

**Dendrochronological Sourcing of Timbers from
the Great Houses of Chaco Canyon, New Mexico:
Building a millennium-length ponderosa pine
tree-ring chronology from the greater
Bandelier-Jemez Landscape**

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INTRODUCTION

The cultural history of Chaco Canyon is characterized by connections with distant landscapes. The “Chaco Phenomenon” during which the Chacoan Anasazi peoples inhabited and utilized the canyon lasted for roughly three centuries (A.D. 850-1130). During this period, Chaco Canyon was the center of a civilization that spread across the San Juan Basin of present day northern New Mexico (Figure 1). On the canyon floor was Chaco’s “downtown,” where great house structures hosted many festivals and activities.

Constructing the great houses of Chaco Canyon required enormous investments in labor and materials, on a scale far greater than most other North American construction efforts at the time. Dean and Warren (1983) estimated that 240,000 trees were harvested to build the great houses. Early archaeologists in Chaco believed these timbers came from a prehistoric forest that blanketed the canyon and was entirely cut down for the civilization (Douglass, 1935; Judd, 1954, 1964). Evidence in support of this hypothesis came from remnant logs and live trees located in secluded areas of the canyon, and from a lone ponderosa pine (*Pinus ponderosa*) log discovered in the west courtyard of Pueblo Bonito, the main great house structure (Judd 1954). Recent research, however, has challenged the interpretation that the plaza tree grew in Pueblo Bonito (Guiterman, Swetnam, Baisan, & Dean, n.d.; Wills, 2012).

Paleoenvironmental reconstructions in Chaco Canyon from plant macrofossils in packrat middens revealed that ponderosa pine, the most common architectural timber after ca. A.D. 920, was not abundant enough in the canyon to provide the necessary quantity of timber for great house construction (Betancourt & Van Devender, 1981). This discovery led to a new interpretation of timber procurement: the immediate environs of Chaco Canyon were not the primary source for timber, and almost all timber must have come from the forested uplands and

mountain ranges surrounding the San Juan Basin. Supporting evidence for the long-distance transport of timbers comes from the identification of spruce (*Picea*) and fir (*Abies*) species within the collections of great house timbers (Betancourt et al. 1986). As was the case through the late Holocene, these species are constricted to high elevations where growing conditions are cooler and wetter than at lower sites. Thus only a few candidate mountains at some distance from Chaco are the likely harvest sites for timbers. These areas have been identified through geochemical provenance methods that identify the source of construction beams by comparing their geochemical signatures (e.g., the strontium isotope ratio [$^{87}\text{Sr}/^{86}\text{Sr}$]) to those of modern trees growing in potential harvesting areas. Strontium isotopes of spruce and fir beams strongly suggest as source areas the Chuska Mountains > 75 km to the west and the San Mateo Mountains (i.e., Mount Taylor) > 80 km to the south of Chaco Canyon (English, Betancourt, Dean, & Quade, 2001).

Reynolds et al. (2005) analyzed the strontium signatures of ponderosa pine beams to determine their source areas, but the results are more difficult to interpret due to a wider realized niche of ponderosa pine and less distinguishable bedrock for geochemical sourcing. We posit that dendrochronological sourcing of timbers might provide a higher resolution view into the timber harvesting and procurement practices employed by the builders of the Chacoan great houses. Using tree-ring width correlations between construction beams and *in situ* chronologies has helped to decipher complex wood trading and transportation patterns across Europe (Bridge 2012; Wazny 2002), but has never been applied in the Southwestern U.S., or at any large scale in North America. Applied to the Chaco Culture, tree-ring sourcing of beams would highlight important areas for timber harvesting, help to distinguish the spatial scale at which timber was harvested (i.e. forest to landscape scales), and the conditions of the prehistoric forests with which

Chacoans interacted. This information would allow for an improved model of human-environmental interactions during the Chaco Phenomenon by reconstructing the timber procurement practices of great house construction.

Sourcing architectural beams from the Chacoan great houses requires tree-ring chronologies that are representative of potential timber harvesting areas. The ideal chronologies would be built from remnant logs found *in situ* rather than from archaeological wood remains with uncertain or unknown growing provenience. To overlap with the Chacoan beams, the chronologies must begin around A.D. 850, thus challenging us to construct or locate millennium-length chronologies. Additionally, the ideal chronology would be built from ponderosa pine, since this species makes up the majority of primary beams vital for the construction of the characteristic large rooms within Chacoan great houses. Despite nearly a century of dendrochronological work in the Southwest, tree-ring chronologies from the Chaco Woodshed that fit this “ideal” are rare. The existing long chronologies are composed of archaeological wood prior to the 1300s, or were built from species such as Douglas-fir (*Pseudotsuga menziesii*), southwestern white pine (*P. strobiformus*), and/or limber pine (*P. flexilis*). Many gaps exist in the spatial distribution of the available chronologies as well, marking the need to build new chronologies from selected locations in order for the reconstruction of timber procurement practices at Chaco to proceed. A noted gap is to the east of Chaco Canyon in the greater Bandelier-Jemez region, where Puebloan peoples are known to have migrated during the depopulation of the Colorado Plateau in the late thirteenth century. Little evidence exists for Chacoan use of the Jemez landscape; however, some obsidian from Chacoan middens has been sourced to the Valles Caldera area (Cameron, 2001). Apparently, this source for obsidian took on more importance later in time, during the occupation at Mesa Verde (Arakawa, Ortman, Shackley, & Duff, 2011). Should Chacoan beams prove to

have grown in the Jemez region, it would signal previously unknown prehistoric ties between Chaco and Bandelier.

