and short-term process: times for the Early Neolithic of southern Britain. In: Bolender DJ, editor. *Eventful archaeologies: new approaches to social transformation in the archaeological record*. New York: SUNY Press. p. 68–87.
- Wilshusen RH. 1986. The relationship between abandonment mode and ritual use in Pueblo I Anasazi Protokivas. *Journal of Field Archaeology* 13(2):245–254.
- Wilshusen RH. 1989. Architecture as artifact. Part II: a comment on Gilman. *American Antiquity* 54(4):826–833.
- Wilshusen RH, Blinman E. 1992. Pueblo I village formation: a reevaluation of sites recorded by Earl Morris on Ute Mountain Ute tribal lands. *Kiva* 57(3):251–269.
- Wilshusen RH, Ortman SG. 1999. Rethinking the Pueblo I period in the San Juan drainage: aggregation migration and cultural diversity. *Kiva* 64(3):369–399.
- Wilshusen RH, Schachner G, Allison JR, editors. 2012. *Crucible of pueblos: the Early Pueblo Period in the northern Southwest*. Los Angeles: Cotsen Institute of Archaeology, University of California.
- Wilshusen RH, Van Dyke RM. 2006. Chaco’s Beginnings. In: Lekson SH, editor. *The archaeology of Chaco Canyon: an eleventh-century Pueblo regional center*. Santa Fe (NM): School of American Research.
- Woodhouse CA, Losleben M, Chowanski K. 2006. McPhee—PIED - ITRDB CO610. Retrieved from National Centers for Environmental Information NESDIS NOAA U.S. Department of Commerce website: <https://www.ncdc.noaa.gov/paleo-search/study/5314?siteId=17659>.