The objective of this study is to investigate the potential for building a millennium-length ponderosa pine tree-ring chronology from the greater Bandelier-Jemez region. Such a chronology would not only benefit efforts to source Chacoan timbers, it would also provide an invaluable record of past environmental and climatic change in the region.

METHODS

The study area includes the landscapes of Bandelier National Monument, the Jemez Mountains, and Mesa Alta at the northern extent of the Jemez (Figure 2). In order to sample ancient tree-ring material, we targeted our search for site locations based on geologic and forest characteristics that indicate the presence of old trees and well preserved remnant logs. Such sites are typically steep and rocky, lacking deep soils and understory vegetation. These conditions hinder rapid growth of trees, which tends to correspond to long-lived individuals (Schulman, 1954) and an elevated climatic signal (Fritts, 1976). Shallow and rocky soils promote dryness of remnant logs and thus slow decomposition rates, which in the Southwest could result in logs that have been on the ground for over 1,000 years. Since ponderosa pine is so well adapted to fire, finding ancient ponderosa logs is extremely difficult due to remnant material being consumed by historically frequent fires. Sites that lack well distributed understory vegetation, such as grasses, are protected from surface fires and thus have the potential for long-term wood preservation. Unfortunately, given the abundance of forest fuels today as a result of fire exclusion and suppression throughout the Southwest (Swetnam & Baisan, 1996, 2003), and increasing

temperatures from global warming, present day fires pose a great risk to remnant tree-ring materials. These rare ecological and climatological resources are more often being consumed by today's large and intense fires, thus making the search for and collection of old wood a necessary and timely effort.

Once we had found what looked to us like a suitable site for building a long ponderosa pine chronology, we sampled ~20 live trees and all remnant logs that met our guidelines, as described below. Every tree and remnant log was identified individually and marked spatially with a GPS device. Of the live trees, we cored all of the oldest looking individuals, and selected the best individuals from smaller and younger-looking size classes. This sampling design enables a long and consistent signal in our tree-ring chronology and ensures a complete record of each ring from present back as far as the oldest living individuals. From each tree, we extracted two cores with an increment borer.

More important to this study, however, were the remnant logs that we sampled. We targeted our sampling for the largest, best preserved, and oldest-looking logs we could find at each site. Although a small proportion of remnants that did not look so old were sampled to ensure overlap with the living tree sample. The attributes on which we targeted our sampling are important for ensuring a long tree-ring series (individual tree chronology), a complete record with solid wood that can be prepared and interpreted with relative ease, and a long overall chronology. It's impossible to estimate the age of a log while in the field, before the rings have been crossdated, but there are several attributes that signify a potentially old log. First, the sapwood must be completely eroded away. Especially in ponderosa pine, which has thick sapwood, the outermost portion of the xylem is the first thing to decompose after the tree dies. Often, sapwood only persists for a century after the tree dies. Next, wood exposed to sun, wind, and freezing

temperatures begins to turn grey or even yellowish in spots, dry out, and flakes off. The “flakiness” of a log indicates that the heartwood is beginning to physically erode, which differs in its appearance and timeframe from the biological decomposition of the sapwood. Third, as the heartwood erodes over time the flakiness will often dissipate, and grooves or narrow slots of erosion into the exposed part of the wood will appear. This makes for characteristic “fins” of wood that follow the vertical orientation of the grain, which on a log that remains from an old tree might have a spiraling shape along the long axis of the bole. Fourth, but not necessarily final, lichen will often be growing on logs that have been on the ground for a long time, and give the log a similar appearance to the rocks on which it’s lying. In addition to these criteria, we note that well preserved logs of any age (especially ancient logs) will be very solid and hard due to their high resin content. Thus, a good kick to a solid log is positive sign for a potentially valuable sample.

Once located, sectioning the logs is necessary for a complete and usable record of each remnant piece. Removing sections is most easily accomplished with a chainsaw, targeting the specimen for the most number of rings on each log. Determining where exactly that point is requires experience and a bit of searching on the log to see the patterns of rings exposed on the outside. Sometimes two or more sections are required to ensure the longest series for that log. Cut sections should be at least 2 inches thick to ensure stability and a quality end product.

In the lab, our sample preparation and analyses followed the standards of dendrochronology (Stokes & Smiley, 1968). We mounted the tree cores and remnant specimens, and then sanded them to a polish with increasingly finer grit sandpaper. The polished surface allows us to clearly see the tree rings and any intra-ring features (e.g., false latewood bands) under magnification. We crossdated the specimens via skeleton plots (Douglass, 1941) and/or by measuring total ring

width and applying correlations to dated chronologies (Grissino-Mayer, 2001). Reference chronologies from the region helped to precisely date each tree and log. Once dated, we measured the entire collection for total ring width (TW), earlywood width (EW), and latewood width (LW) to the nearest 0.001 mm on a velmex measuring system. We distinguished the EW-LW boundary based on the methods of Meko & Baisan (2001). We performed quality control of measurements and a check of crossdating accuracy with the program COFECHA (Grissino-Mayer, 2001).

Standardization of the tree ring series was performed with a cubic smoothing spline at 50% frequency response and a 100-year wavelength (Cook & Peters, 1981). The final LW chronology had to be adjusted (LW_a) to remove biological autocorrelation with the preceding EW, which we did via linear or polynomial regression of each LW measurement against its EW counterpart (Griffin, Meko, Touchan, Leavitt, & Woodhouse, 2011). Signal strength of the chronologies (TW, EW, LW_a) was assessed by calculating effective chronology signal ($\bar{r}_{eff}$) and expressed population signal (EPS). The $\bar{r}_{eff}$ estimates the mean between-tree correlation and thus indicates the strength of the common signal between trees, with values above 0.5 considered significant (Cook & Kairiukstis, 1990). The EPS estimates the overall signal strength of the total population, with values above 0.85 considered necessary for climatic reconstruction (Briffa & Jones, 1990; Wigley, Briffa, & Jones, 1984). All statistical analyses were performed in R (R core team, 2013) using the dplR library (Bunn, 2008) and with additional functions written by C. Guiterman for this study. These functions included one to perform the latewood adjustment for each measured tree-ring series. The function is undergoing more testing and will soon be contributed to the dplR library for public use.

RESULTS

We sampled five sites in the great Bandelier-Jemez Mountains region (Figure 2). At the southern end, our sample locations clustered around the Monument Canyon Natural Research Area, with sampling that updated two chronologies (Cat Mesa [CMM] and Abouseiman Spring [ABM]) and added a new chronology (Padre Alonzo Trail [PAL]). The updated chronologies were originally sampled in the 1980s to produce ponderosa pine chronologies as climatic controls for a study on western spruce budworm (Swetnam & Lynch, 1993). These three sites were sampled as part of broader collaborations and capitalized on two other initiatives: (1) the North American Dendroecological Fieldweek (NADEF), which is a teaching workshop in dendrochronology and is partially supported by the National Science Foundation (NSF). Co-PIs Guiterman and Swetnam were instructors in the fieldweek. And (2) an NSF Coupled Human-Natural Systems project led by Swetnam that is investigating the relationships of the Jemez ancestral populations with local fire regimes in the Jemez Mountains. Since climate and fire are tightly linked, building these new and updated chronologies is a vital piece in the massive effort to understand the human-climate-fire nexus that the study team is investigating.

One of the two northern sites was co-located with an existing 1,364-year long chronology composed of Douglas-fir and southwestern white pine (Touchan, Woodhouse, Meko, & Allen, 2011). We surveyed the site and the area of Mesa Alta in search of ponderosa pine, and found that the exact location of the Touchan et al. (2011) MEA site had great potential for a pure ponderosa pine chronology (this is our Canada del Potrero [CDP] site). With further investigation, we discovered nearly identical site conditions to the east on another finger of Mesa Alta (the Mesa del Camino [MDC] site). In addition, we have identified on aerial photos two

other areas on Mesa Alta that share these conditions and the great potential for long tree-ring records, but that we didn't have the time to investigate on the ground (Figure 3).

From the five sites, we collected specimens from 268 trees and remnant logs (Table 1). All sites provided chronologies over 500 years in length, with the Mesa Alta sites (CDP and MDC) having the only specimens that reached over 1,000 years and overlap with the period of occupation at Chaco Canyon. Therefore, these two sites received the majority of our attention in the sample processing and analyses, and this report will share that focus.

The two sites at Mesa Alta are so closely located to each other that we treated them as a single amalgamated site. The result is a continuous 1,392-year ponderosa pine tree-ring chronology (620-2011) (Figure 4). As far as we know, this is the longest measured ponderosa pine chronology in the Southwest, and the third long ponderosa pine chronology in existence. Crossdating statistics are strong, with an interseries correlation of 0.800 and a mean sensitivity of 0.533. These favorable statistics place the Mesa Alta chronology in the upper 90th percentile of all ponderosa pine chronologies that are publicly available on the ITRDB (<http://www.ncdc.noaa.gov/paleo/treering/cofecha/speciesdata.html>). There are a total of 115 series with 24,219 rings. The average series length is 211 years. In all there are 733 absent rings, or 3.027% of the total.

Sample depth at the Mesa Alta site remains relatively high (≥ 5 series) from present to approximately 1500 (Figure 5). Only two specimens bridged the late-1400s, when a disturbance may have killed many trees at that time. Prior to 1490 the sample depth is again quite good until the early 1200s, though we noted generally short individual series during this period, and the reason for that is a mystery to us. As is common throughout the Southwest, remnant logs predating the 1200s are rare, and sample depth from 620 to 1220 remains between one and three

specimens. While quite low, the chronology clearly demonstrates the potential for building a long ponderosa pine chronology from Mesa Alta should the other two potential sites be sampled at some point in the near future. For the purposes of sourcing archaeological timbers, however, our Mesa Alta chronology may have to be combined with that of Touchan et al. (2011) if the different species indeed share a common signal.

Since all specimens were measured for EW and LW, we analyzed the signal strength of these separate partial ring chronologies (Figure 6). The EW chronology shows strong coherence (Figure 6A), while the LW_a chronology is considerably more noisy, with a wider dispersion of individual series around the mean chronology (Figure 6B). Statistics of signal strength reflect these patterns (Figure 6C), with the EW chronology showing high $\bar{r}_{\text{eff}}$ and EPS values from 1250-2011, while the LW_a never reaches the $\bar{r}_{\text{eff}}$ threshold of 0.5 and only reaches an EPS of 0.85 in 1590 when there are 19 measured radii (Figure 6D). Statistics for TW are similar to EW, but the EPS threshold of 0.85 is reached with only 3 series, in A.D. 980.

DISCUSSION

This study achieved a great success in building a millennium-length tree-ring chronology from ponderosa pine in the Bandelier-Jemez Region. Our chronology from Mesa Alta is one of only five of any species in the Four Corners and San Juan Basin region. The others are the El Malpais Douglas-fir chronology (Grissino-Mayer, 1996; Stahle et al., 2009), a Douglas-fir/limber pine chronology from the southern San Juan Mountains (Bigio, 2013), the Mesa Alta Douglas-fir/southwestern white pine chronology (Touchan et al. 2011), and a ponderosa pine chronology from Narbona Pass in the Chuska Mountains (Guiterman, *unpublished data*). These

chronologies, built from *in situ* remnant materials are vital for future work to decipher the origins of construction timbers from the great houses of Chaco Canyon.

The overall signal strength and crossdating statistics from our Mesa Alta chronology are among the highest in the region, marking the great potential that this chronology has for expanded and improved analyses of climatic variability and reconstructions of precipitation and stream flow. Because it was measured separately for EW and LW, the chronology will also prove useful in reconstructions of long-term variability in summer precipitation. Recent studies have demonstrated the value in LW_a chronologies for reconstructing the dynamics of the North American Monsoon (NAM) (Faulstich, Woodhouse, & Griffin, 2012; Griffin et al., 2011, 2013; Meko & Baisan, 2001; Stahle et al., 2009; Woodhouse, Meko, Griffin, & Castro, 2013). As part of this study, Guiterman and colleagues taught the introductory group during the 2012 NADEF, which updated the Cat Mesa chronology in an attempt to extend it back in time over 500 more years by sampling remnant materials. This ambitious goal was not met, but important lessons came out of the group's work. We discovered that tree-to-tree variability in LW in the northern tier of the NAM (i.e., the Jemez Mountains) is so high that substantial sample collection is required for acceptable signal strength statistics (Brice et al., 2013). At Cat Mesa, 23 trees were needed for an EPS greater than 0.85, which we postulated could be related to relatively deep soils at Cat Mesa. The site conditions could be storing water through the Southwest's pronounced foresummer drought (May and June) and reducing the sensitivity of trees to variability in monsoon moisture.

With this lesson learned prior to our field visit at Mesa Alta, we increased the numbers of samples we would have otherwise collected in the hopes of generating high signal-to-noise ratios in the final chronology. Overall, the effort was met with success. Our Mesa Alta LW_a

chronology is robust for nearly 300 years longer than the Cat Mesa chronology, and required fewer trees to reach an EPS of 0.85. In the coming months, we will begin to analyze the climatic sensitivities of the EW and LW_a chronologies to assess their viability for climatic reconstruction.

Early in the design stages of our tree-ring sourcing project, we hypothesized that LW might be instrumental in deciphering harvesting locations of Chacoan timbers. We reasoned that since NAM-related convective storms during the summer are highly localized, trees from the same mountain ranges should closely share LW variability. However, we later learned that this reasoning may be flawed due to high tree-to-tree variability in LW at the same site (e.g., Brice et al. 2013). Still willing to test the hypothesis directly, we are currently measuring the Chacoan timbers for EW and LW.

With a new and valuable chronology from Mesa Alta added to our network of tree-ring records from the Chacoan Woodshed, we are nearly ready to begin sourcing architectural timbers from the great houses via tree-ring analyses. We plan to have measurements of roughly 150 architectural specimens distributed among as many great houses as possible. We will choose the specimens based on three criteria, listed in order of importance: (1) contain more than 75 measured rings, (2) have a distinct archaeological provenience, and (3) have a cutting date. We will evaluate two approaches to sourcing the timbers. First, we will perform correlations between the timbers and source-area chronologies based on TW, and then calculate T-values and significance of the correlations. The source area with the highest correlation is thus the most likely origin for that tree. This methodology follows the European experience (e.g., Wazny 2002) where the source-area chronologies do not generally correlate against each other (i.e., crossdating is localized). In the Southwest, our chronologies all correlate well against each other ($r > 0.5$), and some method to remove the common signal may be required. Therefore, we will

evaluate a second method, whereby the common signal of all source-area chronologies is quantified through principal components analysis. The first principal component (PC) may explain up to 56% of the common variance among chronologies (e.g., Williams et al., 2013). We can then regress this first PC against the source-area chronologies and keep the residuals, thereby removing the common signal. In theory this should produce localized chronologies that either do not correlate against each other or have much reduced correlations. The same regression method would then be applied to the architectural timbers. Correlations of residuals from the timbers against the source-area residuals will be performed as we did with TW, with the same ranking of significant T-values.

In the next step, we will compile the results from the correlation analyses to highlight areas with the highest correlations of the most timbers. These timbers will be grouped and analyzed for clustering (via PCA or hierarchical clustering [Domínguez-Delmás et al., 2014]). The clusters will be assessed for signal strength as a way of deciphering potential spatial coherency given published results of signal strength from trees sampled *in situ* at sites of various sizes. The goal of this analysis is to try to decipher the spatial extent of harvesting, whether trees were typically cut from small areas—forest to stand scales—or were cut across larger areas perhaps to fulfill certain desired size classes.

The millennium-length ponderosa pine chronology from Mesa Alta that we have built during this project is an invaluable record of past climate, environmental conditions, and tree growth in the greater Bandelier region. While further work is required to strengthen the chronology during its earliest time periods, and possibly extend it even further back, it stands as a significant contribution to dendrochronology in northern New Mexico and the Southwest in general. Among

other purposes we are confident that it will help enable a better understanding of human behavior and human-environmental interactions of ancient southwestern peoples.

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FIGURE AND TABLES

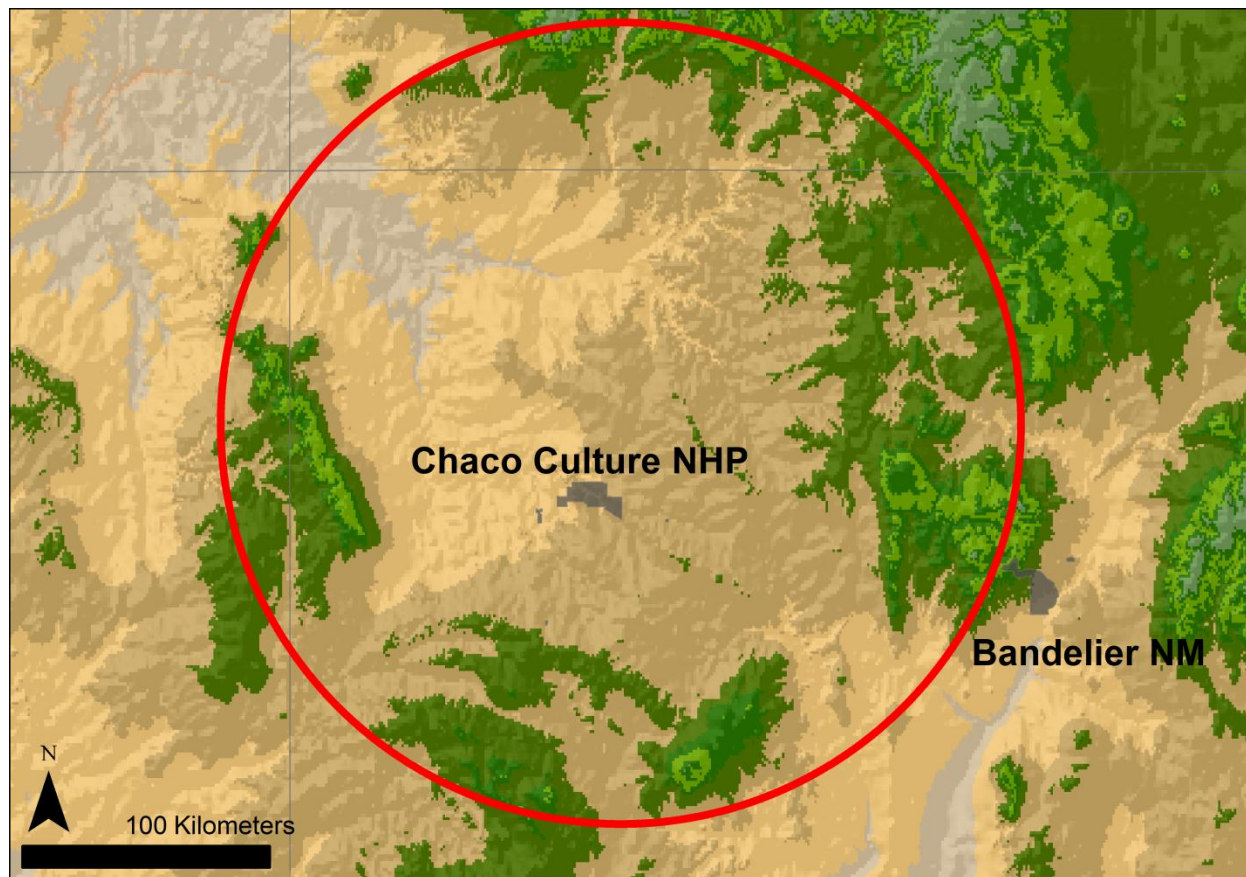


Figure 1. The Chaco Woodshed (red circle) of the San Juan Basin in northern New Mexico. Construction timbers from Chacoan great houses must have been harvested in forested upland areas and hand-carried long distances to Chaco Canyon.

Legend

-  Tree-Ring Site
-  Bandelier NM
-  3,500 m
1,200 m

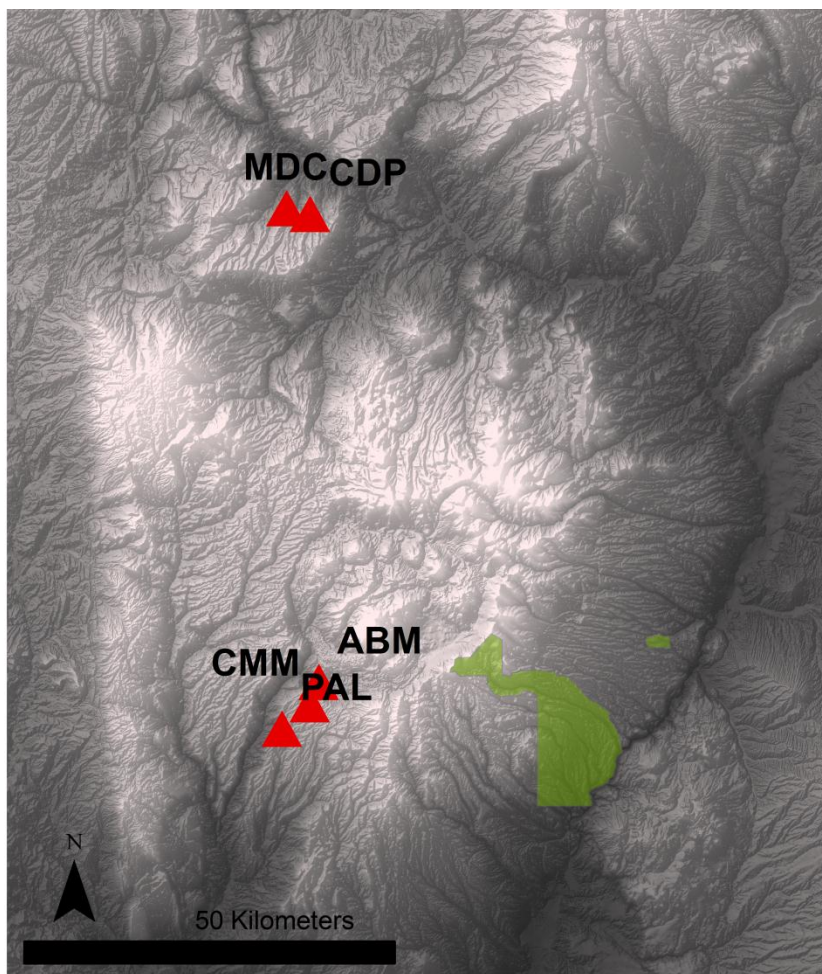


Figure 2. The greater Jemez-Bandelier study region. Study sites were clustered into the two most promising areas for building a long tree-ring chronology that we could find. Site codes are provided in Table 1.

Table 1. Summary of the tree-ring collections. The number of trees sampled is divided into live and remnant. All live trees were cored twice; some remnant logs have more than one sample.

Site Name	Abbreviation	Latitude	Longitude	Elevation (m)	Number of Trees (live, remnant)	Earliest Date
Cat Mesa	CMM	35.80559	-106.626	2561	92 (67, 25)	1335
Abouselman Spring	ABM	35.82167	-106.623	2427	35 (15, 20)	1433
Padre Alonzo	PAL	35.77615	-106.665	2364	33 (12, 21)	1431
Canada del Potrero	CDP	36.28204	-106.631	2532	73 (37, 36)	819
Mesa del Camino	MDC	36.28701	-106.661	2484	35 (0, 35)	620

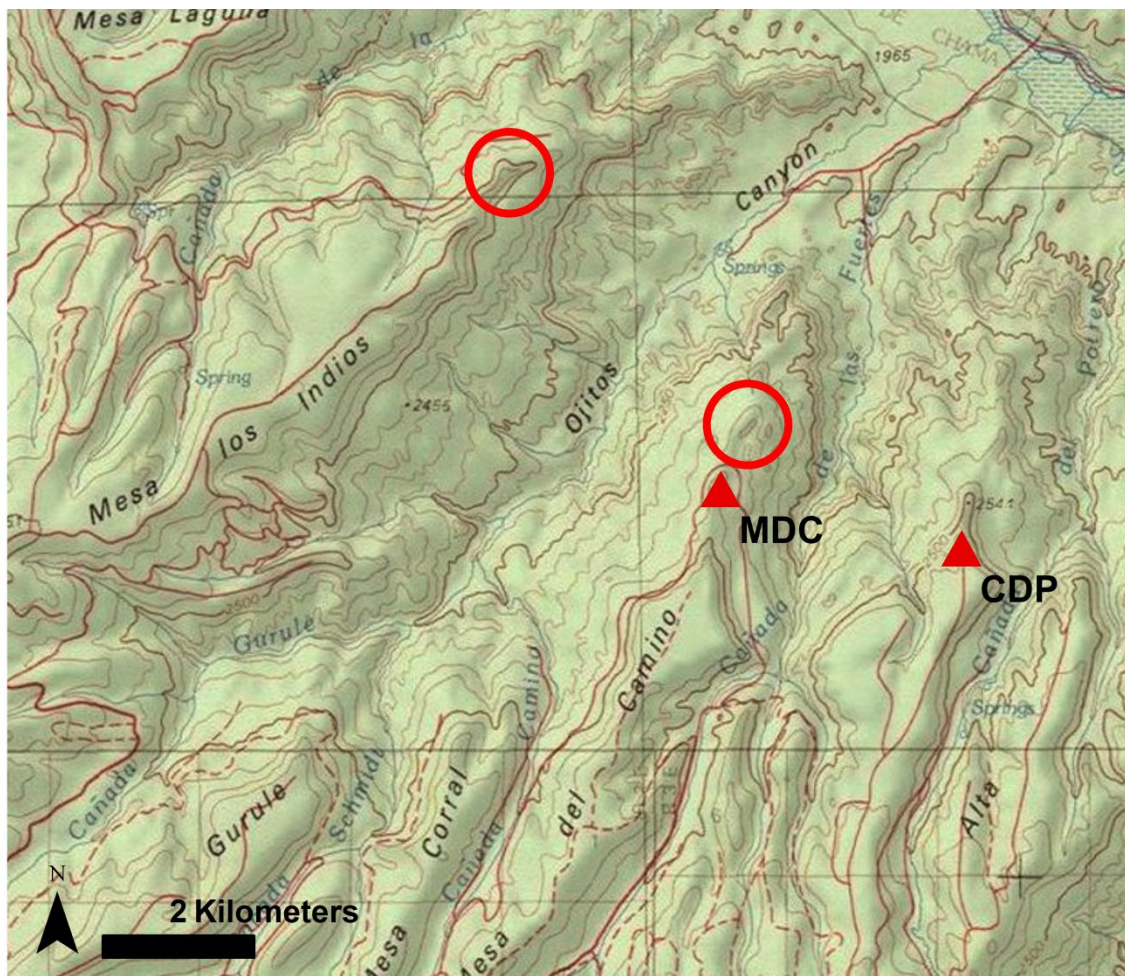


Figure 3. Close-up of the Mesa Alta study sites. Red circles indicate areas where we identified promising site conditions for long tree-ring records on aerial photos. No ground searching has been conducted at these sites.

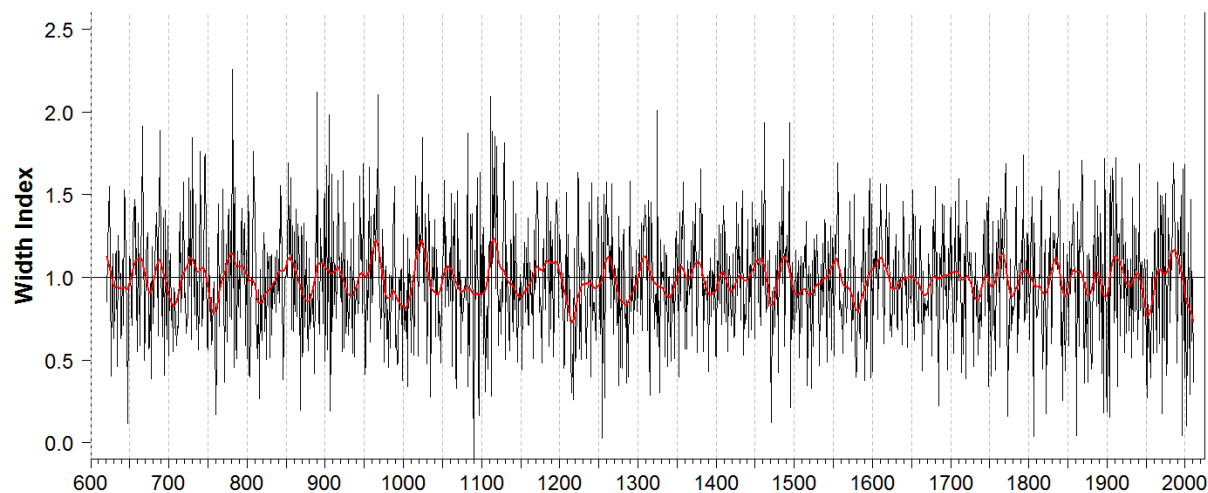


Figure 4. The final Mesa Alta ponderosa pine tree-ring chronology. Annual values are black and a 25-year smoothing spline is shown in red.

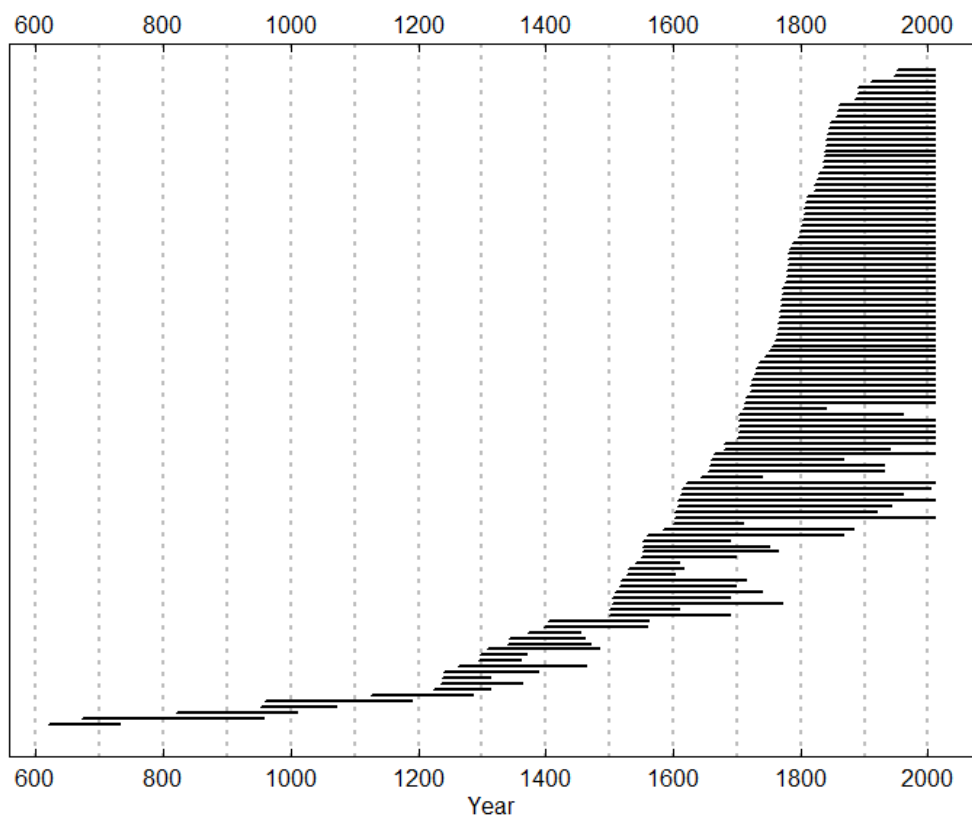


Figure 5. Segment plot showing the sample depth and series lengths from the Mesa Alta ponderosa pine chronology. Each bar represents the time interval of an individual series.

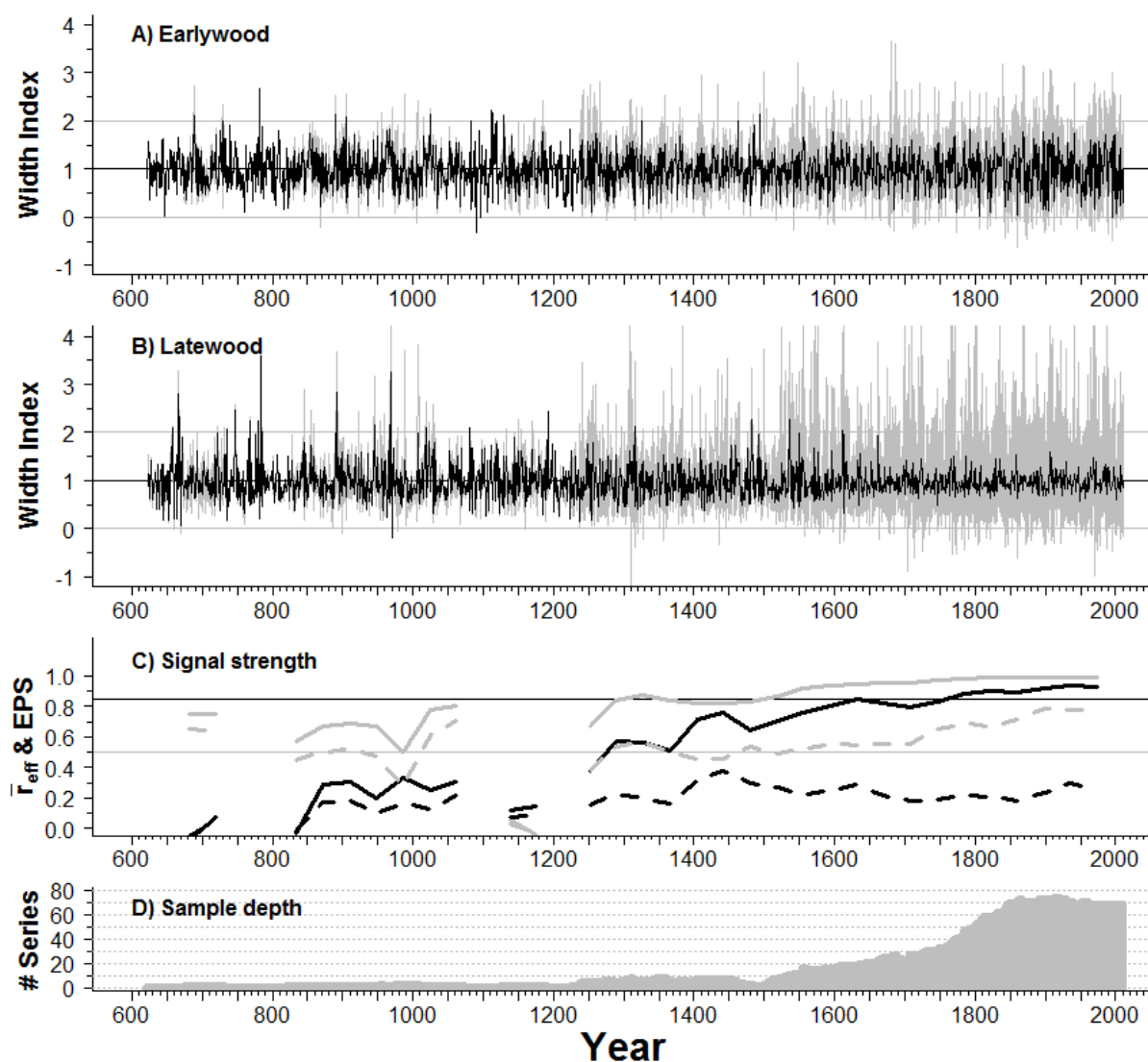


Figure 6. Time series and summary plots for the Mesa Alta partial-rig chronologies. (A) Earlywood series (grey) and mean chronology (black). (B) As in A, but for the adjusted latewood series. (C) Running effective chronology signal ($\bar{r}_{\text{eff}}$; dashed lines) and effective population signal (EPS; solid lines) calculated for 75-year windows. Earlywood values are in grey, adjusted latewood values in black. (D) Sample depth through time.